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**FEBIAD ion source development and geometric
tolerance optimisation for advanced nuclear
physics applications**

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A papà Sandrone

*“Someone told me long ago
There's a calm before the storm
I know, it's been comin' for some time*

*When it's over, so they say
It'll rain on a sunny day
I know, shining down like water*

*I wanna know, have you ever seen the rain?
I wanna know, have you ever seen the rain
Comin' down on a sunny day?”*

*- Creedence Clearwater Revival
Have you ever seen the rain*

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Riassunto

Applicazioni ingegneristiche all'avanguardia sono essenziali per il progresso della ricerca in fisica nucleare, dove dispositivi complessi devono operare in modo affidabile anche in condizioni di lavoro estreme. Questa ricerca si concentra sullo sviluppo della sorgente di ionizzazione Forced Electron Beam Induced Arc Discharge (FEBIAD), uno strumento fondamentale comunemente utilizzato per ionizzare atomi neutri negli impianti Isotope Separation On-Line (ISOL) al fine di produrre fasci ionici radioattivi (Radioactive Ion Beams, RIBs). I RIBs rivestono un ruolo cruciale nello studio delle proprietà dei nuclei instabili, favorendo progressi in diversi ambiti scientifici, tra cui la struttura nucleare, le scienze dei materiali e le applicazioni mediche.

Questo studio è condotto nell'ambito della facility ISOL SPES (Selective Production of Exotic Species) presso i Laboratori Nazionali di Legnaro (LNL) dell'Istituto Nazionale di Fisica Nucleare (INFN). L'infrastruttura SPES, attualmente nella fase finale di commissioning, è progettata per produrre RIBs utilizzando una sorgente di ionizzazione FEBIAD, operante a temperature superiori ai 2000°C e in regime di alto vuoto.

L'accuratezza nell'assemblaggio della sorgente di ionizzazione è fondamentale per garantire un processo di ionizzazione affidabile. Tuttavia, il metodo tradizionale di assemblaggio manuale e i processi di fabbricazione dei componenti introducono variabilità e incertezze nel posizionamento delle parti, causando inconsistenze nelle prestazioni. Pertanto, questo lavoro si propone di migliorare l'accuratezza dell'assemblaggio per incrementare l'affidabilità e la ripetibilità delle prestazioni del dispositivo.

È stato adottato un approccio sistematico basato sui principi del Design for Assembly (DFA) e sull'analisi delle catene di tolleranze per ottimizzare il posizionamento e l'allineamento dei principali componenti della sorgente FEBIAD, in particolare catodo e anodo, la cui distanza reciproca influenza significativamente il processo di ionizzazione. Attraverso analisi funzionali e critiche, è stata sviluppata una procedura di assemblaggio basata su strumenti dedicati, che ha migliorato in modo significativo la precisione e l'affidabilità del posizionamento dei componenti della sorgente FEBIAD durante l'assemblaggio.

Inoltre, questo studio ha esplorato l'integrazione dell'Additive Manufacturing (AM), in particolare della tecnologia Laser Powder Bed Fusion (LPBF), per la produzione di componenti in metallo refrattario destinati alla sorgente FEBIAD. La compatibilità della tecnologia LPBF per tale applicazione è stata dimostrata seguendo una procedura strutturata che comprende metodi di progettazione, simulazioni agli elementi finiti (Finite Element, FE) e test sperimentali sia a temperatura ambiente che a temperature elevate. Tale tecnica di produzione è stata validata attraverso test di ionizzazione off-line condotti presso CERN-ISOLDE, il riferimento mondiale per facility operanti con tecnologia ISOL. I componenti prodotti con LPBF sono stati esposti per la prima volta a condizioni operative realistiche e l'efficienza di ionizzazione di alcuni gas nobili di riferimento è stata misurata.

I risultati promettenti ottenuti pongono le basi per lo sviluppo di componenti innovativi per sorgenti di ionizzazione, sfruttando i gradi di libertà offerti dalla tecnologia LPBF per superare i limiti intrinseci dei metodi di produzione attuali. L'integrazione di tecniche avanzate di manifattura, come la LPBF, con procedure di assemblaggio sistematiche e configurazioni sperimentali innovative, potrebbe migliorare significativamente la ripetibilità e l'affidabilità delle prestazioni della sorgente FEBIAD. Man mano che la facility SPES si avvicina alla piena operatività, le innovazioni sviluppate in questo lavoro contribuiranno a incrementare l'efficienza e l'efficacia della produzione di fasci ionici radioattivi.

Abstract

Cutting-edge engineering applications are essential in advancing research within nuclear physics, where complex devices must operate reliably at extreme working conditions. This research is focused on the development of the Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source, a critical instrument commonly used to perform the ionisation process of neutral atoms in Isotope Separation On-Line (ISOL) facilities to produce Radioactive Ion Beams (RIBs). RIBs are crucial for investigating the properties of unstable nuclei, supporting advances across various scientific fields, including nuclear structure, material sciences, and medical applications.

The study is located within the framework of the ISOL SPES (Selective Production of Exotic Species) facility at Legnaro National Laboratories (LNL) of the Italian Institute for Nuclear Physics (INFN). The SPES facility, which is currently in its final commissioning phase, is aimed to produce RIBs employing a FEBIAD ion source, which operates at temperature above 2000°C and high-vacuum regime.

The accuracy of the ion source assembly is critical for ensuring a reliable ionisation process. However, the traditional manual assembly method and manufacturing processes of the components introduced variability and uncertainties in parts positioning, leading to performance inconsistencies. Consequently, this work is aimed to enhance assembly accuracy in order to improve the reliability and performance repeatability of such a device.

A systematic approach, based on Design for Assembly (DFA) principles and tolerance stack-up analysis, was employed to optimize the positioning and alignment of key FEBIAD components, particularly the cathode and anode, whose mutual distance significantly influences ionization process. Through functional and critical analyses, a tool-based assembly procedure was developed, which significantly improved the accuracy and reliability of the positioning of FEBIAD ion source components during assembly process.

Furthermore, this study explored the integration of Additive Manufacturing (AM), and specifically the Laser Powder Bed Fusion (LPBF) technology, to manufacture refractory metal components for the FEBIAD ion source. The compatibility of the LPBF technology for such an application was demonstrated following a structured procedure consisting of design methods, Finite Element (FE) simulations and experimental tests both at room and high temperature. Moreover, such a manufacturing technique was validated through off-line ionisation tests performed at CERN-ISOLDE, the worldwide reference ISOL facility. LPBF-manufactured components were exposed for the first time to realistic operational conditions and the ionisation efficiency of some reference noble gases was measured.

Such promising results lay the foundations for the development of innovative ion source components, exploiting the degrees of freedom provided by the LPBF technology to overcome the inherent limitation of the current production methods.

The integration of advanced manufacturing techniques, such as LPBF, with systematic assembly procedures and innovative experimental setups, could significantly improve the repeatability and reliability of the FEBIAD ion source performance. As the SPES facility approaches full operational capacity, the innovations developed through this research will be useful to enhance the efficiency and effectiveness of its radioactive ion beam production capabilities.

Chapter 1: Introduction

High-engineering applications are essential for innovations and research in many scientific fields, with nuclear physics being a prime example. The study of nuclear physics which investigates the components and interactions of atomic nuclei, relies on complex devices and systems designed to meet the rigorous demands of research and development. The intersection of the engineering disciplines with nuclear physics led to remarkable technological progress, including the development of innovative radiation detectors, engineered to accurately measure and analyse radiation, which is crucial for both experimental research and practical applications like environmental monitoring and medical diagnostics. Similarly, nuclear reactors, whether used for energy production or research purposes, require advanced engineering to ensure a safe, efficient and sustainable operation. In this framework, this research work is focused on developing and innovating a crucial device used for advanced nuclear physics applications, specifically within facilities that operate using the Isotope Separation On-Line (ISOL) method to produce Radioactive Ion Beams (RIBs)[1,2]. Such a device is the Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source [3] Its features, characteristics and critical issues will be deeply analysed in the following chapters. It is a fundamental instrument for the ISOL facilities as it significantly impacts the efficiency of RIB production. Currently, the FEBIAD ion source is manually assembled performing a complex mounting sequence, which introduces variability in the ion source component positioning and, consequently, on the device performances. Furthermore, the most critical ion source parts are realized with refractory metals that are typically difficult to machine and weld. Therefore, conventional manufacturing processes often result in poor component accuracy and precision, affecting the quality of the ion source assembly. These aspects highlight the need for advancements in manufacturing techniques or a redesign of the components to achieve the necessary precision for consistent performance.

This thesis is aimed at the identification of solutions capable to increase the FEBIAD ion source performance repeatability and reliability, by exploring two different complementary ways: the former is the development of a mounting procedure capable of improving the assembly repeatability o by systematic Design For Assembly (DFA) approach. The latter is the investigation of the new opportunities provided by Additive Manufacturing (AM) technologies, with the aim to design ion source components capable of bridging the gap between desired performance specifications and manufacturing capabilities.

Prior to detail the FEBIAD ion source developments, the following paragraphs will be dedicated on the exploration of the key aspects of the ISOL method, highlighting its applications in many scientific disciplines. Moreover, a comprehensive discussion of the main international facilities employing the ISOL technique and their contributions to scientific advancements will be included. The Selective Production of Exotic Species (SPES) facility at Legnaro National Laboratories of the Italian Institute for Nuclear Physics (LNL-INFN)[4] will be deeply presented as a cutting-edge project that plays a crucial role in advancing RIB production in Italy. Furthermore, the HISOL (High-performance ISOL system for the production of radioactive ion beams) project at LNL-INFN will be introduced, addressing its complementary role to SPES, focusing on its objectives and challenges including the FEBIAD-type ion source development.

1.1 The RIB production and applications

Radioactive Ion Beams consist of accelerated radioactive charged particles (i.e. ions) which are fundamental to study the properties of unstable nuclei and furthermore for advances in research in various scientific fields. One of the most prominent methods for producing RIBs is the ISOL technique, schematized in Figure 1.1: a primary beam usually constituted of light particles (e.g. protons) impinges a thick target generating nuclear reactions. The production and release of neutral radionuclides are allowed by the high working temperature of the target (above 2000 °C), which is also necessary for the migration of the radioactive species to the ion source. The ion source ionises the neutral isotopes producing positive ions, which can be extracted and delivered through electromagnetic systems to a separating magnet. Such a device precisely performs the isobaric selection of the desired isotope to generate the final radioactive ion beam, which can be further accelerated for experimental purposes.

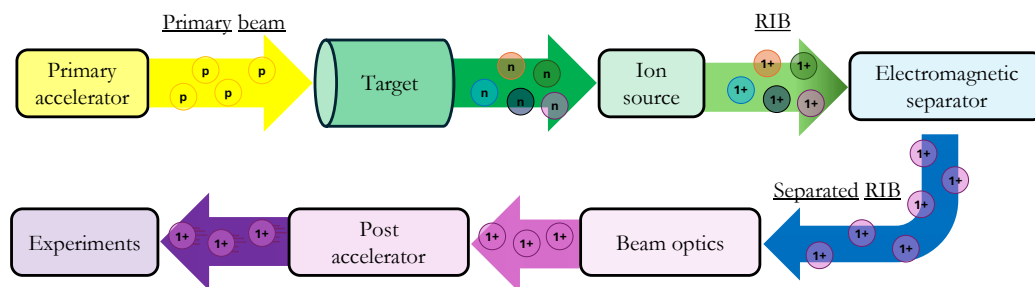


Figure 1.1 Schematic representation of the Isotope Separation On-Line technique; (p) primary proton beam particles, (n) neutral isotopes, (1+) positive ions.

The facilities operating according to the ISOL method in the world are represented in Figure 1.2, the most significant for the community are the following ones:

- ISOLDE at CERN (Geneva) [5–7] is a world-wide reference for the RIB production with more than 50 years of activity. Nuclear reactions are produced through the bombardment of a thick target using a pulsed proton beam with an energy up to 1.4 GeV and an average intensity of 2 μ A. Furthermore, depending on the needed RIB resolution, two separation magnets can be employed: the General Purpose Separator (GPS) and the High Resolution Separator (HRS). The RIBs produced at ISOLDE found application in materials science research particularly on semiconductors and oxides, with recent expansions into nanoparticles and metals. Simultaneously, biophysics research examines the impact of metal ions on biological systems, particularly their toxicity. In addition, the MEDICIS facility carries on the research on nuclear medicine and innovative radiopharmaceuticals used for both therapy and diagnosis;
- ISAC and ARIEL at TRIUMF (Vancouver) [8,9] have the availability of a cyclotron capable of bombarding the production target with protons having energy up to 500 MeV and 100 μ A intensity. The RIBs are delivered to perform research in nuclear astrophysics, which focuses on studying nuclear processes relevant to astrophysical events like nova explosions, x-ray bursts, and supernovae. Furthermore, the electroweak interaction studies conducted at ISAC allows to precisely explore the fundamental symmetries in physics. Then, experiments like TRINAT are designed to search for new physics beyond the Standard Model, including potential new bosons and the properties of neutrinos. Additionally, the ISAC β -NMR facility is unique globally and is used for probing the electromagnetic properties of materials at the atomic level. The facility allows for depth-

resolved studies by controlling the implantation depth of radioactive probe ions, providing insights into the material properties at nanometre scales;

ARIEL is a facility set to expand TRIUMF capabilities by adding two new target stations and a new high-power electron linear accelerator (e-LINAC). This infrastructure will enhance RIB production, supporting simultaneous RIB deliveries and increasing experimental productivity, providing more beam time for experiments and positioning TRIUMF at the forefront of global rare isotope science.

- The SPIRAL facilities at GANIL [10–12] are equipped to deliver ion beams ranging from protons to uranium with energies reaching up to 95 MeV per nucleon. The cyclotron facility together with SPIRAL1 facility operate since 1983 to provide RIBs for various physics experiments. Over the past decade, significant upgrades were installed to the SPIRAL1 to improve its ability to produce RIBs from condensable elements and many enhancements were developed for the Target Ion Source System. Simultaneously, the SPIRAL2 facility began its commissioning process in 2019, initiating with proton beam production. Such a facility is poised to make significant contributions to nuclear astrophysics, particularly in the study of nucleosynthesis processes essential for understanding the formation of heavy elements in the universe. Additionally, SPIRAL2 will be capable to produce a high-energy, high-intensity neutron flux for materials irradiation, cross-section measurements, and research pertaining to nuclear fission and fusion;
- The ALTO facility at IPN Orsay in Paris [13] operates with a 50 MeV electron beam directed at a converter, generating gamma-range photons. These photons then impinge a uranium carbide target, resulting in an expected fission rate of 1.2×10^{11} fissions per second when using a 10 μ A electron beam;
- The HRIBF at ORNL [14] was a recently discontinued facility which was capable to produce a wide range of high-quality RIBs, providing approximately 200 radioactive isotopes including more than 175 neutron-rich species.



Figure 1.2 Most significant ISOL facilities worldwide in 2024.

The growing demand of more intense radioactive ion beams and higher energies led to upgrade existing facilities or to construct new ones[15]. In Italy, a prime example of this effort, is the ongoing development of the Selective Production of Exotic Species (SPES) facility at Legnaro National Laboratories (LNL), part of the Italian Institute for Nuclear Physics (INFN). Such a facility is designed to operate according to the ISOL method, furthermore it is currently in an advanced phase of construction and represents a significant

step forward in the multidisciplinary research employing RIBs. The following section will focus on the specific features and capabilities of the SPES ISOL facility.

1.2 The SPES ISOL facility at LNL

The primary institution representing the field of nuclear physics in Italy is the INFN as it coordinates the national research in nuclear physics, particle physics, theoretical physics, and astroparticle physics. LNL is one of the four national sections of the INFN and the laboratories are equipped with heavy-ion accelerator complex based on a 16 MeV Tandem XTU, a Superconducting Linear Accelerator LINAC (ALPI) and a superconducting Radiofrequency Quadrupole (RFQ) heavy ion injector (PIAVE). In 2010s was approved the SPES project, which is aimed at the construction of a next-generation ISOL facility at LNL [16,17]. The SPES facility, shown in Figure 1.3, is now approaching its final commissioning phase and will soon be fully operational.



Figure 1.3 Left: INFN National laboratories; Right: SPES building at LNL (1).

1.2.1 SPES ISOL facility layout

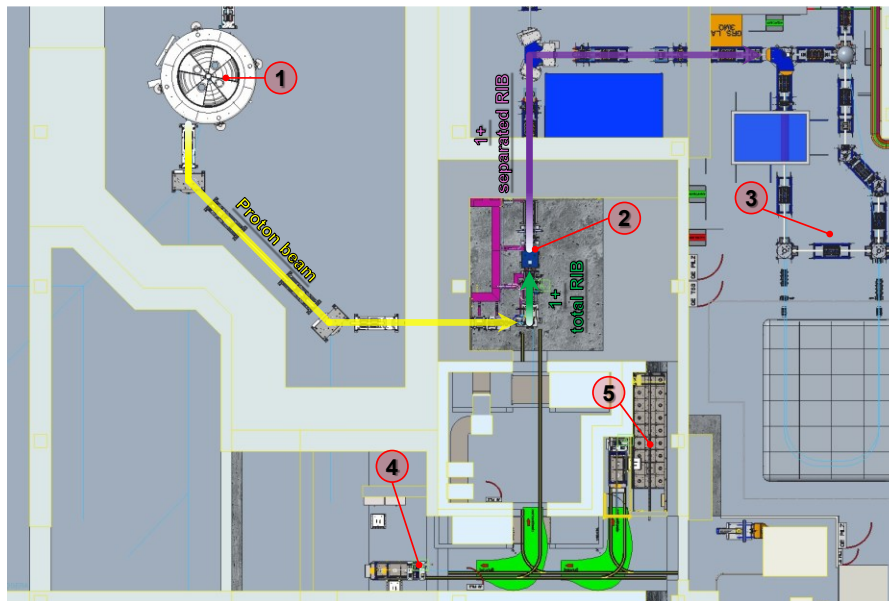


Figure 1.4 SPES building -1 floor layout; (1) Cyclotron, (2) Front-End bunker, (3) experimental halls, (4) Horizontal Handling Machine, (5) Temporary Storage System

The layout of the facility is shown in Figure 1.4. The primary proton beam is extracted from a commercial “70p cyclotron” produced by the Best Cyclotron Systems Inc (1). The transport, setup and successful commissioning of the primary driver were accomplished in 2015-2017.

The machine was installed in dedicated room as shown in Figure 1.5 and is capable to accelerate the proton beam in the 35-70 MeV energy range with a maximum of 700 μA total current.



Figure 1.5 The cyclotron room at SPES

The primary beam is transported along the beam line and is delivered to the Front-End (FE) bunker (2), where it impinges on a target to produce the radioactive isotopes through nuclear reactions. The production target is installed inside an appropriately designed vacuum chamber which includes also the ion source. For this reason, it is named Target and Ion Source (TIS) unit and is considered the core of the ISOL process. The TIS unit is coupled with the Front-End, which includes all the devices crucial for the production, ionisation, first acceleration, and first electromagnetic mass separation (isobaric purification) of the produced isotopes.

Therefore, the output of the FE bunker is an isobaric pure RIB which can be either delivered directly to users for low-energy experiments or eventually further accelerated for the high-energy experimental purposes.



Figure 1.6 The Front-End bunker in an advanced installation phase.

The TIS unit must be regularly replaced (approximately every two weeks of irradiation) during SPES operation due to the intense degradation on the components operating under extreme working conditions (i.e. radioactivity and high temperatures). However, the Front-End bunker is a highly radioactive environment, thus a remote handling system was designed

to manage the entire TIS unit lifecycle without human intervention. The Horizontal Handling Machine (HHM) [18], which is the main remote handling system for SPES, is designed to access the bunker to remove and replace the irradiated TIS unit from the Front-End (4). Once the exhausted TIS unit is collected, it is transported by the HHM to the Temporary Storage System (TSS), an automated facility designed to securely store the radioactive units allowing for their decay in a safe and shielded environment (5).

1.2.2 The radioactive Front-End

The radioactive Front-End [19] houses the TIS unit and is the primary accelerator of the produced RIB. As shown in Figure 1.7, the incoming primary proton beam transported along the beam line impinges the production target installed within the TIS unit (1). The nuclear reactions release a set of neutral isotopes which are ionised by the ion source. The ionised particles are extracted and accelerated from the TIS unit using an extraction electrode (2): the TIS unit is kept at 30-60 kV thanks to a dedicated High Voltage (HV) platform, and it is electrically insulated from the extraction electrode by means of custom-made ceramics insulators. Due to the electric field generated between the extraction electrode and the TIS unit, the positive ions are transported as a total RIB towards the subsequent stages. The term "total" refers to the fact that the ionisation process lacks significant selectivity, meaning that the ion beam at this stage consists of multiple isotopes with varying atomic masses. Subsequently, the total RIB is transported through a series of electrostatic lenses designed to correct the beam trajectory (deflectors or steerers – 3) and to focus the beam (triplets or quadrupole – 4). The total beam properties, including intensity and size, are then assessed at the first diagnostic box (5'). Such a diagnostic step is crucial to ensure proper alignment and optimal beam size before proceeding to the mass separation stage.

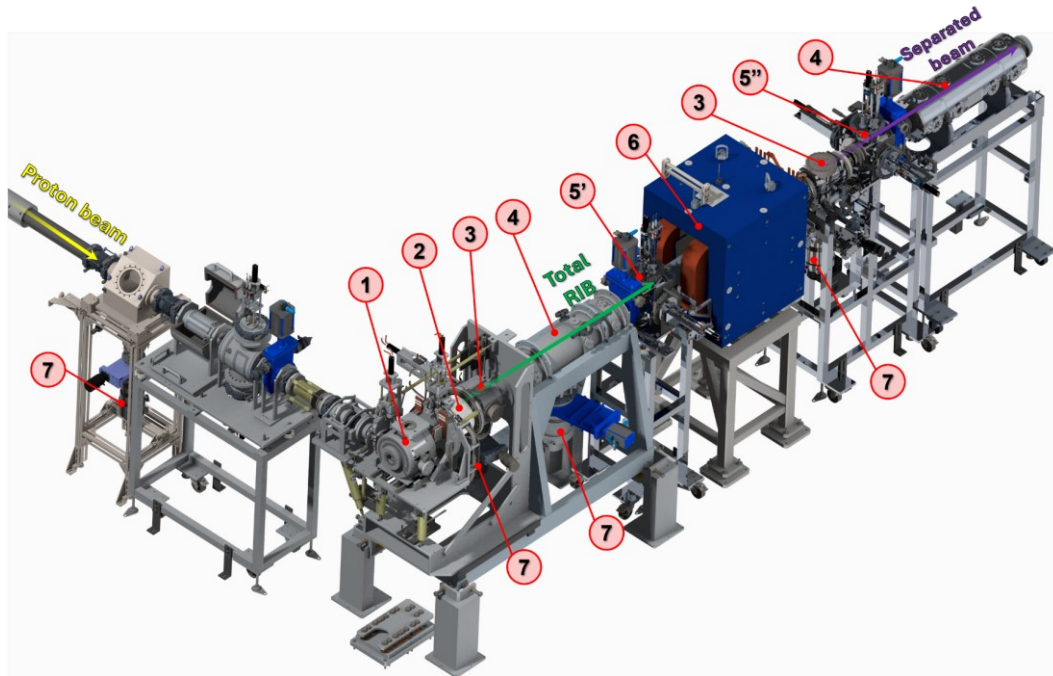


Figure 1.7 Front-End layout. (1) TIS unit, (2) Extraction electrode, (3) deflectors, (4) triplets, (5') total beam current diagnostic box, (5'') separated beam current diagnostic box, (6) Wien Filter, (7) turbomolecular pumps.

The Wien Filter (WF – 6), which acts as a velocity separator, performs the first mass separation step, enabling the extraction of an isobaric (or separated) RIB. Finally, the

separated RIB undergoes further trajectory and focus adjustments using additional electrostatic lenses, moreover its properties are evaluated by a second diagnostic box (5"). The latter is essential to provide detailed information before the RIB exits the Front-End bunker, ensuring that the beam meets the required specifications for subsequent stages. Along the beam line, turbomolecular pumps (7) are installed to provide a vacuum level around 10^{-6} mbar which is crucial both to transport the radioactive beam and to preserve the components working at high temperature from the oxidation process. The following paragraphs will provide a detailed description of the main components of the radioactive Front-End which were previously introduced.

i. Target and Ion Source unit

The TIS unit shown in Figure 1.8 is the core of the ISOL process as is where the nuclear reactions are produced due to the bombardment of the production target by the primary proton beam extracted from the SPES cyclotron.

The SPES target [20] consists of seven coaxial disks (diameter 40 mm, thickness of 1 mm) properly separated and positioned inside a cylindrical graphite box, as shown in Figure 1.9. The space between the target disks was designed to increase the acceptable primary proton beam intensity since the beam power deposition is split between the seven disks. Moreover, such a design allows to achieve a homogeneous temperature in the target. The graphite box is positioned inside a tubular tantalum (Ta) heater, which needs to maintain the target at high temperature (approximately 2000°C) to increase the isotope release. Indeed, most of the nuclear reaction products can be released by the target thanks to diffusion and effusion processes, allowed by the high working temperature of the system.

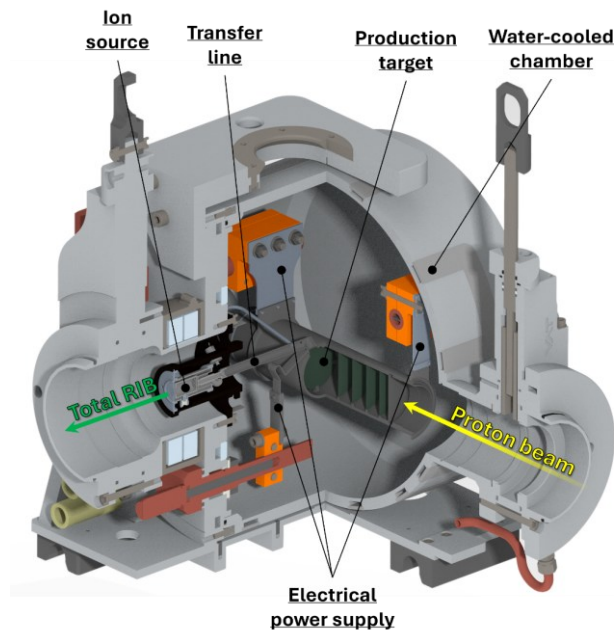


Figure 1.8 SPES Target and Ion Source (TIS) unit.

The material choice for the ISOL target is strongly constrained due to the extreme working conditions during operation. Indeed, only refractory materials resisting above 2000°C and at vacuum level of 10^{-6} mbar. Additionally, the target material selection is affected by the specific isotopic spectrum produced during interaction with the primary proton beam. Consequently, the optimal target material is determined not only by its resistance at such working conditions but also by its ability to generate the specific isotopes required for the intended research activities.

The standard SPES target is made of uranium carbide (UC_x) [21] and operates at temperatures around 2200°C. Although alternative target materials such as titanium carbide (TiC) and silicon carbide (SiC) have been developed [22,23] they are generally employed at lower operating temperatures, typically in the range of 1800–1900 °C for TiC and 1600–1700 °C for SiC.



Figure 1.9 SPES primary production target design

The released particles effuse through a tubular transfer line that connects the ion source, where the incoming neutral radionuclides are ionised. The ionisation process is a fundamental step for the following extraction and acceleration of the radionuclides as a Radioactive Ion Beam (RIB) since it allows both the transport and manipulation of the ionised species by the subsequent electrostatic devices. Different types of ion sources can be employed, however a more detailed discussion of such devices will be provided in Paragraph 1.2.3 .

The SPES TIS unit aluminium vacuum chamber is water cooled to achieve a maximum external temperature of 90°C.

Typically, the whole TIS unit is replaced after a maximum of 15 days of irradiation, utilizing a remote handling system.

ii. Extraction electrode

The extraction electrode (1) shown in Figure 1.10 attracts and accelerates the ionised particles emitted from the TIS unit to produce the total RIB. An alumina insulator (2) needs to electrically insulate the TIS unit and the extraction electrode allowing for the application of an electric field (namely, the extraction potential) between the two parts.

The extraction electrode position strongly affects the RIB properties, for this reason it can be moved thanks to the sliding guides (3) and a pneumatic motor located outside of the beam line.

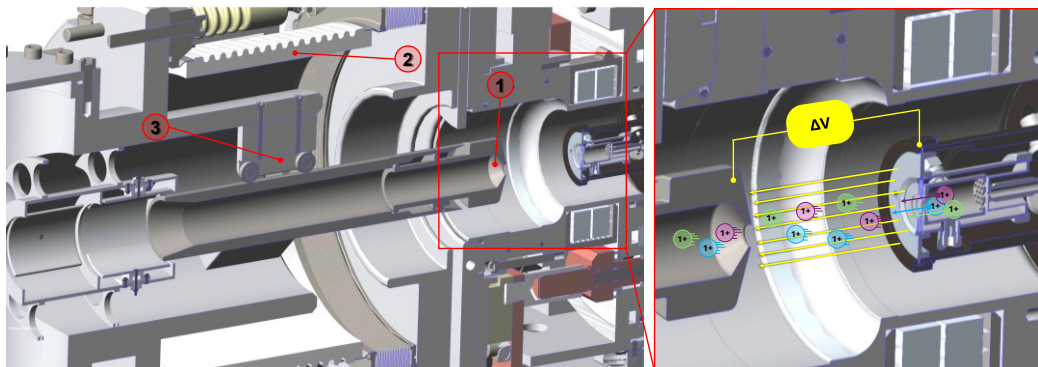


Figure 1.10 (1) Extraction electrode, (2) Alumina insulator, (3) sliding guides.

iii. Deflectors and triplets

Electrostatic devices are positioned along the radioactive ion beam line to correct any beam misalignment resulting from inherent imperfections in the manufacturing and assembly processes of Front-End devices.

The deflectors (or steerers) consist of two plates maintained at different electric potentials, generating an electric field that bends the trajectory of the charged particles. Usually, two pairs of steerers are used to correct the beam misalignment: the first deflector adjusts the beam trajectory, while the second aligns the beam to the centre of the beam line.

The triplets consist of three quadrupoles which are employed to control the beam size along the beam line. These devices are crucial for focusing the RIB, ensuring that it maintains the correct size and shape along its path.

iv. Mass separator (Wien Filter)

The Wien Filter is a device which uses a perpendicular electric and magnetic field to select particles having different velocities. Indeed, the ions produced by the TIS unit are accelerated through the extraction electrode which applies a uniform electric field, however their velocity essentially depends on their atomic mass. Therefore, the WF allows to apply the proper magnetic field to deflect the unwanted particles in order to obtain an isobaric RIB. The current used to generate the magnetic field, namely separation current I_{sep} , is the setting parameter which allows to identify precisely the mass of the selected isotope [24].

Additionally, the mass separator is the device which enables the mass scan process: it allows to precisely characterize the total RIB composition by varying I_{sep} within a specific range, while the second diagnostic box measures the beam intensity. Using this method, it is possible to analyse the RIB composition and to measure the intensity of each isotope extracted from the TIS unit.

v. Diagnostic box

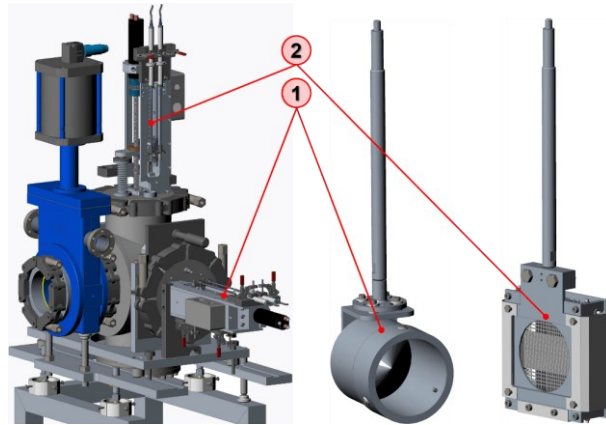


Figure 1.11 The main components of the diagnostic box are the Faraday Cup (1) and the Beam Profiler (2).

Beam diagnostics are crucial equipment of any accelerator as they allow the measurement and characterization of the beam properties and behaviour.

The diagnostic boxes installed in the FE bunker [25], as shown in Figure 1.11, are equipped with a Faraday Cup (FC) and a Beam Profiler (BP) which are inserted and retracted from the beam line by pneumatic motors. Indeed, both devices partially or completely stop the beam, they can not be used continuously, therefore they are used just during the beam preparation or analysis phases.

The Faraday Cup (1) is a beam stopper used to measure the electrical current (i.e. the intensity) of the RIB. When the positively charged particles are deposited over the metallic

and 10 V. The heating current flows through the transfer line (manufactured in Tantalum) and the so-called “hot cavity” (3), consisting of a Tantalum tubular component designed to achieve the desired temperature distribution.

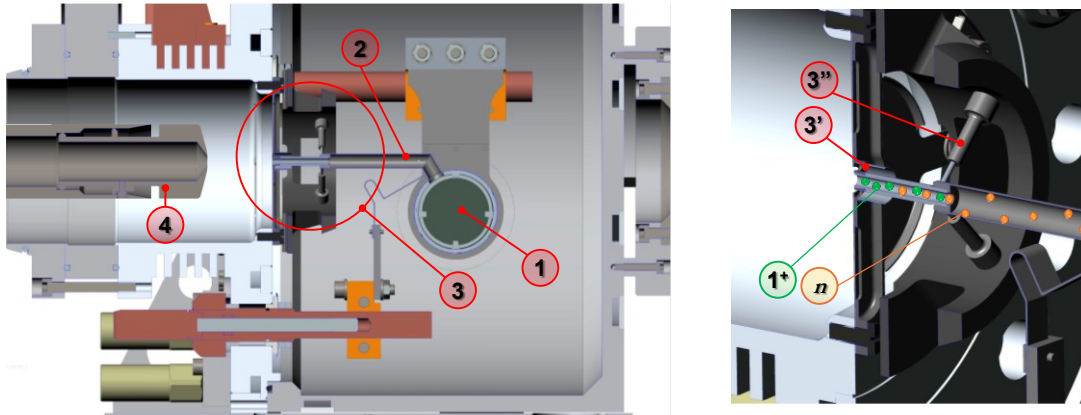


Figure 1.13 Left: (1) Production target, (2) transfer line, (3) Surface ion source, (4) extraction electrode; right: (3') hot cavity, (3'') alignment system, (n) incoming neutral isotopes, (1+) ionised positive ions.

The hot-cavity is usually heated at temperatures above 2000°C to provide sufficient energy to overcome the ionisation potential of the neutral isotopes which hits the surface. Furthermore, a system of four radial pins (3'') is used to align and block lateral movement of the SIS, which could lead to harmful misalignments. Once ionised, the charged particles are extracted from the hot cavity by the extraction electrode (3).

The simplicity and robustness of this method make it a reliable choice to ionise elements characterized by a low ionisation potential as alkali metals.

ii. SPES RILIS ion source

The SPES laser ion source [27] presents the identical mechanical assembly of the SIS ion source, as shown in Figure 1.14. However, Laser beams (1), wavelength-tuned to match the frequency of the photons to the transition energy of the valence electron(s) of a particular element, are introduced into the volume of the ion source from the ion extraction side. The hot-cavity (2) provides a stable environment for ionisation process forming a confining plasma as a result of the presence of ionised atoms and the thermionically emitted electrons from the heated walls.

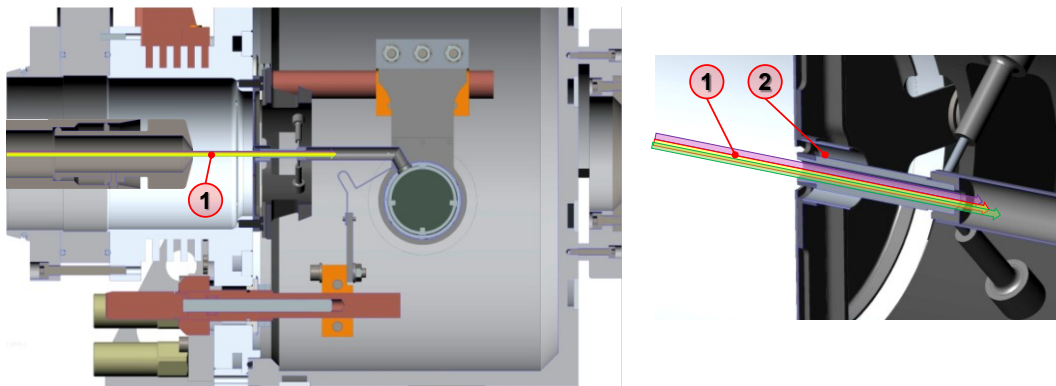


Figure 1.14 The SPES RILIS ion source, (1) Laser introduced from the ion extraction side, (2) hot cavity

The RILIS ionisation method is highly selective and efficient for ionising specific isotopes leading to the production of an almost isobaric beam just after the TIS unit.

iii. SPES FEBIAD ion source

The FEBIAD ion source [28] represented in Figure 1.15 (3) is a versatile device particularly appreciated by the ISOL community for its capability to ionise a wide range of elements.

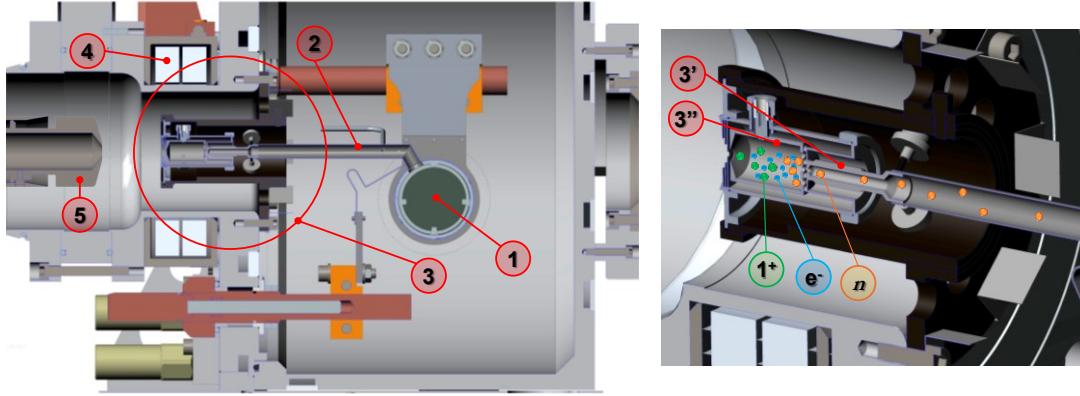


Figure 1.15 Right: (1) Primary target, (2) Transfer line, (3) FEBIAD ion source, (4) Magnet, (5) Extraction electrode; Left: (3') Cathode, (3'') Anode, (n) neutral species (e^-) electrons, ($1+$) positive ions.

The neutral atoms produced by the production target (1) migrate through the transfer line (2) into the ion source. Afterwards, they continue their motion passing through the tubular section of the cathode (3') and are injected into the anode (3''), where the ionisation process occurs.

The FEBIAD ion source relies on the electron bombardment ionisation process: the metallic cathode (usually manufactured in Tantalum), is heated above 2000°C to activate the thermionic effect, which consist of the release of electrons from metallic surfaces due to high temperatures. The electrons are accelerated by an electric field towards the anode, where they bombard neutral atoms, providing the energy required for ionisation process. Additionally, a magnetic field generated by a magnet (4) is used to induce a spiral trajectory to the electrons to increase the probability of impact with the neutral atoms.

Despite the flexibility of the FEBIAD ion source, its design results particularly complex as several components must be accurately assembled and aligned to ensure a correct functioning of the device. In this framework, the research presented in this thesis is focused on the development and innovation of the SPES FEBIAD ion source. Consequently, the next chapters will explore deeply the working principle of such a crucial component, examining also the critical aspects of its design.

1.3 The HISOL project at LNL

The HISOL (High-performance ISOL system for the production of radioactive ion beams) project was approved in 2022 at LNL with a two-year timeline. The primary objective of this project is the production and characterization of innovative, high-performance components for new generation ISOL facilities, which are more and more asking for higher performances (high intensity) and higher RIBs quality standards (high purity). Nevertheless, the conventional manufacturing technologies used to produce devices for ISOL applications are beginning to present significant limitations, hindering the development of alternative design solutions.

Specifically, the key components which will be analysed and optimised for such a purpose are targets and ion sources, that are essential for an efficient and reliable RIB production. Their developments rely on the achievement of the following steps:

- study and development of innovative materials and methods to produce ISOL targets;
- study and development of innovative methods to produce and operate ion sources;
- characterization of the obtained components by means of advanced techniques.

Among the possible manufacturing strategies that could be explored, Additive Manufacturing (AM) surely constitutes a promising opportunity for the whole ISOL community. Indeed, AM allows to overcome the inherent limits of the current production technologies leading to the possibility of designing almost free-form parts optimised for ISOL applications. In this framework, this work focuses on developing innovative methods for producing and operating ion sources, which will be explored in detail in the following sections.

The participants collaborating at the HISOL project are shown in Figure 1.16, furthermore the project organization foresees three Work Packages (WP) characterized by different topics and tasks:

i. WP1: development of high performance ISOL Targets

This work package focuses on developing SiC and TiC target materials with a controlled porosity for ISOL targets using AM techniques like UV-assisted Direct Ink Writing (DIW) and Digital Light Processing (DLP). Such technologies are available at the Ceram Glass research group [29] of the Department of Industrial Engineering at the Padova university (UNIPD-DII). Furthermore, the porosity architecture will be designed using a topological optimisation approach by the UNIPD-DII Mechanical Engineering research unit. This method will enable the performance maximization for the different parameters having contrasting requirements (e.g. compression strength and porosity) for an ideal production target.

Once produced and characterized (see WP3) the SiC and TiC samples, a complete target prototype will be assembled and evaluated under high-temperature conditions to assess their long-term stability. To achieve this, the target prototype will be coupled with a FEBIAD ion source to extract a stable ion beam observing the potential sublimation of target materials. All target disks will be weighted before and after the test to measure the mass losses.

ii. WP2: development of high performance ISOL Ion Sources

The development of high-performance ion source components is aimed to improve the device reliability and performance repeatability, especially for the SPES FEBIAD ion source. In this context, the Development and Innovation for AM (DIAM) laboratory at the Padova Section of the INFN (INFN-PD) have the availability of the Laser Powder Bed Fusion (LPBF) technology, which is an AM technique suitable for producing refractory metals parts. The DIAM lab staff has recently optimised the process parameters and characterized samples produced in Tungsten (W) and Molybdenum (Mo) using the LPBF, therefore such a technology could be used to manufacture the ion source components operating at high temperatures [30,31].

The design and the tolerance specifications for the ion source parts will be provided with the support of the Department of Mechanical and Industrial Engineering of the University of Brescia (UNIBS-DIMI), and new assembly procedures will be developed.

Once prototypical components are produced, at INFN-LNL is foreseen the design and production of dedicated experimental setups which allow to assess the performances of alternative geometries for the ion source components.

The WP2 is also involved on the ionisation tests of some elements of reference (i.e., noble gasses) employing a SPES FEBIAD ion source assembled by components manufactured through the LPBF process. The first ionisation test will be performed at the offline Front-End available at CERN-ISOLDE facility thanks to the collaboration with INFN-LNL.

iii. WP3: Materials characterization and Multiphysics Simulation

The WP3 is involved in thermal characterization for target material and thermal and electrical characterization for refractory metal samples using dedicated experimental setups developed at LNL. Ceramic disk specimens will be produced in partnership with UNIPD-DII, while metallic samples for ion sources will be manufactured by INFN-PD and INFN-LNL.

The mechanical characterization includes tensile, compression and 4-point flexion tests, and they will be carried out at UNIPD-DII using servo-hydraulic and electric machines. Additionally, fractographic analyses will be performed at both INFN-LNL and UNIPD-DII. The UNIPD-DII Metallurgy research unit will perform the materials microstructural characterization employing Optical Microscope (OM) and Scanning Electron Microscope (SEM) in addition to hardness tests and X-Ray Diffraction (XRD) analysis. Furthermore, the DTG metallurgy lab samples will be characterised with SEM-FEG, EDS, TEM and radiographic instrumentation capable of detecting defects (inclusions or pores) down to a resolution of 5 microns.

Multiphysics numerical models will be defined and validated through the collaboration between INFN-LNL, UNIPD-DII and UNIBS-DIMI groups. Specifically, the electrical – thermal and structural Finite Element Methods (FEM) of targets and ion sources will be performed by the INFN-LNL, UNIPD-DII teams in the ANSYS® Mechanical APDL environment. Moreover, the UNIBS-DIMI group, in collaboration with INFN-LNL will be involved on the development of Monte Carlo models for the simulation of the stochastic interaction between particles and matter.

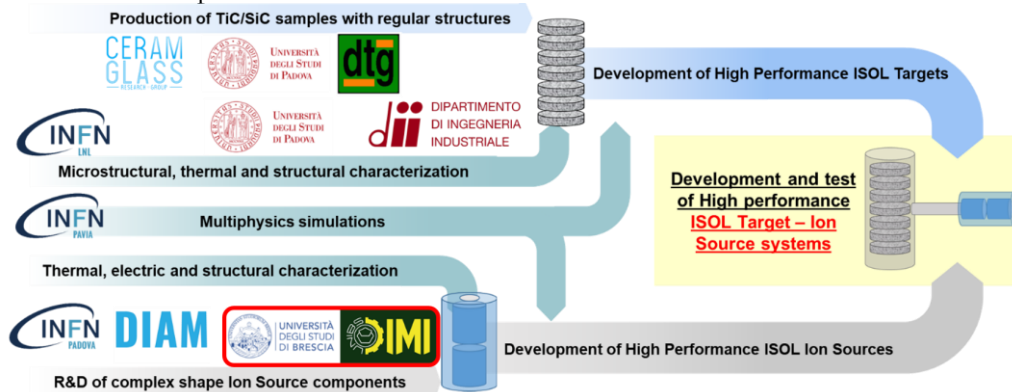


Figure 1.16 Schematic representation of the HISOL project.

1.3.1 Study and development of innovative methods for ion sources

As previously introduced, the reliability of the ion source during operation is highly desirable, therefore every modification on the design of each of its parts must be approved following several steps: the design conceptualization, the evaluation of the proposed design through FEM simulations, the production of a prototype employing the technologies available at INFN, the prototype characterization using the available experimental setups, and finally the evaluation of the ionisation efficiency for some elements of interest (i.e. noble gasses).

The ion source components must be manufactured in refractory metals such as Ta, Mo, W to resist at the requested working conditions. Furthermore, during the design conceptualization phase it is essential to approach the Additive Manufacturing considering both the advantages and limits of the LPBF process.

The prototype characterization includes both a geometrical and thermal analysis: the former will be performed at a room temperature using a Coordinate Measuring Machine (CMM) available at INFN-PD, the latter will be carried out by the HT experimental setups at INFN-LNL which will be presented in Chapter 4.

In addition, a dedicated experimental setup will be designed and produced to perform thermionic emission tests on the developed cathodes

1.4 Conclusions

This chapter provided a comprehensive overview on the ISOL method used to produce RIBs to perform forefront research in nuclear structure, reaction dynamics and interdisciplinary fields like medical, biological and material sciences. The discussion included the operational principles of ISOL facilities worldwide, with particular emphasis on the SPES facility at LNL-INFN, which represents a remarkable milestone in advancing RIBs production in Italy and is currently in an advanced phase of construction.

The ISOL process at the SPES facility is mainly performed within the radioactive Front-End bunker, which includes the devices crucial for the production, ionisation, first acceleration, and first electromagnetic mass separation (isobaric purification) of the released isotopes as a radioactive ion beam. Two of the main components of the process are installed into the TIS unit, namely the production target and the ion source: the former is impinged by the primary proton beam and releases the neutral radioactive species through diffusion and effusion processes. The latter performs the ionisation process, which is essential to transport the produced particles as a RIB. Both these parts operate at temperatures above 2000°C under high-vacuum regime (10^{-6} mbar) to increase the production efficiency of radioactive ions.

The ion source is considered a critical device as its performance and reliability affect directly the efficiency of the entire ISOL process. Furthermore, the SPES TIS unit could be equipped with three different types of ion sources, which are installed depending on their own advantages in producing ion beams suited to different experimental needs: the Surface Ion Source (SIS), the Resonance Ionization Laser Ion Source (RILIS) and the Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source.

The HISOL project at LNL-INFN was introduced as a complementary branch of the SPES R&D program, addressing specific challenges associated with ISOL facilities and contributing to the overall technological progress in the RIBs production. This thesis is collocated within the HISOL framework as it is focused on the development and optimisation of the FEBIAD-type ion source, which is extensively used by the ISOL community due to its capability to ionise a wide range of isotopes.

The following chapter will be dedicated to a detailed examination of the SPES FEBIAD ion source design and assembly procedure. A state-of-the-art review will be provided, covering its working principles and main components. The chapter will also include a systematic functional and critical analysis of the device, which are essential steps to develop and innovate the FEBIAD ion source.

Chapter 2: SPES FEBIAD ion source for radioactive ion beam production

The Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source is a key device used for producing radioactive ion beams[32], especially in ISOL facilities. Its widespread installation across the ISOL community outlines its versatility in producing high-quality ion beams used for forefront research in many scientific disciplines[33–35].

This chapter provides a comprehensive overview of the working principles of the FEBIAD ion source, detailing the operational parameters that critically influence the device performances. Additionally, the current state-of-the-art design of the SPES FEBIAD ion source is presented, including a detailed description of its main components.

The relationships between the ion source functional requirements and its design architecture are systematically evaluated through a functional analysis, while the key issues that could impact the accuracy and reliability of the ion source operation are identified by a critical analysis. Such methodologies provide the basis for a structured approach aimed at identifying the current design weaknesses and exploring alternative design solutions to enhance the FEBIAD ion source performance repeatability and reliability.

2.1 FEBIAD ion source working principle

The FEBIAD ion source is fixed directly to the TIS unit, while it is connected at the primary production target through a tubular transfer line, as shown in Figure 2.1.

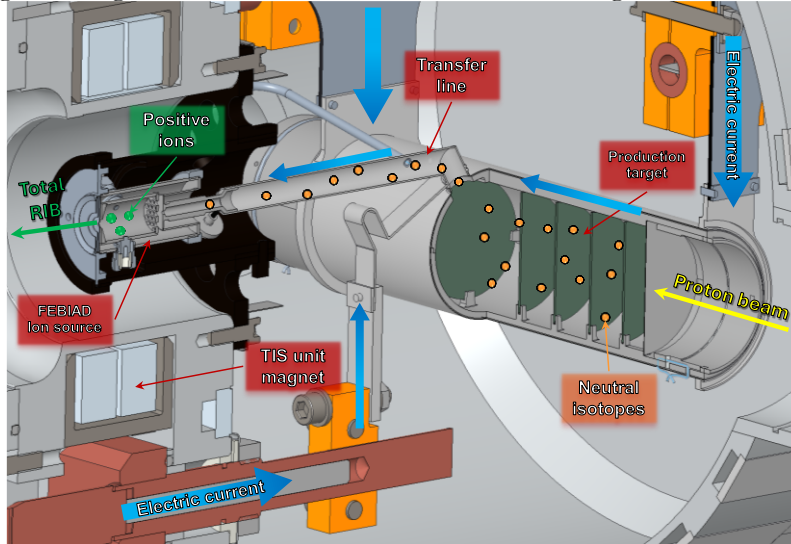


Figure 2.1 The FEBIAD ion source is installed within the TIS unit.

As introduced in Chapter 1, neutral isotopes released by the primary target effuse towards the ion source, exhibiting a random motion and interacting with the transfer line walls. Since the FEBIAD ion source must be maintained at temperatures above 2000°C to ensure a correct functioning of the device, both the transfer line and the ion source are heated by Joule effect using an electric current provided by an independent power supply.

The working principle of the FEBIAD ion source is based on the electron impact ionisation mechanism driven by the interaction between two key components of the device, namely the

cathode and the anode (refer to Figure 2.2): the former (1), produced in tantalum, is heated to approximately 2200°C by the Joule effect allowing thermionic emission of free electrons from its frontal surface (1'). The anode (2), manufactured in molybdenum, is electrically insulated and maintained at about 150V from the rest of the system to generate an electric field between its grid (2') and the cathode frontal surface. The electric field is essential for attracting and accelerating electrons towards the anode hollow volume (plasma chamber), where the ionisation phenomenon occurs. Specifically, the neutral atoms released by the primary target reach the plasma chamber passing through the hollow section of the cathode and the anode grid. In this region, they undergo ionisation due to electron bombardment process, resulting in the release of positive ions. Such a continuous ionisation process leads to the accumulation of both electrons and cations within the confined space of the anode, resulting in the formation of a low density plasma. Additionally, the TIS unit magnet (also named target magnet) generates a magnetic field that increases the local charge density by confining electrons within a helical orbit inside the anode aiming at increasing the interaction probability between neutral species and electrons [36] .

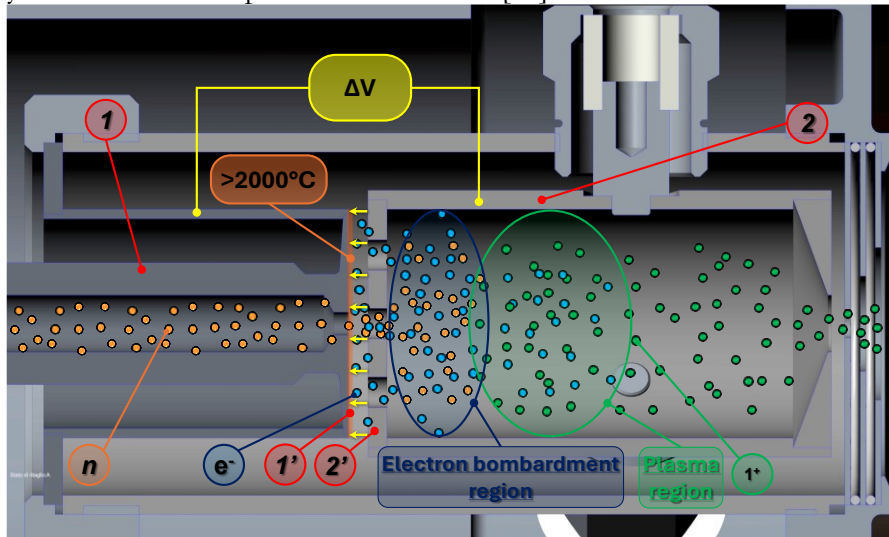


Figure 2.2 (1) Cathode, (1') Cathode frontal surface, (2) Anode, (2') Anode grid; (n) Neutral isotopes, (e-) Electrons, (1+) Positive ions.

The FEBIAD plasma is characterized by its a highly non-homogeneous nature, consisting of a complex mixture of neutral and charged particles with different spatial and energetic distributions. The primary components of the FEBIAD plasma include [23,37]:

- Neutral isotopes
- Electrons:
 - Thermionic emitted electrons by the cathode;
 - Thermionic emitted electrons by other high temperature surfaces;
 - Secondary electrons emitted by the ionisation process;
 - Secondary electrons emitted by the ion impact on the walls;
- Ions:
 - Ions generated by the electron impact ionisation process;
 - Ions generated by the surface ionisation process;
 - Ions generated by the charge exchange into the anode volume;

Understanding the composition and behaviour of the FEBIAD plasma is essential for optimising the ionisation process as the complex interactions between neutral isotopes,

electrons, and ions within the plasma directly affect the conversion of neutral atoms into charged particles. Indeed, the ionisation efficiency, defined as the ratio between the incoming neutral species and the outgoing positively charged particles, is deeply affected by the electron current impinging the anode, which is controlled by the following key parameters [37–40]:

i. Cathode frontal surface temperature

Increasing the cathode frontal temperature increases the electron density emitted by thermionic effect $J_R [A/m^2]$, as described by the Richardson equation (2.1):

$$J_R = A_0 T^2 \exp\left(-\frac{W}{k_B T}\right) \quad (2.1)$$

Where A_0 is a material dependent constant [$A \cdot m^{-1} \cdot K^{-2}$], T is the cathode temperature [K], W is the material dependent work function (eV), and k_B is the Boltzmann constant [$eV \cdot K^{-1}$].

The cathode temperature is controlled by the heating current (namely line current $-I_{line} [A]$), however it must not exceed the material limiting temperature, namely the temperature for which the material starts to sublime in vacuum at a not negligible rate. Consequently, the material choice is crucial to maximize the ion source operating temperature, and the refractory metals are suitable for resisting at temperatures above 2000 °C.

Among all the refractory metals, Ta is especially favourable due to its lower work function [41] to increase the electrons release by thermionic emission. Furthermore, its limiting temperature is around 2200°C at a vacuum level of 10^{-6} mbar making it the material usually employed to manufacture cathodes. However, it should be noted that the vacuum level expected inside the TIS unit is usually one order of magnitude lower than that of the beamline, due to the outgassing of contaminants during operation.

ii. Anode potential and anode grid-cathode frontal surface gap

The distance between the anode grid and the cathode frontal surface (the anode-cathode gap) affects the transmissible electron current density between the cathode and the anode $J_{CL} [A/m^2]$, as described by the Child-Langmuir equation (2.2):

$$J_{CL} = 4 \frac{\epsilon_0}{9} \sqrt{\frac{2e}{m_e}} \cdot \frac{V^{\frac{3}{2}}}{a^2} \quad (2.2)$$

Where $\epsilon_0 [C \cdot V^{-1} \cdot m^1]$ is the vacuum permittivity, $e [C]$ is the electron charge, $m_e [kg]$ is the electron mass, $V [V]$ is the voltage difference between the anode and the cathode and $a [m]$ is the distance between the anode grid and the cathode frontal surface.

Increasing the anode-cathode distance reduces J_{CL} , however a shorter gap increases the risk of contact between the anode and cathode during operation due to thermal expansion of the components at high temperature. The anode-cathode facing surfaces contact would cause a short circuit compromising catastrophically the ion source functioning [42]. Consequently, the whole TIS unit should be replaced and disposed as a radioactive waste. For such reasons the optimal anode-cathode gap is typically between 0.9 and 1.2 mm. Moreover, the parallelism between the anode grid and the cathode frontal surface is essential for achieving a uniform and axially oriented electric field, which significantly affects the trajectory of the free electrons emitted by thermionic effect. Indeed, only the electrons entering within the anode contribute to the ionisation process, while the remaining ones are absorbed by the ion source components.

The anode voltage provides the energy for accelerating the electrons emitted by thermionic effect, consequently increasing the anode potential increases J_{CL} . The anode voltage is a critical factor as it determines the primary electrons trajectories within the plasma chamber,

thereby influencing both the electron confinement and the distribution of the electric potential inside the ion source.

iii. Magnetic field

The magnetic field affects the electrons density within the plasma chamber, consequently it indirectly impacts the extracted ion beam from the ion source. The electric current flowing to the coils used to generate the magnetic field is known as “magnet current” (I_{mag} [A]). However, the magnetic field optimisation is out of the scope of this work.

iv. Operating pressure

The operating pressure mainly affects ion density into the anode volume, which also influences the electrons confinement within the plasma chamber. As the operating pressure increases, more electrons are confined altering the plasma density and affecting ion extraction efficiency.

2.2 SPES FEBIAD ion source state-of-the-art

The SPES FEBIAD ion source [28] presents a similar design of the MK5 model designed by Kirchner at CERN-ISOLDE almost 50 years ago [32]. In this work, the research activities at LNL involve the development of the cathode main body geometry and the introduction of a dedicated centering system, as will be further detailed in the following sections.

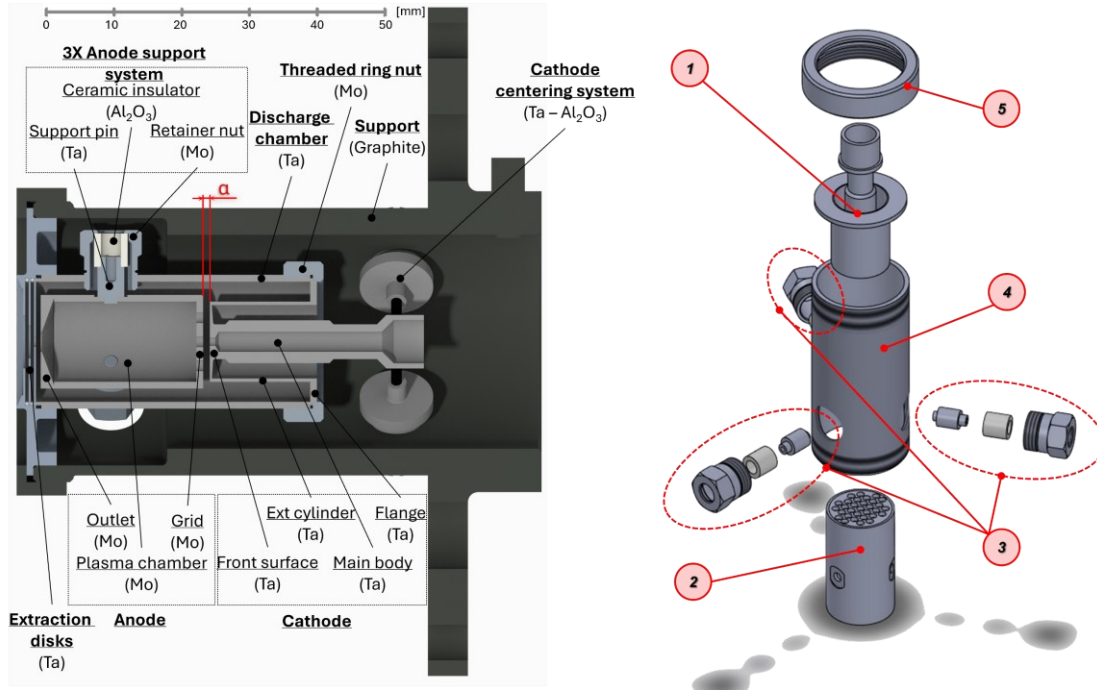


Figure 2.3 Left: FEBIAD ion source components. (1) Cathode, (2) Anode, (3) Anode support system, (4) Discharge chamber, (5) Cathode retainer nut.

The following paragraphs are dedicated to a detailed description of the main SPES FEBIAD ion source components, which are also reported in Figure 2.3; additionally, their technical drawings are reported in Appendix A. The parts produced according to the current state-of-the-art employing the conventional manufacturing technologies will be named as “standard” (STD).

i. Cathode

The SPES cathode is manufactured in Ta and consists of three separate parts, as represented in Figure 2.4: the main body (1), the flange (2) and the external cylinder (3). Currently, the cathode production route foresees the fabrication of the three parts via traditional manufacturing technologies, such as turning operation, followed by their joining through a complex Tungsten Inert Gas (TIG) welding process.

The cathode is considered a critical component as it supplies the electron flow to perform the ionisation process, furthermore it is subjected both to thermal and structural loads.

The electrons are released by thermionic emission at temperatures above 2000°C from the cathode flat surface at the end of the main body facing the anode grid (namely, the frontal surface). At INFN – LNL, the cathode main body geometry was slightly modified compared to the MK5 design increasing the section in a specific region of the component aiming at enhancing the temperature distribution of the frontal surface, as shown in Figure 2.4. Such a development resulted from FEM simulations and experimental measurements presented in [28] and it was essential to increase the electron current released by thermionic effect.

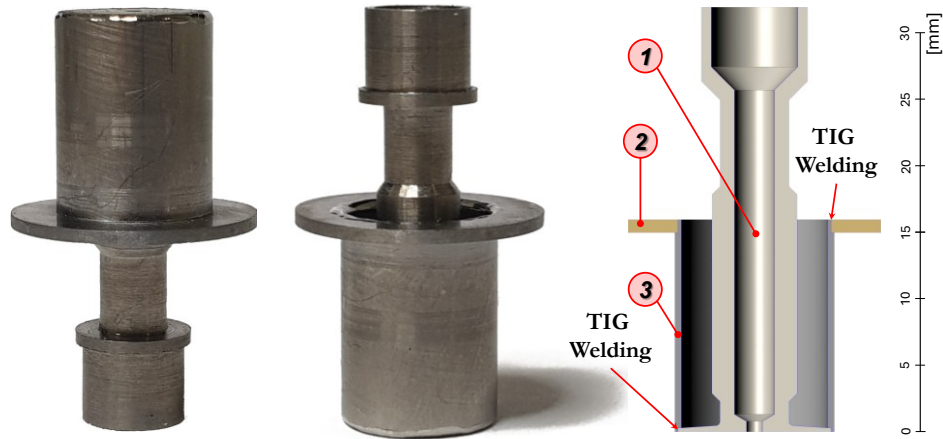


Figure 2.4 SPES cathode; (1) Main body, (2) Flange, (3) External cylinder.

- In [28], the structural loads on the cathode arising from the thermal expansion of the transfer line during operation were evaluated.

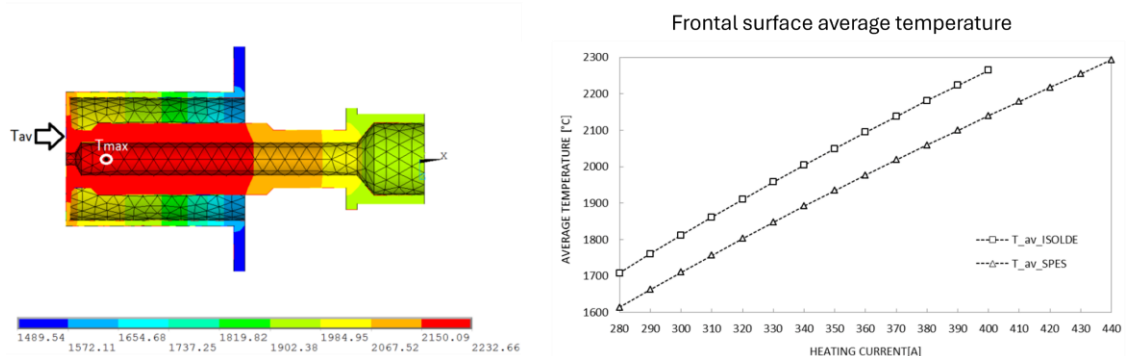


Figure 2.5 FEM analysis performed for the SPES cathode in [28]; left: SPES Cathode temperature distribution; right: comparison of the frontal surface average temperature between the SPES cathode and the MK5 (ISOLDE) cathode.

Specifically, an axial displacement of approximately 1 mm of the cathode frontal surface was estimated. Such a deformation during the SPES ISOL facility operation is considered detrimental for the following key reasons:

- The alteration of the cathode surface geometry, transitioning from flat to curved, affects the thermionic emission process;

In case of excessive axial displacement, a short circuit between the cathode and the anode can occur, drastically compromising the operativity of the ion source.

ii. Anode

The anode is usually made of Mo or Ta and consists of three separated parts, as shown in Figure 2.6: the anode grid (1), the plasma chamber or anode body (2) and the anode outlet (3). Such components are produced via traditional manufacturing technologies and subsequently joined by a spot TIG welding process, similarly to the cathode.

The anode must be held electrically insulated from the cathode and from all the other ion source components to ensure a proper operation of the device.

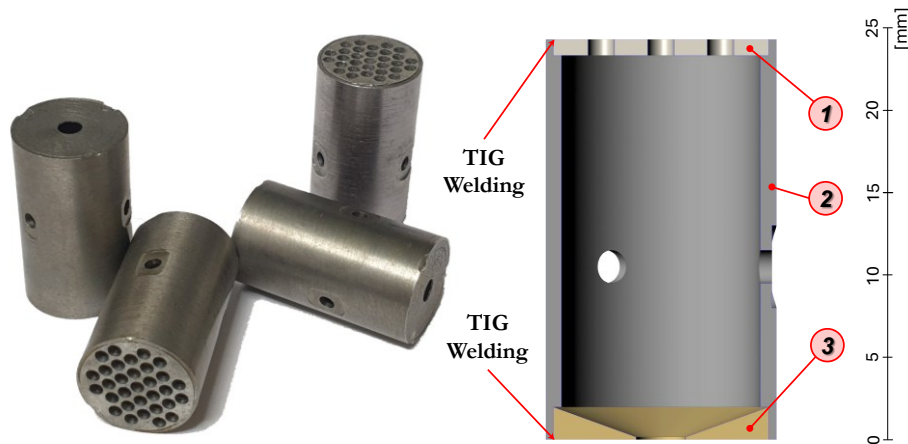


Figure 2.6 SPES anode; (1) Anode grid, (2) Plasma chamber, (3) Anode outlet.

iii. Discharge chamber

The discharge chamber, shown in Figure 2.7, is typically produced in Ta and allows to align and block both the anode and the cathode. It consists of a tubular-shaped body with threaded ends at both extremities: the former is used to screw the retainer nut which blocks the cathode, the latter is designed to properly fix the extraction disks. Furthermore, three radial threaded holes disposed at 120° are used to centre and align the anode through the anode support system.

The discharge chamber conducts the heating current that flows through the cathode, and it works as a thermal screen for both the anode and the cathode from the external graphite support.



Figure 2.7 Discharge chamber.

iv. Anode support system

The anode support system is used to centre and fix the anode within the discharge chamber while ensuring its electrical insulation. The anode support system consists of three parts, as shown in Figure 2.8: both the support pin and the retainer nut are usually manufactured in Ta, while the cylindrical insulator is made of alumina (Al_2O_3).

The pins are coupled directly to the anode radial holes to provide both the fixing of the component and its electrical connection. Indeed, the pin is drilled to accommodate a tantalum wire, which supplies the anode with the required electrical potential thanks to a direct connection to an independent power supply. The alumina insulator electrically insulates the support pin, and consequently the anode, from other parts of the ion source. The retainer nut, which is screwed into the discharge chamber body, blocks the insulator and the support pin.

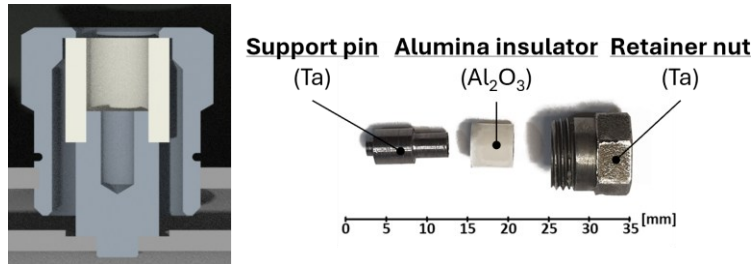


Figure 2.8 Anode support system.

v. Graphite support

The graphite support (Figure 2.9) holds in position the main FEBIAD ion source components and is fixed to the TIS unit by its flange (3) and bolts. Furthermore, the front nut (1) is used to fix the extraction system support, where the discharge chamber is also screwed. It is usually manufactured in graphite as it is easy to be machined and due to the relatively low cost of the material. Moreover, its use reflects the legacy of the all-graphite MK5-type ion source design[3,43].

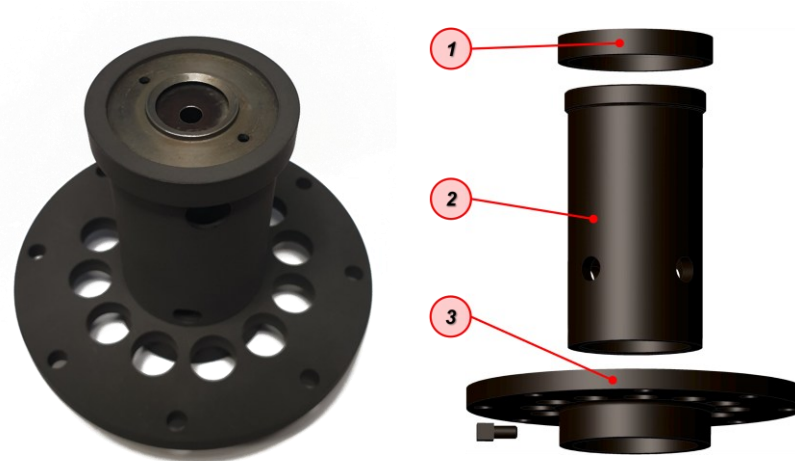


Figure 2.9 Graphite support; (1) Front nut, (2) central body, (3) Flange

vi. Cathode centering system

The cathode centering system, shown in Figure 2.10, was introduced in the SPES FEBIAD ion source design for two main reasons [44,45]:

- It ensures the alignment of the cathode and the transfer line;
- It acts as a constraint against the axial deformations occurring at high temperature during operation due to the thermal expansion of the components.

The radial pins are pressed to the end of the cathode by threaded grubs which are screwed into the graphite support. Furthermore, alumina insulators prevent the cathode heating current from flowing to other ion source components.

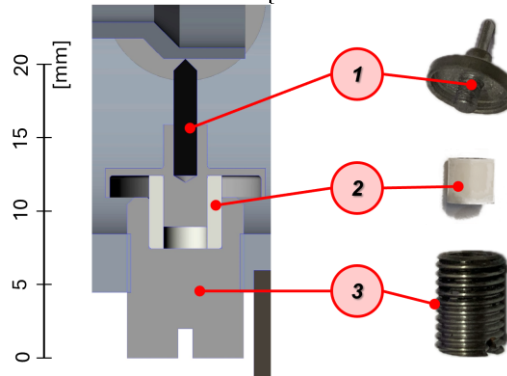


Figure 2.10 Cathode Centering system; (1) Pin, (2) Alumina insulator, (3) Threaded grub screw

vii.Extraction system

The SPES FEBIAD ion source extraction system is composed by three holed disks (1) separated by spacer rings 0.5 mm thick (2) which are housed within a dedicated support structure (3), as show in Figure 2.11. The complete extraction system is screwed to one of the threaded extremities of the discharge chamber and it is blocked to graphite support. The disks are arranged with holes of progressively increasing diameter, forming an aperture angle φ of 127° . Such a configuration was specifically designed to enhance ions extraction from the ion source.

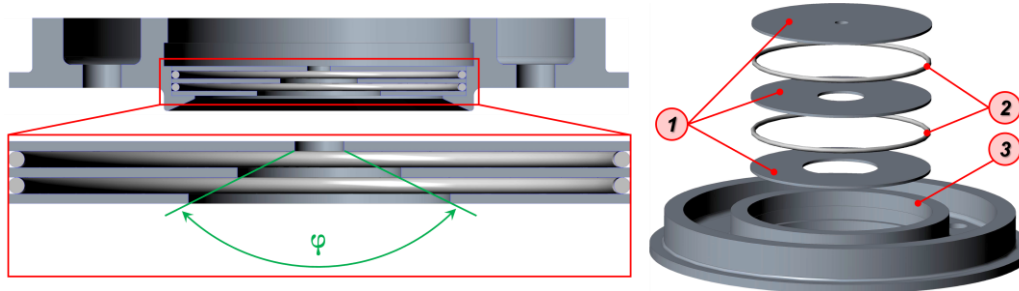


Figure 2.11 SPES FEBIAD ion source extraction system; (1) Outlet disks, (2) Spacer rings, (3) Extraction system support.

2.2.1 Functional analysis

The functional analysis [46] is a methodology used to systematically analyse the mission and performance requirements of a system. It establishes a rigorous connection between the system functions and its resulting architecture, ensuring that every aspect of the design directly contributes to the performance objectives. Such a methodology is crucial to the develop alternative design solutions, as it provides a structured approach for identifying all the functional elements that must be included into the system. Finally, it provides an integrated view of the design to help the designer to understand and manage the system under development leading to a more robust and effective design process.

The functional analysis methodology was employed to clearly identify the functional requirements of each FEBIAD ion source component. Figure 2.12 and Table 2.1 exhibit the method employed to perform the functional analysis for the cathode: different functional requirements were identified and for each one of those a layer was linked (i.e. colours). Subsequently, each surface, volume or dimension of the cathode was analysed by collecting information either from literature or from the experienced operators that usually assemble

or use such a device. Therefore, depending on the specific function of each geometric feature, a layer was assigned using the Autodesk™ software AutoCAD. No layers were assigned to the surfaces/volumes/dimensions without any specific function; Furthermore, some cathode features are constrained as possible changes might have complex effects on the entire system and they would require detailed analyses to be assessed. In such cases, the “to be investigated” layer was assigned.

FEM or experimental analyses are required to validate every design modification of geometric features characterized by a specific layer, while the surfaces/volumes/dimensions with no functional analysis can be modified with reasonable freedom.

In Appendix B are reported the functional analyses of all the ion source components.

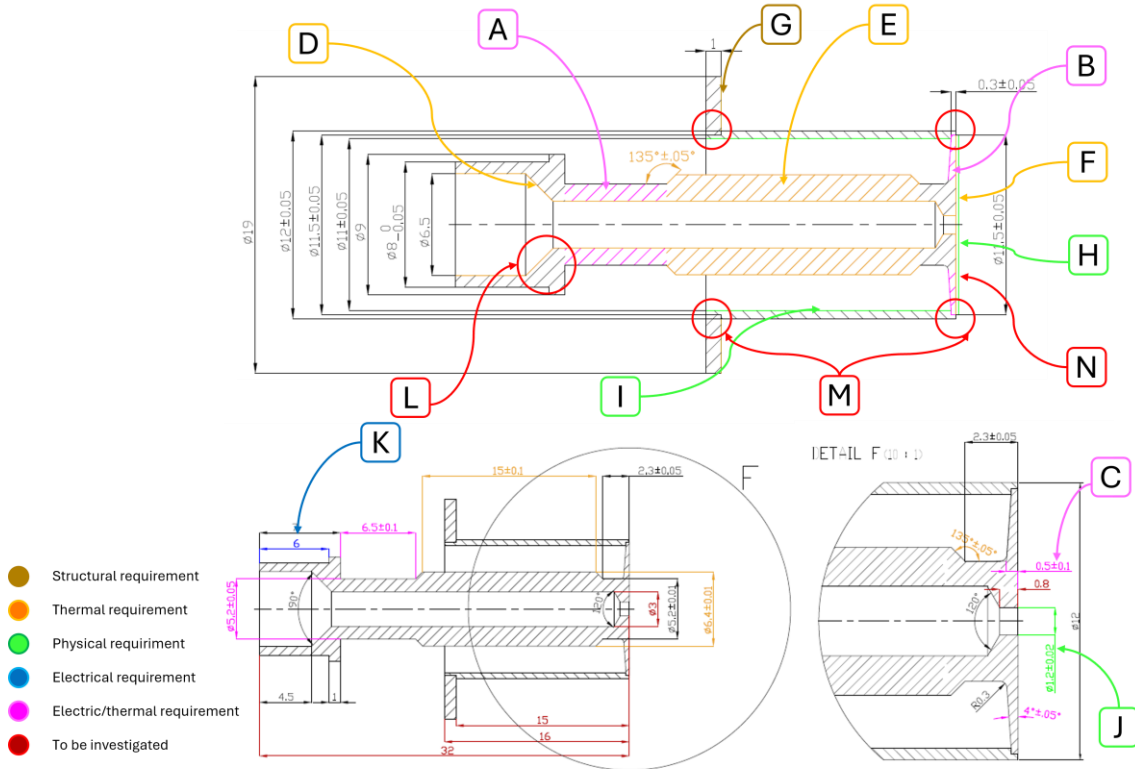


Figure 2.12 Cathode functional analysis. The references are reported in Table 2.1

Table 2.1 References to Figure 2.12

Ref	Description
A	The cross section must be the same of the transfer line ($\varnothing_{\text{ext}}=9 \text{ mm}$, $\varnothing_{\text{in}}=8 \text{ mm}$) to allow the uniformity of power dissipation. Such a solution should ensure an improved temperature uniformity.
B	The thickness of the frontal surface decreases radially. Such geometrical feature was implemented to ensure a quasi-homogeneous cross section along the surface radius. As heat is generated by Joule effect, a more homogeneous temperature is expected
C	A further thickness reduction should be avoided both for the mechanical resistance and for the wear due to ions sputtering.
D	All the surfaces exposed to isotopes released from the target are subjected to a thermal requirement: the temperature must be over 2000°C to avoid "sticking" and consequently an efficiency loss.

E	The added material moves the hot spot towards the cathode electron releasing surface with the aim to improve the temperature homogeneity.
F	The temperature of the cathode electron emitting surface must be as uniform as possible and over 2000°C to allow the thermionic effect.
G	The geometrical features of the flange surface in contact with the discharge chamber, specifically its flatness and the orthogonality of its own axis with respect to the cathode's one, are important to position properly the cathode electron emitting surface towards the anode.
H	With the aim to minimize the electric field perturbation, the cathode electron releasing surface must be polished.
I	The cylinder inner surface reflects the heat transferred by irradiation to guarantee a higher temperature for the internal sections of the cathode.
J	The dimension of the hole must be minimized with the aim to increase the electron releasing surface, while isotopes can still pass through.
K	The contact surface between the transfer line and cathode ensures a good electrical contact between the components at high temperature.
L	Low temperature points which need to be avoided
M	The welding operation could be a cause of distortions due to thermal stresses.
N	The thermal expansion of the transfer line occurring during operations deforms the cathode electron releasing surface.

2.2.2 Critical analysis

The importance of the FEBIAD ion source assembly process was outlined in section 2.1 as it deeply affects the performance of the device. Specifically, the position of both the cathode frontal surface and the anode grid are crucial to ensure the reliability of the device and the performance repeatability.

Consequently, a critical analysis enables the identification of weaknesses and areas for enhancement to improve the reliability and repeatability of the assembly. The critical analysis of both the manufacturing process and the assembly procedure involves a systematic examination of the design, functionality, and potential uncertainty sources detrimental to the components position accuracy.

i. Manufacturing process of single components

The FEBIAD ion source components must be capable to resist at extreme working conditions, therefore are made of refractory materials (e.g., tantalum, molybdenum, alumina, graphite), as previously outlined. Traditionally, the anode and cathode are produced using conventional subtractive manufacturing methods and manual Tungsten Inert Gas (TIG) welding [47]. However, refractory metals present poor machinability and weldability properties, often resulting in components with defects and distortions which have a significant impact on the repeatability of ion source performance and on the device reliability.

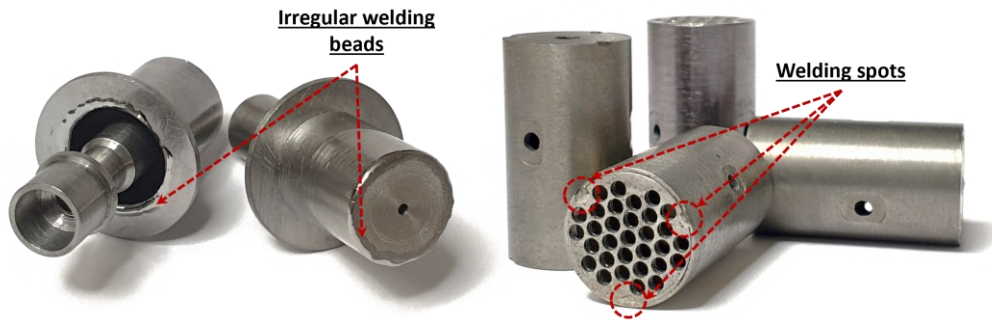


Figure 2.13 Typical cathode (left) and anode (right) defects resulting from TIG welding process.

ii. Manual assembly procedure [48]

The assembly of the SPES FEBIAD ion source involves over 20 components which must be precisely aligned to ensure the correct functioning of the device. The complete manual assembly procedure is reported in Appendix C; however, among all the ion source components, the most challenging to install is the Anode. Such a complexity arises from the need to mount the support system which also ensures the electrical insulation of the anode during operation. The current assembling process of the anode foresees a stainless steel (SS) tubular alignment tool to manually centre the anode within the discharge chamber, as shown in Figure 2.14; nevertheless, the results in terms of the accuracy of such an operation are dependent on the ability of the operator performing the assembly.

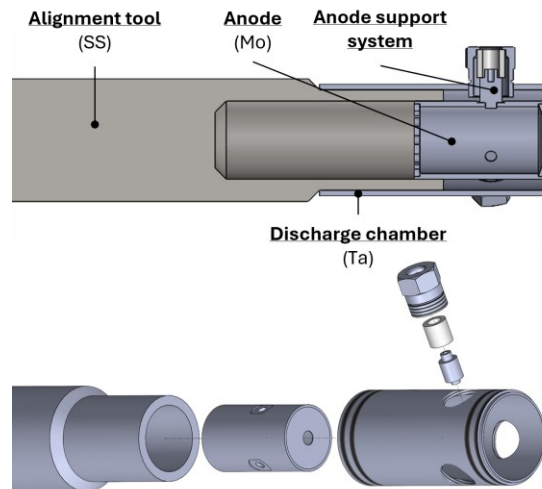


Figure 2.14 Alignment tool used to perform the manual assembly procedure

Moreover, it is an extremely time-consuming procedure as it takes several hours to be completed. The anode assembly process foresees the following key subsequential steps:

- The operator holds the alignment tool horizontally, ensuring stability along its axis;
- The anode is housed within the hollow section of the alignment tool;
- The discharge chamber is inserted into the outer cylindrical part of the alignment tool, aligning the threaded holes in the discharge chamber with those of the anode;
- The tantalum pin must be carefully inserted into the anode hole using tweezers;
- The alumina insulators are positioned coaxially along the pin axis, again using tweezers;
- The retainer nut is screwed into the discharge chamber threaded hole to fix both the alumina insulator and the pin.
- The last three steps must be repeated for each support system (i.e. three times) to accurately fix and centre the anode within the discharge chamber.

The critical analysis identified the main issues and sources of uncertainty in the manual assembly process of the ion source components which affects the anode position:

1. The anode is not properly blocked by the alignment tool allowing its sliding along the z axis, as represented in Figure 2.15;
2. The clearance fits between the alignment tool and the other components are not suitable for an accurate positioning of the parts.
3. The components of the anode support system are particularly difficult to be manually handled due to their small dimensions. Moreover, the fixing of the retainer nuts is problematic since it compromises the position of the anode as it slides along the z axis.

Such key issues related to the mounting procedure are detrimental for the positioning of the anode, resulting in a lack of repeatability of the assembly process and, consequently, on the ion source performances. Furthermore, the operator's skills performing the procedure is a key factor in ensuring the correct assembly of the components

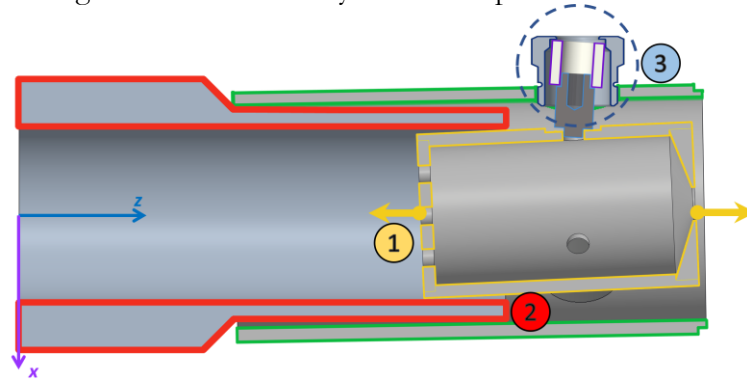


Figure 2.15 Schematic representation of the main issues related to the anode assembly process identified by the critical analysis.

The anode electrical connection consists of a tantalum wire ($\varnothing 1$ mm), which is inserted into the pin hole on one end and connected to the power supply on the other, as shown in Figure 2.16.

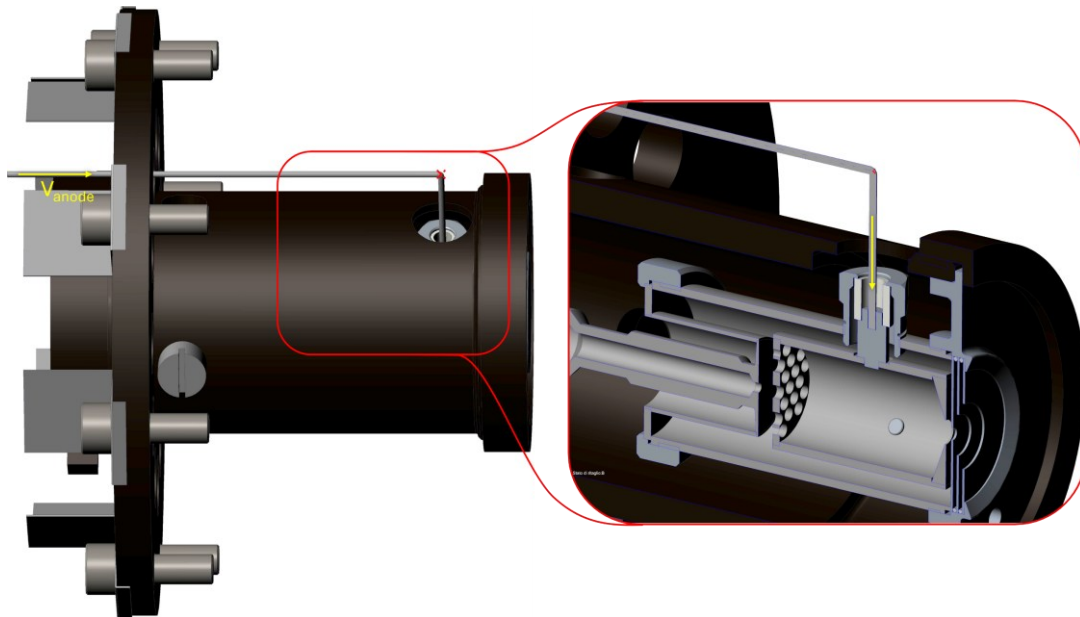


Figure 2.16 Anode electrical connection

Nevertheless, the wire is not securely blocked as it is simply inserted into the pin without additional fixation. Consequently, it is prone to be easily removed, even by minor vibrations of the TIS unit which could occur during its coupling to the Front-End (refer to Chapter 1). Naturally, the removal of the tantalum wire would compromise the anode electrical connection and, consequently, the functioning of the FEBIAD ion source.

2.3 Aim of the PhD project details

Refractory metals such as Ta, Mo, and W, used to manufacture most of the components of the current SPES FEBIAD ion source, are difficult to machine using traditional subtractive processes and they are characterized by a limited TIG weldability. Additionally, the complex manual mounting procedure involving more than 20 components further complicates the assembly accuracy. Consequently, the anode-cathode distance, which significantly affects the ionisation efficiency, is not consistent across every assembled ion source leading to a lack of performance repeatability and reliability.

The aim of this work is to enhance the assembly quality of the SPES FEBIAD ion source by improving the repeatability of the mounting process. Such objective could be achieved through two main phases. Firstly, a new assembly procedure will be developed employing the consolidated standard components through a systematic approach based on Design for Assembly (DFA) principles. Functional and critical analyses presented in Paragraph 2.2 , as well as a tolerance stack-up analysis, will be essential for developing a robust mounting strategy. Indeed, the proper allocation of dimensional and geometric tolerances is crucial to ensure a consistent assembly repeatability.

Subsequently, alternative design solutions will be explored considering Additive Manufacturing as a potential production process. Developing FEBIAD ion source components according to Design for Additive Manufacturing (DFAM) principles would offer two main advantages:

- Improved assembly repeatability and FEBIAD ion source reliability by reducing the number of components (by consolidating parts that are currently manufactured separately into a single piece), thereby simplifying the assembly process;
- Improved performances as the design limitations due to the standard manufacturing technologies could be overcome considering alternative geometries feasible to be produced through AM technologies.

However, achieving complex morphologies by AM processes often requires compromises in geometric precision and surface quality, consequently the subtractive manufacturing techniques cannot be fully abandoned yet. Therefore, the feasibility of producing components through a hybrid process, combining AM with traditional manufacturing methods, will be considered to merge the advantages of both technologies.

2.4 Conclusions

This chapter provided an overview of the SPES FEBIAD ion source, outlining its importance within ISOL facilities for producing high-quality radioactive ion beams. The FEBIAD ion source working principle was detailed, emphasizing key operational parameters such as the cathode temperature, the anode-cathode distance, the anode voltage and the magnetic field, which directly affect the device performance in terms of ionisation efficiency. The current state-of-the-art of the SPES FEBIAD ion source was reviewed, including a comprehensive description of its main components. Additionally, the functional analysis

systematically evaluated the relationships between the ion source functional requirements and its design architecture. Moreover, the critical analysis identified key issues in the manufacturing and assembly processes that could impact the accuracy and reliability of the ion source, particularly concerning the anode-cathode distance. Such an approach lays the basis to enhance the consistency of the assembly process and, consequently, of the ion source performance repeatability.

The identified challenges could be addressed by applying Design for Assembly (DFA) principles to enhance the mounting procedure; furthermore, exploring alternative design solutions, including the integration of Additive Manufacturing technologies, could lead to overcome the inherent limitations of the traditional production techniques to improve the device performances.

The following chapter will focus on the development of a new assembly procedure based on the existing standard components of the FEBIAD ion source, aiming to enhance the repeatability and reliability of the assembly process.

Chapter 3: Assembly procedure development for standard SPES FEBIAD ion source

This chapter is focused on the development of a systematic assembly procedure for the FEBIAD ion source, a key component in the SPES ISOL facility [17,28]. The accuracy of the ion source assembly, particularly the alignment of the anode and cathode, is critical for ensuring reliable ionisation process. However, the traditional manual assembly method introduced variability and uncertainties in component positioning, leading to performance inconsistencies. Therefore, a tool-based assembly strategy, based on Design for Assembly (DFA) principles and tolerance stack-up analysis, was developed. The new procedure significantly reduces operator-dependent variability and improves the alignment precision of critical components. A statistical tolerance optimisation process was applied, and experimental validation was conducted using Coordinate Measuring Machine (CMM) measurements to confirm the improved assembly accuracy. The results demonstrate a significant improvement in the repeatability and reliability of the FEBIAD ion source assembly, contributing to more consistent device performance.

3.1 Introduction

High assembly accuracy is usually required for the most advanced devices employed for R&D activities where the precision of the component mounting can have a remarkable effect on the test reliability or the measurement performance [49–51]. An example of such a kind can be provided by the FEBIAD ion source.

From a geometrical point of view, the accurate alignment of the FEBIAD anode and cathode, namely the two main parts of the ion source, strongly affects the device performance repeatability [28]. The anode and the cathode are subjected to geometrical constraints to enhance the ionisation efficiency: the distance (a) between the anode grid and the cathode frontal surface, highlighted in Figure 3.1, should ideally range between 0.9 and 1.1 mm. Furthermore, the mutual parallelism of such surfaces is essential to ensure a homogeneous and axially oriented electric field.

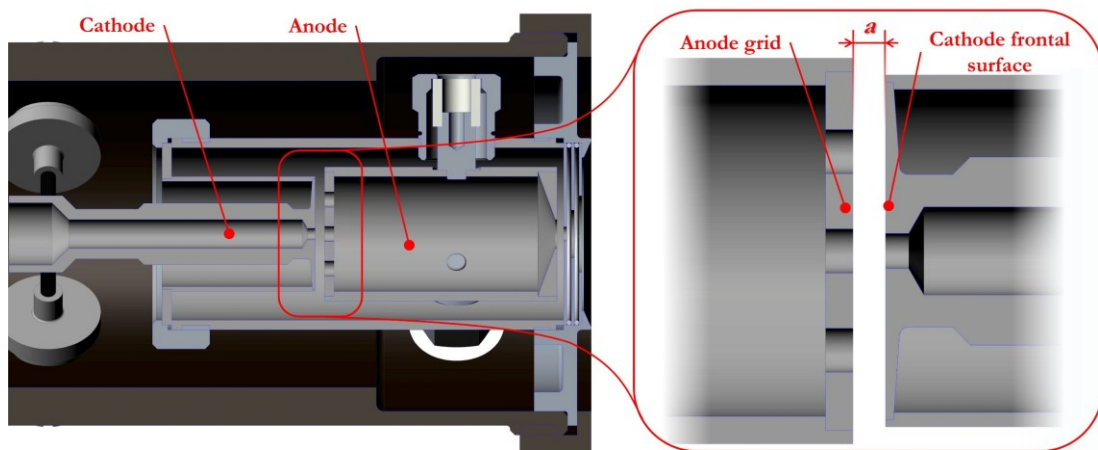


Figure 3.1 Anode-cathode interface

The current manual mounting process does not guarantee the accurate alignment of the components, therefore the development of an assembly strategy for the FEBIAD ion source

became necessary to reduce the elements considered as a source of uncertainty for the positioning of each part of the assembly. Aiming at enhancing the assembly quality and repeatability, a systematic approach based on Design For Assembly (DFA) principles, tolerance stack-up analysis and tolerancing methods was used [48].

3.2 Material and methods

Functional and critical analyses previously presented in Chapter 2 lay the basis for the development of an assembly procedure aimed to reduce the uncertainties arising from the manual mounting strategy.

In addition, a systematic tolerancing process is also necessary to ensure an accurate positioning of the components during the assembly phase. For such a purpose, the tolerance stack-up analysis is a consolidated method widely employed across various high-precision industries, including automotive, aerospace, and machinery, where the reliability and accuracy of the assemblies are crucial.

3.2.1 Tolerance stack-up analysis approach

The primary purpose of a tolerance stack-up analysis is to predict how the cumulative effect of individual part tolerances impacts the overall dimensions and functionality of the assembled product [52]. Such analysis is essential to ensure that the final assembled device meets to specified dimensional and functional requirements, despite inherent variations in individual component dimensions due to manufacturing processes.

The tolerance stack-up analysis of the manual assembly procedure needs to derive the tolerance elements affecting the anode – cathode distance during the mounting process. Indeed, each tolerance element involved in the positioning of the anode grid and cathode frontal surface contributes to increase the uncertainty propagation in the assembly. Consequently, the new mounting procedure must be designed implementing specific tools to reduce as much as possible the number of tolerance stack-up elements impacting on the anode-cathode distance in order to obtain a more reliable and accurate assembly process.

i. Manual assembly procedure

The critical analysis reported in Chapter 2 outlined the main issues related to the assembly of the anode [48], in fact such a component results critical as must be electrically insulated from the rest of the ion source; For this reason, it is fixed through a complex support system, which foresees three alumina cylindrical insulators supported by pins and retainer nuts radially disposed at 120° to each other, as shown in Figure 3.2.

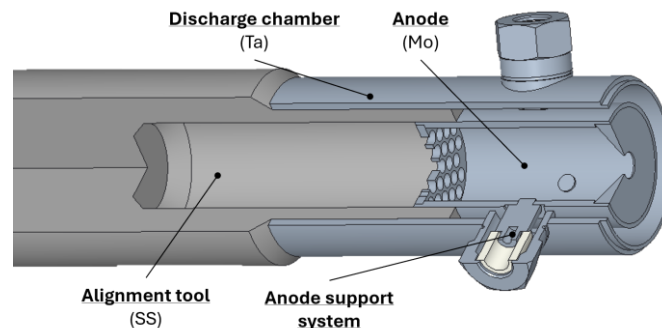


Figure 3.2 Manual assembly procedure

However, the anode is not properly blocked during the assembly procedure, therefore every component involved in this process contributes on the anode grid positioning and they must be considered as tolerance stack-up elements.

The uncertainty propagation due to the several elements of the tolerance stack-up, as a consequence of the unconstrained degrees of freedom of both the anode and its support system, have a detrimental effect on the assembly repeatability. Therefore, a control of the position and inclination of the anode grid is not feasible through the manual mounting strategy. In addition, the assembly operations are extremely time consuming, as the entire assembly procedure required several hours to be completed.

ii. Tool-based assembly procedure

The DFA approach was employed to develop a dedicated tool-based mounting procedure to improve the FEBIAD ion source assembly quality by introducing only minor modifications on the geometry of the components. The modular assembly tool represented in Figure 3.3 was specifically designed to reduce the tolerance stack-up elements related to the anode support system involved in the anode grid position, aiming to reduce uncertainty propagation[48]. Furthermore, the assembly sequence was significantly simplified to entirely exclude the impact of operator's skills on the assembly quality.

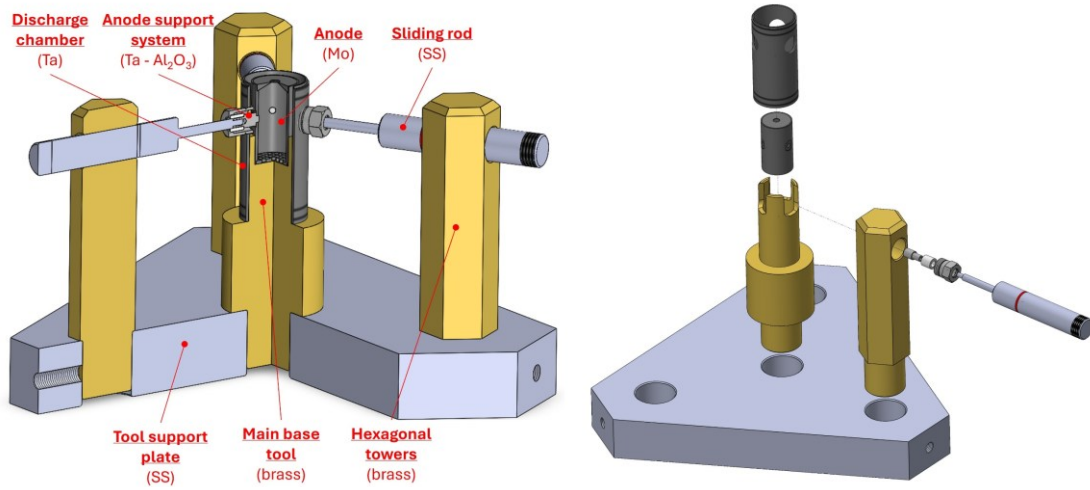


Figure 3.3 Tool-based assembly procedure

The main base tool (or main body) was designed to constrain both the anode and the discharge chamber during the assembly process, removing the degrees of freedom which inherently contribute to the uncertainty propagation of their position.

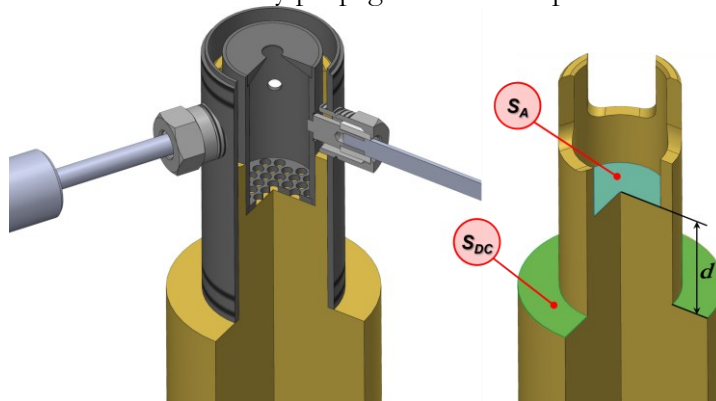


Figure 3.4 Assembly tool main body design; left: The sliding rods align and sustain the anode support system components; right: (S_{DC}) discharge chamber contact surface, (S_A) Anode grid contact surface.

Furthermore, the geometric features and the distance between the tool surfaces in contact with the discharge chamber (SDC) and the anode (S_A), represented in Figure 3.4, are essential to ensure the final accurate positioning of such components in the assembly.

The three radially-oriented sliding rods sustain the anode support system parts (i.e pins, insulators and retainer nuts) which were previously challenging to be positioned using the manual assembly strategy. In Figure 3.5 is reported the sliding rod design, with the M2 threaded end highlighted as is fundamental to secure the pin. The coupling between the sliding rods and the hexagonal towers holes ensures the proper alignment of the anode holes axes with the tantalum pin axes.

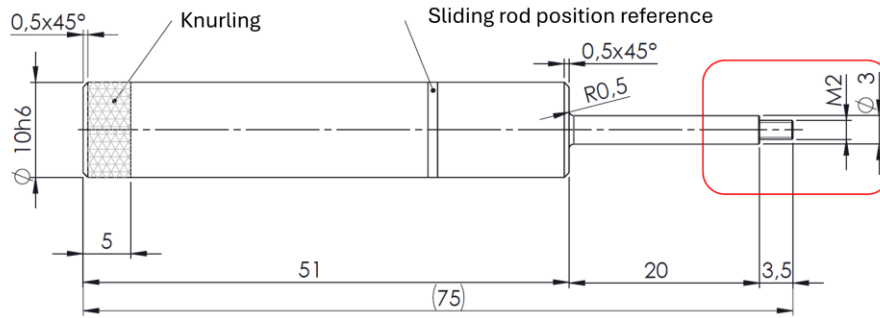


Figure 3.5 Sliding rod detail. The support pin is screwed on the ending threaded part of the sliding rod to be easily positioned during the assembly process.

The only modified component of the FEBIAD ion source in order to be mounted using the assembly tool is the tantalum pin, as illustrated in Figure 3.6: the M2 threaded hole was introduced to enable the coupling with the sliding rod end.

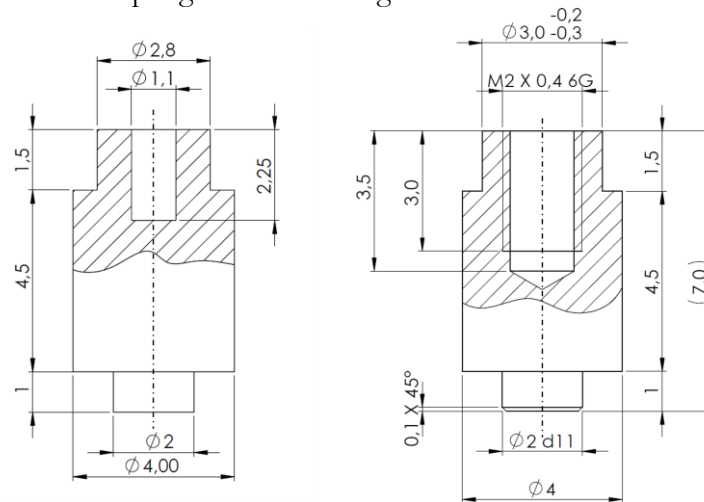


Figure 3.6 Minor modification on the Tantalum pin. Left: old design; right: the new design foresees a M2X0.4 threaded hole.

In addition, such a modification allows for a more reliable electrical connection to the anode. The threaded connector shown in Figure 3.7 can be screwed into the threaded hole of the pin. To complete the electrical circuit, the tantalum wire, which is connected to the anode power supply, can be securely wrapped through the Ø1 mm hole of the connector and fixed as show in Figure 3.8 (1). Even the connector must be manufactured in Tantalum to sustain the high temperature during operation.

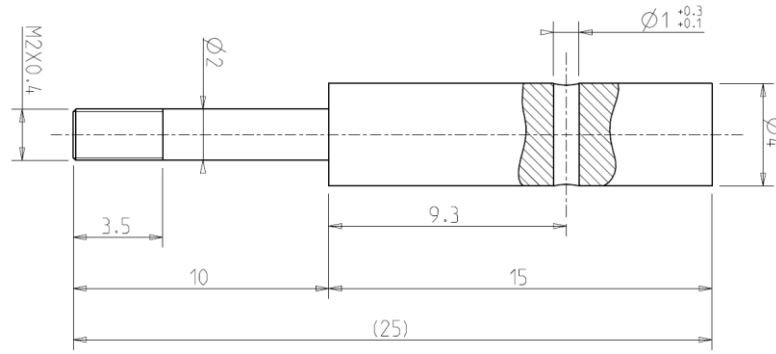


Figure 3.7 FEBIAD ion source anode wire connector

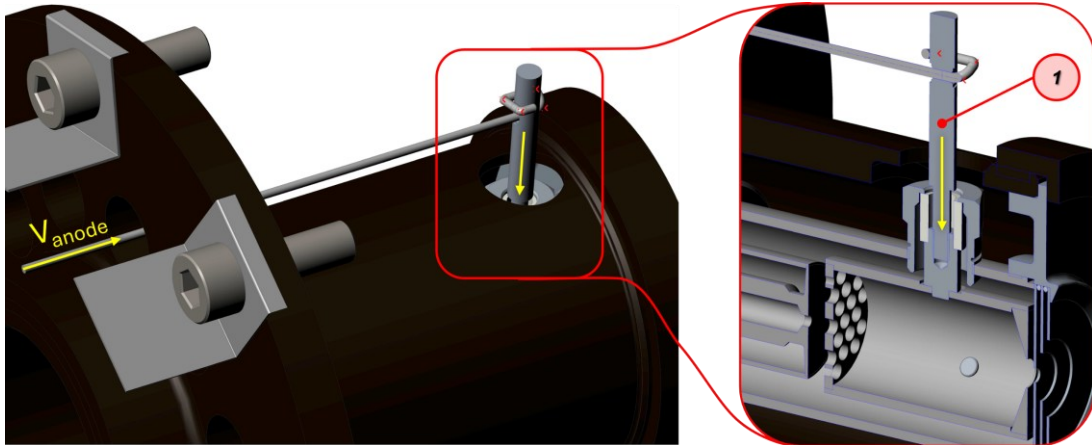


Figure 3.8 New design of the anode electrical connection; (1) the connector is screwed into the anode pin. The tantalum wire which supplies the anode voltage is wrapped and fixed to the connector through the Ø1 mm hole.

3.2.2 Statistical tolerance stack-up analysis

The stack-up elements related at the tool-based assembly strategy have been identified and represented in Table 3.1 which refers to Figure 3.9. It can be also noticed that both the anode grid and the cathode frontal surface refer the common Reference Plane RP outlined in the same figure.

Table 3.1 Tolerance stack-up elements description referring to Figure 3.9.

Tolerance stack-up element	Component	Tolerance type
Cathode flange flatness	Cathode	Geometric
Distance between the cathode flange and the frontal surface (c)	Cathode	Dimensional
Cathode front surface flatness	Cathode	Geometric
Perpendicularity of the cathode frontal surface with respect to the external cylinder axis	Cathode	Geometric
Discharge chamber top surface flatness	Discharge chamber	Geometric
Distance between the discharge chamber top surface and the anode grid (b)	Anode	Dimensional
Anode grid flatness	Anode	Geometric

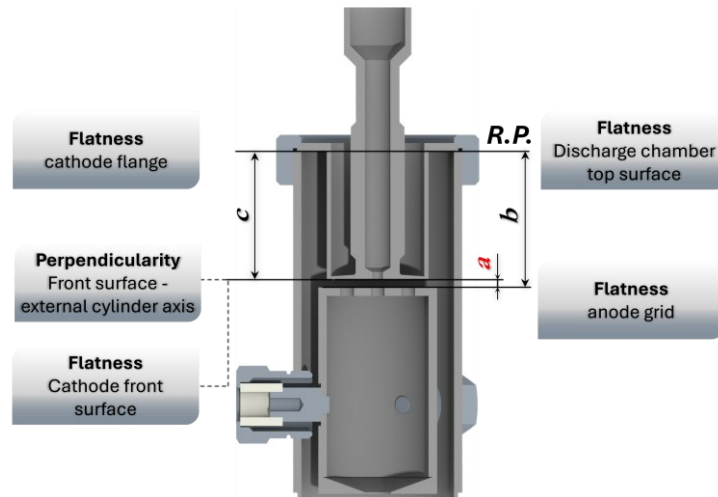


Figure 3.9 FEBIAD ion source tool-based assembly procedure tolerance stack-up analysis schematic representation. The top surface of the discharge chamber is used as the reference plane for the tolerance stack-up.

A custom Python program [53] was developed to execute a statistical 2D tolerance stack-up analysis based on both the Monte Carlo Method (MCM) [54,55] and the Homogenous Transformation Matrices approach [56–58]. The MCM was implemented due to the impossibility to extract a closed-form equation for such a system.

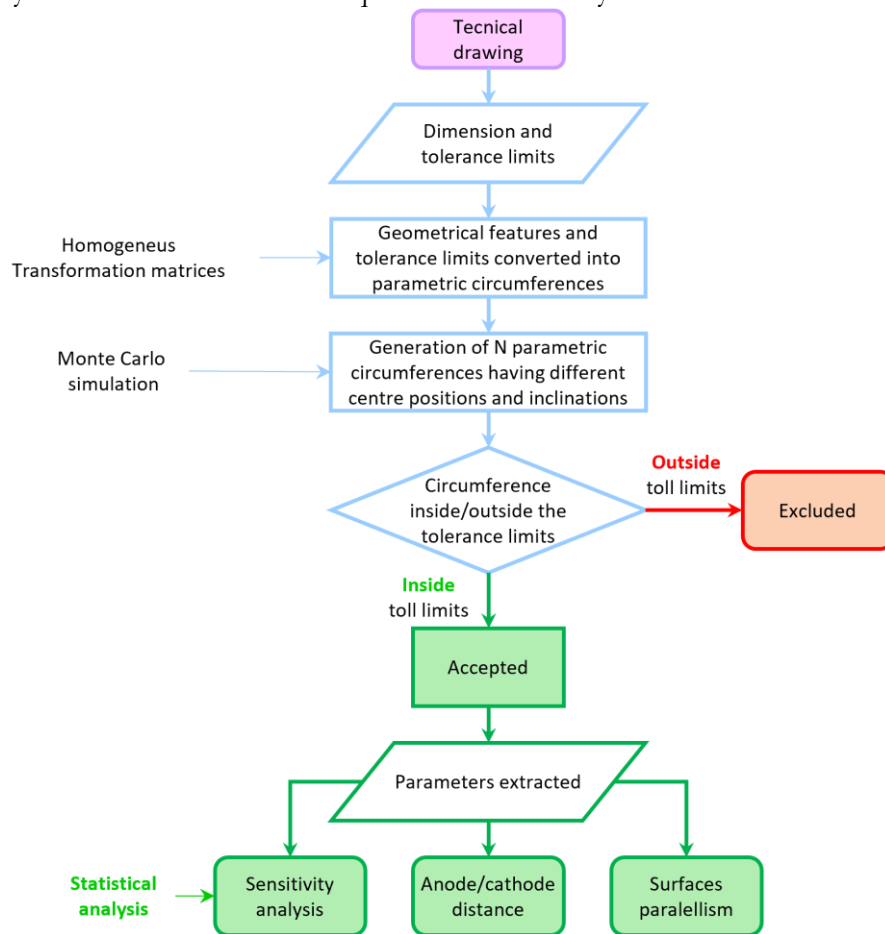


Figure 3.10 Statistical tolerance analysis flowchart

The Homogenous Transformation Matrices approach allowed the representation of tolerances through standardised zones extracted around the theoretical surfaces of each part of the assembly.

Furthermore, a sensitivity analysis based on the first order sensitivity indices method [59] was implemented to assess the influences of tolerance specifications and geometrical deviations on the assembly key characteristics, allowing to derive more suitable tolerancing decisions.

The Flowchart in Figure 3.10 represents the logic behind the developed Python code, moreover the complete script is reported in Appendix D.

Since the FEBIAD ion source is assembled by axisymmetric cylindrical-shaped parts, a set of N (>30000) parametric circumferences for each geometric feature involved in the tolerance stack-up was generated according to MCM.

A Gaussian distribution of the input parameters (radius, distance from the anode/cathode reference planes and the tolerance value) was assumed following the homogeneous transformation matrices approach to mathematically represent the tolerance zones as homogeneous transforms replicating the degrees of invariance associated with the specific zone.

The parametric circumferences that partially exceeded the tolerance limits were excluded from the tolerance analysis, as illustrated in Figure 3.11. Only those entirely within the tolerance limits were accepted to compute the cumulative positional variation of both the anode grid and the cathode front surface, allowing for the anode-cathode distance uncertainty estimation employing the transformation matrices.

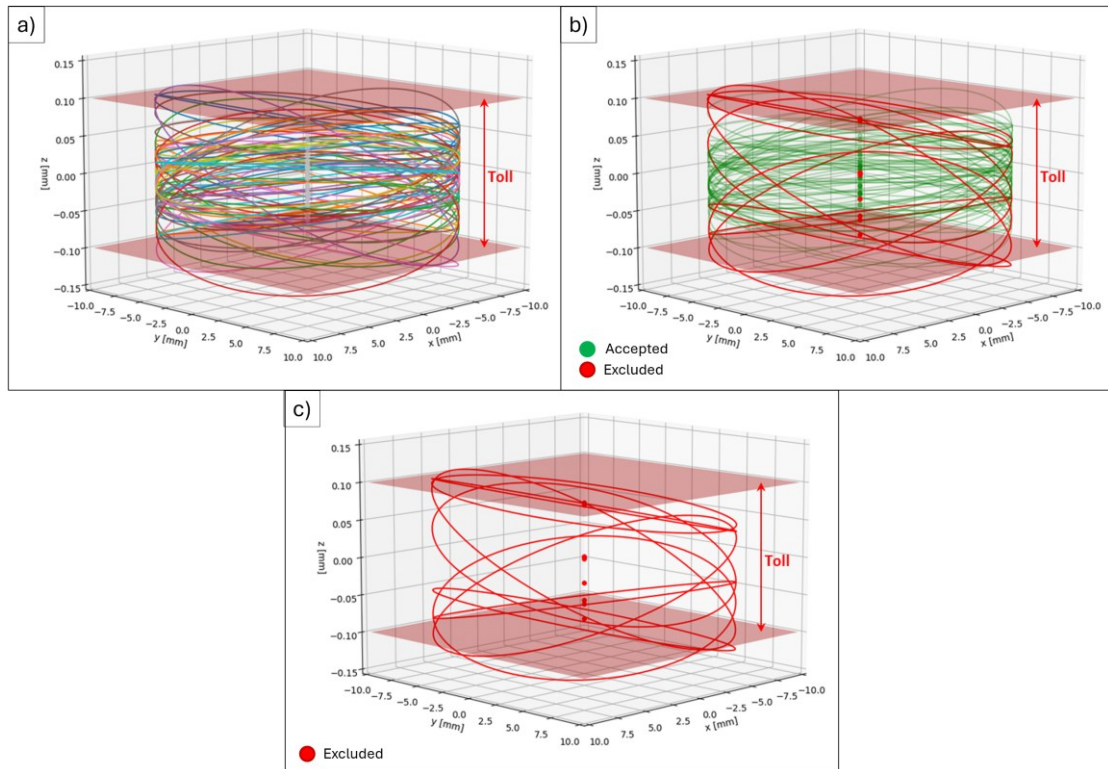


Figure 3.11 According to the MCM method, the Python code randomly generates a set of parametric circumferences (a) and accept those completely within of the tolerance limits to proceed the calculations (b); The parametric circumferences partially or completely outside of the tolerance limits are excluded (c).

3.2.3 Tolerance optimisation method

A custom optimisation algorithm was implemented to the Python program [60] aiming at assigning the proper tolerance values to both the ion source components and the assembly tool. The objective of the optimisation process was to achieve an anode-cathode distance of 1 ± 0.1 mm considering a 3σ confidence level, by maintaining as relaxed as possible the tolerance values. Consequently, it was defined the uncertainty objective as $\sigma_{obj} = 0.033$ mm. The input tolerances for the Python program could be constrained in a reasonable range for each stack-up element to consider the limitation of production technologies to fabricate both the ion source components and the assembly tool. The developed optimisation algorithm discretizes each tolerance range into smaller intervals and generates an array containing all the possible tolerance sets among the considered stack-up elements. In this work, the input tolerance ranged from 0.02 to 0.2 mm and discretized in intervals of 0.02 mm. Each set is subsequently elaborated by the statistical tolerance stack-up analysis to estimate the total uncertainty $\sigma_{i,sim}$. If $\sigma_{i,sim} \leq \sigma_{obj}$, the tolerance set is selected and subjected to the final evaluation: the most suitable option consistent with the optimisation objective is distinguished by the minimum displacement $\delta = \sigma_{obj} - \sigma_{sim}$.

The outcomes of the tolerance analysis and optimisation process are compiled into a report to facilitate the tolerancing process, summarizing:

- (i) The tolerance stack-up elements;
- (ii) The sensitivity index for each tolerance element;
- (iii) The tolerance set resulted from the optimisation process;
- (iv) The position probability distribution with respect to a common reference plane of both the anode grid and the cathode front surface;
- (v) The probability distribution of the anode-cathode distance;
- (vi) The inclination angle θ probability distribution of both the anode grid and the cathode front surface with respect to a common reference plane, as represented in Figure 3.12;
- (vii) The minimum distance between the anode grid and the cathode frontal surface considering the worst-case inclinations scenario (namely a_{MIN}).

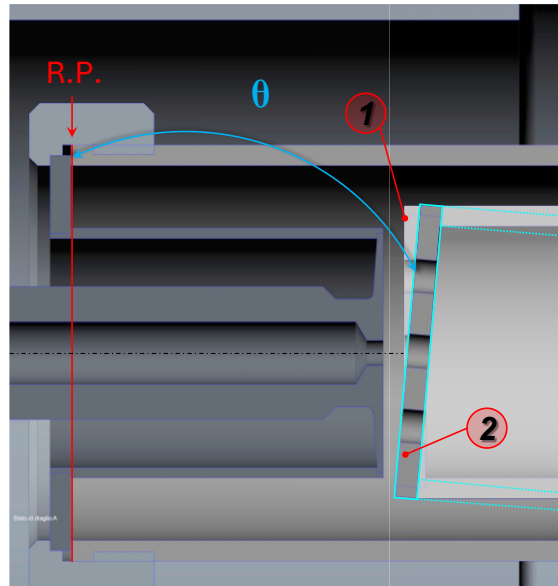


Figure 3.12 The anode grid could be tilted of an inclination angle θ with respect to the Reference Plane (R.P.) because of the assembly issues previously discussed in Paragraph 2.2.2. This figure illustrates both the ideal anode grid position (1) and the tilted configuration (2).

The flowchart presented in Figure 3.13 delineates the procedural steps of the implemented optimisation process.

Subsequently, the outcomes of the report are introduced as tolerance specifications to the technical drawings of the ion source components to meet the functional requirements. Furthermore, both the dimensional and geometric tolerances of the assembly tool depend on the tolerance values assigned to the ion source components. In fact, they must be at least of one order of magnitude less than those allocated to the ion source parts to guarantee the proper positional accuracy.

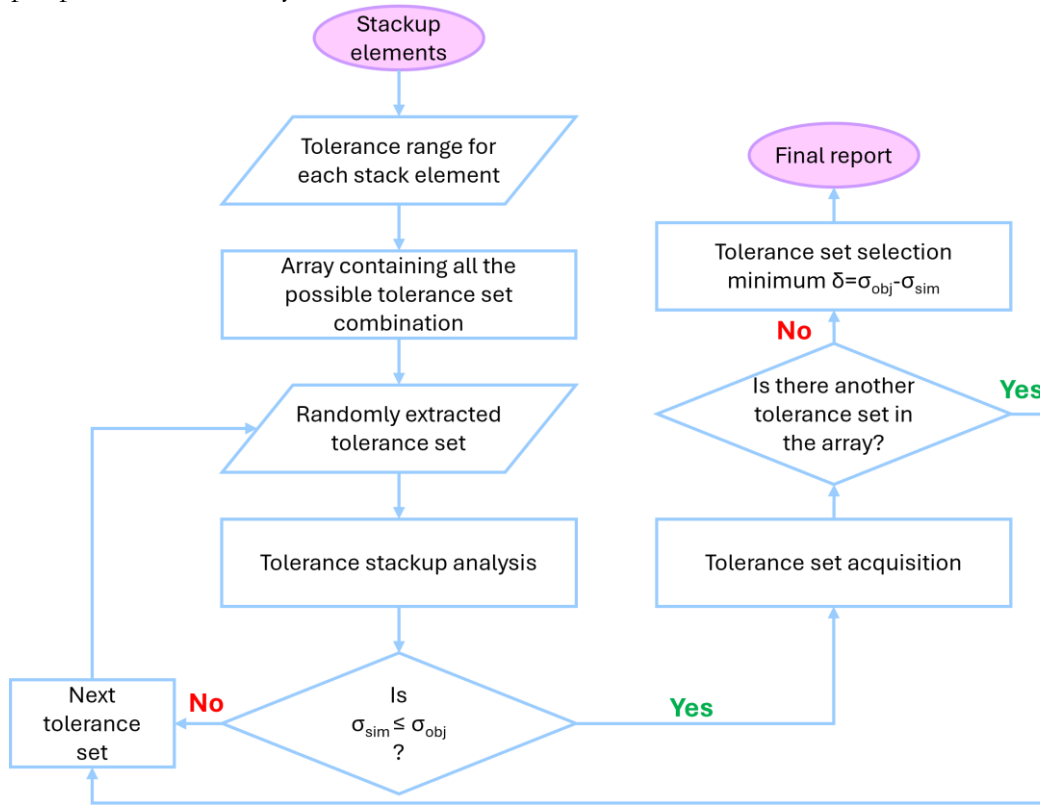


Figure 3.13 Tolerance optimisation method flowchart

This approach can also be extended to other assemblies where tolerance stack-up analysis and optimization are required. However, the modification of the tolerance stack-up to be analysed still requires a deep understanding of the python program functioning and the adjustment of multiple elements across several parts of the script, making its use not user-friendly. Moreover, it was developed for cylindrical parts axisymmetric parts and planar interfaces, consequently a further implementation should be performed to analyse more complex assemblies and coupling configurations.

3.2.4 Experimental validation method

The Zeiss Accura 3D Coordinate Measuring Machine (CMM) available at INFN-PD (shown in Figure 3.14) is employed to validate the numerical values obtained from the simulations by measuring the dimensional and geometric features of the FEBIAD ion source parts involved in the stack-up both before and after the assembly process.



Figure 3.14 CMM available at INFN-PD

The assembly tool prototype to perform the assemblies using the tool-based procedure, shown in Figure 3.14, was manufactured at INFN-LNL workshop.

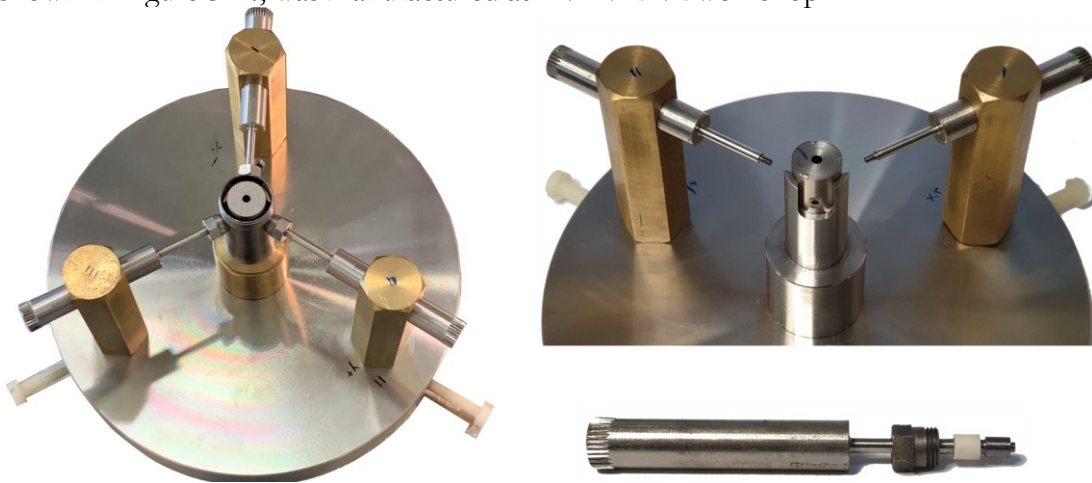


Figure 3.15 Assembly tool prototype manufactured at INFN-LNL workshop.

However, the anode grid and the cathode frontal surface are enclosed within the discharge chamber once assembled, making them inaccessible to the CMM stylus probe. To address this limitation, the cathode was individually measured before the assembly process to get the distance ϵ (distance between the cathode frontal surface and the Reference Plane RP), and the geometric features related to the cathode flange (C') and the cathode frontal surface (C''), which are highlighted in Figure 3.16 left. The anode grid position was determined by fixing only the anode as shown in Figure 3.16 centre.

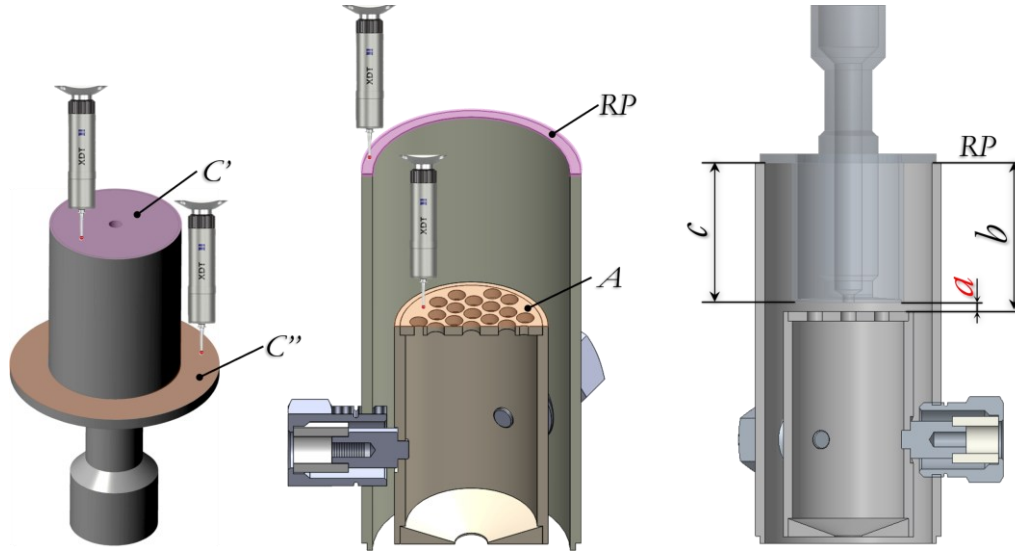


Figure 3.16 The experimental validation of the numerical method relies on performing the CMM measurements on the ion source components; left: the geometrical features and the distance between the frontal surface (C') and the Flange (C'') of the cathode were measured; centre: the geometrical features of the anode grid (A) and the discharge chamber surface in contact with the assembly tool was measured and used as the reference plane (RP); right: The parameters " c " and " b " are used to indirectly calculate the anode-cathode distance " a ".

Afterwards, the CMM stylus probe was carefully driven to acquire at least five coordinate points on the anode grid surface, avoiding the grid holes which could affect the measurements. Such an approach enabled the extraction of the associated integral feature of the anode grid surface (A), allowing the determination of:

- (i) The geometric features of the anode grid surface;
- (ii) The distance b ;
- (iii) The inclination angle θ with respect to the Reference Plane RP .

Finally, the distance between the anode and the cathode a is indirectly calculated subtracting the CMM measurements of c from b , as shown in Figure 3.15 right.

3.3 Results and discussion

3.3.1 Experimental validation of the numerical method

The custom Python code developed to perform the tolerance stack-up analysis was validated by assembling the FEBIAD ion source components manufactured according to the current tolerance specifications. The simulation input parameters, i.e., tolerance specification values involved in the tolerance stack-up highlighted in Figure 3.17, were extracted from the current FEBIAD ion source components technical drawings. Since a tolerance analysis had not been previously conducted on the device, certain tolerance stack-up elements lacked specific tolerance values. In such instances, general tolerances according to the ISO 2768-1 and ISO 2768-2 were applied as input for the simulation.

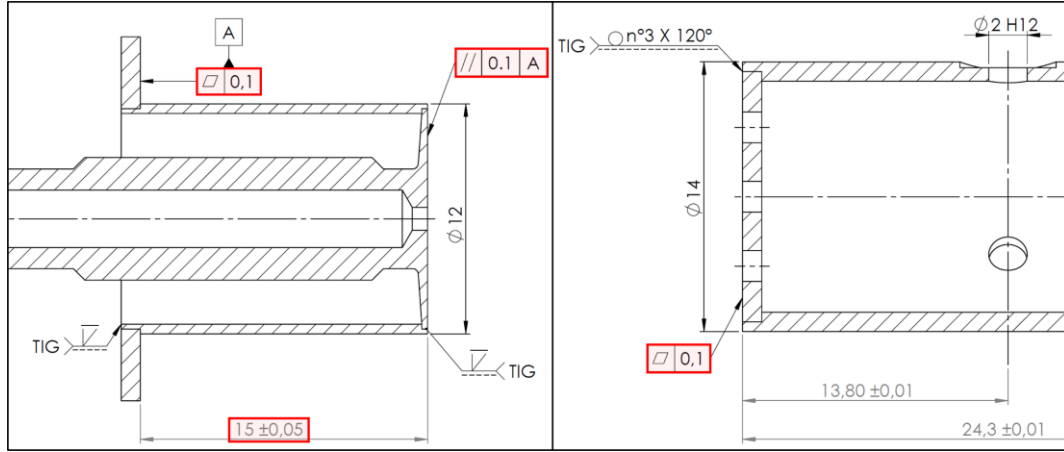


Figure 3.17 Anode and cathode tolerances used as input for the tolerance stack-up analysis.

The assembly tool prototype was successfully tested and used to carry out the assembly process. Subsequently, the positional accuracy of the assembled components was assessed through CMM measurements on 6 different assemblies (i.e. each one with different components) which were compared to the predicted numerical tolerances provided by the Python code. Specifically, two critical geometric features were measured by the CMM to validate the Python code according to the procedure reported in the previous paragraph:

- (i) The anode-cathode distance a shown in Figure 3.9, essential for the proper functioning of the ion source;
- (ii) The inclination angle θ of the anode grid with respect to the discharge chamber reference plane, which is crucial for maintaining a uniform electric field.

As a result, the experimental data for both the anode-cathode distance and the anode grid inclination angle θ fall within the 3σ range predicted by the tolerance stack-up simulation performed by the custom Python code.

A symmetry in the experimental data of the inclination angle θ (Figure 3.18, right) can be observed. Specifically, the CMM measurements provided information about the orientation of the extracted anode grid plane (related to the real surface) with respect to the nominal reference plane. As a result, both positive and negative inclination values were considered in the analysis, as the angular deviation of the grid can occur in either direction during the assembly process.

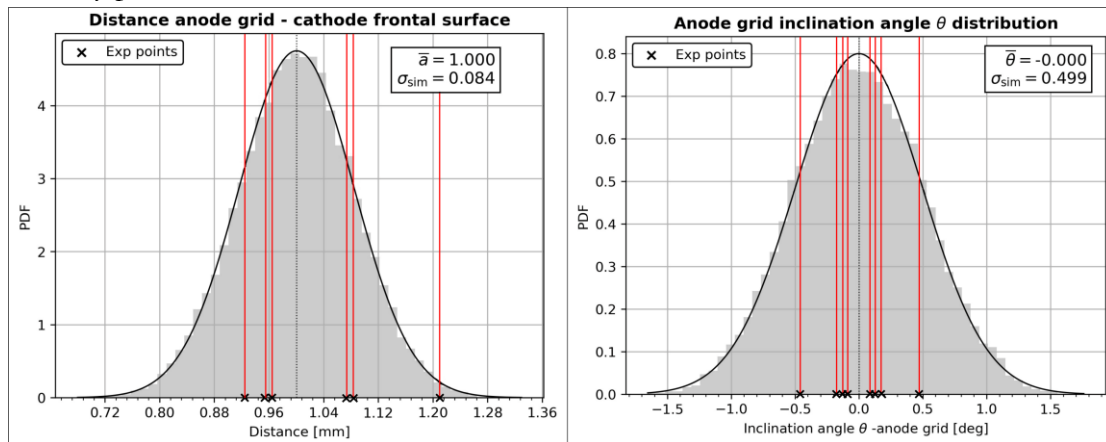


Figure 3.18 Comparison between the numerical and experimental values; left: anode-cathode distance a distribution; right: inclination angle θ distribution.

Such an alignment between the experimental measurements and the simulation results, as reported in Figure 3.18, demonstrates the accuracy and reliability of the Python code in predicting the positional uncertainties during the assembly process. However, the current tolerance values used as input do not achieve the desired σ_{obj} (0.033 mm) within the 3σ confidence interval for the anode-cathode distance. Consequently, while the current tolerances confirm that the positional uncertainties are predictable and within a certain range, further refinement of the tolerance specifications is required to meet the optimal anode-cathode distance of 1 ± 0.1 mm considering a 3σ confidence level aiming at guaranteeing a proper ion source functioning. Achieving such an accuracy would likely involve tighter control of the manufacturing processes and potentially redesigning certain components to reduce their individual tolerance contributions. This iterative process of tolerance analysis, component manufacturing, and assembly validation is essential for optimising the FEBIAD ion source assembly and enhancing its overall performance and reliability.

3.3.2 Assembly procedures comparison

The CMM measurements were also performed on 6 different assemblies prepared with the manual and tool-based assembly procedures aiming at comparing the mounting strategies. The results are resumed in Table 3.2 and on the plots in Figure 3.19.

The plot in Figure 3.19 left depicts the anode-cathode distance values measured by CMM. Assemblies prepared using the tool-based procedure achieved an average distance of approximately 1.035 mm, closely aligning with the nominal value of 1 mm. The manual procedure, however, results in a larger average distance of around 0.841 mm and exhibits greater variability. The largest deviation (Δ) from the nominal value was measured for an assembly prepared using the manual assembly strategy, with distances ranging from 0.615 mm to 1.171 mm. In contrast, the tool-based procedure consistently maintained the anode-cathode distance within a tighter range, reflecting its superior precision and accuracy.

Such variability, especially in assemblies produced manually, may significantly affect the efficiency of the system and increase the risk of failure due to thermal expansion of the cathode frontal surface during operation.

The plot reported in Figure 3.19 right shows inclination angle (θ) of the anode grid surface with respect to the discharge chamber reference plane values measured by CMM; the assemblies realized by the new tool-based assembly procedure exhibit significantly lower variability. Specifically, the average inclination angle for the tool-based procedure is approximately 0.26° , while the manual procedure results in a larger average inclination angle of around 0.55° . The standard deviation for the tool-based procedure is also decreased compared to the manual assembly procedure, indicating a more consistent and reliable assembly process. Furthermore, the manual procedure shows a wider spread of inclination angles, with some measurements exceeding 1.0° , highlighting the inconsistencies introduced by operator-dependent assembly. Additionally, tool-based assembly procedure simplified the mounting operations of the anode and reduced the time required to complete the fixing of the ion source parts from the several hours requested by manual assembly procedure to a few minutes.

Table 3.2 Assembly procedures comparison: CMM measurements summary

Assembly procedure	Average a [mm]	Std. Dev. a [mm]	Average θ [deg]	Std. Dev. [deg]
Tool-based procedure	1.035	0.108	0.260	0.168
Manual procedure	0.841	0.254	0.552	0.389

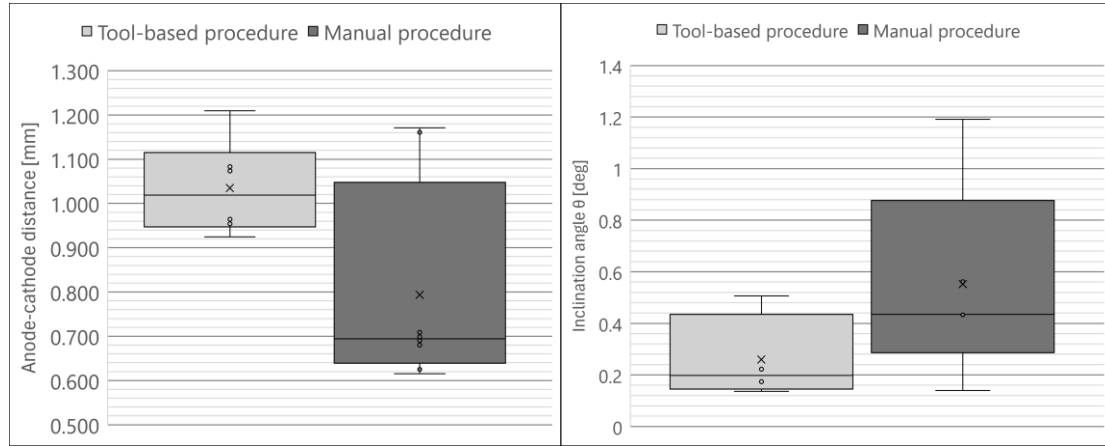


Figure 3.19 Assembly procedures comparison.

Such results underscore the effectiveness of the tool-based assembly procedure in improving the positional accuracy of the FEBIAD ion source components. The reduced deviation and variability in the tool-based assemblies indicate a higher consistency and reliability in achieving the desired geometrical requirements. Such an improvement can be attributed to the reduced reliance on operator skill and on the reduction of the tolerance stack-up elements achieved by the assembly tool.

3.3.3 Tolerance optimisation results

The tolerance optimisation process is a critical step in ensuring the accurate assembly and functionality of the FEBIAD ion source components. The primary objective was to achieve an anode-cathode distance a of 1 ± 0.1 mm with a 3σ confidence level.

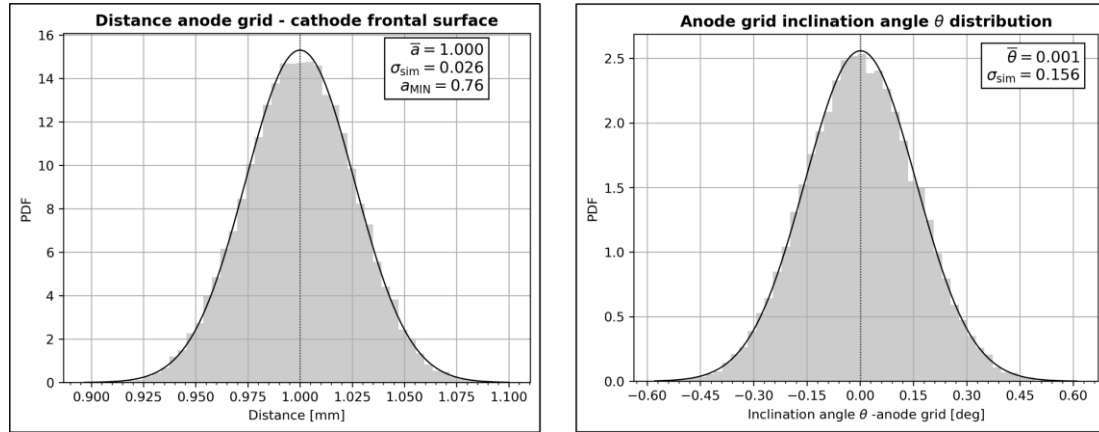


Figure 3.20 Results of the tolerance optimisation process; left: anode-cathode distance, right: anode grid inclination angle θ

Furthermore, it was imposed a minimum distance between the anode grid and the cathode frontal surface considering the worst-case surface inclinations scenario of 0.75 mm. Such requirements necessitate minimizing the positional uncertainties of the assembled components to ensure consistent performance.

To achieve this, the tolerance optimisation process, implemented using the custom Python program, analysed several tolerance combinations related to each tolerance stack-up elements to determine the combination that would meet the desired positional accuracy. The charts in Figure 3.20 demonstrate that the optimisation process successfully met the targeted goals as the resulting σ_{sim} is lower than σ_{obj} .

Nevertheless, the simulations revealed that even improving the mounting strategy using the custom assembly-tool, the optimised tolerances required for the anode-cathode distance and anode grid inclination optimum values remained beyond the achievable limits of the current manufacturing processes especially for the cathode, as can be observed from Figure 3.21 and Figure 3.22. The current production technologies, in particular the manual TIG welding operation, do not possess the precision needed to produce components within tolerance values lower than 0.1 mm for components made of refractory metals. As a result, there is a clear need for either advancements in manufacturing techniques or a redesign of the components to accommodate more achievable tolerances.

It can be also observed that the tolerancing process was performed following the ISO 17450, ISO 1101 and ISO 14660 references. Indeed, the position tolerances allocated to the anode grid and cathode frontal surfaces include also the form and orientation tolerances considered in the tolerance stack-up.

The results of the tolerance stack-up analysis and the optimisation process are into reports in Appendix E.1 and Appendix E.2 . Moreover, the technical drawings are detailed in Appendix A.2 .

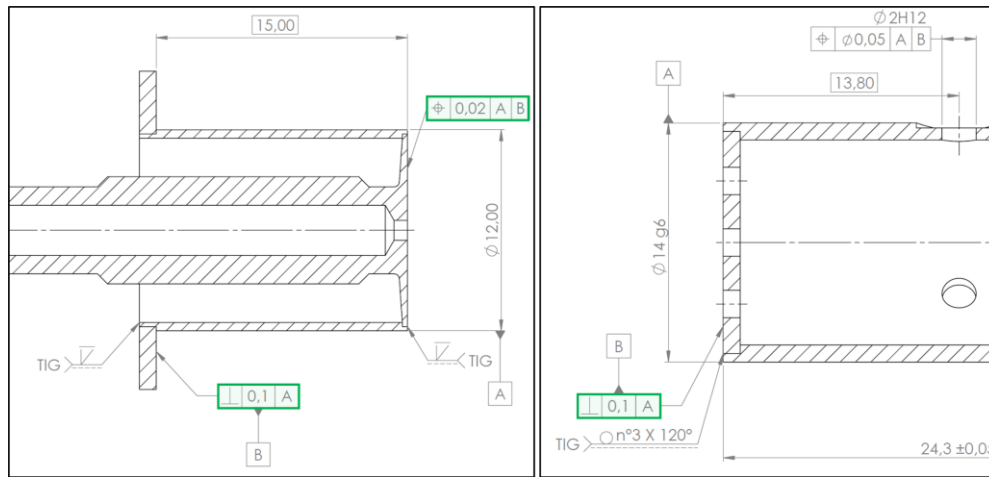


Figure 3.21 Tolerance optimisation results; left: Cathode tolerancing; right: anode tolerancing.

In Figure 3.22 (right) the tolerance specifications allocated at the main body are highlighted of the assembly tool. They are directly related to the anode grid and discharge chamber top surface as they are in contact with the main base tool during the assembly process. In fact, the geometric features in such surfaces should be at least on order of magnitude finer than the contact surfaces of the anode and discharge chamber to guarantee the accurate and reliable positioning of the components.

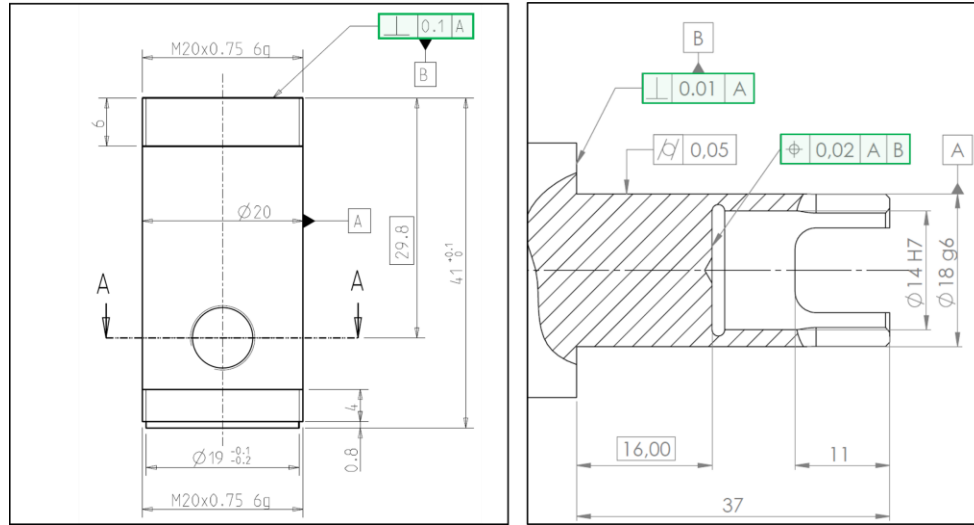


Figure 3.22 Tolerance optimisation results; left: Discharge chamber tolerancing; right: assembly tool main body tolerancing

3.4 Conclusions

The systematic tolerance stack-up analysis and optimisation process conducted for the first time for the SPES FEBIAD ion source has demonstrated several significant outcomes and implications for the assembly and manufacturing processes. The use of a tool-based assembly procedure has significantly improved the accuracy and reliability of the positioning of FEBIAD ion source components during assembly process, which is crucial to ensure performance stability of the device during operation. In addition, the tool-based method greatly simplified the assembly operations, reducing the time required to complete the ion source assembly from several hours using the manual method to just a few minutes.

The custom Python code based on MCM and Homogeneous Transformation Matrices approach developed for tolerance stack-up analysis was validated by assembling FEBIAD ion source components and comparing CMM measurements with simulation predictions. Key geometric features, including anode-cathode distance and anode grid inclination, fell within the 3σ range of the simulations, demonstrating the code accuracy. Furthermore, the tolerance optimisation process implemented in the Python program effectively identified the best tolerance combinations to achieve the desired anode-cathode distance of 1 ± 0.1 mm within a 3σ interval.

However, the current manufacturing processes, particularly the manual TIG welding operation for refractory metals, are not precise enough to meet such an optimised tolerance. This highlights the need for advancements in manufacturing techniques or a redesign of the components to achieve the necessary precision for consistent performance.

To bridge the gap between desired performance specifications and manufacturing capabilities, future work will focus on exploring advanced manufacturing methods, such as Laser Powder Bed Fusion (LPBF) for refractory metals [30,31,47,61,62]. Additionally, further refinement of the ion source design and validation of the tolerance optimisation process with larger sample sizes will be crucial to enhance the robustness and reliability of the assembly process. Indeed, the developed tolerancing methods are versatile instruments that can be employed to assign the proper dimensional and geometric specifications to the re-designed components.

In summary, the results of this study underscore the critical importance of precise tolerance management in the assembly of FEBIAD ion sources. By implementing a structured

optimisation process and utilizing a tool-based assembly method, significant improvements in assembly accuracy and reliability have been achieved. However, addressing the limitations of current manufacturing technologies will be essential for realizing the full potential of the optimised assembly strategy and ensuring the consistent performance of the FEBIAD ion source.

Chapter 4: Compatibility and electro-thermal characterisation of LPBF-Manufactured components for the FEBIAD Ion Source

Traditional manufacturing techniques for FEBIAD components, such as machining and TIG welding, often result in dimensional and geometric inaccuracies affecting the assembly process quality [47]. However, additive manufacturing, specifically the LPBF process, is a promising solution for producing refractory metal components such as molybdenum [31] and tantalum [62], which are essential to resist at the FEBIAD ion source operating conditions. This chapter provides a detailed examination of the LPBF process, its advantages and disadvantages, and its application in the production of tantalum cathodes for high-temperature operation within the FEBIAD ion source. Furthermore, Finite Element (FE) analysis and experimental validation of LPBF-produced cathodes are presented to demonstrate their capability to resist at operational conditions while maintaining similar or improved performance compared to traditionally manufactured cathodes.

4.1 The Laser Powder Bed Fusion (LPBF) process

Powder bed fusion technologies are a category of additive manufacturing techniques which include processes like Laser Sintering (LS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM) [63]. In such methods, a thin layer of powder, typically consisting of the build material, is spread over the build platform surface. An energy source, such as a laser for LS and SLM or an electron beam for EBM, is then employed to scan and selectively melt the material in accordance with the sliced cross-sections of the part being fabricated. After each layer is processed, the build platform lowers incrementally, allowing a new layer of powder to be deposited and similarly melted. Such a layer-by-layer approach enables the gradual construction of the component, as represented in Figure 4.1.

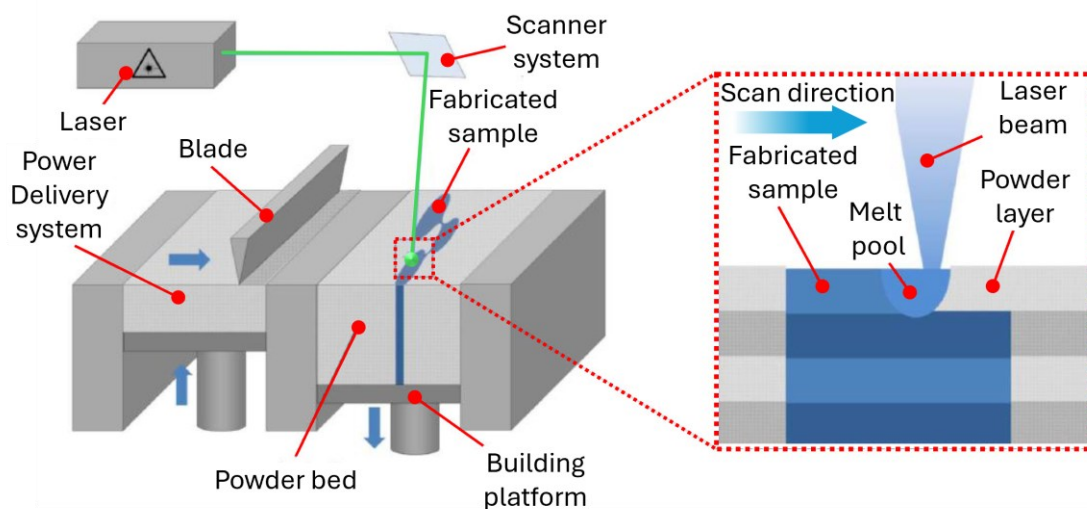


Figure 4.1 Schematic representation of the LPBF process.

Materials commonly used in these processes include stainless steel, aluminium, titanium, cobalt-chrome alloys, and maraging steel (a high-strength tool steel). The mechanical

properties and surface quality of components produced through powder bed fusion are typically comparable to those of cast parts in terms of density, occlusions, or defects[61]. However, as with cast parts, if a smooth or polished surface finish is required, post-processing through traditional machining techniques is generally necessary to achieve the desired finish.

Nevertheless, the Development and Innovation for Additive Manufacturing (DIAM) laboratory of the INFN-Padova section has recently optimised the process parameters and characterized fully-dense samples produced in Tungsten (W) and Molybdenum (Mo) using the LPBF technology [30,31].

Consequently, the LPBF is a promising method to produce the FEBIAD ion source components to overcome the inherent limitations of the current traditional production route. A comprehensive understanding of both the advantages and limitations of such an AM technology lays the basis for optimising the design of components. Such awareness enables the integration of design features that fully benefit the capabilities of the process while accounting for potential constraints [64].

i. LPBF advantages:

- Reduction of component production costs and development time;
- Increased flexibility during the component design phase. It is feasible to design complex geometries without significant increase in costs ("Complexity for free"). As a result, shape can be independent from the production process, prioritizing function.
- Reduced process planning compared to more conventional methods such as CNC (Computerized Numerical Control). Regardless of product complexity, most components can be entirely produced in a single production phase. In contrast to other production technologies, AM-LPBF reduces the amount of processes and resources needed, which speeds up production and eliminates many assembly steps. Furthermore, if design changes are needed during the development phase, the production process does not need to be modified, avoiding delays in production;
- Capability to manufacture a variety of distinct components within a single production batch;
- Ability to produce as a single component assemblies which would be realized by welding or assembly operations using traditional manufacturing technologies;
- The process parameters can be preconfigured and optimised to produce a specific material, moreover the same settings can also be used for different production batches to increase the process repeatability;
- The LPBF process is suitable to produce geometries subjected to topology optimisation both to reduce the material consumption (and consequently costs) and to meet specific design or functional requirements. "Lattice" structures are an example of material efficiency and the high complexity achievable;
- Capability to generate process files independently on the location of the production machines resulting in high flexibility and savings in potential transportation costs and time for the components;

- The LPBF is a Near net shape process that consumes less raw material than subtractive technologies, thus reducing material costs.

ii. LPBF Disadvantages:

- Anisotropy in the mechanical properties of the component depending on the selected build direction (and thus the orientation of the parts) and the process parameters. In contrast, traditional manufacturing processes produce more homogeneous parts.
- Limitations in both the size and quantity of components that can be processed, depending on the dimensions of the production machine.
- Post-processing operations are necessary to remove any supports used during manufacturing, improve surface finish and component quality, or to meet the design tolerance specification. Such additional processes would lead to delays in the delivery of the finished product;
- High initial investment costs due to the purchase of production machines;
- The available raw materials are limited and typically expensive;
- Presence of residual stresses post-manufacturing often lead to additional thermal treatments.

4.1.1 LPBF for manufacturing FEBIAD ion source components at DIAM lab

The EOS M100 DMLS (shown in Figure 4.2) equipment from Electro-Optical Systems GmbH (EOS GmbH, Krailling, Germany) is used at the DIAM lab to manufacture parts made of refractory metals.

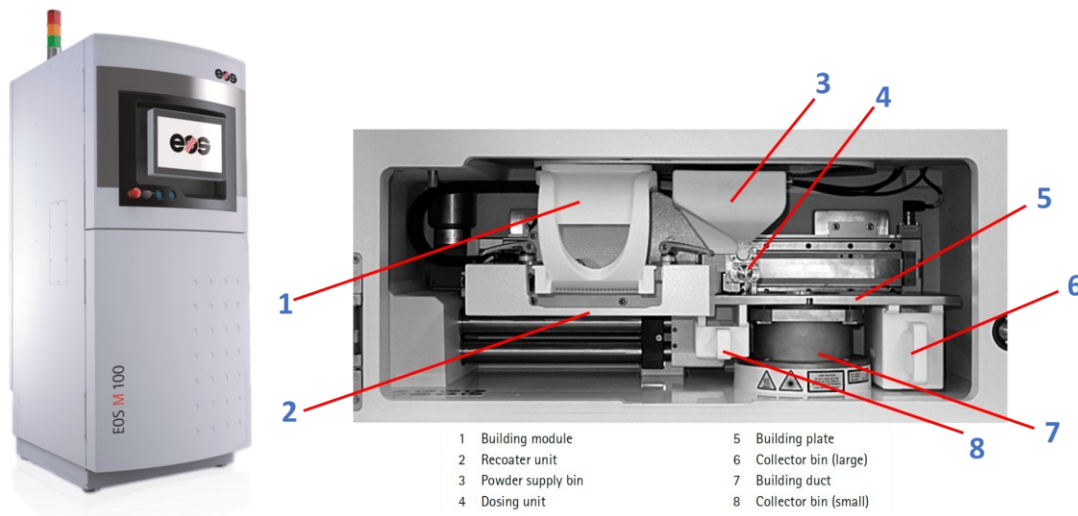


Figure 4.2 EOS M100 DMLS system available at DIAM laboratory [65]

Additionally, the machine's build volume, which is a cylinder with a diameter of 100 mm and a height of 95 mm, along with the other specifications listed in Table 4.1, is well-suited for manufacturing components for the FEBIAD ion source.

The data collected and the expertise gained in optimising process parameters for tungsten (W) and molybdenum (Mo) enabled the production of samples in other refractory metals, such as tantalum (Ta) and niobium (Nb), which were recently characterized at LNL-INFN, as referenced in [66,67] to measure their specific material properties.

Optimising the process parameters for Ta made it feasible to employ the LPBF technology to produce the cathode, a critical component for the FEBIAD ion source, as discussed in previous chapters.

Table 4.1 EOS M100 DMLS system characteristics [65]

Technical data	EOS M100
Building volume	Ø 100 mm x 95 mm
Laser type (maxpower)	Yb (200W)
Focus diameter	40 µm
Scan speed	up to 7 m/s
Inert gas supply	max 50 L/m

This chapter details the development of the cathode as a case study to demonstrate the compatibility between LPBF technology and its application to manufacture ion source components. If the additively manufactured cathode is capable to withstand the thermal and mechanical loads during operation without sudden failures or excessive deformations, while ensuring an electro-thermal performance comparable to the cathode produced via the traditional manufacturing technologies, it would be possible to extend LPBF manufacturing technology to other ion source components. Such fundamental step is essential to further innovate the FEBIAD ion source, exploiting the advantage of the LPBF process, which would lead to re-design the assembly components aiming to:

- Simplify the assembly process by reducing the number of parts, making it easier, more reliable and repeatable in terms of parts positioning;
- Enhance the device performances by optimizing components geometry thanks to the increased flexibility during the component design phase.

Consequently, the goal is to perform an experimental characterization of cathodes produced through the LPBF process to verify the compatibility between the production technology and the high temperature applications.

4.1.2 Design process route

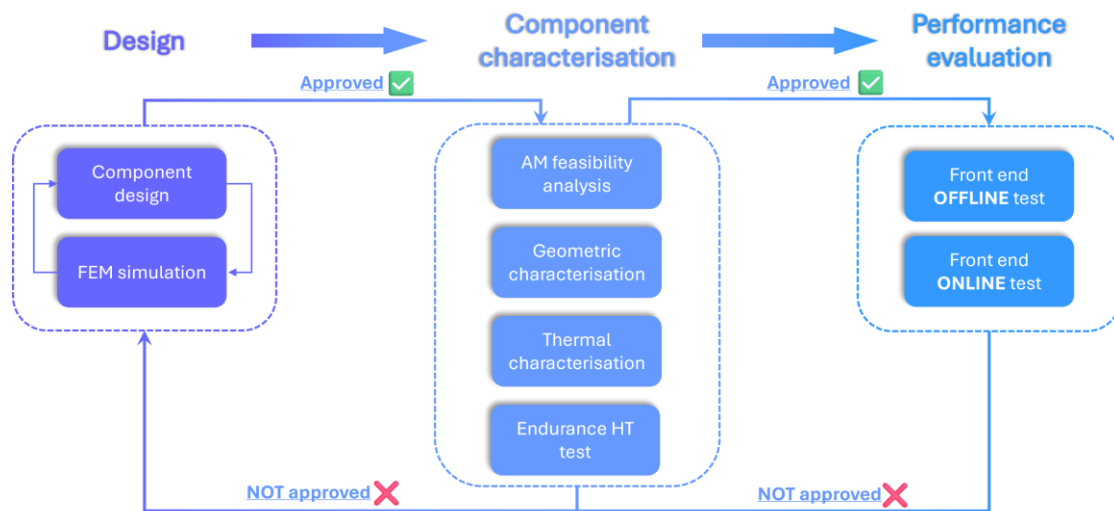


Figure 4.3 Procedure to approve each design modification on the FEBIAD ion source prior to its On-Line implementation.

The primary requirement for the FEBIAD ion source is the reliability as a catastrophic failure during operation, especially in presence of radioactivity, would result in the replacement of the entire TIS unit and its disposal as a radioactive waste. Therefore, at LNL-INFN were developed numerical and experimental methods to verify the compatibility of any design modifications with the operational requirements of the ion source [20,26,28].

In Figure 4.3 are presented the procedural steps required for approving each design modification prior to its On-Line implementation, which involves the actual production of radioactive ion beams.

The following paragraphs address as case study the modification of both the production technology and the design of the cathode, investigating the numerical simulations and experimental methods used from the design phase to the component characterization.

4.2 Component design

The design of the cathode was slightly modified to be entirely produced using the LPBF process without using supports according to Design For Additive Manufacturing (DFAM) approach [68,69], as shown in Figure 4.4. Moreover, in Figure 4.4 is represented the specific growing direction of the samples, which have their frontal surface toward the build platform. Further design modifications were not introduced to maintain the component representative of the conventionally produced cathodes.

Cathodes produced using standard traditional manufacturing technologies will be referred to as “STD”, while those manufactured using the LPBF process with the conventional design will be indicated as “LPBF_conv”. Such a distinction needs to differentiate the two production methods throughout the following analyses.

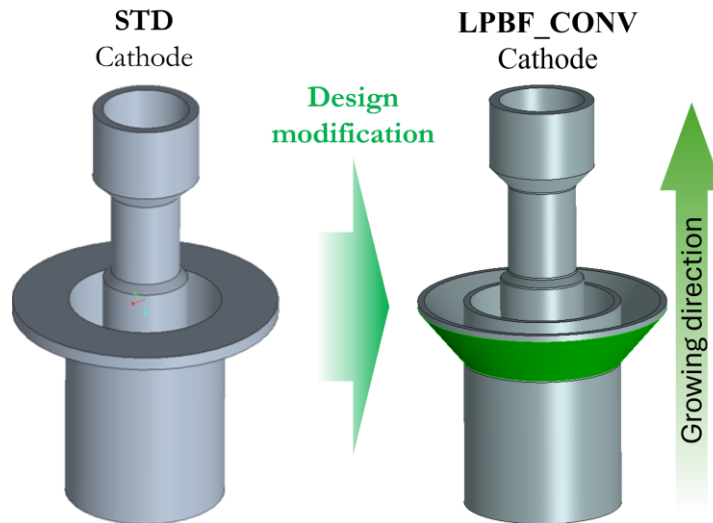


Figure 4.4 The LPBF_conv cathode presents a conical surface compared to the STD cathode to avoid the production of any support during the LPBF process.

The LPBF post-process operations foresaw for the LPBF_conv cathode are the removal from the build platform through the Electrical Discharge Machining (EDM) and a turning machining of the frontal surface to remove the imperfections introduced by the previous process.

4.3 FEM analysis

Prior to production and experimental phases, a coupled electrical-thermal finite element (FE) analysis in ANSYS® software was performed to estimate the temperature distribution of both the STD and LPBF_conv cathodes.

In this study, the temperature distribution estimation is essential for the following main reasons:

- to predict temperature variations between the STD and LPBF_conv at the same feeding electric current;
- to verify if any components overcome their own temperature limit;
- To perform functional and geometric optimisation once validated the FE model.

The numerical method to simulate the FEBIAD ion source behaviour at the operational working conditions was developed at INFN-LNL and published in [28]. The ion source (1) was analysed separately from the production target and the gas injection system (refer Figure 4.5) as they do not impact significantly the cathode temperature distribution. Similarly, the vacuum chamber was not modelled as its internal surface far exceeds the total surface area of the components inside. Consequently, it has a negligible effect on radiative heat transfer, which is dominant considering the high-vacuum regime and the elevated operational temperature. Furthermore, a shorter transfer line compared to the original design (refer to Chapter 2), along with a dedicated electrical connection (3), were included to be representative of the similar configuration employed in the experimental setup discussed in the subsequent paragraph.

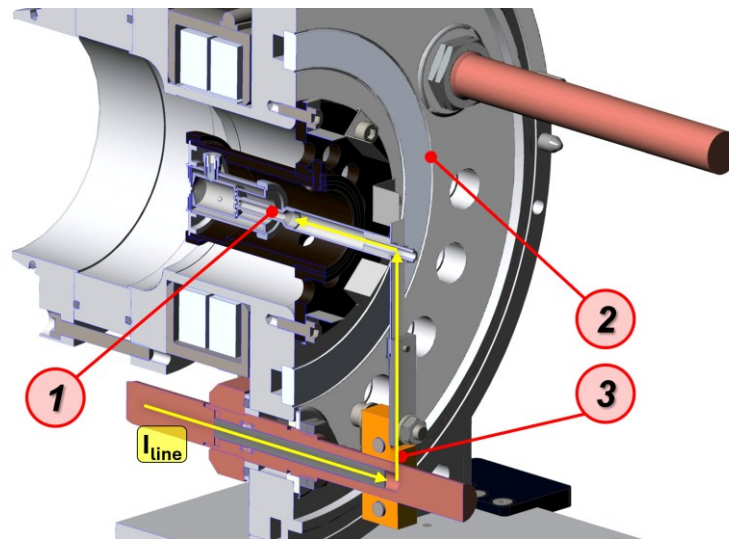


Figure 4.5 The assembly considered for the FEM simulations. (1) FEBIAD ion source, (2) TIS baseplate, (3) electrical connection.

The components were modelled assuming a perfect electrical and thermal connections, despite the real setup is prepared by coupling the parts with clearance or interference fits and the ion source is fixed to the baseplate (3) through bolted joints.

Figure 4.6 illustrates the FEBIAD ion source geometry imported in ANSYS® environment to perform the FE electrical-thermal numerical analysis developed to estimate the cathode temperature distribution. Furthermore, the system of constraints and loads applied to the degrees of freedom (DOF) in the FE model are reported. Concerning the electrical analysis, a constraint of 0 V was applied to the ion source surface directly in contact with the vacuum

chamber baseplate. A current load (I_{line}) was applied to the lower end of the electrical connection. Considering the thermal boundary conditions, a temperature constraint of 50°C was assigned to the same surfaces where the potential constraint and current load were applied. Indeed, such surfaces are positioned in proximity of the vacuum chamber water cooling system. Moreover, T_{constr} value was also applied to the temperature of the surrounding environment, while convective thermal loads were neglected, as the system operates in a high-vacuum regime.

The SOLID226 element type was selected to enable coupled field electrical-thermal simulations, as it accommodates two nodal DOF, i.e. temperature and voltage. Furthermore, the radiative heat transfer problem was solved alongside the conductive heat transfer problem through ANSYS® radiosity solver method, which limits radiation exchange to gray-diffuse surfaces.

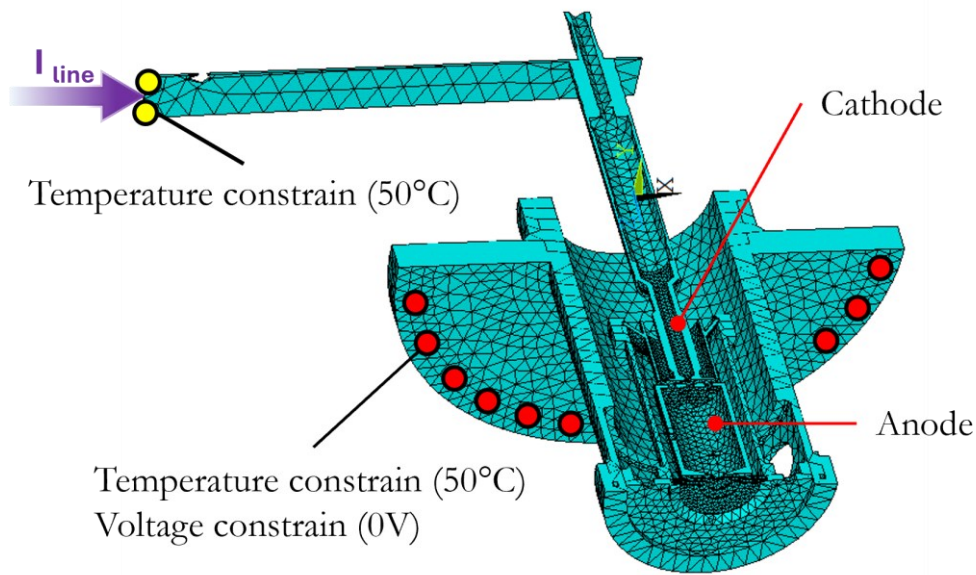


Figure 4.6 Schematic representation of the electrical and thermal constraints and loads applied to the FE electrical-thermal model.

The FEBIAD ion source is assembled by components manufactured in graphite, tantalum, molybdenum, alumina, and stainless steel, as discussed in Chapter 2. Consequently, to calculate the steady-state temperature distribution, it was necessary to consider temperature-dependent material properties such as electrical resistivity, thermal conductivity, and emissivity. The properties of such materials are also influenced by the production method, with differences observed between STD and LPBF materials, as explored in [30,31,67] and shown in Figure 4.7 considering the electrical resistivity as an example.

Furthermore, the emissivity property, which strongly affects thermal radiation, depends significantly on the surface finishing, as can be observed in Figure 4.8 [67]. Therefore, the material properties were compiled into specific macros reported in Appendix G, and assigned to the components for the FE analysis and different material macros were applied to “as-built” and polished (post-processed) surfaces of the cathode.

In Appendix F is reported the complete ANSYS® Parametric Design Language (APDL) used to perform the FE analyses.

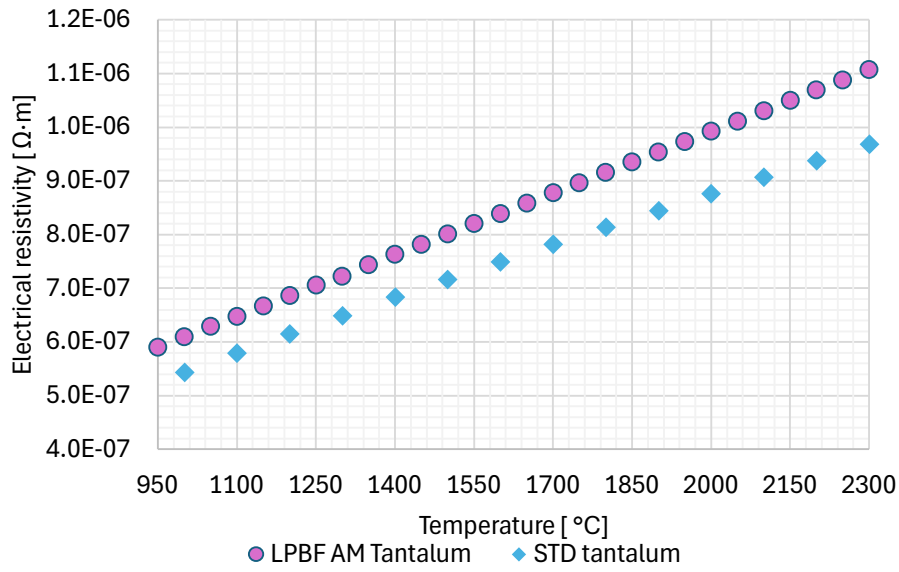


Figure 4.7 Electrical resistivity difference between LPBF Ta and STD Tantalum [67]

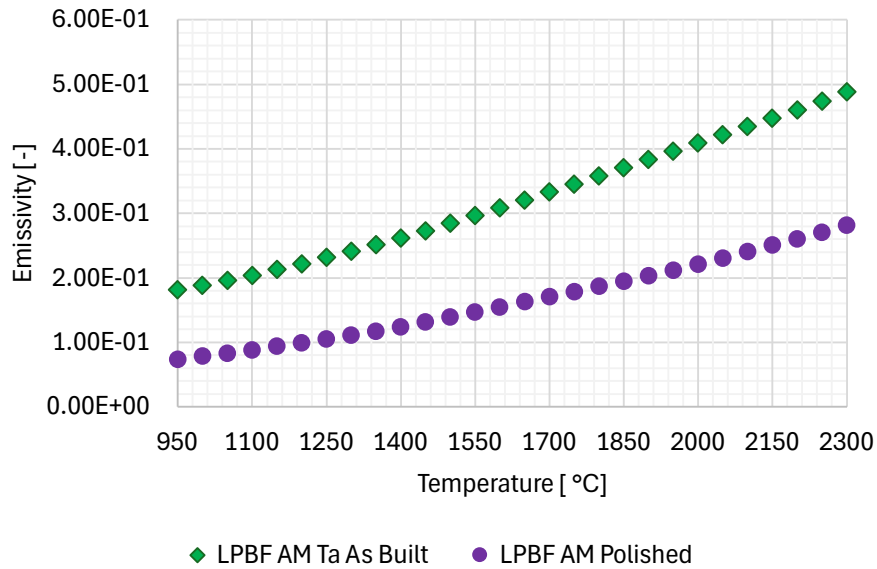


Figure 4.8 Emissivity values difference between As-built and polished samples manufactured in Tantalum by LPBF process[67]

The temperature distribution estimation resulting from the FE analysis of the complete FEBIAD ion source considering a feeding current (I_{line}) of 400 A is detailed in Figure 4.9. Moreover, the temperature distribution of cathodes can be appreciated in Figure 4.10, where the maximum temperature (T_{max}) is also indicated. The STD cathode estimated T_{max} is approximately 45°C higher than the LPBF_conv cathode, however such parameter is not representative of the electro-thermal performance of the ion source as the electron emission is mainly dependant on the frontal surface temperature (refer to Chapter 2).

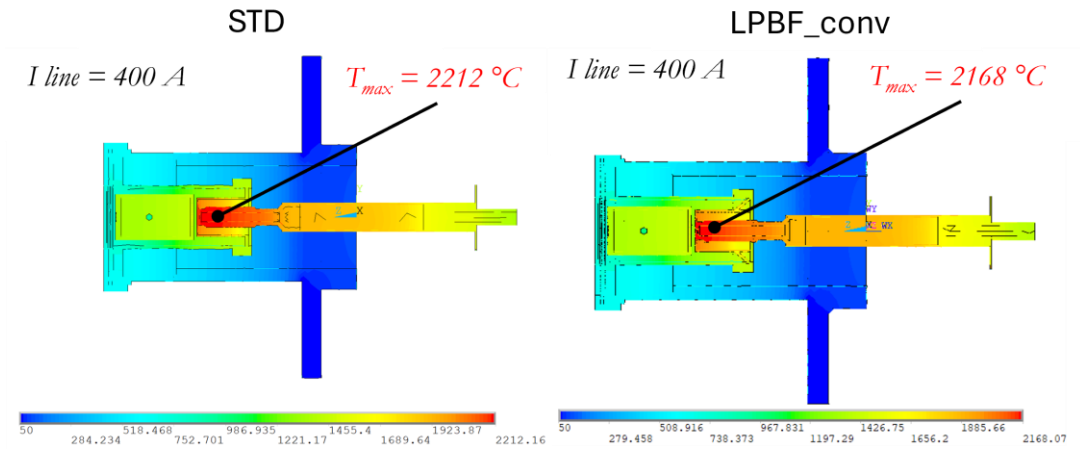


Figure 4.9 Temperature distribution resulting from FE simulation of the complete FEBIAD ion source at $I_{line} = 400$ A. STD (left) and the LPBF_conv (right) cathodes are compared.

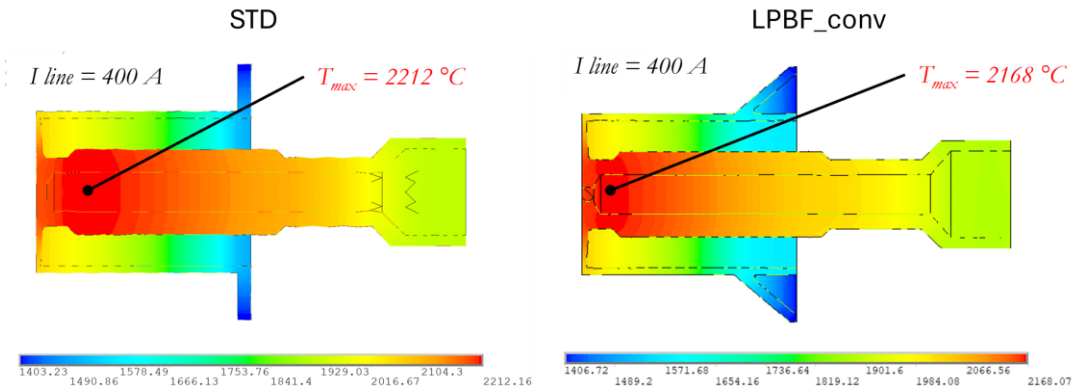


Figure 4.10 Temperature distribution comparison between the STD and LPBF_conv cathodes.

Consequently, the frontal surface radial temperature profile was extracted from the FE solution, mapping temperatures along the path from point (1) to point (2) as shown in Figure 4.11.

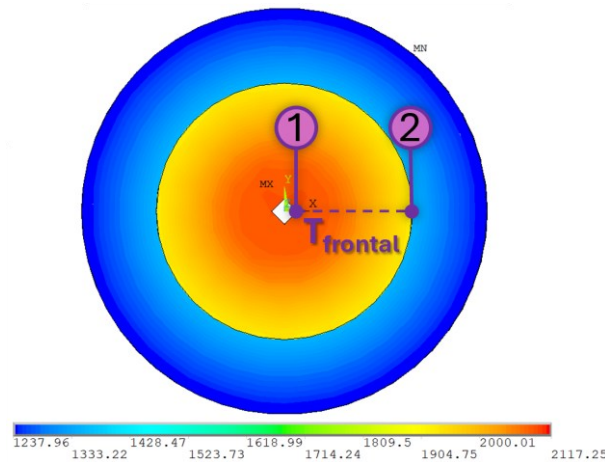


Figure 4.11 The temperature profile of the LPBF_CONV cathodes frontal surfaces resulting from the FEM simulation is extracted from the highlighted path.

The results in Figure 4.12 reveal no significant differences between the frontal surface radial temperature profiles of the LPBF_conv and STD cathodes, with the LPBF_conv cathode exhibiting temperatures that are averagely 1.4% lower.

Once the FE models demonstrated that both STD and LPBF_conv cathodes exhibit comparable behaviour under the same operational conditions, it is possible to advance the feasibility analysis.

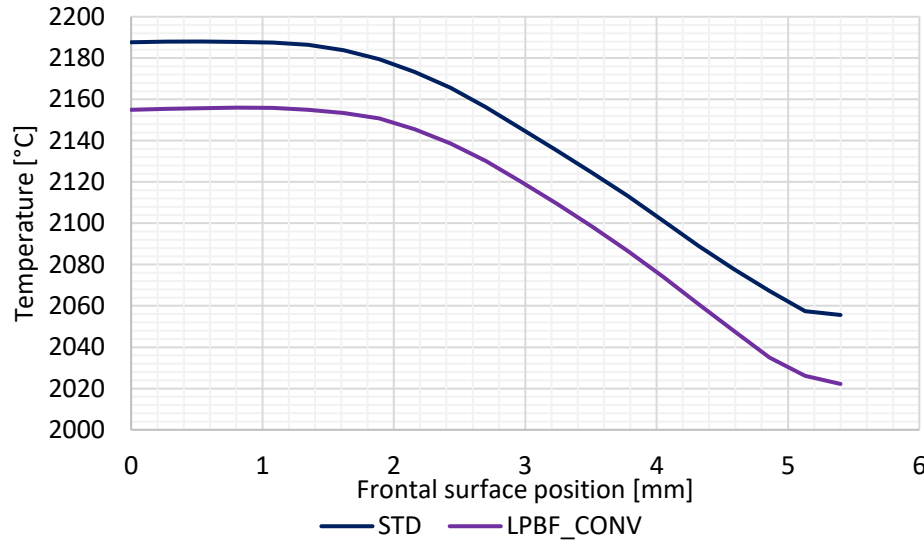


Figure 4.12 STD and LPBF_conv frontal surfaces radial temperature profile at $I_{line}=400A$. The x-axis 0 mm and 5.4 mm positions are respectively related to points (1) and (2) in Figure 4.11.

4.4 Feasibility analysis

The feasibility analysis was performed producing at DIAM lab samples representing the critical parts of the LPBF_conv cathode model, such as the conical surface and the main body [47]. In particular, aiming to define the proper inclination of the conical surfaces, several samples having different slopes were prepared, as shown in Figure 4.13.

Furthermore, the process parameters ensuring the best compromise between surface finishing and geometrical dimensions accuracy were determined by producing three concentric cylinders (representative of central part of the main body) applying different production settings and verifying their dimensional features through CMM measurements. This method allowed to set the proper process parameters for the LPBF_cathode production.

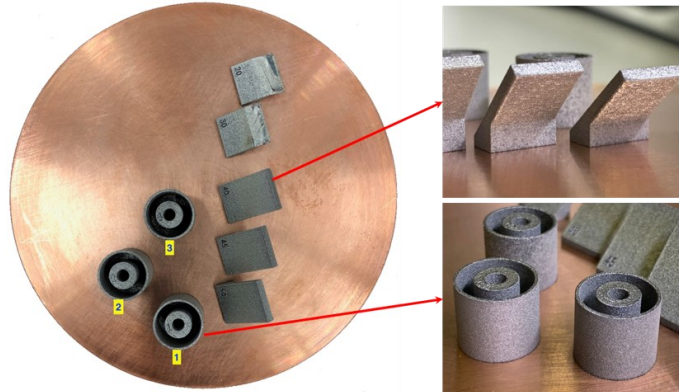


Figure 4.13 LPBF feasibility analysis samples.

The thickness of the frontal part of the cathode strongly affects the temperature distribution on the frontal surface, as stated by the functional analysis in Appendix B. Consequently, it is essential to verify the accuracy of such dimensional feature. However, due to the geometric constraints of the cathode main body, it is not accessible to the CMM stylus probe. Therefore, three samples representative of the cathode frontal surface were produced (refer to Figure 4.14 (left)) and measured by the CMM designing a specific measurement strategy.

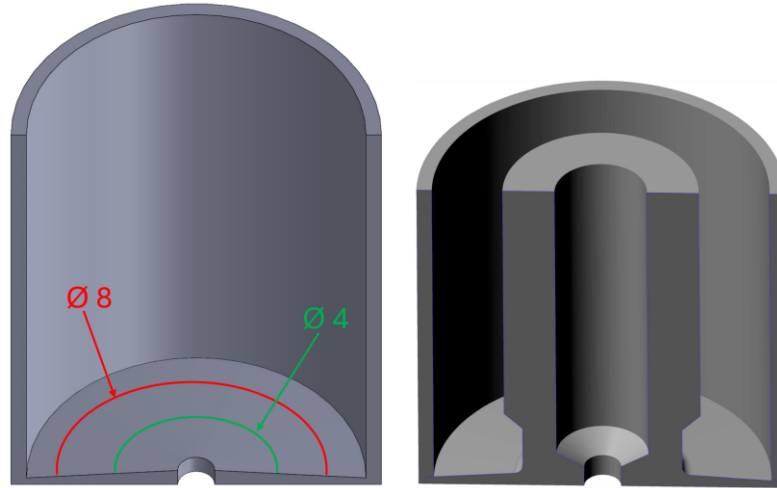


Figure 4.14 Samples representative of the cathode frontal part must be designed to perform the CMM measurements

The top surface of the sample was defined as reference plane (RP), as shown in Figure 4.15, and the CMM stylus is introduced into the samples tracking two different circular paths distant 2 mm ($\varnothing 4$) and 4 mm ($\varnothing 8$) to the specimen axis. This method enables the measurement of the dimensions L, b1 and b2 to calculate the thicknesses t1 and t2.

The results of CMM measurements are reported in Table 4.2, where the displacements with respect to the nominal dimensions can be observed. In particular, thickness deviations ($\Delta t1$ and $\Delta t2$) show negative values, with averages of -0.037 mm and -0.034 mm, respectively. This implies that the actual thickness is slightly lower than the nominal values, however such a small displacement do not significantly impact the temperature distribution on the frontal surface of the cathode.

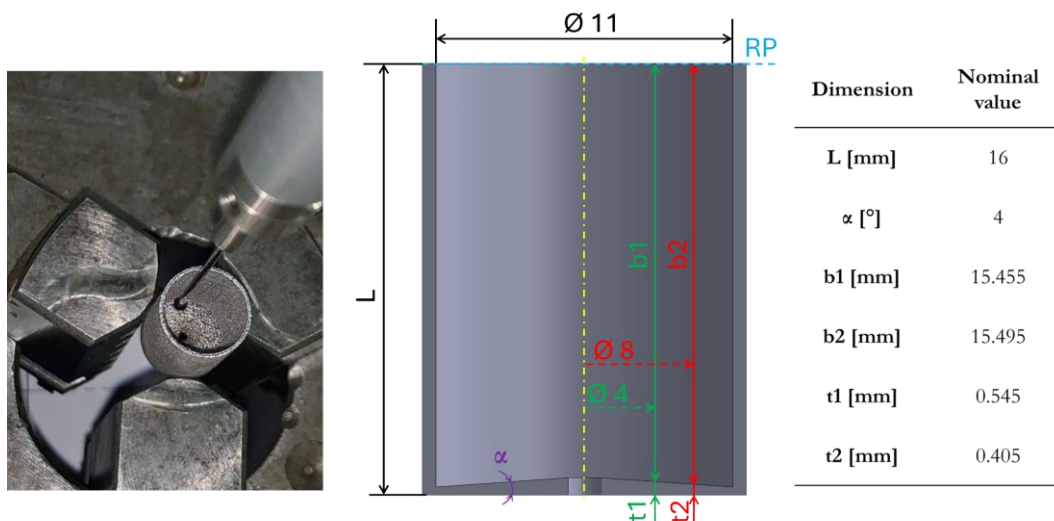


Figure 4.15 Schematic representation of the dimensional features measured on samples to verify the thickness.

Table 4.2 Nominal dimensions displacements measured by CMM to verify the sample thickness.

Sample	$\Delta \alpha$ [°]	ΔL [mm]	$\Delta b1$ [mm]	$\Delta b2$ [mm]	$\Delta t1$ [mm]	$\Delta t2$ [mm]
1	-0.090	-0.006	0.046	0.038	-0.052	-0.044
2	-0.239	0.044	0.040	0.036	0.004	0.008
3	-0.312	-0.034	0.029	0.032	-0.063	-0.066
Avg	-0.213	0.001	0.038	0.035	-0.037	-0.034
Std. Dev.	0.113	0.039	0.009	0.003	0.036	0.038

4.5 Samples production and CMM quality control

The feasibility analysis allowed to determine the proper process parameters to produce cathodes by LPBF technology. Therefore, LPBF_conv cathodes shown were successfully manufactured (refer to in Figure 4.16) using a spherical Tantalum powder produced by Taniobis (Taniobis GmbH, JX Nippon Mining and Metals group, Goslar, Germany) with a Particle Size Distribution (PSD) of $D_{10}=10 \mu\text{m}$, and $D_{90}=63 \mu\text{m}$. The EOS M100 DMLS performed the LPBF process under a controlled atmosphere (Argon gas) in order to keep the oxygen content in the building chamber below 0.1%. Furthermore, the building plate was pure copper as it is particularly suitable for additive manufacturing of refractory metals compared to the commonly used steel platforms [70]. The layer thickness used was 0.03 mm. The LPBF_conv cathodes were removed from the copper platform by EDM and their frontal surface was machined by a turning operation. The preliminary visual inspection of the produced samples (refer to Figure 4.16 (right)) underscored the first two main differences compared to the STD cathodes:

- The “as built” surfaces of the LPBF_conv cathode present significantly higher roughness compared to the STD cathode;
- The defects due to the TIG welding process characteristic of the STD cathode are not detected in the frontal surface of the LPBF_conv cathode.

Subsequently, CMM measurements were performed aiming to compare the geometric accuracy of STD and LPBF_conv samples.



Figure 4.16 LPBF_conv cathodes produced at DIAM lab of INFN-Padova section.

Five cathodes for each production process were inspected by measuring the main dimensional and geometric features involved in the tolerance stack-up discussed in Chapter 3, which are reported in Figure 4.17

Such a limited sample number is due to lack of availability of the STD cathodes because of their high cost of manufacturing, which restricts their stock and makes it impractical to produce a larger batch for inspection purposes.

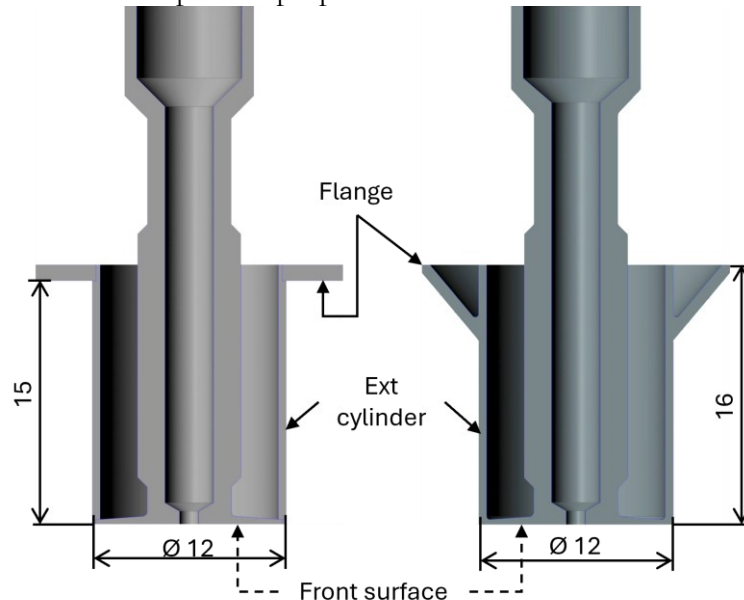


Figure 4.17 Dimensional and geometric features measured by CMM

Table 4.3 and in boxplots represented in Figure 4.18 and Figure 4.19, while the complete analysis is in Appendix H.1 .

The LPBF_conv cathode demonstrates superior geometric accuracy of the perpendicularity of the frontal surface relative to the external cylinder axis compared to the STD cathode. In addition, the LPBF_conv cathode exhibits more accurate control over the flange-to-front distance, showing significantly less deviation and variability. While both cathodes exhibit similar average flatness of the frontal surface, the STD cathode presents slightly greater consistency, with lower variability in this feature. However, Flatness of the LPBF_conv samples could potentially be improved by adjusting turning process parameters, such as feed rate and cutting speed, although this hypothesis requires further experimental validation. Finally, both manufacturing methods achieve comparable accuracy in the diameter of the frontal surface, with no significant difference between the STD and LPBF_conv cathodes.

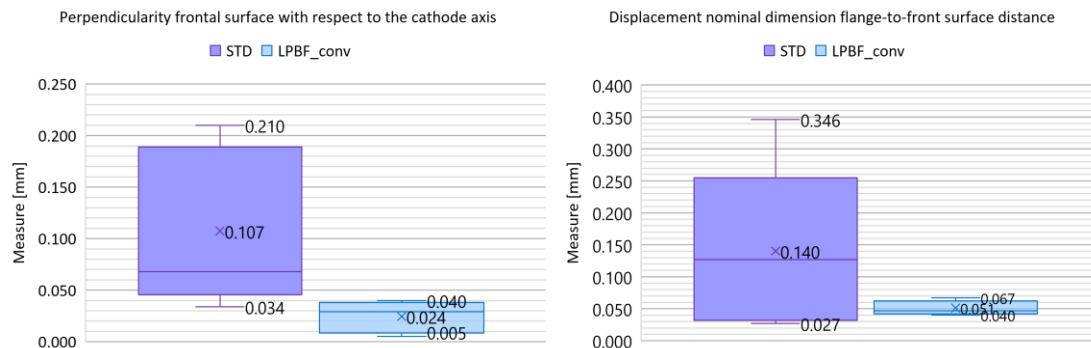


Figure 4.18 Boxplots of CMM measurements on LPBF_conv and STD cathodes. (Left) perpendicularity of the frontal surface with respect to the external cylinder axis, (right) flange-to-frontal surface distance.

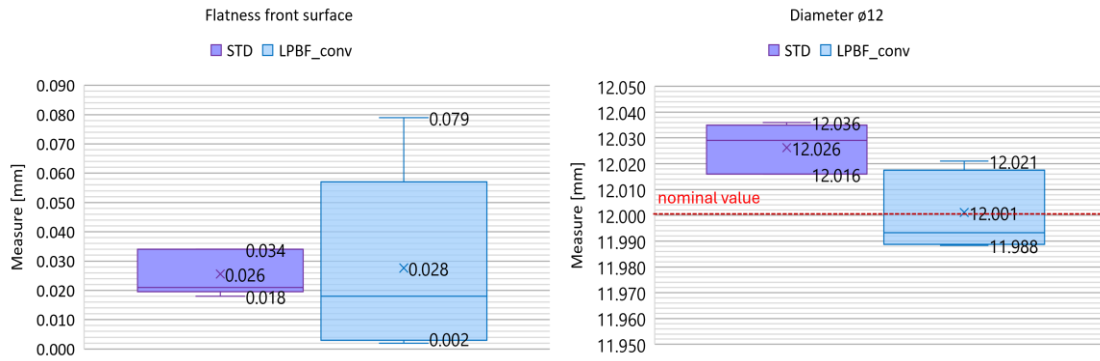


Figure 4.19 Boxplots of CMM measurements on LPBF_conv and STD cathodes. (Left) frontal surface flatness, (right) frontal surface diameter.

Table 4.3 CMM results of the geometric characterisation of LPBF_conv and STD cathodes.

Geometric feature measured by CMM	STD cathode		LPBF_conv cathode	
	Avg	St.dev	Avg	St.dev
Perpendicularity Front-Cyl Ø12 [mm]	0.11	0.07	0.02	0.01
Δ distance Flange - Front [mm]	0.14	0.12	0.05	0.01
Flatness Front surface	0.03	0.01	0.03	0.03
Diameter Ø12 [mm]	12.00	0.01	12.00	0.01

4.6 High Temperature (HT) experimental validation

The experimental setup in Figure 4.20 was developed at INFN-LNL aiming to validate the electro-thermal FE models and to perform a high-temperature (HT) characterisation of the cathode. Such an apparatus is capable to reproduce the operating conditions of the cathode, and its working principle is detailed in [28].

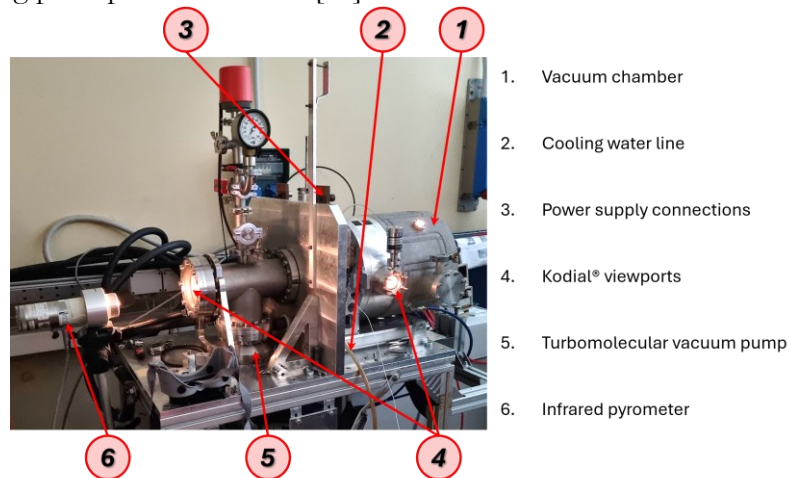


Figure 4.20 HT experimental setup developed at INFN-LNL

The internal view of the vacuum chamber dedicated at HT tests is shown in Figure 4.21. The cathode (1) is installed within a specific support (2) which is fixed to the baseplate (3) to keep it in the middle section of the vacuum chamber and to make it visible through the viewports. The cathode is heated up by joule effect through a dedicated power supply (4), while the high vacuum regime (10^{-6} mbar) is maintained inside the vacuum chamber by a turbomolecular pump. Furthermore, the viewports in Kodial® glass allow to measure the cathodes temperature through infrared pyrometers from both their frontal and lateral surfaces.

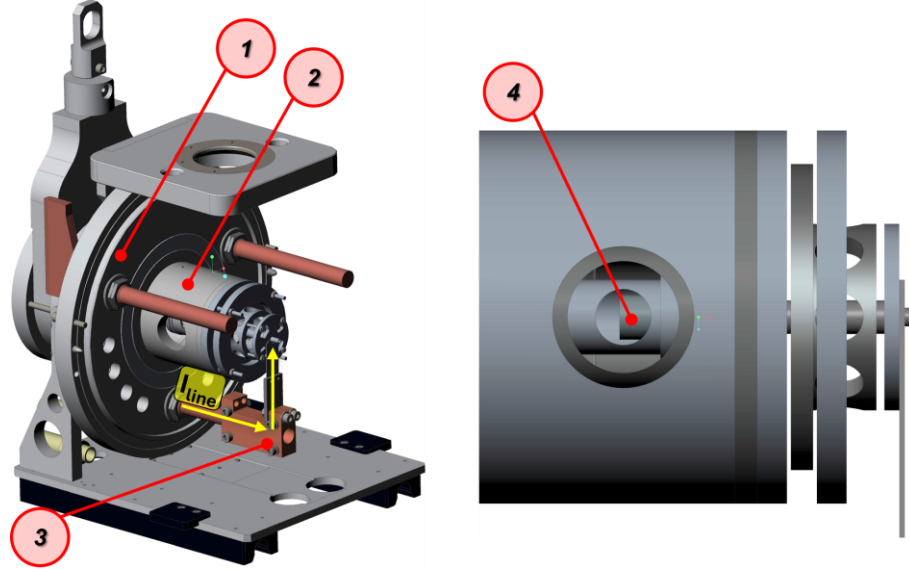


Figure 4.21 Internal view of the vacuum chamber used for HT tests. (1) Baseplate, (2) cathode support, (3) power supply electrical connection, (4) Lateral view of the cathode.

Compared to the STD design of the ion source, both the anode and the extraction system were removed (refer to section view in Figure 4.22), and a lateral hole was implemented in both the cathode support (Figure 4.21 (2)) and the discharge chamber (Figure 4.22 (2)). Such modifications allow to maintain visible the cathode at during the HT tests and measure the temperature through infrared pyrometers from its frontal and lateral surfaces, as can be observed from Figure 4.23.

The constraining system in Figure 4.21(4) was used to reproduce (at the transfer line extremity) the structural effect of the production target, thus imposing a severe constraint (close to zero degree of freedoms) for the displacement in the axial direction.

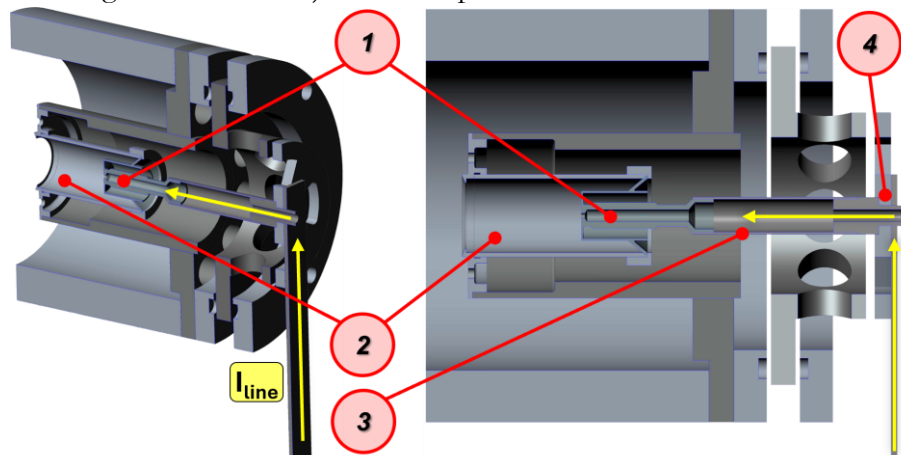


Figure 4.22 Section view of the experimental setup; (1) cathode, (2) discharge chamber, (3) transfer line, (4) constraining system.

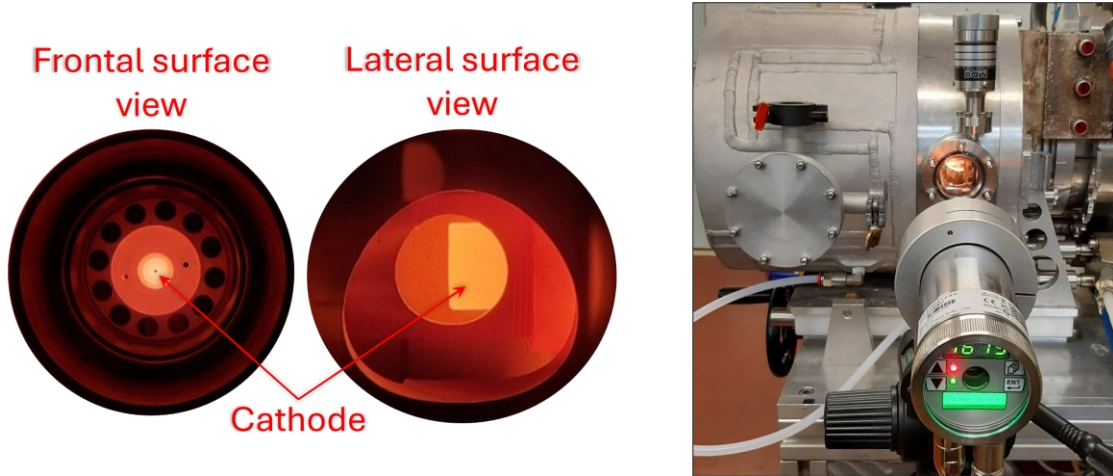


Figure 4.23 The temperature is measured by optical infrared pyrometers. The viewports allow to perform the measurement both on the frontal and lateral surfaces of the cathode

4.6.1 Thermal characterisation

The thermal characterisation is aimed both to validate the numerical FE results with experimental data and to correlate the cathode temperature with the heating current (also referred as line current, I_{line}). To achieve this, the modifications introduced in the previous paragraph were implemented into the FE model to reproduce the geometry of the experimental setup developed for the validation of the model. Subsequently, both STD and LPBF_conv cathodes were heated from 0 to 400A across three heating cycles; the temperature of the frontal and lateral surfaces was measured through infrared pyrometers and the average data collected from such thermal cycles are presented in Figure 4.24 and Figure 4.25. The temperature measurements were reported in the 350–400 A heating current range, as it corresponds to the expected operating temperature interval.

Concerning the frontal surface temperature data in Figure 4.24, the deviation of experimental values is always below the 3% with respect to the numerical results for both the STD and LPBF_conv cathodes, suggesting the validation of the FE model. Furthermore, LPBF_conv and STD cathodes exhibit also similar temperature values, differing less than 1% to each other.

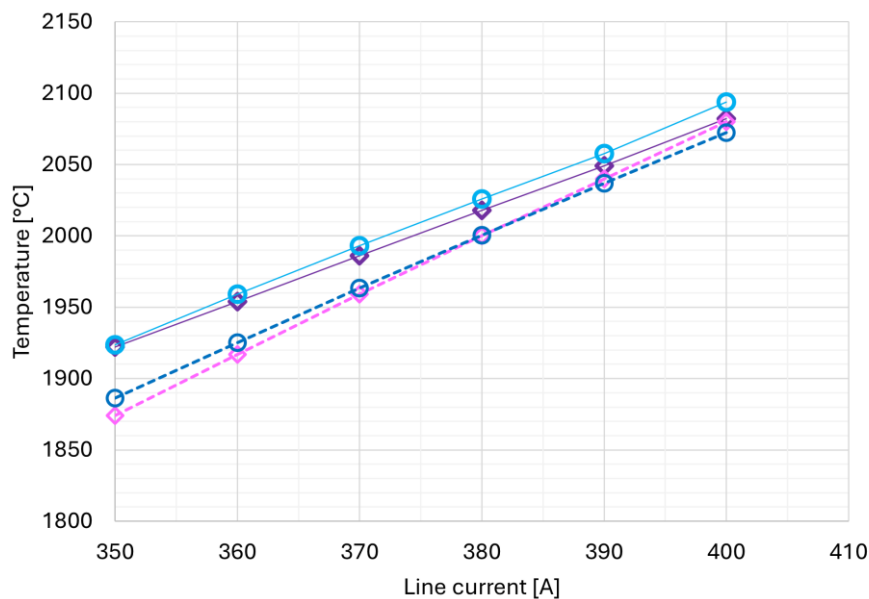


Figure 4.24 LPBF_conv and STD frontal surface high temperature characterisation

The lateral surface measures in Figure 4.25 result in LPBF_conv cathode exhibits lower temperatures (from 8.6 to 9.5%) compared to the STD cathode probably due to the different material properties and higher emissivity due to the worst surface finishing [67]. Concerning the numerical results for the lateral surface a lower accuracy of the model was observed as the deviation between the numerical and experimental values for the STD cathode ranges from 3.8 and 6.4%, while it is always below the 3% regarding the LPBF_conv cathode.

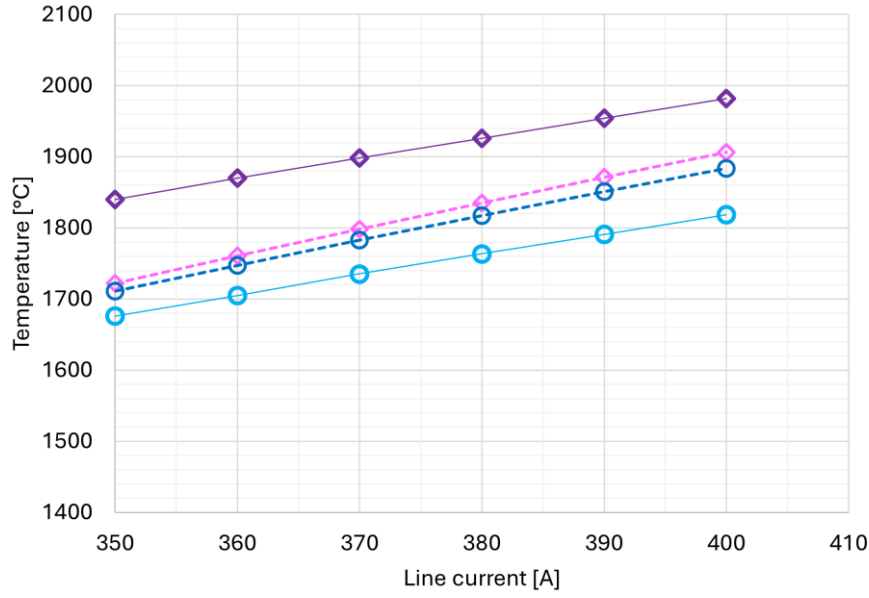


Figure 4.25 LPBF_conv and STD lateral surface high temperature characterisation

4.6.2 Endurance high temperature test

The purpose of the high temperature (HT) endurance test is to assess the resistance of the LPBF_conv cathode to a long-term exposure to thermal stress at the operating condition. In fact, all FEBIAD ion source components, should be capable to resist at least 14 days during the facility operation as detailed in Chapter 1. However, the experimental setup available was not designed for safe continuous operation under such conditions, necessitating an alternative testing procedure. Consequently, two different endurance tests were performed:

1. “HT endurance 1” consists of 15 heating cycles, gradually increasing the heating current from 0 to 440A (heating ramp 20A/120s), followed by 8-hours dwell period at the maximum I_{line} before reducing it back to 0A. In total, the cathode was exposed to 440 A for a cumulative time of 120 hours. The temperatures measured on the frontal surface of the sample are reported in Figure 4.26 where it can be observed that the temperature slightly increased over the first 60h and then remained approximately constant until the end of the test. Such initial temperature increase may be due to the superficial oxide layer removal once it the sample is exposed at high temperature, as observed during the material properties thermal characterisation performed on specimens produced by LPBF in previous works[71].

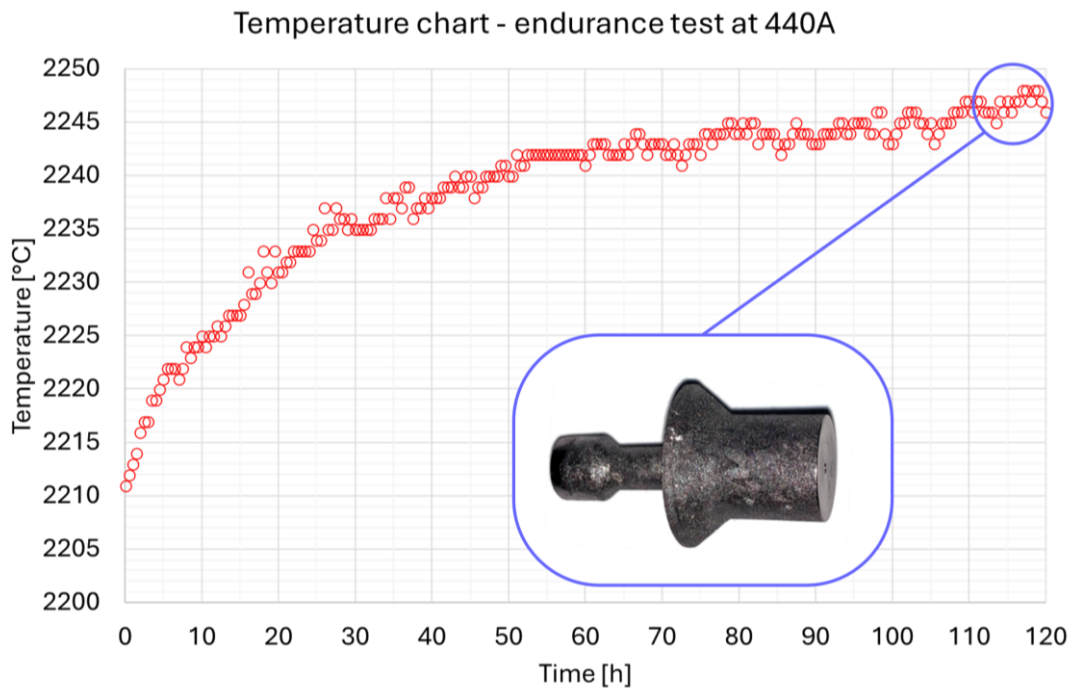
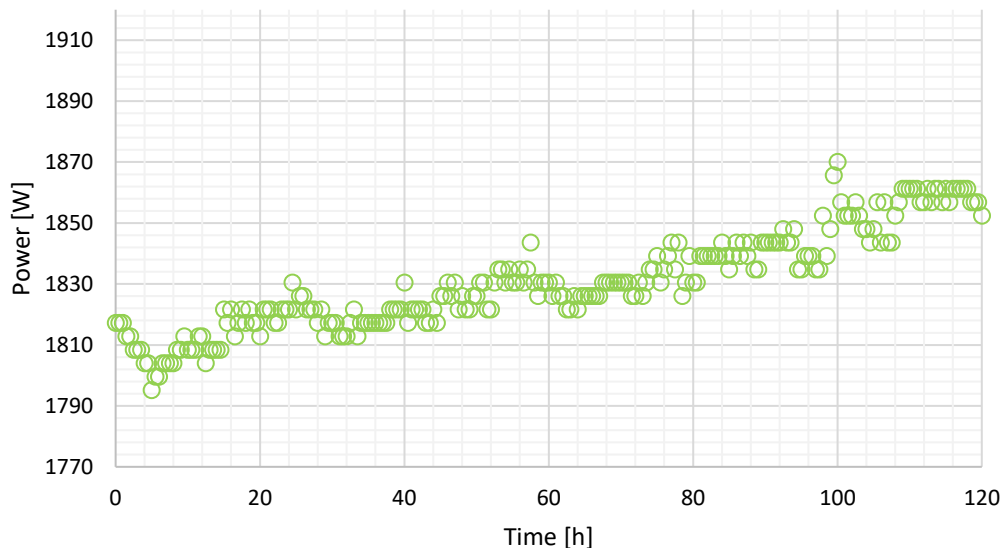


Figure 4.26 “HT endurance 1” frontal surface temperature measurements.

Anyway, the cathode successfully resisted to the test “HT endurance test 1” and no significant deformation were observed after a visual examination of the sample, which is shown in Figure 4.26.

During this test, a slight increase in heating power was observed (Figure 4.27). This trend suggests a progressive variation in the electrical resistance of the cathode material, likely associated with microstructural changes occurring during prolonged exposure to high temperature, as discussed in [67].



1. Figure 4.27 The “HT endurance 2” was performed maintaining the LPBF_conv cathode at a constant heating current of 400A (corresponding to a frontal surface temperature of approximately 1950°C) continuously for approximately 40 hours. Subsequently, CMM geometric characterizations were performed both before and after the “HT endurance 2”, evaluating the LPBF_conv cathode residual deformation after being subjected to

thermal stresses. The profile measure revealed that the frontal surface transitioned from flat to curved as shown by Figure 4.28, exhibiting a deformation of approximately 0.25mm. A similar geometric modification was observed in the STD cathode during previous HT tests [28]. However, the deformation in the STD cathode was more intense, estimated to be around 1 mm. It is important to note that this previous measurement was performed using a conventional digital camera focused on the cathode lateral surface, which is a different measurement system with respect to the CMM used in the current study. Nevertheless, the deformation occurred at the LPBF_conv during the “HT endurance 2” was not large enough to be captured by the same camera, thus the CMM was employed. However, CMM measurements are not suitable to evaluate the extent of the elastic deformation component occurring at high temperature, which could significantly impact the ion source functioning. Consequently, it is relevant to identify a proper experimental procedure capable of measuring the total cathode deformation during operation at high temperature. For such a purpose, a dedicated experimental setup was developed, and it will be detailed in Chapter 6.

Therefore, while the general trend of surface deformation is consistent, a more systematic and precise procedure is needed to ensure accurate comparative measurements between LPBF_conv and STD cathodes. The deformation difference may arise from the different thermomechanical properties achieved by producing Ta components through LPBF, as demonstrated in the case of Mo [31], where thermal and mechanical properties of samples produced through conventional forging and machining processes were compared with those of LPBF specimens.

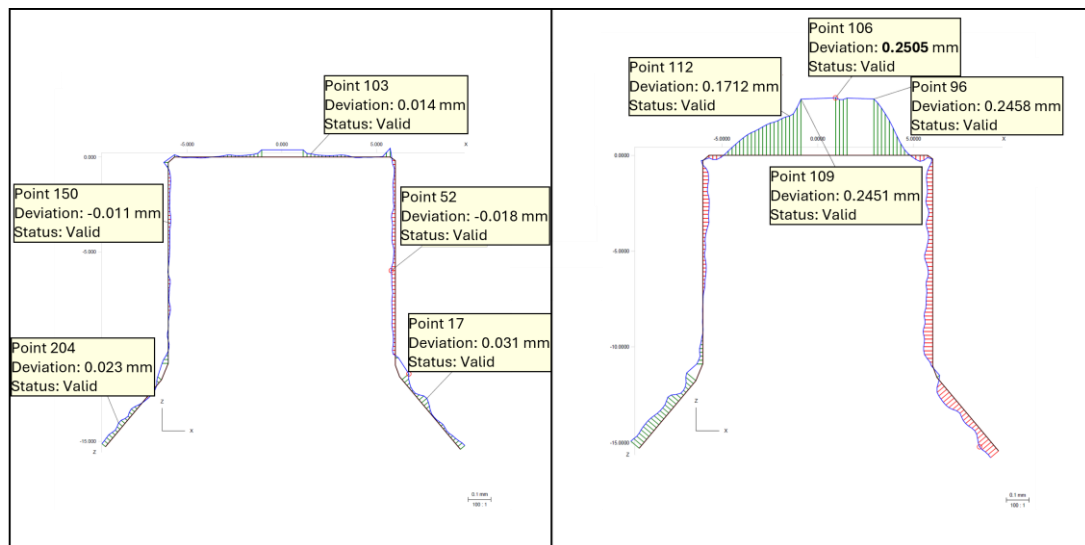


Figure 4.28 CMM profile measurement before (left) and after (right) “HT endurance 2”.

The thermal-electric behaviour of the LPBF_conv cathode is comparable with the STD cathode as similar performance were measured during the thermal characterisation test. Additionally, the endurance tests suggested the suitability of LPBF production process for the manufacturing of tantalum cathodes, since the tested sampled not present significant deformations due to thermal stresses.

Such results lay the foundations for the development of innovative ion source components exploiting the degrees of freedom provided by the LPBF technology.

4.7 Geometry optimisation

The compatibility of the tantalum LPBF production technology with the operating condition of FEBIAD ion source was essential to further optimising component designs to:

- Improve the assembly accuracy and simplify the mounting procedure;
- Reduce the number of components required;
- Enhance the temperature distribution of the cathode to increase device performance.

The following paragraphs will explore the design modifications aimed at improving the key features of the FEBIAD ion source above mentioned [71].

4.7.1 Assembly procedure improvements

The FEBIAD ion source main components were re-designed to be produced in tantalum using LPBF technology with the objective to achieve a more reliable and repeatable assembly process. In this framework, the first re-designed model of the FEBIAD ion source (LPBF_dev1) is shown in Figure 4.29.

The cathode (1), anode (2), discharge chamber (3) and extraction system (4) were specifically designed for production via LPBF process, followed by basic machining operations essential for ensuring accurate assembly.

Such components were developed according to the principles of Design for Additive Manufacturing (DFAM), which refer to a comprehensive set of guidelines aimed at design optimised geometries that fully exploit the advantages offered by additive manufacturing techniques [68,69].

Furthermore, critical elements that could complicate the LPBF production, such as overhangs or geometric features requiring supports, were intentionally avoided to reduce post-processing operations and save raw material.

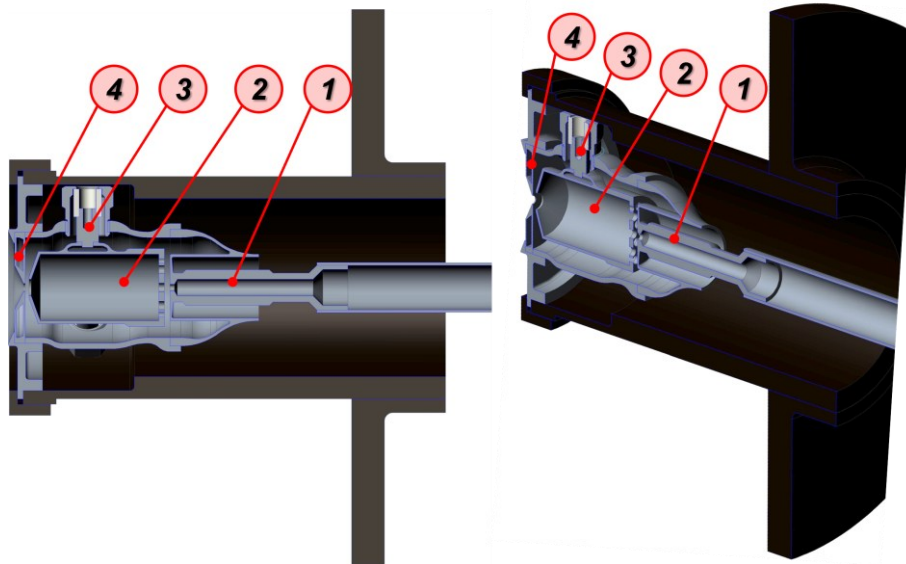


Figure 4.29 LPBF_dev1 ion source. (1) LPBF_dev1 cathode, (2) LPBF anode, (3) anode support system, (4) LPBF extraction system.

i. LPBF_dev1 cathode

The assembly process of the LPBF_dev1 cathode (refer to Figure 4.30) with the LPBF discharge chamber was designed to be performed through a single manual operation. The LPBF_dev1 cathode has an external free-form body with a cylindrical extremity (1), which

can be easily machined using a turning machine. Therefore, it can be manually coupled with the LPBF discharge chamber foreseeing a tight clearance fit (H7/h7), which ensures the manual assembly and the disassembly of the components while ensuring a secure fit.

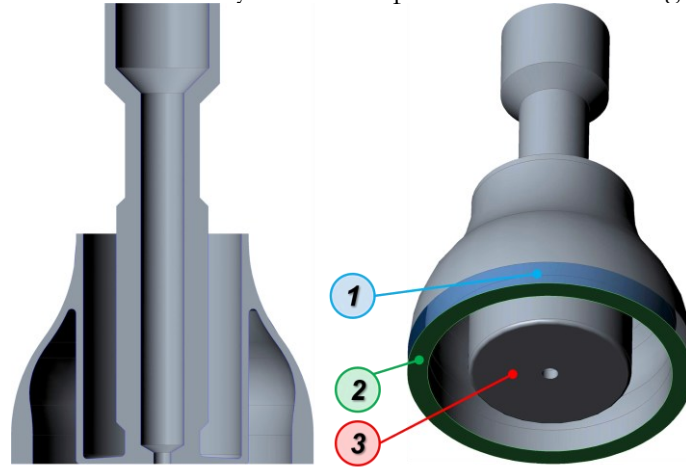


Figure 4.30 LPBF_dev1 cathode design.

Compared to the STD cathode, the contact surface (2) with the discharge chamber was moved to the same plane of the frontal surface (3) aiming at removing the “c” element of the tolerance stack-up as shown in Figure 4.31.

The reduction of the tolerance stack-up elements is essential to limit the uncertainty propagation leading to improve the positioning accuracy of the frontal surface.

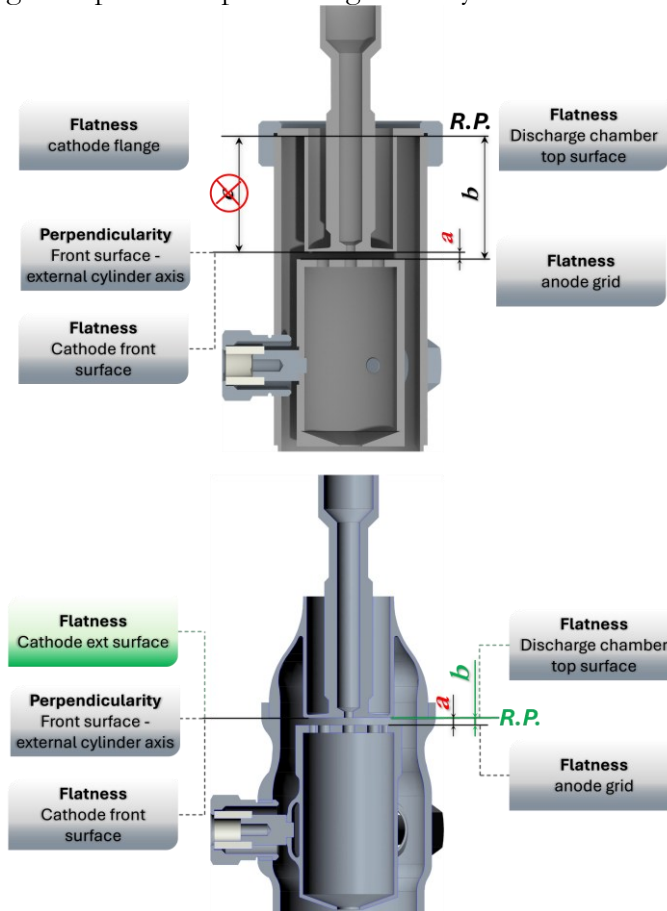


Figure 4.31 tolerance stack-up comparison between STD and LPBF_dev1 FEBIAD ion source

Furthermore, the Python program developed in Chapter 3 to perform the statistical tolerance stack-up analysis and optimisation was employed for the tolerancing process of the LPBF_dev1 components. The reduction of the tolerance stack-up elements allowed to relax some of the allocated tolerances, as the position tolerance of the cathode frontal surface shown in Figure 4.32.

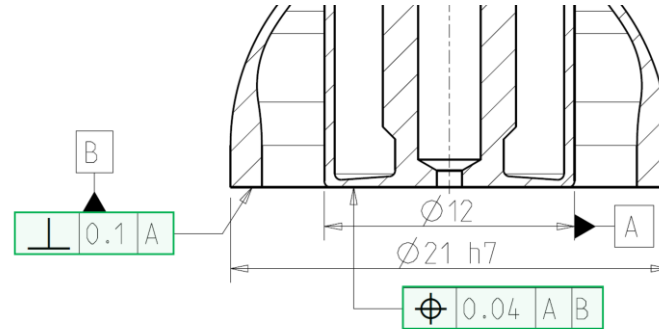


Figure 4.32 LPBF_dev1 cathode tolerancing.

ii. LPBF discharge chamber

The LPBF discharge chamber was designed to couple the LPBF_dev1 cathode using a tight clearance fit. To achieve this, the surfaces (1) and (2) in Figure 4.33 must be machined by turning operations. In addition, the thickness was locally increased in some specific regions (3) to easily perform the threading operations, which are crucial to fix properly the anode support system. Varying wall thicknesses, adding material only where strictly necessary, leads to minimize the material waste. Furthermore, the surface (4) must undergo a boring operation to facilitate the insertion of LPBF discharge chamber within the assembly tool during the mounting operation of the anode.

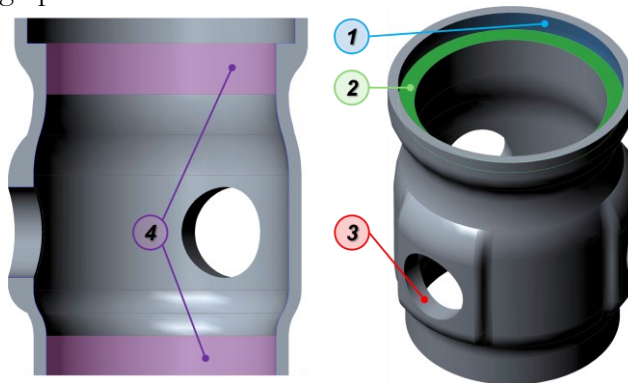


Figure 4.33 LPBF discharge chamber.

The tolerancing process allowed to assign the geometric tolerances on the LPBF discharge chamber outlined in Figure 4.34.

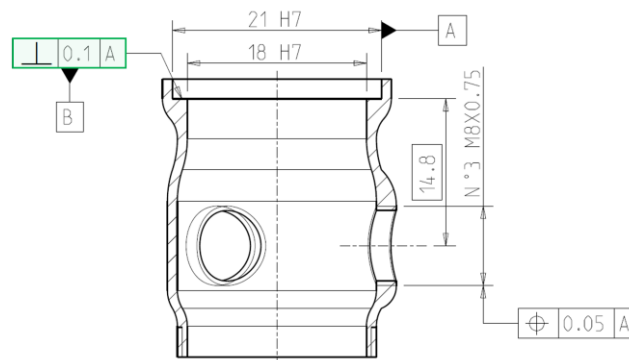


Figure 4.34 LPBF discharge chamber tolerancing.

iii. LPBF anode

The LPBF anode was designed to be manufactured as a single component, unlike its STD version, which is produced joining three different parts through a complex welding process. However, the grid geometry and the internal hollow section (i.e. plasma chamber) were not modified as they significantly affect the functioning of the ion source. Prior to any modification of such features, more detailed analysis must be conducted.

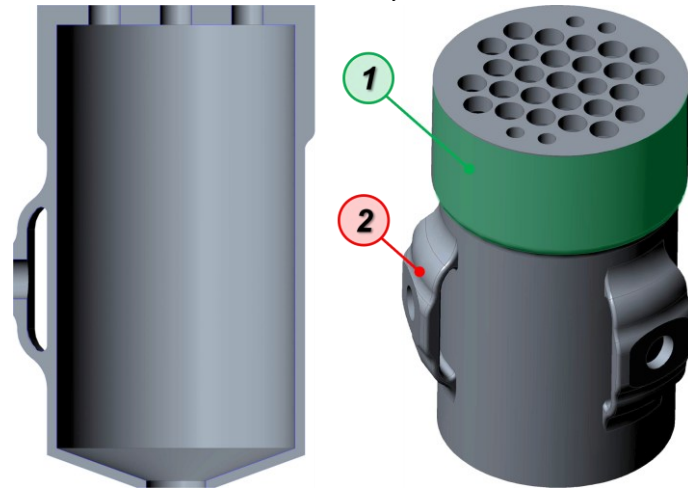


Figure 4.35 LPBF anode.

However, minor functional modifications were introduced in the LPBF anode, as the three holed “wings” highlighted in Figure 4.35 (2). They avoid the contact of the anode support pins with the plasma chamber reducing the heat transfer towards the alumina insulators, which are characterized by a limiting temperature of approximately 1600°C. Furthermore, the anode grid and surface (1) must be machined to ensure an accurate positioning of the component using the assembly tool. The tolerances allocated following the tolerance analysis and optimisation process are highlighted in Figure 4.36.

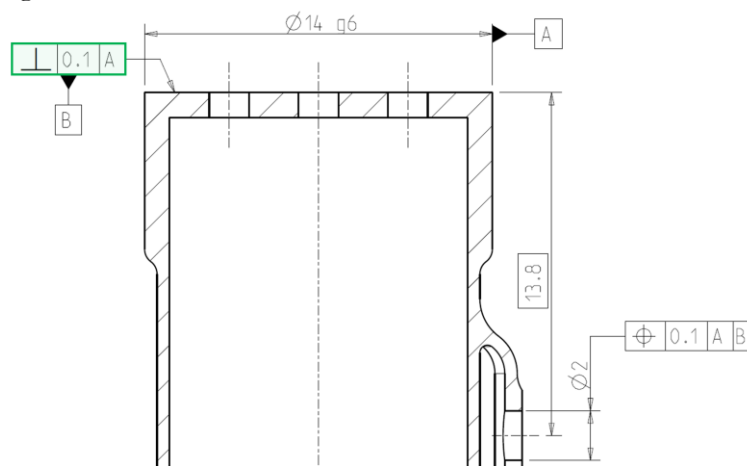


Figure 4.36 LPBF anode tolerancing.

The working principle of the assembly procedure developed in Chapter 3 was maintained and the assembly tool was slightly re-designed to accommodate the modifications implemented in the discharge chamber, as can be observed in Figure 4.37.

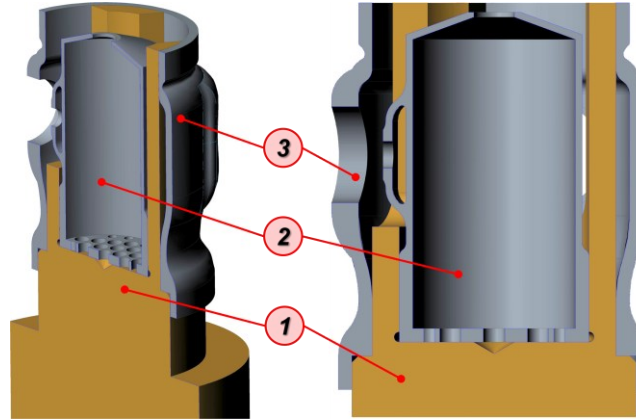


Figure 4.37 Re-designed version of the assembly tool developed in Chapter 3 to assemble the LPBF anode and discharge chamber. (1) Assembly tool, (2) LPBF anode, (3) LPBF discharge chamber.

Despite the reduction of the tolerance stack-up elements on the LPBF_dev1 design, the position tolerance allocated on the assembly-tool was not relaxed compared to the STD anode assembly process, as can be observed from Figure 4.38.

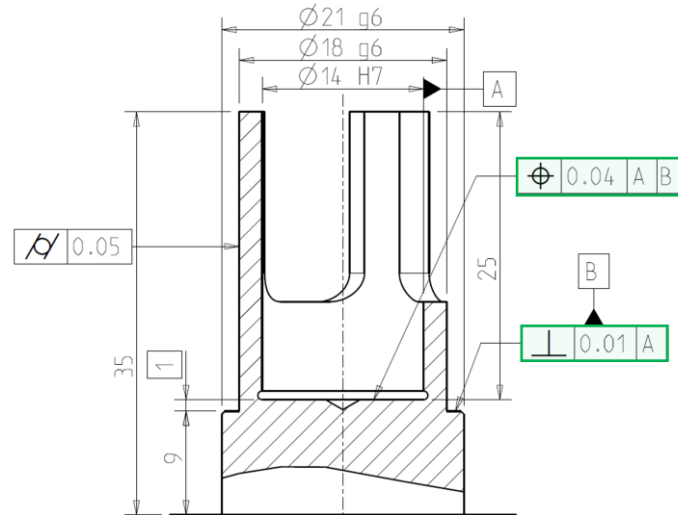


Figure 4.38 LPBF assembly tool tolerancing.

iv. LPBF extraction system

The STD extraction system, which is shown in Figure 4.39 (1), is assembled by three disks separated by two spacer rings, as already introduced in Chapter 2. The LPBF extraction system, in Figure 4.39(2), was re-designed to be produced as a single component, replacing the three disks and the two spacer rings while replicating the same conicity φ ($\approx 127^\circ$) resulting from the increasing diameters of the disks central holes.

However, the LPBF extraction system presents flat surfaces which require internal supports to be successfully produced. Consequently, a lattice structure was employed as structural support for such surfaces during the manufacturing process.

The implementation of a lattice structure reduces material consumption, thereby minimizing the quantity of powder required for the fabrication of supports. The gyroid lattice with periodic open-cell features was specifically selected aiming at ensuring an efficient evacuation of the metallic powder after processing, minimizing the residual raw material and improving the manufacturability of the component. Furthermore, since the extraction system is not subjected to significant mechanical or thermal stresses, no additional requirements were considered.

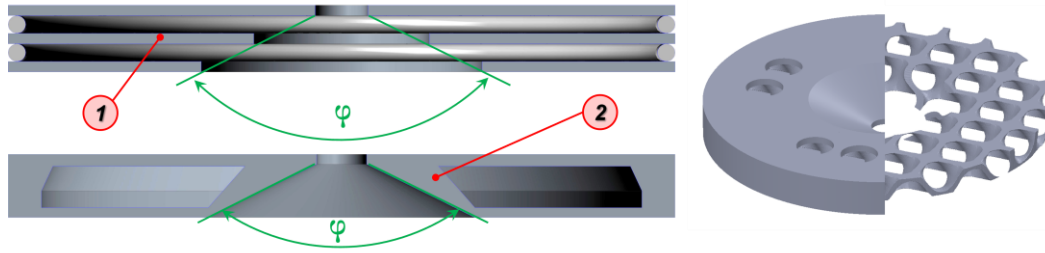


Figure 4.39 The STD extraction system (1) is assembled by three disks spaced by two spacer rings, while the LPBF extraction system (2) is a single component.

4.7.2 Temperature distribution optimisation by FEM simulations

The initial LPBF_dev1 cathode design provided a basis for modifying the assembly procedure to enhance the positioning accuracy of the cathode frontal surface, however its electro-thermal performance was not evaluated.

The optimisation of the cathode temperature distribution was achieved through a series of iterative manual adjustments of the geometry, implemented and evaluated using FEM simulations [71], as schematized in Figure 4.40. Such modifications were aimed at two primary objectives:

- increase the temperature of the frontal surface to enhance the thermionic emission of free electrons;
- improve the temperature homogeneity within the central tubular body to reduce thermal stresses and the condensation of neutral isotopes released by the target in surfaces presenting lower temperatures (“sticking”).

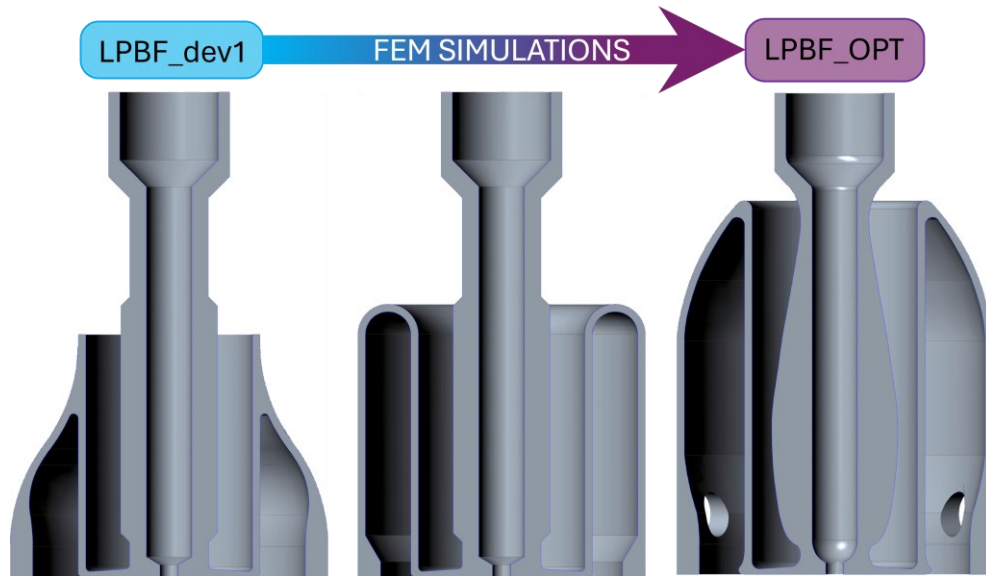


Figure 4.40 The cathode was iteratively modified depending on FEM simulations results.

It is important to note that the optimization process was performed manually rather than through an automated optimization algorithm. The refinement of the cathode carried on was preformed step by step, driven by an understanding of its electro-thermal behaviour: material was strategically added or removed in specific regions aiming to locally alter the electrical resistance and running FEM simulations for each introduced modification, as shown in Figure 4.41.

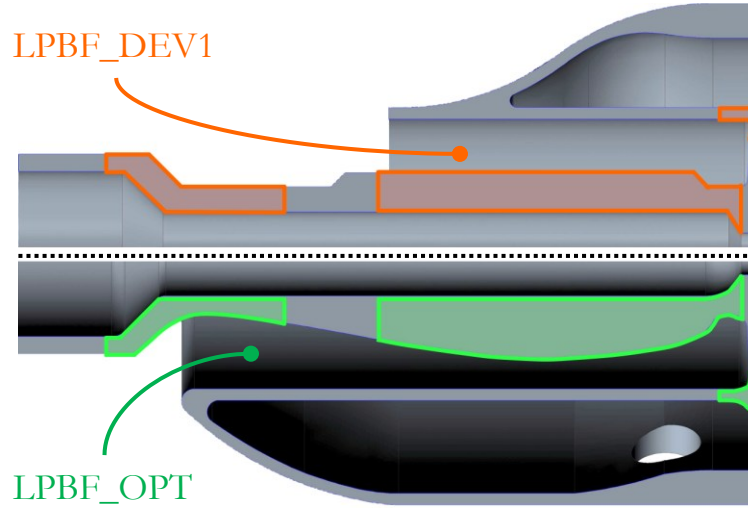


Figure 4.41 Material was strategically added or removed in specific regions to locally alter the electrical resistance. FEM simulations were performed to estimate the results on the temperature distribution of the cathode after each geometry modification

However, the implementation of an optimization algorithm could represent a future development, allowing for a more systematic method to explore the electro-thermal performances of alternative cathode designs.

Each iteration was evaluated under a constant heating current of $I_{line} = 400\text{ A}$, allowing for direct comparisons between successive designs. In particular, the temperature distribution along the central tubular body (T_{tub}) and the frontal surface (T_{front}) were analysed as shown in Figure 4.42. Furthermore, it is important to note that if the simulated temperature exceeded $2200\text{ }^{\circ}\text{C}$, a lower feeding current should be considered to ensure safe operating conditions during operation.

The final model optimised from the iterative process, labelled as LPBF_OPT, is illustrated in Figure 4.40. Furthermore, Figure 4.42 provides a visual comparison of the temperature distribution resulted from FEM simulation between the LPBF_dev1 and the LPBF_OPT designs.

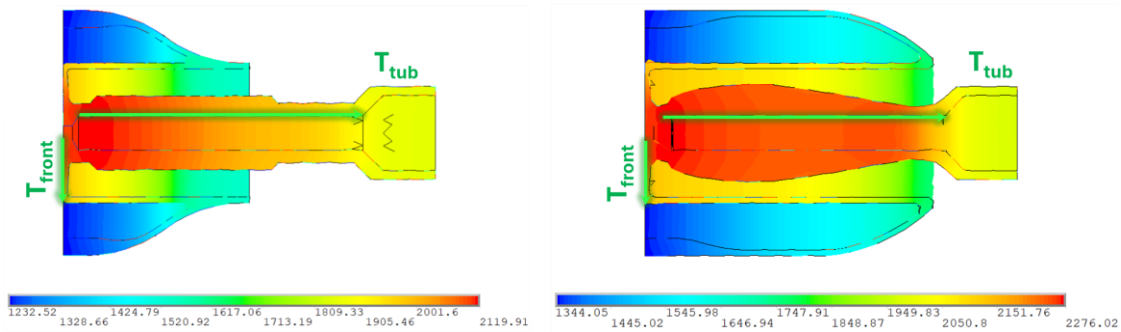


Figure 4.42 Temperature distribution comparison between the LPBF_dev1 (left) and LPBF_OPT (right) cathodes resulting from FEM simulations. The paths employed to extract the temperature distributions along the tubular section (T_{tub}) and the frontal surface (T_{front}) are highlighted.

The LPBF_OPT model introduced a free-form central body, leading to selectively increase the temperature on the frontal surface of the cathode. Furthermore, the external cylinder wall was extended toward the transfer line connection in order to increase and homogenise the temperature along the cathode axis. The comparison of frontal surface temperature distributions between the main cathode models can be appreciated in Figure 4.43. As a result,

the LPBF_OPT cathode frontal surface temperature increased averagely of 3.5% and 7.6% with respect to the STD and LPBF_DEV1 models, applying the same heating current (400A).

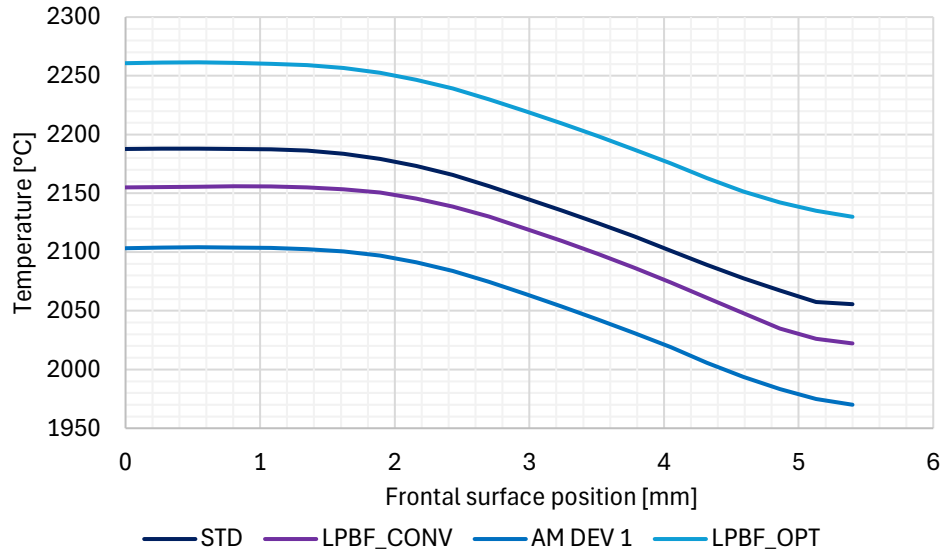


Figure 4.43 The frontal surface temperature distributions of different cathode models resulting from FEM simulations were compared at $I_{line}=400^\circ$.

The optimisation on the central tubular section of the cathode temperature distribution is more consistent, as shown in Figure 4.44. The LPBF_OPT geometry allowed to achieve a plateau over the cathode tubular central body, which led to a temperature increase on the extremity of the model up to 8.3% and 14.2% compared to the STD and LPBF_dev1, respectively.

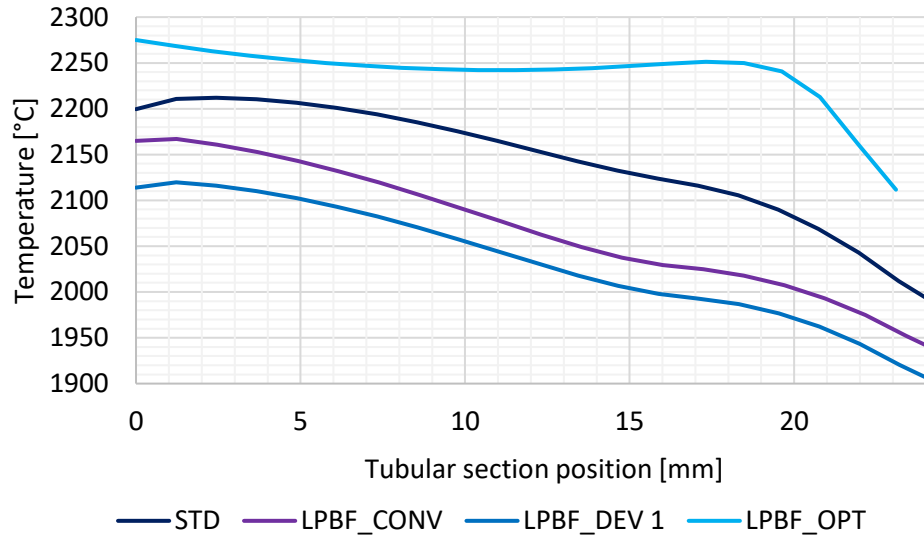


Figure 4.44 The central tubular section temperature distributions of different cathode models resulting from FEM simulations were compared at $I_{line}=400^\circ$

The results of FEM simulations indicated significant improvements in the cathode temperature distribution, particularly in terms of frontal surface temperature uniformity and central tubular body homogeneity. Such an iterative approach successfully led to the development of a more thermally efficient cathode geometry, capable of operating within the rigorous conditions of the FEBIAD ion source.

4.7.3 Production of OPT LPBF components and preliminary geometric characterisation

The components presented in paragraph 4.7.1 were successfully produced in Ta at DIAM lab of INFN - Pd section by the LPBF technology using the process parameters optimised according to paragraph 4.4 , as shown in Figure 4.45.



Figure 4.45 LPBF-manufactured Ta FEBIAD ion source components presented in paragraph 4.7.1 .
(1) Cathode, (2) discharge chamber, (3) anode, (4) extraction system.

The central body of the cathode, which is crucial for controlling the temperature distribution of the component during operation, was examined by CMM measurements [71]. Given the axial symmetry of the specimen, profile measurements were performed along three generatrices to assess the geometric accuracy, as shown in Figure 4.46.

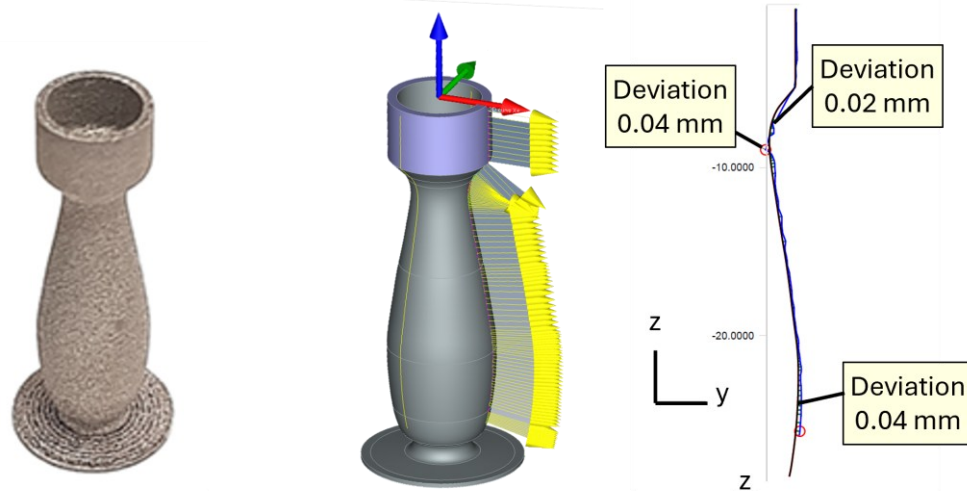


Figure 4.46 Cathode central body CMM profile characterisation.

The geometric characterisation was performed on two central body samples and the CMM results are resumed in Table 4.4. Both samples present maximum and minimum deviations from the nominal profile consistently below 0.1 mm. However, sample B exhibited slightly lower geometric accuracy compared to sample A. Considering both samples were manufactured in the same production batch using identical process parameters, such a difference may arise from their respective positions on the build platform. In fact, during the LPBF process, the uniformity of powder distribution on the build platform could influence the final geometric accuracy, as the powder may not be uniformly distributed over the

platform. Nevertheless, additional samples should be produced to increase the statistical significance and confirm such hypothesis.

Table 4.4 Central body CMM profile measurements

Sample ID	Generatrix ID	N° of points	Min. deviation	Max deviation
A	1	77	-0.04	0.04
	2	96	-0.03	0.04
	3	113	-0.02	0.05
B	1	113	0.02	0.1
	2	104	-0.06	0.09
	3	98	-0.02	0.05

Additionally, the most significant deviations were observed in the downskin sections of the profiles, particularly in sample B (refer to Appendix H.2). This phenomenon can be explained by the inherent challenges of the LPBF process in accurately producing overhanging or downfacing surfaces, where heat dissipation and powder stability are less controlled.

FEM simulations were performed to estimate the cathode temperature distribution considering a profile variation of ± 0.1 mm, as shown in Figure 4.47 and Figure 4.48.

The estimated temperature variation on the frontal surface (refer to Figure 4.47) ranged from -1.1 to +1.6% compared to the nominal profile of the central body.

As expected, the estimated temperature variation on the tubular section (refer to Figure 4.48) is more significant than the frontal surface, ranging from -2.3 to +3.1% compared to the nominal profile of the central body.

Such temperature variation estimated by FEM simulation is not particularly significant, especially on the frontal surface. However, it would be advisable to not exceed this threshold. Consequently, a profile tolerance of 0.1 mm could be allocated as a specification in the technical drawings of the cathode central body.

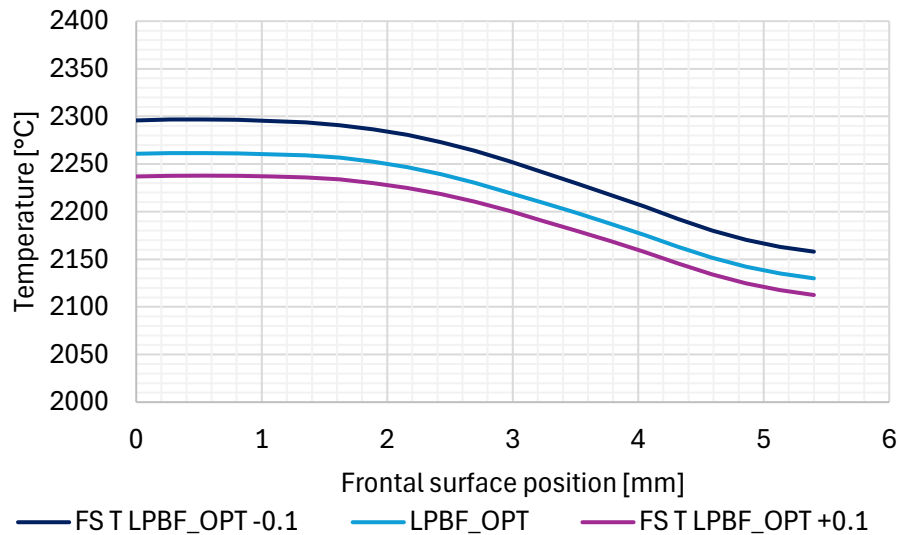


Figure 4.47 Estimated temperature distribution on the cathode frontal surface considering a profile variation of the main body of ± 0.1 mm.

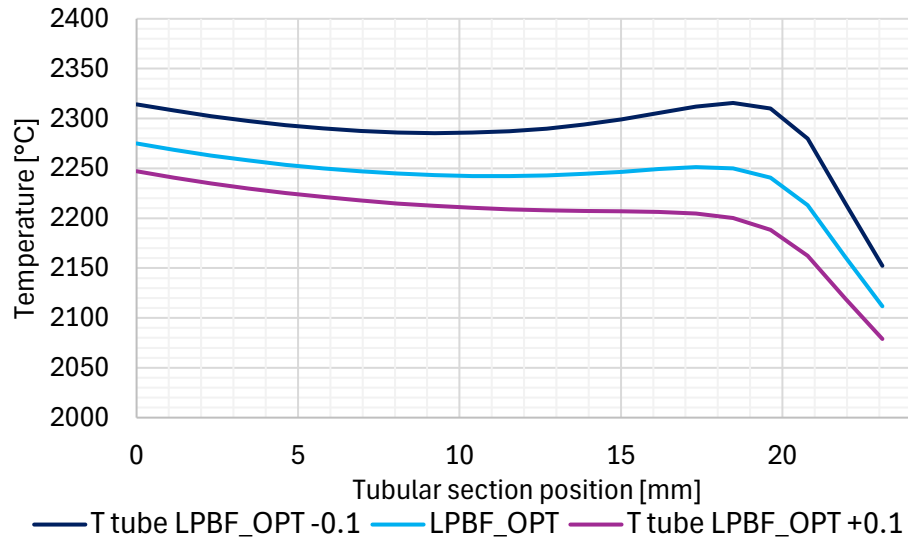


Figure 4.48 Estimated temperature distribution on the cathode tubular section considering a profile variation of the main body of ± 0.1 mm.

4.8 Conclusions

This chapter demonstrated the compatibility of the LPBF technology to manufacture key FEBIAD ion source components following a structured procedure consisting of design, Finite Element Method (FEM) simulations and experimental tests. For such a purpose, the cathode, which is normally subjected both to structural and thermal stresses, was used as a case study.

The feasibility analysis demonstrated the successful production in tantalum of critical geometries using LPBF, including the conical surfaces and the main body of the cathode. Geometric and dimensional characterisation of LPBF-produced cathodes (LPBF_conv) was performed through Coordinate Measuring Machine (CMM) inspections, which indicated that LPBF_conv cathode achieved superior or similar geometric accuracy in several key features compared to the STD cathode.

FEM simulations and experimental results confirmed comparable electro-thermal performance between LPBF-manufactured and STD cathodes. Additionally, the high-temperature experimental tests validated the FEM simulations, exhibiting a minimal deviation between the numerical and experimental temperature measurements, especially for the frontal surface of the cathode. Such a validation of the FE model is a crucial step towards further design optimisation.

The successful high-temperature endurance tests performed on LPBF-produced tantalum cathodes suggest their capability of resisting to typical operating conditions of FEBIAD ion source even with a long-term exposure. Such a promising results laid the basis for the development of alternative cathode designs which could further improve the mounting process accuracy by reducing the tolerance stack-up elements of the assembly. Additionally, the flexibility provided by LPBF process allows for further geometric optimisation, which could lead to improved thermal performance of the cathode, as demonstrated by the iterative FEM simulation process.

The next step, which will be detailed in the following chapter, involves off-line ionisation tests on the LPBF_conv cathode at CERN-ISOLDE, the reference ISOL facility in the world. Additionally, dedicated experimental setups must be developed to perform an in-

Chapter 4: Compatibility and electro-thermal characterisation of LPBF-Manufactured components for the FEBIAD Ion Source

depth characterization of various ion source designs, with the goal of obtaining comprehensive comparative experimental results.

Chapter 5: LPBF FEBIAD Ion Source characterisation at CERN-ISOLDE

Author disclosure statement

The results and analysis presented in this chapter are based exclusively on the ionisation tests performed using the LPBF-manufactured components for the FEBIAD ion source. At the time of writing, tests involving the standard (STD) SPES ion source configuration have not been published yet.

Consequently, direct comparisons between the LPBF and SPES STD versions are beyond the scope of this work. Future studies will address these aspects once the required experimental data becomes available. This approach ensures the current discussion remains focused on the available data and avoids premature conclusions based on incomplete comparisons.

5.1 Introduction

This chapter presents the results of Off-line ionisation tests performed using FEBIAD ion source components manufactured via Laser Powder Bed Fusion (LPBF). The focus is on evaluating the performance of tantalum and molybdenum components produced by LPBF exposed at the ion source operational conditions, with particular emphasis on ionisation efficiency for noble gases. The ionisation efficiency of a specific element is defined as the ratio between the ionised atoms and the neutral atoms injected. Previous chapters outlined the design, assembly, and characterization of these components, while this chapter examines their practical application.

The ionisation tests were performed in collaboration with ISOLDE and TRIUMF Target and Ion Source Development teams at the Off-line laboratory at CERN-ISOLDE [5] to determine the compatibility of the LPBF-manufactured parts with the critical operating condition of the FEBIAD ion source. The analysis covers contaminant presence, transport efficiency and ionisation efficiency measurements of the ion beam produced during the tests. The results provide insight into the potential advantages and limitations of using LPBF technology for key components of the FEBIAD ion source.

5.2 Materials and methods

The experimental setups and procedures to assess the compatibility of LPBF-manufactured components with the ionisation process of noble gases will be detailed in following paragraphs. Such methods allowed for accurate measurements of ionisation efficiency, a crucial parameter for evaluating the FEBIAD ion source performance.

Specifically, the ion source characterisation was performed employing the Front-End Off-line available at the CERN-ISOLDE Offline 1 mass separator facility [72], where a dedicated Target and Ion Source (TIS) unit was assembled and installed.

5.2.1 FEBIAD ion source assembly and TIS unit setup

The devices installed within the TIS unit to perform the ionisation test were assembled in a clean room at CERN-ISOLDE Offline 1 mass separator facility to reduce the amount of contaminants which would compromise the measurements.

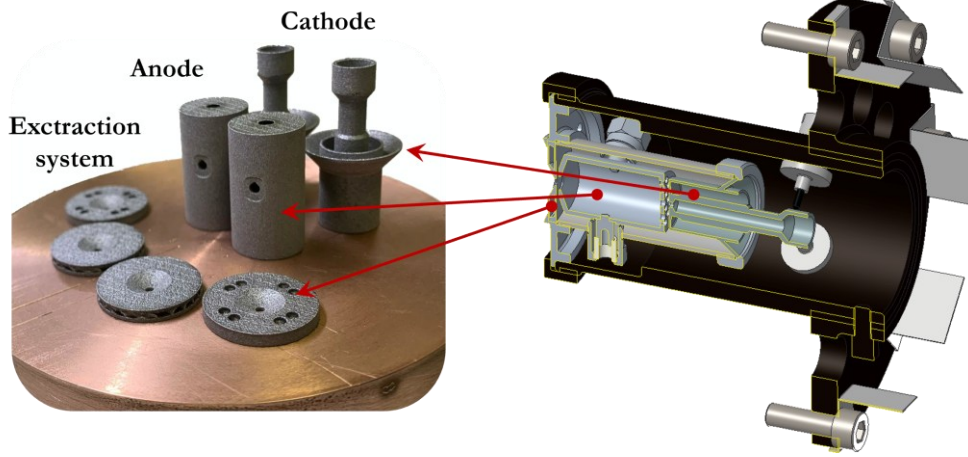


Figure 5.1 LPBF-manufactured ion source components.

The FEBIAD ion source was assembled for the first time using the components indicated in Figure 5.1 produced by LPBF process:

- The cathode (LPBF_conv model) was designed to be produced entirely by LPBF without the use of supports, which would require additional subtractive post-processing machining to be removed. Only the cathode frontal surface was machined by a turning machine;
- The extraction system was manufactured as a single part, as detailed in Chapter 4;
- The anode design was maintained as the conventional one.

The cathode and extraction system were manufactured in Ta at DIAM lab of the INFN-Padova section using the EOS M100 DMLS system from Electro-Optical Systems GmbH (EOS GmbH, Krailling, Germany). Afterwards, two different anodes were produced: the former was manufactured in Ta at CERN Additive Manufacturing laboratory [73], while the latter was fabricated in Mo at DIAM lab. The anodes were assembled by the mounting procedure outlined in [48] and in the previous Chapter 3; furthermore, the same cathode was used during the ionisation test using both the anodes.

The anode-cathode distance was determined by measuring the distances b [mm] and c [mm] using a depth calliper, whereas the dimension L [mm] was measured by a conventional sliding calliper as shown in Figure 5.2. Finally, the distance a [mm] is simply calculated as:

$$a = b - (L - c) \quad (5.1)$$

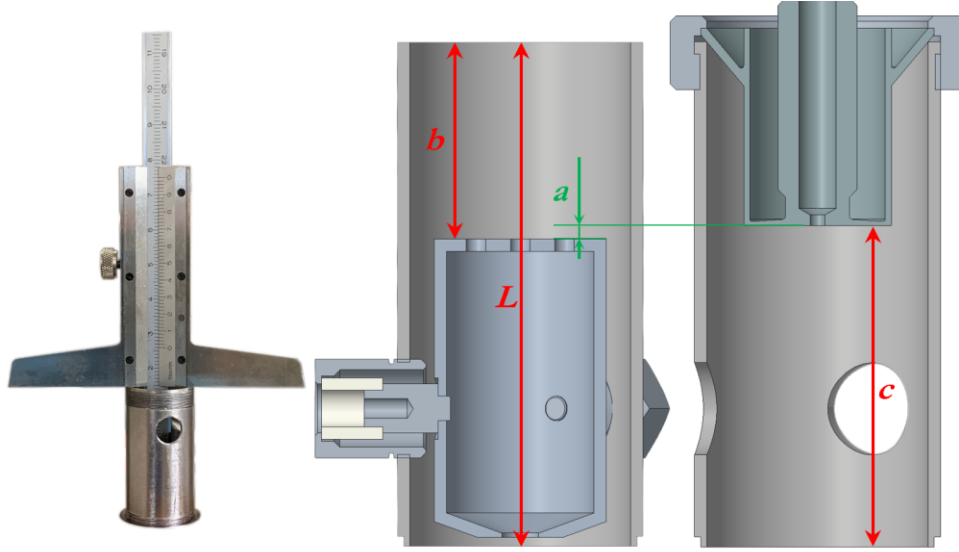


Figure 5.2 Anode-cathode distance measurement procedure.

The TIS unit was properly configured for the ionisation test as shown in Figure 5.3: the production of exotic species is not foreseen for the off-line ionisation test, therefore only the ion source (1) is assembled within the vacuum chamber, while the production target is usually not installed [22,72,74]. The anode is connected to its own power supply through the tantalum wire (2) that is maintained electrically insulated from all the other parts. The cathode was powered through the electrical connection (3), which allows the electric current to flow through the copper electrode, the copper clamp, the tantalum foils and the transfer line. Usually, a controlled gas flow of stable molecules (such as noble gases) is injected into the ion source through a calibrated leak (4) and the tubular connection (5) to reproduce the release of a neutral atom flux from the target.

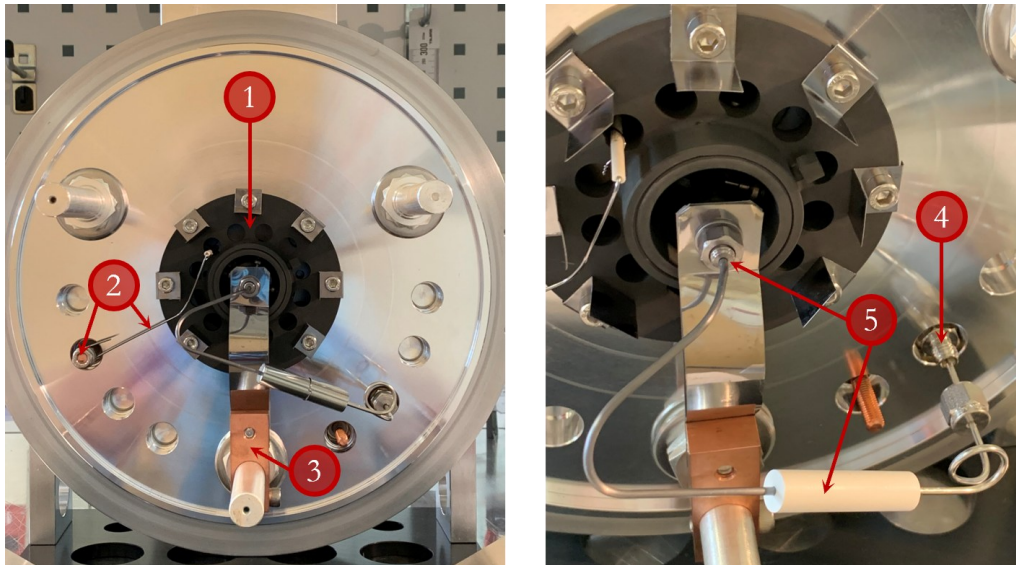


Figure 5.3 Target chamber setup: (1) FEBIAD ion source, (2) anode electrical connection, (3) Cathode electrical connection, (4) Calibrated leak, (5) Gas injection – ion source connection.

5.2.2 Cathode temperature calibration

The calibration Pumpstand is an experimental setup equipped with the service connectors needed to automatically couple a TIS unit [72]. It allows to perform both a high vacuum test of the TIS unit and the ion source temperature calibration. The latter procedure consists of

the cathode frontal surface temperature measurement using a disappearing – filament optical pyrometer at different heating currents (namely, line currents). Indeed, a viewport is installed towards the ion source extraction system to keep visible the device during the calibration process, as shown in Figure 5.4. Such a measurement is fundamental to correlate the cathode frontal surface temperature and the heating current. During the ionisation test, the cathode is no more accessible for a temperature measurement, therefore the calibration data are used to estimate the frontal surface temperature in function of the applied heating current. Furthermore, it allows to compare the cathode temperature of different ion source assemblies.

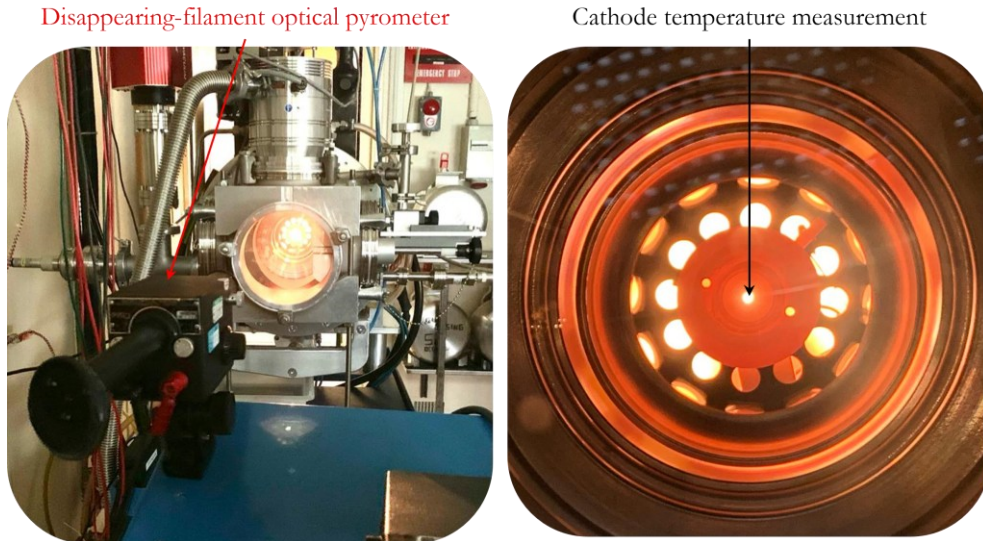


Figure 5.4 Pump stand temperature calibration setup

5.2.3 Ionisation efficiency test of noble gases mix

Once the TIS unit preparation and calibration is completed, it is coupled to the CERN-ISOLDE offline 1 Front-End where the ionisation test is performed. The setup schematized in Figure 5.5 works similarly as the SPES Front-End presented in Chapter 1: in this work, a mixture of 20% of all the stable noble gases (He, Ne, Ar, Kr, Xe) is injected into the TIS unit through a calibrated leak using a gas injection system equipped with a gauge to measure the gas pressure. The heating current (or line current) and the anode voltage are fed by independent power supplies. Furthermore, an independent power supply is used for the high voltage devices. Indeed, the ions produced in the anode chamber are extracted and accelerated from the TIS unit, which is usually kept at around 30 kV, by means of an extraction electrode (or puller electrode) which is instead kept at ground potential and positioned at a distance from the FEBIAD ion source extraction aperture ranging from 0 to 120 mm. For the ionisation tests presented in this work, the extraction potential was set at 31 kV, while the extractor was kept 80 mm distant from the ion source aperture.

The Einzel lens is an electrostatic device which is capable to focus the ion beam to the desired point by applying a proper voltage. In particular, different Einzel potential should be applied to focus the ion beam either to the Faraday Cup 1 (FC1) or to the Faraday Cup 2 (FC2). The former is installed before the mass separator magnet and used to measure the total beam intensity (total beam current), the latter is positioned after the separator magnet, and it is capable to measure the separated beam intensity (beam current). Before the FC2, two horizontal slits are used to stop the unwanted particles deflected by the mass separator, thus ensuring the isobaric purity of the beam. In addition, a horizontal profile scanner (BPM) is installed into the same diagnostic station of the FC2 to verify the size and the

alignment of the ion beam. The use of the BF together with the FC2 allows to properly set both the slits aperture (in this case 10 mm) and the Einzel potential (21 kV when the total beam current is measured, 16 kV for the separated beam current measurement). The beam line is maintained at high vacuum regime (10^{-6} mbar) during the ionisation measurements thanks to two turbomolecular pumps installed close to the TIS unit and the diagnostic station after the mass separator.

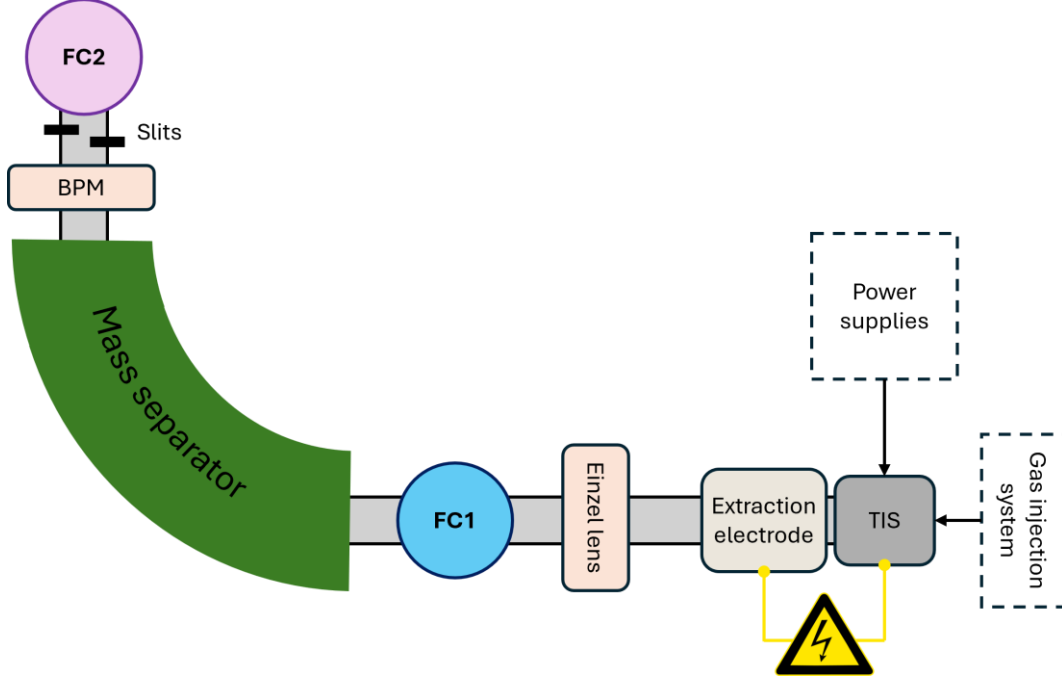


Figure 5.5 Schematic representation of the OFFLINE1 experimental setup available at CERN-ISOLDE.

The separated beam current I_{FC2} [A] measured by the FC2 is directly correlated to the ionisation efficiency as stated from the following equation:

$$I_{FC2} = n_i e \varepsilon_{ion_i} \varepsilon_{t_i} \quad (5.2)$$

Where n_i [atoms/s] is neutral atom flux of a specific isotope i , e [C] is the electron charge, ε_{ion} is the ionisation efficiency (i.e. the ratio between the ionised atoms and the neutral atoms injected) and ε_t is the transport efficiency (i.e. the ratio between the ion current exiting the source extraction system and the ion current measured at the FC2). The latter term must be carefully assessed by the procedure mentioned in the following paragraph to avoid the underestimation of the ionisation efficiency, since it represents the beam losses along the beam line.

The neutral atom flux of the injected isotope i depends strongly the calibrated leak and on the gas pressure set to inject the noble gases, indeed it is calculated as:

$$n_i = \frac{L p_{gas}}{k T 1000} \sqrt{\frac{m_a}{m_i}} v_i A_i 0.1 \quad (5.3)$$

Where L [mbar l/s] is the Helium (He) equivalent leak rate of the calibrated leak, p_{gas} [mbar] is the gas pressure, k [J/K] is the Boltzmann constant, T [K] is the room temperature, m_a [amu] is the He atomic mass, m_i [amu] is the atomic mass of the injected isotope, v_i is the volumetric fraction of i into the gas mixture and A_i is the relative abundance of i .

Therefore, the measurable terms involved to calculate the noble gases efficiency (i.e. n_i , ε_t and I_{FC2}) were evaluated using the procedures reported in the following paragraphs. Additionally, the methods used to characterize the FEBIAD ion source during operation are presented.

i. Leak rate calibration

The calibrated leak is essential to set the proper neutral atoms flow within the TIS unit. Therefore, the certificated flow rate of the calibrated leak was verified by a gas leak detector based on He available at CERN-ISOLDE before its installation to measure the real flow rate values. Afterwards, the flow rate is calculated using the relation (5.3).

ii. Contaminants analysis

Ideally, using such a TIS unit configuration, only the injected gases should be ionised during operation. However, some contaminants are always unintentionally introduced. A careful contaminants analysis is fundamental since they could affect the ion beam properties and consequently the ionisation efficiency. Consequently, the additively manufactured components could introduce different contaminants compared to the conventional ones due to their different production process. The usual main impurities in the MK5 ISOLDE FEBIAD ion sources are sodium, potassium, and carbon monoxide. A key distinction among these impurities is their behaviour during operation: Na and K are usually present in limited quantities, moreover they can be largely outgassed after a period of operation of the ion source at sufficiently high temperatures. In contrast, CO is continuously generated due to the materials used in the ion source (primarily the graphite support), leading to a steady increase in its partial pressure, particularly by increasing the operational temperature.

The analysis consists of different mass scans (refer to Chapter 1) maintaining the same ion source settings over time. With this method, it is possible to characterize the total ion beam measuring the intensity of each isotope extracted from the TIS unit and to the extract information concerning the type and the persistence of specific contaminants; therefore, the outgassing time required to purify the ion beam could be stated. The analysis was performed feeding a heating current (I_{line}) of 380 A, anode voltage (V_{anode}) 125 V, and ion source magnet current (I_{mag}) 2.8-3.8 A.

iii. Drain current analysis

The anode drain current could be defined as the electrons flow released by thermionic effect from the cathode which is absorbed by the anode during operation. Consequently, such a parameter provides a direct indication of the electron current drawn from the cathode, which clearly affects the plasma characteristics and consequently the ionisation process.

The anode drain current is easily measured by its own power supply. It is sensitive to the cathode temperature (according to the Richardson law), and it depends on both the anode-cathode distance and anode voltage (according to the Child-Langmuir relation). The analysis was performed by measuring the drain current at different heating currents (i.e. cathode temperatures) and different anode voltages in different ionisation test days. It also allows to observe the stability of the ion source over time: for instance, a variation of the drain current during operation could be due to geometric modification of the system (e.g. thermal expansion, components failure, etc.) or of the boundary test conditions (e.g. background pressure).

iv. Transport efficiency measurement

The transport efficiency is strongly dependant on the extraction potential used to accelerate the produced ions along the beam line [75]. Normally, the more is the extraction voltage, the more efficient is the beam transport.

Despite the ISOLDE Offline 1 can achieve up to 60 kV of extraction potential (V'_{ext}), usually it is maintained at around 31 kV (V^0_{ext}) to preserve the apparatus from sparks which would compromise the experiments. Therefore, assuming that at V'_{ext} the beam losses could be considered negligible, the transport efficiency is defined as:

$$\varepsilon_t = \frac{I_{FC2}^0}{I'_{FC2}} \quad (5.4)$$

Where I_{FC2}^0 [nA] and I'_{FC2} [nA] are the separated beam currents measured respectively at V_{ext}^0 and V'_{ext} .

Furthermore, the transport efficiency depends on the atomic mass of the separated ion, therefore it was measured for each isotope considered for the ionisation test.

Both the Einzel voltage to focus the separated beam current in FC2 and the mass separator magnet current used to select the ionised isotope of interest are estimated from the following equations:

$$V'_{einz} = V_{einz}^0 \frac{V'_{ext}}{V_{ext}^0} \quad (5.5)$$

Where V'_{einz} [kV] and V_{einz}^0 [kV] are the Einzel voltages used to focus the separated beam current in FC2 at V'_{ext} and V_{ext}^0 respectively.

$$I'_{sep} = I_{sep}^0 \sqrt{\frac{V'_{ext}}{V_{ext}^0}} \quad (5.6)$$

Where I'_{sep} [A] and I_{sep}^0 [A] are the mass separator currents set for a specific isotope separation respectively at V'_{ext} and V_{ext}^0 .

v. Noble gases efficiency measurement

The noble gases efficiency measurement was performed after the outgassing period suggested by the contaminants analysis, ensuring a background pressure below 1.0E-5 mbar. The FEBIAD ion source settings which mainly affects the ionisation process as discussed in Chapter 2 are:

- Anode voltage (V_{anode});
- Ion source magnet current (I_{mag});
- Cathode heating current (I_{line}).

Such parameters were manually optimised to increase the separated beam current in FC2 for each noble gas injected at different heating currents (i.e. temperatures). The procedure used to set the optimum ion source settings to maximize I_{FC2} is the following one:

1. A reasonable anode voltage is fixed: $V_{anode} = 120$ V;
2. A scan of I_{mag} values is performed ranging from 0 to 6 A. I_{FC2} achieves multiple local maximum values;
3. For each one of the local maxima measured during the I_{mag} scan, several V_{anode} values ranging from 80 V to 180 V are applied. Consequently, multiple I_{FC2} maxima are measured, each one characterized by a combination of I_{mag} and V_{anode} ;
4. Each combination is slightly refined by setting I_{mag} and V_{anode} values to increase I_{FC2} ;
5. The optimum combination of I_{mag} and V_{anode} which achieves the maximum I_{FC2} value is employed to calculate the ionisation efficiency.

5.3 Results and discussion

The anode-cathode distance was always measured prior to every Pumpstand calibration for each ion source assembly. Each dimensional feature was measured five times using depth or conventional callipers, following the procedure previously outlined. In Table 5.1 are reported the results of the measurements performed to the FEBIAD ion source assembled with the

LPBF components manufactured in Ta (indicated as LPBF ion source – Ta anode). The anode-cathode distance was set at 1.69 ± 0.04 mm through a spacer ring 1.02 ± 0.01 mm thick positioned between the cathode conical surface and the discharge chamber. Such measurement was approximately 0.7 mm larger than the ideal distance, allowing for accommodate potential deformation of the cathode during operation. This adjustment prevents contact between the anode and cathode, which would require complete replacement of the components, as will be discussed in paragraph 5.3.1 .

Table 5.1 LPBF ion source – Ta anode: anode-cathode measurement.

Dimension	Avg measure [mm]	Std. Dev. [mm]
cathode distance (c)	26.57	0.02
anode distance (b)	16.54	0.01
Spacer ring thickness (t)	1.02	0.01
Discharge chamber length (L+t)	41.42	0.03
Anode-cathode distance (a)	1.69	0.04

After the ionisation test, the FEBIAD ion source was removed from the TIS unit, and the anode-cathode distance was measured again, as presented in Table 5.2.

Table 5.2 LPBF ion source – Ta anode: anode-cathode measurement after the ionisation test.

Dimension	Avg measure [mm]	Std. Dev. [mm]
cathode distance (c)	25.97	0.01
anode distance (b)	16.54	0.01
Spacer ring thickness (t)	1.02	0.01
Discharge chamber length (L+t)	41.42	0.03
Anode-cathode distance (a)	1.09	0.04

The distance “a” decreased by approximately 0.6 mm, resulting in a post-test measurement of 1.09 ± 0.04 mm. Such a variation was attributed to deformation of the cathode during high-temperature exposure, as detailed in the following paragraphs. Subsequently, a new ion source was assembled using a LPBF molybdenum anode and the same deformed LPBF tantalum cathode from the previous test (indicated as LPBF ion source – Mo anode). Since the original distance of 1.69 mm was no longer suitable due to the cathode deformation, the anode-cathode distance for this new assembly was adjusted to 1.23 ± 0.03 mm using a spacer ring of 1.15 mm, closer to the post-test measurement from the previous setup.

Table 5.3 LPBF ion source – Mo anode: anode-cathode measurement

Dimension	Avg measure [mm]	Std. Dev. [mm]
cathode distance (c)	26.17	0.02
anode distance (b)	16.66	0.01
Spacer ring thickness (t)	1.15	0.01
Discharge chamber length (L+t)	41.60	0.01
Anode-cathode distance (a)	1.23	0.03

5.3.1 Preliminary tests for operative condition identification

Before performing the noble gases ionisation efficiency tests, preliminary assemblies of the FEBIAD ion source were prepared and installed into the Offline 1 experimental setup using both a LPBF-manufactured Ta cathode and Ta anode produced at the DIAM lab of the INFN Padova section. Two different ion sources were assembled, one with an initial anode-cathode distance of 1.09 mm and the other with a gap of 1.43 mm. However, both devices experienced failures during the high temperature operations. In both cases, the cathode frontal surface deformed due to thermal expansion, leading to a direct contact with the anode grid. Consequently, a short circuit occurred, and the central area of the anode grid melted, as shown in Figure 5.6.

A similar failure mechanism was observed in a standard-manufactured FEBIAD ion source [38,42], where localised overheating led to deformation of the central region of the anode grid.

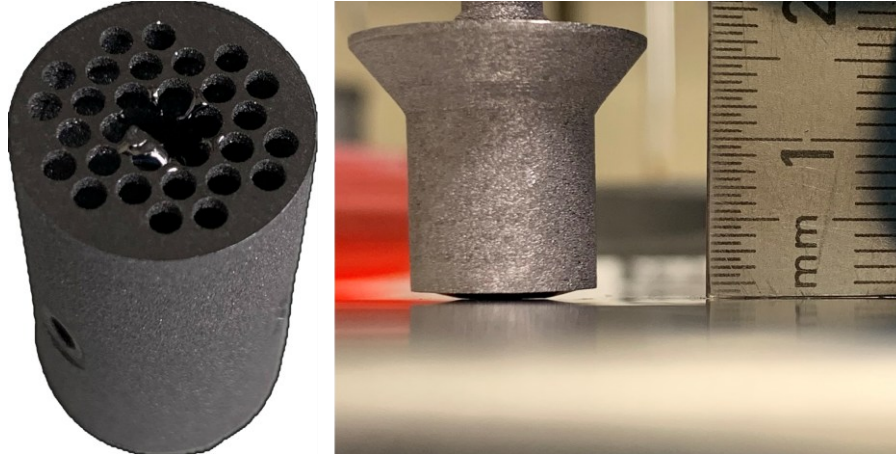


Figure 5.6 The anode grid melted (left) due to the contact with the deformed cathode (right) at high temperature.

Such failures provided fundamental information concerning the operational safety margin of the ion source assembled with LPBF cathodes. In particular, they highlighted the need to increase the nominal anode-cathode distance to account for thermal deformation of the LPBF-manufactured cathode. As a result, subsequent assemblies (refer to the previous paragraph) were configured with larger initial anode – cathode distances to prevent further ion source failures. Moreover, additional information concerning the behaviour of the failed ion source will be provided in the following sections.

Due to the irreversible damage to the anodes and the unavailability of additional DIAM-fabricated Ta anodes, the Additive Manufacturing Laboratory at CERN reproduced the same anode geometry in tantalum by the LPBF process. The component was manufactured in only two working days, minimizing the downtime of the experimental campaign. Such a rapid replacement underlines the flexibility and responsiveness offered by additive manufacturing technologies, which resulted essential to perform the ionisation efficiency tests presented in this work.

No further failures occurred during the subsequent testing campaign. The LPBF Ta cathode functioned continuously for nearly three weeks of operation, confirming its compatibility with the typical working conditions of a FEBIAD ion source.

5.3.2 Cathode temperature calibration

The cathode temperature calibrations for the LPBF ion sources performed at the Pumpstand setup are presented by plotting line current against temperature, power, and temperature raised to the fourth power (T^4) for both the Ta AM anode and the Mo anode configurations (using the same cathode for both ion sources), as shown in Figure 5.7, Figure 5.8, and Figure 5.9.

The consistency of the calibration was further supported by the data collected from a failed ion source. Despite its limited operation, its electro-thermal performances aligned with the trends observed in the other tested configurations.

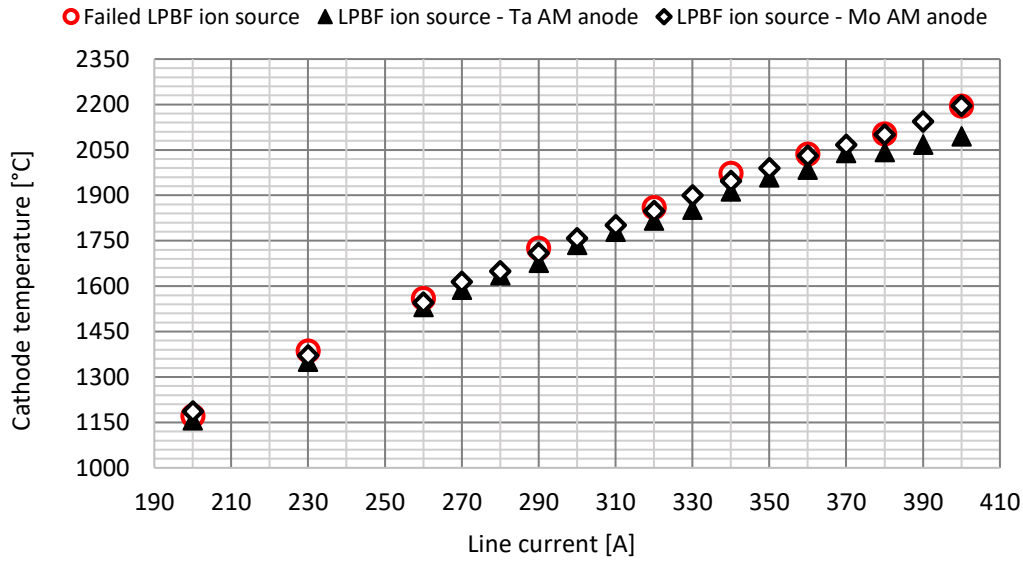


Figure 5.7 Line current against temperature Pumpstand calibration measurement

The plot in Figure 5.7 demonstrates a similar behaviour between the ion sources as their temperature difference is consistently below 3% except for the last three data points measured at heating currents above 360A. Especially the calibration of LPBF ion source – Ta AM anode was affected by the inherent uncertainty related with the manual temperature measurement using the disappearing – filament optical pyrometer.

Despite this, the plot in Figure 5.8 confirms the expected linear correlation between power and the temperature raised to the fourth power (T^4). Therefore, linear interpolation was applied to estimate the data points beyond heating currents of 370A for the LPBF ion source – Ta AM anode, ensuring the availability of reliable data for subsequent analysis.

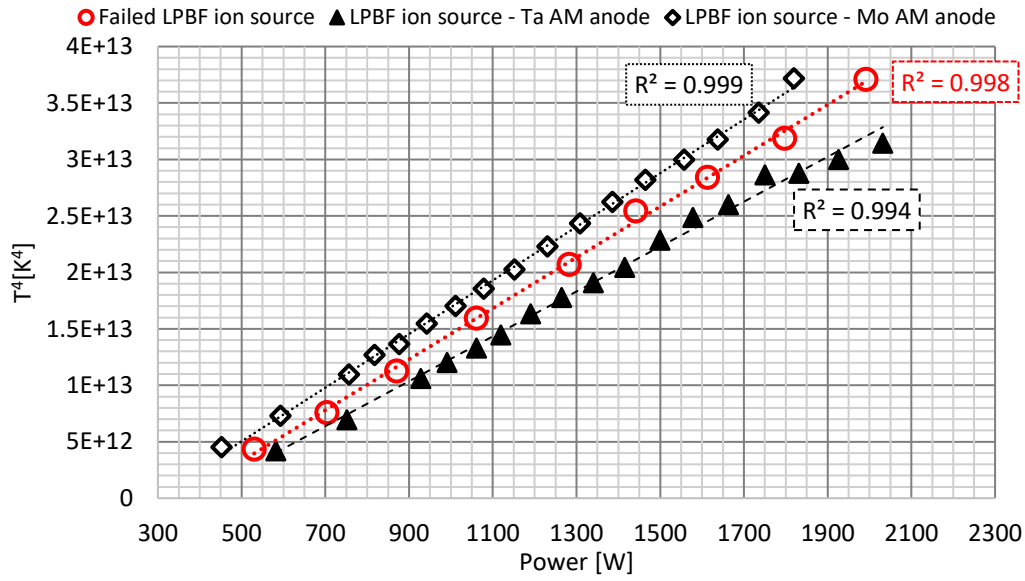


Figure 5.8 Power against temperature raised to the fourth power.

Furthermore, the chart in Figure 5.9 reveals slight differences in the power dissipated by the ion sources. Such variations can be attributed to minor differences during the assembly process, where the components were secured using fits and bolts. These assembly inconsistencies likely influenced the power generation and dissipation characteristics of each ion source.

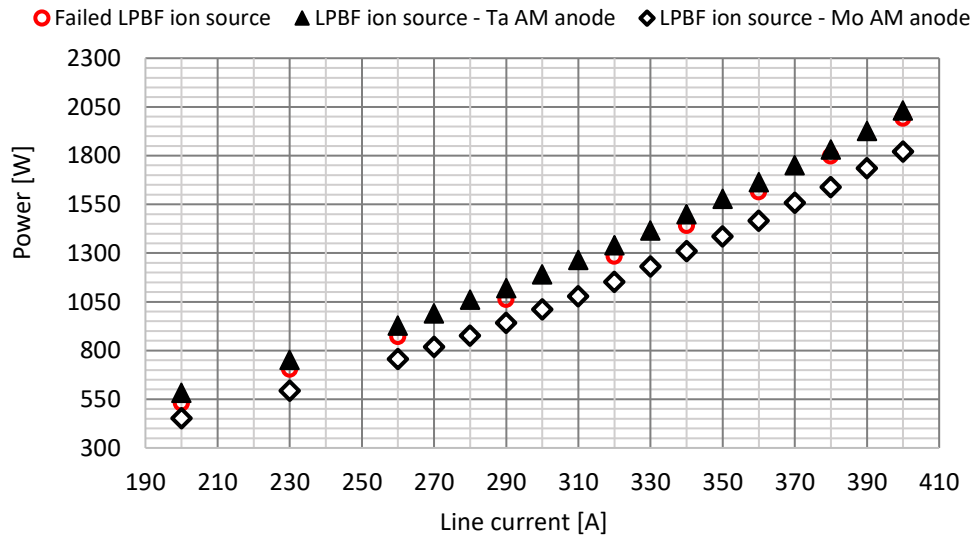


Figure 5.9 Line current against power Pumpstand calibration measurement

5.3.3 Ionisation efficiency test of noble gases mix

This section summarizes the ionisation efficiency tests performed on a noble gases mix using LPBF-manufactured components. The results focus on the performance of the FEBIAD ion source at different operating conditions for argon, krypton, and xenon ionisation process.

i. Leak rate calibration

The certificated calibrated leak, with a nominal He equivalent leak rate of 1.0 E-5 mbarl/s , was verified by a helium-based gas leak detector available at CERN-ISOLDE. The measured

He leak rate was 8.3 E-6 mbarl/s , which was subsequently used to calculate the neutral atom flux of the injected atoms by Equation (5.3).

ii. Contaminants analysis

The systematic analysis of contaminants was conducted on the LPBF ion source – Ta anode by performing multiple mass scans over time, without modifying the FEBIAD ion source settings. Figure 5.10 shows the first mass scan feeding a heating current (I_{line}) of 380 A, where each peak represents the beam current (measured in FC2) corresponding to a specific isotope of detected elements.

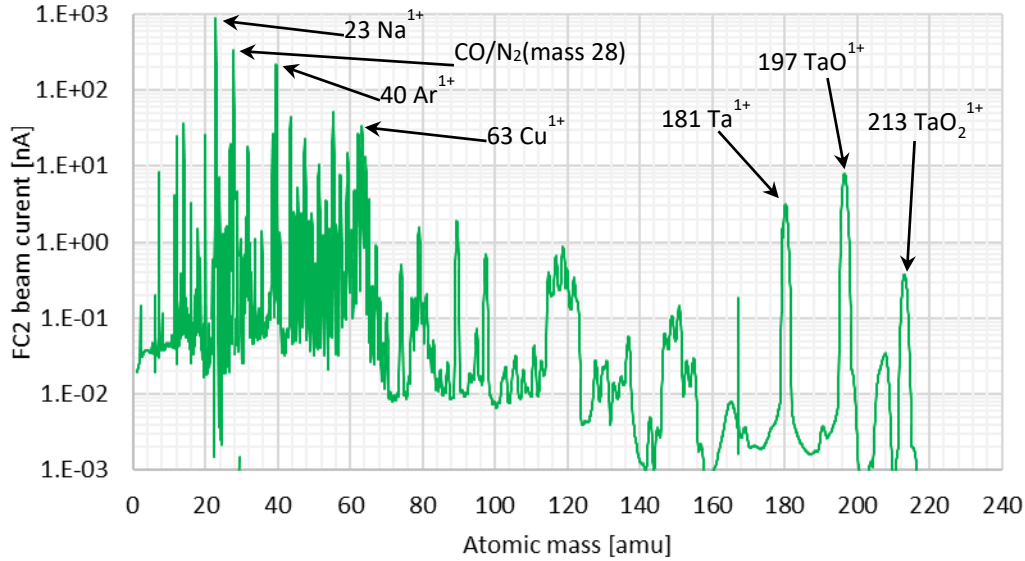


Figure 5.10 Mass scan measurement at $I_{\text{line}} 380\text{A}$, $V_{\text{anode}} 125\text{V}$, $I_{\text{mag}} 2.8\text{A}$ introducing a flux of pure argon on the first ionisation test day.

Additionally, the investigation was performed injecting only pure argon within the TIS unit, as the introduction of other noble gases would produce overlapping peaks, complicating contaminant identification.

Figure 5.11 and Figure 5.12 display the beam intensity (i.e. FC2 current) over time of the most common standard MK5 ion source contaminants: sodium and the mass 28 isotopes (mainly CO and N₂) [37].

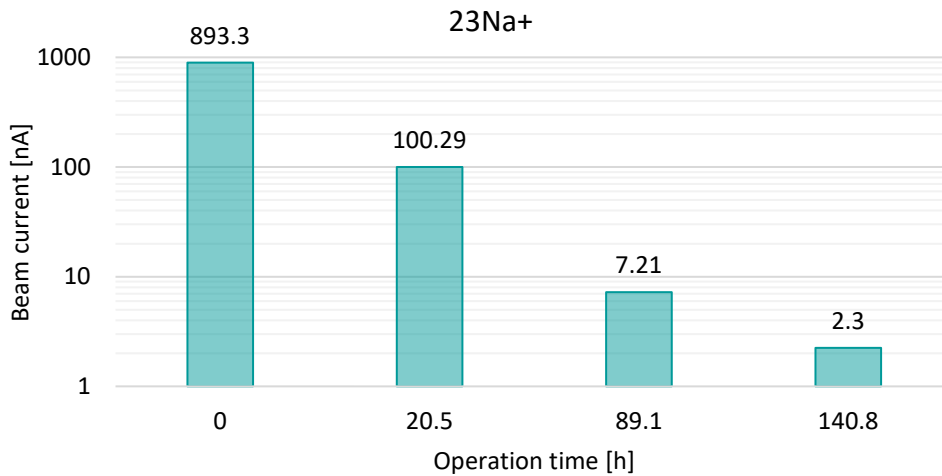


Figure 5.11 Sodium beam intensity over time. $I_{\text{line}}=380\text{A}$, $V_{\text{anode}}=125\text{V}$, $I_{\text{mag}}=2.8\text{A}$.

The sodium intensity decreases significantly after a relatively short period of degassing, which is consistent with the STD MK5 ion source behaviour. It suggests that sodium, probably originating from the manufacturing environment or residuals on the component surfaces, was progressively outgassed as the ion source reached operational temperatures. Similarly, mass 28 isotopes exhibited an initial decrease in ion beam current before stabilizing, indicating that CO and N₂ contaminants were released gradually as the system reached equilibrium. Such a stabilization is inherent to the FEBIAD ion source setup due to the presence of the graphite support.

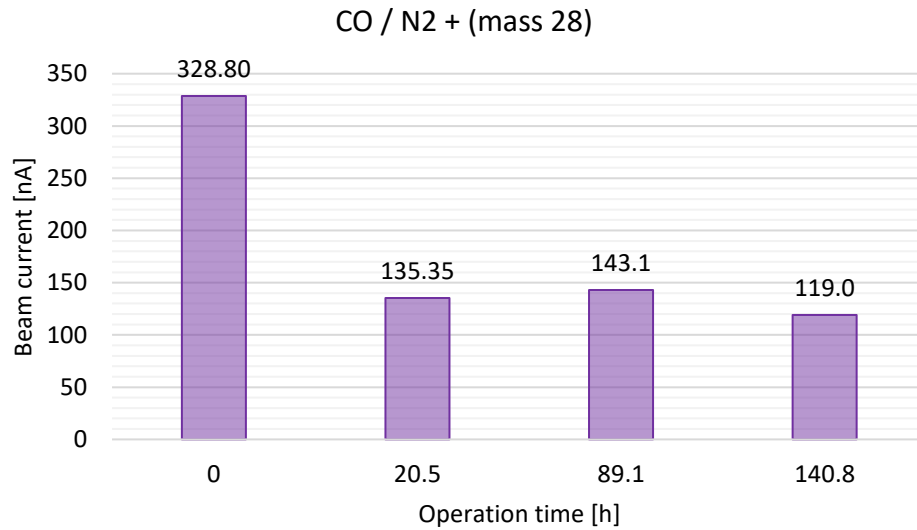


Figure 5.12 Beam intensity of isotopes having mass 28, mainly CO and N₂. $I_{line}=380A$, $V_{anode}=125V$, $I_{mag}=2.8A$.

Copper contamination was also observed, as shown in Figure 5.13. The potential sources of copper include the friction between the anode and the main body of the assembly tool manufactured in brass (less probable), or the copper build platform used to produce the components by the LPBF process (more probable).

Such a finding emphasizes the need to carefully consider the material substrates used during LPBF manufacturing, nevertheless the copper beam intensity also decreased over time, indicating that it was gradually degassed during the testing period.

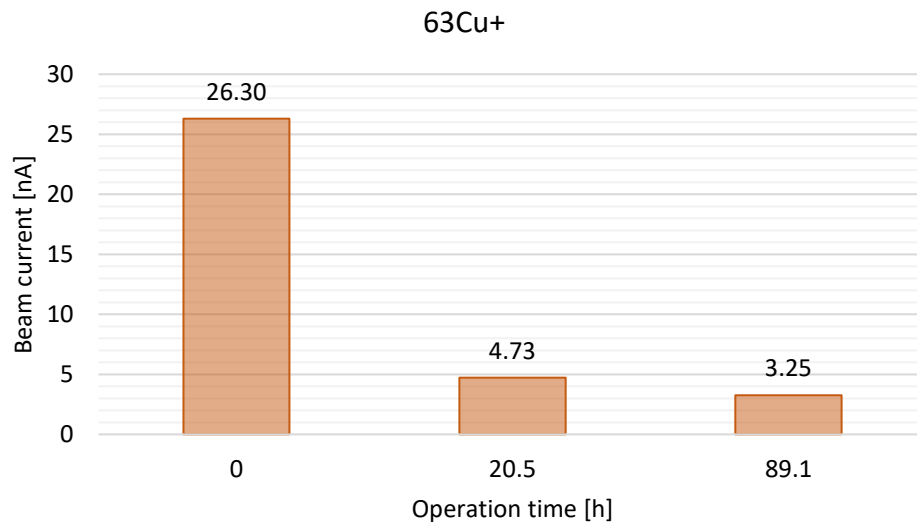


Figure 5.13 Beam intensity of copper over time. $I_{line}=380A$, $V_{anode}=125V$, $I_{mag}=2.8A$.

Figure 5.14 shows the gradual reduction in beam current for tantalum and tantalum oxides beam current decrease which may be attributed to the removal of the surface oxide layer naturally formed on tantalum components. The continuous detecting of pure Ta beam current is likely due to the superficial evaporation occurring to high temperature tantalum components.

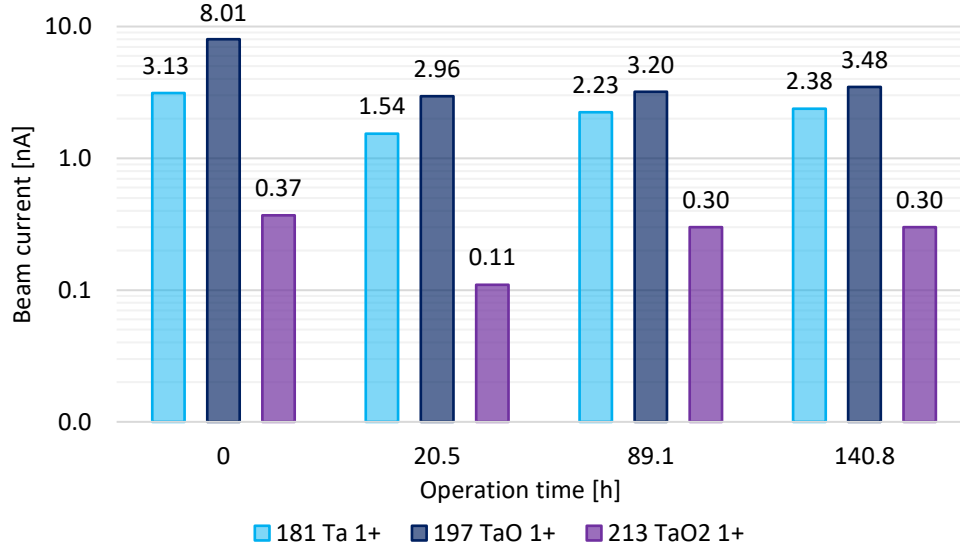


Figure 5.14 Beam intensity of Ta and Ta oxides over time. $I_{line}=380A$, $V_{anode}=125V$, $I_{mag}=2.8A$.

The data reported in Figure 5.15 indicates that while Ta beam current is consistent across both anodes, the presence of tantalum oxides vary, with the Ta anode favouring single-oxide formation (TaO^+) and the Mo anode showing a tendency towards higher double-oxide levels (TaO_2^+). Such a difference could be due to differing chemical interactions or thermal properties that influence oxide stability at high temperatures, however further dedicated in-depth analysis should be done to confirm the hypothesis.

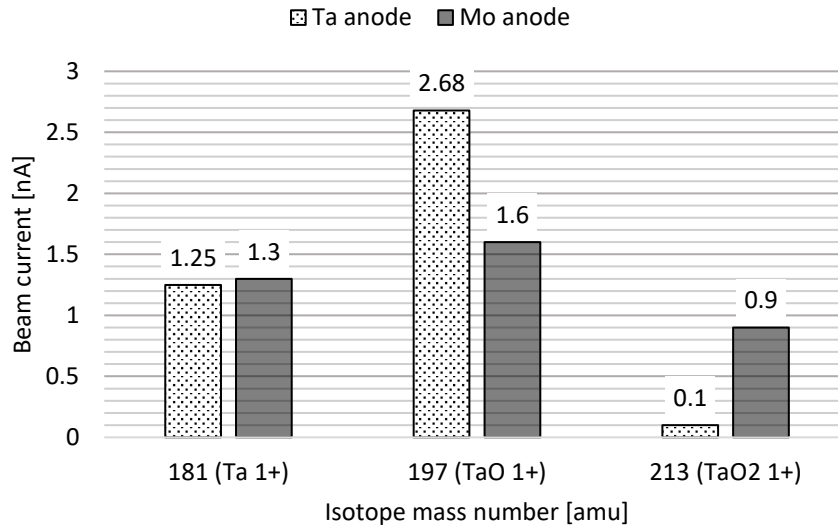


Figure 5.15 Tantalum and tantalum oxides beam currents post-outgassing comparison between LPBF ion sources assembled with the Ta anode and the Mo anode. $I_{line}=380A$, $V_{anode}=125V$, $I_{mag}=2.8A$.

Although the contaminants analysis was primarily focused on the Ta anode, similar contaminants were detected with the LPBF-manufactured Mo anode, suggesting that the

contaminations are more related to the manufacturing and assembly processes than to the specific anode material.

As a result, the ionisation tests must be performed after sufficient outgassing of contaminants, as residual gases and surface impurities can significantly affect the ionisation efficiency and overall beam quality. Ensuring proper outgassing will reduce contamination and improve the accuracy and reliability of the ionisation tests. In this context, a dedicated conditioning procedure in a vacuum oven could be employed prior to the installation of the components in the TIS unit, in order to perform early outgassing and minimize the release of volatile species during operation.

iii. Drain current analysis

The drain current analysis presented in this paragraph includes data collected powering the ion sources at 360A and considers only the last ionisation test day to provide comprehensive information concerning the thermionic emission of such devices. However, the full analysis is available in Appendix I.

During the initial hours of operation, the drain current for the LPBF ion source – Ta anode was not stable, as shown in Figure 5.16. The instability may be attributed to several factors, including thermal expansion, which might alter the geometry of the cathode, as well as microstructural stabilization processes that naturally occur when the device is exposed to high operational temperatures. These factors likely caused shifts in the anode-cathode distance and electron emission characteristics, resulting in fluctuating drain current measurements. However, after a period of continuous operation (approximately 86 hours), the drain current began to stabilize, providing more consistent and reliable measurements.

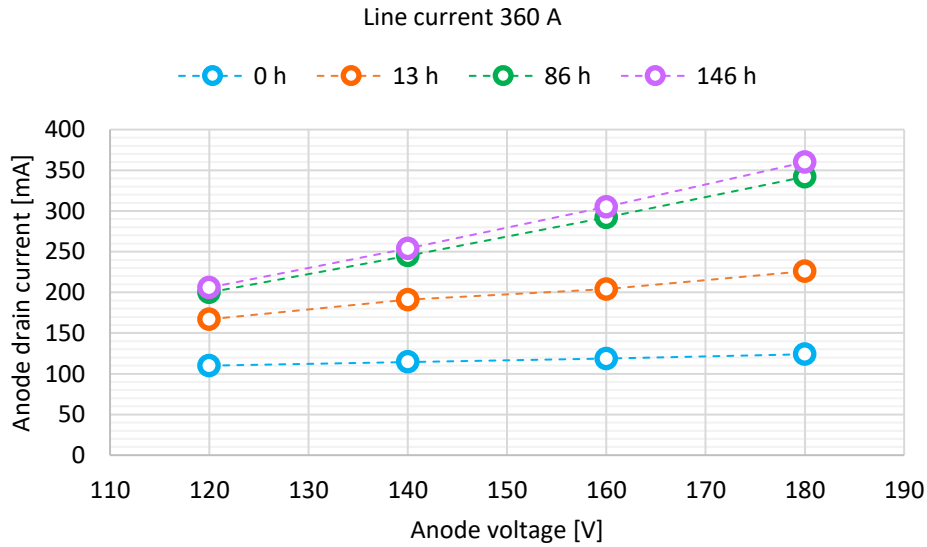


Figure 5.16 LPBF Ta anode at 360A drain current analysis at different operation hours (cathode calibration temperature 1985°C).

Figure 5.17 shows the drain current data collected at different cathode temperatures (i.e. I_{line}) and V_{anode} , revealing a significant deviation between experimental and numerical values.

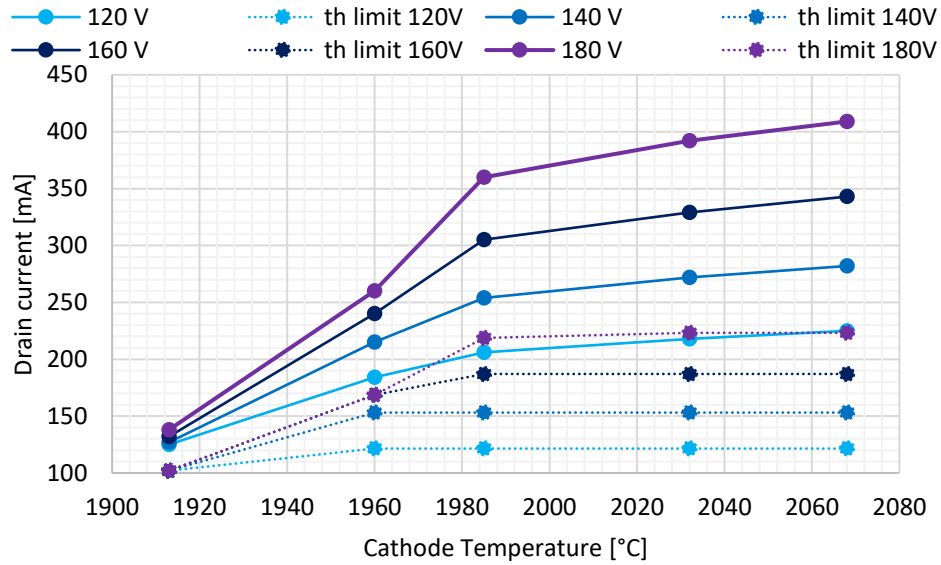


Figure 5.17 AM Ta anode drain current analysis on the last ionisation test day.

The theoretical drain current limits were estimated from Richardson and Child-Langmuir equations, which were previously discussed in Chapter 2. Therefore, the numerical results were calculated applying the cathode temperatures measured at the Pumpstand setup and the anode-cathode distance in Table 5.1 as input parameters.

However, the cathode frontal surface was assumed at a uniform temperature, while it was demonstrated in Chapter 4 that it decreased radially from the centre of the cathode. Such assumption overestimates the theoretical thermionic emission, as the experimental value of the cathode temperature were measured from the centre of the frontal surface. Conversely, the experimental drain current values were consistently lower than the numerical estimations, which suggests that factors not considered in the theoretical model significantly alter the calculation.

In particular, once concluded the ionisation test, the FEBIAD ion source was removed from the TIS unit, and the anode-cathode distance was measured again according to the procedure outlined in Paragraph 5.2.1 The results in Table 5.2 underscore a decrease of 0.6 mm compared to the initial value reported in Table 5.1. Such a reduction is attributed to the cathode frontal surface deformation, which transitioned from flat to curved due thermal and structural loads during operation, as shown in Figure 5.18.

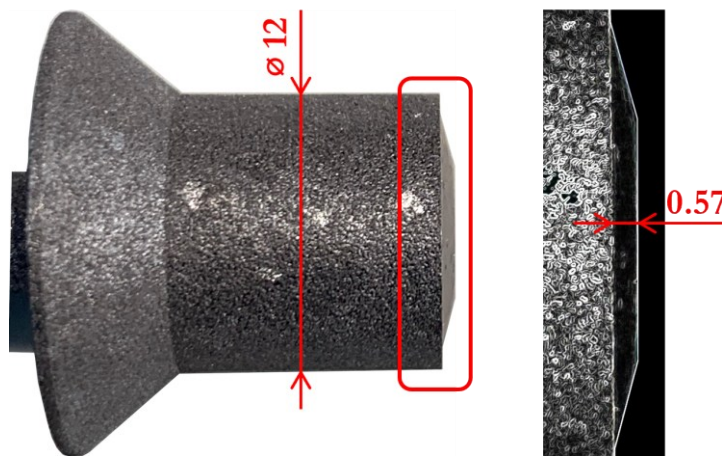


Figure 5.18 LPBF Ta cathode deformation. The highlighted measures are in mm.

The cathode deformation was further estimated using the software ImageJ, a public domain Java image processing program [76]. The estimated deformation value was 0.57 mm, which is aligned with the anode-cathode distances measurement post ionisation test.

The reduction of the anode-cathode distance led to an increase of the Child-Langmuir current limit, thereby increasing the transmissible electron flow between the cathode and the anode. As a result, the drain current was significantly affected by the deformation, leading to experimental values that exceeded the numerical predictions. However, the impact of thermionic emission from a non-flat surface requires further in-depth analysis to better explain the observed experimental data.

The analysis of the LPBF ion source – Mo anode revealed more stable and consistent drain current results compared to the Ta anode, as shown in Figure 5.19.

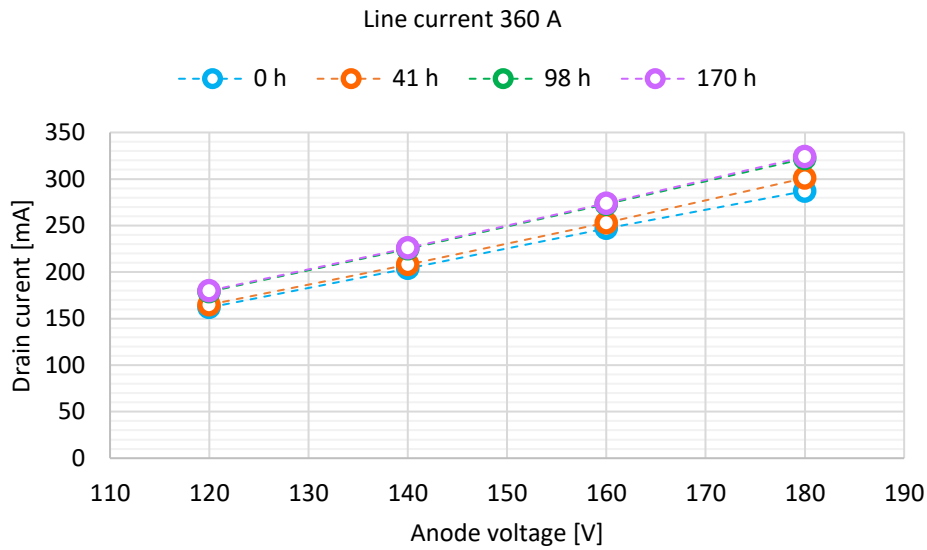


Figure 5.19 LPBF Mo anode at 360A drain current analysis at different operation hours (cathode calibration temperature 2031°C)

Such increased stability is probably due to the conditioning and stabilization of the cathode during the previous tests, which minimized further thermal deformation and microstructural changes during the ionisation test with the Mo anode.

In Figure 5.20 the deviations between numerical and experimental results are smaller than those observed in the Ta anode test. The anode-cathode distance used for the numerical estimation (refer to Table 5.3), likely remained stable during the measurements, as the cathode was already conditioned from earlier testing. The theoretical values consistently exceed the drain current experimental measurements, aligning with the numerical model assumptions previously discussed. Such consistency further supports the validity of the theoretical approach, while also highlighting the importance of a stable anode-cathode distance for more accurate predictions.

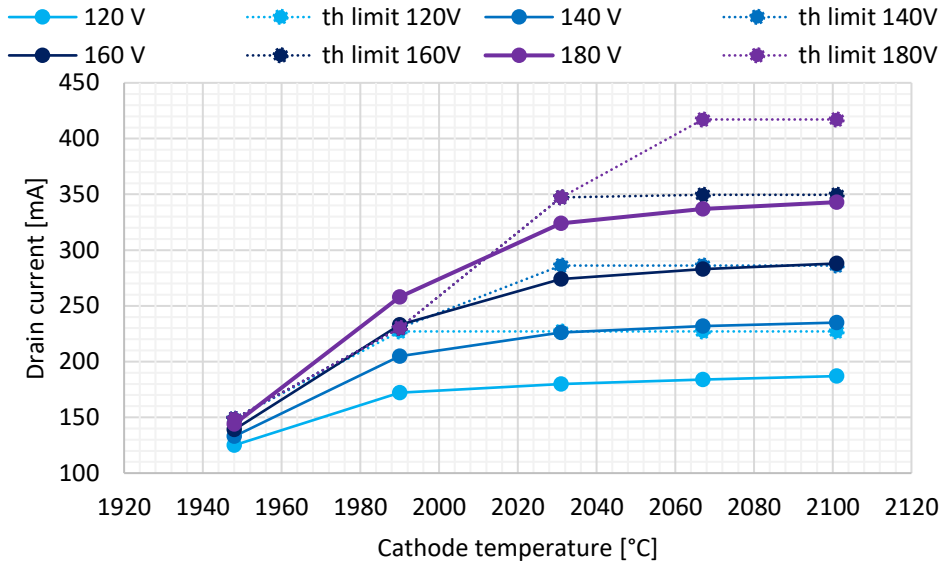


Figure 5.20 LPBF Mo anode drain current analysis on the last ionisation test day.

Regardless of the ion source configuration, a drain current saturation was observed above cathode temperatures exceeding 2000°C due to the space charge limit at the anode grid, which is consistent with the results found in literature[75]. Furthermore, both the Ta and Mo anode configurations exhibited higher drain current values compared to previous studies reported in previous studies [23,28,75,77], which include data on STD ion sources operating at similar cathode temperatures and anode voltages. One important difference is the larger anode-cathode distance of 1.5 mm in those analysis, while the current analysis maintained a smaller distance, which may explain the observed increase in drain current.

Additionally, it should be noted that in [75], where a STD SPES FEBIAD ion source was tested using an anode-cathode gap of 1.15 mm, the measured drain current values were comparable to those collected in this study at the same operative conditions.

Systematic experimental studies to correlate the anode-cathode distance with drain currents could further explore the impact of manufacturing processes, such as LPBF technology compared to traditional methods, on the drain current in FEBIAD ion source.

It should also be noted that elevated drain current values, particularly those exceeding 400 mA, are considered harmful to the ion source[37]. Therefore, it was decided not to investigate the behaviour of the device at line currents above 380A and anode voltages over 180V to avoid potential damage to the system.

In Figure 5.21 is shown the drain current comparison between the failed ion source and the other configurations analysed in this study. The drain current measured for the failed ion source was significantly higher than both the LPBF Ta and Mo anode configurations. Such a marked difference is due to the cathode deformation combined with a smaller initial anode - cathode distance in the failed assembly, which led to a lower effective gap and enhanced electron transmission according to the Child–Langmuir law.

Moreover, this elevated drain current may have contributed to the melting of the central area anode grid because of a localized power deposition in that region, as discussed in [42].

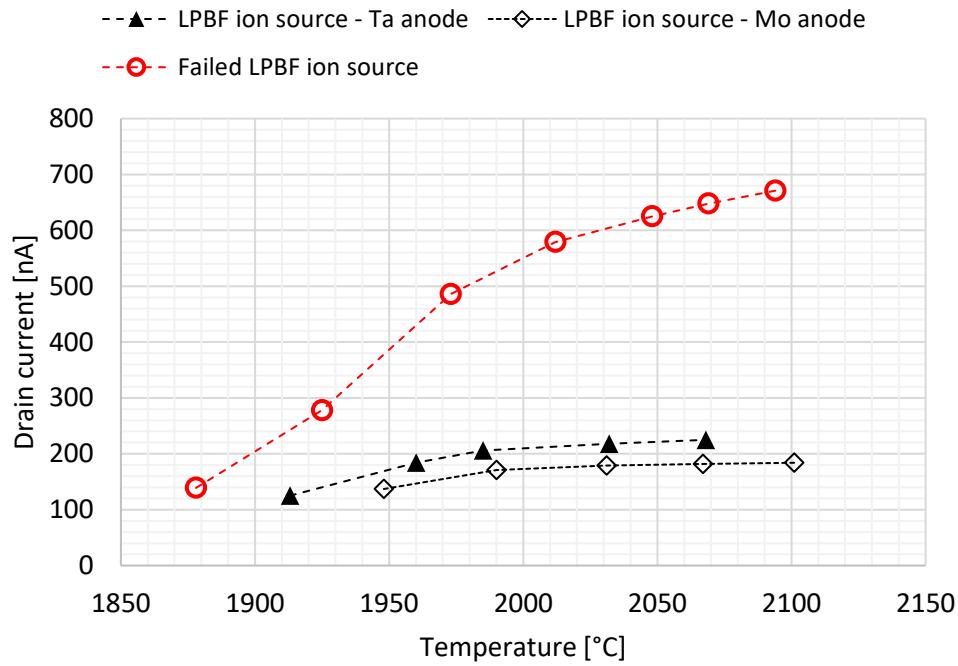


Figure 5.21 Drain current comparison between the LPBF failed ion source and the other ion source configurations. The anode voltage was set at 120V.

iv. Transport efficiency of noble gases mix

Figure 5.22 compares the transport efficiency setting an extraction voltage of 31 kV of argon ($^{40}\text{Ar}^+$), krypton ($^{84}\text{Kr}^+$) and Xenon ($^{129}\text{Xe}^+$) isotopes in a noble gas mix between the two ion sources, namely the Ta anode and Mo anode configurations.

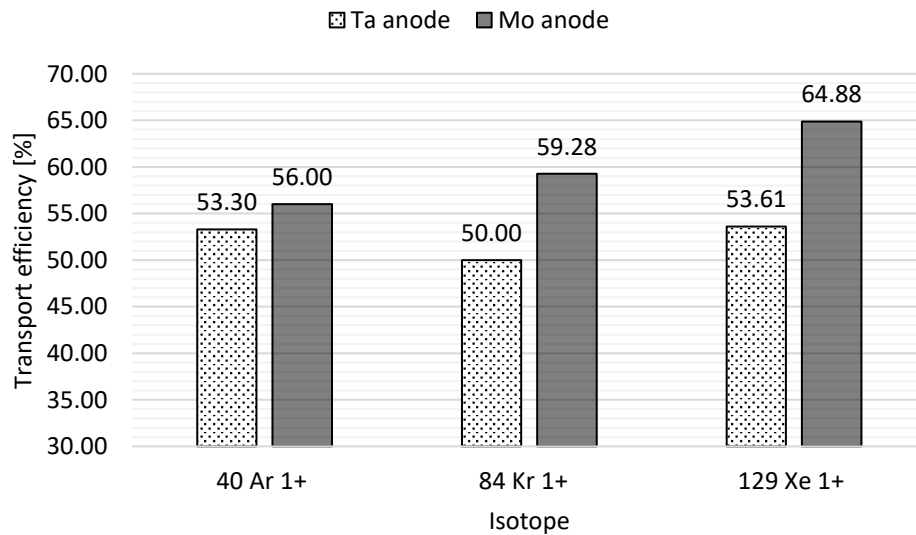


Figure 5.22 Gas mix isotopes transport efficiency comparison between the ion source configurations setting an extraction voltage of 31 kV.

The argon transport efficiency was consistent between the two ion sources, suggesting that both configurations handled the lighter noble gas with similar losses.

However, an anomalous transport efficiency was observed in the Ta anode configuration for both krypton and xenon, with transport efficiency 9% and 11% lower, respectively, than the Mo anode configuration.

The observed discrepancy in the krypton transport efficiency between the two ion source configurations may be attributed to the significantly different optimum ion source parameters set during the ionisation efficiency tests, especially the anode voltage (refer to Table 5.4 and Table 5.5 in the next paragraph), that may affect the extracted beam emittance. The total beam current varies across noble gases when operating at their different optimum conditions, as shown in Figure 5.23 and Figure 5.24. In particular, the Mo anode configuration presents more similar total beam current values across the noble gases, which can be attributed to the more uniform optimum operating parameters selected for each species.

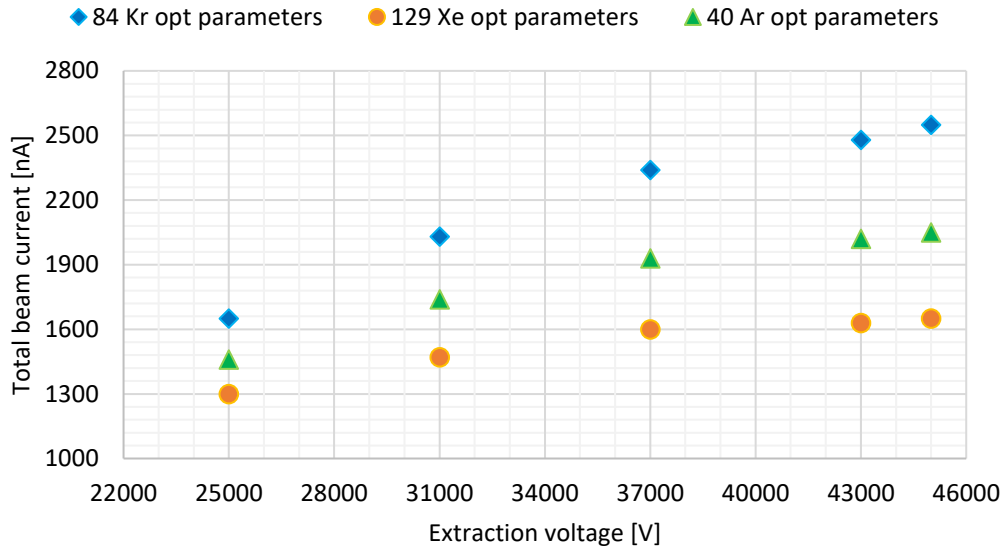


Figure 5.23 Total beam current measured setting the optimum ion source parameters for Ar, Kr, Xe at different extraction voltages – LPBF Ta anode configuration

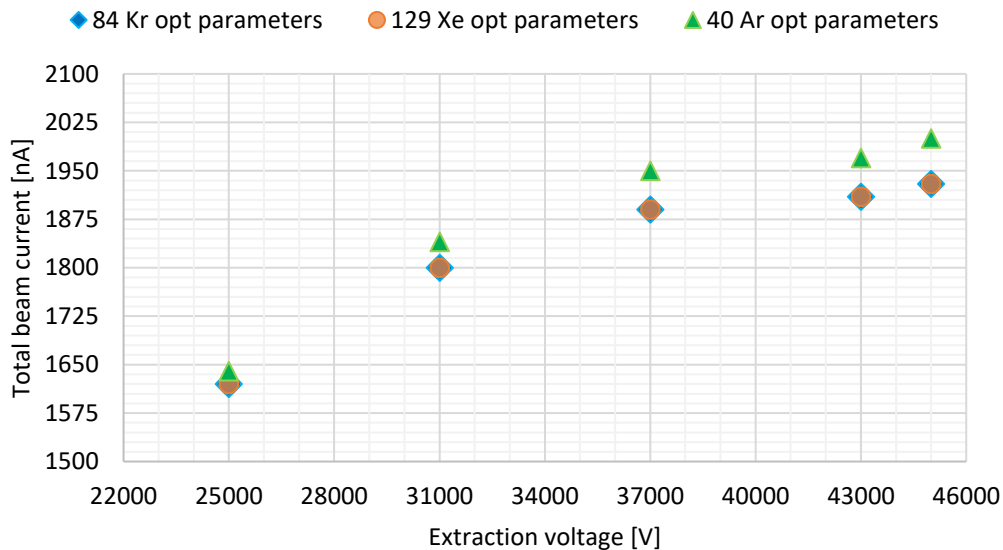


Figure 5.24 Total beam current measured setting the optimum ion source parameters for Ar, Kr, Xe at different extraction voltages – LPBF Mo anode configuration

The anomalous behaviour observed for the Kr transport efficiency during the tests with the Ta anode configuration is more evident when compared to the data reported in literature

[75] , where Kr is expected to exhibit higher transport efficiency than Ar when operating at similar working conditions, as shown in Figure 5.25.

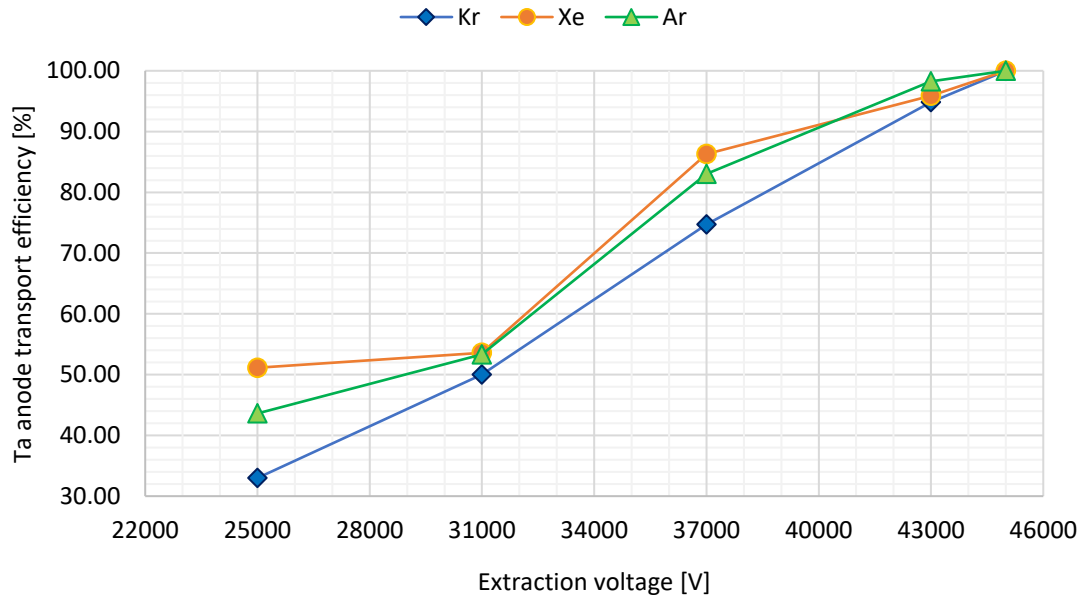


Figure 5.25 Noble gases transport efficiency measured at different extraction voltages - LPBF Ta anode configuration

The transport efficiency trends observed for the Mo anode configuration are qualitatively similar to those reported in [75] , with Ar exhibiting the lowest transport efficiency among the tested noble gases, as shown in Figure 5.26. Nevertheless, the absolute values are significantly lower in the present study, with deviations amounting to approximately 8% for Ar, 14.8% for Kr, and 13.5% for Xe at the extraction potential of 31 kV when compared to the data presented in [75].

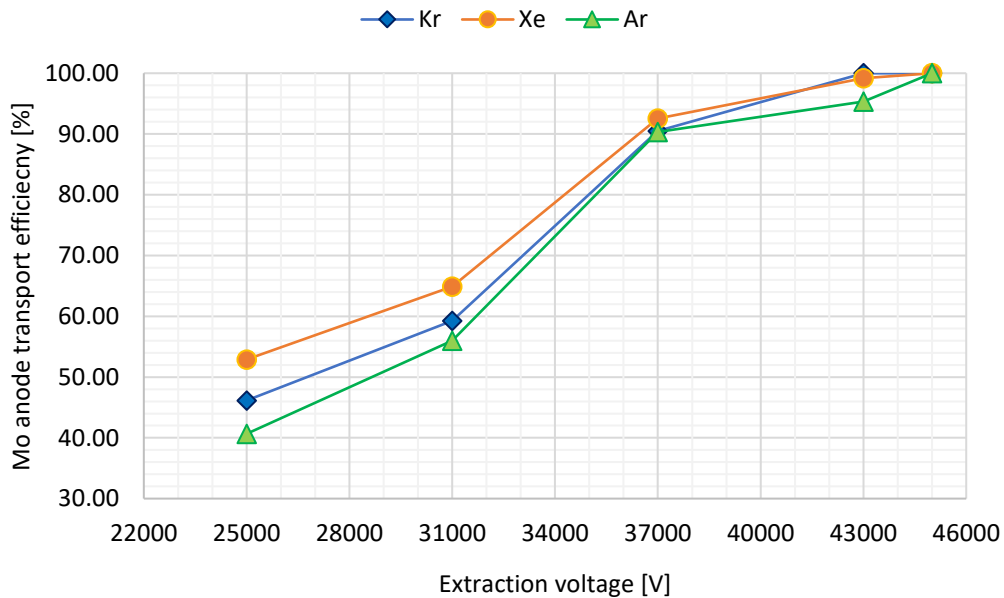


Figure 5.26 Noble gases transport efficiency measured at different extraction voltages - LPBF Mo anode configuration

These discrepancies require further investigation into the ion source working parameters to provide more clarity on the specific reasons for the transport efficiency anomalous

behaviour. In addition, the observed inconsistency in the transport efficiency values suggests the need for further experimental tests to validate the reproducibility of the measurements. It may be also considered to test each LPBF-manufactured component individually, as in this study they were assembled together within the same ion source configuration. Such a stepwise approach would be useful to assess the contribution of each individual part to the overall transport efficiency.

Furthermore, setting extraction voltages above 45 kV and Einzel lens voltages exceeding 22.5 kV systematically led to discharge sparks, compromising the execution of the tests. Consequently, the transport efficiency measurements were performed at a maximum extraction voltage of 45 kV, with the Einzel lens voltage set about 1 kV below the ideal focusing conditions (especially at extraction voltages above 37 kV).

v. Ionisation efficiency of noble gases mix measurement

The ionisation efficiency tests for the noble gases mix were conducted following the outgassing phase and the stabilization of the drain current for both the Ta and Mo anode configurations. Furthermore, the ionisation tests were performed under comparable gas pressures: 1010 mbar for the Ta anode configuration and 1090 mbar for the Mo anode configuration. The mass scans, as illustrated in Figure 5.27, demonstrate the capability of the FEBIAD ion source, assembled with LPBF-manufactured components, to effectively ionise noble gases such as argon, krypton, and xenon.

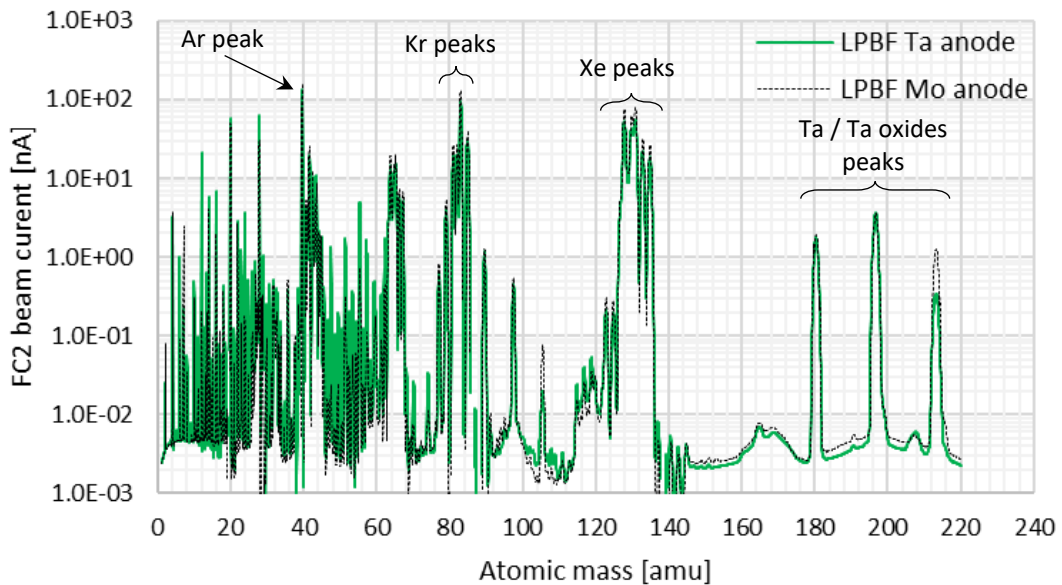


Figure 5.27 Mass scans performed setting the optimal parameters for Ar ionisation.

Figure 5.28 and Figure 5.29 highlight the importance of setting proper optimised parameters at each cathode temperature to enhance the beam current for argon. The same approach was used for krypton and xenon, with their corresponding optimised settings provided in Appendix I. A clear correlation between the drain current and the maximum FC2 beam currents, representing ionisation efficiency, was observed across both anode configurations. Such relationship, well-documented in literature [23,75,77–79], highlights the direct impact of drain current on ionisation performance. As the drain current increased, the FC2 beam current and ionisation efficiency achieved their respective maxima, confirming the importance of optimising the operating conditions.

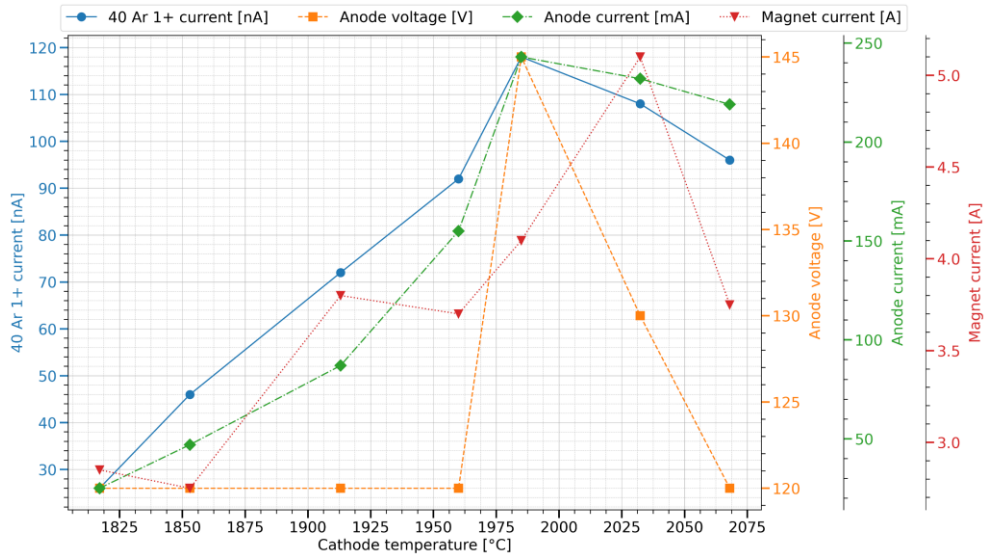


Figure 5.28 LPBF ion source – Ta anode optimum parameters for $^{40}\text{Ar}^+$ ionisation.

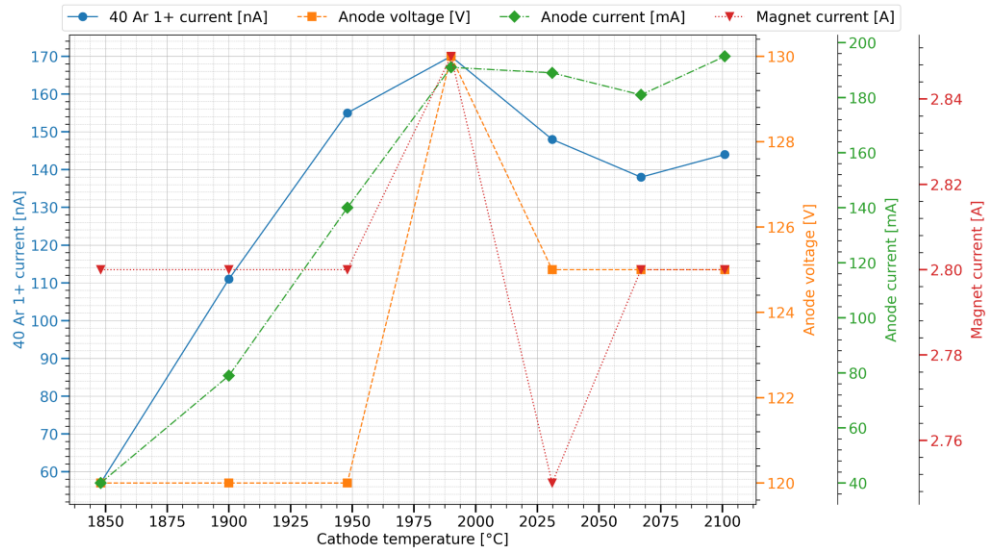


Figure 5.29 LPBF ion source – Mo anode optimum parameters for $^{40}\text{Ar}^+$ ionisation.

Table 5.4 and Table 5.5 resume the optimum parameters used for the ionisation efficiency measurement of noble gases for both the Ta and Mo anode configuration. The optimum ionisation conditions were achieved at cathode temperatures between 1950°C and 1990°C for both configurations, highlighting the consistency between the setups. At such temperatures, the thermionic emission from the cathode is saturated, contributing to more efficient ionisation. The lower optimal temperature observed for Xe might be due to its higher atomic mass. Since the kinetic energy of the atoms mainly depends on temperature, heavier atoms move more slowly increasing their residence time in the FEBIAD ion source and, therefore, their probability to be ionised [75].

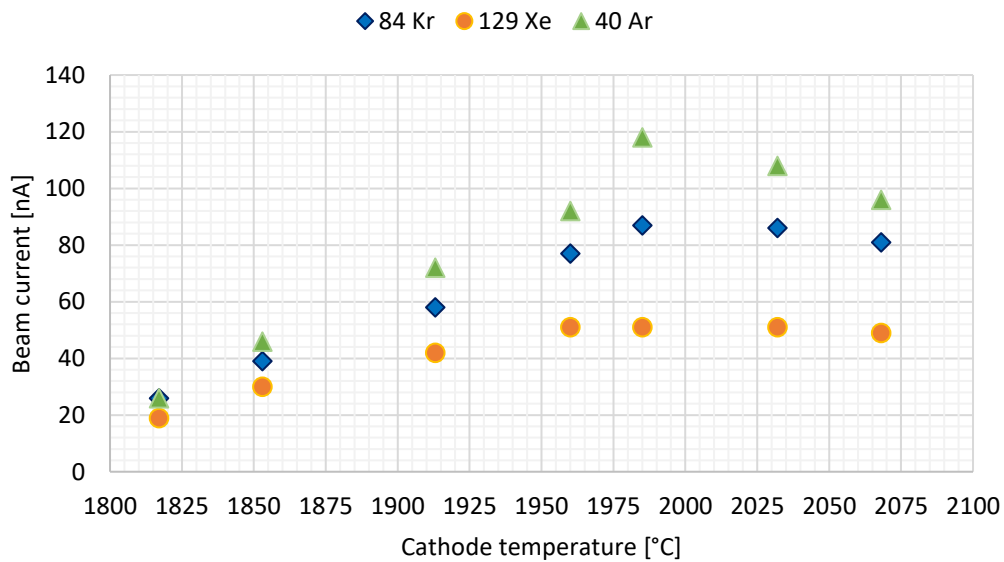
Table 5.4 LPBF FEBIAD ion source optimum parameters for Ta anode configuration.

Isotope	I_{line} [A]	Cathode temperature [°C]	V_{anode} [V]	I_{anode} [mA]	I_{mag} [A]
$^{40}\text{Ar}^+$	360	1985	145	243	4.5
$^{84}\text{Kr}^+$	360	1985	170	245	4.5
$^{129}\text{Xe}^+$	350	1960	120	154	3.7

Table 5.5 LPBF FEBIAD ion source optimum parameters for Mo anode configuration.

Isotope	I_{line} [A]	Cathode temperature [°C]	V_{anode} [V]	I_{anode} [mA]	I_{mag} [A]
$^{40}\text{Ar}^+$	350	1990	130	191	2.85
$^{84}\text{Kr}^+$	350	1990	125	182	2.75
$^{129}\text{Xe}^+$	340	1948	120	141	2.8

The ionisation efficiency trends observed in the test results are consistent with those reported in previous works. Figure 5.30 presents the maximum measured beam currents for the Ta anode configuration, while Figure 5.31 shows similar data for the Mo anode configuration. Both figures underscore the importance of operating the ion source under optimal conditions to achieve maximum efficiency for each noble gas. While the Ta anode configuration performed well, the Mo anode offered slightly better results, particularly for xenon.

*Figure 5.30 Maximized noble gas mix beam currents – Ta anode configuration.*

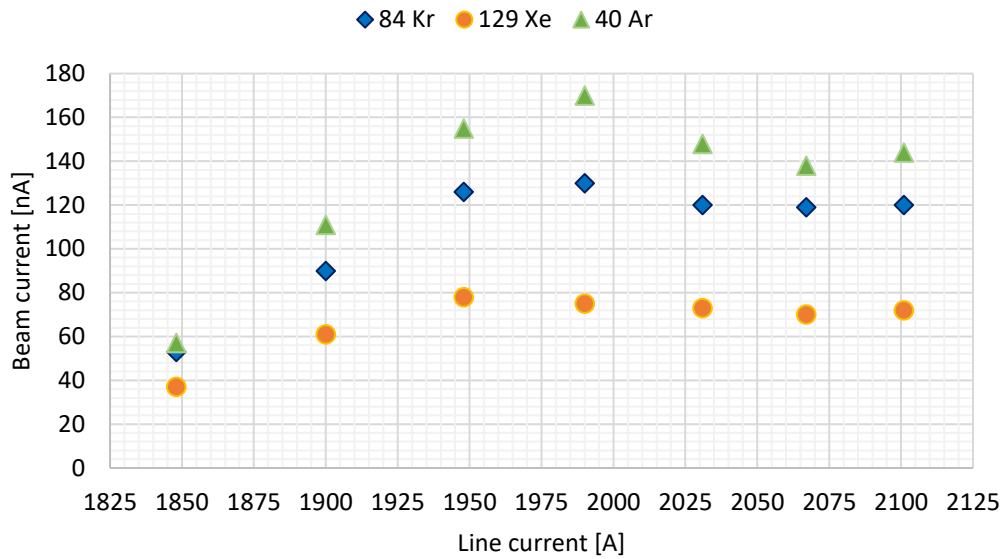


Figure 5.31 Maximized noble gases mix beam currents – Mo anode configuration

Preliminary ionisation efficiency measurements were also performed with the failed LPBF ion source (before its failure), by injecting pure argon as buffer gas (Ar gas pressure 1020 mbar). Although the data collected cannot be considered fully reliable due to the limited operational time, they provide indicative trends.

As shown in Figure 5.32, a saturation behaviour of the ionisation efficiency was observed, similarly to the other tested ion source configurations. In particular, the efficiency appears to follow the plateau observed in the anode drain current. Such a correlation suggests that operating the ion source at excessively high drain currents (and temperatures) does not result in substantial efficiency improvements.

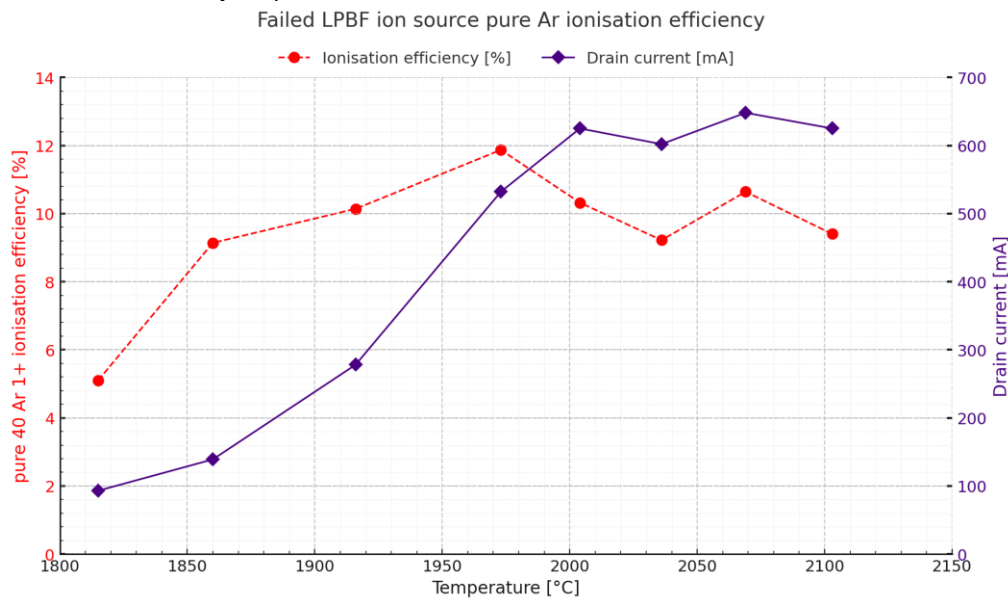


Figure 5.32 Preliminary efficiency measurements performed using the failed LPBF ion source injecting pure Ar as buffer gas.

The ionisation efficiency measurements for argon, krypton, and xenon using both the Ta and Mo anode configurations are shown in Figure 5.33 and resumed in Table 5.6. Comparable results were obtained between the Ta and Mo anode configurations, with the Mo anode showing slightly higher ionisation efficiencies on all noble gases. However, the

overall differences were not significant, therefore the performance of the FEBIAD ion source remains stable across different anode materials.

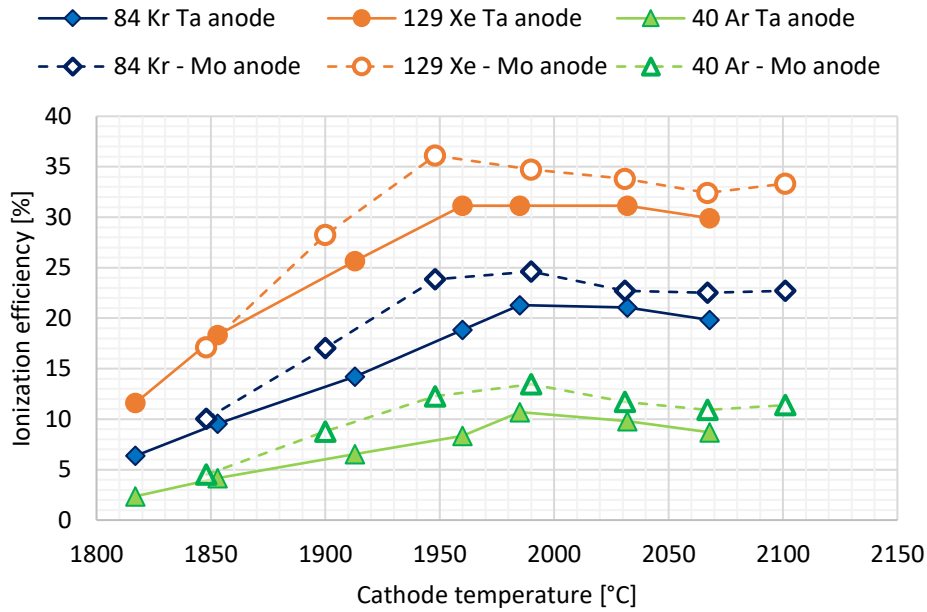


Figure 5.33 Ionisation efficiency measurements on noble gases installing LPBF Ta and Mo components on FEBIAD ion source.

Ionisation efficiency values for noble gases vary significantly throughout different studies on similar MK5 ion source models, mainly due to differences in experimental conditions. For instance, in [23] at CERN-ISOLDE reported 35% efficiency for krypton and 50% for xenon, nevertheless such results were achieved at higher temperatures, with a different gas composition, and with lower drain currents compared to those in the present work. Similarly, [38] at TRIUMF-ARIEL observed 16% efficiency for argon using a slightly different setup and grid geometry which inherently affect the results. In [79] at SPIRAL1-GANIL investigation reported an efficiency of around 20% for Ar, but the lack of specific experimental details complicates a direct comparison.

Furthermore in [75] the performances of the standard SPES FEBIAD ion source were evaluated in similar conditions with respect to this study. The results revealed consistently higher ionisation efficiencies for noble gases. The performance gap suggests a margin for improvement in the current configuration based on LPBF-manufactured components. Further ionisation tests shall be performed to increase the experimental know-how and to exploit the design flexibility offered by additive manufacturing for enhancing the ionisation process. Despite such differences, the trends observed in the present study align with those reported in the literature [23,75,77–79], reinforcing the reliability and consistency of the ionisation efficiency measurements using LPBF-manufactured components.

Table 5.6 Summary of the maximum measured efficiency values for noble gases.

LPBF ion source	$\epsilon_{\text{ion Ar}}$ [%]	$\epsilon_{\text{ion Kr}}$ [%]	$\epsilon_{\text{ion Xe}}$ [%]
Ta anode	10.7	21.3	31.1
Mo anode	13.5	24.6	36.1

5.4 Conclusions

The ionisation efficiency tests performed in the Off-line 1 Front-End facility available at CERN-ISOLDE confirmed the suitability of LPBF-manufactured components for FEBIAD ion source operation. Both the LPBF Ta and Mo anode configurations demonstrated consistent ionisation performance across the considered range of noble gases, including argon, krypton, and xenon. Despite the Mo anode configuration showed slightly higher efficiencies, particularly for xenon, the overall results between the two configurations were comparable, indicating that FEBIAD ion sources utilizing LPBF components can achieve reliable performance.

The contaminants analysis confirm that outgassing is essential before ionisation tests to ensure accurate measurements, similarly as ion sources assembled with STD components. Mass scans performed after outgassing revealed a significant reduction in unwanted elements such as sodium, carbon monoxide and copper. Furthermore, Ta and Mo anode configurations operate with comparable levels of residual contamination.

The drain current analysis revealed important information concerning the behaviour of the ion source at different operating conditions. Both Ta and Mo anode configurations exhibited elevated drain currents compared to previous studies, which could be due both to the smaller anode-cathode distance used in this work and to the different manufacturing process used to produce the cathode. However, more systematic experimental studies should be developed to assess the impact of the manufacturing process on the drain current.

A key observation during the tests was the cathode frontal surface deformation, which affected the anode-cathode distance. Such deformation was measured and accounted during the ionisation efficiency tests, highlighting the importance of understanding and controlling the thermal and structural stability of cathode at the ion source operational conditions. The deformation contributed to variations in performance, particularly in the drain current measurements, resulting in the need to further optimise the cathode design to ensure stable and repeatable results over extended operational periods.

The ionisation tests were successfully performed for Argon, Krypton and Xenon by optimising key ion source parameters such as the cathode temperature, anode voltage, magnet current.

Additionally, despite the differences in experimental setups compared to literature, the ionisation efficiency trends observed in this study were consistent with those reported in previous works. Such result supports the reliability of the ionisation test measurements and reinforces the conclusion that LPBF technology is a promising approach for producing FEBIAD ion source components.

However, future developments should focus on developing experimental setups to carefully assess the impact of anode-cathode distance and the manufacturing process on drain current behaviour. Additionally, the design of a more robust cathode frontal surface is necessary to reduce deformation without compromising performance. This could be achieved through structural simulations, such as ANSYS[®], to optimise the mechanical stability of the cathode under operational conditions.

Chapter 6: Development of experimental setups and procedures for FEBIAD ion sources comparative-quantitative analysis

6.1 Introduction

Chapters 4 and 5 demonstrated the suitability of the LPBF process to produce FEBIAD ion source components, exploiting the advantages of the additive manufacturing to improve both the assembly accuracy and the performance of the device. Furthermore, it was highlighted that a comprehensive understanding of the performance requires to assess the impact of several factors which affect the thermionic emission process. To achieve this, it is essential to develop experimental setups capable of systematically analysing the behaviour of key components at the ion source operational conditions.

This chapter presents the development of experimental setups designed to perform comparative and quantitative analyses of key parameters affecting the thermionic emission from the cathode of FEBIAD ion sources. The experimental procedures were developed to evaluate factors such as the anode grid geometry, cathode-anode interface designs, surface finishing, the deformation of the cathode at high temperatures and the manufacturing technology.

6.2 Thermionic emission setup

The thermionic emission setup was designed as an upgrade of the HT experimental apparatus discussed in Chapter 4. The preliminary design is shown in Figure 6.1, which details the key components necessary to evaluate the thermionic emission process under operational conditions.

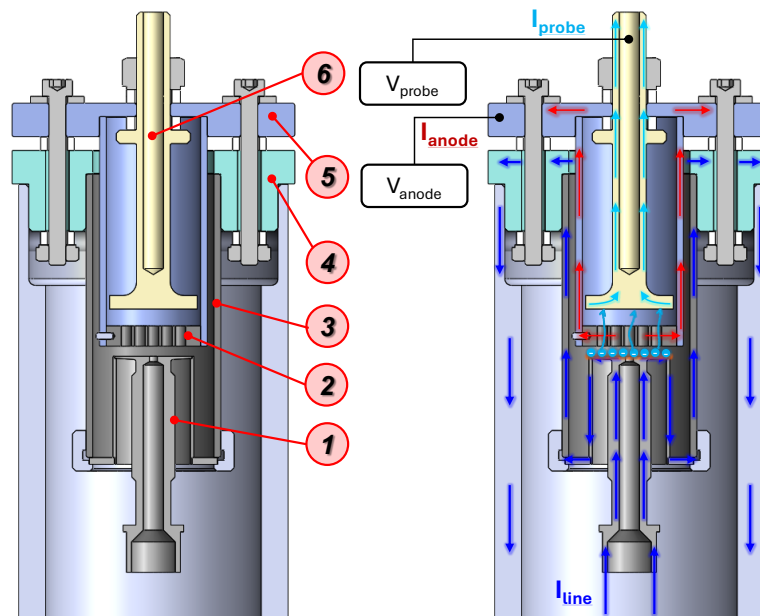


Figure 6.1 Functional scheme of the thermionic emission setup. (1) Cathode, (2) anode grid, (3) discharge chamber, (4) cathode support, (5) anode grid support, (6) probe.

The cathode (1) is heated by an electric current (I_{line}) through the Joule effect, achieving temperatures above 2000°C to activate thermionic emission process. Consequently, free electrons are released from the heated cathode frontal surface. The anode grid is electrically insulated and kept at a different voltage (V_{anode}) from the rest of the system, which creates an electric field that accelerates the free electrons toward the anode [28].

A fraction of the electrons is absorbed by the anode grid, generating the anode current (I_{anode}). The remaining electrons pass through the grid and continue toward the probe (6), which is also electrically insulated and maintained at an independent voltage (V_{probe}). The electrons absorbed by the probe generate the probe current (I_{probe}). Both the cathode and the anodes are fixed to their own supports (3), (4) and (5) which are electrically insulated by means of alumina insulators.

The setup was designed to be installed within the vacuum chamber in order to replicate exactly the working conditions of the TIS unit, similarly at the apparatus described in Chapter 4 and [28].

A critical feature of this apparatus is the capability to independently measure the electron currents absorbed by the anode (I_{anode}) and the probe (I_{probe}), allowing for a detailed investigation of the thermionic emission process under controlled operational conditions. I_{probe} specifically measures the electrons passing through the anode grid, which is representative of the electrons available for the ionisation process during the operation of the FEBIAD ion source. Therefore, increasing I_{probe} is crucial for enhancing the ionisation performance of the device.

Consequently, the thermionic emission setup is aimed to investigate through comparative analysis the impact on the thermionic effect of the following key features:

- Anode grid geometry (transparency);
- Innovative cathode-anode interfaces;
- Cathode high temperature (HT) deformation;
- Surface finishing of both the anode grid and the cathode frontal surface;
- Manufacturing technology.

Such measurements offer a comprehensive framework for evaluating how various design and material parameters influence the efficiency and stability of thermionic emission.

6.2.1 STD assembly

Figure 6.2 shows the final design of the thermionic emission setup that can be used to assemble and test STD or LPBF_conv cathodes. The apparatus includes the following features and components, that must be precisely assembled step-by-step:

- Transfer line connection: the transfer line (1) is connected to the cathode (2), similarly to a standard ion source. Furthermore, the same constraining system discussed in Chapter 4 was included at the transfer line extremity to reproduce the structural effect of the production target;
- Cathode assembly: the cathode is fixed to its own support (3) through the retainer nut, as discussed in Chapter 2;
- Anode grid assembly: the anode grid (4) is screwed within its own support (5), which is electrically insulated from the cathode support by alumina insulators (6);
- Adjustable anode-cathode distance: the distance between the anode grid and the cathode frontal surface can be adjusted by screwing or unscrewing the anode grid. This feature allows for compensation of any dimensional or geometric imperfections in the

components and to set the same anode-cathode distance for different comparative analysis.

- Probe assembly: the probe is electrically insulated by alumina insulators. Moreover, the threaded end of the probe allows to secure the component by a couple of nuts.
- External support assembly: the subsystem assembled as in Figure 6.2 (right) is screwed within the external support (8) by the threaded cathode support.
- External box assembly: the entire system is fixed to the external box through threaded bars, which are also used to secure the thermionic setup into the vacuum chamber;
- Holed components: the cathode support (3), external support (8) and external box (9) are designed with coaxial holes to keep the anode-cathode interface accessible during operation. Such a feature allows temperature measurement on the cathode lateral surface by infrared pyrometers.

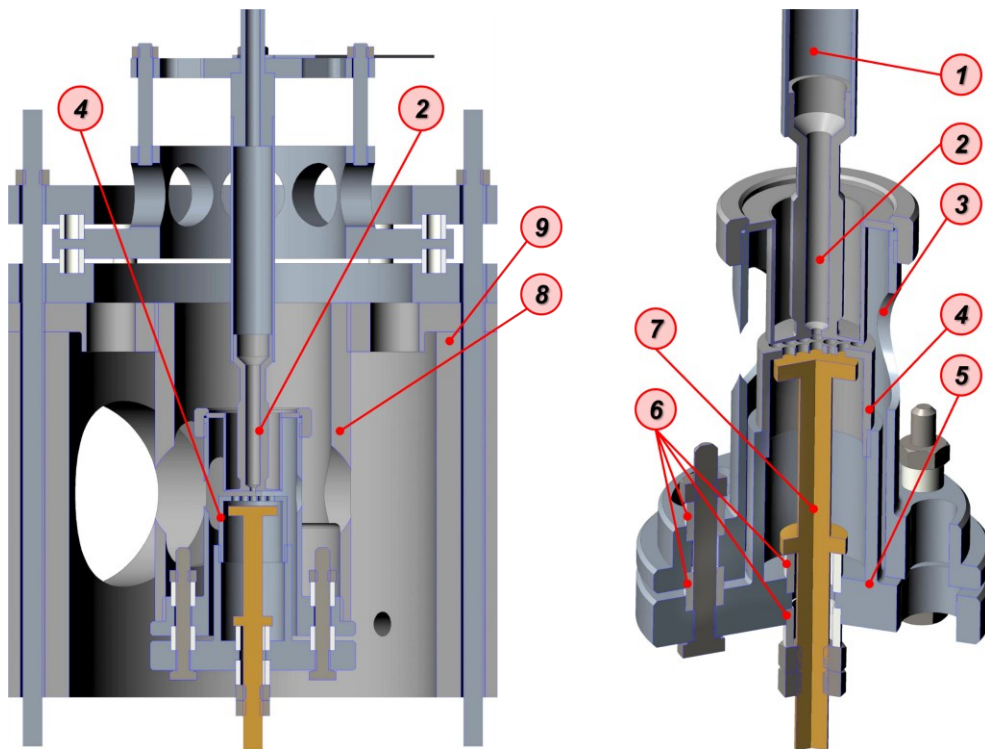


Figure 6.2 Final version of the thermionic emission setup. (1) transfer line, (2) STD cathode, (3) cathode support, (4) anode grid, (5) anode support, (6) Alumina insulators, (7) probe, (8) external support, (9) external box.

The thermionic emission setup was modelled in the ANSYS® environment to perform coupled electro-thermal FEM simulations, implementing the assumptions presented in Chapter 4 [20,26,28]. Numerical results are crucial for estimating the temperature of the cathode lateral surface, which can then be compared to the experimental temperatures measured by the infrared pyrometer. Since direct temperature measurements of the cathode frontal surface are not possible during operation, it is essential to provide a reliable estimation of the cathode temperature distribution by validating the FEM model, as shown in Figure 6.3. Additionally, accurate simulation results allow for more detailed information concerning the thermionic emission process.

Furthermore, such a method enables comparisons of different cathode geometries and designs by matching the frontal surface temperatures. This approach allows for comprehensive comparative analyses of the drain currents (I_{anode} and I_{probe}) generated during

thermionic emission tests, offering effective comprehensions into the performance of various design configurations.

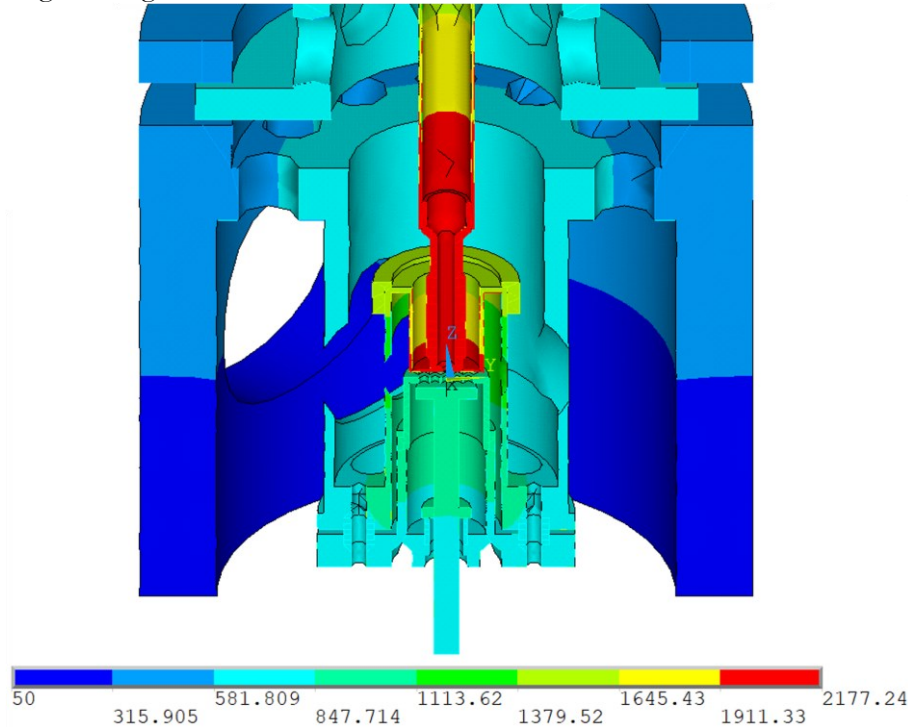


Figure 6.3 FEM simulation at 400 A of the thermionic emission setup for STD components.

The temperature estimation was also necessary to verify whether the selected materials for the thermionic setup components are suitable to withstand the operational conditions. In particular, the probe and the supports for the cathode and anode should be manufactured in tantalum due to its high-temperature resistance. The probe, having a simple design, was produced using conventional machining methods from a tantalum bar. In contrast, the supports, which have more complex geometries, were manufactured via LPBF process. Subsequently, they were conventionally machined to meet the required specifications reported in technical drawings in Appendix J.

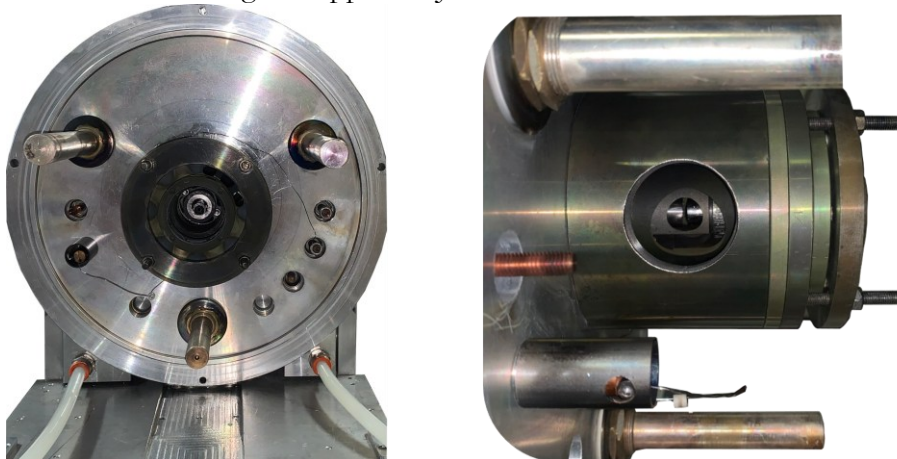


Figure 6.4 Frontal (left) and lateral (right) views of the thermionic emission setup assembled within the vacuum chamber.

The anode grid was also produced by LPBF process and machined with traditional methods to produce the threaded end.

The components were actually assembled and mounted within the vacuum chamber after the production and post-processing phases, as shown in Figure 6.4.

6.2.2 Preliminary high temperature results

The experimental setup was successfully heated at the ion source operational temperature to perform a thermal characterisation and a preliminary thermionic emission test, as shown in Figure 6.5. Specifically, two configurations were compared in order to assess the impact of the cathode manufacturing technology on the drain current: the former was assembled installing a STD cathode, the latter was prepared installing a LPBF_conv cathode.

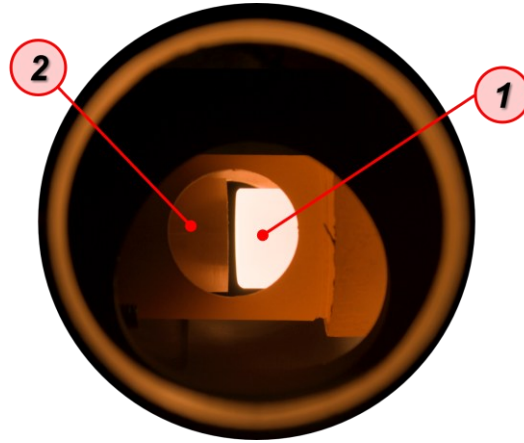


Figure 6.5 Thermionic setup during operation at high-temperature. (1) cathode, (2) anode

In both configurations, the anode-cathode distance was set to approximately 1.2 mm during assembly.

vi. Thermal characterisation

The numerical and experimental results for the STD cathode configuration are closely aligned with deviations consistently below 2%, indicating reliable accuracy in the electro-thermal FEM simulations, as shown in Figure 6.6.

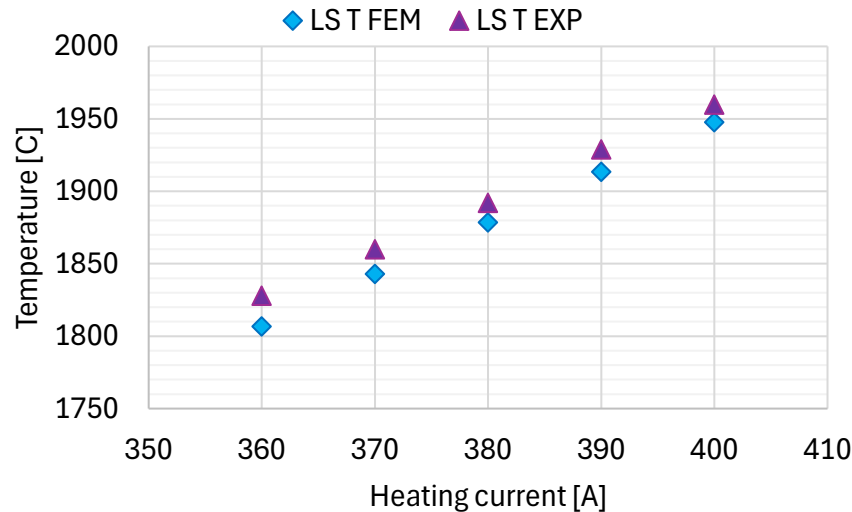


Figure 6.6 Lateral surface temperature (LS T) comparison between numerical (FEM) and experimental (EXP) results for the STD cathode.

Such strong alignment between the numerical and experimental data allows to reliably estimate the temperature profile on the cathode frontal surface at different heating currents, as shown in Figure 6.7.

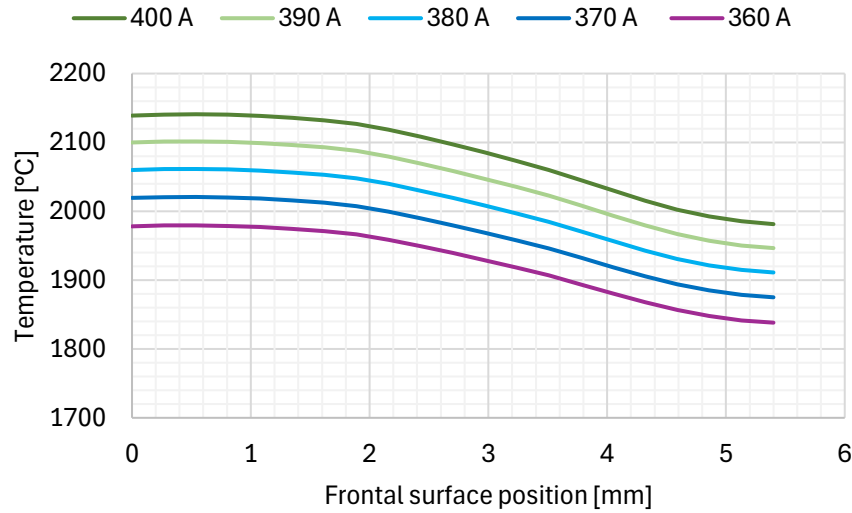


Figure 6.7 STD frontal surface temperature profile estimated by FEM simulation.

Comparable results were observed during the thermal characterisation of the LPBF_conv cathode configuration, as shown in Figure 6.8. The experimental data are aligned with the numerical simulations, with deviations consistently remaining below 2%. Such a consistency underscores the accuracy of the simulations and validates their use in further analyses of the thermal behaviour of the LPBF_conv cathode under operational conditions of the thermionic setup. Furthermore, the estimated temperature profile of the frontal surface is shown in Figure 6.9.

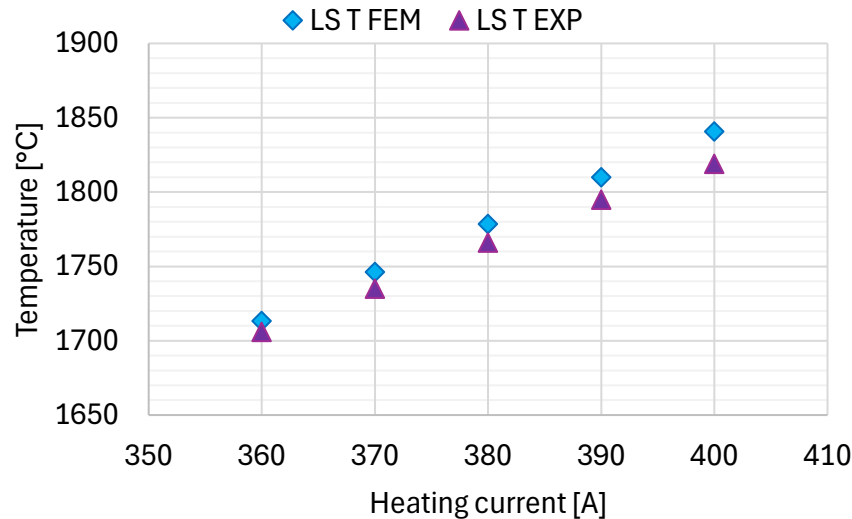


Figure 6.8 Lateral surface temperature (LS T) comparison between numerical (FEM) and experimental (EXP) results for the LPBF_conv cathode.

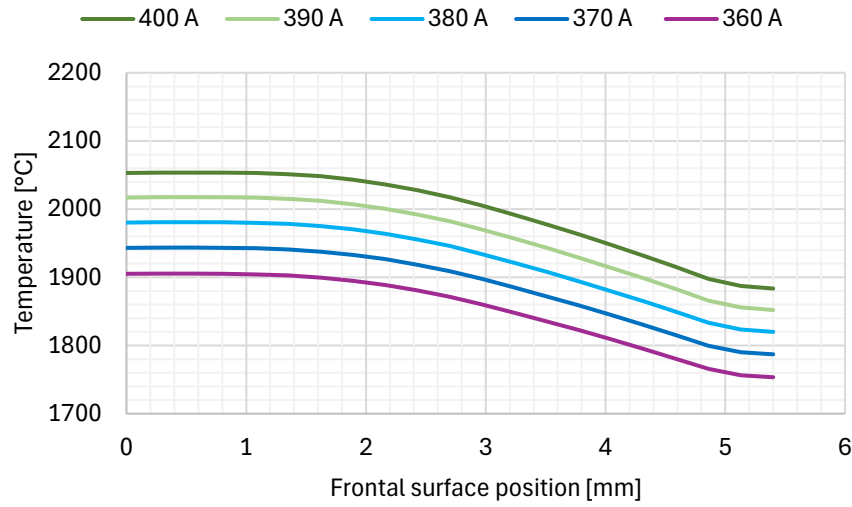


Figure 6.9 LPBF_conv frontal surface temperature profile estimated by FEM simulation.

vii. Preliminary thermionic emission test results

A preliminary comparative investigation was performed to assess the thermionic emission characteristics of both the STD cathode and the LPBF_conv cathode. For such a purpose, both configurations employed an anode grid manufactured by LPBF process, which was positioned at a fixed distance of 1.2 mm from the cathode. The experimental setup was carefully controlled, with the anode voltage (V_{anode}) set to 150 V and the probe voltage (V_{probe}) maintained at 200 V.

The LPBF_conv cathode consistently demonstrated higher drain currents, approximately three times greater than those produced by the STD cathode, across the temperature range considered during the test, as shown in Figure 6.10.

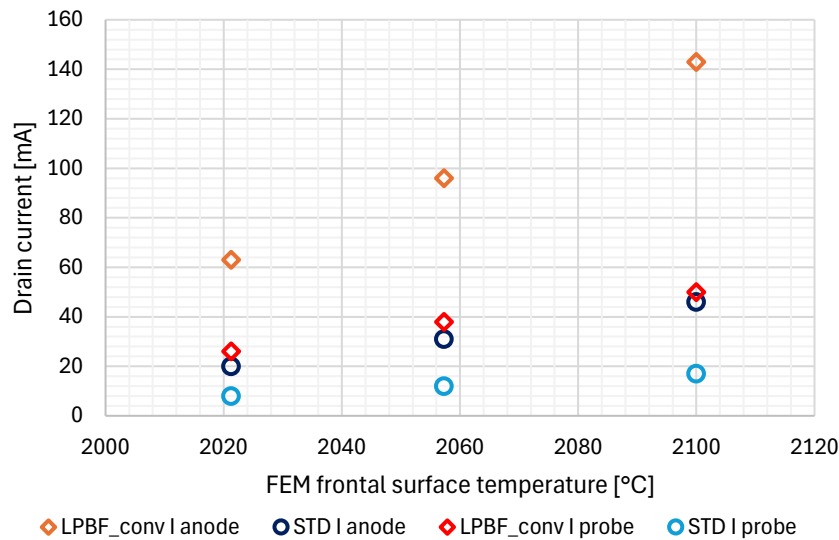


Figure 6.10 The anode drain current (I_{anode}) and the probe drain current (I_{probe}) were separately measured for STD and LPBF_conv cathodes.

Such observations indicates that the LPBF_conv cathode exhibits enhanced thermionic emission properties compared to the standard configuration, which may be attributed to differences in the material work function [41,42](refer to Richardson law in Chapter 2) due to the alternative manufacturing technology used to produce the samples. However, further

analysis and a larger number of samples are required to provide more statistically reliable results.

The absolute drain current ($I_{\text{tot}} = I_{\text{anode}} + I_{\text{probe}}$) values collected during the thermionic emission tests, which are shown in Figure 6.11, were lower than those typically observed in FEBIAD ion source operation [23,77,79], as reported in Chapter 4. Such deviations may be attributed to several key factors:

- Components design differences: the components used in the thermionic emission test were modified with respect to the FEBIAD ion source, including features such as holes for temperature measurement. Such modifications may alter the electric field distribution between the cathode frontal surface and the anode grid, thereby affecting the measured drain currents;
- Probe interference: the presence of the probe in the experimental setup inherently altered the electric field in the proximity of the cathode-anode interface. This interference may affect the electrons trajectory;
- Absence of ionisation: in a standard FEBIAD ion source, the ionisation process releases secondary electrons, which contribute to the overall drain current. In the thermionic emission test, no ionisation occurs, therefore secondary electrons are not present, further explaining the lower drain current measurements.

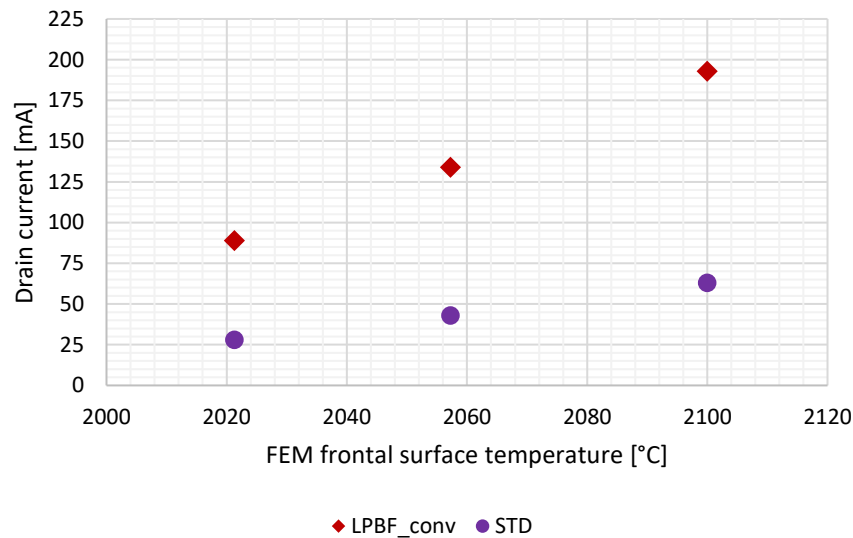


Figure 6.11 Total drain current comparison between STD and LPBF_conv cathodes

However, to fully validate these hypotheses regarding the relationship between probe current (I_{probe}) and ionisation performance, it is essential to perform comprehensive Multiphysics analyses and simulations of the electron flow. Such simulations would provide deeper information concerning the electron trajectories and interactions, offering a more robust confirmation of the observed trends.

Despite such differences between the thermionic emission setup and the actual conditions within a FEBIAD ion source, the primary objective of these preliminary tests was to perform a comparative analysis by maintaining identical experimental parameters for each test. This procedure allows to evaluate the relative performance of different component geometries in a systematic and reproducible method.

The experimental setup worked as intended at the operational conditions, allowing the separate measurement of anode and probe drain currents, which enables the quantification of the electron flow passing through the grid.

The comparative approach is particularly valuable for identifying cathode designs that exhibit enhanced thermionic emission properties. The tests could provide information on factors affecting the thermionic emission performance by isolating the effects of geometry, manufacturing technology, material, and surface finishing. Moreover, the results may lay the basis for the optimisation of other FEBIAD ion source components, such as the anode grid, aiming to maximize the thermionic emission process during operation.

6.2.3 LPBF OPT assembly

The thermionic emission setup design detailed in paragraph 6.2.1 is not suitable for testing the LPBF_OPT cathode model, presented in Chapter 4, due to its different coupling interface with the discharge chamber.

Consequently, the thermionic setup was further modified to accommodate the LPBF_OPT cathode [71]. In particular, the design of the cathode support was carefully revised to ensure compatibility with the LPBF_OPT cathode. The modifications included adjustments to the mounting interface, as shown in Figure 6.12.

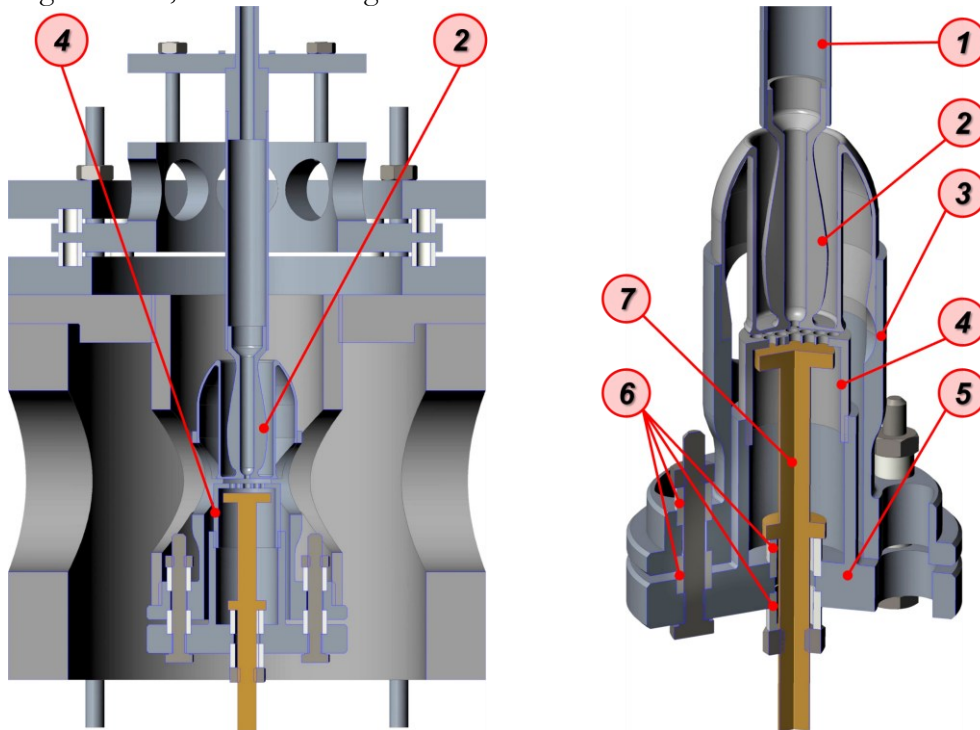


Figure 6.12 Thermionic emission setup for alternative cathode geometries. (1) transfer line, (2) LPBF_OPT cathode, (3) cathode support, (4) anode grid, (5) anode support, (6) Alumina insulators, (7) probe, (8) external support, (9) external box.

Coupled electro-thermal FEM simulations were performed following the procedure outlined in Paragraph 6.2.1, with the aim to estimate the temperature distribution of the modified thermionic setup for LPBF_OPT cathode under operational conditions, as shown in Figure 6.13.

Such numerical estimations are crucial, as direct temperature measurements on the cathode frontal surface are not possible during operation.

While numerical results are critical for understanding the electro-thermal behaviour of the setup, they must be validated through experimental thermal characterization to ensure their accuracy and reliability, as detailed in Paragraph 6.2.2.

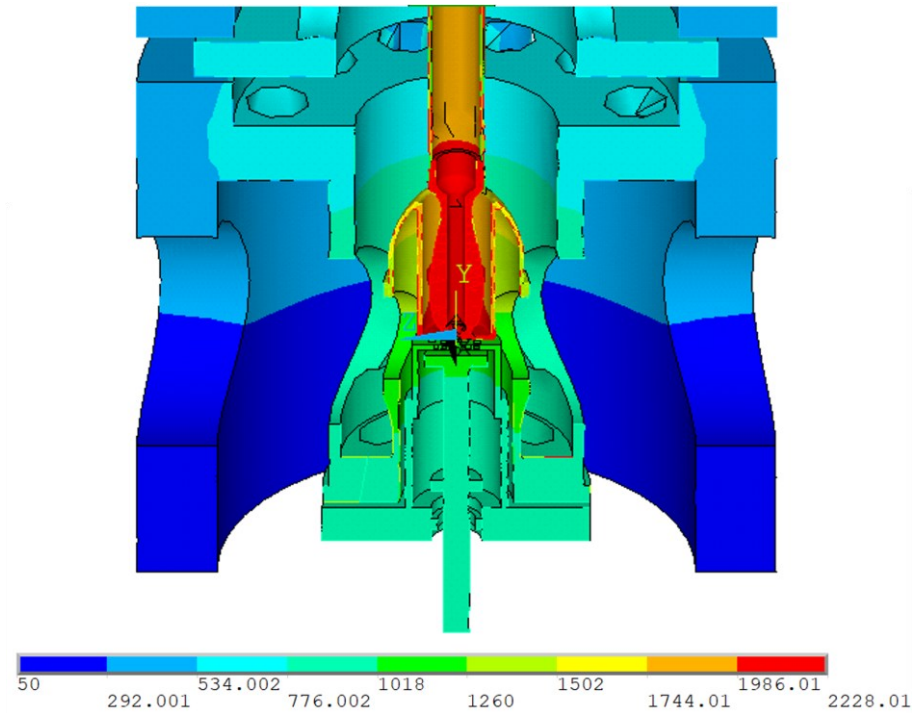


Figure 6.13 FEM simulation of the thermionic emission setup for LPBF components at 400A.
Currently, the first batch of LPBF_OPT components was successfully produced via LPBF process, and a portion of those was machined in preparation for the final assembly, as shown Figure 6.14.



Figure 6.14 Thermionic emission setup parts and cathodes produced via LPBF process.

6.3 High temperature cathode deformation accurate measurements

During the operation of the FEBIAD ion source, any deformation of the cathode frontal surface is considered detrimental, as previously detailed in previous chapters. A key issue is the transitioning of such surface geometry from flat to curved, which significantly alters the thermionic emission process. Additionally, an excessive axial displacement of the cathode

frontal surface would increase the risk of short circuit between the cathode and the anode, which would compromise the functionality of the ion source [28]. Considering the potential operational risks of cathode deformation, it is crucial to define and implement an accurate experimental procedure to monitor and measure the total deformation of the frontal surface during high-temperature operation. To achieve this, a vision system incorporating a digital camera and a proper lens was designed to be installed outside the vacuum chamber, implemented with dedicated viewports, and integrated to the thermionic setup presented in Paragraph 6.2 .

6.3.1 System requirements

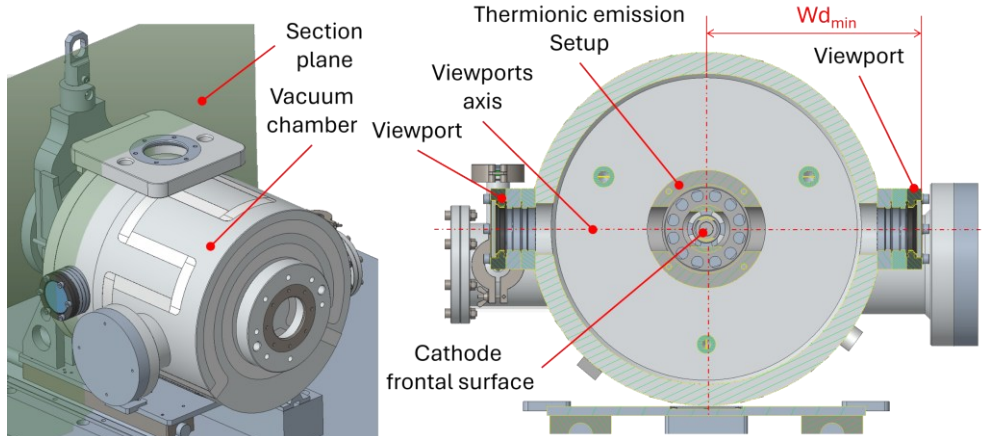


Figure 6.15 Representation of components and geometrical constraints of the thermionic emission setup.

The selection of the appropriate vision system is strongly dependent on the measured sample dimensional characteristics and the experimental setup constraints. In particular, the successful execution of the experiment relies on the fulfilment of the following criteria:

1. The vision system must be positioned outside the vacuum chamber and axially oriented with respect to the viewports. For this reason, the lens working distance must be larger than dimension Wd_{min} in Figure 6.15 (182 mm);
2. The arrangement of a calibration master aiming at properly calibrate the vision system is necessary. Furthermore, the calibration master must be positioned at the same working distance previously outlined. Accurate calibration is critical for achieving reliable deformation measurements during operation;
3. According to CMM assessment in Chapter 4 and the ionisation tests in Chapter 6, the minimum axial displacement of the cathode frontal surface is expected to be on the order of 10^{-1} mm. Therefore, the accuracy of the instrument must be at least one order of magnitude finer (10^{-2} mm) to accurately detect deformations;
4. The sample profile must exhibit sufficient resolution to enable an accurate evaluation of geometric modifications during the high-temperature operation. Without high-resolution imaging, deformations could be undetected or inaccurately assessed, compromising the experiment reliability;
5. The sample is positioned inside the vacuum chamber, therefore it is insufficiently illuminated for observation during the initial phase of the heating process. In fact, it becomes visible once it reaches incandescence at approximately 900°C . Consequently, a proper illumination system must be installed to enable the cathode observation from the beginning of the heating process;

6. The vision system must be mounted on appropriate positioning stages capable of providing an accurate alignment along all three axes.

6.3.2 Preliminary design and proof-of-concept

The complete experimental setup designed for fulfilling the requirements detailed in Paragraph 6.3.1 is represented in Figure 6.16.

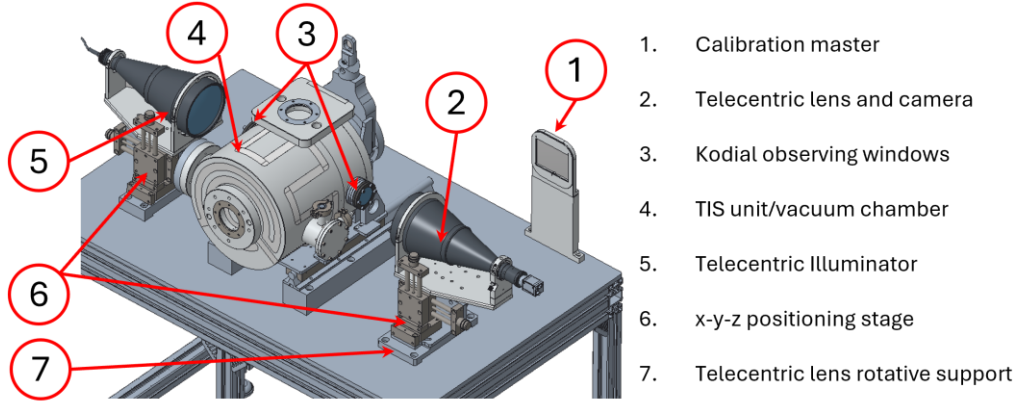


Figure 6.16 Deformation measurement setup design.

The appropriate lens selection process involved a proof-of-concept [80] for traditional cathode profile acquisition at room temperature. A conventional lens was compared with a telecentric lens, which is capable of eliminate perspective errors. The sample profile acquired with the telecentric lens exhibited significantly enhanced definition compared to the conventional lens, as shown in Figure 6.17.

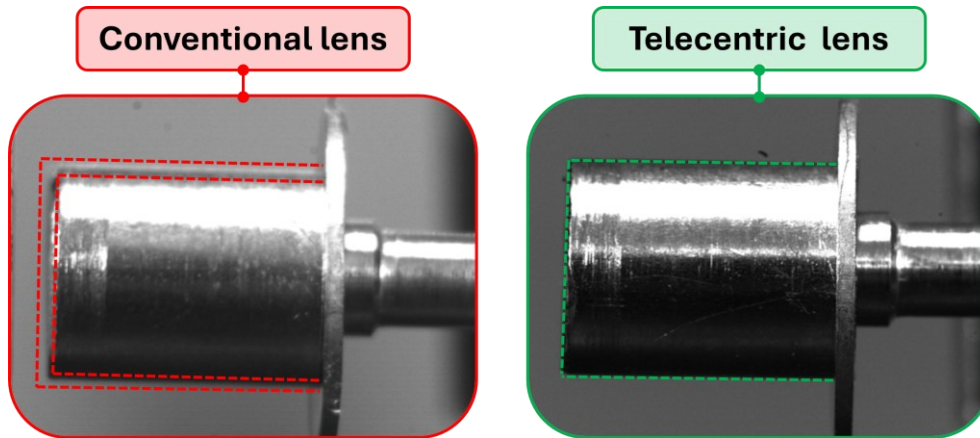


Figure 6.17 Difference between images taken with conventional and telecentric lenses.

The attainment of requirements 1, 3 and 4 outlined in the previous paragraphs depends on the characteristics of both the camera and the lens selected. Specifically, an $8 \mu\text{m}/\text{px}$ resolution and 0.02 mm accuracy were achieved by combining the telecentric lens Opto Engineering model TC3MHR096-C [81] (working distance 278.6 mm, field depth 17.7 mm) with the camera Basler model acA3800-10gm [82] (10 MP, resolution 3840 x 2748 px).



TC3MHR096-C | DATASHEET

OPTO ENGINEERING

High resolution telecentric lens for 1.1" detectors, magnification 0.153x, C mount



KEY ADVANTAGES

- Wide image circle for sensors up to 1.1".
- Excellent resolution and low distortion.
- Simple and robust design for industrial environments.
- Detailed test report with certified optical parameters
- Easy phase adjustment

SPECIFICATIONS

Optical specifications		
Magnification		0.153
Image circle	(mm)	17.6
Max sensor size		1.1"
Working distance ¹	(mm)	278.6
wf/N^2		8
Telecentricity typical (max) ³	(°)	<0.08 (0.10)
Distortion typical (max) ⁴	(%)	<0.08 (0.10)
Field depth ⁵	(mm)	17.7
Resolution (max) ⁶	(μm)	33

Figure 6.18 Telecentric lens datasheet[81].

The requirement 5 is achieved by implementing the telecentric illuminator Opto Engineering model LTCLHP096-G [83], designed to back-illuminate the sample and remove the border effects. Additionally, both the lens and illuminator are mounted on positioning stages (requirement 6) to accurately regulate their alignment along the three axes. Finally, the calibration master was positioned at the optimal working distance from the lens, orthogonal to the viewports. Consequently, the telecentric lens is arranged on a rotative support to orient the vision system towards the calibration master.

The experimental setup, incorporating telecentric lenses and precise positioning stages, demonstrates the feasibility of reliably measuring deformation with the appropriate resolution and accuracy. Moreover, the integration of such measurement system with the thermionic setup presented in Paragraph 6.2 allows to real-time anode-cathode distance monitoring, which is crucial to ensure the repeatability of the experiments and to ensure the feasibility of comparative analysis.

6.4 Conclusions

In this chapter, the development of experimental setups and procedures to perform comparative-quantitative analysis of FEBIAD ion sources performance was explored. The primary focus was to analyse the thermionic emission process by examining key factors such as the geometry of the anode grid, cathode-anode interface designs, surface finishing, and cathode deformation under high-temperature conditions.

For such a purpose, the thermionic emission setup was designed including an electrically insulated probe positioned back to the anode grid, which is capable to absorb the electrons emitted by the cathode passing through the grid. Furthermore, coupled electro-thermal FEM simulations in Ansys environment were performed to estimate the temperature distribution of the system during operation. Such simulations are crucial for estimate the temperature profile of the cathode frontal surface, as direct temperature measurements are not feasible. The components were successfully produced and implemented to enable independent measurements of anode (I_{anode}) and probe (I_{probe}) drain currents, allowing for a detailed

investigation of the thermionic emission process. Preliminary high-temperature tests were performed to verify the functioning of the setup in evaluating different cathode configurations, particularly the STD and LPBF_conv cathodes, with the latter demonstrating superior thermionic emission characteristics, showing approximately three times higher drain currents than the STD cathode at various frontal surface temperatures above 2000°C.

Preliminary thermionic emission test results indicated that while the LPBF_conv cathode shows promising performance, further testing with additional samples and comprehensive simulations are necessary to fully confirm the observed trends. The tests also revealed that the total drain current (I_{tot}) was lower than typically observed in FEBIAD ion sources, mainly due to several factors such as differences in components design, the probe interference, and the absence of ionisation.

The thermionic emission setup was also implemented to accommodate alternative cathode designs, such as the LPBF_OPT cathode. Such a feature required significant modifications to the cathode support design and coupled electro-thermal FEM simulations performed to estimate the temperature distribution of the modified setup.

Additionally, a vision system was designed to be integrated in the setup to accurately measure the deformation of the cathode frontal surface during high-temperature operation. The vision system incorporates a digital camera and a carefully selected telecentric lens, both mounted outside the vacuum chamber, which was implemented with dedicated viewports.

The telecentric lens was selected due to its ability to eliminate perspective errors, providing a more accurate representation of the cathode profile. A proof-of-concept test comparing a conventional lens to the telecentric lens demonstrated significantly enhanced definition in the captured sample profile using the telecentric lens, achieving a resolution of 8 $\mu\text{m}/\text{px}$ and an accuracy of 0.02 mm after calibration. Such accuracy is essential for detecting the cathode frontal surface deformations, which are expected to be on the order of 0.1 mm according to previous analyses.

Furthermore, the vision system allows for real-time monitoring of the anode-cathode distance during the thermionic emission test, ensuring the repeatability of experiments and reliable comparative analysis of different components design.

Overall, the integration of additive manufacturing techniques and advanced measurement systems offers promising methods for enhancing the performance and reliability of FEBIAD ion sources in ISOL facilities. The increased degrees of freedom provided by LPBF additive manufacturing technology laid the basis for the design of alternative cathode-anode interfaces, as well as innovative grid and cathode geometries. Such a flexibility allows for more optimised configurations aiming at significantly improve thermionic emission characteristics. The complete experimental setup, which combines the thermionic emission apparatus with the vision system, offers a powerful tool for systematically evaluating different FEBIAD ion source designs with the final goal to increase the operational efficiency and reliability of the device.

Chapter 7: Conclusions and future developments

7.1 Conclusions

This thesis presented a comprehensive exploration into the development and optimisation of the Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source [3,32], a critical component employed at the Selective Production of Exotic Species (SPES) facility operating according to the Isotope Separation On-Line (ISOL) at Legnaro National Laboratories of the Italian Institute for Nuclear Physics (LNL-INFN) [4,16,17]. Such a device is essential for producing Radioactive Ion Beams (RIBs) to perform forefront research in interdisciplinary fields like nuclear physics, material science, biology, and medicine.

According to the ISOL method [2], a primary proton beam impinges a production target generating nuclear reactions, which release neutral radionuclides. Subsequently, the ion source ionises the neutral isotopes producing positive ions, which are extracted and delivered through electromagnetic systems to a separating magnet. Such a device precisely performs the isobaric selection of the desired isotope to generate the final radioactive ion beam, that can be further accelerated for experimental purposes.

The FEBIAD ion source working principle [28], based on electron bombardment ionisation process, is driven by the interaction between the two main components of the device, namely the anode and cathode. The cathode is heated in a high-vacuum regime (pressure below 10^{-6} mbar) to temperatures above 2000°C by an electric current through Joule effect, allowing the release of free electrons through thermionic emission. Such electrons are accelerated by an electric field generated between the cathode and the anode, which is electrically insulated and kept at approximately 150V from the rest of the system. Neutral atoms outcoming from the production target are transported within the anode hollow body (plasma chamber), where they are ionised by electron bombardment, leading to the production of positive ions. Refractory metals such as tantalum and molybdenum, along with ceramics like graphite and alumina are employed to manufacture the components to withstand the operational conditions of the ion source.

The research was aimed to address the critical issues associated with both the assembly and manufacturing processes of the FEBIAD ion source, which actually affect the performance and the reliability of the device. Sharing the research results with other ISOL facilities worldwide [5,9,10,12,15] has the potential to significantly enhance the overall efficiency of RIB production.

The initial phase of this work focused on overcoming the limitations introduced by the manual assembly methods traditionally employed in mounting the FEBIAD ion source [48]. The accurate alignment of components, particularly the anode and cathode, is essential to ensure proper performances and overall reliability of the device. However, the inherent variability in manual assembly led to inconsistencies in the positioning of such components, which impacted the ion source functioning. Consequently, a tool-based assembly procedure was designed by a systematic method including functional and critical analyses of manual assembly mounting process, tolerance stack-up analysis and Design for Assembly (DFA) principles[48].

The use of a tool-based assembly procedure significantly improved the accuracy and reliability of the positioning of FEBIAD ion source components during assembly process, which is crucial to ensure performance stability of the device during operation.

Furthermore, a custom Python code [53] based on Monte Carlo Method (MCM) and Homogeneous Transformation Matrices approach [54,57,58] was developed to perform a statistical tolerance stack-up analysis and optimisation[60]. The numerical method was validated through Coordinate Measuring Machine (CMM) measurements on assembled FEBIAD ion source components and subsequently used for the tolerancing process aimed to ensure that key parameters, particularly the anode-cathode distance were consistently within the optimal range. Furthermore, the integration of the tool-based assembly procedure reduced the time required to complete the ion source assembly from several hours using the manual method to few minutes.

Nevertheless, the limitations of conventional manufacturing methods [47], particularly in terms of geometric and dimensional accuracy, led to significant challenges in achieving the specifications resulted from the tolerancing process. Therefore, the potential of advanced manufacturing techniques to overcome the constraints of traditional production methods was explored. Additive manufacturing, specifically Laser Powder Bed Fusion (LPBF) [61,64], was investigated as an alternative to the conventional machining and TIG welding processes traditionally used for FEBIAD components. LPBF process, offers the capability to manufacture refractory metals [30,31,62] for producing more complex geometries, making it an ideal candidate for manufacturing components exposed to the extreme operational conditions of the FEBIAD ion source.

In this context, the research demonstrated the feasibility and advantages of LPBF through a systematic case study focused on the production of tantalum cathodes [47]. The LPBF-manufactured cathodes showed comparable electro-thermal performance to those produced using traditional techniques. The intersection between coupled electro-thermal simulations and experimental validation of such cathodes confirmed their capability to maintain structural integrity and functional reliability over extended periods of operation. Such results suggested that the LPBF process not only ensures comparable performance but also introduces opportunities for further design optimisations that were previously constrained by traditional manufacturing limitations. The inherent flexibility of LPBF allows for more complex geometries to optimise the thermal and structural characteristics of the cathode, further enhancing the ion source performance.

The application of LPBF technology was validated through off-line ionisation tests performed at CERN-ISOLDE [72], where LPBF-manufactured components were exposed for the first time to realistic operational conditions. The ionisation tests, which consist of ionisation efficiency measurements on noble gases (Argon, Krypton, Xenon), confirmed the suitability of LPBF process for producing FEBIAD ion source components.

The ionisation tests were successfully completed for Ar, Kr, and Xe by optimising key ion source operational parameters, such as cathode temperature, anode voltage, and magnet current. Both tantalum and molybdenum anodes were tested, demonstrating consistent performance for the noble gases ionisation.

Moreover, the tests highlighted the importance of addressing cathode frontal surface deformation at high temperatures, which strongly affects the ionisation process.

However, despite differences in experimental setups compared to previously published studies, the ionisation efficiency trends observed in this research were consistent with those reported in the literature [23,38,77,79].

Such promising results lay the foundation for the development of alternative cathode designs which could further improve the mounting process accuracy by reducing the tolerance stack-up elements of the assembly. Additionally, the flexibility provided by LPBF process allows for further geometric optimisation, which could lead to improved thermal performance of

the cathode, as demonstrated by performing iterative coupled electro-thermal FEM simulations [71].

In addition, this thesis empathized the development of experimental setups and procedures designed to perform comparative-quantitative analysis on different FEBIAD ion source models. In particular, the primary focus was to analyse the thermionic emission process by examining key factors such as the geometry of the anode grid, cathode-anode interface designs, surface finishing, and cathode deformation during high-temperature operation. To achieve this, the thermionic emission experimental setup was designed, and preliminary high-temperature test were successfully performed comparing cathodes produced via conventional and LPBF processes. The main feature of such an experimental setup is the capability of measuring the electrons flow passing through the anode grid. To achieve this, an electrically insulated metallic probe was positioned on the back of the grid and connected to a power supply which allows both to apply the desired potential and measure the drain current of the incoming electrons. Such an implementation allows to independently measure the anode and probe drain currents.

As a preliminary result, the LPBF-manufactured cathode demonstrated thermionic emission currents three times higher than the conventionally-produced cathode. However, further testing with additional samples and comprehensive simulations are necessary to fully confirm the observed trends.

Additionally, a vision system was integrated in the setup to accurately measure the real-time deformation of the cathode frontal surface during high-temperature operation.

Such a system incorporates dedicated camera and telecentric lens for capturing accurately the cathode profile during the high-temperature operation, achieving a resolution of 8 $\mu\text{m}/\text{px}$ and an accuracy of 0.02 mm after calibration at room temperature.

The complete experimental setup, which combines the thermionic emission apparatus with the vision system, offers a powerful tool for systematically evaluating different FEBIAD ion source designs with the final goal to increase the operational efficiency and reliability of the device.

In conclusion, the research presented in this thesis represents a significative contribution to the field of FEBIAD ion source development. By addressing the critical challenges associated with assembly accuracy, manufacturing limitations, and performance evaluation, this work has laid the basis for the next generation of high-performance ion sources. The integration of advanced manufacturing techniques, such as LPBF, with systematic assembly procedures and cutting-edge experimental setups, could significantly improve the repeatability and reliability of the FEBIAD ion source performance. As the SPES facility approaches full operational capacity, the innovations developed through this research will be useful to enhance the efficiency and effectiveness of its radioactive ion beam production capabilities. Furthermore, the methodologies and technologies introduced can be used for broader applications within the ISOL research community, offering a path forward for the continued optimisation and innovation of ion source technology.

7.2 Future developments

The research presented in this thesis identified several promising paths for further optimising the FEBIAD ion source, focusing on LPBF process, assembly accuracy, and performance assessment during operation.

However, although significant progress has been made, several aspects still require in-depth investigation to enhance the overall efficiency, reliability, and long-term operation of the

FEBIAD ion source. The following paragraphs outline key areas for future development, each addressing specific challenges.

7.2.1 Optimised LPBF-manufactured components experimental tests

The Laser Powder Bed Fusion process was confirmed as a manufacturing technology suitable for producing FEBIAD ion source components, with the aim to overcome the inherent limitations of traditional machining and TIG welding techniques. Future developments will focus on the experimental tests of optimised LPBF-manufactured components, with particular emphasis on the verification of tolerance specifications necessary for ensuring an accurate assembly process. Therefore, such optimised components must be machined to meet the allocated tolerance specifications and subsequently the dimensional and geometric accuracy of the individual parts must be verified by CMM inspections. Whether the geometric verification is approved, also the quality of the assembly itself must be evaluated through additional CMM measurements, ensuring that the final assembled ion source meets the positioning criteria needed for reliable performance during operation.

Once verified and approved the assembly accuracy, the components will be subjected to high-temperature tests, including both thermal characterization and long-term endurance test. The resistance at the device operational condition allows to continue with the off-line ionisation tests, where their functionality and ionisation efficiency will be systematically evaluated.

7.2.2 Thermionic emission test with vision system

The thermionic emission setup was assembled, and its functionality was verified through preliminary high-temperature tests. Future developments will include the installation and commissioning of the dedicated vision system which will enable real-time, accurate measurements of cathode deformation at elevated temperatures. In addition, this vision system will provide control on the anode-cathode distance, which directly affects thermionic emission during the tests. This approach will allow for the assembly of different anode and cathode configurations while maintaining the same anode-cathode distance, enabling comparative analysis of other factors impacting the thermionic emission process.

Preliminary evaluations on LPBF-manufactured components have already been performed; however, additional experimental tests are required to fully assess their performance. Such an ongoing investigation will be critical to further validate the use of LPBF technology to manufacture FEBIAD ion source parts.

Furthermore, the impact of surface finishing of the anode and cathode facing surfaces on thermionic emission process was not fully investigated yet. Different samples of anode and cathodes will be prepared by modifying only the surface finishing of their facing surfaces, and an optical profilometer will be employed to measure the surface roughness. Subsequently, such specimens will be installed and experimentally tested using the thermionic emission setup to identify the optimal surface finishing for maximizing electron emission. This approach allows to assign the proper surface finishing specifications on the anode grid and cathode frontal surface, which is an information currently absent in the technical drawings.

The thermionic emission setup will also allow for the exploration of alternative anode grid designs [84], as the LPBF process unlocked the possibility of such modifications. With this method, the aim to improve the flow of electrons passing through the grid, thereby making more electrons available in the plasma chamber to enhance the ionisation process.

7.2.3 Design of innovative anode-cathode interfaces

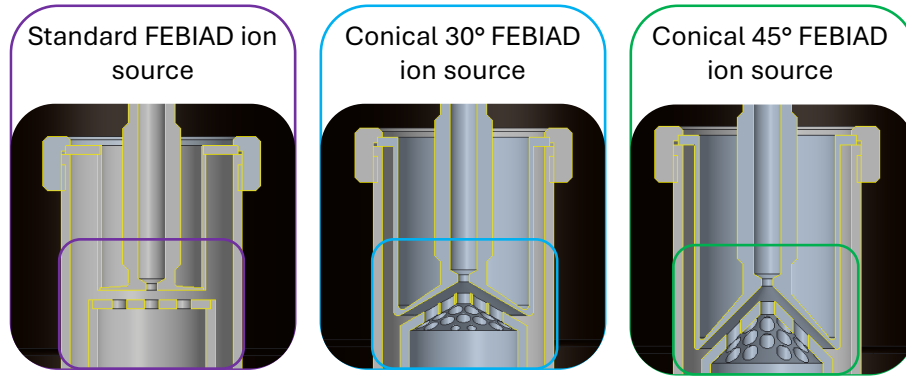


Figure 7.1 Alternative anode-cathode conical interfaces.

The capabilities introduced by the LPBF process enabled the development of innovative anode-cathode interfaces, allowing for further improvements of the FEBIAD ion source performance. One promising direction is the design of conical interfaces, as shown in Figure 7.1, which would expand the cathode thermionic emission surface area, allowing for more electrons release by thermionic effect. In addition to increase the electron-emitting surface, the development of alternative interfaces will aim to improve the temperature distribution of the ion source components, especially on the anode grid and cathode frontal surface. In this framework, the thermionic emission setup can also be used to test the proposed interface designs at high temperatures and perform experimental comparative analyses.

7.2.4 Cathode deformation reduction

The deformation of the cathode frontal surface during operation remains a significant issue for the long-term reliability of the FEBIAD ion source. In future work, the design of more robust cathode frontal surfaces will be explored through simulation techniques and experimental testing.

Comparative structural simulations using FEM analysis will be performed on different cathode designs by importing the temperature distribution obtained from coupled electro-thermal analyses, as suggested in [28]. The final aim is to design more robust cathode frontal surfaces without compromising the temperature distribution of the components. However, it will be necessary to measure the mechanical properties of LPBF-manufactured materials at high temperatures to obtain more accurate and reliable results.

Additionally, the introduction of compliant elements upstream of the cathode, such as along the transfer line, would allow to further reduce deformation of the cathode frontal surface during operation.

7.2.5 Additively manufactured electrical insulators

The re-design of the anode assembly procedure for an increased reliability and repeatability highlighted the limitations provided by the current design of the cylindrical alumina insulators. To overcome such limitations, future developments will be devoted to design of innovative design of insulators exploiting the advantages of the Additive Manufacturing technologies available, such as the Fused Filament Fabrication (FFF). Currently ZrO_2 and Al_2O_3 insulators were produced with FFF starting from commercially available filaments. CMM measurements on the produced cylindrical samples highlighted the high accuracy achieved and a high temperature testing campaign was successfully performed evaluating their compatibility with the operation in vacuum at a temperature level up to 1500°C [85]. Such promising results laid the foundations to develop more geometrically complex

insulators, shown in Figure 7.2, which allow a self-positioning of the anode during the assembly procedure.

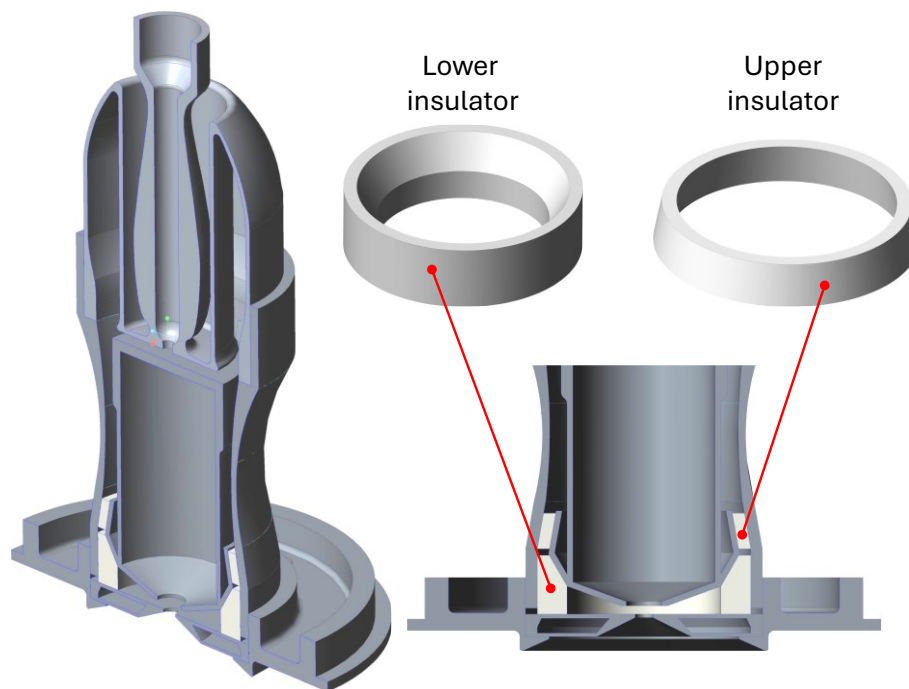


Figure 7.2 The anode assembly procedure can be drastically re-designed modifying the insulators geometry.

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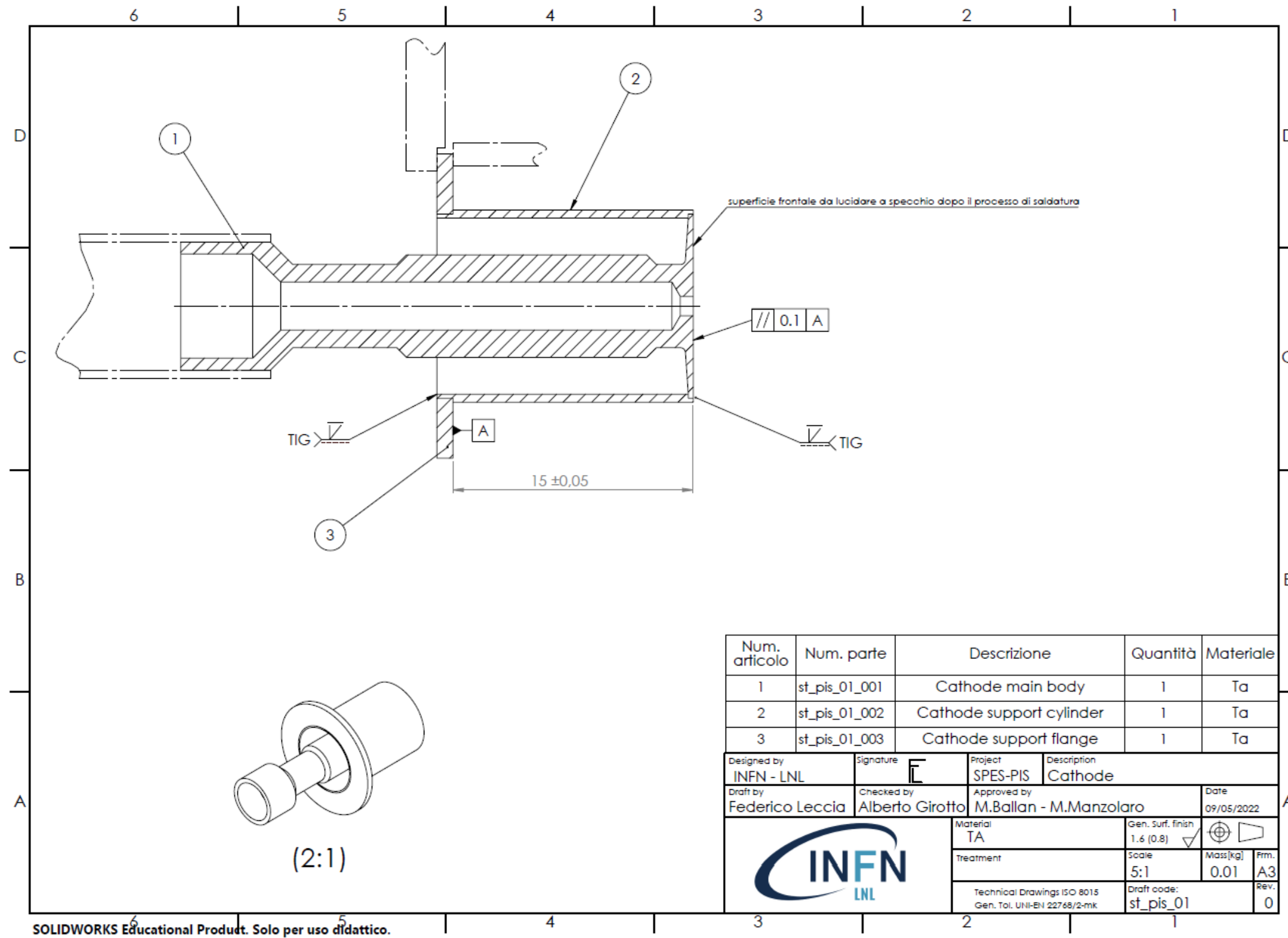
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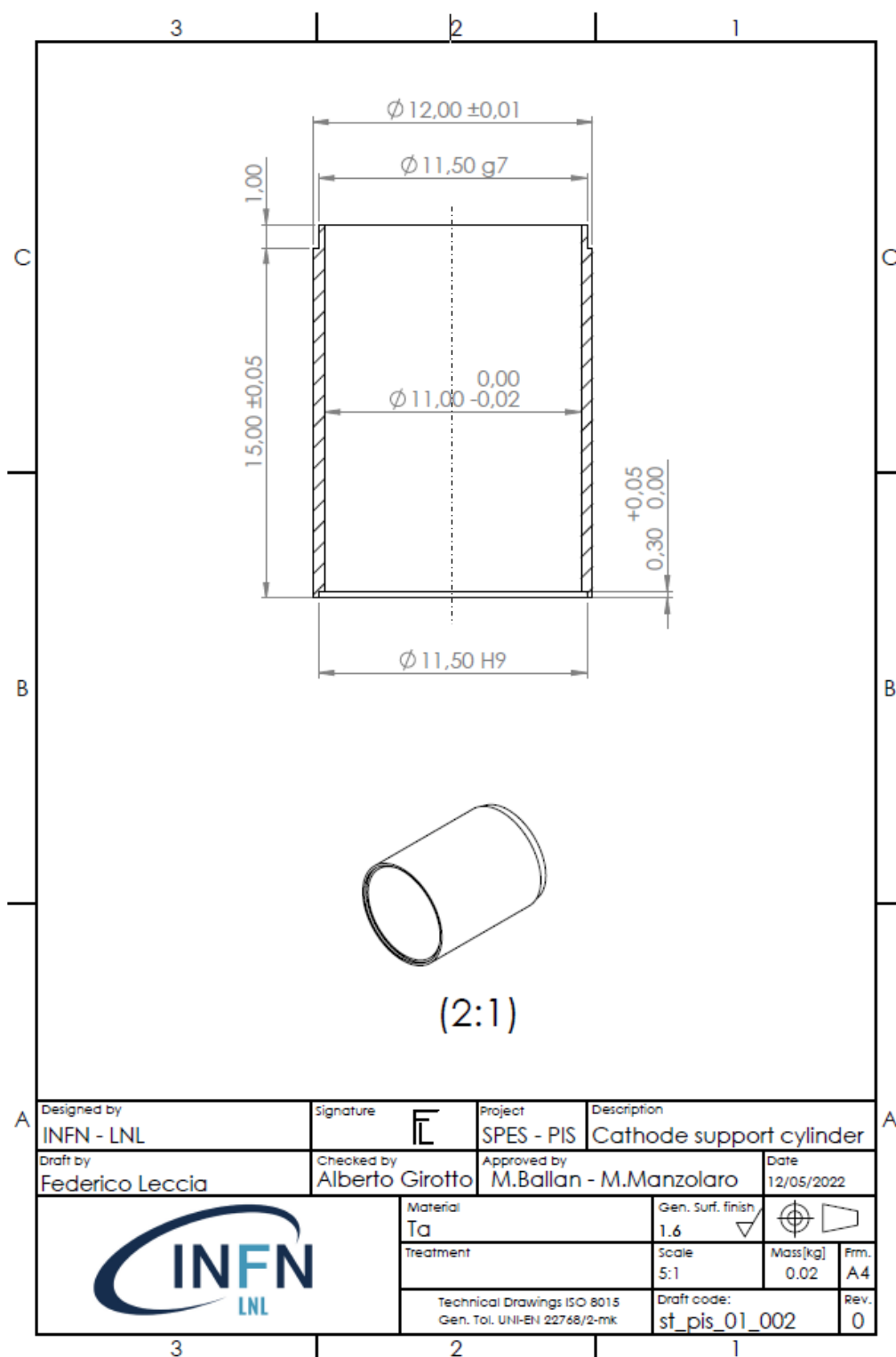
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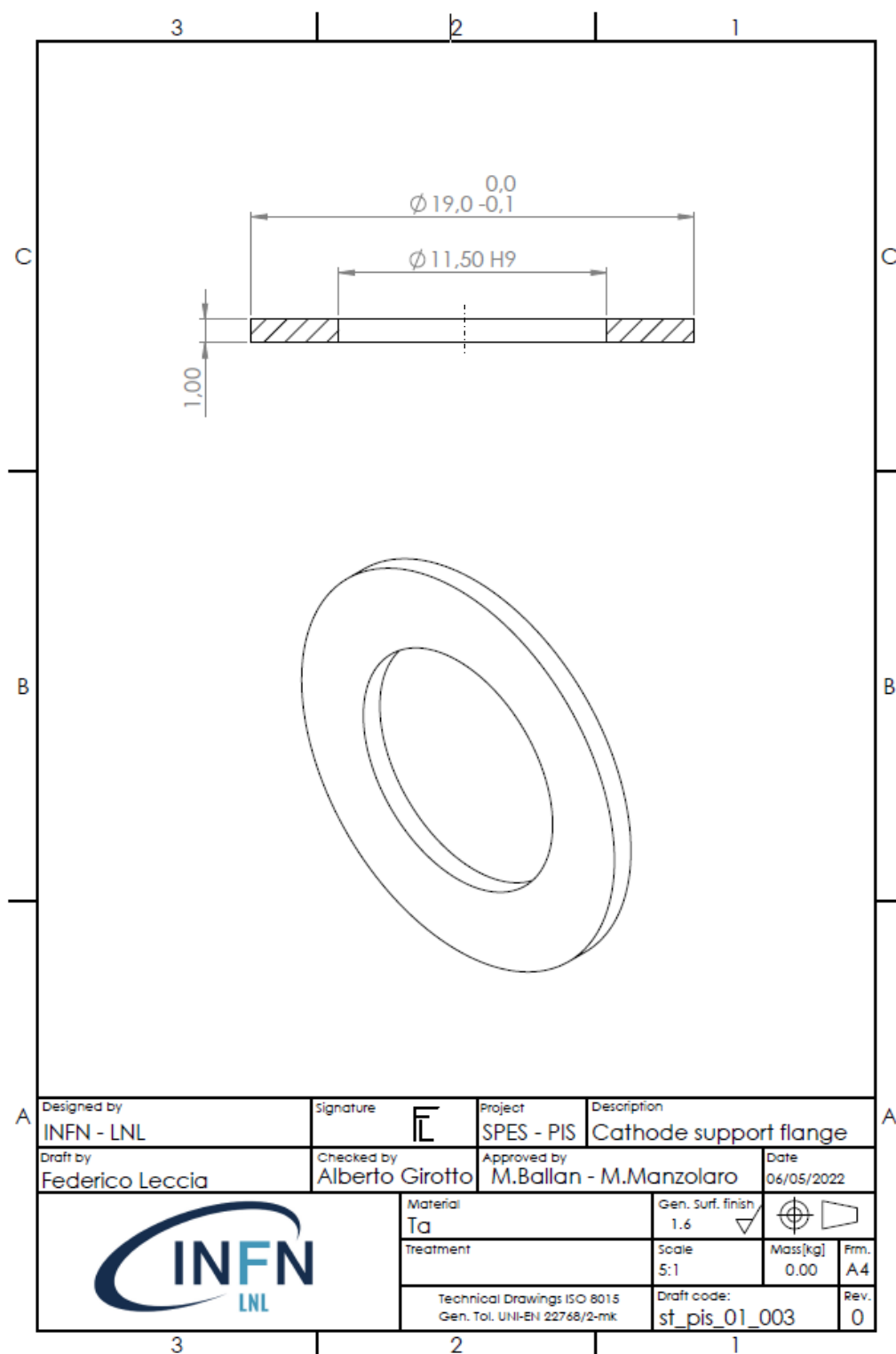
Appendixes

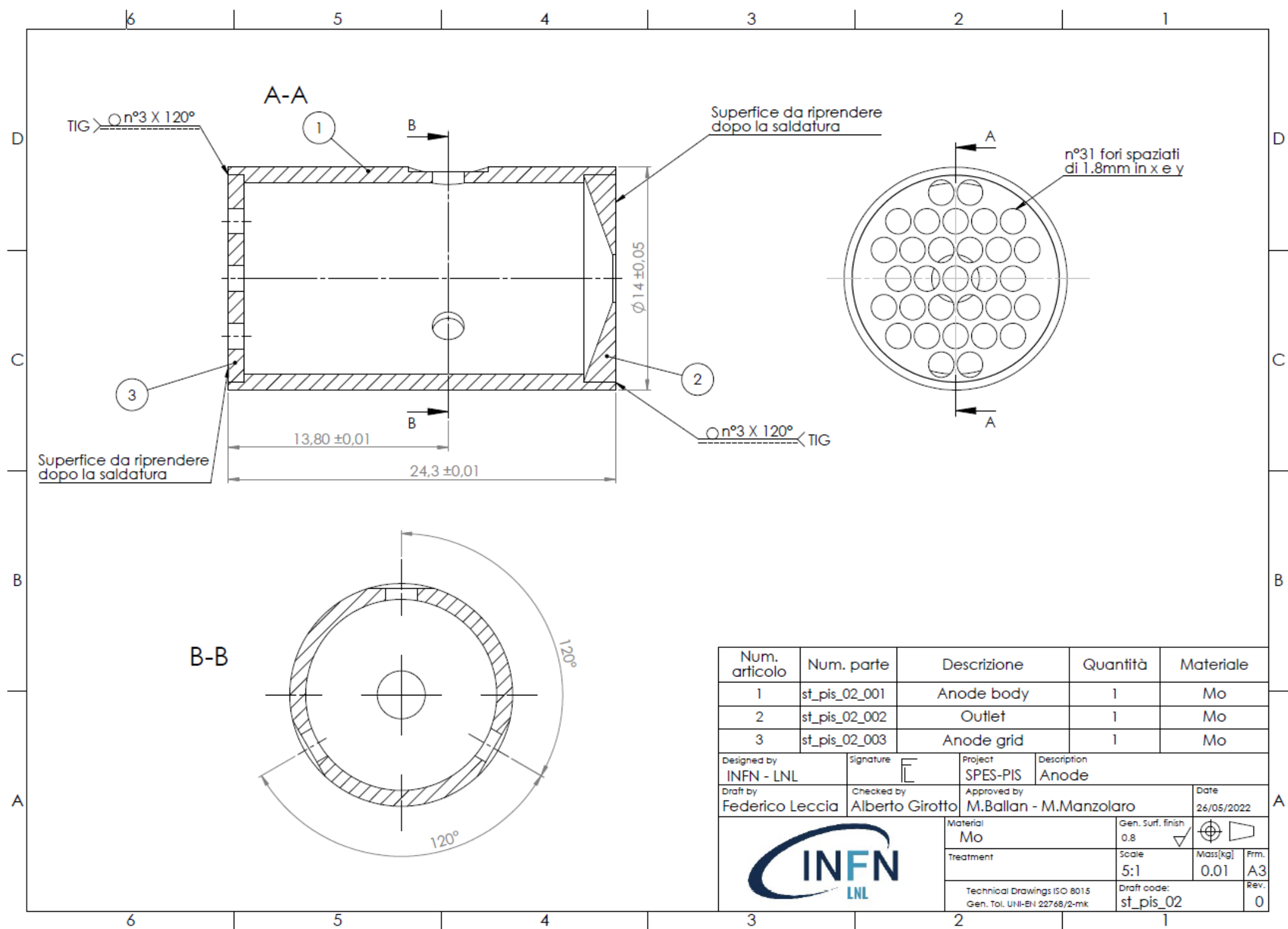
Appendix A STD FEBIAD ion source technical drawings

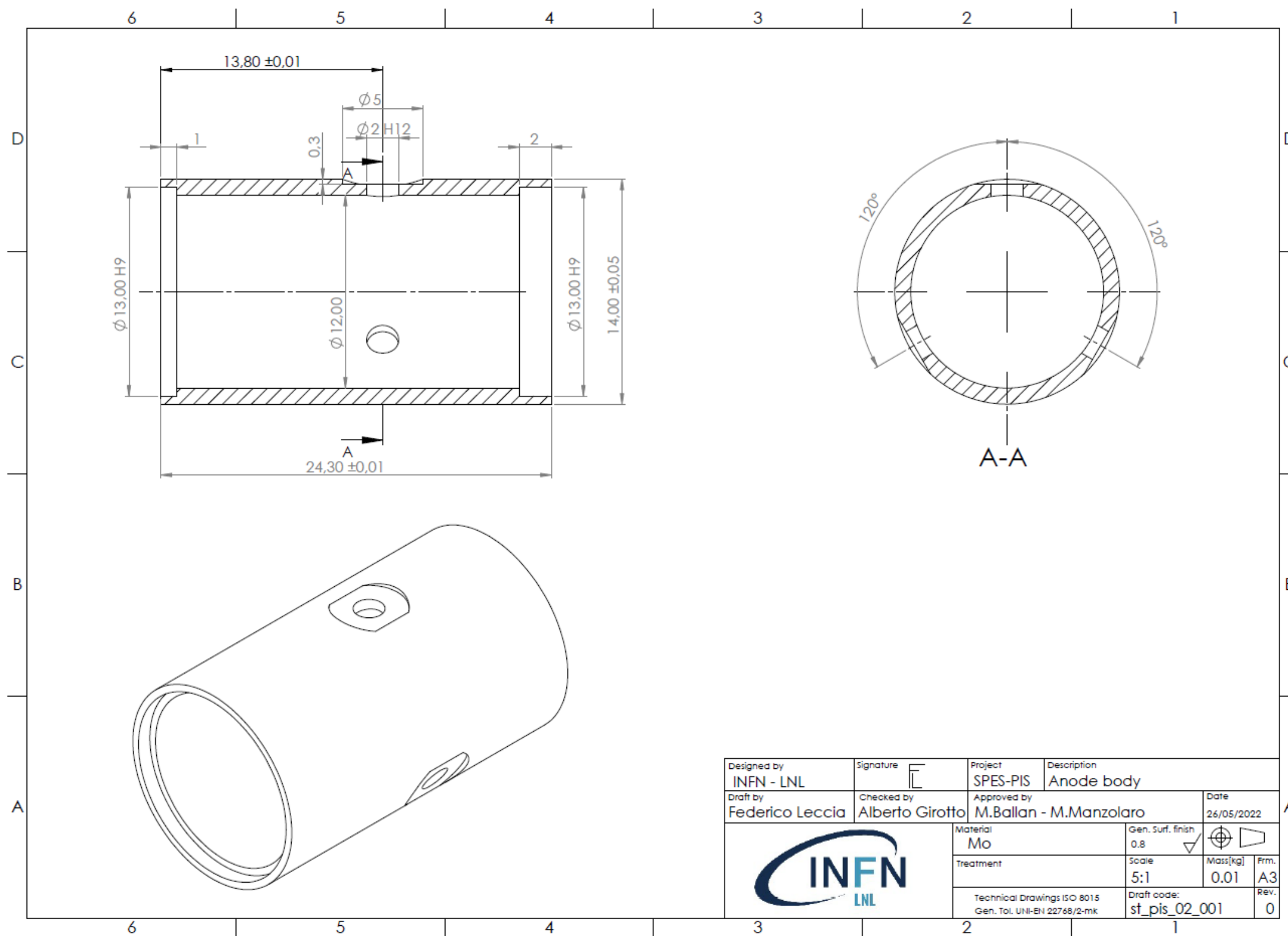
Appendix A.1 FEBIAD ion source

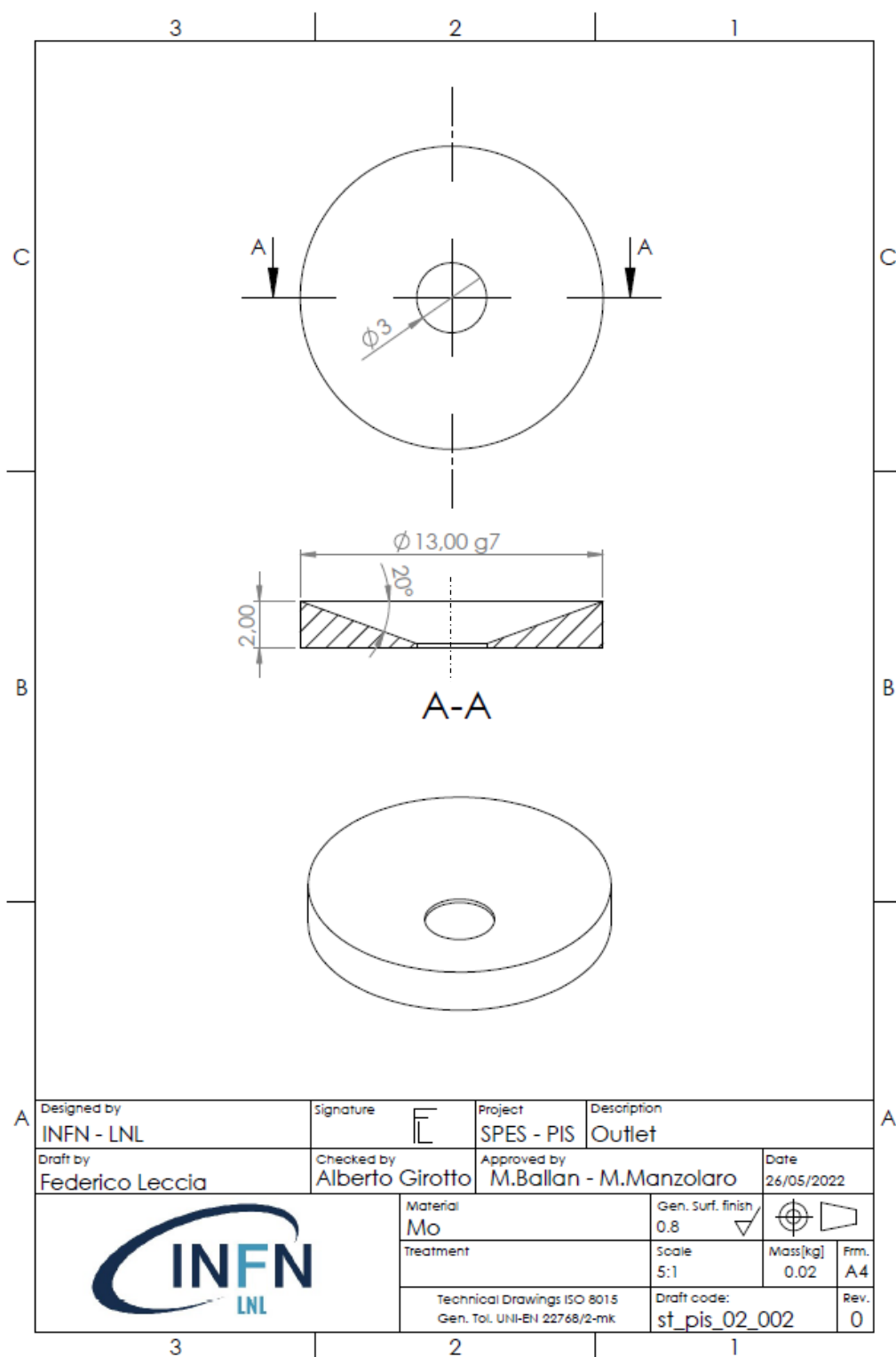


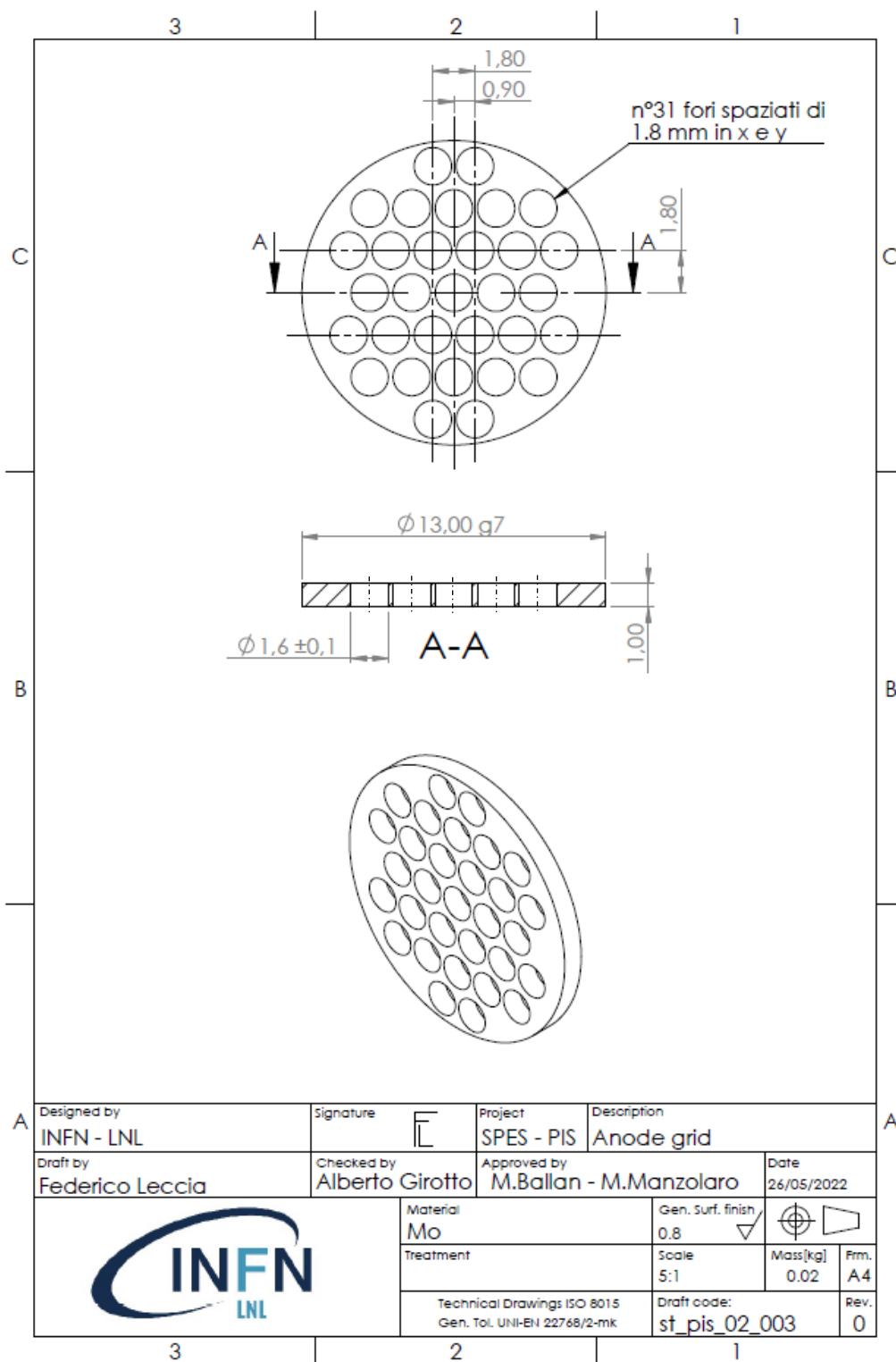


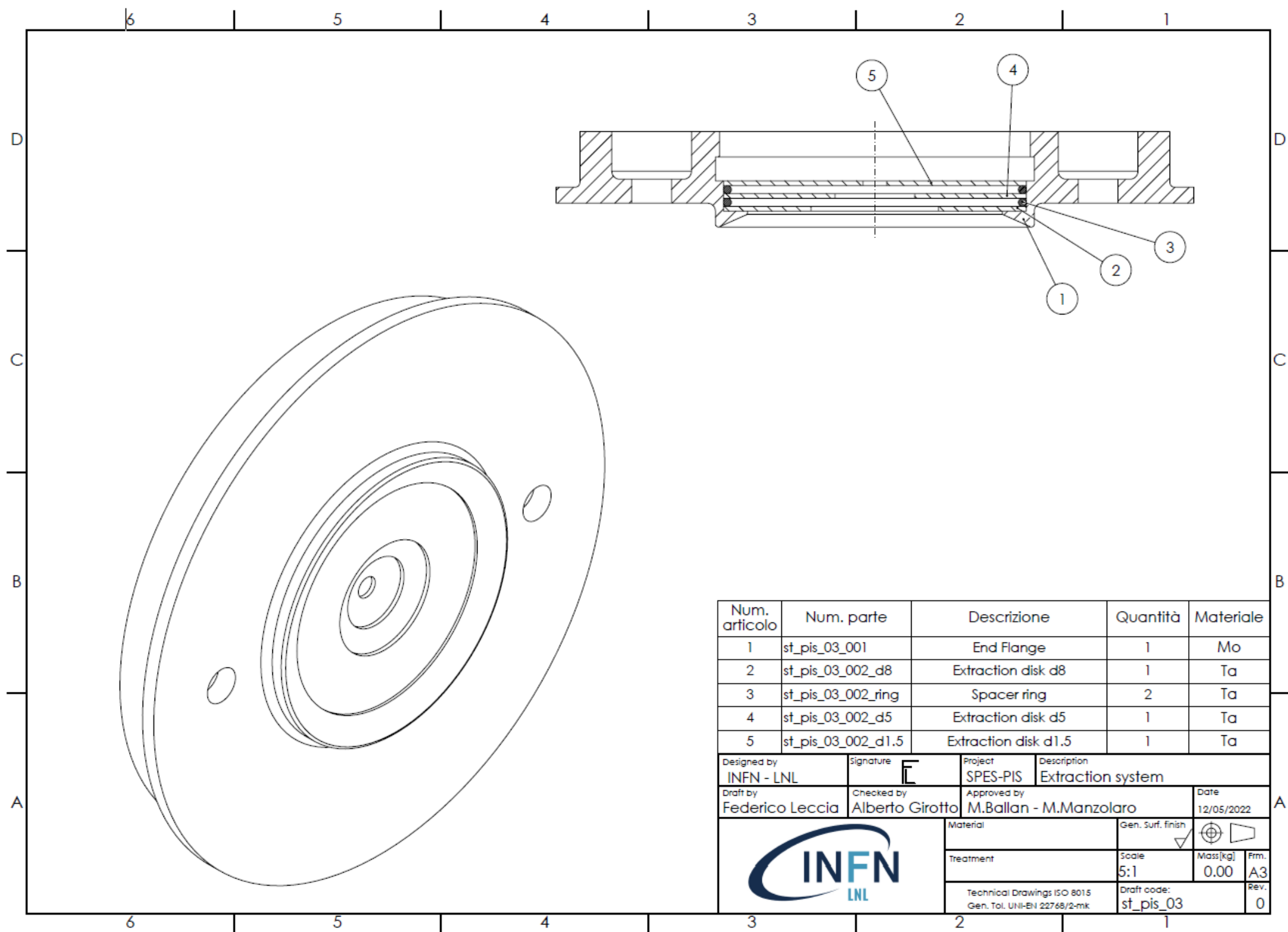


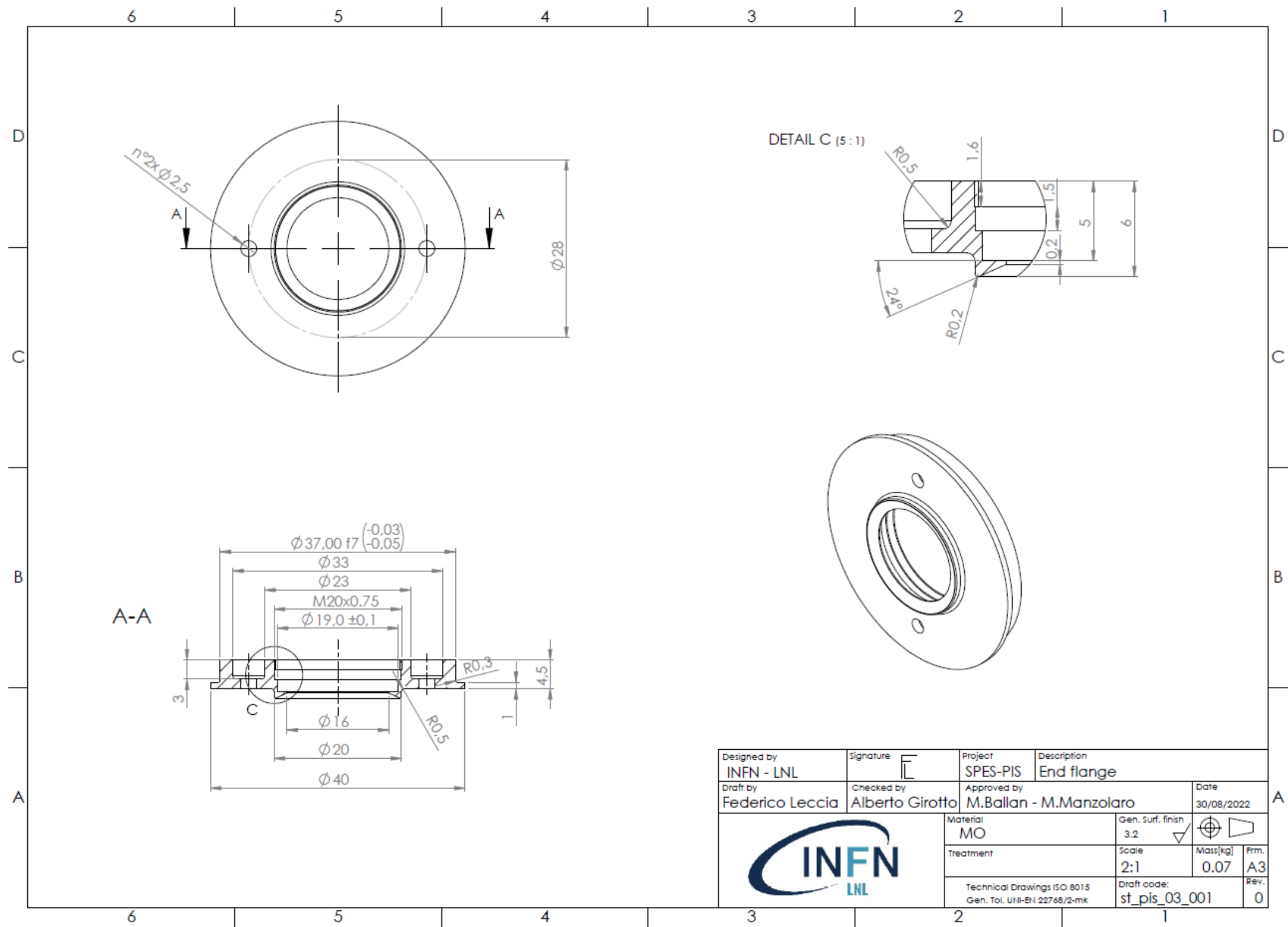


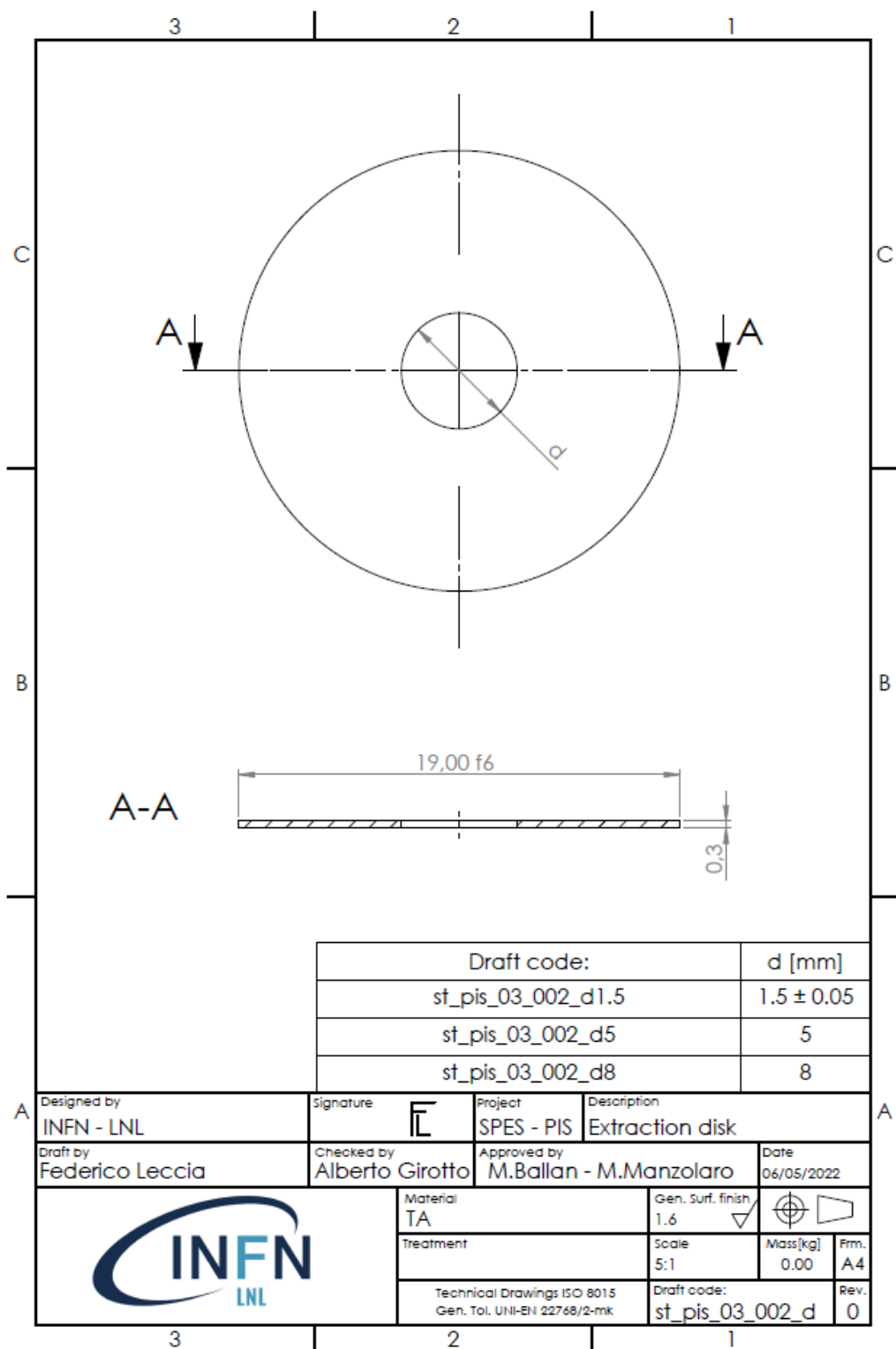


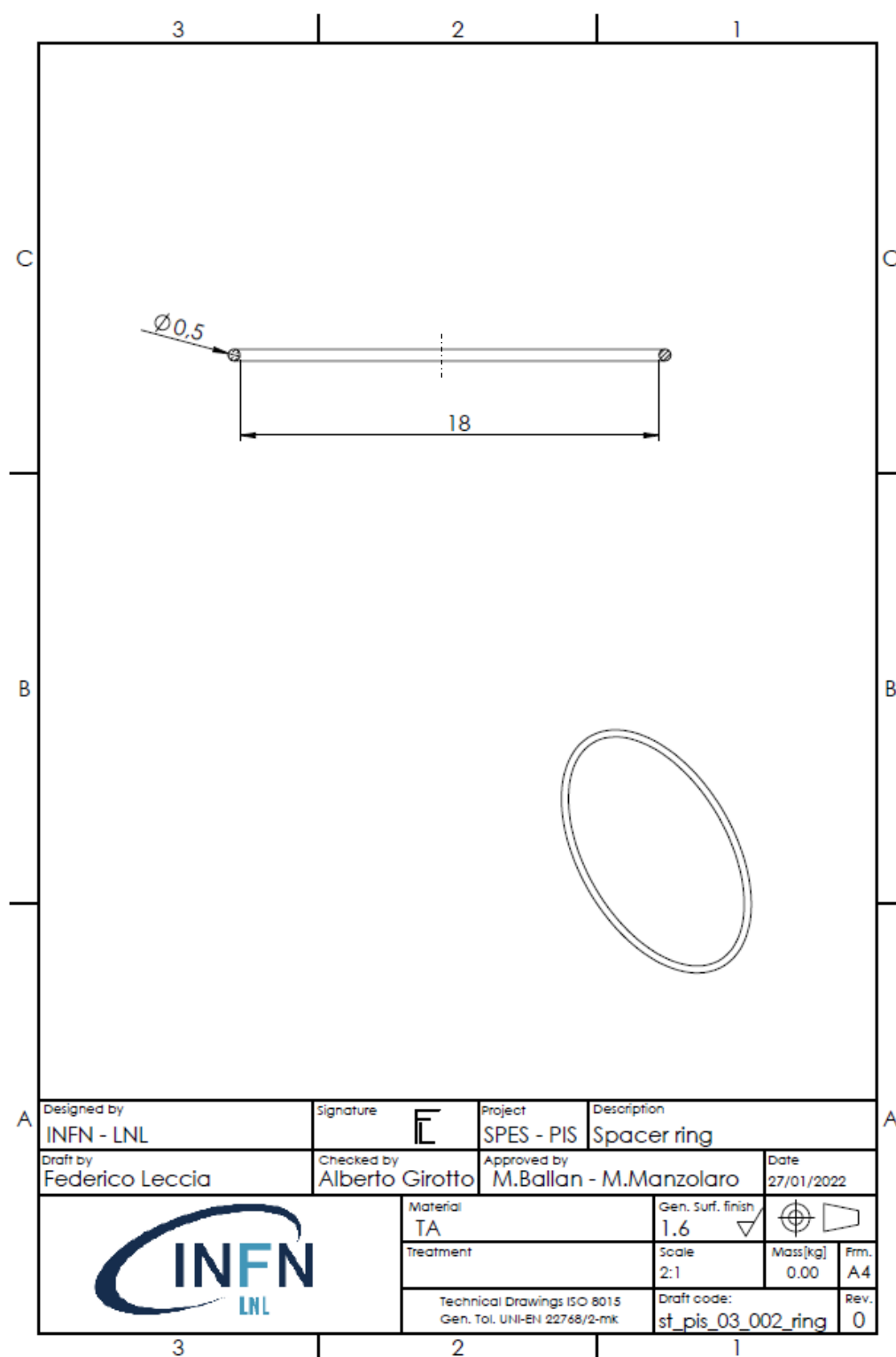


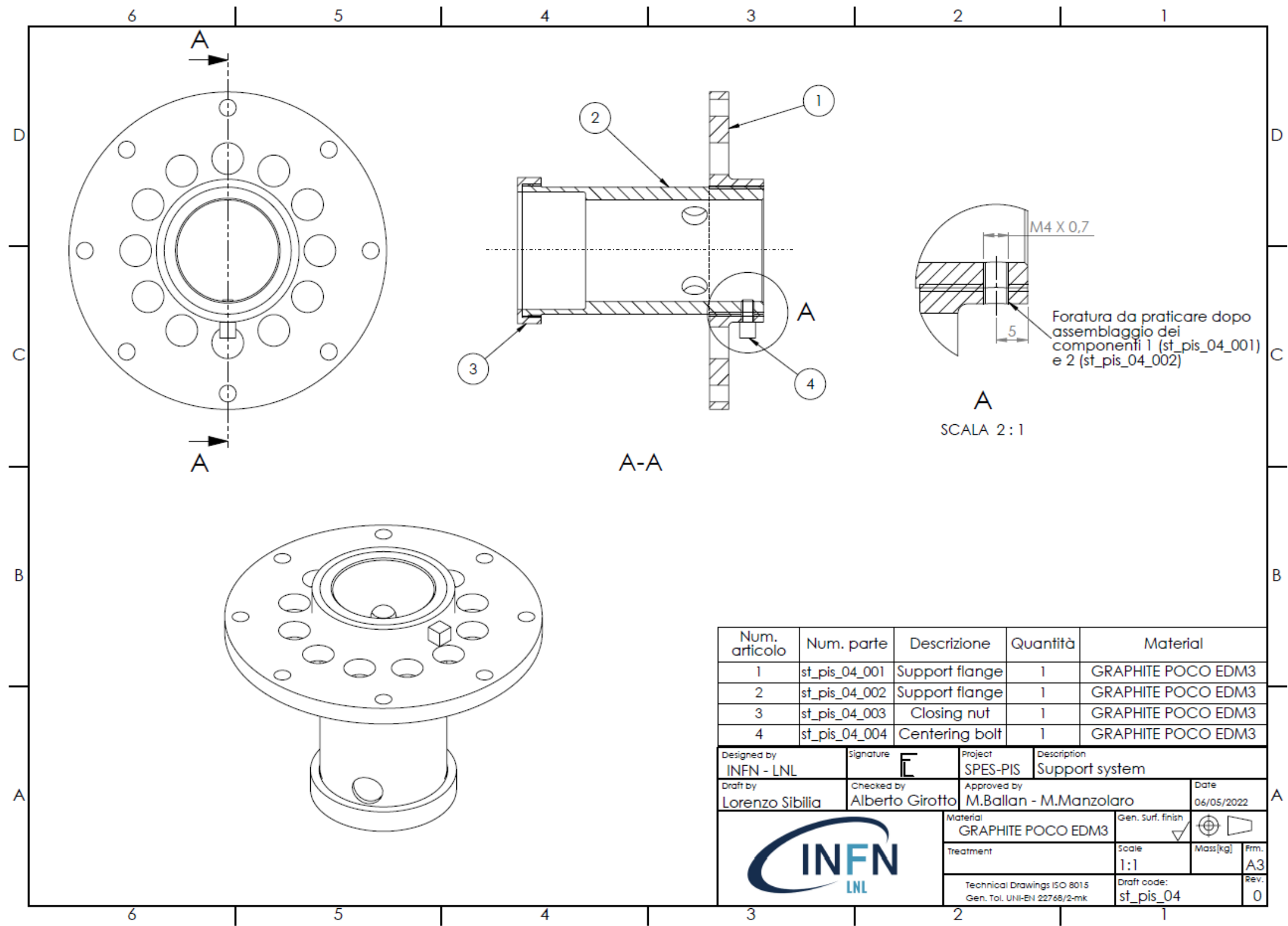


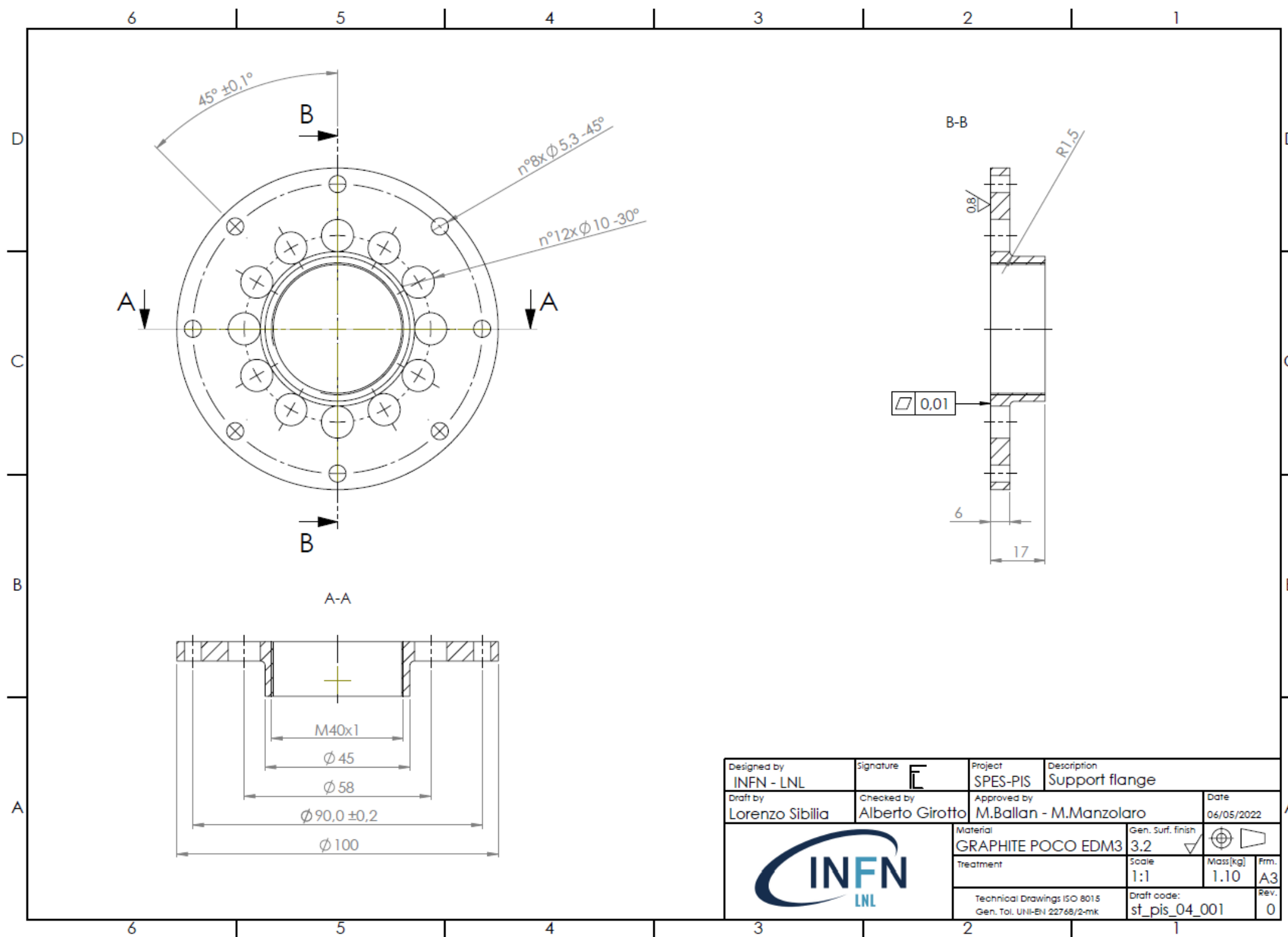


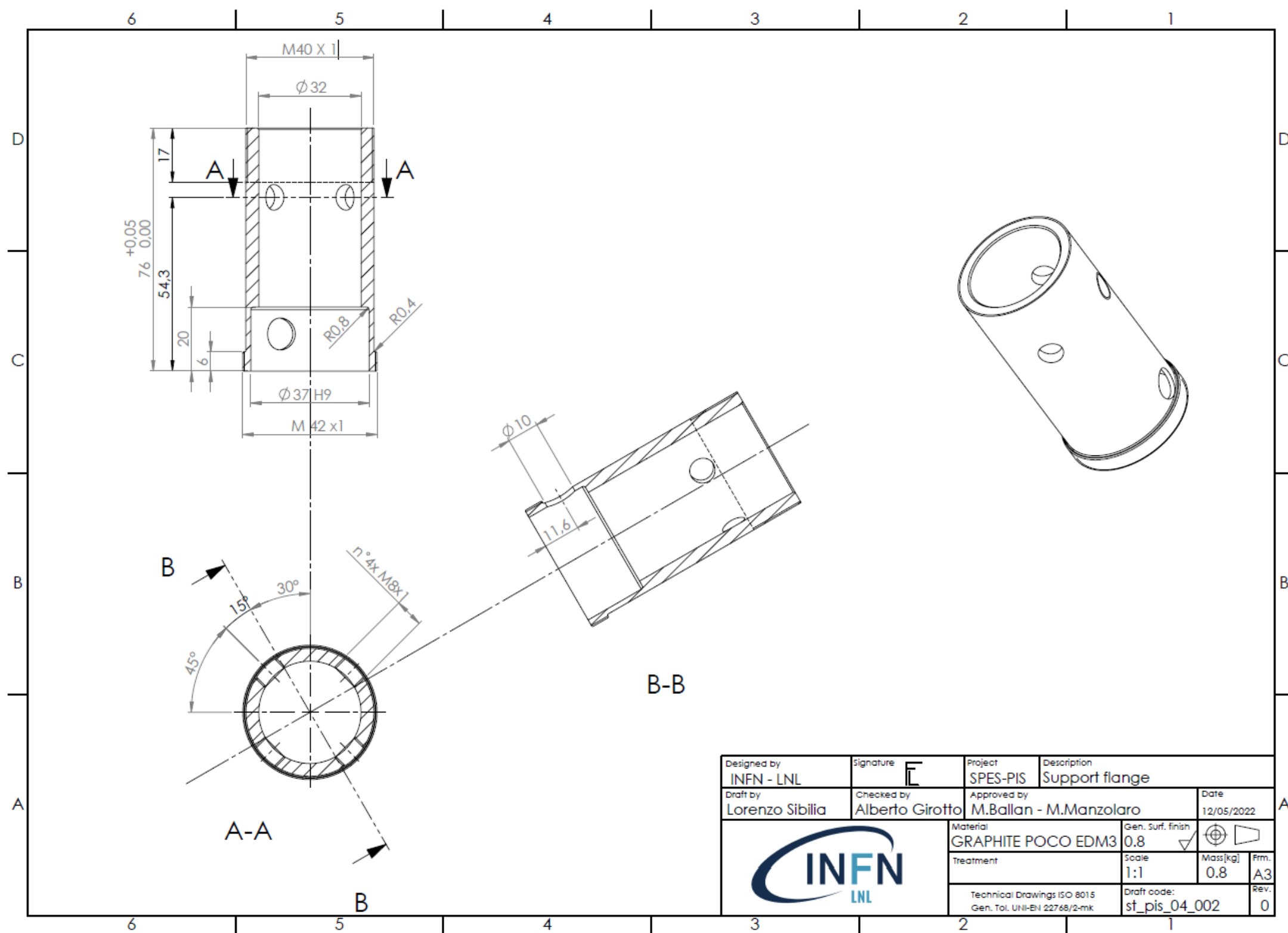


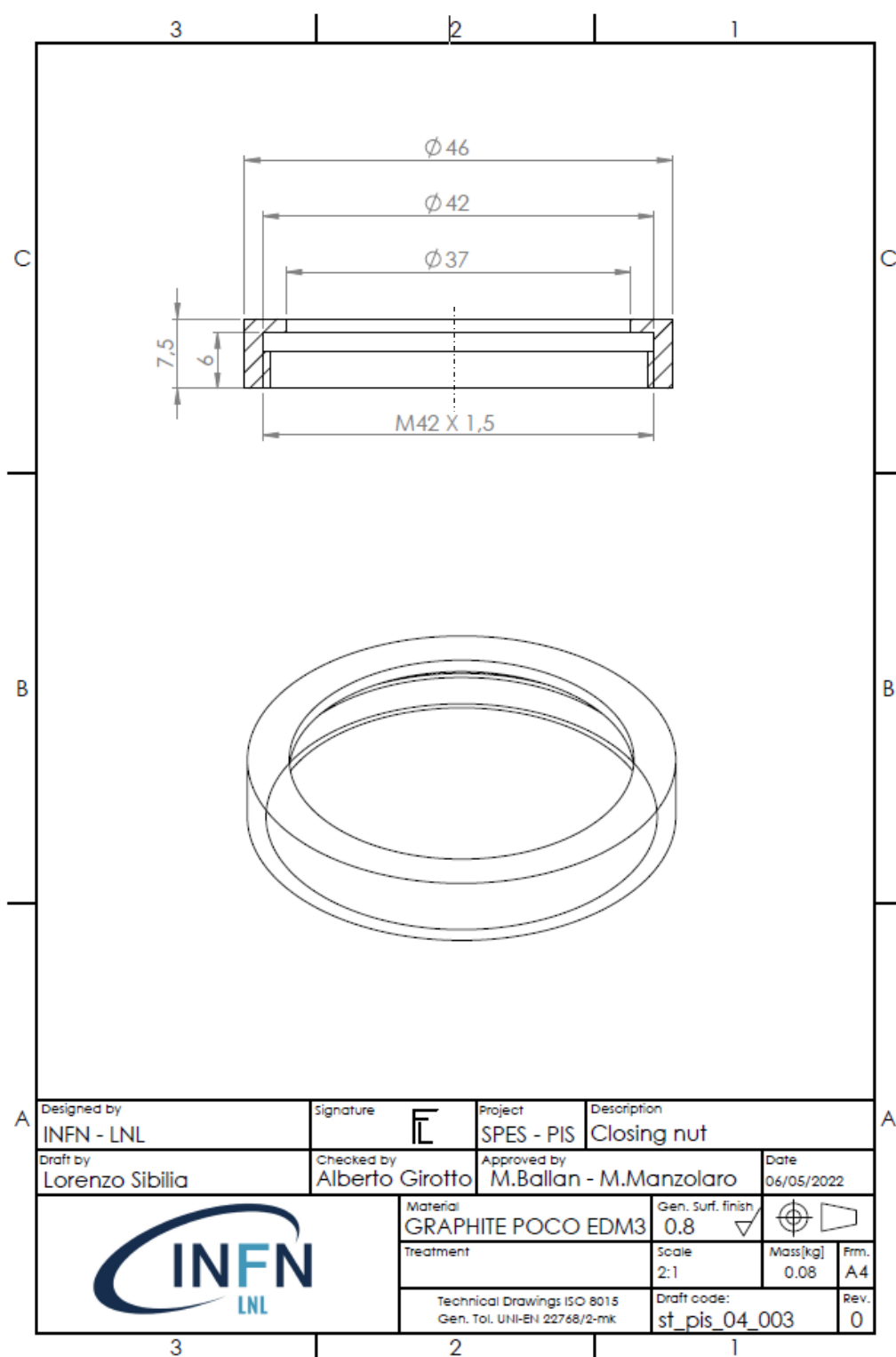


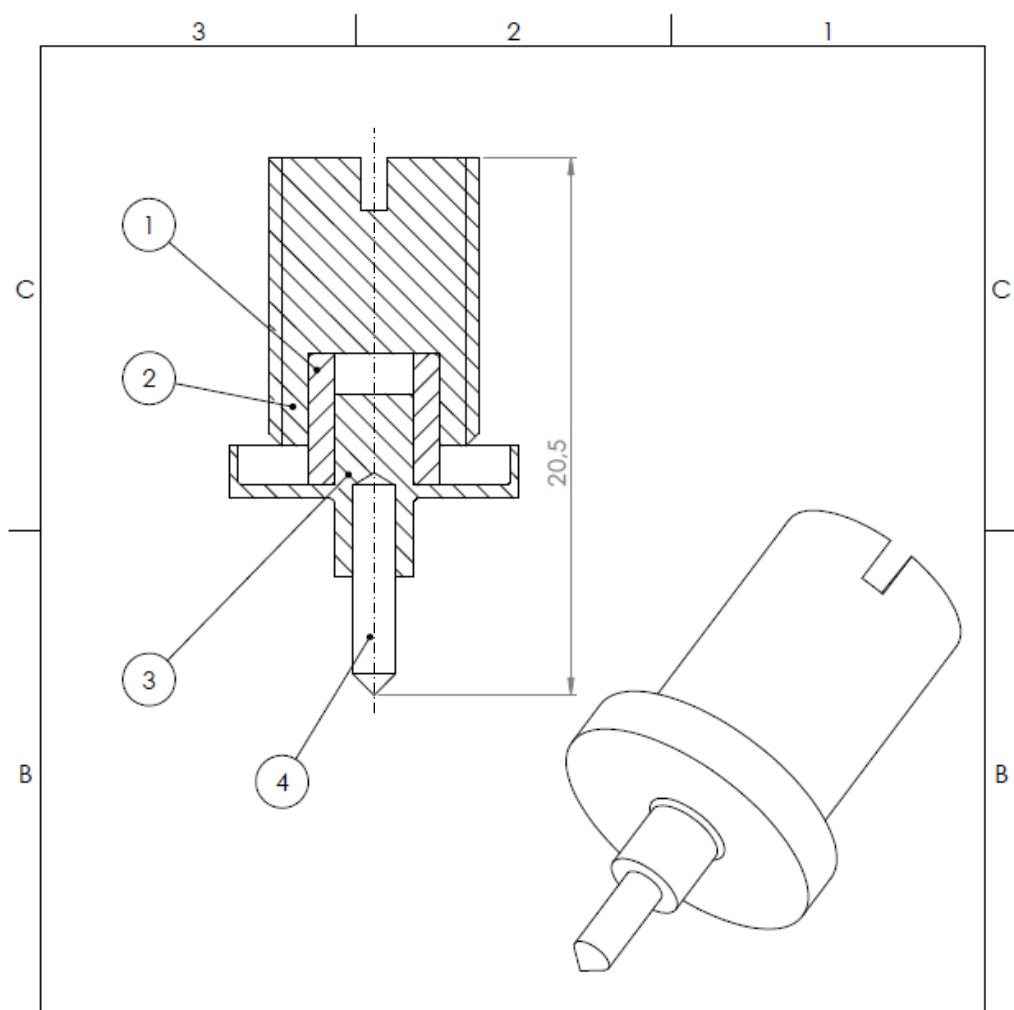






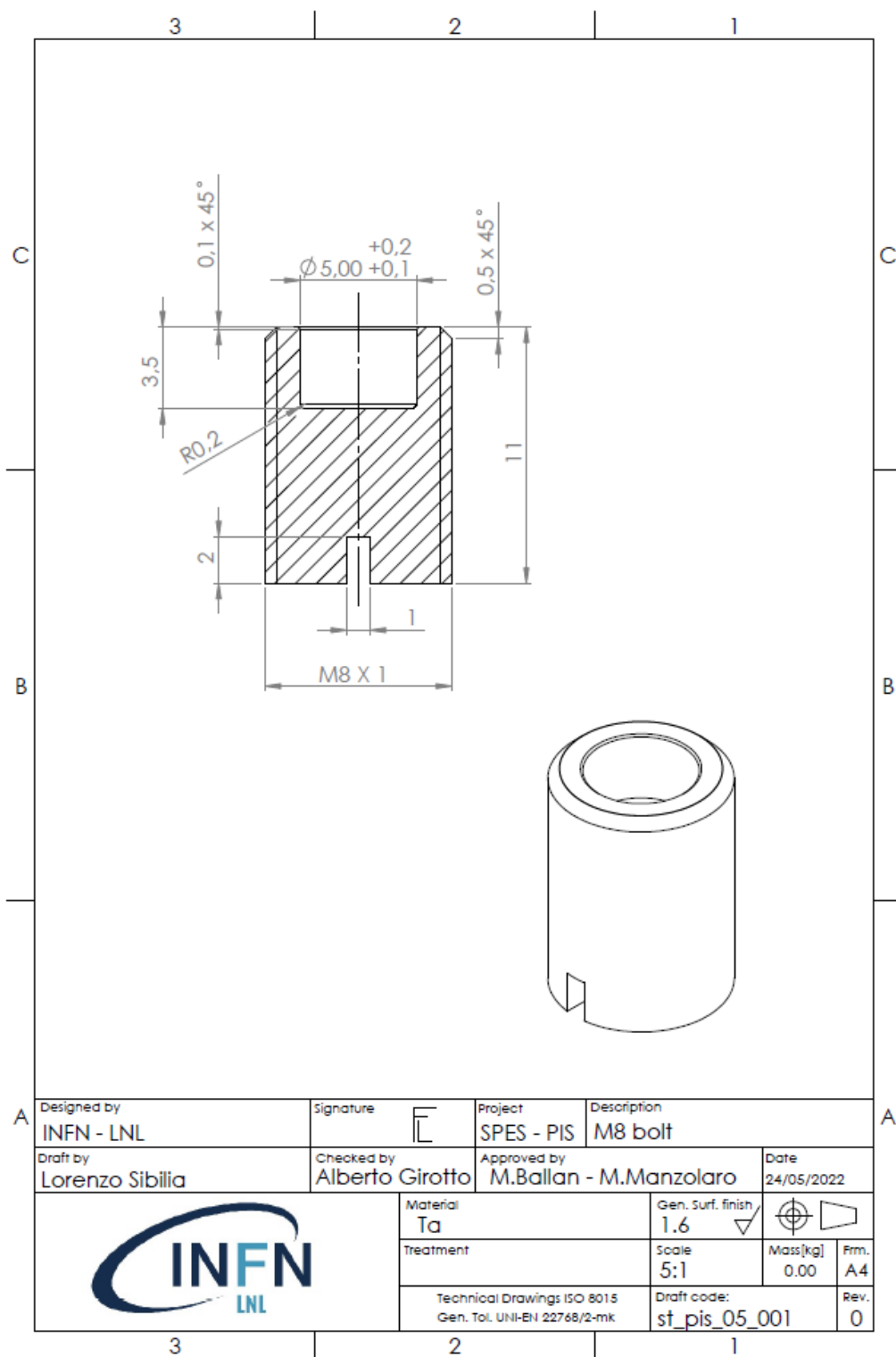


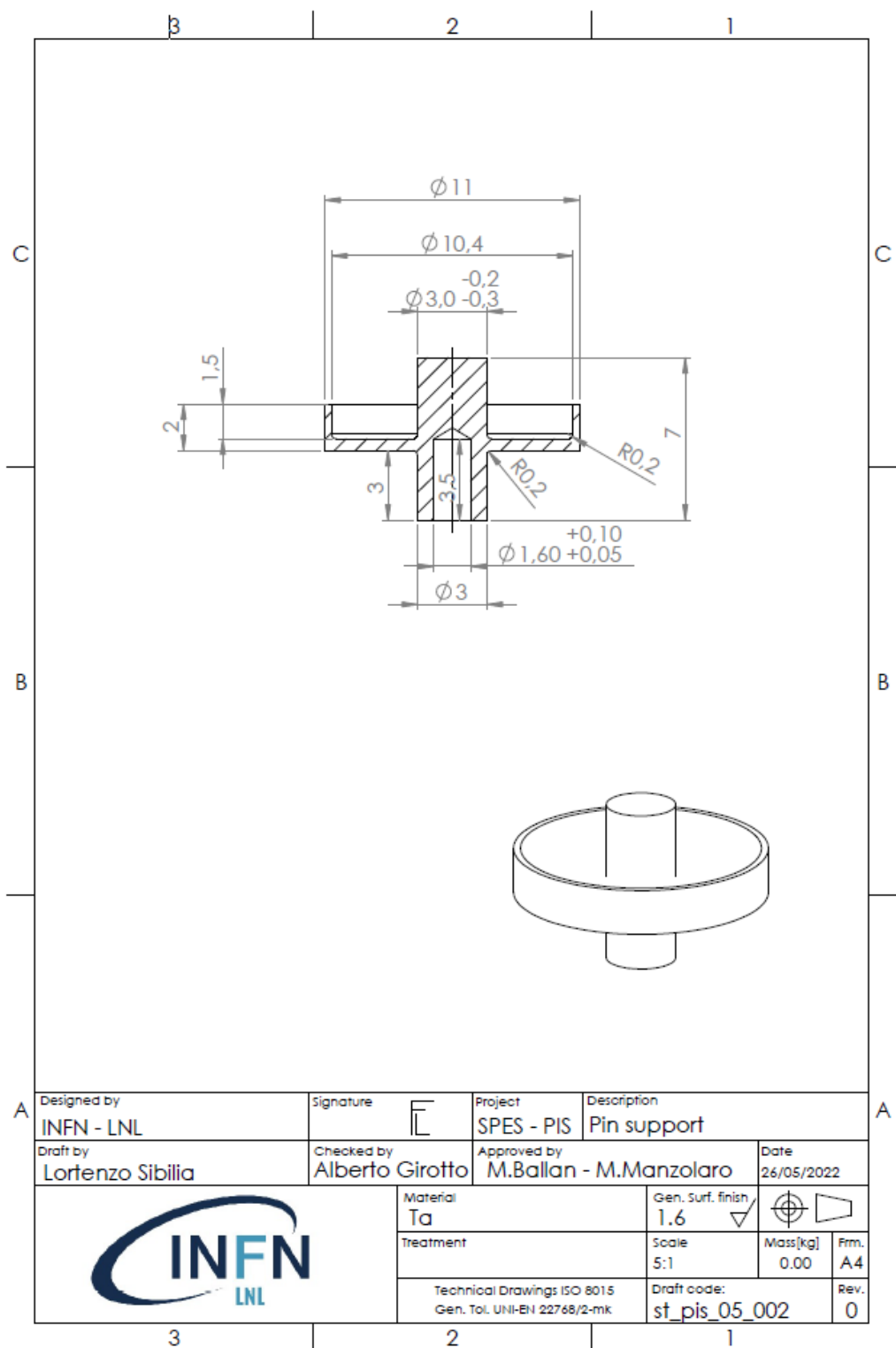


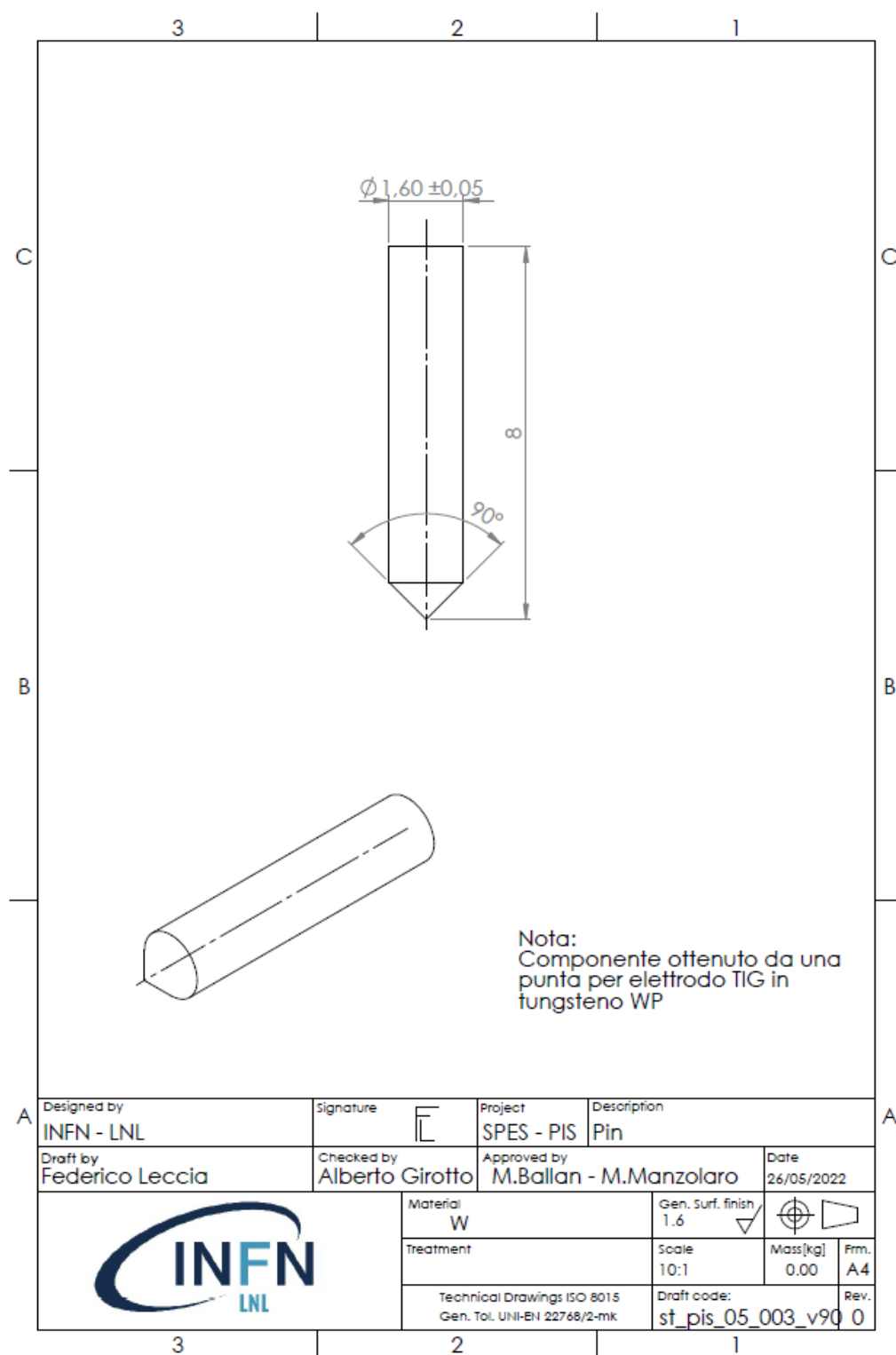


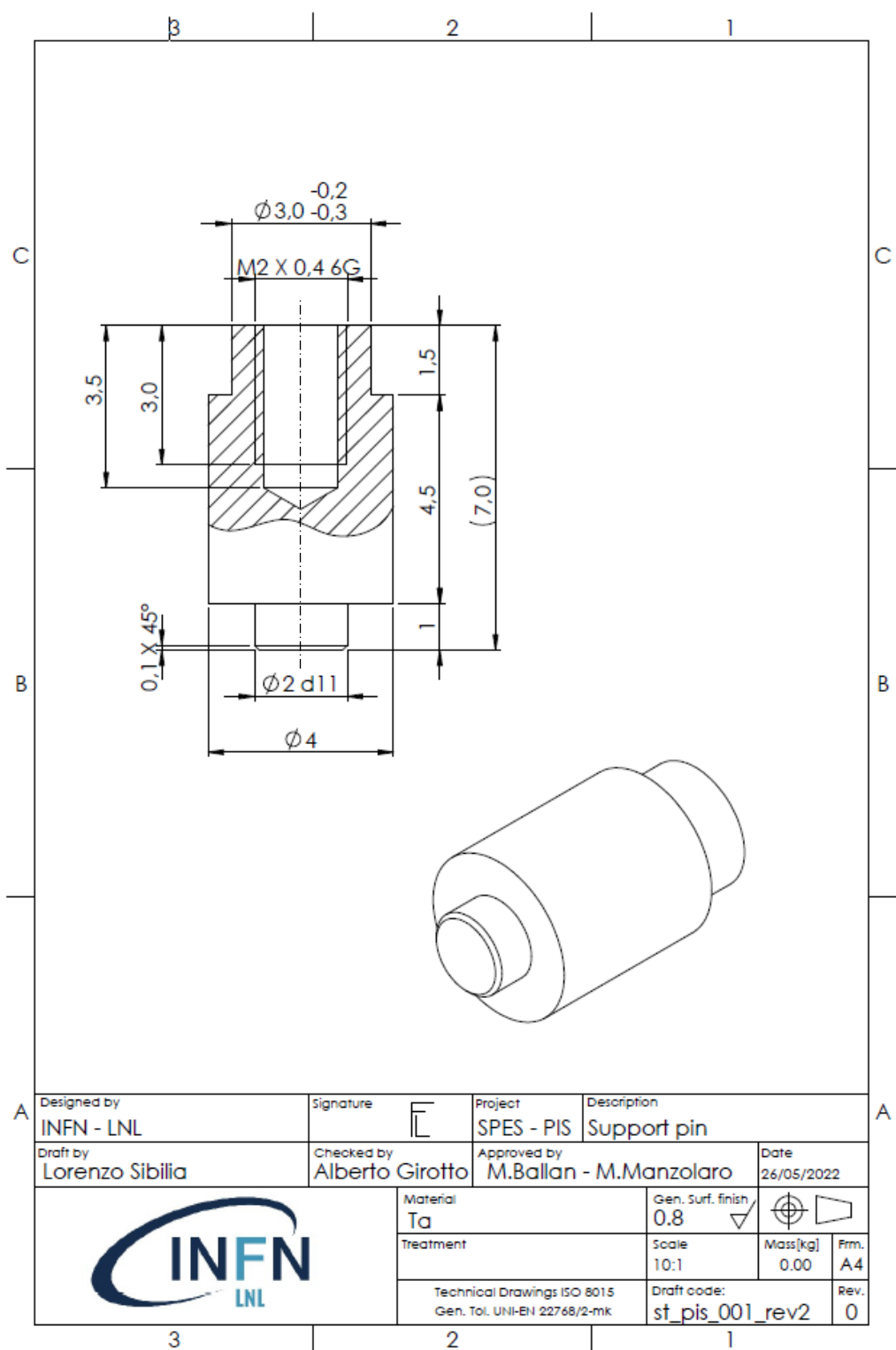
Num. articolo	Num. parte	Descrizione	Quantità	Material
1	st_pis_002	Pin insulator	1	Al ₂ O ₃
2	st_pis_05_001	M8 Bolt	1	TA
3	st_pis_05_002	Pin support	1	TA
4	st_pis_05_003	Pin	1	W

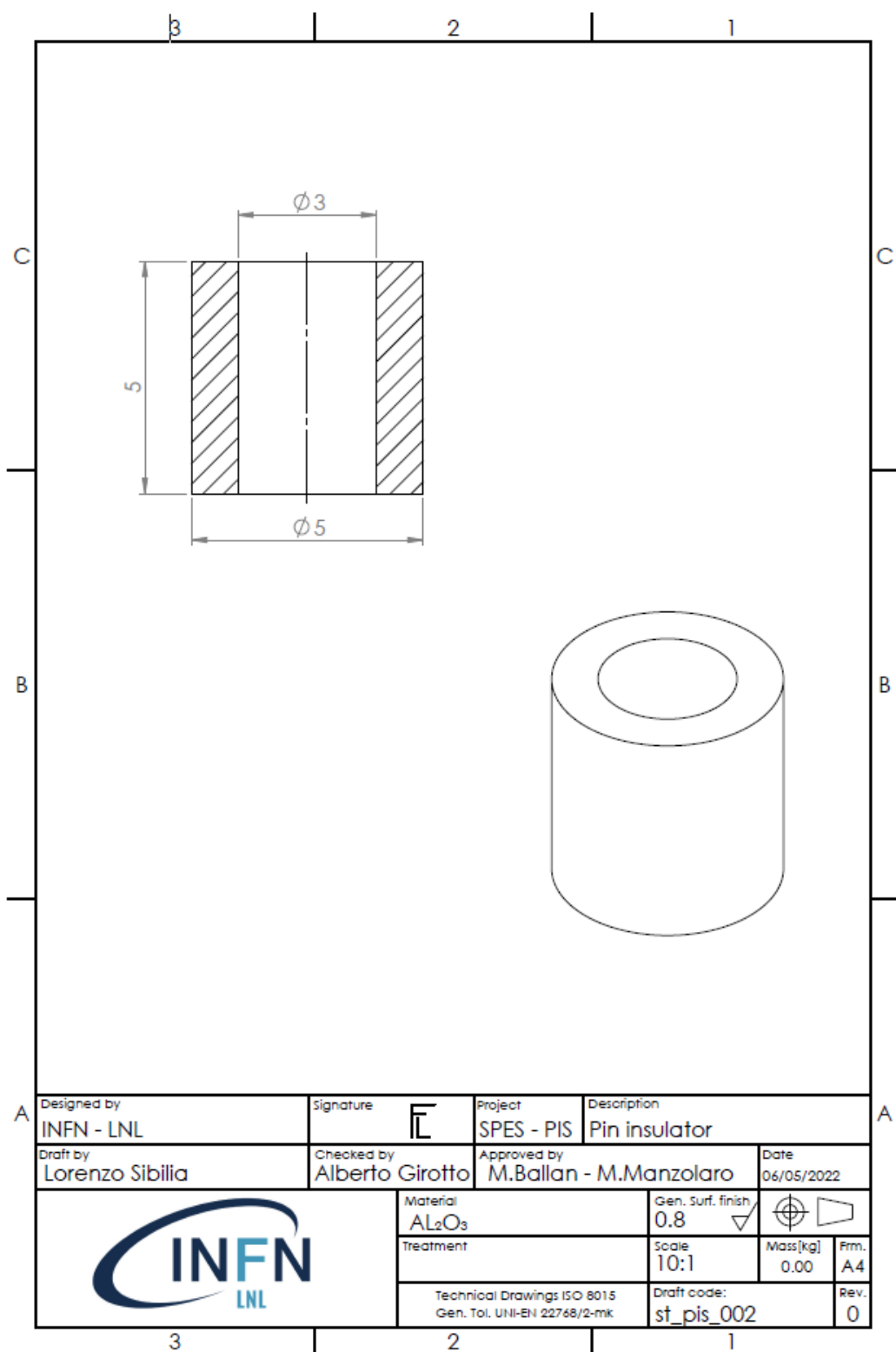
A	Designed by INFN - LNL		Signature 	Project SPES - PIS	Description Centering pin		A
	Draft by Lorenzo Sibilia		Checked by Alberto Giroto	Approved by M.Ballan - M.Manzolaro		Date 24/05/2022	
			Material	Gen. Surf. finish ☒			
Treatment			Scale 5:1	Mass[kg] 0.00			Frm. A4
		Technical Drawings ISO 8015 Gen. Tol. UNI-EN 22768/2-mk		Draft code: st_pis_05		Rev. 0	

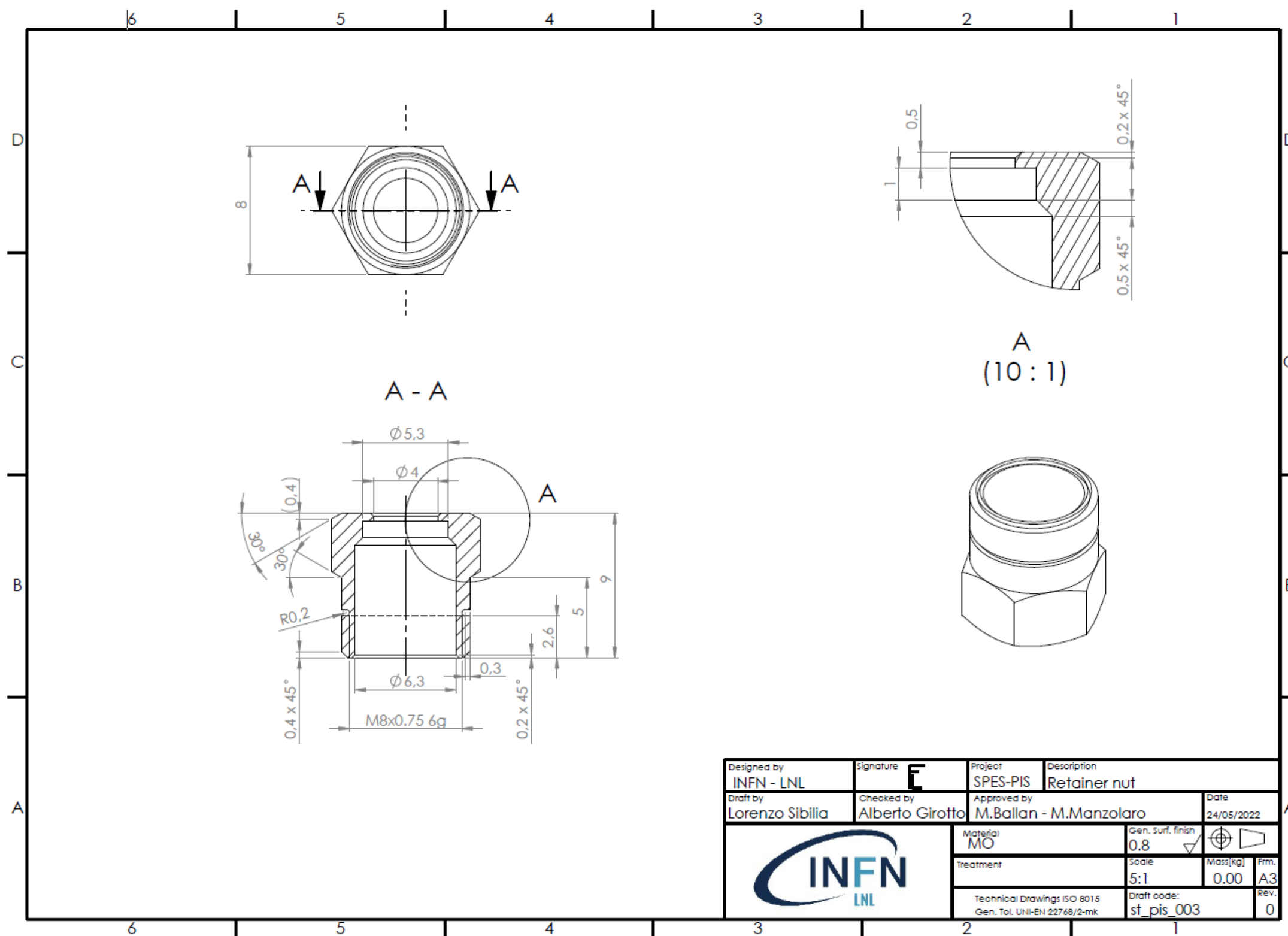


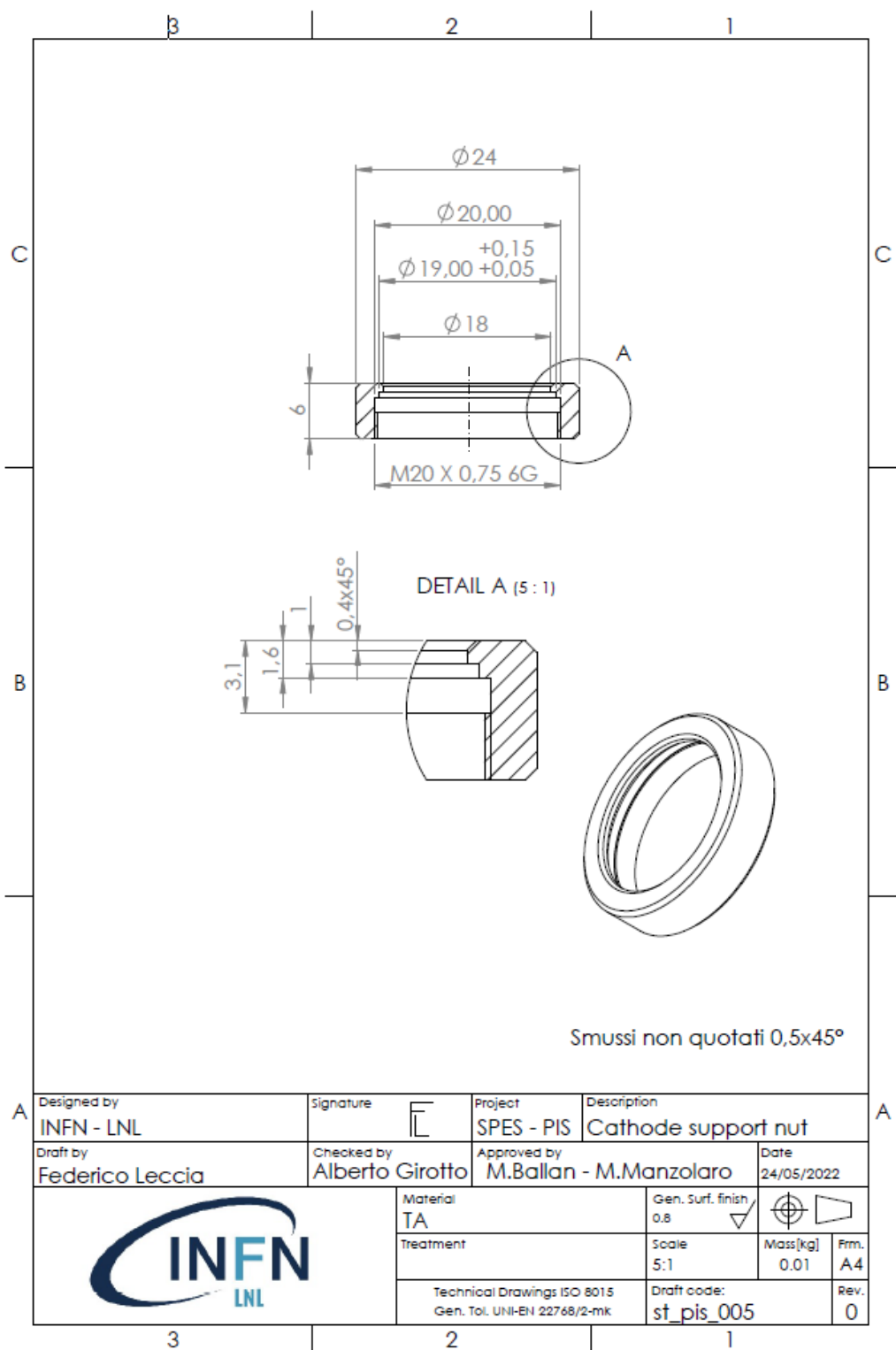


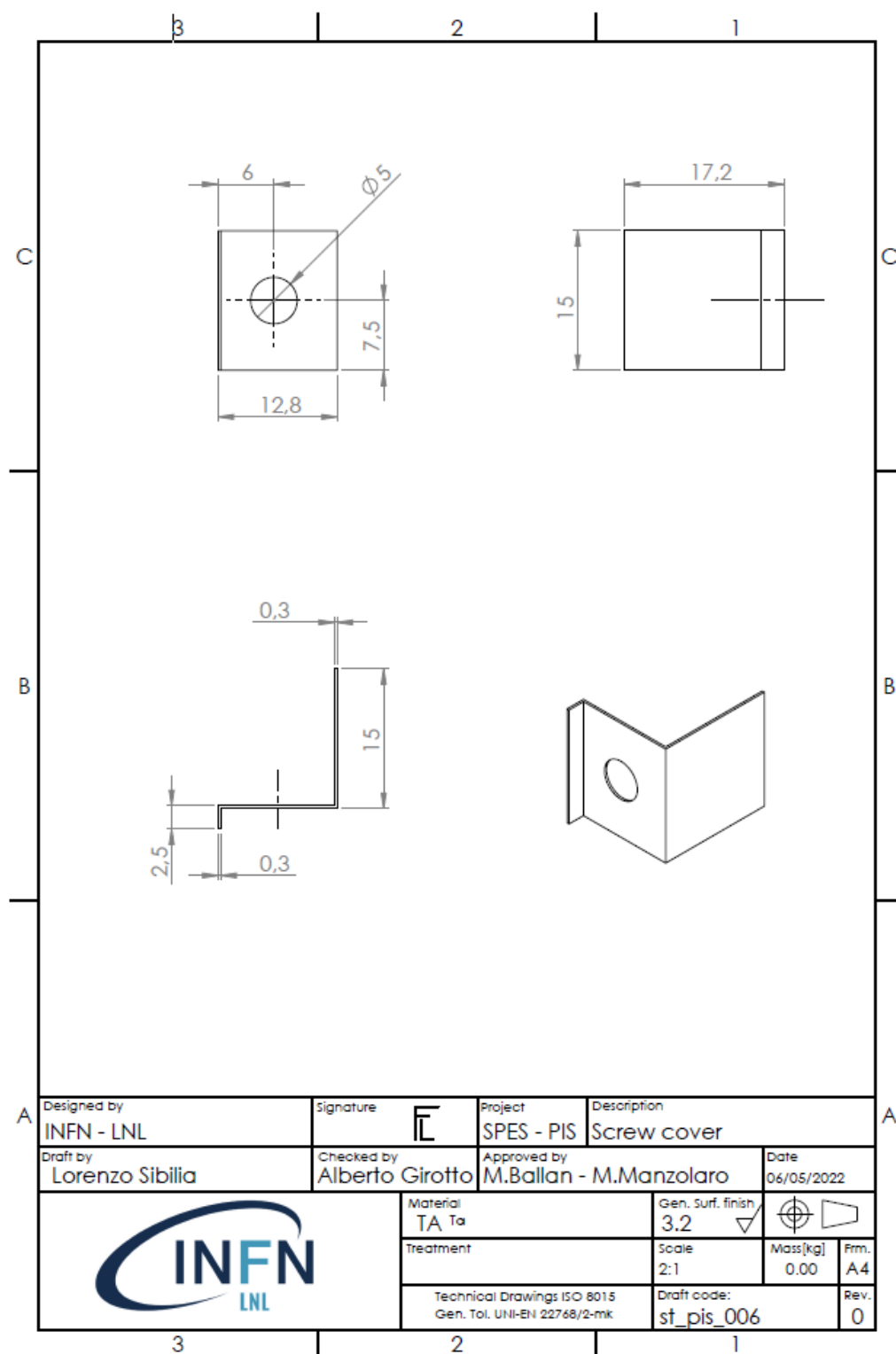


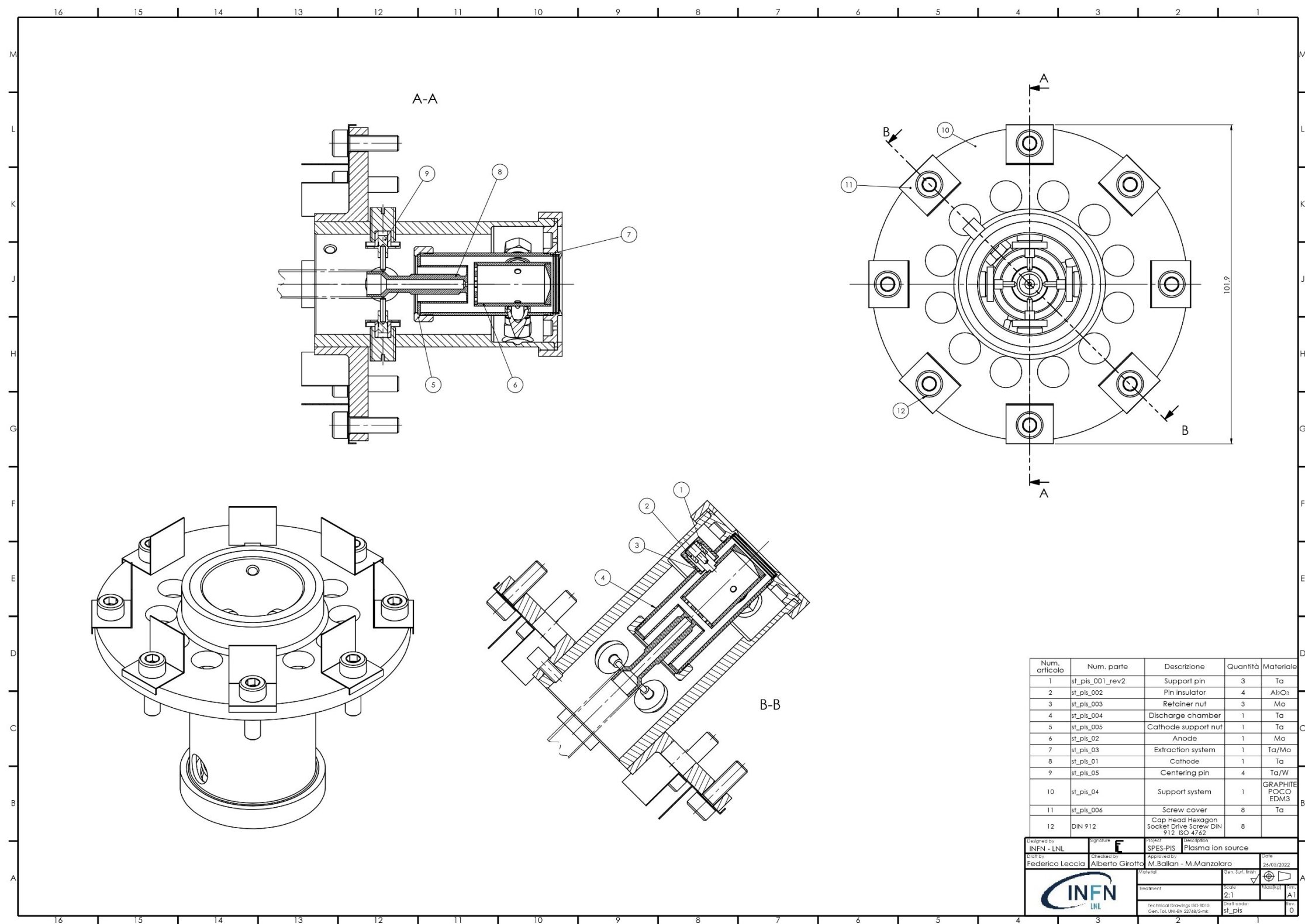




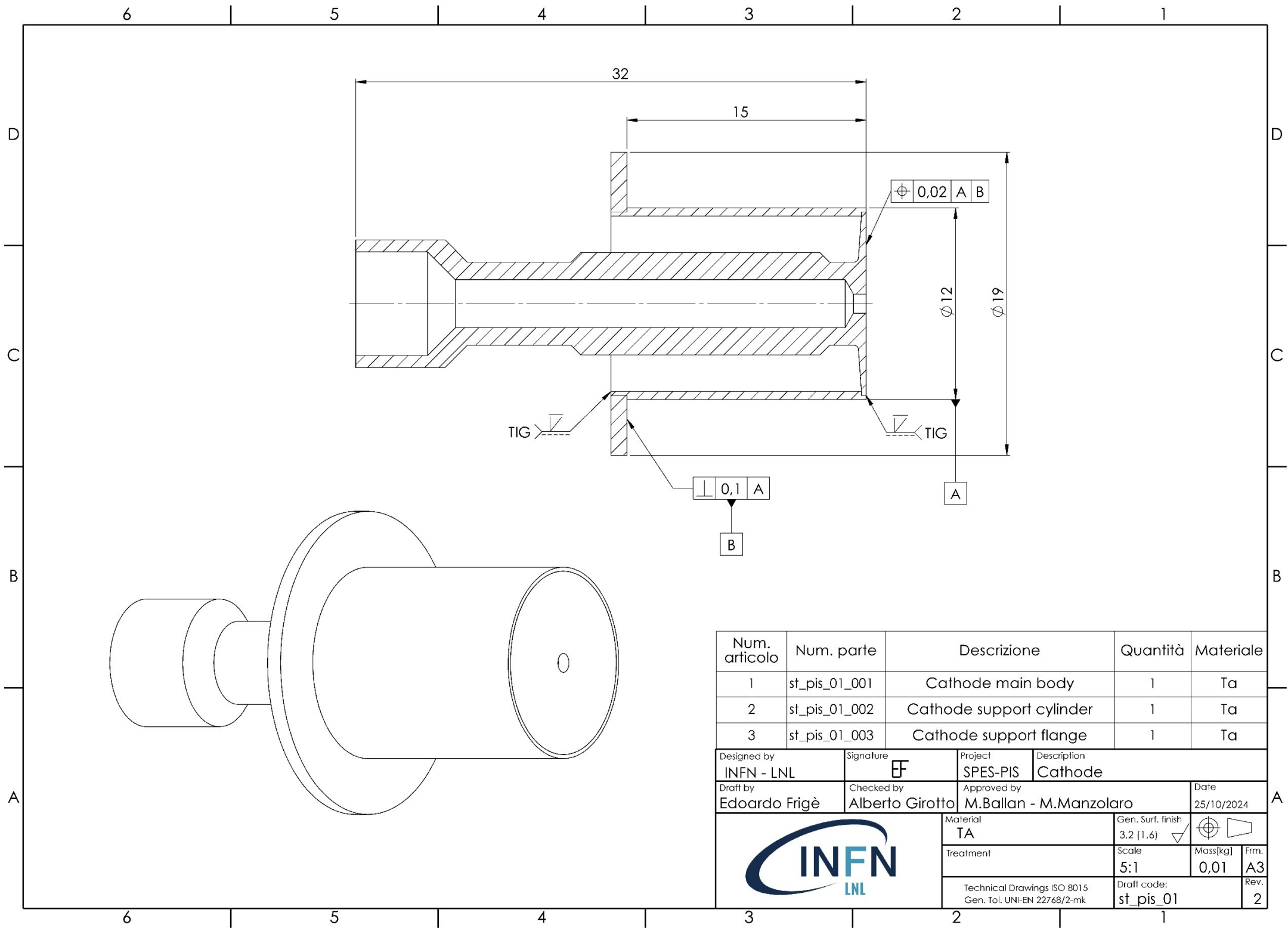


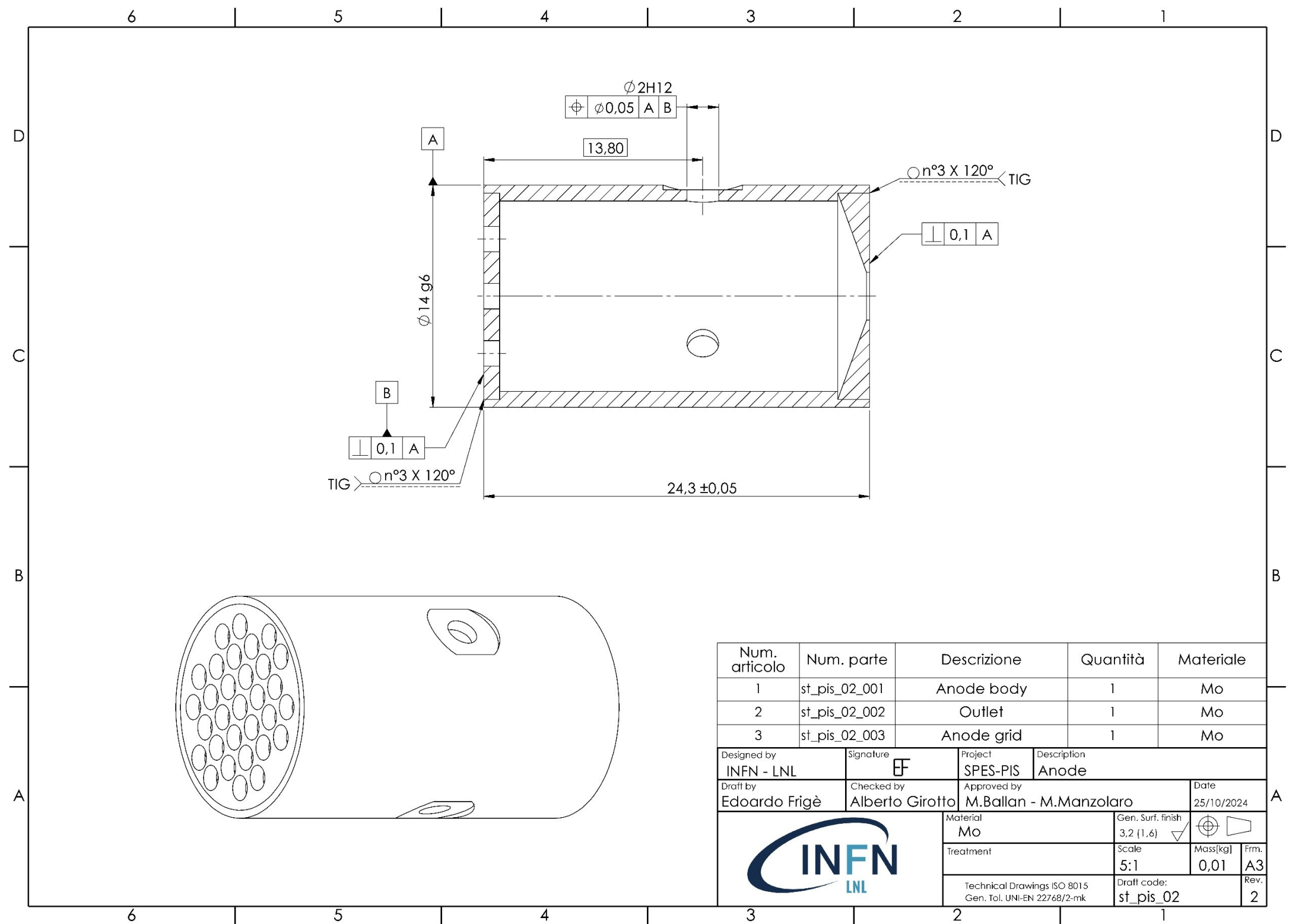


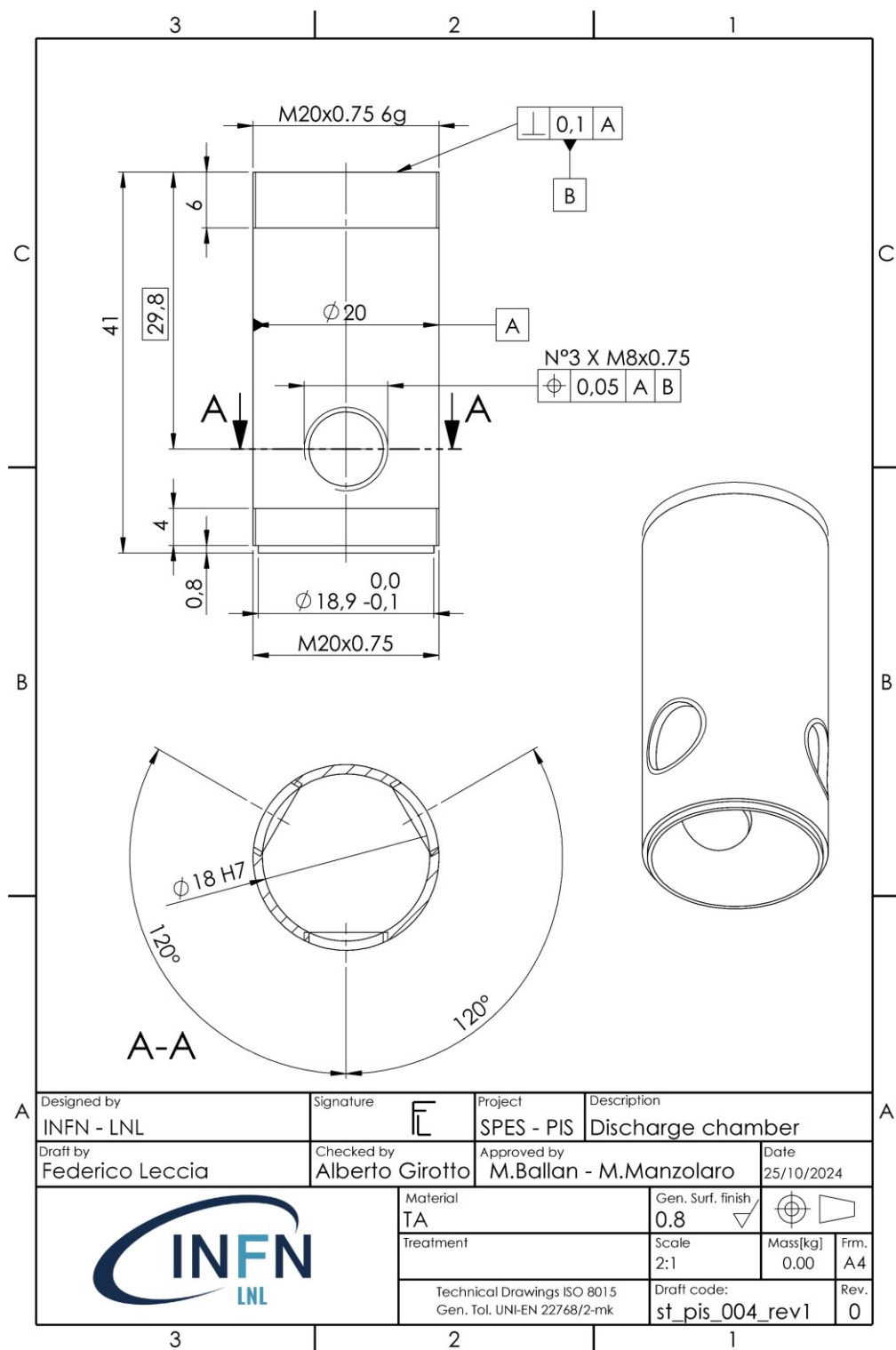




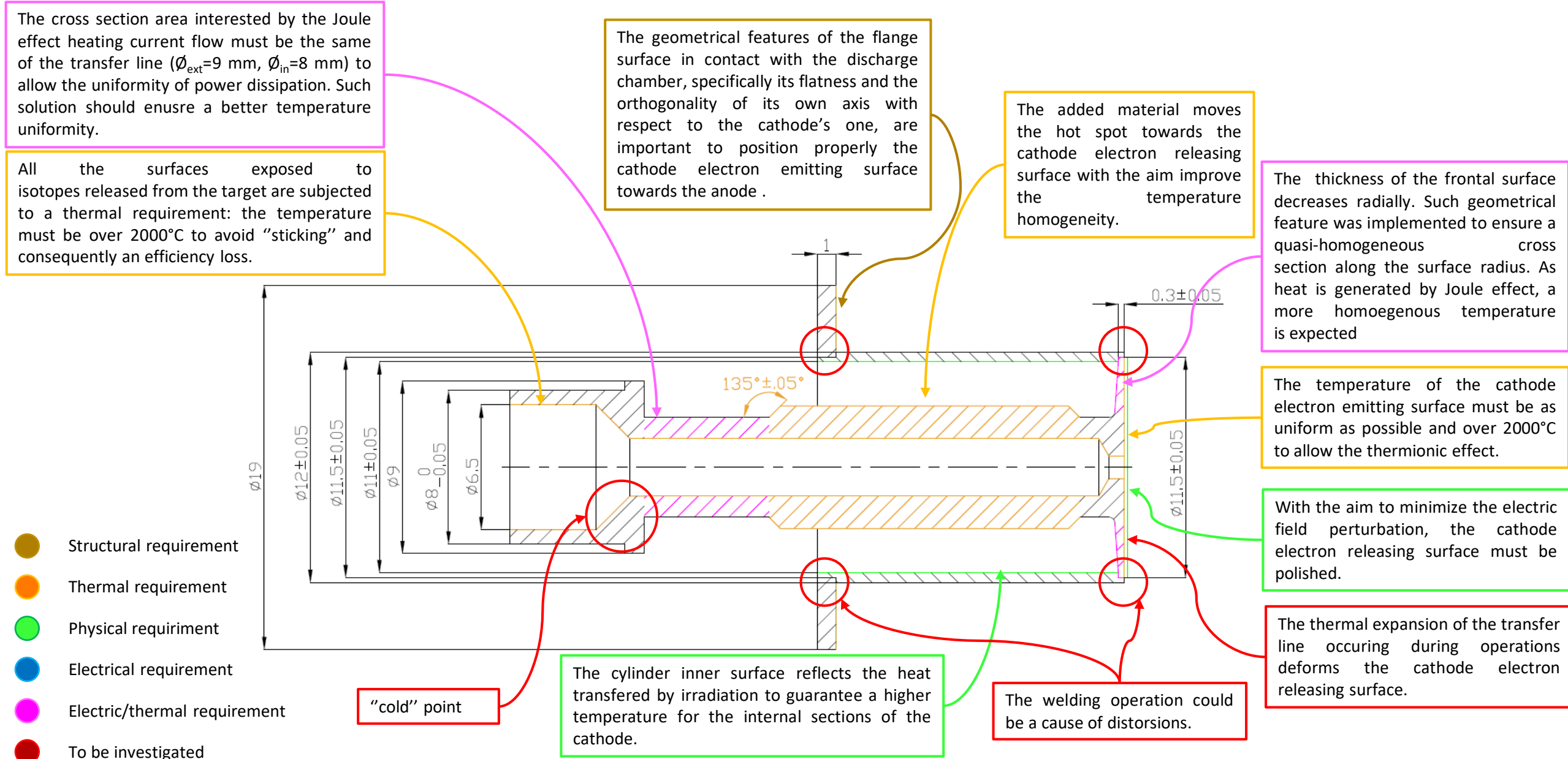
Appendix A.2 Tolerance optimisation FEBIAD ion source



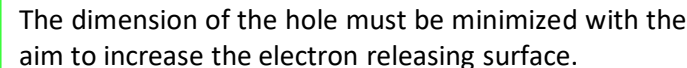
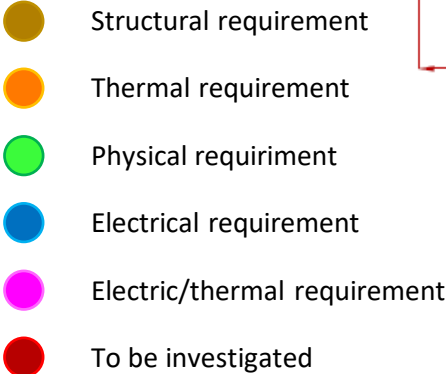




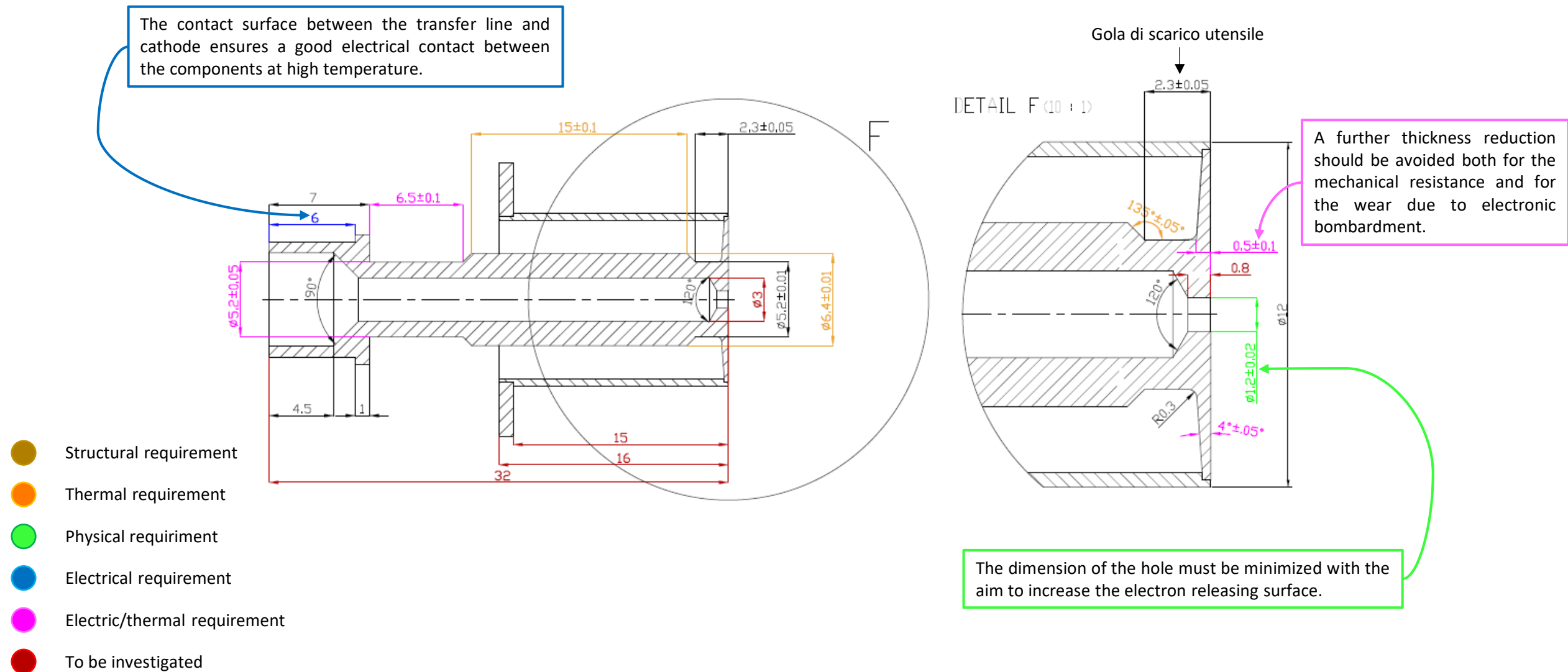
Cathode functional analysis: surfaces/volumes



Cathode functional analysis: dimensions



Cathode functional analysis: dimensions

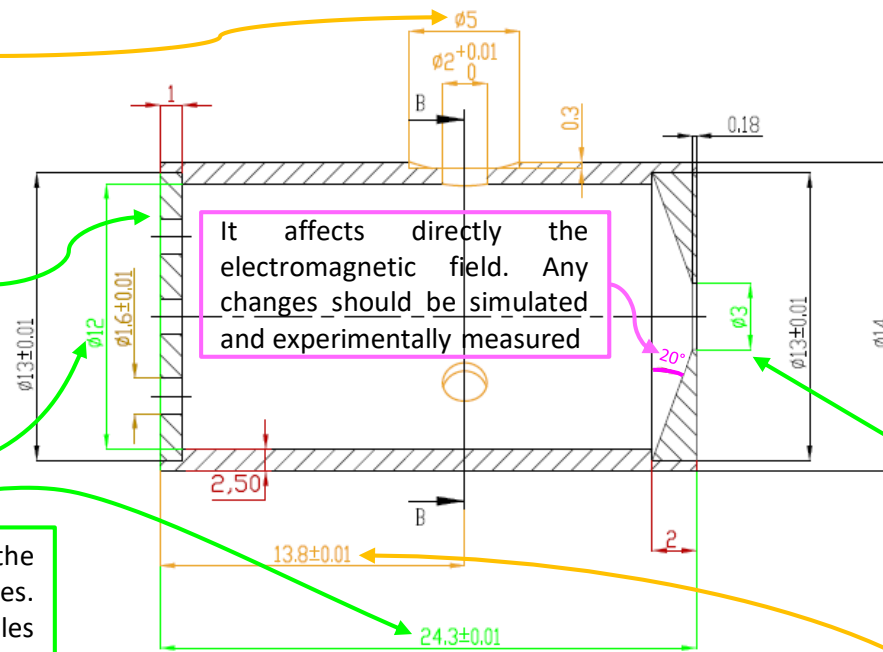


Anode functional analysis

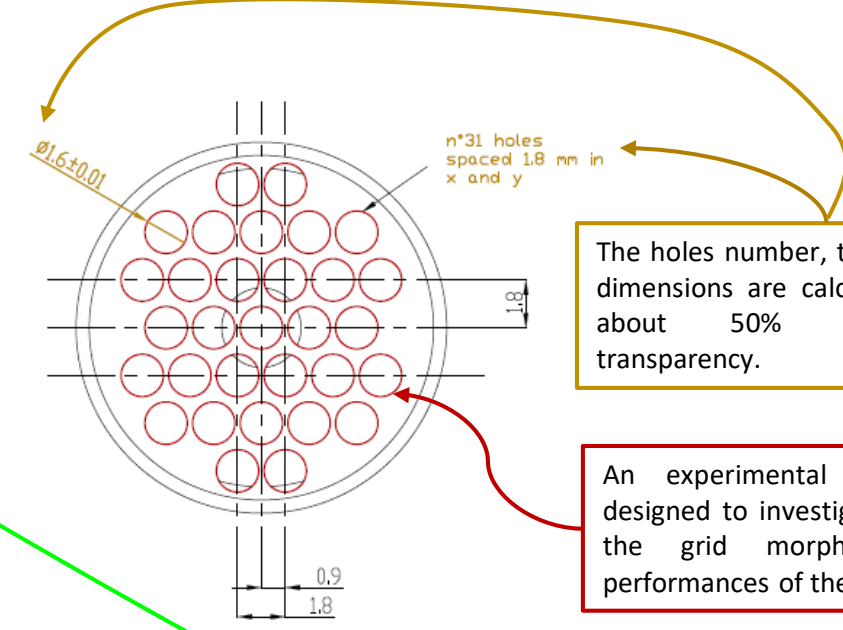
Decreasing the pin dimensions allows to minimize the heat transfer towards the alumina insulators ($T_{\max}=1500^{\circ}\text{C}$)

Aiming to minimize the electric field perturbation, the anode grid surface must be polished.

Decreasing the anode dimensions the temperature control improves. Moreover, the density of the particles that should be ionized increases.



It affects directly the electromagnetic field. Any changes should be simulated and experimentally measured

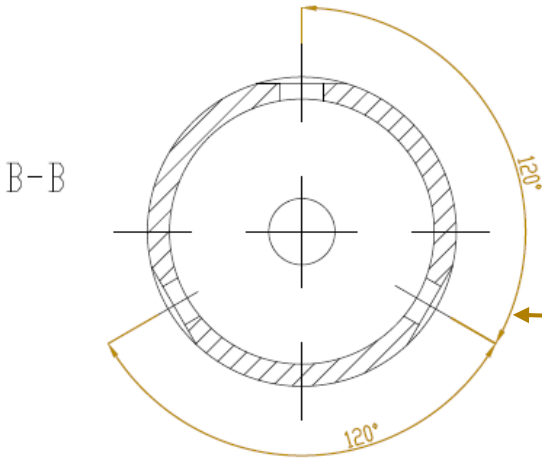


The holes number, their position and dimensions are calculated to obtain about 50% of geometric transparency.

An experimental setup can be designed to investigate the effect of the grid morphology on the performances of the ion source.

It controls directly the distance between the pins (i.e. alumina insulators) and the cathode HT surface. It must be enough to ensure a $T_{\max}$ of 1400°C for the alumina insulators.

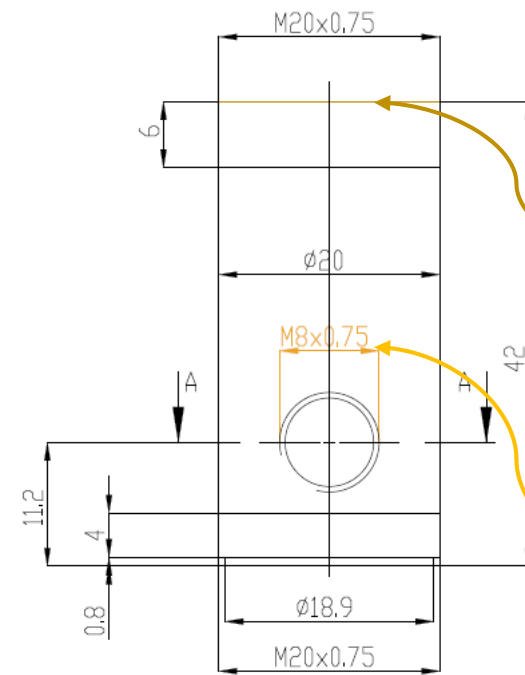
Reducing the extraction hole dimension reduces the emittance of the ionic beam (the probability to have the longitudinal component of extracted particles velocity greater than the others increases). Nevertheless, whether it is too small, the probability of the particles extraction decreases.



The pin housings are disposed at 120° to properly align the anode.

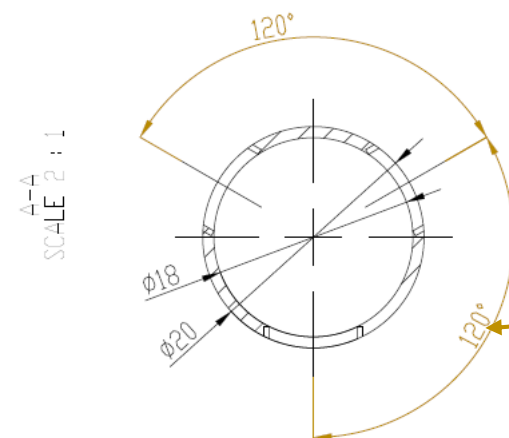
- Structural requirement
- Thermal requirement
- Physical requirement
- Electrical requirement
- Electric/thermal requirement
- To be investigated

Discharge chamber functional analysis



The geometric features of the discharge chamber surface in contact with the cathode flange affect the relative position between the anode grid and the cathode HT surface. Specifically its flatness and the perpendicularity with respect to the discharge chamber axis.

The dimension depends on the size of the pins and retainer nuts.

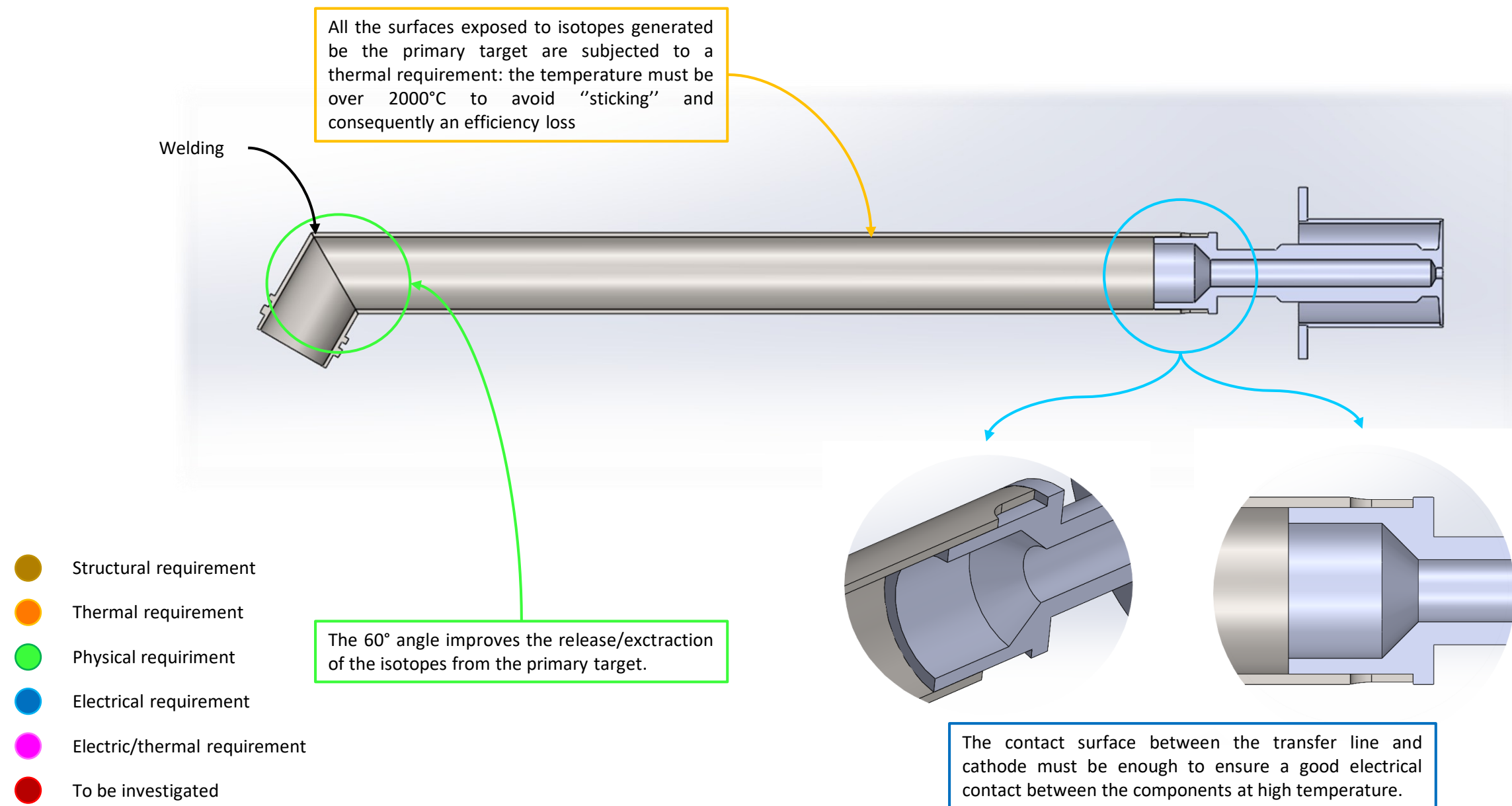


The retainer nuts housings are disposed at 120° to properly align the anode.

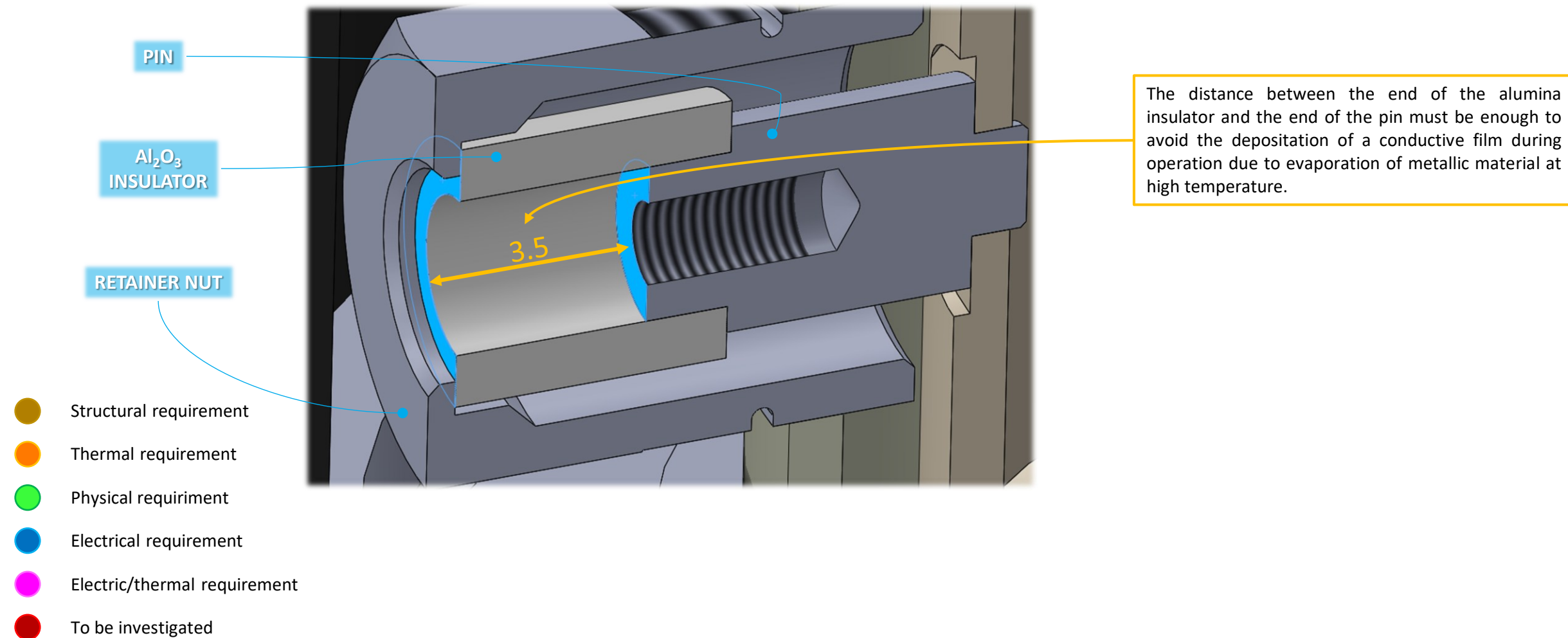
- Structural requirement
- Thermal requirement
- Physical requirement
- Electrical requirement
- Electric/thermal requirement
- To be investigated



Transfer line functional analysis



Anode support system functional analysis





Guideline for the assembly of the SPES Plasma Ion Source

F. Visentin, G. Vivian, M. Manzolaro

Abstract

In the context of the SPES project, the standardization of the assembly procedures ensures the required quality level for the Target Ion Source unit construction.

This document provides a standard procedure the SPES Plasma Ion Source assembly.

LNL - INFN
September 2015

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2.Cleaning	5
3.Assembly	5
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The PIS Assembly

The following paragraphs will list the equipment and material necessary to carry out the assembly operation and will describe the relative procedure. It is necessary to standardize the operation to obtain always the same configuration of the source, so the performance would be equal in any case. The component in exams is shown figure 1.

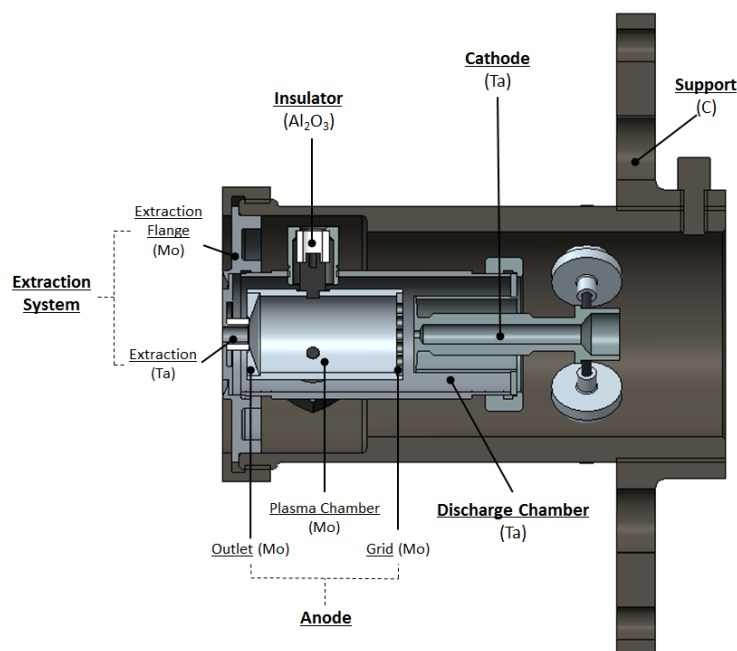


Figure 7.3: Electron Beam Plasma Ion Source (EBPIS)

PREPARATION

- 1) Obtain a good, full-size drawing of the ion source with all component (ST_PIS; AC_0005)
- 2) Get a current EBPIS parts list (Table 1). Some components for preliminary tests could be made in Tantalum or Molybdenum that have similar electrical properties.
- 3) Take a pair of latex gloves to prevent pollution of the PIS component
- 4) Collect all of the required ion source parts that are listed
- 5) Collect all the necessary tools for the assembly:
 - Tweezers
 - Screwdrivers
 - Allen
 - Alignment tool
 - Wrench
 - Caliber

- Tester

- 6) Evaluate the cleaning status of the component and the tools

Table 1 – EBPIS Parts List

Item	Material	Part No.	Quantity
Auxiliary component		AC_0005	1
Transfer line sub assembly		AC_0005_01	1
Electrical Clamp	Cu_ETP	AC_0005_003	2
Tantalum screw	Ta	AC_0005_004	2
Rectangular Nut M6	Mo	AC_0005_005	4
Thickness	Mo	AC_0005_006	1
Tantalum bush	Ta	AC_0005_001	1
Gas connection		AC_0007	1
Gas tube	Ta	AC_0005_002	1
Swagelok 90° elbow	Stainless Steel	SS-3M0-9	2
CABURN current break 3.2 mm	Stainless Steel + Al ₂ O ₃	CYB3_SW	1
Cathode			
Cathode sub assembly	Ta	ST_PIS_01	1
Cathode spacer 0.3	Mo		1
Support nut	Mo	ST_PIS_005	1
Anode			
Anode sub-assembly		ST_PIS_02	1
Anode tube	Ta / Mo	ST_PIS_02_001	1
Outlet	Ta / Mo	ST_PIS_02_002	1
Grid	Ta / Mo	ST_PIS_02_003	1
Anode support nut	Mo	ST_PIS_003	3
Anode support insulator	Al ₂ O ₃	ST_PIS_002	3
Anode support pin	Mo	ST_PIS_001	3
Anode Wire	Ta(2.5%W)		1
Discharge chamber	Ta	ST_PIS_004	1
Extraction system		ST_PIS_03	1
Extraction flange	Mo	ST_PIS_03_001	1
Extractor	Ta	ST_PIS_03_002	1
Extraction insulator	Al ₂ O ₃	ST_PIS_006	1
PIS Support		ST_PIS_04	1
Head flange	C	ST_PIS_04_001	1

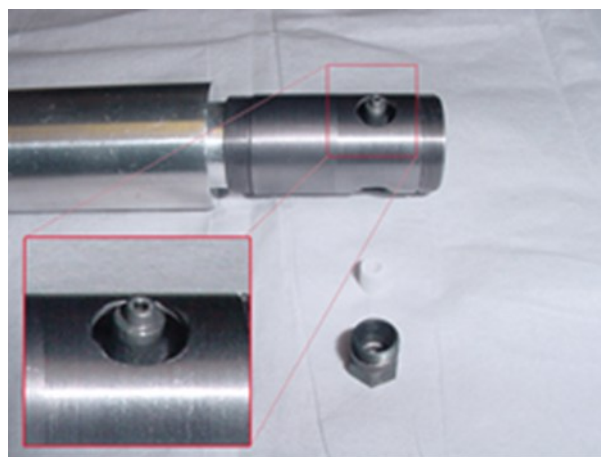
Outer tube	C	ST_PIS_04_002	1
End flange	C	ST_PIS_04_003	1
Centering set screw M4.5	C	ST_PIS_04_004	1
Alignment system		ST_PIS_05	4
Pin	W	ST_PIS_05_003	4
Support	Ta	ST_PIS_05_002	4
Insulator	Al ₂ O ₃	ST_PIS_002	4
M8 set screw	Ta	ST_PIS_05_001	4

CLEANING

Clean all metallic parts accurately using an ultra-sound cleaner and keep them clean by using latex gloves to handle the parts after cleaning and during assembly. Insulator and support system haven't to be clean because they absorb the cleaning liquid . (See as reference *Cleaning procedure for the metallic composing the SPES target-ion source system*, F. D'Agostini, 2015). Before washing the component evaluate their structural status. Try to pre assembly them to verify the correct relative position. If tools are not cleanliness, use acetone to clean them.

ASSEMBLY

- 1) First we have to assemble the anode with the discharge chamber. Insert the anode sub-assembly in the alignment tool. Then insert the discharge chamber and align its holes with the correspondent ones made in the anode. Make sure that a hole stay on top;
- 2) Take a support pin with tweezers and insert it in the anode hole. It has to fit perfectly to avoid the dis-alignment of the anode when it will be fixed;



Figur: Insertion of the support pin of the anode

- 3) Take an insulator of 5 mm length (make sure that all insulator have quietly the same length) and put it gently on the support pin. Be careful because reused Molybdenum material are very fragile;



Figure 7.4: Insulator positioning

- 4) Then take a support nut and screw it on the discharge chamber to fix the components already installed. The fixing hasn't to be strong because some adjustment are needing;

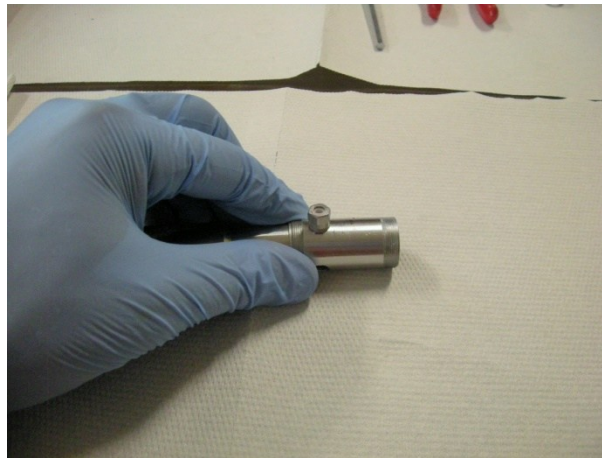


Figure 7.5: Assembly of the first anode support

- 5) Rotate the alignment tool of 120° and repeat the operation from 2) to 4);



Figure 7.6: Complete assembly of the anode support

- 6) When all anode support are installed proceed to fix and center the item by screwing the support nuts. Pay attention that the distances between anode and discharge chamber has to be equal in radial direction. Use a little screwdriver to evaluate the distances. Also the longitudinal inclination of the anode axis is very important. To avoid problem of high anode-cathode gap value it is necessary to push the anode in the cathode direction;



Figure 7.7: Control the gap between anode and discharge chamber

- 7) Use a tester to verify the isolation of the anode respect to the discharge chamber;
- 8) Take a caliper and measure the position of the anode, take 15 measurements and mediate them. Make the same operation on the cathode sub-assembly. The difference between the two measurements gives the anode-cathode gap. The gap has to be between 0.9 and 1.4 mm (best from 1.0 and 1.2 mm). If it is less we can

use a spacer to increase this distance, if it is higher it is necessary to reassemble the anode;



Figure 7.8: Measure of the gap between anode grid and cathode front surface

- 9) Now the extraction system can be assembled. Put the insulator on the extractor and then put all in the extraction flange;

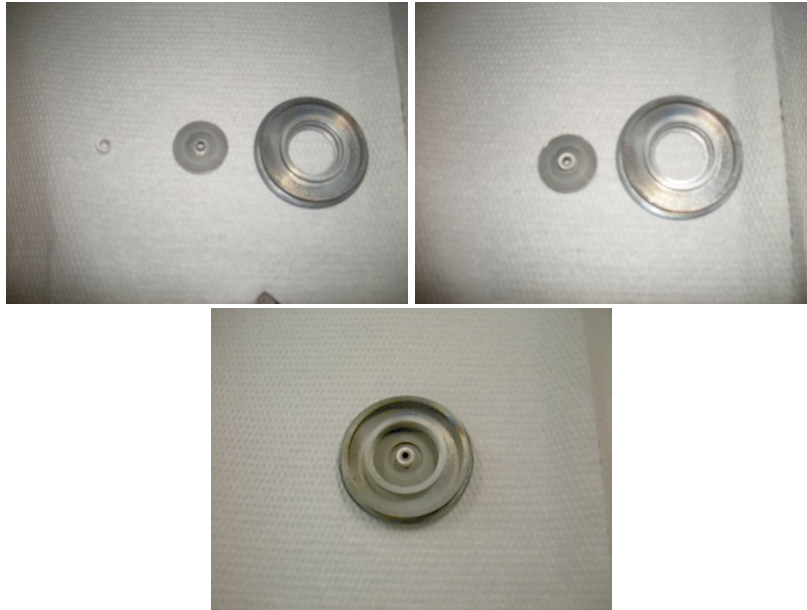


Figure 7.9: Extraction system assembly

- 10) Take the discharge chamber and screw it with the extraction system. Watch out that the anode touches the insulator but not the metallic part of extraction;



Figure 7.10: Discharge chamber assembled with the extraction flange

- 11) Recheck with the tester if the anode is electrically isolated;



Figure 7.11: Isolation check

- 12) Put the cathode inside the discharge chamber (use spacer if necessary) and fix it with the retainer nut. Hand fixing is enough;



Figure 7.12: Anode - Cathode sub assembly

- 13) Take the outer tube of the support system and put the anode-cathode sub-assembly into the relative hole. The extraction flange has the same diameter of the internal diameter of the support so it is automatically centered. Rotate quietly the flange to make sure that one of the anode retainer nut is aligned to the hole that allows the connection with the Tantalum wire. Than fix the component with the end flange;



Figure 7.13: Outer tube after assemble

- 14) It is possible to assemble the centering pin. Take first the insulator and put it into the pocket made on the M8 set screw. Screw the M8 set screw with hand but don't let it go too much inside the tube;

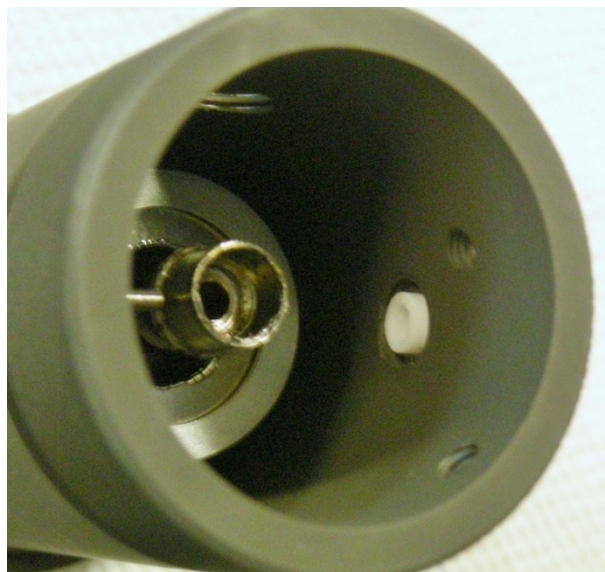


Figure 7.14: Tantalum M8 nuts assembled for mounting the centering pin

- 15) Put the pin into the relative support. Take the pre-assembled support pin and insert it into the support tube with the help of tweezers. Then screw again the M8 screw set until the pin makes contact with the cathode. Don't fix it hard;

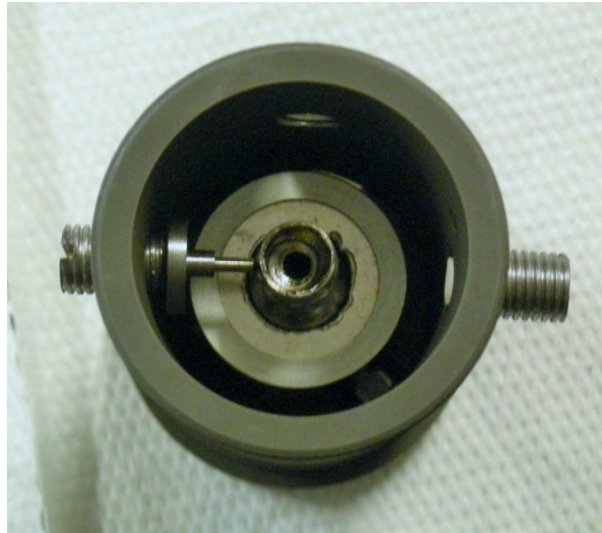


Figure 7.15: Opposite pin assembling

- 16) Repeat the operation 14) 15) for the other centering pin proceeding assembling the opposite first. Check with a caliber that the distance from the upper side of the cathode and the pin is higher than 3,7mm (+0.8mm radius of the pin-> 4.5mm). Some little adjustment are possible;

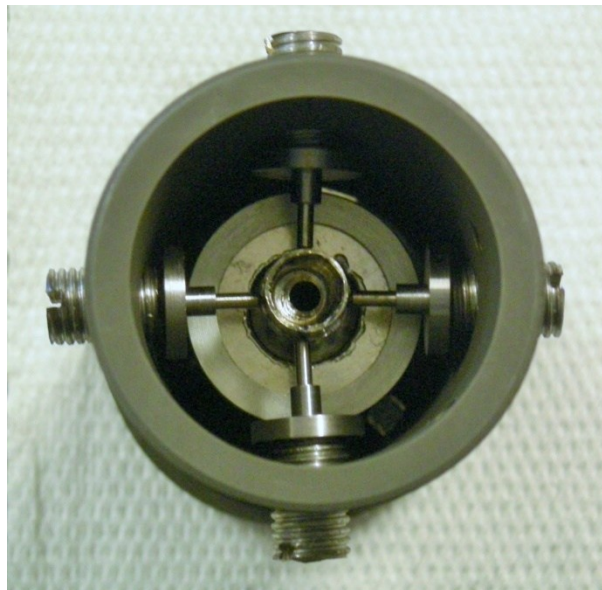


Figure 7.16: Centering pin assembled

- 17) Now the support flange can be screwed on the outer tube. Screw it until the hole for the set screw is aligned, then insert the M4 Graphite or Tantalum set screw;

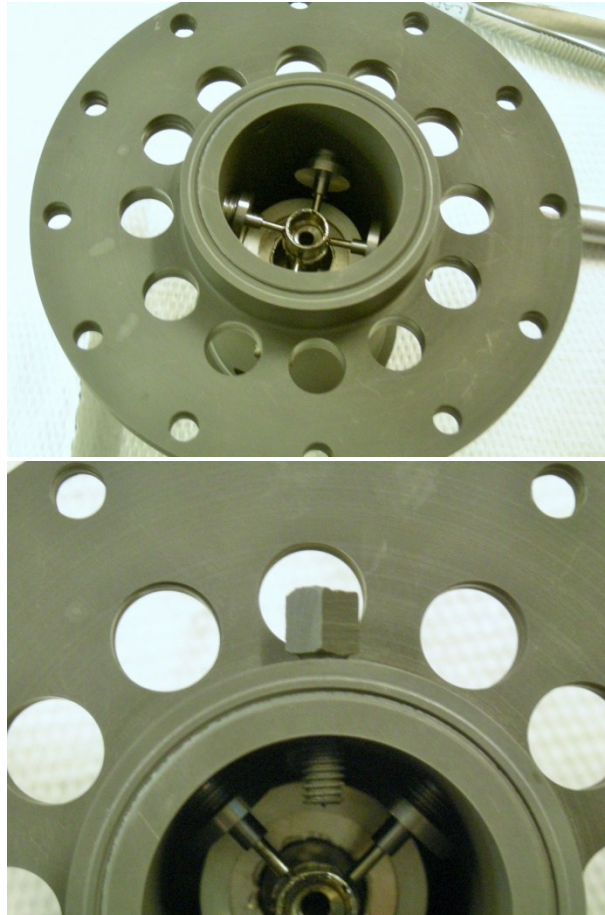


Figure 7.17: PIS after assembling the support flange

- 18) Take the transfer line sub assembly and connect it with the cathode. After this operation the M8 set screw can be fixed with a screwdriver but it needs attention because Graphite is fragile. Centering pin has to be screwed as hard as possible to fix the Cathode. Transfer line must be held in position because the tightening of pins on cathode can make it rotate. Control also that the frontal flange doesn't rotate and the hole for the insertion of the anode wire is aligned;



Figure 7.18: Assembling of the transfer line

- 19) A filament in Tantalum can be connected to the anode by the hole on the support outer tube. It has to pass into the holes of the flange because it will be connected to the chamber. Use an insulator (15 – 20 mm length) to avoid contact with the support;

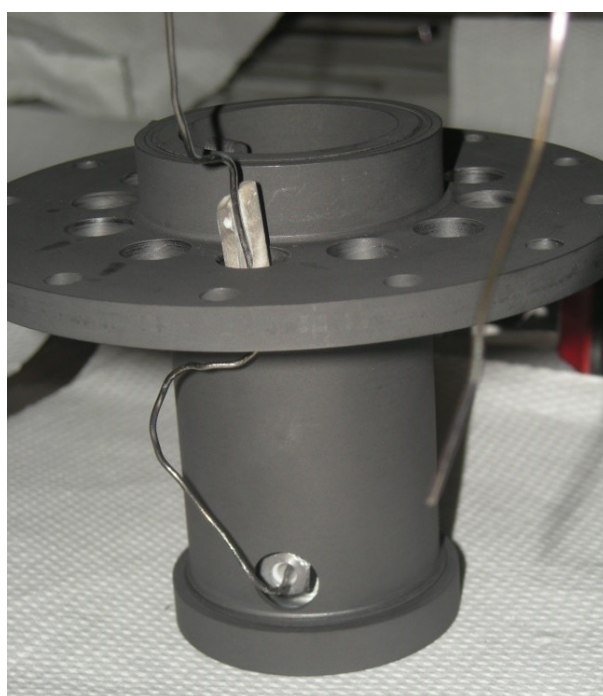


Figure 7.19: Anode wire connection

- 20) Now the PIS is complete, it is possible to mount it on the chamber. Insert it carefully in the chamber hole. Put first a Screw on top so the Ion source stand by itself. Then Screw the other three (or seven if the screw are in SS) and fix the

position. If the screws are in Tantalum use 4 of them instead if they are in Stainless steel use 8 to avoid heat by joule effect;

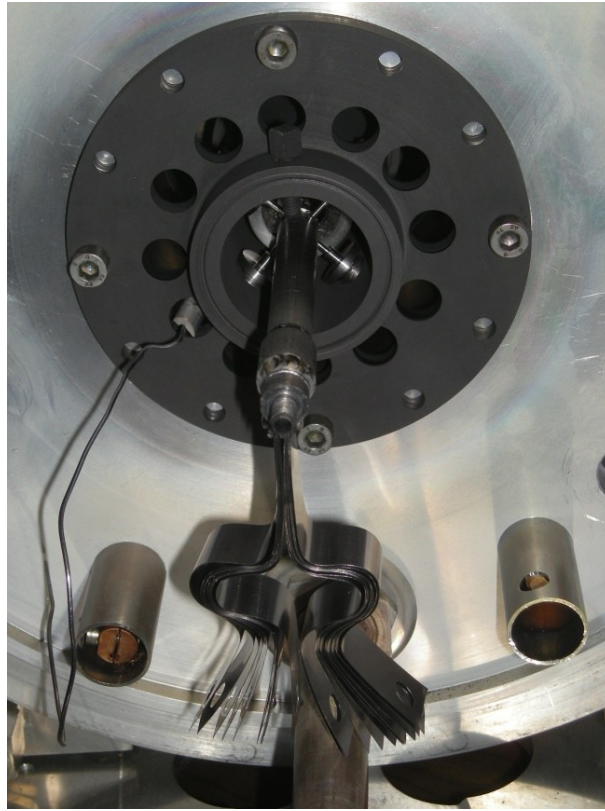


Figure 7.20: PIS assembled on the chamber

- 21) Now it is possible to connect the electrical clamps and the anode filament to the chamber;



Figure 7.21: Anode wire and electrical connection attached to the chamber

- 22) At the end the gas tube can be connected to the transfer line after checking that the gas insulator is isolated;



Figure 7.22: Gas connection protected by Tantalum sheet

- 23) Then isolate all thermal sensible parts with Tantalum sheets. Now the chamber can be closed and installed into the Front-End.

References

- [1] D. Stracener, GUIDELINE FOR ASSEMBLY of Electron-Beam-Plasma Ion Source, internal report, HRIBF, ORNL (US Department Of Energy).
- [2]. Mattia Manzolaro, Study, design and test of the Target – Ion Source system for the INFN SPES facility, Ph.D. thesis, Università degli Studi di Padova, 2010.

Appendix D Python code tolerance stack-up analysis and optimisation

Appendix D.1 Main

```
# Per prima cosa importo le librerie necessarie:
import random

from tolleranze3 import *
from funzioni import *
import numpy as np
import matplotlib.pyplot as plt

from scipy.stats import invgauss
import math

# import pandas lib as pd
import pandas as pd
# Aggiungere anche libreria openpyxl

# Export multiple plots in a PDF (multiple pages): https://stackoverflow.com/questions/38938454/python-saving-multiple-subplot-figures-to-pdf/38943527#38943527
from matplotlib.backends.backend_pdf import PdfPages

# Per gestione data:
from datetime import datetime
import time

# per aprire automaticamente pdf generato:
import os

# Per permutazioni?
import itertools

# Per calcolo tempo esecuzione
import time

# Importo file con funzione per tolerance stackup analysis, spostata in un file a sè stante
```



```

# Prendo inizio generale programma:
startTime = time.time()

#
'''
# || ***** SEZIONE PER LETTURA DATI DA FILE EXCEL E GENERAZIONE DATI PER SIMULAZIONI
*****
#
'''

# Modificare qua solo se è necessario apportare modifiche alla lettura del file o ai dati:
# Definisco i tipi di dati delle colonne presenti nel file Excel
tipiDati = {'Matrice Rototraslazione': str, 'Elemento': str, 'Misura': float, 'Note': str}

# Genero i dataframe contenenti i fogli excel dell'anodo e del catodo, dai quali poi estrarrò i dati
necessari:
dataframeAnodo = pd.read_excel(nomeFileExcel + '.xlsx', sheet_name='Anodo', na_values="NA",
converters=tipiDati)
dataframeAnodo.drop(columns='Note:', inplace=True) # Rimuovo colonna "Note:", non serve averla nel
dataframe
dataframeCatodo = pd.read_excel(nomeFileExcel + '.xlsx', sheet_name='Catodo', na_values="NA",
converters=tipiDati)
dataframeCatodo.drop(columns='Note:', inplace=True) # Rimuovo colonna "Note:", non serve averla nel
dataframe

# Imposto gli index del dataframe in base al nome della misura, utile per la selezione successiva del
valore appropriato
dataframeAnodo.set_index(['Matrice Rototraslazione', 'Elemento'], drop=True, append=False, inplace=True,
verify_integrity=True)
dataframeCatodo.set_index(['Matrice Rototraslazione', 'Elemento'], drop=True, append=False, inplace=True,
verify_integrity=True)

```



```

+ int(round(dataframeAnodo.loc[('M01', 'Tolleranza INCREMENTO'), 'Misura']*(10**decimMax))),
int(round(dataframeAnodo.loc[('M01', 'Tolleranza INCREMENTO'), 'Misura']*(10**decimMax)))
    valTollAnodoM12 = np.arange(int(round(dataframeAnodo.loc[('M12', 'Tolleranza MIN'),
'Misura']*(10**decimMax))), int(round(dataframeAnodo.loc[('M12', 'Tolleranza MAX'), 'Misura']*(10**decimMax)))
+ int(round(dataframeAnodo.loc[('M12', 'Tolleranza INCREMENTO'), 'Misura']*(10**decimMax))),
int(round(dataframeAnodo.loc[('M12', 'Tolleranza INCREMENTO'), 'Misura']*(10**decimMax)))
    valTollAnodoM23 = np.arange(int(round(dataframeAnodo.loc[('M23', 'Tolleranza MIN'),
'Misura']*(10**decimMax))), int(round(dataframeAnodo.loc[('M23', 'Tolleranza MAX'), 'Misura']*(10**decimMax)))
+ int(round(dataframeAnodo.loc[('M23', 'Tolleranza INCREMENTO'), 'Misura']*(10**decimMax))),
int(round(dataframeAnodo.loc[('M23', 'Tolleranza INCREMENTO'), 'Misura']*(10**decimMax)))

    if debug:
        print('Valori di tolleranza ammissibili per ogni elemento della catena, moltiplicati per
10^('+str(decimMax)+'):', flush=True)
        print(valTollCatodoM01, flush=True)
        print(valTollCatodoM12, flush=True)
        print(valTollCatodoM23, flush=True)
        print(valTollCatodoM34, flush=True)
        print(valTollAnodoM01, flush=True)
        print(valTollAnodoM12, flush=True)
        print(valTollAnodoM23, flush=True)

    multidim = [valTollCatodoM01, valTollCatodoM12, valTollCatodoM23, valTollCatodoM34, valTollAnodoM01,
valTollAnodoM12, valTollAnodoM23]

    numElemCatToll = len(multidim) # Praticamente contiene il numero totale degli elementi della catena di
tolleranza (catodo+anodo)

# https://stackoverflow.com/questions/70476797/all-combinations-of-all-elements-of-a-2d-array
startTimeGenerComb = time.process_time()
combinazioniToll = np.stack(np.meshgrid(*multidim), axis=-1).reshape(-1, len(multidim))
if debug:
    print('combinazioni calcolate, INT:', flush=True)
    print(combinazioniToll, flush=True)
    #pd.DataFrame(combinazioniToll).to_csv('combinazioniTollOrigINT.csv', mode='w', index=False,

```



```

header=False)
print('', flush=True)
# Ora riporto le combinazioni ai valori "corretti" dividendo tutti gli elementi per 10^(decimMax)
combinazioniToll = combinazioniToll/(10**decimMax)
if debug:
    print('combinazioni calcolate, valori float:', flush=True)
    print(combinazioniToll, flush=True)
print(str(len(combinazioniToll)) + ' combinazioni tolleranze calcolate in: ' + str(time.process_time() -
startTimeGenerComb) + ' s\n', flush=True)
#pd.DataFrame(combinazioniToll).to_csv('combinazioniTollDivisioneFLOAT.csv', mode='w', index=False,
header=False)
print('', flush=True)
# Ottengo la lista dei file presenti nella cartella attuale, per non eseguire nuovamente iterazioni già
presenti.
directory = os.getcwd() # Ottiene la directory attuale (CurrentWorkingPath)
if debug:
    print(directory, flush=True)
# onlyfiles = [os.path.join(directory, f) for f in os.listdir(directory) if
os.path.isfile(os.path.join(directory, f))]
# print(onlyfiles)
# nomiFile = {s.removesuffix(cwd) for s in onlyfiles} # Ottengo solo i nomi dei file
nomiFile = [f for f in os.listdir(directory) if f.endswith('.pdf')] # Ottengo la lista dei file PDF
presenti nella directory
if debug:
    print('File pdf presenti nella directory di lavoro:', flush=True)
    print(nomiFile, flush=True)

# Per ogni stringa mantengo gli ultimi 48 caratteri, ovvero i parametri delle tolleranze (e l'estensione
'.pdf'), senza i valori di sigma e la valutazione della simulazione:
caratteriTolleranzeConEstens = 3 + 5 * numElemCatToll # 3 per estensione "pdf", 5 per ogni valore di
tolleranza ""
nomiFile = [e[-caratteriTolleranzeConEstens:] for e in nomiFile]
if debug:
    print('\n*****\n', flush=True)
    print(nomiFile, flush=True)

```

```

# Carico dati delle combinazioni da scartare oppure ne viene creato uno vuoto se il csv non esiste
if os.path.exists(nomeFileScarti + '.csv'):
    try:
        iterScartate = pd.read_csv(nomeFileScarti + '.csv', header=None)
        print('File csv "' + nomeFileScarti + '" caricato')
    except pd.errors.EmptyDataError: # Se ho csv vuoto viene lanciata exception
        print('File csv "' + nomeFileScarti + '" vuoto!')
        listVuota = [0] * numElemCatToll
        iterScartate = pd.DataFrame([listVuota])#, listVuota]) # In questo caso vado ad aggiungere una
        # prima riga nulla (combinazione da scartare a prescindere)
        iterScartate.to_csv(nomeFileScarti + '.csv', mode='x', index=False, header=False) #
        # http://pandas.pydata.org/pandas-docs/dev/reference/api/pandas.DataFrame.to\_csv.html
        # https://docs.python.org/3/library/functions.html#open https://tutorial.eyehunts.com/python/python-file-modes-open-write-append-r-r-w-w-x-etc/
        print('"' + nomeFileScarti + '.csv" correttamente inizializzato!')
        #continue
        #columns = ['t1c', 't2c', 't3c', 't4c', 't5c', 't6c', 't1a', 't2a', 't3a']
    else: # Se non c'è un file csv lo creo e gli inserisco una prima riga nulla
        listVuota = [0] * numElemCatToll
        iterScartate = pd.DataFrame([listVuota])#, listVuota])
        #columns = ['t1c', 't2c', 't3c', 't4c', 't5c', 't6c', 't1a', 't2a', 't3a'] # forse inutile
        iterScartate.to_csv(nomeFileScarti + '.csv', mode='x', index=False, header=False) #
        # http://pandas.pydata.org/pandas-docs/dev/reference/api/pandas.DataFrame.to\_csv.html
        # https://docs.python.org/3/library/functions.html#open
        print('File "' + nomeFileScarti + '.csv" creato e inizializzato!')

# Funzione che si occupa di eseguire la singola iterazione, eseguita da vari worker
def eseguiIterazione(iterazione):

    # Aggiorno variabile del worker contenente le iterazioni da scartare solo se ne sono state aggiunte di
    # nuove:
    global indiceScarti, iterScartate

    # Se ho
    # un aggiornamento delle iterazioni da scartare le aggiungo alla variabile interna del worker

```

[illegible]

```

global nomiFile, queueScarti
if nomeIterazione in nomiFile:
    scarto = [False, False, 0]
    queueScarti.put(scarto)
    if debugWorkerIterazione:
        print('Iterazione ' + str(numeroIterExec) + ' gia\' calcolata, passo alla successiva!', flush=True)
    elif (iterScartate.shape[0] != 0) and any(np.equal(iterScartate, iterazione).all(1)): # Verifico se
l'iterazione è presente tra quelle da scartare (come array numpy), prima controllo se iterScartate ha elementi
all'interno, altrimenti la funzione np.equal lancia eccezione!
        scarto = [False, False, 0]
        queueScarti.put(scarto)
        if debugWorkerIterazione:
            print('Iterazione ' + str(numeroIterExec) + ' da scartare, passo alla successiva!', flush=True)
    else:
        # Una nuova combinazione la vado a calcolare solo se la coda non è intasata, altrimenti rimango in
        attesa:
        while sharedObject.pause:
            print('Coda piena, pausa worker TSUA...', flush=True)
            time.sleep(7) # Se ho troppi elementi nella coda
            #startTimeIter = time.process_time() # SE NON RESETTO IL TIMER VADO A TENERE CONTO ANCHE DELL'ATTESA
            SVUOTAMENTE CODA
            global dataframeCatodo, dataframeAnodo, sigmaDesiderato, stampaRisultati, stampaInfoAggiuntive,
            stampaMatriciRotaz
            toleranceStackUpAnalysis(queueScarti, dataframeCatodo, dataframeAnodo, iterazione[0], iterazione[1],
            iterazione[2],
                                     iterazione[3], iterazione[4], iterazione[5], iterazione[6], sigmaDesiderato,
            sigmaInf,
                                     stampaRisultati, stampaInfoAggiuntive, stampaMatriciRotaz)
            if debugWorkerIterazione:
                print('Iterazione ' + str(numeroIterExec) + ' eseguita in: ' + str(time.process_time() - startTimeIter)
+ ' secondi\n', flush=True)

# initialize worker processes: Assegno le variabili da utilizzare ai vari processi (ogni processo ha la sua
copia)

```

```
# https://superfastpython.com/multiprocessing-pool-shared-global-variables/
def init_worker(queueIn, sharedNameObjectGlob, decimMaxGlob, iterScartateGlob, indiceScartiGlob,
dataframeCatodoGlob, dataframeAnodoGlob, combinazioniTollGlob, nomiFileGlob, sigmaDesideratoGlob, sigmaInfGlob,
stampaRisultatiGlob, stampaInfoAggiuntiveGlob, stampaMatriciRotazGlob, debugWorkerIterazioneGlob):
    # declare scope of a new global variable
    global dataframeCatodo
    # store argument in the global variable for this process
    dataframeCatodo = dataframeCatodoGlob
    global dataframeAnodo
    dataframeAnodo = dataframeAnodoGlob
    global combinazioniToll
    combinazioniToll = combinazioniTollGlob
    global nomiFile
    nomiFile = nomiFileGlob
    global sigmaDesiderato
    sigmaDesiderato = sigmaDesideratoGlob
    global sigmaInf
    sigmaInf = sigmaInfGlob
    global stampaRisultati
    stampaRisultati = stampaRisultatiGlob
    global stampaInfoAggiuntive
    stampaInfoAggiuntive = stampaInfoAggiuntiveGlob
    global stampaMatriciRotaz
    stampaMatriciRotaz = stampaMatriciRotazGlob
    global queueScarti
    queueScarti = queueIn
    global sharedObject
    sharedObject = sharedNameObjectGlob
    global decimMax
    decimMax = decimMaxGlob
    global indiceScarti
    indiceScarti = indiceScartiGlob
    global iterScartate
    iterScartate = iterScartateGlob
    global debugWorkerIterazione
    debugWorkerIterazione = debugWorkerIterazioneGlob
```

```

def gestioneScarti(queueScarti, sharedObject, nomeFileScarti, dataframeCatodo, dataframeAnodo, decimMax,
numIterTOT, tempoInizio, debugGestoreScarti): # riceve dai processi le combinazioni che sono da scartare,
calcola il necessario e le aggiunge alla variabile degli scarti generale
    print('\nGestore tolleranze da scartare attivo!', flush=True)
    delayCSV = 0
    numIterStampate = 0
    numeroIterazioniGlobali = 0 # tiene traccia iterazioni globali di tutto il programma
    while True:
        # Aspetto di ricevere un elemento nella coda
        scarto = queueScarti.get() # NOTA: scarto = [scarto SUP, scarto INF, tutti i valori tolleranza...]
        if debugGestoreScarti:
            print('Valore queue ricevuto: ' + str(scarto), flush=True)
            print('Lunghezza queue approssimativa: ' + str(queueScarti.qsize()))
        # Se la coda aumenta troppo devo mettere in pausa i worker TSUA
        if (queueScarti.qsize() > 50) & (sharedObject.pause == False):
            sharedObject.pause = True
        elif queueScarti.qsize() < 5 & (sharedObject.pause == True):
            sharedObject.pause = False
        startTimeIterScarti = time.process_time()
        # Arrivo qua quando nella coda è presente un dato
        # Vedo se è scarto SUP o INF, genero le relative combinazioni
        if scarto is None: # Per primo verifico caso None, altrimenti poi "None[0]" ritorna errore
            tempoDelta=time.time() - tempoInizio
            velEsec=numeroIterazioniGlobali/tempoDelta+0.05
            print('\nIterazioni totali eseguite: ' + str(numeroIterazioniGlobali) + ' / ' + str(numIterTOT) +
            ', ' + str(round((numeroIterazioniGlobali*100)/numIterTOT, 2)) + '%, ' + 'in: ' + str(round(tempoDelta, 2)) +
            ' secondi - media: ' + str(round(velEsec, 2)) + ' iter/sec - Tempo rimanente stimato: ' +
            str(round((numIterTOT-numeroIterazioniGlobali)/(velEsec * 60), 2)) + ' minuti', flush=True) # +0.05 per
            evitare caso divisione per zero
            print('Scarti presenti nel CSV: ' + str(len(sharedObject.scarti)) + ' - combinazioni scartate \\'a
            priori\': ' + str(len(sharedObject.scarti) - sharedObject.numero), flush=True) # Per avere le combinazioni
            scartate senza alcun calcolo devo rimuovere le volte che sono state calcolate combinazioni da scartare
            print('\nElemento \\'None\' rilevato, salvo CSV e termino gestore.', flush=True)
            scartiUnicidf = pd.DataFrame(sharedObject.scarti)
            scartiUnicidf.to_csv(nomeFileScarti + '.csv', mode='w', index=False, header=False) #

```



```

# Usando le funzioni messe a disposizione da Pandas ho un possibile decremento delle prestazioni
(array numpy da convertire ogni volta in un dataframe Pandas)
# Per limitare queste perdite di tempo, aggiorni il CSV una volta ogni 100 cicli
if delayCSV >= 200:
    startTimeIterScartiAggiorn = time.process_time()
    scartiUnicidf = pd.DataFrame(scartiUnici)
    scartiUnicidf.to_csv(nomeFileScarti + '.csv', mode='w', index=False, header=False) #
    delayCSV = 0
    print('Nuovi scarti aggiunti al CSV in: ' + str(time.process_time() -
    startTimeIterScartiAggiorn) + ' secondi\n', flush=True)
    print('Scarti presenti nel CSV: ' + str(len(sharedObject.scarti)), flush=True)
else:
    delayCSV = delayCSV + 1
# scarti unici contiene ora l'ultima versione degli scarti, aggiorni quindi la sharedObject
sharedObject.scarti = scartiUnici
# Incrementa la variabile che tiene traccia della "versione" degli scarti presenti nella
sharedObject
sharedObject.numero = sharedObject.numero + 1
# print('Combinazioni scartate \a priori\': ' + str(len(sharedObject.scarti)-sharedObject.numero),
flush=True) # Per avere le combinazioni scartate senza alcun calcolo devo rimuovere le volte che sono state
calcolate combinazioni da scartare
numeroIterazioniGlobali += 1
# Parte di output con informazioni generali sul numero delle iterazioni eseguite, il tempo impiegato e
gli scarti
if (numeroIterazioniGlobali - numIterStampate) >= 10: # Per non saturare l'output aggiorni ogni tot
cicli
    numIterStampate = numeroIterazioniGlobali
    tempoDelta=time.time() - tempoInizio
    velEsec=numeroIterazioniGlobali/tempoDelta+0.05
    print('\nIterazioni totali eseguite: ' + str(numeroIterazioniGlobali) + ' / ' + str(numIterTOT) +
', ' + str(round((numeroIterazioniGlobali*100)/numIterTOT, 2)) + '%, ' + 'in: ' + str(round(tempoDelta, 2)) +
' secondi - media: ' + str(round(velEsec, 2)) + ' iter/sec - Tempo rimanente stimato: ' +
str(round((numIterTOT-numeroIterazioniGlobali)/(velEsec * 60), 2)) + ' minuti', flush=True) # +0.05 per
evitare caso divisione per zero
    print('Scarti presenti nel CSV: ' + str(len(sharedObject.scarti)) + ' - combinazioni scartate \a

```

```

priori\': ' + str(len(sharedObject.scarti) - sharedObject.numero), flush=True) # Per avere le combinazioni
scartate senza alcun calcolo devo rimuovere le volte che sono state calcolate combinazioni da scartare
    print('Gestore terminato.', flush=True)
    return True

if __name__ == '__main__': # Parte eseguita solo la prima volta che viene lanciato il programma, non quando
partono i worker
    if debug:
        print('DENTRO __main__', flush=True) # https://superfastpython.com/multiprocessing-print/
    if multiprocessing:
        # Creo la coda che conterrà le combinazioni calcolate che non rientrano nel range, saranno da elaborare
e aggiungere alla variabile degli scarti letta da tutti i worker
        queueScarti = Queue()
        # Randomizzo la variabile contenente tutte le combinazioni:
        np.random.shuffle(combinazioniToll)
        #combinazioniToll = combinazioniToll.tolist()
        with Manager() as manager:
            # Sorta di oggetto condiviso tra i vari worker, conterrà tutte le combinazioni da saltare
            sharedObject = manager.Namespace()
            sharedObject.scarti = np.array(iterScartate.values.tolist()) # Aggiungo la list dei valori da
scartare calcolati all'inizio, o combinazione di zeri oppure lette da csv (vedi codice sopra)
            sharedObject.numero = 0 # Incrementati ad ogni aggiornamento della variabile, per sapere se i
worker devono aggiornarsi
            sharedObject.pause = False
            indiceScarti = -1 # Tiene traccia della versione degli scarti a cui il worker è aggiornato,
inizializzato a -1 per fare aggiornare la variabile ai worker nel loro primo ciclo
            # Questo worker controlla la coda e ad ogni ingresso calcola tutto e aggiorna la variabile con
tutti gli scarti
            print('\nInizializzazione Worker gestione scarti in corso...', flush=True)
            gestoreAggiunteScarti = Process(target=gestioneScarti, args=(queueScarti, sharedObject,
nomeFileScarti, dataframeCatodo, dataframeAnodo, decimMax, combinazioniToll.shape[0], startTime,
debugGestoreScarti,))
            gestoreAggiunteScarti.start() # eseguo il worker

            # Inizializzo il pool di worker fornendo ad ognuno le variabili globali necessarie (altrimenti non
le vedrebbero)

```

```

        print('\nInizializzazione POOL in corso...', flush=True)

        # https://stackoverflow.com/questions/3827065/can-i-use-a-multiprocessing-queue-in-a-function-
        # called-by-pool-imap?rq=1
        with Pool(numWorker, initializer=init_worker, initargs=(queueScarti, sharedObject, decimMax,
            iterScartate, indiceScarti, dataframeCatodo, dataframeAnodo, combinazioniToll, nomiFile, sigmaDesiderato,
            sigmaInf, stampaRisultati, stampaInfoAggiuntive, stampaMatriciRotaz, debugWorkerIterazione)) as pool:
            # print('Dentro POOL', flush=True)
            print('\nPool inizializzata:', flush=True)
            print(pool, flush=True)
            print(flush=True)
            pool.map(func=eseguiIterazione, iterable=combinazioniToll) # , chunksize=100) # Con i vari
            worker, eseguo la funzione "eseguiIterazione" dando ogni volta in ingresso un elemento di combinazioniToll.
            Eseguo le iterazioni in modo parallelo, suddivise in blocchi da "chunksize"
            print('Esecuzione TSUA terminata, chiudo pool di worker...', flush=True)
            # shutdown the process pool
            pool.close()
            # wait for tasks to complete
            pool.join()
            # Finita l'esecuzione vado a terminare anche il worker gestore scarti
            queueScarti.put(None)
            time.sleep(1) # Aspetto 1 secondo per far terminare il gestore

#####
#####
else: # VEDI DI TOGLIERLO ED IMPLEMENTARE IL SINGLE PROCESSING CAMBIANDO IL NUMERO DI WORKER NELLA
POOL!!!*****
*****
        # Eseguito senza multiprocessing
        numeroIter = 1
        for iterazione in combinazioniToll:

```

```

# Verifico ora che l'iterazione attuale non sia stata già calcolata, genero quello che sarà poi il
nome del report in PDF (senza sigma) e verifico se è già presente nella cartella.
nomeIterazione = str(round(iterazione[0], 4)) + '-' + str(round(iterazione[1], 4)) + '-' + str(
    round(iterazione[2], 4)) + '-' + str(round(iterazione[3], 4)) + '-' + str(
    round(iterazione[4], 4)) + '-' + str(round(iterazione[5], 4)) + '-' + str(
    round(iterazione[6], 4)) + '-' + str(round(iterazione[7], 4)) + '-' + str(
    round(iterazione[8], 4)) + '.pdf'
# nomeIterazione = nomeIterazione + '.pdf'

startTimeIter = time.process_time()
print('Esecuzione iterazione ' + str(numeroIter) + ': ' + str(iterazione))
if nomeIterazione in nomiFile:
    print('Iterazione ' + str(numeroIter) + ' già\'' calcolata, passo alla successiva!')
else:
    toleranceStackUpAnalysis(dataframeCatodo, dataframeAnodo, iterazione[0], iterazione[1],
iterazione[2],
                                iterazione[3], iterazione[4], iterazione[5], iterazione[6],
iterazione[7],
                                iterazione[8], sigmaDesiderato, sigmaInf, stampaRisultati,
stampaInfoAggiuntive,
                                stampaMatriciRotaz)
    print('Iterazione ' + str(numeroIter) + ' eseguita in: ' + str(time.process_time() - startTimeIter)
+ ' secondi-ore-giorni\n')
    numeroIter = numeroIter + 1
    print()

print('Programma completo eseguito in ' + str(time.time() - startTime) + ' secondi', flush=True)
# Arrivo qua --> TUTTO OK
print('\n\nProgramma terminato correttamente!')

```

Appendix D.2 Transform matrices

```
import numpy as np;

##### ROTZIONE ATTORNO AD X
#####
def rotx(angle):
    """
    This function generates the rototraslational matrix
    associated to a rotation of an angle (in radiants)
    of a frame around the X axe of a base frame
    """
    #creo la matrice di rotazione
    Rx=[ [ 1 , 0 , 0 , 0 ],
          [ 0 , np.cos(angle) , -np.sin(angle) , 0 ],
          [ 0 , np.sin(angle) , np.cos(angle) , 0 ],
          [ 0 , 0 , 0 , 1 ]];

    #arrotondo tutte le celle a 3 cifre dopo la virgola
    #Rx=np.round(Rx,3);

    return Rx
#####

##### ROTZIONE ATTORNO AD Y
#####
def roty(angle):
    """
    This function generates the rototraslational matrix
    associated to a rotation of an angle (in radiants)
    of a frame around the Y axe of a base frame
    """
    Ry=[ [ np.cos(angle) , 0 , np.sin(angle) , 0 ],
          [ 0 , 1 , 0 , 0 ]];
```

```

        [ -np.sin(angle) ,      0      , np.cos(angle) ,      0      ],
        [      0      ,      0      ,      0      ,      1      ]];

#arrotondo tutte le celle a 3 cifre dopo la virgola
#Ry=np.round(Ry,3);

    return Ry
#####

##### ROTZIONE ATTORNO AD Z
#####
def rotz(angle):
    """
    This function generates the rototraslational matrix
    associated to a rotation of an angle (in radiants)
    of a frame around the Z axe of a base frame
    """
    Rz=[ [ np.cos(angle) , -np.sin(angle) ,      0      ,      0      ],
          [ np.sin(angle) , np.cos(angle) ,      0      ,      0      ],
          [      0      ,      0      ,      1      ,      0      ],
          [      0      ,      0      ,      0      ,      1      ]];

    #arrotondo tutte le celle a 3 cifre dopo la virgola
    #Rz=np.round(Rz,3);

    return Rz
#####

##### TRASLAZIONE LUNGO X
#####
def trasx(distance):
    """
    This function generates the rototraslational matrix
    associated to a rigid traslation of a distance

```



```

of a frame along the X axe of a base frame
"""
Tx=[ [      1      ,      0      ,      0      ,      distance ],
      [      0      ,      1      ,      0      ,      0      ],
      [      0      ,      0      ,      1      ,      0      ],
      [      0      ,      0      ,      0      ,      1      ]];

#arrotondo tutte le celle a 3 cifre dopo la virgola
#Tx=np.round(Tx,3);

return Tx
#####

##### TRASLAZIONE LUNGO Y
#####

def trasy(distance):
    """
    This function generates the rototraslational matrix
    associated to a rigid traslation of a distance
    of a frame along the Y axe of a base frame
    """
    Ty=[ [      1      ,      0      ,      0      ,      0      ],
          [      0      ,      1      ,      0      ,      distance ],
          [      0      ,      0      ,      1      ,      0      ],
          [      0      ,      0      ,      0      ,      1      ]];

    #arrotondo tutte le celle a 3 cifre dopo la virgola
    #Ty=np.round(Ty,3);

    return Ty
#####

##### TRASLAZIONE LUNGO Z

```

```
#####
def trasz(distance):
    """
    This function generates the rototraslational matrix
    associated to a rigid traslation of a distance
    of a frame along the Z axe of a base frame
    """
    Tz=[ [      1      ,      0      ,      0      ,      0      ],
          [      0      ,      1      ,      0      ,      0      ],
          [      0      ,      0      ,      1      ,      distance ],
          [      0      ,      0      ,      0      ,      1      ]];

    #arrotondo tutte le celle a 3 cifre dopo la virgola
    #Tz=np.round(Tz,3);

    return Tz
#####
#####
```

Appendix D.3 Functions

```
import numpy as np;
from rotmat import *

##### TOLLERANZA DIMENSIONALE
#####
def tolldim(nominal_measure,tolerance_inf,tolerance_sup,samples):
    """
    INPUT: (nominal_measure, tolerance_inf, tolerance_sup,sample)
    where:
    - nominal_measure is the exact measure (ideal) without tollerance.
    - tolerance_inf is the negative part of the tollerance
    - tolerance_sup is the positive part of the tollerance
    - samples is the number of sample the normal distribution has to generate
    example1:
    10+-1 -> nominal_measure=10, tolerance_inf=-1, tolerance_sup=+1
    example2:
    12+1-0.5 -> nominal_measure=12, tolerance_inf=-0.5, tolerance_sup=+1

    OUTPUT: a vector in which every cell contains a measure that is contained inside the
    acceptable values (between nominal_measure-tolerance_inf and between
    nominal_measure+tolerance_sup)
    """

    #faccio in modo che anche se la toll inferiore viene inserita con segno negativo, sia interpretata con
    segno positivo
    #all'interno della funzione in modo da poter svolgere sempre correttamente i calcoli:
    tolerance_inf=np.abs(tolerance_inf);

    #calcolo la media della misura reale (ATTENZIONE, LO DEVO FARE PERCHE SE I LIMITI DI TOLL SUP ED INF NON
    SONO SIMMETRICI
    #VUOL DIRE CHE LA MISURA MEDIA NON CORRISPONDE CON LA MISURA ESATTA, QUELLO SAREBBE UN CASO PARTICOLARE)
    mu=((nominal_measure-tolerance_inf)+(nominal_measure+tolerance_sup))/2);

    #calcolo sigma come metà della differenza tra i due limiti di tolleranza:
    sigma=np.sqrt(((nominal_measure+tolerance_sup)-(nominal_measure-tolerance_inf))*2/4);
```

```

#calcolo i valori distribuiti secondo la gaussiana e li salvo nel vettore chiamato rnd:
rnd=np.random.normal(mu,sigma/3,int(samples))

#controllo quali valori contenuti all'interno di rnd sono accettabili (ovvero sono contenuti nei limiti di
tolleranza imposti)
#questo perché avendo scelto come sigma quello scritto al passo precedente, alcuni valori (relativi alle
code della campana)
#in teoria non dovrebbero essercene fuori range ma faccio comunque un controllo:
#scelgo solo quelli al di sopra del limite inferiore:
rnd=rnd[rnd<(nominal_measure+tollerance_sup)]
#di quelli accettati prendo solo quelli al di sotto del limite superiore
rnd=rnd[rnd>(nominal_measure-tollerance_inf)]

#questi valori li salvo nel vettore di output chiamato rnd_ok
rnd_ok=rnd

#fornisco in output il vettore dei numeri generati:
return rnd_ok
#####

##### TOLLERANZA DI PLANARITA' DI UN PIANO CIRCOLARE CENTRATO IN (0,0,0) E DI RAGGIO R
#####
def tollplancir(toll, r, samples, nominal_measure=0):
    """
    INPUT: (nominal_measure, tollerance_inf, tollerance_sup,r,sample)
           where:
           - toll is the distance between the 2 parallel planes descrtibed by the parallel tollerance
           - tollerance_sup is the positive part of the tollerance
           - r is the radius value ot the planar circle
           - samples is the number of sample the normal distribution has to generate
           - nominal_measure is the exact measure (ideal) where the centre of the circular plane is located
    without tollerance.
    example1:
    """

```

```

10+-1 -> nominal_measure=10, tollerance_inf=-1, tollerance_sup=+1
example2:
12+1-0.5 -> nominal_measure=12, tollerance_inf=-0.5, tollerance_sup=+1

    OUTPUT: a list of transformation matrices in which there is only the rotations around 2 axes (x,y) and the
only translation is
            along the z axe where each angles couple is checked with to respect the ortogonality tolerance for
the circular plane
    """
    toll = toll / 2
    t=0
    points = 100

    mu_d=0
    sigma_d=toll/3
    d = np.random.normal(mu_d,sigma_d,int(samples))

    mu_ang = 0
    sigma_ang = np.arctan((toll/np.sqrt((r)**2-toll**2)))/3

    alpha = np.random.normal(mu_ang,sigma_ang,int((samples)))

    beta = np.random.normal(mu_ang,sigma_ang,int((samples)))

    tht = np.linspace(0, 2 * np.pi, int((points)))

    alphalist = []
    betalist = []
    dlist = []

    for i in range(samples):

        x = r * np.sin(alpha[i]) * np.sin(beta[i]) * np.sin(tht) + r * np.cos(beta[i]) * np.cos(tht) + t *
np.sin(beta[i]) * np.cos(alpha[i])

        y = r * np.sin(tht) * np.cos(alpha[i]) - t * np.sin(alpha[i])

```

```

        z = d[i] + r * np.sin(alpha[i]) * np.sin(tht) * np.cos(beta[i]) - r * np.sin(beta[i]) * np.cos(tht) + t
* np.cos(alpha[i]) * np.cos(beta[i])

    # conto il numero di valori della circonferenza al di fuori del limite di tolleranza imposto
    zoffp = sum(1 if z1 > toll else 0 for z1 in z)
    # print('numero di valori di z maggiori di toll/2\n', zoffp)
    zoffn = sum(1 if z1 < -toll else 0 for z1 in z)
    # print('numero di valori di z minori di -toll/2\n', zoffn)

    if (zoffp == 0 and zoffn == 0):
        alphalist.append(alpha[i])
        betalist.append(beta[i])
        dlist.append(d[i])

    t = [nominal_measure+dist for dist in dlist]

    #taglio i vettori di h, k e t per avere il numero prescelto di campioni:
    #h=h[0:samples];
    #k=k[0:samples];
    #t=t[0:samples];

    Tz = [trasz(dist) for dist in t]
    Ry = [roty(angle) for angle in betalist]
    Rx = [rotx(angle) for angle in alphalist]
    TzRy = [np.matmul(x,y) for x,y in zip(Tz,Ry)]
    TzRyRx = [np.matmul(x,y) for x,y in zip(TzRy,Rx)]

    return TzRyRx

#####
#####

```

Appendix D.4 Tolerance stack-up analysis and optimisation

```
# Per prima cosa importo le librerie necessarie:

from tolleranze3 import *
from funzioni import *
import numpy as np
import matplotlib.pyplot as plt
from matplotlib.ticker import MultipleLocator, MaxNLocator, AutoLocator, AutoMinorLocator

from scipy.stats import invgauss
import math

# import pandas lib as pd
import pandas as pd
# Aggiungere anche libreria openpyxl

# Export multiple plots in a PDF (multiple pages): https://stackoverflow.com/questions/38938454/python-saving-multiple-subplot-figures-to-pdf/38943527#38943527
from matplotlib.backends.backend_pdf import PdfPages

# Per generare le tabelle, matplotlib è rognoso da usare
# Installare da terminale conda (se non si riesce da pycharm) con il comando "pip install plottable"
from plottable import Table
from plottable import ColumnDefinition

# Per gestione data:
from datetime import datetime
import time

# per aprire automaticamente pdf generato:
import os

# Per calcolo tempo esecuzione
import time
```



```

del catodo
    r2c = dfCatodo.loc[('M12', 'Raggio'), 'Misura'] # mm raggio ext flangia catodo OPPURE mm raggio ext camera
di scarico
????????????????????????????????????????????????????????????????????????????????????*****+
    sample2c = int(dfCatodo.loc[('M12', 'Campioni'), 'Misura'])
    nominal2c = dfCatodo.loc[('M12', 'Misura nominale'), 'Misura'] # mm distanza da frame 1C a frame 2C
(superficie di contatto flangia catodo - camera di scarico)
    M12c = tollplancir(toll12c, r2c, sample2c, nominal2c) # genero le matrici di R-T tra riferimento 1 e 2

    # genero la prima matrice M23:
    #toll13c = dataframeCatodo.loc[('M23', 'Tolleranza'), 'Misura'] # mm misura della planarità della
superficie superiore della camera di scarico
    r3c = dfCatodo.loc[('M23', 'Raggio'), 'Misura'] # mm raggio ext camera di scarico OPPURE raggio superficie
HT
catodo????????????????????????????????????????????????????????????????????????????????????*****
****
    sample3c = int(dfCatodo.loc[('M23', 'Campioni'), 'Misura'])
    nominal3c = dfCatodo.loc[('M23', 'Misura nominale'), 'Misura'] # mm distanza da frame 2C a 3C
    M23c = tollplancir(toll13c, r3c, sample3c, nominal3c) # genero le matrici di R-T tra riferimento 2 e 3

    # genero la prima matrice M34:
    #toll14c = dfCatodo.loc[('M34', 'Tolleranza'), 'Misura'] # mm toll dimensionale distanza flangia -
superficie HT catodo ***NEW***
    r4c = dfCatodo.loc[('M34', 'Raggio'), 'Misura'] # mm raggio superficie HT catodo
    sample4c = int(dfCatodo.loc[('M34', 'Campioni'), 'Misura'])
    nominal4c = dfCatodo.loc[('M34', 'Misura nominale'), 'Misura'] # mm distanza da frame 2C a 3C (15 mm)
    M34c = tollplancir(toll14c, r4c, sample4c, nominal4c) # genero le matrici di R-T tra riferimento 3 e 4

    # Calcolo le matrici di R-T tra 0 e 4 moltiplicando le varie matrici.
    # per fare questo considero il numero massimo di matrici che posso, ovvero
    # tra i 3 vettori di matrici che ho generato (M01, M12, M23) prendo il numero di matrici minimo delle 3.
    n_matricesc = min(len(M01c), len(M12c), len(M23c), len(M34c))
    # visualizzo il numero di matrici per vedere che sia conforme con quanto specificato:
    if stampaInfoAggiuntive:
        print("numero di campioni\n", n_matricesc)

```

```

# rendo tutte le matrici della stessa lunghezza prendendo i primi elementi (n_matrices)
M01c = M01c[0:n_matricesc];
M12c = M12c[0:n_matricesc];
M23c = M23c[0:n_matricesc];
M34c = M34c[0:n_matricesc];

# faccio la moltiplicazione delle prime n matrici di M01, M12, M23 prese in ordine (tanto i valori al loro
interno sono random)
M02c = [np.matmul(x, y) for x, y in zip(M01c, M12c)]
M03c = np.array([np.matmul(x, y) for x, y in zip(M02c, M23c)])
M04c = np.array([np.matmul(x, y) for x, y in zip(M03c, M34c)])

# estraggo dalle matrici M03 i valori di scostamento lungo l'asse y tra il frame 0 ed il frame 3
# e salvo tutti i valori di scostamento all'interno della list dy03:
dz04c = [x[2, 3] for x in M04c]

#
# CATODO | Calcolo i valori dei parametri che definiscono la gaussiana ottenuta:
#
# MEDIA:
mu_dz04c = np.mean(dz04c)
# DEVIAZIONE STANDARD:
sigma_dz04c = np.std(dz04c)
var_dz04c = sigma_dz04c ** 2

if stampaRisultati:
    # Visualizzo i valori di media e dev. Std per vedere che abbiano senso:
    # Media:
    print("Distanza media superficie HT catodo da frame di riferimento\n", round(mu_dz04c, 7))

    # Deviazione standard:
    print("Sdv distanza superficie HT catodo da frame di riferimento\n", round(sigma_dz04c, 7))

# Estraggo dalla matrice di rototraslazione completa solo gli elementi relativi alla rotazione della faccia

```

```

del catodo
rot04c = np.array([x[0:3, 0:3] for x in M04c])
if stampaMatriciRotaz:
    print("matrici di rotazione\n", rot04c.round(10))

# Calcolo la media degli elementi della matrice di rotazione della faccia del catodo
mu_rot04c = sum(rot04c) / n_matricesc
if stampaInfoAggiuntive:
    print("media elementi della matrice di rotazione del catodo\n", mu_rot04c.round(10))

# Calcolo gli angoli d'inclinazione della superficie HT del catodo alfac e betac
# alphac
salphac = [x[1, 2] for x in M04c]
sigma_salphac = np.std(salphac)
var_salphac = np.var(salphac)

alphac = np.arcsin(salphac) * 180 / np.pi # NOTA: np.arcsin() ritorna in radianti, io poi converto in
gradi
mu_alphac = sum(alphac) / n_matricesc
delta_alphac = (alphac - mu_alphac) ** 2
sigma_alphac = np.sqrt(sum(delta_alphac) / n_matricesc)
if stampaInfoAggiuntive:
    print("angolo " r"$\alpha$" " catodo\n", mu_alphac)

# betac
sbetac = [x[2, 0] for x in M04c]
betac = np.arcsin(sbetac) * 180 / np.pi
mu_betac = sum(betac) / n_matricesc
delta_betac = (betac - mu_betac) ** 2
sigma_betac = np.sqrt(sum(delta_betac) / n_matricesc)
if stampaInfoAggiuntive:
    print("angolo " r"$\beta$" " catodo\n", mu_betac)

# Calcolo la deviazione std degli elementi della matrice di rotazione della faccia del catodo
deltarotc = (rot04c - mu_rot04c) ** 2
# print("Deltarotc\n", delta)

```

```

sigma_rot4c = np.sqrt(sum(deltarotc) / n_matricesc)
if stampaInfoAggiuntive:
    print("Sdv elementi della matrice di rotazione del catodo \n", sigma_rot4c.round(10))

#
# ***** FACCIA ANODO *****
#

# Genero la prima matrice M01:
#toll1a = dataframeAnodo.loc[('M01', 'Tolleranza'), 'Misura'] # 1.5786 #mm
##### DA CHIEDERE AL PROF SE VA BENE COME L'HAI RICAIVATA scostamento dei fori
della camera di scarico dalla posizione nominale lungo l'asse
r1a = dfAnodo.loc[('M01', 'Raggio'), 'Misura'] # mm raggio camera di scarico
sample1a = int(dfAnodo.loc[('M01', 'Campioni'), 'Misura']) # mm
nominal1a = dfAnodo.loc[('M01', 'Misura nominale'), 'Misura'] # mm distanza da frame 0 a frame 1A (dalla
superficie della camera di scarico nel frame 0 al centro dei fori della camera di scarico)
M01a = tollplancir(toll1a, r1a, sample1a, nominal1a) # genero le matrici di R-T tra riferimento 0 e 1

# Genero la seconda matrice M12:
#toll2a = dataframeAnodo.loc[('M12', 'Tolleranza'), 'Misura'] # 0.6284 #mm
##### DA CHIEDERE AL PROF SE VA BENE COME L'HAI RICAIVATA scostamento dei fori
dell'anodo dalla posizione nominale lungo l'asse
r2a = dfAnodo.loc[('M12', 'Raggio'), 'Misura'] # mm raggio ext anodo
sample2a = int(dfAnodo.loc[('M12', 'Campioni'), 'Misura']) # mm
nominal2a = dfAnodo.loc[('M12', 'Misura nominale'), 'Misura'] # mm
M12a = tollplancir(toll2a, r2a, sample2a, nominal2a) # genero le matrici di R-T tra riferimento 1 e 2

# Genero la prima matrice M23:
#toll3a = dataframeAnodo.loc[('M23', 'Tolleranza'), 'Misura'] # mm #####
planarità griglia anodo
r3a = dfAnodo.loc[('M23', 'Raggio'), 'Misura'] # mm raggio ext anodo
sample3a = int(dfAnodo.loc[('M23', 'Campioni'), 'Misura']) # mm
nominal3a = dfAnodo.loc[
    ('M23', 'Misura nominale'), 'Misura'] # mm distanza tra frame 2A e frame 3A (fori anodo - griglia
anodo)

```

```

M23a = tollplancir(toll3a, r3a, sample3a, nominal3a) # genero le matrici di R-T tra riferimento 2 e 3

# Calcolo le matrici di R-T tra 0 e 3 moltiplicando le varie matrici.
# per fare questo considero il numero massimo di matrici che posso, ovvero
# tra i 3 vettori di matrici che ho generato (M01, M12, M23) prendo il numero di matrici minimo delle 3.
n_matricesa = min(len(M01a), len(M12a), len(M23a))
# visualizzo il numero di matrici per vedere che sia conforme con quanto specificato:
if stampaInfoAggiuntive:
    print("numero di matrici accettate \n", len(M01a))

# Rendo tutte le matrici della stessa lunghezza prendendo i primi elementi (n_matricesa)
M01a = M01a[0:n_matricesa];
M12a = M12a[0:n_matricesa];
M23a = M23a[0:n_matricesa];

# Faccio la moltiplicazione delle prime n matrici di M01, M12, M23 prese in ordine (tanto i valori al loro
interno sono random)
M02a = [np.matmul(x, y) for x, y in zip(M01a, M12a)]
M03a = [np.matmul(x, y) for x, y in zip(M02a, M23a)]

# Estraggo dalle matrici M03 i valori di scostamento lungo l'asse y tra il frame 0 ed il frame 3
# e salvo tutti i valori di scostamento all'interno della list dy03:
dz03a = [x[2, 3] for x in M03a]
max_dz03a = np.max(dz03a)
min_dz03a = np.min(dz03a)
delta_dz03a = max_dz03a - min_dz03a

#
# 

|       |                                                                       |
|-------|-----------------------------------------------------------------------|
| ANODO | Calcolo i valori dei parametri che definiscono la gaussiana ottenuta: |
|-------|-----------------------------------------------------------------------|


#
# MEDIA:
mu_dz03a = np.mean(dz03a)
if stampaInfoAggiuntive:
    print("Distanza media griglia anodo da frame di riferimento\n", round(mu_dz03a, 4))

# DEVIAZIONE STANDARD:

```

```

sigma_dz03a = np.sqrt((np.sum([(x - mu_dz03a) ** 2 for x in dz03a])) / n_matricesa)
var_dz03a = sigma_dz03a ** 2
if stampaInfoAggiuntive:
    print("Sdv distanza griglia anodo da frame di riferimento\n", round(sigma_dz03a, 4))

# Estraggo dalla matrice di rototraslazione completa solo gli elementi relativi alla rotazione della faccia
dell'anodo
rot03a = np.array([x[0:3, 0:3] for x in M03a])
if stampaInfoAggiuntive:
    print(rot03a.round(6))

# Calcolo la media degli elementi della matrice di rotazione della faccia dell'an
mu_rot03a = sum(rot03a) / n_matricesc
if stampaInfoAggiuntive:
    print("media elementi della matrice di rotazione dell'anodo \n", mu_rot03a.round(10))

# Calcolo gli angoli d'inclinazione della griglia del catodo alfa_a e gamma_a
# alfaaa
salphaa = [x[1, 2] for x in M03a]
sigma_salphaa = np.std(salphaa)
var_salphaa = sigma_salphaa ** 2

alphaaa = np.arcsin(salphaa) * 180 / np.pi
mu_alphaa = sum(alphaaa) / n_matricesc
delta_alphaa = (alphaaa - mu_alphaa) ** 2
sigma_alphaa = np.sqrt(sum(delta_alphaa) / n_matricesc)
if stampaInfoAggiuntive:
    print("angolo " r"$\alpha$" " catodo\n", mu_alphaa)

# betaa
sbetaa = [x[2, 0] for x in M03a]
betaa = np.arcsin(sbetaa) * 180 / np.pi

mu_betaa = sum(betaa) / n_matricesc
delta_betaa = (betaa - mu_betaa) ** 2
sigma_betaa = np.sqrt(sum(delta_betaa) / n_matricesc)

```

```

if stampaInfoAggiuntive:
    print("angolo " r"$\beta$" " catodo\n", mu_betaa)

# Calcolo la deviazione std degli elementi della matrice di rotazione della faccia dell'anodo
deltarota = (rot03a - mu_rot03a) ** 2
# Print("Deltarotc\n", delta)
sigma_rot03a = np.sqrt(sum(deltarota) / n_matricesc)
if stampaInfoAggiuntive:
    print("Sdv elementi della matrice di rotazione dell'anodo \n", sigma_rot03a.round(10))

#
# ***** ANALISI POSIZIONE RELATIVA *****
#

# Calcolo la differenza di posizione relativa (distanza del punto centrale del piano) tra anodo e catodo
delle varie combinazioni
dz03ac = [x - y for x, y in zip(dz04c, dz03a)]

#
# POSIZIONE RELATIVA | Calcolo i valori dei parametri che definiscono la gaussiana ottenuta:
#

# MEDIA:
mu_dz03ac = np.mean(dz03ac)
if stampaInfoAggiuntive:
    print("Distanza media anodo-catodo\n", round(mu_dz03ac, 4))
# DEVIAZIONE STANDARD:
sigma_dz03ac = np.sqrt((np.sum([(x - mu_dz03ac) ** 2 for x in dz03ac])) / n_matricesa)
if stampaInfoAggiuntive:
    print("Sdv distanza anodo-catodo\n", round(sigma_dz03ac, 4))

# Continuo con i calcoli SOLO se il risultato è in tolleranza (distanza Anodo-Catodo = 1mm +- 0,1, ovvero
sigma = 0,03333)
if (sigma_dz03ac <= sigmaDesiderato) & (sigma_dz03ac >= sigmaInf):

```



```

# In quel caso verifico anche il tilt della circonferenza con alfa e beta:
scostCatodo = scostMaxAngoli(r4c, mu_alphac+3*sigma_alphac, mu_betac+3*sigma_betac)
scostAnodo = scostMaxAngoli(r3a, mu_alphaa+3*sigma_alphaa, mu_betaa+3*sigma_betaa)
distMinCA = (abs(mu_dz03a+3*sigma_dz03a)-scostAnodo)-(abs(mu_dz04c-3*sigma_dz04c)+scostCatodo)
if True:
    print('\nScostamento catodo tilt='+str(scostCatodo))
    print('Scostamento anodo tilt=' + str(scostAnodo))
    print('Distanza minima caso peggiore tilt=' + str(distMinCA))
# Verifico ora la distanza anodo-catodo nel caso peggiore considerando l'inclinazione delle facce:
if (distMinCA > -1):#0.8): # sistema poi valore
*****
*****
#
# ***** ANALISI DEL PARALELLISMO *****
#

# trovo Vzc catodo, vettore normale a Vxc e Vyc che definiscono il piano corrispondente alla
superficie HT del catodo
Vzc = rot04c[:, 2]
Vzc = Vzc.tolist()
if stampaInfoAggiuntive:
    print(np.linalg.norm(Vzc, axis=1))

# trovo Vza anodo, vettore normale a Vx e Vy che definiscono il piano corrispondente alla griglia
dell'anodo
Vza = rot03a[:, 2]
Vza = Vza.tolist()
if stampaInfoAggiuntive:
    print(np.linalg.norm(Vza, axis=1))

# calcolo l'angolo tra i vettori Vza e Vza come prodotto scalare tra i vettori
scprod = []

for v1, v2 in zip(Vzc, Vza):
    scprod.append(np.dot(v1, v2))

```

```

w = np.arccos(scprod) * 180 / np.pi
mu_w = np.mean(w)
if stampaInfoAggiuntive:
    print("angolo medio formato tra le superfici contrapposte di anodo e catodo\n", mu_w)
delta_w = (mu_w - w) ** 2
sigma_w = np.sqrt(sum(delta_w) / n_matricesc)
if stampaInfoAggiuntive:
    print("St dev dell'angolo formato tra le superfici contrapposte di anodo e catodo\n", sigma_w)

#
# ***** ANALISI DI SENSITIVITÀ *****
#
if stampaInfoAggiuntive:
    print('\nAnalisi di sensitività\n')

# DISTANZA d (z)
# Catodo
dz01c = [x[2, 3] for x in M01c]
sigma_dz01c = np.std(dz01c)
var_dz01c = np.var(dz01c)

dz12c = [x[2, 3] for x in M12c]
sigma_dz12c = np.std(dz12c)
var_dz12c = np.var(dz12c)

dz23c = [x[2, 3] for x in M23c]
sigma_dz23c = np.std(dz23c)
var_dz23c = np.var(dz23c)

dz34c = [x[2, 3] for x in M34c]
sigma_dz34c = np.std(dz34c)
var_dz34c = np.var(dz34c)

# Anodo
dz01a = [x[2, 3] for x in M01a]

```

```

sigma_dz01a = np.std(dz01a)
var_dz01a = np.var(dz01a)

dz12a = [x[2, 3] for x in M12a]
sigma_dz12a = np.std(dz12a)
var_dz12a = np.var(dz12a)

dz23a = [x[2, 3] for x in M23a]
sigma_dz23a = np.std(dz23a)
var_dz23a = np.var(dz23a)

# ANGOLO ALPHA
# Catodo
salpha_01c = [x[1, 2] for x in M01c]
sigma_salpha_01c = np.std(salpha_01c)
var_salpha_01c = np.var(salpha_01c)

salpha_12c = [x[1, 2] for x in M12c]
sigma_salpha_12c = np.std(salpha_12c)
var_salpha_12c = np.var(salpha_12c)

salpha_23c = [x[1, 2] for x in M23c]
sigma_salpha_23c = np.std(salpha_23c)
var_salpha_23c = np.var(salpha_23c)

salpha_34c = [x[1, 2] for x in M34c]
sigma_salpha_34c = np.std(salpha_34c)
var_salpha_34c = np.var(salpha_34c)

# Anodo
salpha_01a = [x[1, 2] for x in M01a]
sigma_salpha_01a = np.std(salpha_01a)
var_salpha_01a = np.var(salpha_01a)

salpha_12a = [x[1, 2] for x in M12a]
sigma_salpha_12a = np.std(salpha_12a)

```

```

var_salpα_12a = np.var(salpα_12a)

salpα_23a = [x[1, 2] for x in M23a]
sigma_salpα_23a = np.std(salpα_23a)
var_salpα_23a = np.var(salpα_23a)

# ANALISI SENSITIVITA' d
if stampaInfoAggiuntive:
    print('\nAnalisi di sensitività traslazione lungo z\n')
# CATODO
S_01c = var_dz01c * 100 / (var_dz04c)
S_12c = var_dz12c * 100 / (var_dz04c)
S_23c = var_dz23c * 100 / (var_dz04c)
S_34c = var_dz34c * 100 / (var_dz04c)
if stampaInfoAggiuntive:
    print('\nCatodo:\n')
    print('S_01\n', S_01c)
    print('S_12\n', S_12c)
    print('S_23\n', S_23c)
    print('S_34\n', S_34c)
# ANODO
S_01a = var_dz01a * 100 / (var_dz03a)
S_12a = var_dz12a * 100 / (var_dz03a)
S_23a = var_dz23a * 100 / (var_dz03a)
if stampaInfoAggiuntive:
    print('\nAnodo:\n')
    print('S_01\n', S_01a)
    print('S_12\n', S_12a)
    print('S_23\n', S_23a)

# ANALISI SENSITIVITA' ALPHA
if stampaInfoAggiuntive:
    print('\nAnalisi di sensitività rotazione attorno ad alpha\n')
# CATODO
S_01c_alpha = (var_salpα_01c) * 100 / (var_salpαc)

```

```

S_12c_alpha = (var_salpha_12c) * 100 / (var_salphac)
S_23c_alpha = (var_salpha_23c) * 100 / (var_salphac)
S_34c_alpha = (var_salpha_34c) * 100 / (var_salphac)
if stampaInfoAggiuntive:
    print('\nCatodo:\n')
    print('S_01c_alpha\n', S_01c_alpha)
    print('S_12c_alpha\n', S_12c_alpha)
    print('S_23c_alpha\n', S_23c_alpha)
    print('S_34c_alpha\n', S_34c_alpha)
# ANODO
S_01a_alpha = (var_salpha_01a) * 100 / (var_salphaa)
S_12a_alpha = (var_salpha_12a) * 100 / (var_salphaa)
S_23a_alpha = (var_salpha_23a) * 100 / (var_salphaa)
if stampaInfoAggiuntive:
    print('\nAnodo:\n')
    print('S_01a_alpha\n', S_01a_alpha)
    print('S_12a_alpha\n', S_12a_alpha)
    print('S_23a_alpha\n', S_23a_alpha)

# Genero un dataframe contenente i risultati dell'analisi di sensitività:
dfSensitivita = pd.DataFrame(columns=['Elemento', 'Valore'])
# Aggiungo le varie RIGHE:
dfSensitivita.loc[len(dfSensitivita)] = ['<b>Cathode frontal surface position:<b>', ''] # CATODO:
dfSensitivita.loc[len(dfSensitivita)] = ['Cathode flange flatness', float(f"{S_01c:.4g}")]
dfSensitivita.loc[len(dfSensitivita)] = ['Distance cathode flange - frontal surface',
float(f"{S_12c:.4g}")]
dfSensitivita.loc[len(dfSensitivita)] = ['Cathode front surface flatness', float(f"{S_23c:.4g}")]
dfSensitivita.loc[len(dfSensitivita)] = ['Perpendicularity cathode frontal surface - external
cylinder axis', float(f"{S_34c:.4g}")]

dfSensitivita.loc[len(dfSensitivita)] = ['<b>Anode frontal surface position:<b>', ''] # ANODO:
dfSensitivita.loc[len(dfSensitivita)] = ['Discharge chamber top surface flatness',
float(f"{S_01a:.4g}")]
dfSensitivita.loc[len(dfSensitivita)] = ['Distance discharge chamber top surface - the anode grid',

```

```

float(f"{S_12a:.4g}")]
    dfSensitivita.loc[len(dfSensitivita)] = ['Anode grid flatness', float(f"{S_23a:.4g}")]

    dfSensitivita.loc[len(dfSensitivita)] = ['<b>Cathode inclination angle:<b>', ''] # ALFA-CATODO:
    dfSensitivita.loc[len(dfSensitivita)] = ['Cathode flange flatness', float(f"{S_01c_alpha:.4g}")]
    dfSensitivita.loc[len(dfSensitivita)] = ['Distance cathode flange - frontal surface',
float(f"{S_12c_alpha:.4g}")]
    dfSensitivita.loc[len(dfSensitivita)] = ['Cathode front surface flatness',
float(f"{S_23c_alpha:.4g}")]
    dfSensitivita.loc[len(dfSensitivita)] = ['Perpendicularity cathode frontal surface - external
cylinder axis', float(f"{S_34c_alpha:.4g}")]

    dfSensitivita.loc[len(dfSensitivita)] = ['<b>Anode grid inclination angle:<b>', ''] # ALFA-ANODO:
    dfSensitivita.loc[len(dfSensitivita)] = ['Discharge chamber top surface flatness',
float(f"{S_01a_alpha:.4g}")]
    dfSensitivita.loc[len(dfSensitivita)] = ['Distance discharge chamber top surface - the anode grid',
float(f"{S_12a_alpha:.4g}")]
    dfSensitivita.loc[len(dfSensitivita)] = ['Anode grid flatness', float(f"{S_23a_alpha:.4g}")]
    # dfSensitivita.loc[len(dfSensitivita)] = ['', ]

#
# ***** PROVA CALCOLO VOTO SOLUZIONE TROVATA *****
#
# Logica di voto provvisoria
# Qua ipotizzo votazione sigmaDesiderato-->=100, sigma=0.01-->=0
votoSigma=(sigma_dz03ac-0.01)*100/(sigmaDesiderato)

# Qua ipotizzo che il voto della singola tolleranza è tale che tollMAX=100, tollMin=1
# Vado poi a moltiplicare il voto per la relativa sensitività
votoTollMIN = 1
votoTollMAX = 100
# Se valore tolleranza minima e massima sono diversi, calcolo la differenza, altrimenti tengo il
valore stesso, usato poi dopo nel calcolo votazione (evito bug divisione per zero in caso di tollMin=tollMax)
deltaToll1c = dfCatodo.loc[('M01', 'Tolleranza MAX'), 'Misura'] - dfCatodo.loc[('M01', 'Tolleranza
MIN'), 'Misura'] if dfCatodo.loc[('M01', 'Tolleranza MAX'), 'Misura'] - dfCatodo.loc[('M01', 'Tolleranza MIN'),
'Misura'] != 0 else dfCatodo.loc[('M01', 'Tolleranza MIN'), 'Misura']

```

```

        deltaToll2c = dfCatodo.loc[('M12', 'Tolleranza MAX'), 'Misura'] - dfCatodo.loc[('M12', 'Tolleranza MIN'), 'Misura'] if dfCatodo.loc[('M12', 'Tolleranza MAX'), 'Misura'] - dfCatodo.loc[('M12', 'Tolleranza MIN'), 'Misura'] != 0 else dfCatodo.loc[('M12', 'Tolleranza MIN'), 'Misura']
        deltaToll3c = dfCatodo.loc[('M23', 'Tolleranza MAX'), 'Misura'] - dfCatodo.loc[('M23', 'Tolleranza MIN'), 'Misura'] if dfCatodo.loc[('M23', 'Tolleranza MAX'), 'Misura'] - dfCatodo.loc[('M23', 'Tolleranza MIN'), 'Misura'] != 0 else dfCatodo.loc[('M23', 'Tolleranza MIN'), 'Misura']
        deltaToll4c = dfCatodo.loc[('M34', 'Tolleranza MAX'), 'Misura'] - dfCatodo.loc[('M34', 'Tolleranza MIN'), 'Misura'] if dfCatodo.loc[('M34', 'Tolleranza MAX'), 'Misura'] - dfCatodo.loc[('M34', 'Tolleranza MIN'), 'Misura'] != 0 else dfCatodo.loc[('M34', 'Tolleranza MIN'), 'Misura']
        deltaToll1a = dfAnodo.loc[('M01', 'Tolleranza MAX'), 'Misura'] - dfAnodo.loc[('M01', 'Tolleranza MIN'), 'Misura'] if dfAnodo.loc[('M01', 'Tolleranza MAX'), 'Misura'] - dfAnodo.loc[('M01', 'Tolleranza MIN'), 'Misura'] !=0 else dfAnodo.loc[('M01', 'Tolleranza MIN'), 'Misura']
        deltaToll2a = dfAnodo.loc[('M12', 'Tolleranza MAX'), 'Misura'] - dfAnodo.loc[('M12', 'Tolleranza MIN'), 'Misura'] if dfAnodo.loc[('M12', 'Tolleranza MAX'), 'Misura'] - dfAnodo.loc[('M12', 'Tolleranza MIN'), 'Misura'] !=0 else dfAnodo.loc[('M12', 'Tolleranza MIN'), 'Misura']
        deltaToll3a = dfAnodo.loc[('M23', 'Tolleranza MAX'), 'Misura'] - dfAnodo.loc[('M23', 'Tolleranza MIN'), 'Misura'] if dfAnodo.loc[('M23', 'Tolleranza MAX'), 'Misura'] - dfAnodo.loc[('M23', 'Tolleranza MIN'), 'Misura'] !=0 else dfAnodo.loc[('M23', 'Tolleranza MIN'), 'Misura']

        votoToll1c = (votoTollMAX-votoTollMIN) * (toll1c-dfCatodo.loc[('M01', 'Tolleranza MIN'), 'Misura']) / (deltaToll1c) + votoTollMIN
        votoToll2c = (votoTollMAX-votoTollMIN) * (toll2c-dfCatodo.loc[('M12', 'Tolleranza MIN'), 'Misura']) / (deltaToll2c) + votoTollMIN
        votoToll3c = (votoTollMAX-votoTollMIN) * (toll3c-dfCatodo.loc[('M23', 'Tolleranza MIN'), 'Misura']) / (deltaToll3c) + votoTollMIN
        votoToll4c = (votoTollMAX-votoTollMIN) * (toll4c-dfCatodo.loc[('M34', 'Tolleranza MIN'), 'Misura']) / (deltaToll4c) + votoTollMIN
        votoToll1a = (votoTollMAX-votoTollMIN) * (toll1a-dfAnodo.loc[('M01', 'Tolleranza MIN'), 'Misura']) / (deltaToll1a) + votoTollMIN
        votoToll2a = (votoTollMAX-votoTollMIN) * (toll2a-dfAnodo.loc[('M12', 'Tolleranza MIN'), 'Misura']) / (deltaToll2a) + votoTollMIN
        votoToll3a = (votoTollMAX-votoTollMIN) * (toll3a-dfAnodo.loc[('M23', 'Tolleranza MIN'), 'Misura']) / (deltaToll3a) + votoTollMIN

        # Come voto complessivo delle tolleranze, moltiplico ogni votoTollXX per il suo valore di
        # sensitività e poi sommo tutto, correggo il valore dividendo per 1000, sensitività in percentuale più un altro

```

```

10 per la somma...?:
    votoToll = (votoToll11c*S_01c + votoToll12c*S_12c + votoToll13c*S_23c + votoToll14c*S_34c +
votoToll11a*S_01a + votoToll12a*S_12a + votoToll13a*S_23a)/1000

    # Ottengo il voto totale sommando quello relativo al valore di sigma e quello relativo alle
tolleranze:
    votoTot = votoSigma + votoToll

    #
    # ***** CREO DATAFRAME PER REPORT PDF *****
    #

    dfTabCatodoM01 = pd.DataFrame(columns=['Elemento', 'Valore'])
    M01cTitolo = 'Cathode flange flatness:'
    dfTabCatodoM01.loc[len(dfTabCatodoM01)] = ['M01 - Tolleranza [mm]', toll11c]
    dfTabCatodoM01.loc[len(dfTabCatodoM01)] = ['M01 - Raggio [mm]', dfCatodo.loc[('M01', 'Raggio'),
'Misura']]
    dfTabCatodoM01.loc[len(dfTabCatodoM01)] = ['M01 - Misura nominale [mm]', dfCatodo.loc[('M01',
'Misura nominale'), 'Misura']]
    dfTabCatodoM01.loc[len(dfTabCatodoM01)] = ['M01 - Campioni', int(dfCatodo.loc[('M01', 'Campioni'),
'Misura'])]

    M12cTitolo = 'Distance cathode flange - frontal surface:'
    dfTabCatodoM12 = pd.DataFrame(columns=['Elemento', 'Valore'])
    dfTabCatodoM12.loc[len(dfTabCatodoM12)] = ['M12 - Tolleranza [mm]', toll12c]
    dfTabCatodoM12.loc[len(dfTabCatodoM12)] = ['M12 - Raggio [mm]', dfCatodo.loc[('M12', 'Raggio'),
'Misura']]
    dfTabCatodoM12.loc[len(dfTabCatodoM12)] = ['M12 - Misura nominale [mm]', dfCatodo.loc[('M12',
'Misura nominale'), 'Misura']]
    dfTabCatodoM12.loc[len(dfTabCatodoM12)] = ['M12 - Campioni', int(dfCatodo.loc[('M12', 'Campioni'),
'Misura'])]

    M23cTitolo = 'Cathode front surface flatness:'
    dfTabCatodoM23 = pd.DataFrame(columns=['Elemento', 'Valore'])
    dfTabCatodoM23.loc[len(dfTabCatodoM23)] = ['M23 - Tolleranza', toll13c]
    dfTabCatodoM23.loc[len(dfTabCatodoM23)] = ['M23 - Raggio', dfCatodo.loc[('M23', 'Raggio'),

```



```

'Misura']]
dfTabCatodoM23.loc[len(dfTabCatodoM23)] = ['M23 - Misura nominale', dfCatodo.loc[('M23', 'Misura
nominale'), 'Misura']]
dfTabCatodoM23.loc[len(dfTabCatodoM23)] = ['M23 - Campioni', int(dfCatodo.loc[('M23', 'Campioni'),
'Misura'])]

M34cTitolo = 'Perpendicularity cathode frontal surface - external cylinder axis:'
dfTabCatodoM34 = pd.DataFrame(columns=['Elemento', 'Valore'])
dfTabCatodoM34.loc[len(dfTabCatodoM34)] = ['M34 - Tolleranza', toll4c]
dfTabCatodoM34.loc[len(dfTabCatodoM34)] = ['M34 - Raggio', dfCatodo.loc[('M34', 'Raggio'),
'Misura']]
dfTabCatodoM34.loc[len(dfTabCatodoM34)] = ['M34 - Misura nominale', dfCatodo.loc[('M34', 'Misura
nominale'), 'Misura']]
dfTabCatodoM34.loc[len(dfTabCatodoM34)] = ['M34 - Campioni', int(dfCatodo.loc[('M34', 'Campioni'),
'Misura'])]

# DATI ANODO:
M01aTitolo = 'Discharge chamber top surface flatness:'
dfTabAnodoM01 = pd.DataFrame(columns=['Elemento', 'Valore'])
dfTabAnodoM01.loc[len(dfTabAnodoM01)] = ['M01 - Tolleranza [mm]', toll11a]
dfTabAnodoM01.loc[len(dfTabAnodoM01)] = ['M01 - Raggio [mm]', dfAnodo.loc[('M01', 'Raggio'),
'Misura']]
dfTabAnodoM01.loc[len(dfTabAnodoM01)] = ['M01 - Misura nominale [mm]', dfAnodo.loc[('M01', 'Misura
nominale'), 'Misura']]
dfTabAnodoM01.loc[len(dfTabAnodoM01)] = ['M01 - Campioni', int(dfAnodo.loc[('M01', 'Campioni'),
'Misura'])]

M12aTitolo = 'Distance discharge chamber top surface - the anode grid:'
dfTabAnodoM12 = pd.DataFrame(columns=['Elemento', 'Valore'])
dfTabAnodoM12.loc[len(dfTabAnodoM12)] = ['M12 - Tolleranza [mm]', toll12a]
dfTabAnodoM12.loc[len(dfTabAnodoM12)] = ['M12 - Raggio [mm]', dfAnodo.loc[('M12', 'Raggio'),
'Misura']]
dfTabAnodoM12.loc[len(dfTabAnodoM12)] = ['M12 - Misura nominale [mm]', dfAnodo.loc[('M12', 'Misura
nominale'), 'Misura']]
dfTabAnodoM12.loc[len(dfTabAnodoM12)] = ['M12 - Campioni', int(dfAnodo.loc[('M12', 'Campioni'),

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```

'Misura']]

M23aTitolo = 'Anode grid flatness:'
dfTabAnodoM23 = pd.DataFrame(columns=['Elemento', 'Valore'])
dfTabAnodoM23.loc[len(dfTabAnodoM23)] = ['M23 - Tolleranza [mm]', toll13a]
dfTabAnodoM23.loc[len(dfTabAnodoM23)] = ['M23 - Raggio [mm]', dfAnodo.loc[('M23', 'Raggio'),
'Misura']]
dfTabAnodoM23.loc[len(dfTabAnodoM23)] = ['M23 - Misura nominale [mm]', dfAnodo.loc[('M23', 'Misura
nominale'), 'Misura']]
dfTabAnodoM23.loc[len(dfTabAnodoM23)] = ['M23 - Campioni', int(dfAnodo.loc[('M23', 'Campioni'),
'Misura'])]
dfTabAnodoM23.set_index('Elemento') # Imposto la prima colonna come indice del dataframe,
altrimenti ne aggiunge uno numerato
# Dataframe con dati sulla votazione complessiva
dfVoto = pd.DataFrame(columns=['Elemento', 'Valore'])
dfVoto.loc[len(dfVoto)] = ['Voto complessivo:', votoTot]
dfVoto.loc[len(dfVoto)] = ['Voto sigma:', votoSigma]
dfVoto.loc[len(dfVoto)] = ['Voto tolleranza:', votoToll]
# Dataframe con dati sui voti degli elementi del catodo
dfVotoCatodo = pd.DataFrame(columns=['Elemento', 'Valore'])
dfVotoCatodo.loc[len(dfVotoCatodo)] = ['Voto toll MIN:', votoTollMIN]
dfVotoCatodo.loc[len(dfVotoCatodo)] = ['Voto toll MAX:', votoTollMAX]
dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M01 - valore toll MIN:', dfCatodo.loc[('M01', 'Tolleranza
MIN'), 'Misura']]
dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M01 - Valore toll MAX:', dfCatodo.loc[('M01', 'Tolleranza
MAX'), 'Misura']]
dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M01 - valore toll:', toll11c]
dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M01 - voto toll:', votoToll11c]
dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M12 - valore toll MIN:', dfCatodo.loc[('M12', 'Tolleranza
MIN'), 'Misura']]
dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M12 - Valore toll MAX:', dfCatodo.loc[('M12', 'Tolleranza
MAX'), 'Misura']]
dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M12 - valore toll:', toll12c]
dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M12 - voto toll:', votoToll12c]
dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M23 - valore toll MIN:', dfCatodo.loc[('M23', 'Tolleranza
MIN'), 'Misura']]

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```

        dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M23 - Valore toll MAX:', dfCatodo.loc[('M23', 'Tolleranza
MAX'), 'Misura']]
        dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M23 - valore toll:', toll3c]
        dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M23 - voto toll:', votoToll3c]
        dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M34 - valore toll MIN:', dfCatodo.loc[('M34', 'Tolleranza
MIN'), 'Misura']]
        dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M34 - Valore toll MAX:', dfCatodo.loc[('M34', 'Tolleranza
MAX'), 'Misura']]
        dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M34 - valore toll:', toll4c]
        dfVotoCatodo.loc[len(dfVotoCatodo)] = ['M34 - voto toll:', votoToll4c]

# Dataframe con dati sui voti degli elementi dell'anodo
dfVotoAnodo = pd.DataFrame(columns=['Elemento', 'Valore'])
dfVotoAnodo.loc[len(dfVotoAnodo)] = ['Voto toll MIN:', votoTollMIN]
dfVotoAnodo.loc[len(dfVotoAnodo)] = ['Voto toll MAX:', votoTollMAX]
dfVotoAnodo.loc[len(dfVotoAnodo)] = ['M01 - valore toll MIN:', dfAnodo.loc[('M01', 'Tolleranza
MIN'), 'Misura']]
dfVotoAnodo.loc[len(dfVotoAnodo)] = ['M01 - Valore toll MAX:', dfAnodo.loc[('M01', 'Tolleranza
MAX'), 'Misura']]
dfVotoAnodo.loc[len(dfVotoAnodo)] = ['M01 - valore toll:', toll1a]
dfVotoAnodo.loc[len(dfVotoAnodo)] = ['M01 - voto toll:', votoToll1a]
dfVotoAnodo.loc[len(dfVotoAnodo)] = ['M12 - valore toll MIN:', dfAnodo.loc[('M12', 'Tolleranza
MIN'), 'Misura']]
dfVotoAnodo.loc[len(dfVotoAnodo)] = ['M12 - Valore toll MAX:', dfAnodo.loc[('M12', 'Tolleranza
MAX'), 'Misura']]
dfVotoAnodo.loc[len(dfVotoAnodo)] = ['M12 - valore toll:', toll2a]
dfVotoAnodo.loc[len(dfVotoAnodo)] = ['M12 - voto toll:', votoToll2a]
dfVotoAnodo.loc[len(dfVotoAnodo)] = ['M23 - valore toll MIN:', dfAnodo.loc[('M23', 'Tolleranza
MIN'), 'Misura']]
dfVotoAnodo.loc[len(dfVotoAnodo)] = ['M23 - Valore toll MAX:', dfAnodo.loc[('M23', 'Tolleranza
MAX'), 'Misura']]
dfVotoAnodo.loc[len(dfVotoAnodo)] = ['M23 - valore toll:', toll3a]
dfVotoAnodo.loc[len(dfVotoAnodo)] = ['M23 - voto toll:', votoToll3a]

#
# ***** GENERAZIONE E SALVATAGGIO GRAFICI *****

```

```

#
cm = 1 / 2.54 # centimeters in inches

# Genero stringa contenente la data:
timestamp = time.time()
date_time = datetime.fromtimestamp(timestamp)
# convert timestamp to string in yyyy-mm-dd - HH-MM-SS
str_date_time = date_time.strftime("%Y-%m-%d - %H-%M-%S")

# Genero il nome da assegnare al file
#
# if nomePDFPersonalizzato == '':
#     nomePDF = nomeFileExcel # se non specifico il nome uso quello del file excel
# else:
#     nomePDF = nomePDFPersonalizzato
#
# if aggiungiData:
#     nomePDF += ' ' + str_date_time

# nomePDFAUTOM = '' + str(round(votoTot, 4)) + '-' + str(round(sigma_dz03ac, 4)) + '-' +
str(round(toll1c, 4)) + '-' + str(round(toll2c, 4)) + '-' + str(round(toll3c, 4)) + '-' + str(round(toll4c, 4))
+ '-' + str(round(toll5c, 4)) + '-' + str(round(toll6c, 4)) + '-' + str(round(toll1a, 4)) + '-' +
str(round(toll2a, 4)) + '-' + str(round(toll3a, 4))
# nomePDFAUTOM = '' + '{:.4f}'.format(round(votoTot, 4)) + '-' + '{:.4f}'.format(round(sigma_dz03ac,
4)) + '-' + '{:.4f}'.format(round(toll1c, 4)) + '-' + '{:.4f}'.format(round(toll2c, 4)) + '-' +
'{:.4f}'.format(round(toll3c, 4)) + '-' + '{:.4f}'.format(round(toll4c, 4)) + '-' +
'{:.4f}'.format(round(toll5c, 4)) + '-' + '{:.4f}'.format(round(toll6c, 4)) + '-' +
'{:.4f}'.format(round(toll1a, 4)) + '-' + '{:.4f}'.format(round(toll2a, 4)) + '-' +
'{:.4f}'.format(round(toll3a, 4))
nomePDFAUTOM = '' + '{:.4f}'.format(round(votoTot, 4)) + '-' + '{:.4f}'.format(round(sigma_dz03ac,
4)) + '-' + combTollString([toll1c, toll2c, toll3c, toll4c, toll1a, toll2a, toll3a])

# Inizio a generare le varie pagine del PDF:
with PdfPages(nomePDFAUTOM + '.pdf') as pdf:
    # Genero il plot contenente le tabelle dei dati della simulazione

```

```

plt.figure(0)
fig, ax = plt.subplots(4, 1, figsize=(21 * cm, 29.7 * cm))
# hide axes
fig.patch.set_visible(False)
fig.subplots_adjust(left=None, bottom=None, right=None, top=None, wspace=None, hspace=0.3)
# fig.get_layout_engine().set_layout_engine(Layout='Constrained')
# Dati simulazione catodo
ax[0].text(1.05, -4, s='Simulation results: cathode frontal surface stack-up', fontsize=18,
weight='bold', horizontalalignment='center')
ax[0].axis('off')
#ax[0].axis('tight')
tabCat = Table(dfTabCatodoM01, ax=ax[0], index_col='Elemento', footer_divider=True,
               column_definitions=[
                   ColumnDefinition(border='both', name='Elemento', title='', textprops={"ha":
"left"}, width=2),
                   ColumnDefinition(border='both', name='Valore', title='Valore',
textprops={"ha": "center"}, width=0.23)])
ax[0].set_title(M01cTitolo, weight='semibold', pad=2, y=1.000001) # Parametro "y" usato per
far funzionare il padding verso il basso, vedi https://github.com/matplotlib/matplotlib/issues/16805/

ax[1].axis('off')
# ax[1].axis('tight')
tabCat = Table(dfTabCatodoM12, ax=ax[1], index_col='Elemento', footer_divider=True,
               column_definitions=[
                   ColumnDefinition(border='both', name='Elemento', title='', textprops={"ha":
"left"}, width=2),
                   ColumnDefinition(border='both', name='Valore', textprops={"ha": "center"},
width=0.23)])
ax[1].set_title(M12cTitolo, weight='semibold', pad=2, y=1.000001)

ax[2].axis('off')
#ax[2].axis('tight')
tabCat = Table(dfTabCatodoM23, ax=ax[2], index_col='Elemento', footer_divider=True,
               column_definitions=[
                   ColumnDefinition(border='both', name='Elemento', title='', textprops={"ha":

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```

"left"}, width=2),
                                ColumnDefinition(border='both', name='Valore', textprops={"ha": "center"},
width=0.23)])
    ax[2].set_title(M23cTitolo, weight='semibold', pad=2, y=1.000001)

    ax[3].axis('off')
    #ax[3].axis('tight')
    tabCat = Table(dfTabCatodoM34, ax=ax[3], index_col='Elemento', footer_divider=True,
                    column_definitions=[
                        ColumnDefinition(border='both', name='Elemento', title='', textprops={"ha":
"left"}, width=2),
                                ColumnDefinition(border='both', name='Valore', textprops={"ha": "center"},
width=0.23)])
    ax[3].set_title(M34cTitolo, weight='semibold', pad=2, y=1.000001)
    # fig.tight_layout()
    # Salvo pagina
    pdf.savefig()

    # Dati simulazione ANODO
    plt.figure(1)
    fig, ax = plt.subplots(6, 1, figsize=(21 * cm, 29.7 * cm))
    # hide axes
    fig.patch.set_visible(False)
    fig.subplots_adjust(left=None, bottom=None, right=None, top=None, wspace=None, hspace=0.3)
    # fig.get_layout_engine().set_layout_engine(Layout='Constrained')
    # Dati simulazione catodo
    ax[0].text(1.05, -4, s='Simulation results: anode grid stack-up', fontsize=18, weight='bold',
horizontalalignment='center')
    ax[0].axis('off')
    #ax[0].axis('tight')
    tabAno = Table(dfTabAnodoM01, ax=ax[0], index_col='Elemento', footer_divider=True,
                    column_definitions=[
                        ColumnDefinition(border='both', name='Elemento', title='', textprops={"ha":
"left"}, width=2),
                                ColumnDefinition(border='both', name='Valore', title='Valore',
textprops={"ha": "center"}, width=0.23)])

```

```

        ax[0].set_title(M01aTitolo, weight='semibold', pad=2, y=1.000001) # Parametro "y" usato per
far funzionare il padding verso il basso, vedi https://github.com/matplotlib/matplotlib/issues/16805/

        ax[1].axis('off')
        # ax[1].axis('tight')
        tabAno = Table(dfTabAnodoM12, ax=ax[1], index_col='Elemento', footer_divider=True,
            column_definitions=[
                ColumnDefinition(border='both', name='Elemento', title='', textprops={"ha":
"left"}, width=2),
                ColumnDefinition(border='both', name='Valore', textprops={"ha": "center"},
width=0.23)])
        ax[1].set_title(M12aTitolo, weight='semibold', pad=2, y=1.000001)

        ax[2].axis('off')
        #ax[2].axis('tight')
        tabAno = Table(dfTabAnodoM23, ax=ax[2], index_col='Elemento', footer_divider=True,
            column_definitions=[
                ColumnDefinition(border='both', name='Elemento', title='', textprops={"ha":
"left"}, width=2),
                ColumnDefinition(border='both', name='Valore', textprops={"ha": "center"},
width=0.23)])
        ax[2].set_title(M23aTitolo, weight='semibold', pad=2, y=1.000001)
        # Nascondo gli assi degli altri subplot
        ax[3].axis('off')
        ax[4].axis('off')
        ax[5].axis('off')
        # Salvo pagina
        pdf.savefig()

        # CATODO:
        plt.figure(2, figsize=(33.867 * cm, 19.05 * cm))
        fig, ax = plt.subplots()
        # for label in (ax.get_xticklabels() + ax.get_yticklabels()): #RIMOSSE ANCHE DAI PLOT
        SUCCESSIVI, SONO CREATI TROPPO GRANDI!

```

```

        # label.set_fontsize(22)
        # creo e plotto l'istogramma della distribuzione della distanza (che dovrebbe risultare ancora
gaussiana):
        histc = plt.hist(dz04c, 50, density=True, color="black", alpha=0.2) # per non fare il grafico
normalizzato metti density=False
        # ci disegno sopra anche il profilo della gaussiana associata
        plt.plot(np.linspace(min(dz04c), max(dz04c), 1000),
                 gaussian(np.linspace(min(dz04c), max(dz04c), 1000), mu_dz04c,
sigma_dz04c), color="black", linewidth=1)
        max_ticks=9
        ax.xaxis.set_major_locator(MaxNLocator(max_ticks))
        minor_locator_X = AutoMinorLocator(5)
        ax.xaxis.set_minor_locator(minor_locator_X)
        # plotto linea verticale per segnare la media:
        plt.axvline(mu_dz04c, 0.0, 1, color="black", linewidth=0.75, linestyle="dotted")
        plt.title("Distance cathode frontal surface - reference frame", weight='semibold',
                 size='large') # , fontsize=28) --> inutile, è adattata automaticamente
        plt.xlabel("distance [mm]") # , fontsize=28)
        plt.ylabel("PDF") # , fontsize=28)
        plt.text(0.9, 0.9,
f'$\overline{{c}}=${mu_dz04c:.4f}$n$\sigma_{{\mathrm{{sim}}}}=${sigma_dz04c:.4f}', transform=ax.transAxes,
                 horizontalalignment='right', verticalalignment='center', bbox=dict(facecolor='white',
alpha=1)) # , fontsize=28)
        plt.grid(True, which='major')
        # Salvo pagina
        pdf.savefig()

        # ANODO
        plt.figure(3, figsize=(33.867 * cm, 19.05 * cm))
        fig, ax = plt.subplots()
        # creo e plotto l'istogramma della distribuzione della distanza (che dovrebbe risultare ancora
gaussiana):
        hista = plt.hist(dz03a, 50, color="black", alpha=0.2, density=True) # per non fare il grafico
normalizzato metti density=False
        # ci disegno sopra anche il profilo della gaussiana associata
        plt.plot(np.linspace(min(dz03a), max(dz03a), 1000),

```



```

        gaussian(np.linspace(min(dz03a), max(dz03a), 1000), mu_dz03a, sigma_dz03a),
color="black", linewidth=1)
    max_ticks=9
    ax.xaxis.set_major_locator(MaxNLocator(max_ticks))
    minor_locator_X = AutoMinorLocator(5)
    ax.xaxis.set_minor_locator(minor_locator_X)
    # plotto linea verticale per segnare la media:
    plt.axvline(mu_dz03a, 0.0, 1, color="black", linewidth=0.75, linestyle="dotted")
    plt.title("Distance anode grid - reference frame", weight='semibold', size='large')
    plt.xlabel("distance [mm]")
    plt.ylabel("PDF")
    plt.text(0.9, 0.9,
f'$\overline{{b}}={\mu_{dz03a:.4f}}\backslash n$\sigma_{\mathrm{{sim}}}={\sigma_{dz03a:.4f}}$',
horizontalalignment='right',
        verticalalignment='center', transform=ax.transAxes, bbox=dict(facecolor='white',
alpha=1))

    plt.grid(True, which='major')
    # Salvo pagina
    pdf.savefig()

    # POSIZIONE RELATIVA
    plt.figure(4, figsize=(33.867 * cm, 19.05 * cm))
    fig, ax = plt.subplots()
    # creo e plotto l'istogramma della distribuzione della differenza di posizione relativa anodo
catodo
    # (che dovrebbe risultare ancora gaussiana):
    histac = plt.hist(dz03ac, 50, color="black",
        density=True, alpha=0.2) # per non fare il grafico normalizzato metti
density=False
    # ci disegno sopra anche il profilo della gaussiana associata
    plt.plot(np.linspace(min(dz03ac), max(dz03ac), 1000),
        gaussian(np.linspace(min(dz03ac), max(dz03ac), 1000), mu_dz03ac, sigma_dz03ac),
color="black", linewidth=1)
    max_ticks=9
    ax.xaxis.set_major_locator(MaxNLocator(max_ticks))
    minor_locator_X = AutoMinorLocator(5)

```

```

ax.xaxis.set_minor_locator(minor_locator_X)
# plotto linea verticale per segnare la media:
plt.axvline(mu_dz03ac, 0.0, 1, color="black", linewidth=0.75, linestyle="dotted")
plt.title("Distance anode grid - cathode frontal surface", weight='semibold', size='large')
plt.xlabel("Distance [mm]")
plt.ylabel("PDF")
plt.text(0.9,
0.9,f'$\overline{\{a\}}=\{\mu_{dz03ac:.3f}\}\backslash n\$\\sigma_{\{\mathrm{\{sim\}}\}}=\{\sigma_{dz03ac:.3f}\}$',horizontalalignment='r
ight', verticalalignment='center', transform=ax.transAxes, bbox=dict(facecolor='white', alpha=1), fontsize=12)
    plt.text(0.9,
0.9,f'$\overline{\{a\}}=\{\mu_{dz03ac:.3f}\}\backslash n\$\\sigma_{\{\mathrm{\{sim\}}\}}=\{\sigma_{dz03ac:.3f}\}\backslash n\$a_{\{\mathrm{\{MIN\}}\}}=
\{distMinCA:.2f\}$',horizontalalignment='right', verticalalignment='center',
transform=ax.transAxes, bbox=dict(facecolor='white', alpha=1), fontsize=12)
plt.grid(True, which='major')

# Read scattered points from Excel file
scatter_data = pd.read_excel("exp_data_anode_cathode_distance.xlsx") # Update with your Excel
file path
x_scatter_excel = scatter_data["x_column_name"] # Update with the column name containing x
values

# Compute corresponding y-values using the Gaussian PDF
y_scatter_excel = gaussian(x_scatter_excel, mu_dz03ac, sigma_dz03ac)

# Plot scattered points
plt.scatter(x_scatter_excel, y_scatter_excel, color='black', marker='x', label='Exp points')

plt.legend(loc='upper left', facecolor='white', framealpha=1, edgecolor='black') # Show legend
plt.savefig('anode_cathode_distance.png', dpi=300, bbox_inches='tight')
pdf.savefig()

# ANALISI DEL PARALLELISMO
# plotto gli angoli alpha del catodo
plt.figure(5, figsize=(33.867 * cm, 19.05 * cm))
fig, ax = plt.subplots()

```

```

        histalphac = plt.hist(alphac, 50, color="black",
                                density=True, alpha=0.2) # per non fare il grafico normalizzato metti
density=False
        plt.plot(np.linspace(min(alphac), max(alphac), 1000), gaussian(np.linspace(min(alphac),
max(alphac), 1000), mu_alphac, sigma_alphac), color="black", linewidth=1)
        max_ticks=9
        ax.xaxis.set_major_locator(MaxNLocator(max_ticks))
        minor_locator_X = AutoMinorLocator(5)
        ax.xaxis.set_minor_locator(minor_locator_X)
        # plotto linea verticale per segnare la media:
        plt.axvline(mu_alphac, 0.0, 1, color="black", linewidth=0.75, linestyle="dotted")
        plt.title(r"Inclination angle  $\gamma$  distribution - cathode", weight='semibold',
size='large')
        plt.xlabel(r" $\alpha$  [deg]")
        plt.ylabel("PDF")
        plt.text(0.9, 0.9,
f' $\overline{\gamma} = \mu_{\text{alphac}} \pm \sigma_{\text{alphac}}$ ',
transform=ax.transAxes,
        horizontalalignment='right', verticalalignment='center', bbox=dict(facecolor='white',
alpha=1))

        plt.grid(True, which='major')
        pdf.savefig()

        # plotto gli angoli beta del catodo
        plt.figure(6, figsize=(33.867 * cm, 19.05 * cm))
        fig, ax = plt.subplots()
        histbetac = plt.hist(betac, 50, color="black",
                                density=True, alpha=0.2) # per non fare il grafico normalizzato metti
density=False
        plt.plot(np.linspace(min(betac), max(betac), 1000),
        gaussian(np.linspace(min(betac), max(betac), 1000), mu_betac, sigma_betac),
color="black", linewidth=1)
        max_ticks=9
        ax.xaxis.set_major_locator(MaxNLocator(max_ticks))
        minor_locator_X = AutoMinorLocator(5)
        ax.xaxis.set_minor_locator(minor_locator_X)

```

```

# plotto linea verticale per segnare la media:
plt.axvline(mu_betac, 0.0, 1, color="black", linewidth=0.75, linestyle="dotted")
plt.title(r"Inclination angle  $\gamma$  distribution - cathode", weight='semibold',
size='large')
plt.xlabel(r" $\beta$  [deg]")
plt.ylabel("PDF")
plt.text(0.9, 0.9,
f' $\overline{\gamma_1} = \mu_{\text{betac}} : .4f \backslash n \sigma_{\{\mathrm{\sim}\}} = \sigma_{\text{betac}} : .4f$ ',
transform=ax.transAxes,
horizontalalignment='right', verticalalignment='center', bbox=dict(facecolor='white',
alpha=1))

plt.grid(True, which='major')
pdf.savefig()

# plotto gli angoli alpha dell'anodo
plt.figure(7, figsize=(33.867 * cm, 19.05 * cm))
fig, ax = plt.subplots()
histaalpha = plt.hist(alphaa, 50, density=True, color="black",
alpha=0.2) # per non fare il grafico normalizzato metti density=False
plt.plot(np.linspace(min(alphaa), max(alphaa), 1000),
gaussian(np.linspace(min(alphaa), max(alphaa), 1000), mu_alphaa, sigma_alphaa),
color="black", linewidth=1)
max_ticks=9
ax.xaxis.set_major_locator(MaxNLocator(max_ticks))
minor_locator_X = AutoMinorLocator(5)
ax.xaxis.set_minor_locator(minor_locator_X)
# plotto linea verticale per segnare la media:
plt.axvline(mu_alphaa, 0.0, 1, color="black", linewidth=0.75, linestyle="dotted")
plt.title("Anode grid inclination angle  $\theta$  distribution", weight='semibold',
size='large')
plt.xlabel("Inclination angle  $\theta$  -anode grid [deg]")
plt.ylabel("PDF")
plt.text(0.96, 0.96,
f' $\overline{\theta} = \mu_{\text{alphaa}} : .3f \backslash n \sigma_{\{\mathrm{\sim}\}} = \sigma_{\text{alphaa}} : .3f$ ',
transform=ax.transAxes,
horizontalalignment='right', verticalalignment='top', bbox=dict(facecolor='white',

```

```

alpha=1), fontsize=12)
    plt.grid(True, which='major')

    # Read scattered experimental points from Excel file
    scatter_data = pd.read_excel("exp_data_anode_grid_angle.xlsx") # Update with your Excel file
path
    x_scatter_excel = scatter_data["x_column_name"] # Update with the column name containing x
values

    # Compute corresponding y-values using the Gaussian PDF
    y_scatter_excel = gaussian(x_scatter_excel, mu_alphaa, sigma_alphaa)

    # Plot scattered points
    plt.scatter(x_scatter_excel, y_scatter_excel, color='black', marker='x', label='Exp points')

    plt.legend(loc='upper left', facecolor='white', framealpha=1, edgecolor='black')
    plt.savefig('theta angles.png', dpi=300, bbox_inches='tight')
    pdf.savefig()

    # plotto gli angoli beta dell'anodo
    plt.figure(8, figsize=(33.867 * cm, 19.05 * cm))
    fig, ax = plt.subplots()
    histbetaa = plt.hist(betaa, 50, density=True, color="black",
                        alpha=0.2) # per non fare il grafico normalizzato metti density=False
    plt.plot(np.linspace(min(betaa), max(betaa), 1000),
            gaussian(np.linspace(min(betaa), max(betaa), 1000), mu_betaa, sigma_betaa),
color="black", linewidth=1)
    max_ticks=9
    ax.xaxis.set_major_locator(MaxNLocator(max_ticks))
    minor_locator_X = AutoMinorLocator(5)
    ax.xaxis.set_minor_locator(minor_locator_X)
    # plotto linea verticale per segnare la media:
    plt.axvline(mu_betaa, 0.0, 1, color="black", linewidth=0.75, linestyle="dotted")
    plt.title("Anode grid inclination angle  $\theta$  distribution", weight='semibold',
size='large')
    plt.xlabel("Inclination angle  $\theta$  -anode grid [deg]")

```

```

        plt.ylabel("PDF")
        plt.text(0.9, 0.9,
f'\$\overline{{\{\theta_{1}\}}}=\${\mu_{\text{betaa:.4f}}}\n$\sigma_{\{\mathrm{{\sim}}\}}=\${\sigma_{\text{betaa:.4f}}}',
transform=ax.transAxes,
        horizontalalignment='right', verticalalignment='center', bbox=dict(facecolor='white',
alpha=1))

    plt.grid(True, which='major')
    pdf.savefig()

    # plotto l'istogramma della distribuzione dell'angolo formato tra superfici HT del catodo e
griglia dell'anodo
    plt.figure(9, figsize=(33.867 * cm, 19.05 * cm))
    fig, ax = plt.subplots()
    histac = plt.hist(w, 100, color="darkred", density=True,
        alpha=1) # per non fare il grafico normalizzato metti density=False
    # plotto linea verticale per segnare la media:
    plt.axvline(mu_w, 0.0, 1, color="red")
    plt.title("Angle between cathode frontal surface and anode grid", weight='semibold',
size='large')
    plt.xlabel("Angle [deg]")
    plt.ylabel("PDF")
    # plt.show()
    pdf.savefig()

    # In ultima pagina aggiungo la tabella contenente i risultati dell'analisi di sensitività:
    plt.figure(10)
    fig, ax = plt.subplots()
    # hide axes
    fig.patch.set_visible(False)
    ax.axis('off')
    ax.axis('tight')
    tabella = ax.table(cellText=dfSensitivita.values, colLabels=dfSensitivita.columns, loc='upper
center',
        cellLoc='left')
    tabella.auto_set_column_width(
        col=list(range(len(dfSensitivita.columns)))) # Provide integer list of columns to adjust

```

```

        ax.set_title("Sensitivity analysis:", weight='semibold')
        #fig.tight_layout()
        # Salvo pagina
        pdf.savefig()

plt.figure(11)
fig, ax = plt.subplots()
# hide axes
fig.patch.set_visible(False)
ax.axis('off')
#ax.axis('tight')
        tabella = ax.table(cellText=dfVoto.values, colLabels=dfVoto.columns, loc='upper center',
cellLoc='left')
        tabella.auto_set_column_width(
            col=list(range(len(dfVoto.columns)))) # Provide integer list of columns to adjust
        ax.set_title("Voto risultati simulazione:", weight='semibold')
        ax.text(x=0, y=-0.13, s='Codice v2.3', fontsize=10, verticalalignment='bottom',
horizontalalignment='center', transform=ax.transAxes)
        # fig.tight_layout()
        # Salvo pagina
        pdf.savefig()

plt.figure(12)
fig, ax = plt.subplots(figsize=(19.05 * cm, 33.867 * cm))
# hide axes
fig.patch.set_visible(False)
ax.axis('off')
#ax.axis('tight')
        tabella = ax.table(cellText=dfVotoCatodo.values, colLabels=dfVotoCatodo.columns, loc='upper
center', cellLoc='left')
        tabella.auto_set_column_width(
            col=list(range(len(dfVotoCatodo.columns)))) # Provide integer list of columns to adjust
        ax.set_title("Votazione elementi Catodo:", weight='semibold')
        # fig.tight_layout()
        # Salvo pagina
        pdf.savefig()

```

```

plt.figure(13)
fig, ax = plt.subplots()
# hide axes
fig.patch.set_visible(False)
ax.axis('off')
# ax.axis('tight')
tabella = ax.table(cellText=dfVotoAnodo.values, colLabels=dfVotoAnodo.columns, loc='upper
center', cellLoc='left')
tabella.auto_set_column_width(
    col=list(range(len(dfVotoAnodo.columns)))) # Provide integer list of columns to adjust
ax.set_title("Votazione elementi Anodo:", weight='semibold')
# fig.tight_layout()
# Salvo pagina
pdf.savefig()

#Chiudo tutte le figure per liberare memoria
plt.close('all')

#print('\n\nGenerato PDF: ' + nomePDF + '\n')

# Primi due elementi FALSE indicano che non è uno scarto, usato per incrementare contatore
iterazioni globali
iterazioneCalcolata = [False, False, toll1c, toll2c, toll3c, toll4c, toll1a, toll2a, toll3a]
queueScarti.put(iterazioneCalcolata)

# ritorno al chiamante i valori di mu e sigma ottenuti
return [mu_dz03ac, sigma_dz03ac] # Per ora inutilizzati, si potrebbero togliere
else:
#CASO IN CUI SIGMA VERIFICATO MA FUORI TOLL PER ANGOLI
print('Deviazione STD accettabile ('+str(sigma_dz03ac)+'), ma inclinazione facce fuori limite!',
flush=True)
print('Dist minima caso peggiore=' + str(distMinCA), flush=True)
# Aggiungo alla queueScarti la combinazione di tolleranza da aggiungere agli scarti
# scarto = [scarto SUP, scarto INF, tutti i valori tolleranza...]
# Questo scarto è di tipo SUP (dovrò stringere le tolleranze)

```



```

# ***** Gestione combinazioni tolleranze di scarto *****
#
# In file principale...
#
# ***** XXXXXXXXXXXXXXXXXXXXXXXX *****
#

def generaCombSuperiori(dataframeCatodo, dataframeAnodo, decimMax, toll1cMin, toll2cMin, toll3cMin, toll4cMin,
toll1aMin, toll2aMin, toll3aMin):
    # Devo generare un array con tutte le combinazioni di tolleranze con valori maggiori o uguali a quelli
    # forniti in ingresso
    # La funzione arange() di numpy deve lavorare con interi, altrimenti può ritornare valori errati per errori
    # di arrotondamento. Quindi moltiplico ogni elemento per 10^decimMax per avere tutti numeri interi, arrotondo "a
    # zero decimali" e li trasformo in int()
    # https://numpy.org/doc/stable/reference/generated/numpy.arange.html
    valTollSupCatodoM01 = np.arange(int(round(toll1cMin*(10**decimMax))), int(round(dataframeCatodo.loc[('M01',
'Tolleranza MAX'), 'Misura']*(10**decimMax))) + int(round(dataframeCatodo.loc[('M01', 'Tolleranza INCREMENTO'),
'Misura']*(10**decimMax))), int(round(dataframeCatodo.loc[('M01', 'Tolleranza INCREMENTO'),
'Misura']*(10**decimMax))))
    valTollSupCatodoM12 = np.arange(int(round(toll2cMin*(10**decimMax))), int(round(dataframeCatodo.loc[('M12',
'Tolleranza MAX'), 'Misura']*(10**decimMax))) + int(round(dataframeCatodo.loc[('M12', 'Tolleranza INCREMENTO'),
'Misura']*(10**decimMax))), int(round(dataframeCatodo.loc[('M12', 'Tolleranza INCREMENTO'),
'Misura']*(10**decimMax))))
    valTollSupCatodoM23 = np.arange(int(round(toll3cMin*(10**decimMax))), int(round(dataframeCatodo.loc[('M23',
'Tolleranza MAX'), 'Misura']*(10**decimMax))) + int(round(dataframeCatodo.loc[('M23', 'Tolleranza INCREMENTO'),
'Misura']*(10**decimMax))), int(round(dataframeCatodo.loc[('M23', 'Tolleranza INCREMENTO'),
'Misura']*(10**decimMax))))
    valTollSupCatodoM34 = np.arange(int(round(toll4cMin*(10**decimMax))), int(round(dataframeCatodo.loc[('M34',
'Tolleranza MAX'), 'Misura']*(10**decimMax))) + int(round(dataframeCatodo.loc[('M34', 'Tolleranza INCREMENTO'),
'Misura']*(10**decimMax))), int(round(dataframeCatodo.loc[('M34', 'Tolleranza INCREMENTO'),
'Misura']*(10**decimMax))))
    valTollSupAnodoM01 = np.arange(int(round(toll1aMin*(10**decimMax))), int(round(dataframeAnodo.loc[('M01',
'Tolleranza MAX'), 'Misura']*(10**decimMax))) + int(round(dataframeAnodo.loc[('M01', 'Tolleranza INCREMENTO'),
'Misura']*(10**decimMax))), int(round(dataframeAnodo.loc[('M01', 'Tolleranza INCREMENTO'),
'Misura']*(10**decimMax))))

```

```

    valTollSupAnodoM12 = np.arange(int(round(toll2aMin*(10**decimMax))), int(round(dataframeAnodo.loc[('M12',
'Tolleranza MAX'), 'Misura']*(10**decimMax))) + int(round(dataframeAnodo.loc[('M12', 'Tolleranza INCREMENTO'),
'Misura']*(10**decimMax))), int(round(dataframeAnodo.loc[('M12', 'Tolleranza INCREMENTO'),
'Misura']*(10**decimMax))))
    valTollSupAnodoM23 = np.arange(int(round(toll3aMin*(10**decimMax))), int(round(dataframeAnodo.loc[('M23',
'Tolleranza MAX'), 'Misura']*(10**decimMax))) + int(round(dataframeAnodo.loc[('M23', 'Tolleranza INCREMENTO'),
'Misura']*(10**decimMax))), int(round(dataframeAnodo.loc[('M23', 'Tolleranza INCREMENTO'),
'Misura']*(10**decimMax))))
    multidimScarto = [valTollSupCatodoM01, valTollSupCatodoM12, valTollSupCatodoM23, valTollSupCatodoM34,
valTollSupAnodoM01, valTollSupAnodoM12, valTollSupAnodoM23]
    combinazioniTollScarto = np.stack(np.meshgrid(*multidimScarto), axis=-1).reshape(-1, len(multidimScarto))
    return combinazioniTollScarto/(10**decimMax) # Trasformo di nuovo in decimali

```

```

#
#
#

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*****
XXXXXXXXXXXXXXXXXXXXXXXXX
*****

```

```

def generaCombInferiori(dataframeCatodo, dataframeAnodo, decimMax, toll1cMax, toll2cMax, toll3cMax, toll4cMax,
toll1aMax, toll2aMax, toll3aMax):
    # Devo generare un array con tutte le combinazioni di tolleranze con valori minori o uguali a quelli
    # forniti in ingresso
    # La funzione arange() di numpy deve lavorare con interi, altrimenti può ritornare valori errati per errori
    # di arrotondamento. Quindi moltiplico ogni elemento per 10^decimMax per avere tutti numeri interi, arrotondo "a
    # zero decimali" e li trasformo in int()
    # https://numpy.org/doc/stable/reference/generated/numpy.arange.html
    valTollInfCatodoM01 = np.arange(int(round(dataframeCatodo.loc[('M01', 'Tolleranza MIN'),
'Misura']*(10**decimMax))), int(round(toll1cMax*(10**decimMax))) + int(round(dataframeCatodo.loc[('M01',
'Tolleranza INCREMENTO'), 'Misura']*(10**decimMax))), int(round(dataframeCatodo.loc[('M01', 'Tolleranza
INCREMENTO'), 'Misura']*(10**decimMax))))
    valTollInfCatodoM12 = np.arange(int(round(dataframeCatodo.loc[('M12', 'Tolleranza MIN'),
'Misura']*(10**decimMax))), int(round(toll2cMax*(10**decimMax))) + int(round(dataframeCatodo.loc[('M12',
'Tolleranza INCREMENTO'), 'Misura']*(10**decimMax))), int(round(dataframeCatodo.loc[('M12', 'Tolleranza
INCREMENTO'), 'Misura']*(10**decimMax))))
    valTollInfCatodoM23 = np.arange(int(round(dataframeCatodo.loc[('M23', 'Tolleranza MIN'),
'Misura']*(10**decimMax))), int(round(toll3cMax*(10**decimMax))) + int(round(dataframeCatodo.loc[('M23',

```

```

'Tolleranza INCREMENTO'), 'Misura']*(10**decimMax))), int(round(dataframeCatodo.loc[('M23', 'Tolleranza
INCREMENTO'), 'Misura']*(10**decimMax))))
    valTollInfCatodoM34 = np.arange(int(round(dataframeCatodo.loc[('M34', 'Tolleranza MIN'),
'Misura']*(10**decimMax))), int(round(toll14cMax*(10**decimMax))) + int(round(dataframeCatodo.loc[('M34',
'Tolleranza INCREMENTO'), 'Misura']*(10**decimMax))), int(round(dataframeCatodo.loc[('M34', 'Tolleranza
INCREMENTO'), 'Misura']*(10**decimMax))))
    valTollInfAnodoM01 = np.arange(int(round(dataframeAnodo.loc[('M01', 'Tolleranza MIN'),
'Misura']*(10**decimMax))), int(round(toll11aMax*(10**decimMax))) + int(round(dataframeAnodo.loc[('M01',
'Tolleranza INCREMENTO'), 'Misura']*(10**decimMax))), int(round(dataframeAnodo.loc[('M01', 'Tolleranza
INCREMENTO'), 'Misura']*(10**decimMax))))
    valTollInfAnodoM12 = np.arange(int(round(dataframeAnodo.loc[('M12', 'Tolleranza MIN'),
'Misura']*(10**decimMax))), int(round(toll12aMax*(10**decimMax))) + int(round(dataframeAnodo.loc[('M12',
'Tolleranza INCREMENTO'), 'Misura']*(10**decimMax))), int(round(dataframeAnodo.loc[('M12', 'Tolleranza
INCREMENTO'), 'Misura']*(10**decimMax))))
    valTollInfAnodoM23 = np.arange(int(round(dataframeAnodo.loc[('M23', 'Tolleranza MIN'),
'Misura']*(10**decimMax))), int(round(toll13aMax*(10**decimMax))) + int(round(dataframeAnodo.loc[('M23',
'Tolleranza INCREMENTO'), 'Misura']*(10**decimMax))), int(round(dataframeAnodo.loc[('M23', 'Tolleranza
INCREMENTO'), 'Misura']*(10**decimMax))))
    multidimScarto = [valTollInfCatodoM01, valTollInfCatodoM12, valTollInfCatodoM23, valTollInfCatodoM34,
valTollInfAnodoM01, valTollInfAnodoM12, valTollInfAnodoM23]
    combinazioniTollScarto = np.stack(np.meshgrid(*multidimScarto), axis=-1).reshape(-1, len(multidimScarto))
    return combinazioniTollScarto/(10**decimMax) # Trasformo di nuovo in decimali

def getDecimali(numero, oldCode=False): #dovrebbe ritornare il numero di decimali di numero --> BUG CON
GESTIONE FLOAT E ERRORI MACCHINA NUMERI BINARI
    if oldCode: # Non usa libreria Decimal però soffre di errori arrotondamento float. Es: 2.2%1 =
0.200000000000000018 che fa aumentare il numero di decimali
        i = 0
        debug = numero%1
        if numero % 1 == 0:
            return i
        while True:
            i += 1
            numero *= 10
            debug = numero % 1

```



```

valTollCatodoM01INC = dfCatodo.loc[('M01', 'Tolleranza INCREMENTO'), 'Misura']
valTollCatodoM12MIN = dfCatodo.loc[('M12', 'Tolleranza MIN'), 'Misura']
valTollCatodoM12MAX = dfCatodo.loc[('M12', 'Tolleranza MAX'), 'Misura']
valTollCatodoM12INC = dfCatodo.loc[('M12', 'Tolleranza INCREMENTO'), 'Misura']
valTollCatodoM23MIN = dfCatodo.loc[('M23', 'Tolleranza MIN'), 'Misura']
valTollCatodoM23MAX = dfCatodo.loc[('M23', 'Tolleranza MAX'), 'Misura']
valTollCatodoM23INC = dfCatodo.loc[('M23', 'Tolleranza INCREMENTO'), 'Misura']
valTollCatodoM34MIN = dfCatodo.loc[('M34', 'Tolleranza MIN'), 'Misura']
valTollCatodoM34MAX = dfCatodo.loc[('M34', 'Tolleranza MAX'), 'Misura']
valTollCatodoM34INC = dfCatodo.loc[('M34', 'Tolleranza INCREMENTO'), 'Misura']
valTollAnodoM01MIN = dfAnodo.loc[('M01', 'Tolleranza MIN'), 'Misura']
valTollAnodoM01MAX = dfAnodo.loc[('M01', 'Tolleranza MAX'), 'Misura']
valTollAnodoM01INC = dfAnodo.loc[('M01', 'Tolleranza INCREMENTO'), 'Misura']
valTollAnodoM12MIN = dfAnodo.loc[('M12', 'Tolleranza MIN'), 'Misura']
valTollAnodoM12MAX = dfAnodo.loc[('M12', 'Tolleranza MAX'), 'Misura']
valTollAnodoM12INC = dfAnodo.loc[('M12', 'Tolleranza INCREMENTO'), 'Misura']
valTollAnodoM23MIN = dfAnodo.loc[('M23', 'Tolleranza MIN'), 'Misura']
valTollAnodoM23MAX = dfAnodo.loc[('M23', 'Tolleranza MAX'), 'Misura']
valTollAnodoM23INC = dfAnodo.loc[('M23', 'Tolleranza INCREMENTO'), 'Misura']
# Li metto in una lista
lista = [valTollCatodoM01MIN, valTollCatodoM01MAX, valTollCatodoM01INC, valTollCatodoM12MIN,
valTollCatodoM12MAX, valTollCatodoM12INC, valTollCatodoM23MIN, valTollCatodoM23MAX, valTollCatodoM23INC,
valTollCatodoM34MIN, valTollCatodoM34MAX, valTollCatodoM34INC, valTollAnodoM01MIN, valTollAnodoM01MAX,
valTollAnodoM01INC, valTollAnodoM12MIN, valTollAnodoM12MAX, valTollAnodoM12INC, valTollAnodoM23MIN,
valTollAnodoM23MAX, valTollAnodoM23INC]
decim = []
# Ricavo il numero di decimali per ogni valore
for val in lista:
    decim.append(getDecimali(val))
# Ritorno il valore massimo di decimali presenti
return max(decim)

```

```

#
#
#

```

```
*****
```

```
Verifica angoli alfa-beta
```

```
*****
```

```

def scostMaxAngoli(r, alfa, beta, punti=200, radianti=False, d=0):
    # radianti si riferisce agli elementi alfa e beta forniti in ingresso, per sapere se sono da convertire in
    # radianti o se lo sono già, di default si aspetta di riceverli in gradi (=li converte in rad)
    # punti indice in quanti punti suddividere la circonferenza (nei quali verranno poi effettuate le
    # verifiche)
    # d regola l'altezza z del centro della circonferenza, se non dato è inizializzato a zero
    t = 0 # t serve per poter tenere le equazioni delle circonferenze "come da traccia", solo che qua la
    # traslazione su asse z è fatta da "d"
    tht = np.linspace(0, 2 * np.pi, int((punti)))
    if not radianti: # se radianti=False converto i dati in radianti, perchè "np.sin()" ecc.. prendono dato in
    # radianti!
        alfa=alfa*np.pi/180
        beta=beta*np.pi/180
    x = r * np.sin(alfa) * np.sin(beta) * np.sin(tht) + r * np.cos(beta) * np.cos(tht) + t * np.sin(beta) *
    np.cos(alfa)
    y = r * np.sin(tht) * np.cos(alfa) - t * np.sin(alfa)
    z = d + r * np.sin(alfa) * np.sin(tht) * np.cos(beta) - r * np.sin(beta) * np.cos(tht) + t * np.cos(alfa) *
    np.cos(beta)

    return max(abs(z))

```


Appendix E Tolerance stack-up analysis and optimisation results
Appendix E.1 Tolerance stack-up analysis STD FEBIAD ion source

Simulation results: cathode frontal surface stack-up

Cathode flange flatness:

Valore

M01 - Tolleranza [mm]	0.1
M01 - Raggio [mm]	9.5
M01 - Misura nominale [mm]	0.0
M01 - Campioni	35000.0

Distance cathode flange - frontal surface:

Valore

M12 - Tolleranza [mm]	0.1
M12 - Raggio [mm]	6.0
M12 - Misura nominale [mm]	-15.0
M12 - Campioni	35000.0

Cathode front surface flatness:

Valore

M23 - Tolleranza	0.4
M23 - Raggio	6.0
M23 - Misura nominale	0.0
M23 - Campioni	35000.0

Perpendicularity cathode frontal surface - external cylinder axis:

Valore

M34 - Tolleranza	0.1
M34 - Raggio	6.0
M34 - Misura nominale	0.0
M34 - Campioni	35000.0

Simulation results: anode grid stack-up

Discharge chamber top surface flatness:

	Valore
M01 - Tolleranza [mm]	0.1
M01 - Raggio [mm]	10.0
M01 - Misura nominale [mm]	0.0
M01 - Campioni	35000.0

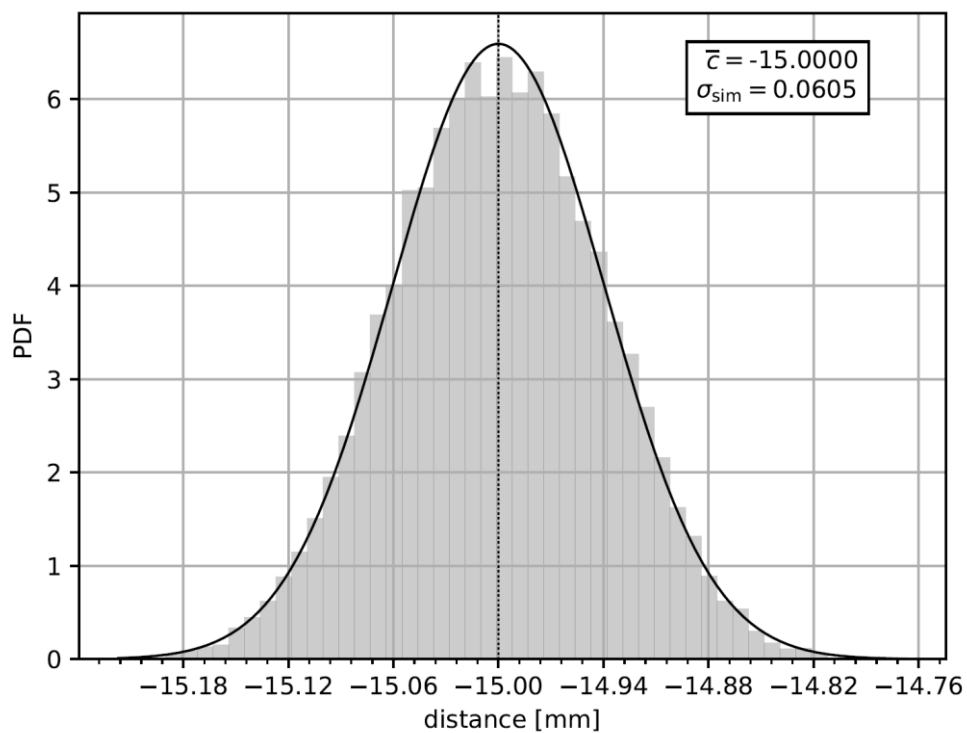
Distance discharge chamber top surface - the anode grid:

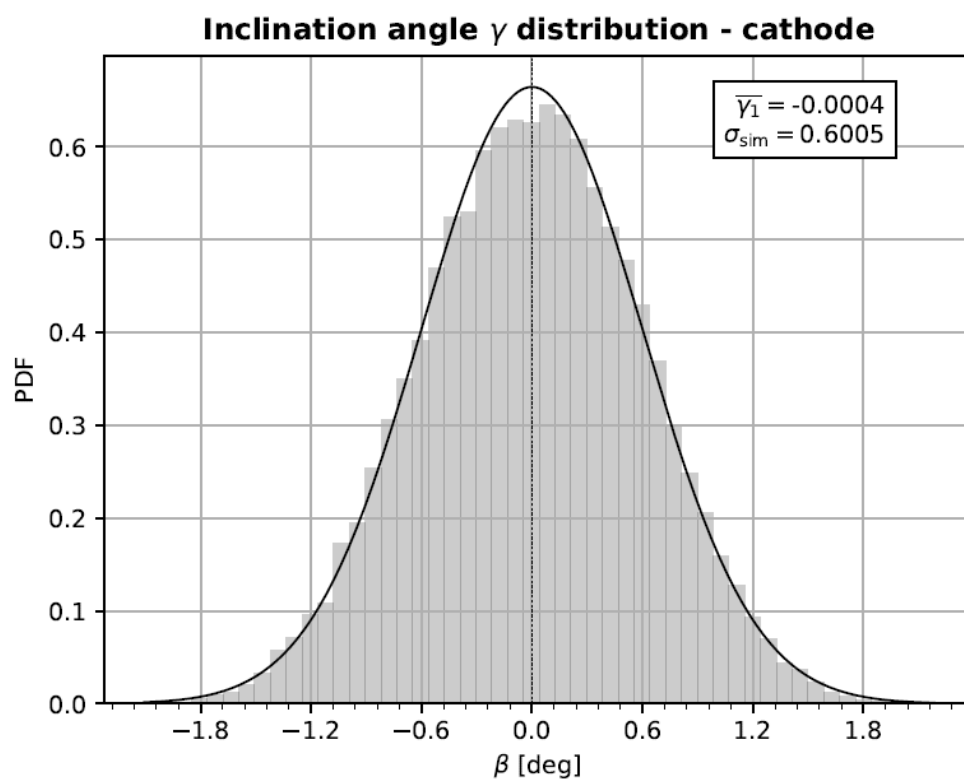
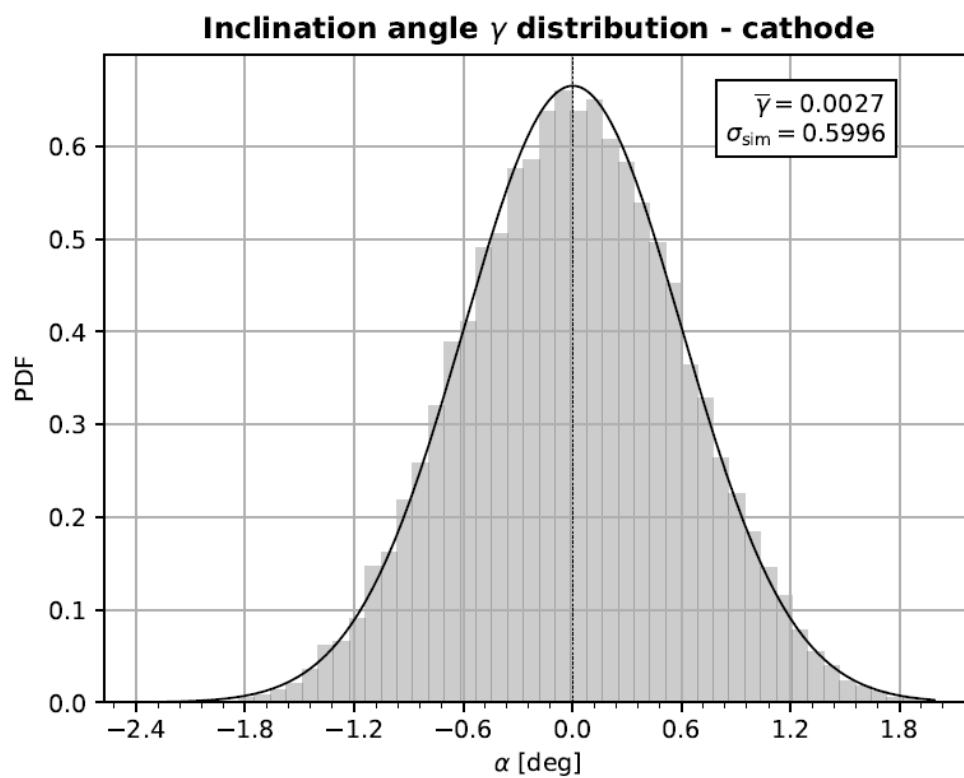
	Valore
M12 - Tolleranza [mm]	0.4
M12 - Raggio [mm]	7.0
M12 - Misura nominale [mm]	-16.0
M12 - Campioni	35000.0

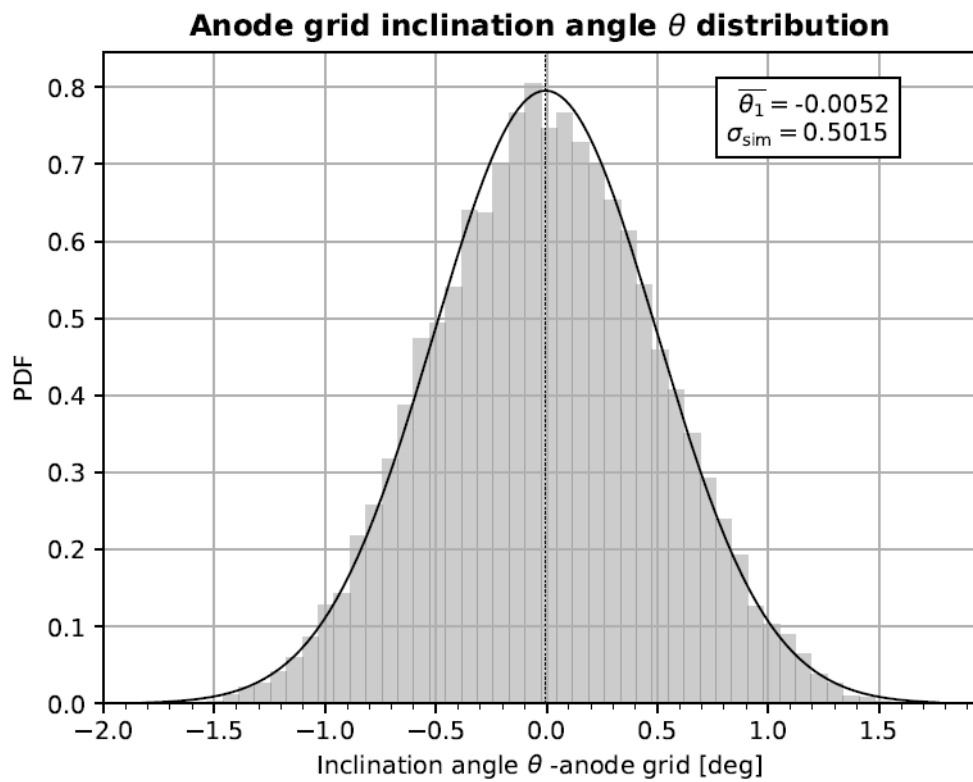
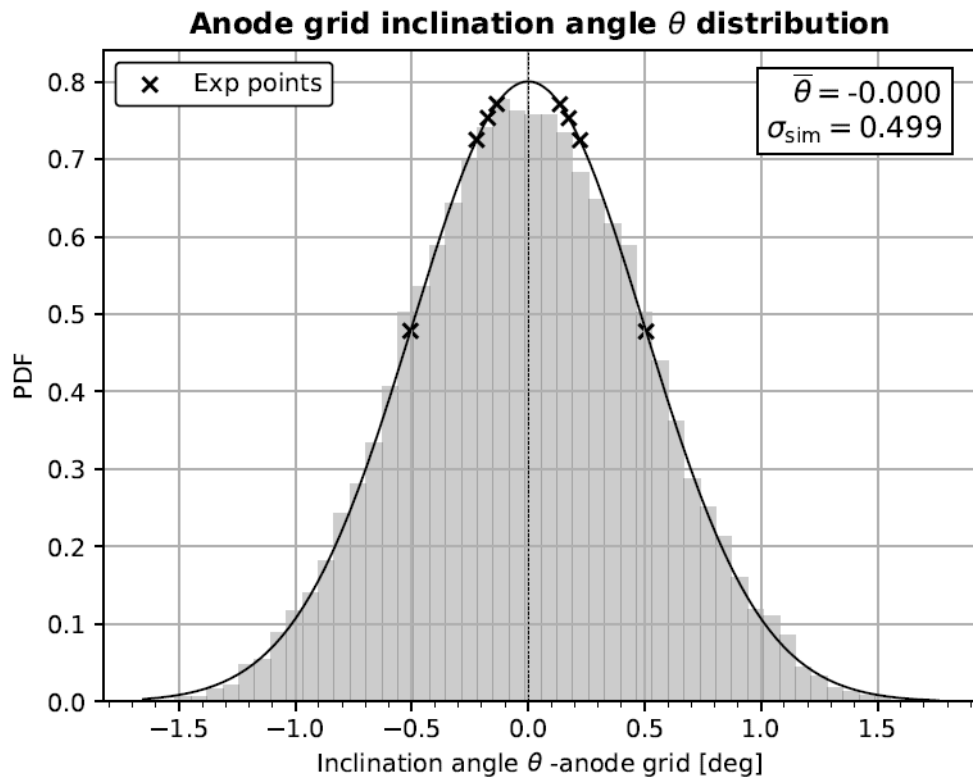
Anode grid flatness:

	Valore
M23 - Tolleranza [mm]	0.1
M23 - Raggio [mm]	7.0
M23 - Misura nominale [mm]	0.0
M23 - Campioni	35000.0

Distance cathode frontal surface - reference frame







Sensitivity analysis:

Elemento	Valore
Cathode frontal surface position:	
Cathode flange flatness	5.25
Distance cathode flange - frontal surface	5.282
Cathode front surface flatness	83.7
Perpendicularity cathode frontal surface - external cylinder axis	5.17
Anode frontal surface position:	
Discharge chamber top surface flatness	5.638
Distance discharge chamber top surface - the anode grid	88.87
Anode grid flatness	5.664
Cathode inclination angle:	
Cathode flange flatness	2.173
Distance cathode flange - frontal surface	5.521
Cathode front surface flatness	87.04
Perpendicularity cathode frontal surface - external cylinder axis	5.495
Anode grid inclination angle:	
Discharge chamber top surface flatness	2.886
Distance discharge chamber top surface - the anode grid	91.81
Anode grid flatness	5.819

Simulation results: cathode frontal surface stack-up

Cathode flange flatness:

Valore

M01 - Tolleranza [mm]	0.1
M01 - Raggio [mm]	9.5
M01 - Misura nominale [mm]	0.0
M01 - Campioni	35000.0

Distance cathode flange - frontal surface:

Valore

M12 - Tolleranza [mm]	0.04
M12 - Raggio [mm]	6.0
M12 - Misura nominale [mm]	-15.0
M12 - Campioni	35000.0

Cathode front surface flatness:

Valore

M23 - Tolleranza	0.04
M23 - Raggio	6.0
M23 - Misura nominale	0.0
M23 - Campioni	35000.0

Perpendicularity cathode frontal surface - external cylinder axis:

Valore

M34 - Tolleranza	0.02
M34 - Raggio	6.0
M34 - Misura nominale	0.0
M34 - Campioni	35000.0

Simulation results: anode grid stack-up

Discharge chamber top surface flatness:

	Valore
M01 - Tolleranza [mm]	0.1
M01 - Raggio [mm]	10.0
M01 - Misura nominale [mm]	0.0
M01 - Campioni	35000.0

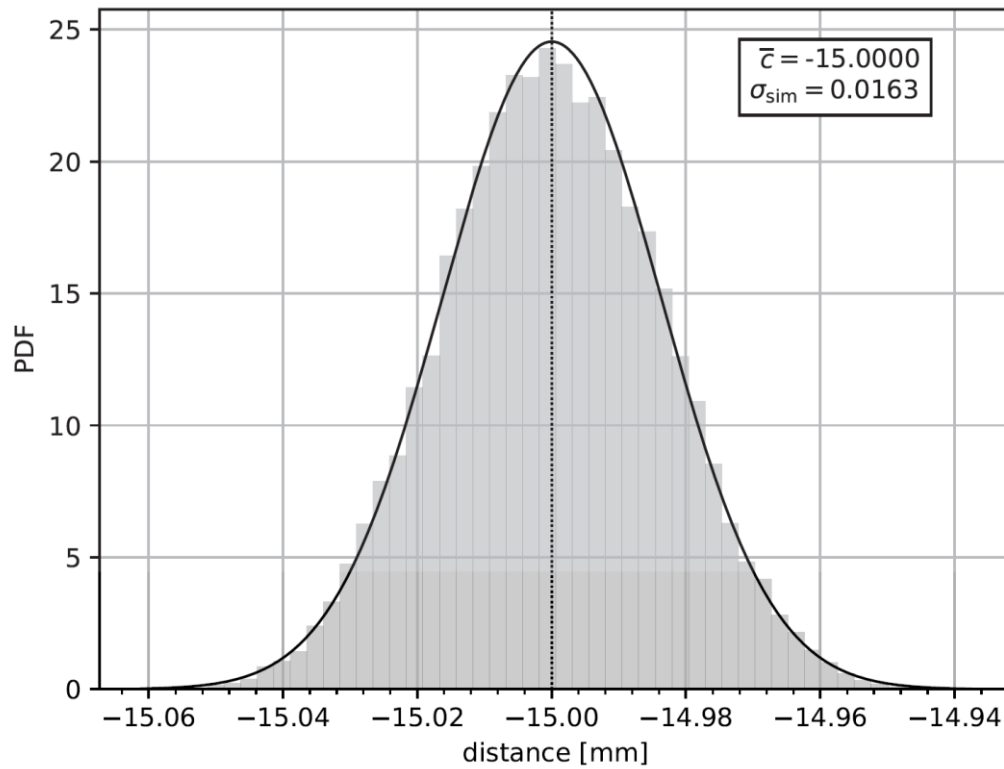
Distance discharge chamber top surface - the anode grid:

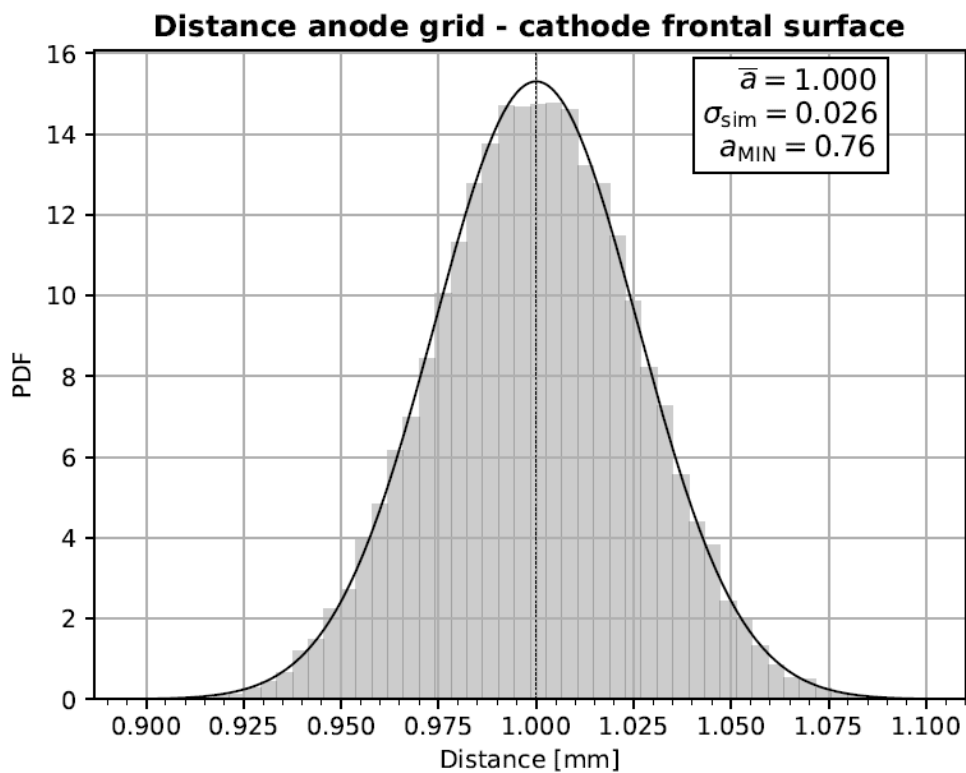
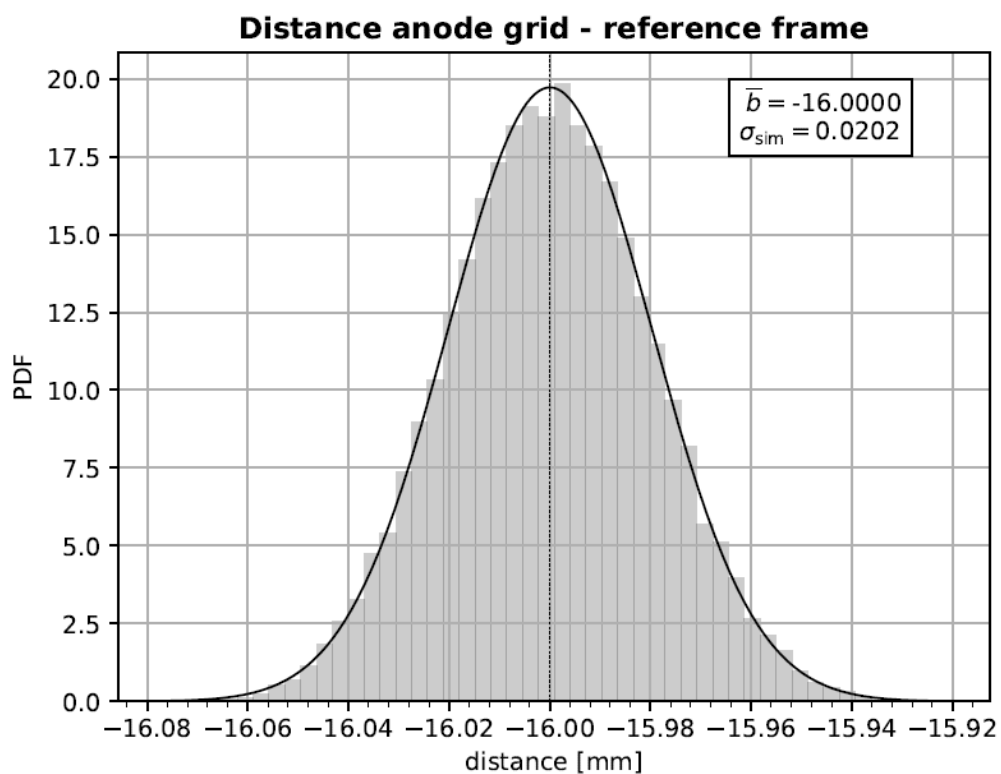
	Valore
M12 - Tolleranza [mm]	0.04
M12 - Raggio [mm]	7.0
M12 - Misura nominale [mm]	-16.0
M12 - Campioni	35000.0

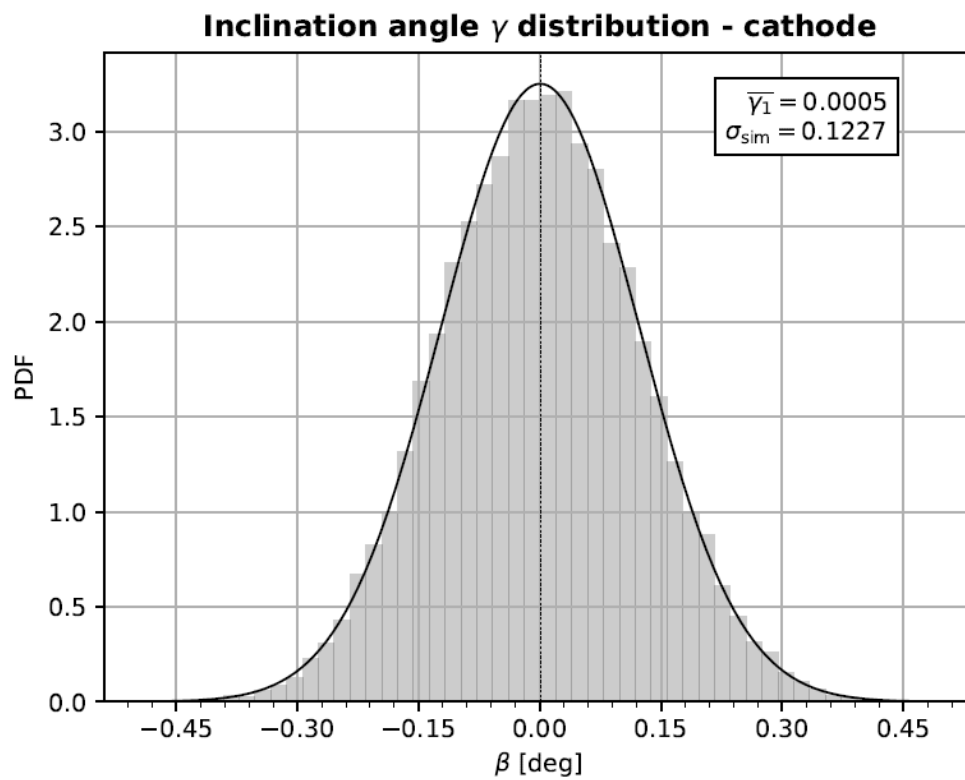
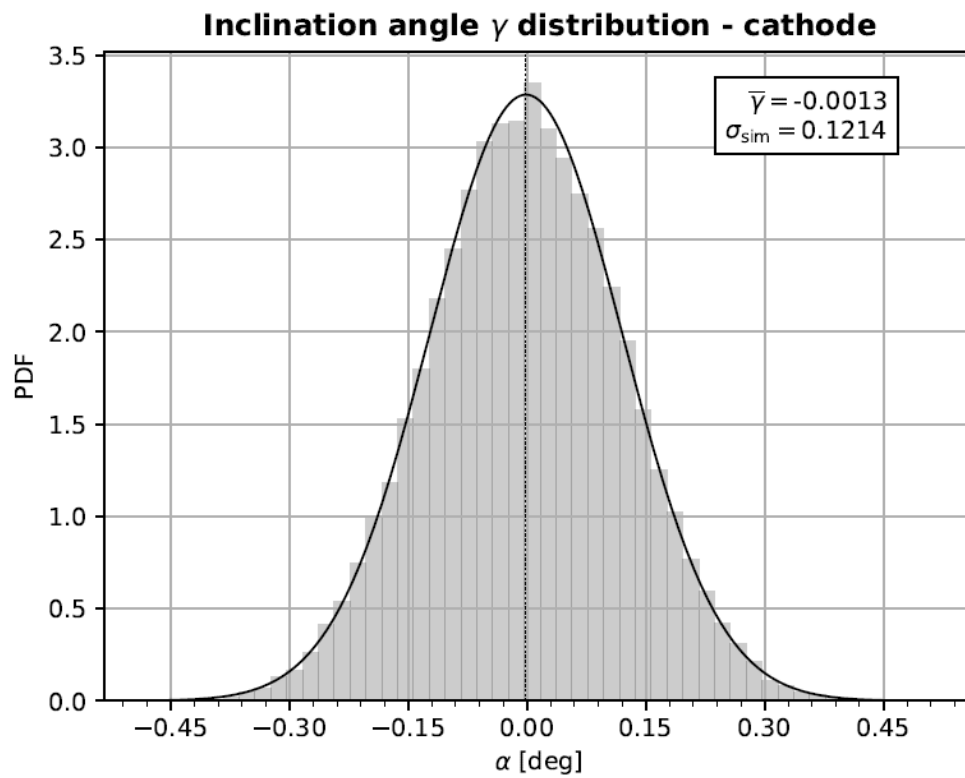
Anode grid flatness:

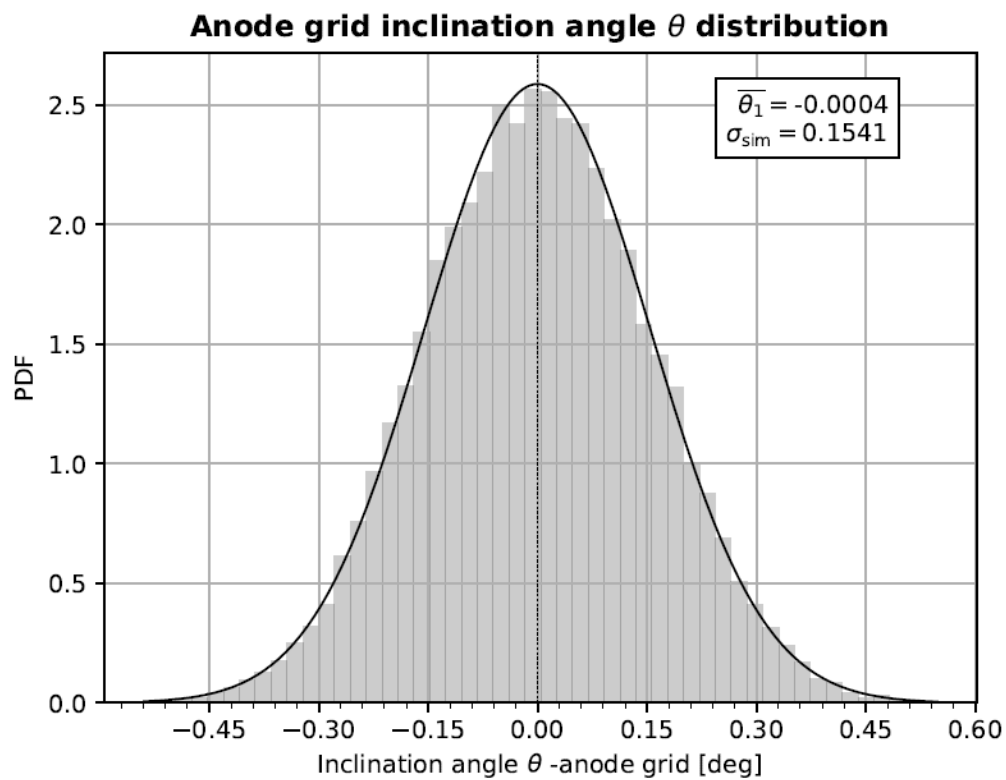
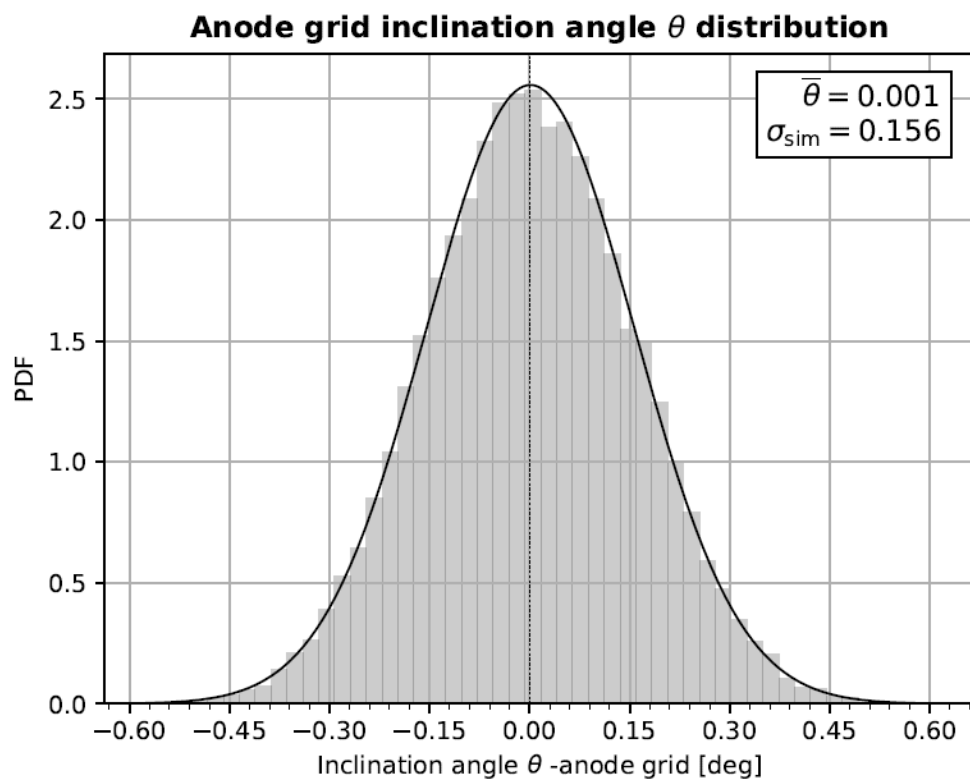
	Valore
M23 - Tolleranza [mm]	0.1
M23 - Raggio [mm]	7.0
M23 - Misura nominale [mm]	0.0
M23 - Campioni	35000.0

Distance cathode frontal surface - reference frame









Sensitivity analysis:

Elemento	Valore
Cathode frontal surface position:	
Cathode flange flatness	72.93
Distance cathode flange - frontal surface	11.74
Cathode front surface flatness	11.48
Perpendicularity cathode frontal surface - external cylinder axis	2.924
Anode frontal surface position:	
Discharge chamber top surface flatness	46.44
Distance discharge chamber top surface - the anode grid	7.5
Anode grid flatness	46.25
Cathode inclination angle:	
Cathode flange flatness	53.57
Distance cathode flange - frontal surface	21.15
Cathode front surface flatness	21.21
Perpendicularity cathode frontal surface - external cylinder axis	5.276
Anode grid inclination angle:	
Discharge chamber top surface flatness	29.36
Distance discharge chamber top surface - the anode grid	9.432
Anode grid flatness	60.42

Appendix E.3 Tolerance stack-up optimisation LPBF_OPT cathode

Cathode external surface flatness:

Valore

M01 - Tolleranza [mm]	0.1
M01 - Raggio [mm]	10.5
M01 - Misura nominale [mm]	0.0
M01 - Campioni	35000.0

Perpendicularity cathode frontal surface - external cylinder axis:

Valore

M23 - Tolleranza	0.04
M23 - Raggio	6.0
M23 - Misura nominale	0.0
M23 - Campioni	35000.0

Cathode front surface flatness:

Valore

M34 - Tolleranza	0.04
M34 - Raggio	6.0
M34 - Misura nominale	0.0
M34 - Campioni	35000.0

Simulation results: anode grid stack-up

Discharge chamber surface flatness:

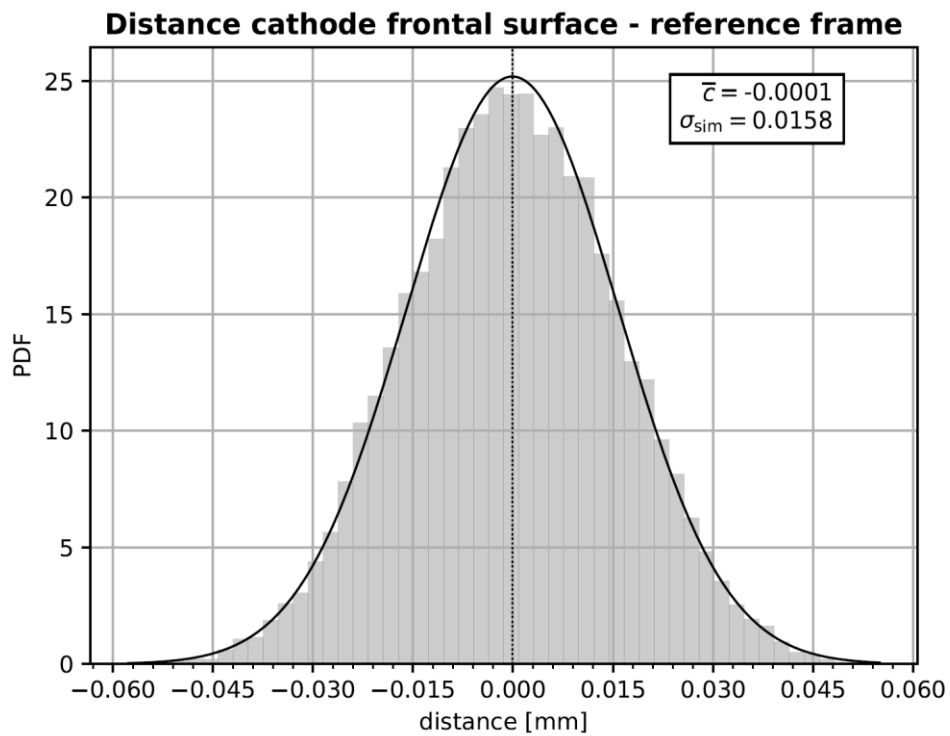
	Valore
M01 - Tolleranza [mm]	0.1
M01 - Raggio [mm]	10.5
M01 - Misura nominale [mm]	0.0
M01 - Campioni	35000.0

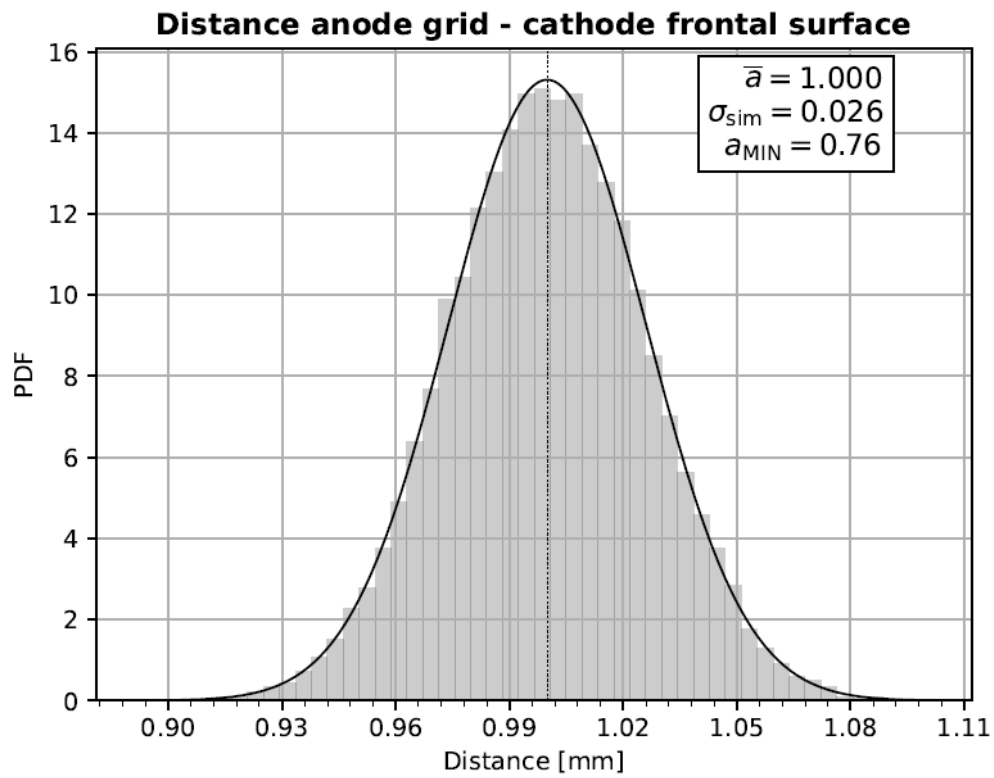
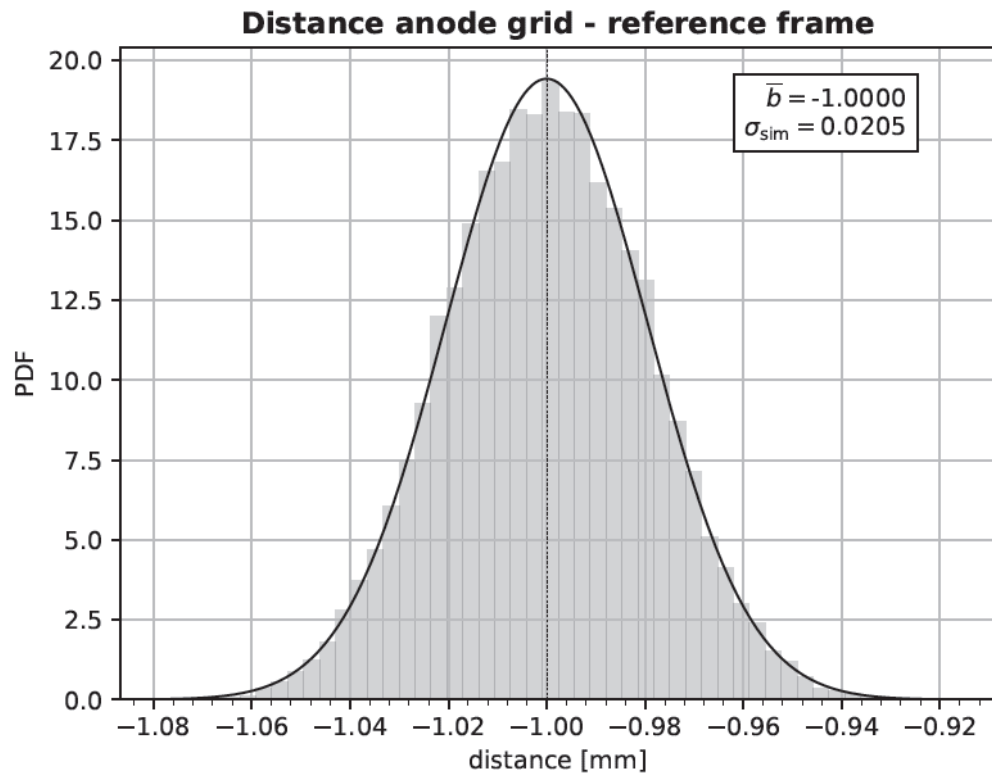
Distance discharge chamber top surface - the anode grid:

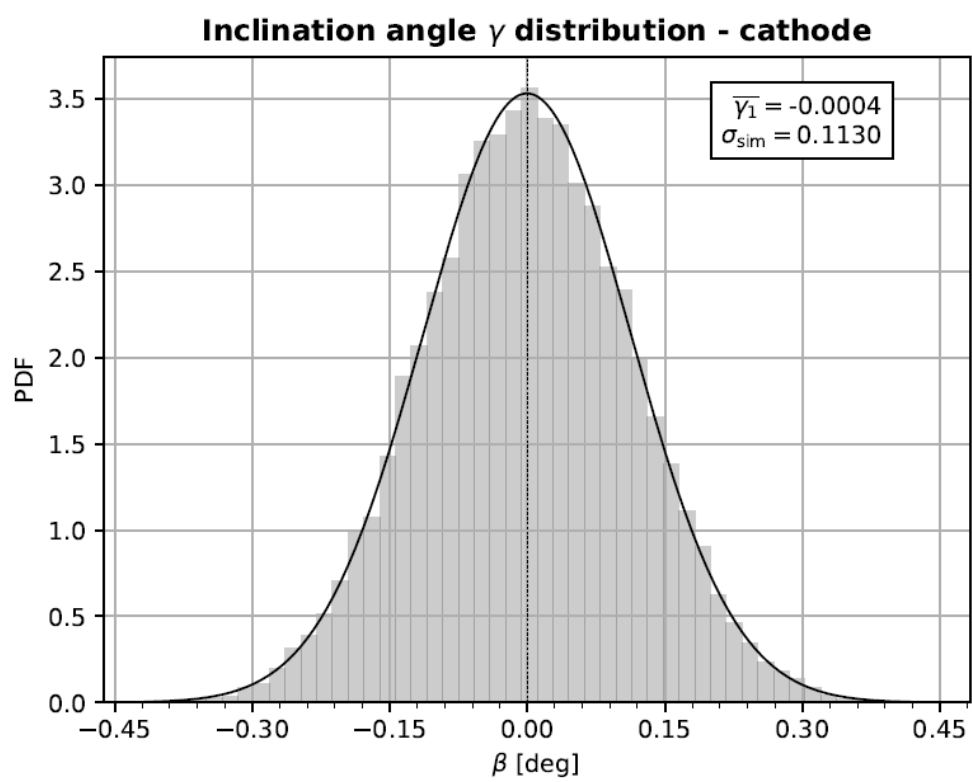
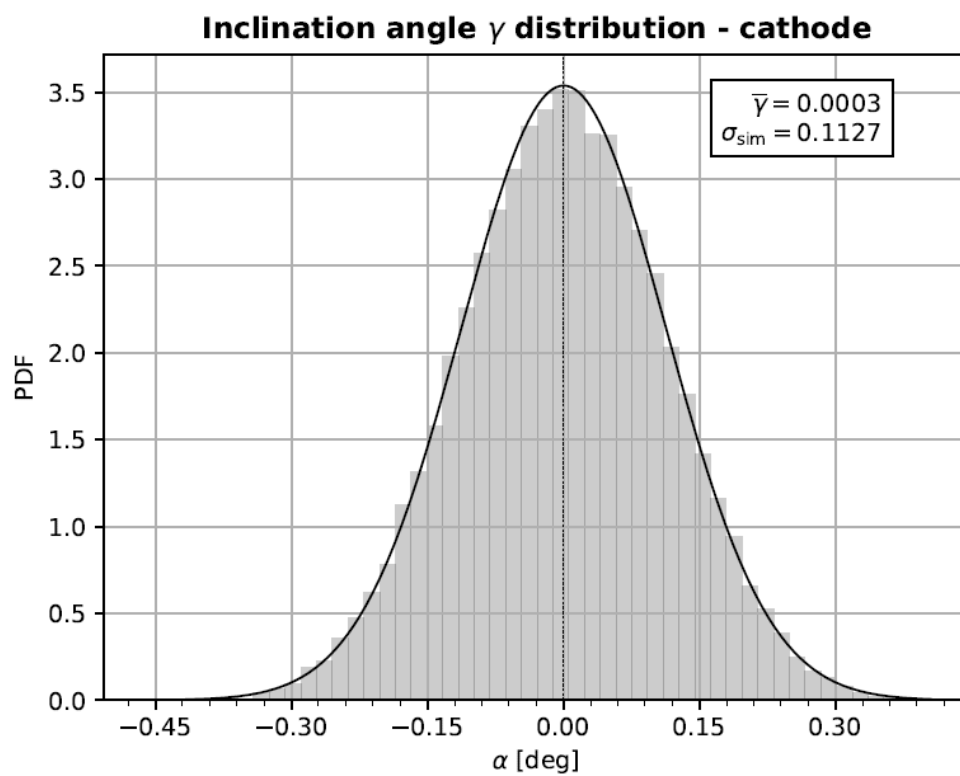
	Valore
M12 - Tolleranza [mm]	0.04
M12 - Raggio [mm]	7.0
M12 - Misura nominale [mm]	-1.0
M12 - Campioni	35000.0

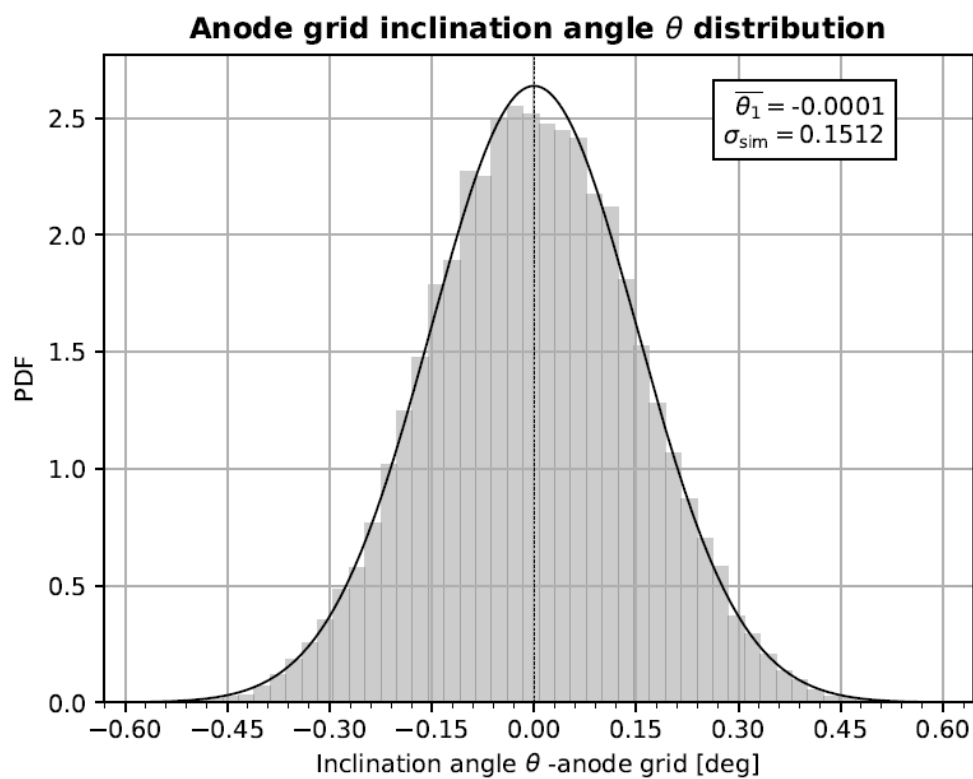
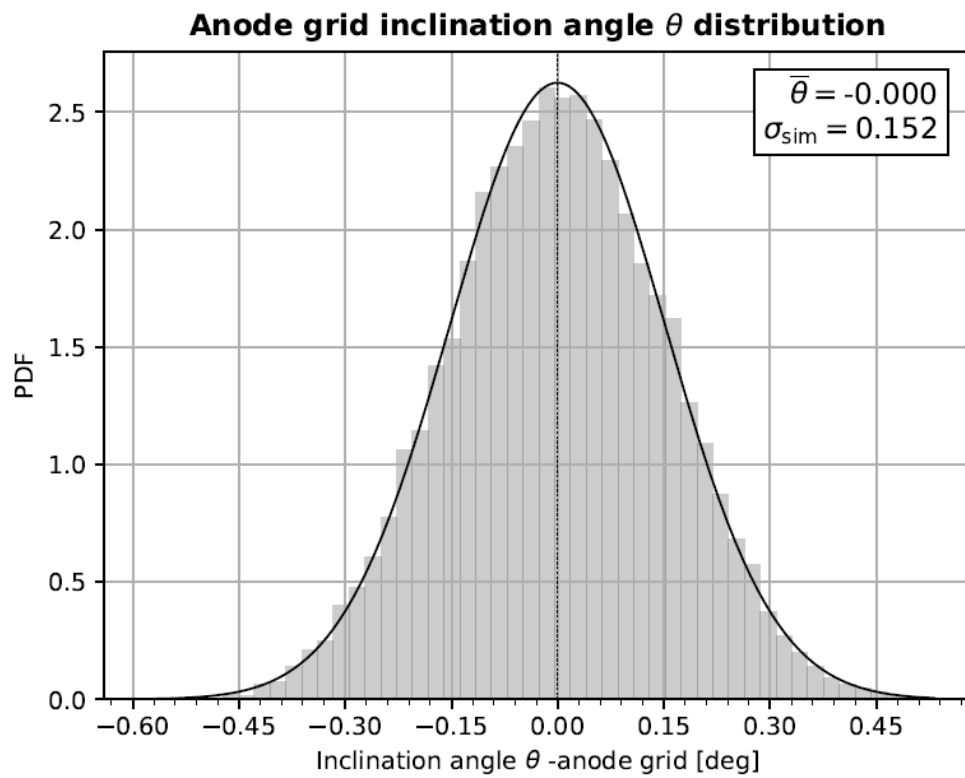
Anode grid flatness:

	Valore
M23 - Tolleranza [mm]	0.1
M23 - Raggio [mm]	7.0
M23 - Misura nominale [mm]	0.0
M23 - Campioni	35000.0









Risultati analisi sensitività:

Elemento	Valore
Cathode frontal surface position:	
Cathode flange flatness	75.71
Cathode front surface flatness	12.35
Perpendicularity cathode frontal surface - external cylinder axis	12.06
Anode frontal surface position:	
Discharge chamber top surface flatness	45.84
Distance discharge chamber top surface - the anode grid	7.283
Anode grid flatness	45.22
Cathode inclination angle:	
Cathode flange flatness	50.39
Cathode front surface flatness	24.64
Perpendicularity cathode frontal surface - external cylinder axis	24.94
Anode grid inclination angle:	
Discharge chamber top surface flatness	27.68
Distance discharge chamber top surface - the anode grid	9.964
Anode grid flatness	62.45

Appendix F APDL coupled electro-thermal FEM simulations

!APDL Sorgente AM optimised DEV4 - Cathode-Transferline as a single component

FINISH

/CLEAR, START

/TITLE,FEBIAD IS optimised DEV 4

/CONFIG,NRES,100000

!PRINCIPALI PARAMETRI SCALARI

T_{par} = 50 !temperature on the side of electrical connection [°C]

T_{line} = 2000!temperature in the electrical connection [°C]

/PREP7

!DEFINIZIONE DEI MATERIALI IMPIEGATI

M26Ta!Macro Tantalio standard

M24TaAMab!Macro Tantalio AM as built

M25TaAMp!Macro Tantalio AM polished

M29C_ATJ!Macro Grafite

M30Mo !Macro Molibdeno

M31Al203!Macro Alluminio

M50SS316!Acciaio Inossidabile

!-----

!DEFINIZIONE DEGLI ELEMENT TYPES

ET,1,SOLID226

KEYOPT,1,1,110

ET,2,SOLID90!Per i volumi dell'anodo perchè non sono interessati dal passaggio di corrente

!-----

! Start of build of geometrical model

! geometry import

FINISH !exits normally from a processor

/AUX15 !enters the IGES file transfer processor

IOPTN,IGES,SMOOTH !controls options relating to importing a model
IOPTN,MERGE,YES !controls options relating to importing a model
IOPTN,SOLID,YES !controls options relating to importing a model
IOPTN,SMALL,YES !controls options relating to importing a model
IOPTN,GTOLER,0.00001 !controls options relating to importing a model

!IMPORTAZIONE GEOMETRIE

IGESIN,'anode_conical_open_2','igs'
IGESIN,'cathode_additive_2','igs'
IGESIN,'chamber_conical_2','igs'
IGESIN,'end_flange','igs'
IGESIN,'extraction_grid_lattice_1','igs'
IGESIN,'perno_transfer_line','igs'
IGESIN,'st_pis_04_001_001','igs'
IGESIN,'st_pis_04_002_001','igs'
IGESIN,'st_pis_04_003_001','igs'
IGESIN,'transfer_line_foils','igs'

wpro,,,30.000000
wpro,,,30.000000
wpro,,,30.000000
wpro,,,30.000000
wpro,,,30.000000
wpro,,,30.000000
/GRAPHICS,POWER
/TYPE,1,7
/CPLANE,1
/SHADE,1,1
/HBC,1,0
/REPLOT
/VIEW,1,1
/ANG,1
/REP,FAST

FINISH !exits normally from a processor
/PREP7 !enters the model creation preprocessor

!c: thermal contact effects are not considered
!c: all the components are considered welded

!c: gluing of volumes

BTOL,0.0001

VGLUE,10,6
VGLUE,12,2

```
VGLUE,10,3
VGLUE,2,5
VGLUE,3,4
VGLUE,5,9
VGLUE,3,8
VGLUE,7,9
```

!c: scaling geometry from "mm" to "m"

```
VLSCALE,ALL,,,0.001,0.001,0.001,,,1    !generates a scaled set of volumes from a pattern
of volumes
```

```
NUMCMP,VOLU      !compressed entity number
NUMCMP,AREA
NUMCMP,LINE
NUMCMP,KP
ALLSEL
VPLOT
```

```
!-----
-----
```

!ANODO

```
MAT,TaAMab
TYPE,2
MSHAPE,1,3D      !for elements that support multiple shapes, specifies the element
shape
!to be used for meshing
MSHKEY,0          !specifies whether free meshing or mapped meshing should be used
to mesh a model
VSEL,S,,,1
VPLOT
ALLSEL,BELOW,VOLU
AESIZE,ALL,0.0015
VMESH,ALL
ALLSEL
```

!CATODO

```
MAT,TaAMab
TYPE,1
MSHAPE,1,3D
MSHKEY,0
VSEL,S,,,10
VPLOT
ALLSEL,BELOW,VOLU
AESIZE,ALL,0.0012
```

VMESH,ALL
ALLSEL

!CAMERA DI SCARICO

MAT,TaAMab
TYPE,1
MSHAPE,1,3D
MSHKEY,0
VSEL,S,,,2
VPLOT
ALLSEL,BELOW,VOLU
AESIZE,ALL,0.004
VMESH,ALL
ALLSEL

!TRANSFER LINE

!MAT,Ta
!TYPE,1
!MSHAPE,1,3D
!MSHKEY,0
!VSEL,S,,,8
!VPLOT
!ALLSEL,BELOW,VOLU
!AESIZE,ALL,0.0028
!VMESH,ALL
!ALLSEL

!PERNO

MAT,Ta
TYPE,1
MSHAPE,1,3D
MSHKEY,0
VSEL,S,,,6
VPLOT
ALLSEL,BELOW,VOLU
AESIZE,ALL,0.0025
VMESH,ALL
ALLSEL

!CONNESSIONE ELETTTRICA

MAT,Ta
TYPE,1
MSHAPE,1,3D
MSHKEY,0
VSEL,S,,,9

```
VPLOT
ALLSEL,BELOW,VOLU
AESIZE,ALL,0.004
VMESH,ALL
ALLSEL
```

!FLANGIA DI ESTRAZIONE

```
MAT,Ta
TYPE,1
MSHAPE,1,3D
MSHKEY,0
VSEL,S,,,8
VPLOT
ALLSEL,BELOW,VOLU
AESIZE,ALL,0.0019
VMESH,ALL
ALLSEL
```

!SUPPORT HOUSE NUT

```
MAT,TaAMab
TYPE,1
MSHAPE,1,3D
MSHKEY,0
VSEL,S,,,4
VPLOT
ALLSEL,BELOW,VOLU
AESIZE,ALL,0.003
VMESH,ALL
ALLSEL
```

!SUPPORT HOUSE MESHING

```
MAT,C_ATJ
TYPE,1
MSHAPE,1,3D
MSHKEY,0
VSEL,S,,,3
VSEL,A,,,7
VSEL,A,,,5
VPLOT
ALLSEL,BELOW,VOLU
AESIZE,ALL,0.003
VMESH,ALL
ALLSEL
```

```
VSEL,ALL
EPLOT
```

!-----

!c: defining the Radiating Surfaces (Single ENCLOSURE)

SPCTEMP,1,T_par !defines a free-space ambient temperature for radiation using
the Radiosity method [°C]

!c: SUPPORT_HOUSING (radiating surfaces)

VSEL,R,MAT,,Ta !selects a subset of volumes
ALLSEL,BELOW,VOLU !selects all entities with a single command
SFA,ALL,,RDSF,-Ta,1 !specifies surface loads on the selected areas
ALLSEL !selects all entities with a single command

VSEL,R,MAT,,TaAMab !selects a subset of volumes
ALLSEL,BELOW,VOLU !selects all entities with a single command
SFA,ALL,,RDSF,-TaAMab,1 !specifies surface loads on the selected areas
ALLSEL !selects all entities with a single command

!Cathode AM frontal surface polished -> TaAMp
VSEL,S,,,10 !selects a subset of volumes
ALLSEL,BELOW,VOLU !selects all entities with a single command
SFA,84,,RDSF,-TaAMp,1 !specifies surface loads on the selected areas
ALLSEL !selects all entities with a single command

!Anode AM grid polished -> TaAMp
VSEL,S,,,1 !selects a subset of volumes
ALLSEL,BELOW,VOLU !selects all entities with a single command
SFA,227,,RDSF,-TaAMp,1 !specifies surface loads on the selected areas
ALLSEL !selects all entities with a single command

!VSEL,R,MAT,,Mo !selects a subset of volumes
!ALLSEL,BELOW,VOLU !selects all entities with a single command
!SFA,ALL,,RDSF,-Mo,1 !specifies surface loads on the selected areas
!ALLSEL . !selects all entities with a single command

VSEL,R,MAT,,C_ATJ !selects a subset of volumes
ALLSEL,BELOW,VOLU !selects all entities with a single command
SFA,ALL,,RDSF,-C_ATJ,1 !specifies surface loads on the selected areas
ALLSEL !selects all entities with a single command

*GET,nvolu,VOLU,0,COUNT ! Gets the number of volumes and register it as the
parameter "nvolu"

*SET,nn,0 ! Initializes the variable "nn" (iteration number for the DO cycle)

*DO,i,1,nvolu ! DO cycle form 1 to "nvolu"

*SET,nn,vlnext(nn) ! Iteration: adds 1 to the variable "nn"

VSEL,ALL ! Selects all volumes

```

VSEL,U,VOLU,,nn ! Unselects volume number "nn"
ALLSEL,BELOW,VOLU ! Selects all entities attached to the selected set of volumes (in
particular areas)*
VSEL,S,VOLU,,nn ! Selects only volume "nn" (not the attached entities)
ASLV,R ! Selects areas attached to the volume "nn" from the preselected set of areas (see
*)
SFADELE,ALL,,RDSF ! Deletes surface loads on the selected areas
ALLSEL,ALL
*ENDDO
!-----
-----

```

!c: thermal initial conditions

```

TUNIF,T_par ! assigns a uniform temperature to all nodes [°C]

```

!c: thermal loads

```

!c: ELECTRICAL_CONNECTION temperature constraint
ASEL,S,AREA,,387 !selects a subset of areas (flangia di input)
APLOT
DA,ALL,TEMP,T_par !defines DOF constraints on areas [°C]
ALLSEL

```

```

!c: SUPPORT HOUSE FLANGE temperature constraint
ASEL,S,AREA,,10 !selects a subset of areas (DISCHARGING CAMERA)
APLOT
DA,ALL,TEMP,T_par !defines DOF constraints on areas [°C]
ALLSEL

```

!c: electrical loads

```

!c: SUPPORT HOUSE FLANGE voltage constraint
ASEL,S,AREA,,10 !selects a subset of areas (DISCHARGING CAMERA)
APLOT
DA,ALL,VOLT,0 !defines DOF constraints on areas [°C]
ALLSEL

```

```

!ASEL,S,AREA,,189 !selects a subset of areas (DISCHARGING CAMERA) è l'area
dell'anodo
!ASEL,A,AREA,,188
!APLOT
!DA,ALL,VOLT,0 !defines DOF constraints on areas [°C]
!ALLSEL

```

!APPLICAZIONE CARICHI ELETTRICI A GRADINI

*DIM,I_HEATER_IN,TABLE,12,1,1,TIME!creazione di una table di dimensione 12x2x1
con indice il tempo

*SET,I_HEATER_IN(1,0),0 ! TIME [s]
*SET,I_HEATER_IN(1,1),350 ! I_HEATER [A]

*SET,I_HEATER_IN(2,0),3000
*SET,I_HEATER_IN(2,1),350

*SET,I_HEATER_IN(3,0),3001
*SET,I_HEATER_IN(3,1),360

*SET,I_HEATER_IN(4,0),6000
*SET,I_HEATER_IN(4,1),360

*SET,I_HEATER_IN(5,0),6001
*SET,I_HEATER_IN(5,1),370

*SET,I_HEATER_IN(6,0),9000
*SET,I_HEATER_IN(6,1),370

*SET,I_HEATER_IN(7,0),9001
*SET,I_HEATER_IN(7,1),380

*SET,I_HEATER_IN(8,0),12000
*SET,I_HEATER_IN(8,1),380

*SET,I_HEATER_IN(9,0),12001
*SET,I_HEATER_IN(9,1),390

*SET,I_HEATER_IN(10,0),15000
*SET,I_HEATER_IN(10,1),390

*SET,I_HEATER_IN(11,0),15001
*SET,I_HEATER_IN(11,1),400

*SET,I_HEATER_IN(12,0),18000
*SET,I_HEATER_IN(12,1),400

!c: power generation - Joule effect / current load for the main clamp [A]

ASEL,S,AREA,,387 !selects a subset of areas

APLOT

NSLA,S,1 !selects those nodes associated with the selected areas

cp,1,volt,all !defines (or modifies) a set of coupled degrees of freedom

ni=ndnext(0) !c: master node definition

F,ni,AMPS,%I_HEATER_IN%!applicazione "forza" di tipo corrente (AMPS) sui nodi
"ni"

ALLSEL !selects all entities with a single command

!c: OPTIONS

!c: defining Solution Options

STEF,5.67e-8 !specifies Stefan-Boltzmann radiation constant [W/(m²*K⁴)]

RADOPT,,0.001,0,20000,0.1,0.1 !specifies Gauss-Seidel Radiosity Solver options

TOFFST,273.15 !specifies the temperature offset from absolute zero to zero [°C]

!c: defining View Factor Options

HEMIOPT,100 !specifies options for Hemicube view factor calculation

VFOPT,OFF !specifies options for view factor file

FINISH !exits normally from a processor

!c: SOLVER

/SOLU !enters the solution processor

SOLCONTROL,ON !specifies whether to use optimised nonlinear solution defaults

!and some enhanced internal solution algorithms

ANTYPE,TRANS !specifies the analysis type and restart status

AUTOTS,ON !use automatic time stepping

KBC,1 !specifies stepped or ramped loading within a load step

DELTIM,0.0001,0.00005,100 !specifies the time step sizes to be used for this load step

OUTRES,NSOL,ALL !controls the solution data written to the database

TIME,18000 !sets the time for a load step

SAVE,,,ALL

SOLVE !starts a solution

SAVE,,,ALL !saves all current database information

FINISH !exits normally from a processor

Appendix G Material properties macro implemented in FEM simulations

Appendix G.1 STD Tungsten purity 99.9%

!-----1-----2-----3-----4-----5-----6-----7-----8

!-----
!Tungsten
!Composition: purity 99.9% or higher
!-----
!Version 1.0 (Mar 08) by
!Ing. Mattia Manzolaro
!Istituto Nazionale di Fisica Nucleare
!Laboratori di Legnaro
!Viale dell'Universita' n. 2; 35020 Legnaro (PD) - Italy
!Phone: +39 049 8068423
!fax: +39 049 641925
!e-mail: Mattia.Manzolaro@lnl.infn.it
!-----
!
!Ver. 1.0 - 20 Mar 08
!-----

/prep7

W=27 !Material number in the ANSYS library
MPDELE,all,W

!-----
!ELECTRICAL RESISTIVITY
!
!NOTE 1 - Data are taken from:
!P.D. Desai, T.K. Chu, H.M. James and C.Y. Ho, J. Phys. Ref. Data, vol 13, no. 4, p1069
(1984),
!vol 13, no. 4, p1069 (1984).
!
!NOTE 2 - data below 200K is for a residual resistivity of 0.000015×10^{-8} ohm-m;
!not corrected for thermal expansion; 5% error.
!
!NOTE 3 - the S.I. system of units is used.
!-----

!Temperature table [°C]
MPTEMP ! erase previous table
MPTEMP, 1, 0., 200., 400.,
MPTEMP, 4, 600., 800., 1000.,
MPTEMP, 7, 1200., 1400., 1600.,
MPTEMP, 10, 1800., 2000., 2100.,

MPTEMP, 13, 2200., 2300., 2400.,

!Electrical resistivity table [ohm m]

MPDATA,RSVX , W , 1, 4.8825E-08, 9.7768E-08, 1.5076E-07,
MPDATA,RSVX , W , 4, 2.0722E-07, 2.6664E-07, 3.2856E-07,
MPDATA,RSVX , W , 7, 3.9260E-07, 4.5842E-07, 5.2575E-07,
MPDATA,RSVX , W , 10, 5.9439E-07, 6.6419E-07, 6.9950E-07,
MPDATA,RSVX , W , 13, 7.3507E-07, 7.7090E-07, 8.0700E-07,

!-----

!THERMAL CONDUCTIVITY

!

!NOTE 1 - Data are taken from:

!Thermophysical Properties of Matter, v1, Y.S. Touloukian, R.W. Powell, C.Y. Ho & P.G.
Klemens,
!1970, IFI/Plenum, NY, NY

!

!NOTE 2 - thermal conductivity is strongly dependent on impurities.

!

!NOTE 3 - well-annealed with residual resistivity of 0.00170 uohm-cm.

!NOTE 4 - error is 3% near RT, 3-5% at others.

!

!NOTE 5 - the S.I. system of units is used.

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP, 1, 0., 200., 400.,
MPTEMP, 4, 600., 800., 1000.,
MPTEMP, 7, 1200., 1400., 1600.,
MPTEMP, 10, 1800., 2000., 2100.,
MPTEMP, 13, 2200., 2300., 2400.,

!Thermal conductivity table [W/m°C]

MPDATA,KXX , W , 1, 1.8170E+02, 1.5210E+02, 1.3445E+02,
MPDATA,KXX , W , 4, 1.2569E+02, 1.1870E+02, 1.1313E+02,
MPDATA,KXX , W , 7, 1.0867E+02, 1.0504E+02, 1.0202E+02,
MPDATA,KXX , W , 10, 9.9449E+01, 9.7194E+01, 9.6161E+01,
MPDATA,KXX , W , 13, 9.5182E+01, 9.4256E+01, 9.3383E+01,

!-----

!EMISSIVITY (hemispherical total emissivity)

!

!NOTE 1 - Data are taken from:

!Thermophysical Properties of Matter, v7, Y.S. Touloukian & D.P. DeWitt,
!1970, IFI/Plenum, NY, NY.

!
!NOTE 2 - polished; 5% error.
!-----

!Temperature table [°C]
MPTEMP ! erase previous table
MPTEMP, 1, 127., 200., 400.,
MPTEMP, 4, 600., 800., 1000.,
MPTEMP, 7, 1200., 1400., 1600.,
MPTEMP, 10, 1800., 2000., 2100.,
MPTEMP, 13, 2200., 2300., 2400.,

!Emissivity table [-]
MPDATA,EMIS , W , 1, 3.1893E-02, 3.6965E-02, 5.4998E-02,
MPDATA,EMIS , W , 4, 7.8466E-02, 1.0653E-01, 1.3835E-01,
MPDATA,EMIS , W , 7, 1.7309E-01, 2.0622E-01, 2.3086E-01,
MPDATA,EMIS , W , 10, 2.5197E-01, 2.6991E-01, 2.7781E-01,
MPDATA,EMIS , W , 13, 2.8505E-01, 2.9168E-01, 2.9775E-01,

!-----
!DENSITY
!
!NOTE 1 - Data are calculated from the linear expansion.
!
!NOTE 2 - the S.I. system of units is used.
!-----

!Temperature table [°C]
! MPTEMP ! erase previous table
! MPTEMP, 1, 0., 200., 400.,
! MPTEMP, 4, 600., 800., 1000.,
! MPTEMP, 7, 1200., 1400., 1600.,
! MPTEMP, 10, 1800., 2000., 2100.,
! MPTEMP, 13, 2200., 2300., 2400.,

!Density table [kg/m^3]
! MPDATA,DENS , W , 1, 1.9304E+04, 1.9252E+04, 1.9199E+04,
! MPDATA,DENS , W , 4, 1.9144E+04, 1.9086E+04, 1.9027E+04,
! MPDATA,DENS , W , 7, 1.8966E+04, 1.8902E+04, 1.8835E+04,
! MPDATA,DENS , W , 10, 1.8766E+04, 1.8692E+04, 1.8654E+04,
! MPDATA,DENS , W , 13, 1.8614E+04, 1.8573E+04, 1.8531E+04,

! --- constant value assigned ---
MP,DENS,W,1.8692E+04 !density [kg/m^3]
! --- constant value assigned ---

```

!-----
!SPECIFIC HEAT
!
!NOTE 1 - Data are taken from:
!G.K. White and S.J. Collocott, J. Phys. Chem. Ref. Data, vol 13, no 4, p1251 (1984)
!
!NOTE 2 - error less than 2%.
!
!NOTE 3 - the S.I. system of units is used.
!-----

```

```

!Temperature table [°C]
! MPTEMP ! erase previous table
! MPTEMP,      1,      0.,      200.,      400.,
! MPTEMP,      4,      600.,      800.,      1000.,
! MPTEMP,      7,      1200.,      1400.,      1600.,
! MPTEMP,     10,      1800.,      2000.,      2100.,
! MPTEMP,     13,      2200.,      2300.,      2400.,

```

```

!Specific heat table [J/kg°C]
! MPDATA,C , W   , 1,  1.3092E+02, 1.3652E+02, 1.4108E+02,
! MPDATA,C , W   , 4,  1.4538E+02, 1.4953E+02, 1.5365E+02,
! MPDATA,C , W   , 7,  1.5793E+02, 1.6257E+02, 1.6780E+02,
! MPDATA,C , W   ,10,  1.7389E+02, 1.8114E+02, 1.8531E+02,
! MPDATA,C , W   ,13,  1.8988E+02, 1.9493E+02, 2.0048E+02,

```

```

! --- constant value assigned ---
! MP,C,W,1.8114E+02 !specific heat [J/kg°C]
! --- constant value assigned ---

```

```

!-----
!COEFFICIENT OF THERMAL EXPANSION
!
!NOTE 1 - Data are taken from:
!Thermophysical Properties of Matter, v12, Y.S. Touloukian, R.K. Kirby,
!R.E. Taylor & P.D. Desai, 1975, IFI/Plenum, NY, NY.
!
!NOTE 2 - 3% error.
!
!NOTE 3 - the S.I. system of units is used.
!-----

```

```

!Temperature table [°C]

```

```

! MPTEMP ! erase previous table
! MPTEMP,      1,      0.,      200.,      400.,
! MPTEMP,      4,      600.,      800.,      1000.,
! MPTEMP,      7,      1200.,      1400.,      1600.,
! MPTEMP,     10,      1800.,      2000.,      2100.,
! MPTEMP,     13,      2200.,      2300.,      2400.,

!Secant coefficient of thermal expansion [1/°C]
! MPDATA,ALPX , W      , 1,  4.4951E-06,  4.5818E-06,  4.7994E-06,
! MPDATA,ALPX , W      , 4,  5.0065E-06,  5.1981E-06,  5.3689E-06,
! MPDATA,ALPX , W      , 7,  5.5140E-06,  5.6474E-06,  5.8952E-06,
! MPDATA,ALPX , W      ,10,  6.2657E-06,  6.7444E-06,  7.0198E-06,
! MPDATA,ALPX , W      ,13,  7.3169E-06,  7.6338E-06,  7.9687E-06,

```

```

!-----
!ELASTIC MODULUS
!
!NOTE 1 - Data are taken from:
!Lowrie R. and Gonas A.M., J. Applied Physics, v.38, p.4505, (1967);
!below 298K W. Koester, Z. Metallkde., v39(1), p1 (1948).
!
!NOTE 2 - fully annealed; 3% error.
!
!NOTE 2 - the S.I. system of units is used.
!-----

```

```

!Temperature table [°C]
! MPTEMP ! erase previous table
! MPTEMP,      1,      0.,      200.,      400.,
! MPTEMP,      4,      600.,      800.,      1000.,
! MPTEMP,      7,      1200.,      1400.,      1600.,
! MPTEMP,     10,      1800.,      2000.,      2100.,
! MPTEMP,     13,      2200.,      2300.,      2400.,

!Elastic modulus [Pa]
! MPDATA,EX , w      , 1,  4.0011E+11,  3.9201E+11,  3.8330E+11,
! MPDATA,EX , w      , 4,  3.7399E+11,  3.6407E+11,  3.5355E+11,
! MPDATA,EX , w      , 7,  3.4242E+11,  3.3070E+11,  3.1836E+11,
! MPDATA,EX , w      ,10,  3.0544E+11,  2.8055E+11,  2.6666E+11,
! MPDATA,EX , w      ,13,  2.5180E+11,  2.3597E+11,  2.1920E+11,

```

```

!-----
!POISSON'S RATIO
!
!NOTE 1 - Data are taken from:
!calculated from Elastic modulus and Shear modulus: errors may be large.
!

```

!NOTE 2 - values above 1800°C are kept constant to match the temperature table
!used for the Elastic Modulus (this is a constraint imposed by ANSYS)

!

!-----

!Temperature table [°C]

! MPTEMP ! erase previous table

! MPTEMP, 1, 0., 200., 400.,

! MPTEMP, 4, 600., 800., 1000.,

! MPTEMP, 7, 1200., 1400., 1600.,

! MPTEMP, 10, 1800., 2000., 2100.,

! MPTEMP, 13, 2200., 2300., 2400.,

!Poisson's ratio [-]

! MPDATA,PRXY , W , 1, 2.8202E-01, 2.8398E-01, 2.8636E-01,

! MPDATA,PRXY , W , 4, 2.8918E-01, 2.9243E-01, 2.9612E-01,

! MPDATA,PRXY , W , 7, 3.0023E-01, 3.0478E-01, 3.0976E-01,

! MPDATA,PRXY , W , 10, 3.1516E-01, 3.1516E-01, 3.1516E-01,

! MPDATA,PRXY , W , 13, 3.1516E-01, 3.1516E-01, 3.1516E-01,

Appendix G.2 STD Molybdenum

```
!-----1-----2-----3-----4-----5-----6-----7-----8

!*****
!Molibdenum

!*****
!create by
!Nicola Baccini
!University of Padova
!Phone: +39 3289455733
!e-mail: nicola.baccini@yahoo.it

!*****
!
!Ver. 1.0 - 9 Sept 2009

!*****

!PREP7

Mo=30!material number in the ANSYS library
MPDELE,ALL,Mo

!*****
!ELECTRICAL RESISTIVITY
!Reference: P.D. Desai, T.K. Chu, H.M. James and C.Y. Ho, J.
!Phys. Ref. Data, vol 13, no. 4, p1069 (1984)

!*****

!Temperature table [°C]
MPTEMP!erase previous table
MPTEMP, 1,0,100,200,
MPTEMP, 4,300,400,500,
MPTEMP, 7,600,700,800,
MPTEMP,10,900,1000,1100,
MPTEMP,13,1200,1300,1400,
MPTEMP,16,1500,1600,1700,
MPTEMP,19,1800,1900,2000,
MPTEMP,22,2100,2200,2300,
```

```
!Electrical resistivity table [ohm m]
MPDATA,RSVX,Mo, 1,4.9147E-08,7.3993E-08,9.9298E-08,
MPDATA,RSVX,Mo, 4,1.2505E-07,1.5122E-07,1.7780E-07,
MPDATA,RSVX,Mo, 7,2.0478E-07,2.3214E-07,2.5986E-07,
MPDATA,RSVX,Mo, 10,2.8792E-07,3.1632E-07,3.4503E-07,
MPDATA,RSVX,Mo, 13, 3.7404E-07,4.0333E-07,4.3288E-07,
MPDATA,RSVX,Mo, 16,4.6269E-07,4.9273E-07,5.2299E-07,
MPDATA,RSVX,Mo, 19,5.5345E-07,5.8410E-07,6.1492E-07,
MPDATA,RSVX,Mo, 22,6.4589E-07,6.7700E-07,7.0823E-07,
```

```
!*****
!THERMAL CONDUCTIVITY
!Composition: 99.95%
!Note: well-annealed with residual resistivity of 0.167 uohm-cm;
!error is 4% near RT, 4-10% at others
!Reference: Thermophysical Properties of Matter, v1,
!Y.S. Touloukian, R.W. Powell, C.Y. Ho & P.G. Klemens, 1970, IFI/Plenum, NY, NY
```

```
!*****
```

```
!Temperature table [°C]
MPTEMP!erase previous table
MPTEMP,1,0,100,200,
MPTEMP,4,300,400,500,
MPTEMP,7,600,700,800,
MPTEMP,10,900,1000,1100,
MPTEMP,13,1200,1300,1400,
MPTEMP,16,1500,1600,1700,
MPTEMP,19,1800,1900,2000,
MPTEMP,22,2100,2200,2300,
```

```
!Thermal conductivity table [W/m°C]
MPDATA,KXX,Mo,1,1.3904E+02,1.3505E+02,1.3106E+02,
MPDATA,KXX,Mo,4,1.2711E+02,1.2322E+02,1.1944E+02,
MPDATA,KXX,Mo,7,1.1578E+02,1.1228E+02,1.0895E+02,
MPDATA,KXX,Mo,10,1.0580E+02,1.0285E+02,1.0012E+02,
MPDATA,KXX,Mo,13,9.7601E+01,9.5305E+01,9.3229E+01,
MPDATA,KXX,Mo,16,9.1369E+01,8.9720E+01,8.8270E+01,
MPDATA,KXX,Mo,19,8.7006E+01,8.5910E+01,8.4962E+01,
MPDATA,KXX,Mo,22,8.4138E+01,8.3411E+01,8.2750E+01,
```

!*****

!HEMISPHERICAL TOTAL EMISSIVITY

!note: polished; 25% error

!Reference: Thermophysical Properties of Matter, v7,

!Y.S. Touloukian & D.P. DeWitt, 1970, IFI/Plenum, NY, NY

!*****

!Temperature table [°C]

MPTEMP!erase previous table

MPTEMP,1,200,300,400,

MPTEMP,4,500,600,700,

MPTEMP,7,800,900,1000,

MPTEMP,10,1100,1200,1300,

MPTEMP,13,1400,1500,1600,

MPTEMP,16,1700,1800,1900,

MPTEMP,19,2000,2100,2200,

!Emissivity table

MPDATA,EMIS,Mo,1,6.2388E-02,7.3011E-02,8.3558E-02,

MPDATA,EMIS,Mo,4,9.4030E-02,1.0443E-01,1.1475E-01,

MPDATA,EMIS,Mo,7,1.2499E-01,1.3516E-01,1.4525E-01,

MPDATA,EMIS,Mo,10,1.5527E-01,1.6521E-01,1.7508E-01,

MPDATA,EMIS,Mo,13,1.8487E-01,1.9459E-01,2.0423E-01,

MPDATA,EMIS,Mo,16,2.1379E-01,2.2328E-01,2.3269E-01,

MPDATA,EMIS,Mo,19,2.4203E-01,2.5129E-01,2.6048E-01,

!*****

!DENSITY

!calculated from the linear expansion

!*****

!Temperature table [°C]

! MPTEMP!erase previous table

! MPTEMP,1,00,100,200,

! MPTEMP,4,300,400,500,

! MPTEMP,7,600,700,800,

! MPTEMP,10,900,1000,1100,

! MPTEMP,13,1200,1300,1400,

! MPTEMP,16,1500,1600,1700,

! MPTEMP,19,1800,1900,2000,

! MPTEMP,22,2100,2200,2300,

```

!Density table [Kg/m^3]
! MPDATA,DENS,Mo,1,1.0203E+04,1.0188E+04,1.0172E+04,
! MPDATA,DENS,Mo,4,1.0156E+04,1.0140E+04,1.0124E+04,
! MPDATA,DENS,Mo,7,1.0107E+04,1.0089E+04,1.0071E+04,
! MPDATA,DENS,Mo,10,1.0052E+04,1.0033E+04,1.0012E+04,
! MPDATA,DENS,Mo,13,9.9907E+03,9.9681E+03,9.9444E+03,
! MPDATA,DENS,Mo,16,9.9194E+03,9.8931E+03,9.8654E+03,
! MPDATA,DENS,Mo,19,9.8362E+03,9.8055E+03,9.7732E+03,
! MPDATA,DENS,Mo,22,9.7392E+03,9.7035E+03,9.6660E+03,

! --- constant value assigned ---
MP,DENS,Mo,9.7732E+03 !density [kg/m^3]
! --- constant value assigned ---

!*****
!SPECIFIC HEAT
!Note: for the non-superconducting state; 1.5% to 3% error
!Reference: P.D. Desai, J. Phys. Chem. Ref. Data, v16(1), p91 (1987)

!*****

!Temperature table [°C]
! MPTEMP,1,0,100,200,
! MPTEMP,4,300,400,500,
! MPTEMP,7,600,700,800,
! MPTEMP,10,900,1000,1100,
! MPTEMP,13,1200,1300,1400,
! MPTEMP,16,1500,1600,1700,
! MPTEMP,19,1800,1900,2000,
! MPTEMP,22,2100,2200,2300,

!Specific Heat table
! MPDATA,C,Mo,1,2.4386E+02,2.5699E+02,2.6611E+02,
! MPDATA,C,Mo,4,2.7284E+02,2.7841E+02,2.8334E+02,
! MPDATA,C,Mo,7,2.8804E+02,2.9290E+02,2.9817E+02,
! MPDATA,C,Mo,10,3.0406E+02,3.1069E+02,3.1810E+02,
! MPDATA,C,Mo,13,3.2626E+02,3.3504E+02,3.4426E+02,
! MPDATA,C,Mo,16,3.5363E+02,3.6282E+02,3.7388E+02,
! MPDATA,C,Mo,19,3.8675E+02,4.0055E+02,4.1529E+02,
! MPDATA,C,Mo,22,4.3128E+02,4.4910E+02,4.6967E+02,

! --- constant value assigned ---
MP,C,Mo,4.1529E+02 !specific heat [J/kg°C]
! --- constant value assigned ---

```

!*****

!COEFFICIENT OF THERMAL EXPANSION

!Note: the reference temperature is 20C; 3% error below 900K, 5% above 900K

!Reference: Thermophysical Properties of Matter, v12,

!Y.S. Touloukian, R.K. Kirby, R.E. Taylor & P.D. Desai, 1975, IFI/Plenum, NY, NY

!*****

!Temperature table [°C]

! MPTEMP!erase previous table

! MPTEMP,1,0,100,200,

! MPTEMP,4,300,400,500,

! MPTEMP,7,600,700,800,

! MPTEMP,10,900,1000,1100,

! MPTEMP,13,1200,1300,1400,

! MPTEMP,16,1500,1600,1700,

! MPTEMP,19,1800,1900,2000,

! MPTEMP,22,2100,2200,2300,

!Coefficient of thermal expansion table

! MPDATA,ALPX,Mo,1,4.7229E-06,4.8771E-06,5.0508E-06,

! MPDATA,ALPX,Mo,4,5.2420E-06,5.4486E-06,5.6683E-06,

! MPDATA,ALPX,Mo,7,5.8990E-06,6.1386E-06,6.3849E-06,

! MPDATA,ALPX,Mo,10,6.6358E-06,6.8732E-06,7.1020E-06,

! MPDATA,ALPX,Mo,13,7.3632E-06,7.6622E-06,8.0045E-06,

! MPDATA,ALPX,Mo,16,8.3955E-06,8.8407E-06,9.3454E-06,

! MPDATA,ALPX,Mo,19, 9.9151E-06,1.0555E-05,1.1271E-05,

! MPDATA,ALPX,Mo,22,1.2069E-05,1.2952E-05,1.3929E-05,

!*****

!ELASTIC MODULUS

!Composition: commercially pure

!Note: values below 298K were decreased by 2% to match the high temperature values

!Reference: ASM Handbook, vol 2, 10th edition, ASM International (1992);

!below 273K W. Koester, Z. Metallkde., v39(1), p1 (1948) (in German)

!*****

!Temperature table [°C]

! MPTEMP!erase previous table

```

! MPTEMP,1,0,100,200,
! MPTEMP,4,300,400,500,
! MPTEMP,7,600,700,800,
! MPTEMP,10,900,1000,1100,
! MPTEMP,13,1200,1300,1400,
! MPTEMP,16,1500,1600,1700,
! MPTEMP,19,1800,1900,

```

!Elastic modulus table

```

! MPDATA,EX,Mo,1,3.2827E+11,3.2179E+11,3.1602E+11,
! MPDATA,EX,Mo,4,3.1080E+11,3.0596E+11,3.0135E+11,
! MPDATA,EX,Mo,7,2.9681E+11,2.9219E+11,2.8731E+11,
! MPDATA,EX,Mo,10,2.8203E+11,2.7619E+11,2.6963E+11,
! MPDATA,EX,Mo,13,2.6218E+11,2.5370E+11,2.4402E+11,
! MPDATA,EX,Mo,16,2.3299E+11,2.2044E+11,2.0623E+11,
! MPDATA,EX,Mo,19,1.9018E+11,1.7215E+11,

```

!*****

!POISSON'S RATIO

!Note: calculated from E and G; errors may be large

!Reference: see E and G

!*****

!Temperature table [°C]

```

! MPTEMP!erase previous table
! MPTEMP,1,25,100,150,
! MPTEMP,4,200,250,300,
! MPTEMP,7,350,400,450,
! MPTEMP,10,500,550,600,
! MPTEMP,13,650,700,750,
! MPTEMP,16,800,850,

```

! Poisson's ratio table

```

! MPDATA,PRXY,Mo,1,3.6861E-01,3.6036E-01,3.5627E-01,
! MPDATA,PRXY,Mo,4,3.5321E-01,3.5112E-01,3.4992E-01,
! MPDATA,PRXY,Mo,7,3.4955E-01,3.4992E-01,3.5097E-01,
! MPDATA,PRXY,Mo,10,3.5263E-01,3.5482E-01,3.5748E-01,
! MPDATA,PRXY,Mo,13,3.6052E-01,3.6389E-01,3.6749E-01,
! MPDATA,PRXY,Mo,16,3.7128E-01,3.7516E-01,

```

Appendix G.3 ATJ graphite

!-----1-----2-----3-----4-----5-----6-----7-----8

```
!-----
!ATJ graphite
!Composition: isomolded graphite
!-----
!Version 1.0 (Mar 08) by
!Ing. Mattia Manzolaro
!Istituto Nazionale di Fisica Nucleare
!Laboratori di Legnaro
!Viale dell'Universita' n. 2; 35020 Legnaro (PD) - Italy
!Phone: +39 049 8068423
!fax: +39 049 641925
!e-mail: Mattia.Manzolaro@lnl.infn.it
!-----
!
!Ver. 1.0 - 01 Apr 08
!-----
```

/prep7

```
C_ATJ=29      !Material number in the ANSYS library
MPDELE,all,C_ATJ
```

```
!-----
!ELECTRICAL RESISTIVITY
!
!NOTE 1 - Data are taken from:
!R.E. Taylor, F.E. Davis and R.W. Powell, High Temperatures-High Pressures, v1,
!p663 (1969).
!
!NOTE 2 - values over 2126.9°C are calculated by linear extrapolation.
!
!NOTE 3 - 5% error; National Carbon Co.
!
!NOTE 4 - the S.I. system of units is used.
!-----
```

```
!Temperature table [°C]
MPTEMP ! erase previous table
MPTEMP,      1,      727.,      800.,      900.,
MPTEMP,      4,      1000.,      1100.,      1200.,
MPTEMP,      7,      1300.,      1400.,      1500.,
MPTEMP,     10,      1600.,      1700.,      1800.,
```

MPTEMP,	13,	1900.,	2000.,	2100.,
MPTEMP,	16,	2126.,	2200.,	2300.,
MPTEMP,	19,	2400.,		

!Electrical resistivity table [ohm m]

MPDATA,RSVX , C_ATJ	, 1,	6.6151E-06,	6.7224E-06,	6.8702E-06,
MPDATA,RSVX , C_ATJ	, 4,	7.0193E-06,	7.1698E-06,	7.3215E-06,
MPDATA,RSVX , C_ATJ	, 7,	7.4746E-06,	7.6290E-06,	7.7847E-06,
MPDATA,RSVX , C_ATJ	, 10,	7.9417E-06,	8.1001E-06,	8.2598E-06,
MPDATA,RSVX , C_ATJ	, 13,	8.4208E-06,	8.5831E-06,	8.7468E-06,
MPDATA,RSVX , C_ATJ	, 16,	8.7909E-06,	8.9105E-06,	9.0742E-06,
MPDATA,RSVX , C_ATJ	, 19,	9.2379E-06,		

!-----

!THERMAL CONDUCTIVITY

!

!NOTE 1 - Data are taken from:

!R.E. Taylor, F.E. Davis and R.W. Powell, High Temperatures-High Pressures,
!v1, p663 (1969).

!

!NOTE 2 - thermal conductivity is strongly dependent on impurities.

!

!NOTE 3 - 5% error; National Carbon Co.

!

!NOTE 4 - the S.I. system of units is used.

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	1227.,	1300.,	1400.,
MPTEMP,	4,	1500.,	1600.,	1700.,
MPTEMP,	7,	1800.,	1900.,	2000.,
MPTEMP,	10,	2100.,	2127.,	

!Thermal conductivity table [W/m°C]

MPDATA,KXX , C_ATJ	, 1,	5.6386E+01,	5.4953E+01,	5.3090E+01,
MPDATA,KXX , C_ATJ	, 4,	5.1337E+01,	4.9695E+01,	4.8163E+01,
MPDATA,KXX , C_ATJ	, 7,	4.6743E+01,	4.5433E+01,	4.4233E+01,
MPDATA,KXX , C_ATJ	, 10,	4.3145E+01,	4.2871E+01,	

!-----

!EMISSION (hemispherical total emissivity)

!

!NOTE 1 - Data are taken from:

!R.E. Taylor, F.E. Davis and R.W. Powell, High Temperatures-High Pressures,
!v1, p663 (1969).

!

!NOTE 2 - 5% error; National Carbon Co..

!

!NOTE 3 - values over 2126.9°C are calculated by linear extrapolation.

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	727,	800,	900,
MPTEMP,	4,	1000,	1100,	1200,
MPTEMP,	7,	1300,	1400,	1500,
MPTEMP,	10,	1600,	1700,	1800,
MPTEMP,	13,	1900.,	2000.,	2100.,
MPTEMP,	16,	2127.,	2200.,	2300.,
MPTEMP,	19,	2400.,		

!Emissivity table [-]

MPDATA,EMIS , C_ATJ	, 1,	7.6156E-01,	7.6216E-01,	7.6299E-01,
MPDATA,EMIS , C_ATJ	, 4,	7.6382E-01,	7.6465E-01,	7.6547E-01,
MPDATA,EMIS , C_ATJ	, 7,	7.6630E-01,	7.6713E-01,	7.6796E-01,
MPDATA,EMIS , C_ATJ	, 10,	7.6879E-01,	7.6961E-01,	7.7044E-01,
MPDATA,EMIS , C_ATJ	, 13,	7.7127E-01,	7.7210E-01,	7.7292E-01,
MPDATA,EMIS , C_ATJ	, 16,	7.7315E-01,	7.7374E-01,	7.7456E-01,
MPDATA,EMIS , C_ATJ	, 19,	7.7538E-01,		

!-----

!DENSITY

!

!NOTE 1 - UCAR "Technical Data Sheet: 31": Grade ATJ Isomolded Graphite.

!

!NOTE 2 - the S.I. system of units is used.

!-----

!Temperature table [°C]

! MPTEMP ! erase previous table

! MPTEMP, 1, 20.,

!Density table [kg/m^3]

! MPDATA,DENS , C_ATJ , 1, 1.76E+03,

```
! --- constant value assigned ---
MP,DENS,C_ATJ,1.76E+03 !density [kg/m^3]
! --- constant value assigned ---
```

```
!-----
!SPECIFIC HEAT
!
!NOTE 1 - Data are taken from:
!UCAR Data Sheet (file "UCAR_vol.2.pdf")
!-----
```

```
! MPTEMP ! erase previous table
! MPTEMP,      1,      0.,      500.,      1000.,
! MPTEMP,      4,      1500.,      2000.,      2500.,
```

```
!Specific heat table [J/kg°C]
! MPDATA,C , C_ATJ      , 1,      600,      1550,      1800,
! MPDATA,C , C_ATJ      , 4,      1900,      2000,      2000,
```

```
! --- constant value assigned ---
MP,C,C_ATJ,2000 !specific heat [J/kg°C]
! --- constant value assigned ---
```

```
!-----
!COEFFICIENT OF THERMAL EXPANSION
!
!NOTE 1 - Data are taken from:
!Thermophysical Properties of Matter, v13, Y.S. Touloukian, R.K.
!Kirby, R.E. Taylor & T.Y.R. Lee, 1977, IFI/Plenum, NY, NY.
!
!NOTE 2 - 10% error; National Carbon Co..
!
!NOTE 3 - the S.I. system of units is used.
!-----
```

```
!Temperature table [°C]
! MPTEMP ! erase previous table
! MPTEMP,      1,      20.,      100.,      500.,
! MPTEMP,      4,      1000.,      1500.,      1600.,
! MPTEMP,      7,      1700.,      1800.,      1900.,
! MPTEMP,     10,      2000.,      2100.,      2200.,
```

! MPTEMP, 13, 2300., 2400., 2500.,
! MPTEMP, 16, 2600., 2700., 2800.,

!Secant coefficient of thermal expansion [1/°C]

! MPDATA,ALPX , C_ATJ , 1, 2.2162E-06, 2.4088E-06, 3.2597E-06,
! MPDATA,ALPX , C_ATJ , 4, 4.1250E-06, 4.8376E-06, 4.9649E-06,
! MPDATA,ALPX , C_ATJ , 7, 5.0872E-06, 5.2044E-06, 5.3162E-06,
! MPDATA,ALPX , C_ATJ , 10, 5.4224E-06, 5.5227E-06, 5.6165E-06,
! MPDATA,ALPX , C_ATJ , 13, 5.7034E-06, 5.7828E-06, 5.8539E-06,
! MPDATA,ALPX , C_ATJ , 16, 5.9159E-06, 5.9681E-06, 6.0096E-06,

!-----

!ELASTIC MODULUS

!

!NOTE 1 - Data are taken from:

!UCAR "Technical Data Sheet: 31": Grade ATJ Isomolded Graphite

!

!NOTE 2 - the S.I. system of units is used.

!-----

!Temperature table [°C]

! MPTEMP ! erase previous table

! MPTEMP, 1, 20.,

!Elastic modulus [Pa]

! MPDATA,EX , C_ATJ , 1, 9.8E+09,

!-----

!POISSON'S RATIO

!

!NOTE 1 - No data available:

!To perform thermo-structural analysis we assign the "reasonable" value of 0.3.

!

!-----

!Temperature table [°C]

! MPTEMP ! erase previous table

! MPTEMP, 1, 20.,

!Poisson's ratio [-]

! MPDATA,PRXY , C_ATJ , 1, 3.0E-01,

Appendix G.4 Copper

!-----1-----2-----3-----4-----5-----6-----7-----8

!-----

!Copper

!-----

!create by

!Mirko Libralato

!University of Padova

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!e-mail: Mirko.Libralato@gmail.com

!-----

!

!Ver. 1.0 - 14 Oct 2008

!-----

!PREP7

Cu=28!material number in the ANSYS library

MPDELE,ALL,Cu

!-----

!ELECTRICAL RESISTIVITY

!

!Composition: - purity 99.9% or higher;

!Note: - data below 55K is for Cu with a residual resistivity

!of 0.002×10^{-8} ohm-m;

! - the S.I. system of units is used.

!Reference: - R.A. Matula, J. Phys. Chem. Ref. Data,

! vol 8, no. 4, p 1147 (1979).

!-----

!Temperature table [°C]

MPTEMP!erase previous table

MPTEMP, 1, 0, 100, 200

MPTEMP, 4, 300, 400, 500

MPTEMP, 7, 600, 700, 800

MPTEMP, 10, 900, 1000

!Electrical resistivity table [ohm m]

MPDATA,RSVX,Cu, 1, 1.5327E-08, 2.2139E-08, 2.9003E-08

MPDATA,RSVX,Cu, 4, 3.5980E-08, 4.3132E-08, 5.0520E-08

MPDATA,RSVX,Cu, 7, 5.8206E-08, 6.6251E-08, 7.4717E-08

MPDATA,RSVX,Cu, 10, 8.3666E-08, 9.3160E-08

!-----
!THERMAL CONDUCTIVITY
!
!Composition: - purity 99.999%
!Note: - well-annealed with residual resistivity of 0.000851 uohm-cm;
! - error is 3% near RT, 3-5% at others;
! - the S.I. system of units is used.
!Reference: - Thermophysical Properties of Matter, v1, Y.S. Touloukian,
! R.W.Powell, C.Y. Ho & P.G. Klemens, 1970, IFI/Plenum, NY, NY.
!-----

!Temperature table [°C]
MPTEMP,1,erase previous table
MPTEMP, 1, 0, 100, 200
MPTEMP, 4, 300, 400, 500
MPTEMP, 7, 600, 700, 800
MPTEMP, 10, 900, 1000

!Thermal conductivity table [W/m°C]
MPDATA,KXX,Cu, 1, 4.0253E+02, 3.9389E+02, 3.8911E+02
MPDATA,KXX,Cu, 4, 3.8393E+02, 3.7835E+02, 3.7237E+02
MPDATA,KXX,Cu, 7, 3.6598E+02, 3.5920E+02, 3.5201E+02
MPDATA,KXX,Cu, 10, 3.4442E+02, 3.3643E+02

!-----
!HEMISPHERICAL TOTAL EMISSIVITY
!
!Note: - polished;
! - the S.I. system of units is used.
!Reference: - Thermophysical Properties of Matter, v7,
! Y.S. Touloukian & D.P. DeWitt, 1970, IFI/Plenum, NY, NY.
!-----

!Temperature table [°C]
MPTEMP,1,erase previous table
MPTEMP, 1, 0, 100, 200
MPTEMP, 4, 300, 400, 500
MPTEMP, 7, 600, 700, 800
MPTEMP, 10, 900

!Emissivity table
MPDATA,EMIS,Cu, 1, 2.9484E-02, 3.0726E-02, 3.1491E-02
MPDATA,EMIS,Cu, 4, 3.2118E-02, 3.2949E-02, 3.4322E-02
MPDATA,EMIS,Cu, 7, 3.6578E-02, 4.0057E-02, 4.5099E-02
MPDATA,EMIS,Cu, 10, 5.2044E-02

!-----
!DENSITY
!
!Note: - the S.I. system of units is used.
!
!Reference: - calculated from the linear expansion.
!-----

!Temperature table [°C]
MPTEMP!erase previous table
MPTEMP, 1, 0, 100, 200
MPTEMP, 4, 300, 400, 500
MPTEMP, 7, 600, 700, 800
MPTEMP, 10, 900, 1000

!Density table [kg/m³]
MPDATA,DENS,Cu, 1, 8.9659E+03, 8.9226E+03, 8.8768E+03
MPDATA,DENS,Cu, 4, 8.8288E+03, 8.7787E+03, 8.7265E+03
MPDATA,DENS,Cu, 7, 8.6723E+03, 8.6163E+03, 8.5586E+03
MPDATA,DENS,Cu, 10, 8.4991E+03, 8.4382E+03

!-----
!SPECIFIC HEAT
!
!Note: - error less than 2%
! - the S.I. system of units is used.
!
!Reference: - G.K. White and S.J. Collocott, J. Phys. Chem. Ref. Data,
! vol 13, no 4, p1251 (1984)
!-----

!Temperature table [°C]
MPTEMP!erase previous table
MPTEMP, 1, 0, 100, 200
MPTEMP, 4, 300, 400, 500
MPTEMP, 7, 600, 700, 800
MPTEMP, 10, 900, 1000

!Specific heat table [J/kg°C]
MPDATA,C,Cu, 1, 3.7967E+02, 3.9238E+02, 4.0332E+02
MPDATA,C,Cu, 4, 4.1285E+02, 4.2123E+02, 4.2899E+02
MPDATA,C,Cu, 7, 4.3691E+02, 4.4607E+02, 4.5781E+02
MPDATA,C,Cu, 10, 4.7376E+02, 4.9580E+02

!-----

!COEFFICIENT OF THERMAL EXPANSION

!

!Note: - 3% error ;

! - the S.I. system of units is used.

!

!Reference: - Thermophysical Properties of Matter, v12, Y.S. Touloukian,

! R.K.Kirby, R.E. Taylor & P.D. Desai, 1975, IFI/Plenum, NY, NY

!-----

!Temperature table [°C]

MPTEMP!erase previous table

MPTEMP, 1, 0, 100, 200

MPTEMP, 4, 300, 400, 500

MPTEMP, 7, 600, 700, 800

MPTEMP, 10, 900, 1000

!Secant coefficient of thermal expansion [1/°C]

MPDATA,ALPX,Cu, 1, 1.6312E-05, 1.7368E-05, 1.8131E-05

MPDATA,ALPX,Cu, 4, 1.8737E-05, 1.9283E-05, 2.0036E-05

MPDATA,ALPX,Cu, 7, 2.1019E-05, 2.2150E-05, 2.3343E-05

MPDATA,ALPX,Cu, 10, 2.4515E-05, 2.5582E-05

!-----

!ELASTIC MODULUS

!

!Composition: - high purity

!

!Note: - annealed;

! - 2% error, data above 300K was multiplied

!by 0.975 to match the low teperature data;

! - dynamic method;

! - the S.I. system of units is used.

!

!Reference: - below 300K N.J. Simon, E.S. Drexler, R.P. Reed,

! NIST Monograph 177, Properties of Copper

! and Copper Alloys at Cryogenic Temperatures (1992);

! - above 300K H.M. Ledbetter, J. Phys. Chem. Reference Data,

!vol 6, p1181 (1977).

!-----

!Temperature table [°C]

MPTEMP!erase previous table

MPTEMP, 1, 0, 20, 100

MPTEMP, 4, 200, 300, 400

MPTEMP, 7, 500, 600, 700

MPTEMP, 10, 800, 900, 976.85

!Elastic modulus [Pa]

```

MPDATA,EX,Cu, 1, 1.2752E+11, 1.2609E+11, 1.2150E+11
MPDATA,EX,Cu, 4, 1.1570E+11, 1.0964E+11, 1.0333E+11
MPDATA,EX,Cu, 7, 9.6757E+10, 8.9925E+10, 8.2836E+10
MPDATA,EX,Cu, 10, 7.5487E+10, 6.7880E+10, 6.1859E+10

```

```

!-----
!POISSON'S RATIO
!
!Note:      - calculated from E and G;
!  - errors may be large;
!  - values above 20°C are kept constant at 3.3507E-01 (assumption);
!  - the S.I. system of units is used.
!-----

```

```

!Temperature table [°C]
MPTEMP!erase previous table
MPTEMP, 1, 0, 20, 100
MPTEMP, 4, 200, 300, 400
MPTEMP, 7, 500, 600, 700
MPTEMP, 10, 800, 900, 976.85

```

```

!Poisson's ratio
MPDATA,PRXY,Cu, 1, 3.3545E-01, 3.3507E-01, 3.3507E-01
MPDATA,PRXY,Cu, 4, 3.3507E-01, 3.3507E-01, 3.3507E-01
MPDATA,PRXY,Cu, 7, 3.3507E-01, 3.3507E-01, 3.3507E-01
MPDATA,PRXY,Cu, 10, 3.3507E-01, 3.3507E-01, 3.3507E-01

```


Appendix G.5 Aluminum oxide Al_2O_3

!-----1-----2-----3-----4-----5-----6-----7-----8

!*****

!Al2O3_XX (alpha)

!*****

!create by

!Nicola Baccini

!University of Padova

!Phone: +39 3289455733

!e-mail: nicola.baccini@yahoo.it

!*****

!

!Ver. 1.0 - 9 Sept 2009

!*****

!PREP7

Al2O3_XX=31!material number in the ANSYS library

MPDELE,ALL,Al2O3_XX

!*****

!THERMAL CONDUCTIVITY

!Composition: 99.5 Al2O3_XX

!Note: 98% dense; error is 6% from 500-1000K, 6-10% at others; alpha

!Reference: Thermophysical Properties of Matter, v2,

!Y.S. Touloukian, R.W. Powell, C.Y. Ho & P.G. Klemens, 1970, IFI/Plenum, NY, NY

!*****

!Temperature table [°C]

MPTEMP!erase previous table

MPTEMP,1,0,100,200,

MPTEMP,4,300,400,500,

MPTEMP,7,600,700,800,

MPTEMP,10,900,1000,1100,

MPTEMP,13,1200,1300,1400,

MPTEMP,16,1500,1600,1700,
MPTEMP,19,1800

!Thermal conductivity table [W/m°C]

MPDATA,KXX,Al2O3_XX,1,3.9486E+01,2.8637E+01,2.1662E+01,
MPDATA,KXX,Al2O3_XX,4,1.6899E+01,1.3406E+01,1.0908E+01,
MPDATA,KXX,Al2O3_XX,7,9.3546E+00,8.1919E+00,7.3374E+00,
MPDATA,KXX,Al2O3_XX,10,6.7210E+00,6.2846E+00,5.9824E+00,
MPDATA,KXX,Al2O3_XX,13,5.7812E+00,5.6599E+00,5.6097E+00,
MPDATA,KXX,Al2O3_XX,16,5.6342E+00,5.7491E+00,5.9828E+00,
MPDATA,KXX,Al2O3_XX,19,6.3756E+00,

!*****

!HEMISFERICAL TOTAL EMISSIVITY

!Composition: 52,9 Al, 47,1 O (wt%)

!Note: sapphire; depends on purity; alpha

!Reference: R.J. Tiernan and J.E. Saunders, J. Applied Physics, v 64(2), p459 (1988)

!*****

!Temperature table [°C]

MPTEMP!erase previous table

MPTEMP,1,750,800,850,

MPTEMP,4,900,950,1000,

MPTEMP,7,1050,1100,1150,

MPTEMP,10,1200,

!Emissivity table [-]

MPDATA,EMIS,Al2O3_XX,1,2.6511E-01,2.5020E-01,2.3588E-01,

MPDATA,EMIS,Al2O3_XX,4,2.2216E-01,2.0903E-01,1.9649E-01,

MPDATA,EMIS,Al2O3_XX,7,1.8454E-01,1.7319E-01,1.6243E-01,

MPDATA,EMIS,Al2O3_XX,10,1.5227E-01,

!*****

!ELECTRICAL RESISTIVITY

!Composition:

!Note:

!Reference:

!*****

!Temperature table [°C]

MPTEMP!erase previous table
 MPTEMP,1,0,500,600,
 MPTEMP,4,700,800,900,
 MPTEMP,7,1000,1100,1200,
 MPTEMP,10,1300

!Electrical resistivity table [Kg/m^3]
 MPDATA,RSVX,Al2O3_XX,1,1E+14, 5.012E+13,2.09E+13,
 MPDATA,RSVX,Al2O3_XX,4,1.585E+13,1.7380E+12,7.586E+10,
 MPDATA,RSVX,Al2O3_XX,7,1.38E+09,5.012E+07,3.02E+06,
 MPDATA,RSVX,Al2O3_XX,10,2.884E+05,

!*****

!DENSITY
 !Composition: 52,9 Al, 47,1 O (wt%)
 !Note: alpha
 !Reference: calculated from the linear expansion

!*****

!Temperature table [°C]
 MPTEMP!erase previous table
 MPTEMP,1,0,100,200,
 MPTEMP,4,300,400,500,
 MPTEMP,7,600,700,800,
 MPTEMP,10,900,1000,1100,
 MPTEMP,13,1200,1300,1400,
 MPTEMP,16,1500,1600,

!Density table [Kg/m^3]
 MPDATA,DENS,Al2O3_XX,1,3.9896E+03,3.9826E+03,3.9745E+03,
 MPDATA,DENS,Al2O3_XX,4,3.9656E+03,3.9560E+03,3.9460E+03,
 MPDATA,DENS,Al2O3_XX,7,3.9356E+03,3.9250E+03,3.9142E+03,
 MPDATA,DENS,Al2O3_XX,10,3.9032E+03,3.8922E+03,3.8810E+03,
 MPDATA,DENS,Al2O3_XX,13,3.8696E+03,3.8579E+03,3.8459E+03,
 MPDATA,DENS,Al2O3_XX,16,3.8333E+03,3.8201E+03,

!*****

!SPECIFIC HEAT
 !Composition: 52,9 Al, 47,1 O (wt%)
 !Note: less than 1% error; alpha

!Reference: D.A. Archer, J. Phys. Chem. Ref. Data, v22(6), p1441 (1993)

!*****

!Temperature table [°C]

MPTEMP!erase previous table

MPTEMP,1,0,100,200,

MPTEMP,4,300,400,500,

MPTEMP,7,600,700,800,

MPTEMP,10,900,1000,1100,

MPTEMP,13,1200,1300,1400,

MPTEMP,16,1500,1600,1700,

MPTEMP,19,1800,1900,

!Specific Heat table

MPDATA,C,Al2O3_XX,1,7.1784E+02,9.0600E+02,1.0187E+03,

MPDATA,C,Al2O3_XX,4,1.0885E+03,1.1357E+03,1.1701E+03,

MPDATA,C,Al2O3_XX,7,1.1948E+03,1.2157E+03,1.2336E+03,

MPDATA,C,Al2O3_XX,10,1.2493E+03,1.2634E+03,1.2762E+03,

MPDATA,C,Al2O3_XX,13,1.2883E+03,1.2998E+03,1.3110E+03,

MPDATA,C,Al2O3_XX,16,1.3220E+03,1.3329E+03,1.3435E+03,

MPDATA,C,Al2O3_XX,19,1.3537E+03,1.3633E+03,

!*****

!COEFFICIENT OF THERMAL EXPANSION

!Composition: 52,9 Al, 47,1 O (wt%)

!Note: the reference temperature is 20C; 3% error; alpha

!Reference: Thermophysical Properties of Matter, v13,

!Y.S. Touloukian, R.K. Kirby, R.E. Taylor & T.Y.R. Lee, 1977, IFI/Plenum, NY, NY

!*****

!Temperature table [°C]

MPTEMP!erase previous table

MPTEMP,1,0,100,200,

MPTEMP,4,300,400,500,

MPTEMP,7,600,700,800,

MPTEMP,10,900,1000,1100,

MPTEMP,13,1200,1300,1400,

MPTEMP,16,1500,1600,

!Coefficient of thermal expansion table

MPDATA,ALPX,Al2O3_XX,1,5.0548E-06,6.8436E-06,7.4041E-06,

MPDATA,ALPX,Al2O3_XX,4,7.7599E-06,8.1000E-06,8.4243E-06,

MPDATA,ALPX,Al2O3_XX,7,8.7329E-06,9.0257E-06,9.3027E-06,
MPDATA,ALPX,Al2O3_XX,10,9.5640E-06,9.8095E-06,1.0039E-05,
MPDATA,ALPX,Al2O3_XX,13,1.0253E-05,1.0452E-05,1.0634E-05,
MPDATA,ALPX,Al2O3_XX,16,1.0801E-05,1.0952E-05,

!*****
!ELASTIC MODULUS
!Composition: 52,9 Al, 47,1 O (wt%)
!Note: average of hot-pressed (from Avco) and sintered samples (from GE),
!>99% pure, >99% dense; the modulus decreases by approx. 5% per 1% of density;
!dynamic method; alpha
!Reference: N. Soga and O.L. Anderson, J. American Ceramic Society, v49(7), p355,
(1966)

!*****

!Temperature table [°C]
MPTEMP!erase previous table
MPTEMP,1,50,100,200,
MPTEMP,4,300,400,500,
MPTEMP,7,600,700,800,
MPTEMP,10,900,1000,1100,

!Elastic modulus table
MPDATA,EX,Al2O3_XX,1,3.9110E+11,3.8866E+11,3.8373E+11,
MPDATA,EX,Al2O3_XX,4,3.7874E+11,3.7368E+11,3.6855E+11,
MPDATA,EX,Al2O3_XX,7,3.6336E+11,3.5811E+11,3.5278E+11,
MPDATA,EX,Al2O3_XX,10,3.4740E+11,3.4194E+11,3.3642E+11,

!*****

!POISSON'S RATIO
!Composition: 52,9 Al, 47,1 O (wt%)
!Note: calculated from E and G; errors may be large; alpha
!Reference: see E and G

!*****

!Temperature table [°C]
MPTEMP!erase previous table
MPTEMP,1,50,100,200,
MPTEMP,4,300,400,500,

MPTEMP,7,600,700,800,
MPTEMP,10,900,1000,1100,

!Poisson's ratio table

MPDATA,PRXY,Al2O3_XX,1,2.2849E-01,2.2932E-01,2.3093E-01,
MPDATA,PRXY,Al2O3_XX,4,2.3249E-01,2.3401E-01,2.3547E-01,
MPDATA,PRXY,Al2O3_XX,7,2.3689E-01,2.3825E-01,2.3957E-01,
MPDATA,PRXY,Al2O3_XX,10,2.4084E-01,2.4205E-01,2.4322E-01,

Appendix G.6 Stainless steel AISI 316

!-----1-----2-----3-----4-----5-----6-----7-----8

```
!*****
!Stainless Steel 316
```

```
!*****
!create by
!Mattia Manzolaro
!INFN
!Phone: +39 349 2824765
!e-mail: mattia.manzolaro@lnl.infn.it
```

```
!*****
!
!Ver. 1.0 - 30/11/2012
```

```
!*****
```

!PREP7

SS316=50!material number in the ANSYS library
MPDELE,ALL,SS316

```
!*****
!ELECTRICAL RESISTIVITY
!Composition: bal. Fe, 16.8 Cr, 11.66 Ni, 2.2 Mo, 1.6 Mn, 0.1 C, 0.26 Si (wt%)
!Note: Allegheny Ludlum Corp.
!Reference: M. Rouby and P. Blanchard, Physical and Mechanical Properties of
!Stainless Steels, Stainless Steels, les editions de physique, p111-158, (1993)
!and A.F. Clark, G.E. Childs and G.H. Wallace, Cryogenics, v10, p295 (1970)
```

```
!*****
```

!Temperature table [°C]
MPTEMP!erase previous table
MPTEMP, 1,0,100,200,
MPTEMP, 4,300,400,500,
MPTEMP, 7,600,

!Electrical resistivity table [ohm m]
MPDATA,RSVX,SS316, 1,7.33E-07,8.01E-07,8.64E-07,
MPDATA,RSVX,SS316, 4,9.24E-07,9.81E-07,1.03E-06,
MPDATA,RSVX,SS316, 7,1.08E-06,

!*****
!THERMAL CONDUCTIVITY
!Composition: bal. Fe, 16.8 Cr, 11.66 Ni, 2.2 Mo, 1.6 Mn, 0.1 C, 0.26 Si (wt%)
!Note: material below 110K is reported as 316LN; Allegheny Ludlum Corp.
!Reference: below 110K O. Umezawa and K. Ishikawa, Cryogenics, v32(10), p873 (1992);
!above 135K Lucks, C.F., Thompson, H.B., Smith, A.R., Curry, F.P., Deem, H.W. and
!Bing, G.F., USAF TR 6145, I, p1-127, 1951 [ATI 117 715]

!*****

!Temperature table [°C]
MPTEMP!erase previous table
MPTEMP,1,0,100,200,
MPTEMP,4,300,400,500,
MPTEMP,7,600,700,800,
MPTEMP,10,900,

!Thermal conductivity table [W/m°C]
MPDATA,KXX,SS316,1,1.29E+01,1.45E+01,1.60E+01,
MPDATA,KXX,SS316,4,1.74E+01,1.87E+01,2.00E+01,
MPDATA,KXX,SS316,7,2.13E+01,2.24E+01,2.35E+01,
MPDATA,KXX,SS316,10,2.46E+01,

!*****

!HEMISPHERICAL TOTAL EMISSIVITY (!!! NORMAL TOTAL EMISSIVITY !!!)
!Composition: bal. Fe, 16.8 Cr, 11.66 Ni, 2.2 Mo, 1.6 Mn, 0.1 C, 0.26 Si (wt%)
!Note: cleaned as-received; 30% error; Allegheny Ludlum Corp.
!Reference: Thermophysical Properties of Matter, v7, Y.S.
!Touloukian & D.P. DeWitt, 1970, IFI/Plenum, NY, NY

!*****

!Temperature table [°C]
MPTEMP!erase previous table
MPTEMP,1,100, 200,300,
MPTEMP,4,400, 500,600,

MPTEMP,7,700, 800,900,

!Emissivity table

MPDATA,EMIS,SS316,1,2.91E-01,3.02E-01,3.10E-01,

MPDATA,EMIS,SS316,4,3.18E-01,3.32E-01,3.57E-01,

MPDATA,EMIS,SS316,7,3.96E-01,4.56E-01,5.41E-01,

!*****

!DENSITY

!calculated from the linear expansion

!*****

! --- constant value assigned ---

MP,DENS,SS316,8000!density [kg/m^3]

! --- constant value assigned ---

!*****

!SPECIFIC HEAT

!Note: for the non-superconducting state; 1.5% to 3% error

!Reference: P.D. Desai, J. Phys. Chem. Ref. Data, v16(1), p91 (1987)

!*****

! --- constant value assigned ---

MP,C,SS316,600!specific heat [J/kg°C]

! --- constant value assigned ---

Appendix G.7 STD Tantalum purity 99%

!-----1-----2-----3-----4-----5-----6-----7-----8

!-----

!Tantalum

!Composition: purity 99.9% or higher

!-----

!Version 1.0 (Mar 08) by

!Ing. Mattia Manzolaro

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!-----

!

!Ver. 1.0 - 19 Mar 08

!-----

/prep7

Ta=26 !Material number in the ANSYS library

MPDELE,all,Ta

!-----

!ELECTRICAL RESISTIVITY

!

!NOTE 1 - Data are taken from:

!P.D. Desai, T.K. Chu, H.M. James and C.Y. Ho, J. Phys. Ref. Data,

!vol 13, no. 4, p1069 (1984).

!

!NOTE 2 - data below 60K is for Ta with a residual resistivity of 0.1×10^{-8} ohm-m;

!not corrected for thermal expansion; 2% error.

!

!NOTE 3 - the S.I. system of units is used.

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP, 1, 0., 100., 200.,

MPTEMP, 4, 300., 400., 500.,

MPTEMP, 7, 600., 700., 800.,

MPTEMP, 10, 900., 1000., 1100.,

MPTEMP, 13, 1200., 1300., 1400.,

MPTEMP,	16,	1500.,	1600.,	1700.,
MPTEMP,	19,	1800.,	1900.,	2000.,
MPTEMP,	22,	2100.,	2200.,	2300.,
MPTEMP,	25,	2400.,	2500.,	2600.,

!Electrical resistivity table [ohm m]

MPDATA,RSVX , Ta	, 1,	1.2237E-07,	1.7023E-07,	2.1664E-07,
MPDATA,RSVX , Ta	, 4,	2.6165E-07,	3.0533E-07,	3.4774E-07,
MPDATA,RSVX , Ta	, 7,	3.8895E-07,	4.2902E-07,	4.6802E-07,
MPDATA,RSVX , Ta	, 10,	5.0601E-07,	5.4305E-07,	5.7922E-07,
MPDATA,RSVX , Ta	, 13,	6.1458E-07,	6.4918E-07,	6.8311E-07,
MPDATA,RSVX , Ta	, 16,	7.1641E-07,	7.4916E-07,	7.8142E-07,
MPDATA,RSVX , Ta	, 19,	8.1326E-07,	8.4474E-07,	8.7592E-07,
MPDATA,RSVX , Ta	, 22,	9.0687E-07,	9.3766E-07,	9.6835E-07,
MPDATA,RSVX , Ta	, 25,	9.9900E-07,	1.0297E-06,	1.0605E-06,

!-----

!THERMAL CONDUCTIVITY

!

!NOTE 1 - Data are taken from:

!Thermophysical Properties of Matter, v1, Y.S. Touloukian, R.W. Powell,

!C.Y. Ho & P.G. Klemens, 1970, IFI/Plenum, NY, NY.

!

!NOTE 2 - thermal conductivity is strongly dependent on impurities.

!

!NOTE 3 - error is 5% near RT, 5-10% at others.

!

!NOTE 4 - the S.I. system of units is used.

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	0.,	100.,	200.,
MPTEMP,	4,	300.,	400.,	500.,
MPTEMP,	7,	600.,	700.,	800.,
MPTEMP,	10,	900.,	1000.,	1100.,
MPTEMP,	13,	1200.,	1300.,	1400.,
MPTEMP,	16,	1500.,	1600.,	1700.,
MPTEMP,	19,	1800.,	1900.,	2000.,
MPTEMP,	22,	2100.,	2200.,	2300.,
MPTEMP,	25,	2400.,	2500.,	2600.,

!Thermal conductivity table [W/m°C]

MPDATA,KXX , Ta	, 1,	5.7415E+01,	5.7703E+01,	5.8047E+01,
MPDATA,KXX , Ta	, 4,	5.8503E+01,	5.8887E+01,	5.9279E+01,
MPDATA,KXX , Ta	, 7,	5.9677E+01,	6.0080E+01,	6.0485E+01,
MPDATA,KXX , Ta	, 10,	6.0891E+01,	6.1297E+01,	6.1701E+01,
MPDATA,KXX , Ta	, 13,	6.2100E+01,	6.2494E+01,	6.2880E+01,

MPDATA,KXX ,Ta , 16, 6.3258E+01, 6.3624E+01, 6.3978E+01,
 MPDATA,KXX ,Ta , 19, 6.4318E+01, 6.4642E+01, 6.4948E+01,
 MPDATA,KXX ,Ta , 22, 6.5235E+01, 6.5501E+01, 6.5745E+01,
 MPDATA,KXX ,Ta , 25, 6.5964E+01, 6.6157E+01, 6.6322E+01,

!-----

!EMISSION (hemispherical total emissivity)

!

!NOTE 1 - Data are taken from:

!Thermophysical Properties of Matter, v7, Y.S. Touloukian & D.P. DeWitt,
 !1970, IFI/Plenum, NY, NY.

!

!NOTE 2 - polished; 10% error.

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	727.,	800.,	900.,
MPTEMP,	4,	1000.,	1100.,	1200.,
MPTEMP,	7,	1300.,	1400.,	1500.,
MPTEMP,	10,	1600.,	1700.,	1800.,
MPTEMP,	13,	1900.,	2000.,	2100.,
MPTEMP,	16,	2200.,	2300.,	2400.,
MPTEMP,	19,	2500.,	2600.,	

!Emissivity table [-]

MPDATA,EMIS ,Ta , 1,	1.0811E-01,	1.1867E-01,	1.3273E-01,
MPDATA,EMIS ,Ta , 4,	1.4634E-01,	1.5952E-01,	1.7225E-01,
MPDATA,EMIS ,Ta , 7,	1.8455E-01,	1.9640E-01,	2.0782E-01,
MPDATA,EMIS ,Ta , 10,	2.1879E-01,	2.2932E-01,	2.3942E-01,
MPDATA,EMIS ,Ta , 13,	2.4907E-01,	2.5828E-01,	2.6705E-01,
MPDATA,EMIS ,Ta , 16,	2.7538E-01,	2.8328E-01,	2.9073E-01,
MPDATA,EMIS ,Ta , 19,	2.9774E-01,	3.0431E-01,	

!-----

!DENSITY

!

!NOTE 1 - Data are calculated from the linear expansion.

!

!NOTE 2 - the S.I. system of units is used.

!-----

!Temperature table [°C]

! MPTEMP ! erase previous table

! MPTEMP,	1,	0.,	100.,	200.,
! MPTEMP,	4,	300.,	400.,	500.,
! MPTEMP,	7,	600.,	700.,	800.,

```

! MPTEMP,      10,      900.,      1000.,      1100.,
! MPTEMP,      13,      1200.,      1300.,      1400.,
! MPTEMP,      16,      1500.,      1600.,      1700.,
! MPTEMP,      19,      1800.,      1900.,      2000.,
! MPTEMP,      22,      2100.,      2200.,      2300.,
! MPTEMP,      25,      2400.,      2500.,      2600.,

```

!Density table [kg/m³]

```

! MPDATA,DENS ,Ta   , 1,  1.6606E+04, 1.6574E+04, 1.6542E+04,
! MPDATA,DENS ,Ta   , 4,  1.6509E+04, 1.6475E+04, 1.6441E+04,
! MPDATA,DENS ,Ta   , 7,  1.6406E+04, 1.6371E+04, 1.6336E+04,
! MPDATA,DENS ,Ta   ,10,  1.6300E+04, 1.6264E+04, 1.6227E+04,
! MPDATA,DENS ,Ta   ,13,  1.6190E+04, 1.6152E+04, 1.6113E+04,
! MPDATA,DENS ,Ta   ,16,  1.6072E+04, 1.6031E+04, 1.5987E+04,
! MPDATA,DENS ,Ta   ,19,  1.5942E+04, 1.5894E+04, 1.5843E+04,
! MPDATA,DENS ,Ta   ,22,  1.5789E+04, 1.5731E+04, 1.5668E+04,
! MPDATA,DENS ,Ta   ,25,  1.5601E+04, 1.5528E+04, 1.5448E+04,

```

! --- constant value assigned ---

MP,DENS,Ta,1.5843E+04 !density [kg/m³]

! --- constant value assigned ---

!-----

!SPECIFIC HEAT

!

!NOTE 1 - Data are taken from:

!I. Barin, Thermochemical Data of Pure Substances, pub. VCH, Weinheim (1993)

!

!NOTE 2 - the S.I. system of units is used.

!-----

! MPTEMP ! erase previous table

```

! MPTEMP,      1,      20.,      100.,      200.,
! MPTEMP,      4,      300.,      400.,      500.,
! MPTEMP,      7,      600.,      700.,      800.,
! MPTEMP,     10,      900.,      1000.,      1100.,
! MPTEMP,     13,     1200.,      1300.,      1400.,
! MPTEMP,     16,     1500.,      1600.,      1700.,
! MPTEMP,     19,     1800.,      1900.,      2000.,
! MPTEMP,     22,     2100.,      2200.,      2300.,
! MPTEMP,     25,     2400.,      2500.,      2600.,

```

!Specific heat table [J/kg°C]

```

! MPDATA,C ,Ta   , 1,  1.4046E+02, 1.4229E+02, 1.4429E+02,
! MPDATA,C ,Ta   , 4,  1.4603E+02, 1.4759E+02, 1.4902E+02,

```

```

! MPDATA,C ,Ta , 7, 1.5039E+02, 1.5174E+02, 1.5312E+02,
! MPDATA,C ,Ta , 10, 1.5457E+02, 1.5613E+02, 1.5782E+02,
! MPDATA,C ,Ta , 13, 1.5967E+02, 1.6169E+02, 1.6388E+02,
! MPDATA,C ,Ta , 16, 1.6627E+02, 1.6883E+02, 1.7157E+02,
! MPDATA,C ,Ta , 19, 1.7448E+02, 1.7753E+02, 1.8070E+02,
! MPDATA,C ,Ta , 22, 1.8416E+02, 1.8836E+02, 1.9285E+02,
! MPDATA,C ,Ta , 25, 1.9751E+02, 2.0257E+02, 2.0853E+02,

```

! --- constant value assigned ---

MP,C,Ta,1.8070E+02 !specific heat [J/kg°C]

! --- constant value assigned ---

!-----

!COEFFICIENT OF THERMAL EXPANSION

!

!NOTE 1 - Data are taken from:

!Thermophysical Properties of Matter, v12, Y.S. Touloukian, R.K. Kirby,

! R.E. Taylor & P.D. Desai, 1975, IFI/Plenum, NY, NY.

!

!NOTE 2 - 3% error below 1100K, 5% from 1100-2100K, 10% above 2100K.

!

!NOTE 3 - the S.I. system of units is used.

!-----

!Temperature table [°C]

! MPTEMP ! erase previous table

```

! MPTEMP, 1, 0., 100., 200.,
! MPTEMP, 4, 300., 400., 500.,
! MPTEMP, 7, 600., 700., 800.,
! MPTEMP, 10, 900., 1000., 1100.,
! MPTEMP, 13, 1200., 1300., 1400.,
! MPTEMP, 16, 1500., 1600., 1700.,
! MPTEMP, 19, 1800., 1900., 2000.,
! MPTEMP, 22, 2100., 2200., 2300.,
! MPTEMP, 25, 2400., 2500., 2600.,

```

!Secant coefficient of thermal expansion [1/°C]

```

! MPDATA,ALPX ,Ta , 1, 6.2542E-06, 6.5206E-06, 6.7324E-06,
! MPDATA,ALPX ,Ta , 4, 6.8984E-06, 7.0274E-06, 7.1281E-06,
! MPDATA,ALPX ,Ta , 7, 7.2093E-06, 7.2797E-06, 7.3481E-06,
! MPDATA,ALPX ,Ta , 10, 7.4233E-06, 7.5140E-06, 7.6289E-06,
! MPDATA,ALPX ,Ta , 13, 7.7769E-06, 7.9666E-06, 8.2069E-06,
! MPDATA,ALPX ,Ta , 16, 8.5065E-06, 8.8741E-06, 9.3186E-06,
! MPDATA,ALPX ,Ta , 19, 9.8486E-06, 1.0473E-05, 1.1200E-05,
! MPDATA,ALPX ,Ta , 22, 1.2040E-05, 1.2999E-05, 1.4089E-05,

```

! MPDATA,ALPX ,Ta , 25, 1.5316E-05, 1.6690E-05, 1.8220E-05,

!-----

!ELASTIC MODULUS

!

!NOTE 1 - Data are taken from:

!R. Farraro and R.B. McLellan, Metall. Trans., vol 10A, p1699, (1979);

!above 2100K P.E. Armstrong and H.L. Brown, Trans. AIME, v230, p962 (1964).

!

!NOTE 2 - fully annealed; 3% error.

!

!NOTE 2 - the S.I. system of units is used.

!-----

!Temperature table [°C]

! MPTEMP ! erase previous table

! MPTEMP,	1,	0.,	100.,	200.,
! MPTEMP,	4,	300.,	400.,	500.,
! MPTEMP,	7,	600.,	700.,	800.,
! MPTEMP,	10,	900.,	1000.,	1100.,
! MPTEMP,	13,	1200.,	1300.,	1400.,
! MPTEMP,	16,	1500.,	1600.,	1700.,
! MPTEMP,	19,	1800.,	1900.,	2000.,
! MPTEMP,	22,	2100.,	2200.,	2300.,
! MPTEMP,	25,	2400.,		

!Elastic modulus [Pa]

! MPDATA,EX ,Ta , 1,	1.8328E+11,	1.8220E+11,	1.7904E+11,
! MPDATA,EX ,Ta , 4,	1.7240E+11,	1.6647E+11,	1.6216E+11,
! MPDATA,EX ,Ta , 7,	1.5946E+11,	1.5813E+11,	1.5689E+11,
! MPDATA,EX ,Ta , 10,	1.5563E+11,	1.5434E+11,	1.5302E+11,
! MPDATA,EX ,Ta , 13,	1.5167E+11,	1.5030E+11,	1.4890E+11,
! MPDATA,EX ,Ta , 16,	1.4890E+11,	1.4602E+11,	1.4453E+11,
! MPDATA,EX ,Ta , 19,	1.4302E+11,	1.3980E+11,	1.3472E+11,
! MPDATA,EX ,Ta , 22,	1.3472E+11,	1.2030E+11,	1.1097E+11,
! MPDATA,EX ,Ta , 25,	1.0024E+11,		

!-----

!POISSON'S RATIO

!

!NOTE 1 - Data are taken from:

!calculated from Elastic modulus and Shear modulus: errors may be large.

!

!NOTE 2 - values above 600°C are kept constant to match the temperature table

!used for the Elastic Modulus (this is a constraint imposed by ANSYS)

!

!-----

```

!Temperature table [°C]
! MPTEMP ! erase previous table
! MPTEMP,      1,      0.,      100.,      200.,
! MPTEMP,      4,      300.,      400.,      500.,
! MPTEMP,      7,      600.,      700.,      800.,
! MPTEMP,     10,      900.,     1000.,     1100.,
! MPTEMP,     13,     1200.,     1300.,     1400.,
! MPTEMP,     16,     1500.,     1600.,     1700.,
! MPTEMP,     19,     1800.,     1900.,     2000.,
! MPTEMP,     22,     2100.,     2200.,     2300.,
! MPTEMP,     25,     2400.,

```

```

!Poisson's ratio [-]
! MPDATA,PRXY ,Ta  , 1, 2.7745E-01, 2.7760E-01, 2.7778E-01,
! MPDATA,PRXY ,Ta  , 4, 2.7797E-01, 2.7816E-01, 2.7835E-01,
! MPDATA,PRXY ,Ta  , 7, 2.7853E-01, 2.7868E-01, 2.7868E-01,
! MPDATA,PRXY ,Ta  , 10, 2.7868E-01, 2.7868E-01, 2.7868E-01,
! MPDATA,PRXY ,Ta  , 13, 2.7868E-01, 2.7868E-01, 2.7868E-01,
! MPDATA,PRXY ,Ta  , 16, 2.7868E-01, 2.7868E-01, 2.7868E-01,
! MPDATA,PRXY ,Ta  , 19, 2.7868E-01, 2.7868E-01, 2.7868E-01,
! MPDATA,PRXY ,Ta  , 22, 2.7868E-01, 2.7868E-01, 2.7868E-01,
! MPDATA,PRXY ,Ta  , 25, 2.7868E-01,

```


Appendix G.8 Tantalum additively manufactured (as built)

!-----1-----2-----3-----4-----5-----6-----7-----8

!-----

!Tantalum AM

!-----

!Version 1.0 (Aug 24) by

!Giacomo Voltan

!Proprietà AM

!Resistività elettrica

!Conducibilità termica calcolata con legge di Wiedemann-Franz

!Emissività provini con finitura "as-built"

!-----

/prep7

TaAMab=24 !Material number in the ANSYS library

MPDELE,all,TaAMab

!-----

!ELECTRICAL RESISTIVITY

!

!Experimental data

!Istituto Nazionale di Fisica Nucleare

!Laboratori Nazionali di Legnaro

!

!NOTE 3 - the S.I. system of units is used.

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP, 1, 950., 1000., 1050.,

MPTEMP, 4, 1100., 1150., 1200.,

MPTEMP, 7, 1250., 1300., 1350.,

MPTEMP, 10, 1400., 1450., 1500.,

MPTEMP, 13, 1550., 1600., 1650.,

MPTEMP, 16, 1700., 1750., 1800.,

MPTEMP, 19, 1850., 1900., 1950.,

MPTEMP, 21, 2000., 2050., 2100.,

MPTEMP, 24, 2150., 2200., 2250.,

MPTEMP, 27, 2300., 2350., 2400.,

!Electrical resistivity table [ohm m]

MPDATA,RSVX , TaAMab , 1, 5.9032E-07, 6.0945E-07, 6.2859E-07,

MPDATA,RSVX , TaAMab , 4, 6.4772E-07, 6.6686E-07, 6.8599E-07,

MPDATA,RSVX , TaAMab , 7, 7.0513E-07, 7.2247E-07, 7.4340E-07,

MPDATA,RSVX , TaAMab	, 10,	7.6254E-07,	7.8167E-07,	8.0081E-07,
MPDATA,RSVX , TaAMab	, 13,	8.1995E-07,	8.3908E-07,	8.5822E-07,
MPDATA,RSVX , TaAMab	, 16,	8.7735E-07,	8.9649E-07,	9.1563E-07,
MPDATA,RSVX , TaAMab	, 19,	9.3476E-07,	9.5390E-07,	9.7303E-07,
MPDATA,RSVX , TaAMab	, 21,	9.9217E-07,	1.0113E-06,	1.0304E-06,
MPDATA,RSVX , TaAMab	, 24,	1.0495E-06,	1.0687E-06,	1.0878E-06,
MPDATA,RSVX , TaAMab	, 27,	1.1069E-06,	1.1261E-06,	1.1452E-06,

!-----
!THERMAL CONDUCTIVITY
!
!Data calculated using Wiedemann-Franz law
!Istituto Nazionale di Fisica Nucleare
!Laboratori Nazionali di Legnaro!
!
!NOTE 4 - the S.I. system of units is used.
!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	950.,	1000.,	1050.,
MPTEMP,	4,	1100.,	1150.,	1200.,
MPTEMP,	7,	1250.,	1300.,	1350.,
MPTEMP,	10,	1400.,	1450.,	1500.,
MPTEMP,	13,	1550.,	1600.,	1650.,
MPTEMP,	16,	1700.,	1750.,	1800.,
MPTEMP,	19,	1850.,	1900.,	1950.,
MPTEMP,	21,	2000.,	2050.,	2100.,
MPTEMP,	24,	2150.,	2200.,	2250.,
MPTEMP,	27,	2300.,	2350.,	2400.,

!Thermal conductivity table [W/m°C]

MPDATA,KXX , TaAMab	, 1,	5.0639E+01,	5.0934E+01,	5.1228E+01,
MPDATA,KXX , TaAMab	, 4,	5.1523E+01,	5.1817E+01,	5.2111E+01,
MPDATA,KXX , TaAMab	, 7,	5.2406E+01,	5.2700E+01,	5.2995E+01,
MPDATA,KXX , TaAMab	, 10,	5.3289E+01,	5.3584E+01,	5.3878E+01,
MPDATA,KXX , TaAMab	, 13,	5.4172E+01,	5.4467E+01,	5.4761E+01,
MPDATA,KXX , TaAMab	, 16,	5.5056E+01,	5.5350E+01,	5.5644E+01,
MPDATA,KXX , TaAMab	, 19,	5.5939E+01,	5.6233E+01,	5.6528E+01,
MPDATA,KXX , TaAMab	, 21,	5.6822E+01,	5.7116E+01,	5.7411E+01,
MPDATA,KXX , TaAMab	, 24,	5.7705E+01,	5.8000E+01,	5.8294E+01,
MPDATA,KXX , TaAMab	, 27,	5.8589E+01,	5.8883E+01,	5.9177E+01,

!-----
!EMISSIVITY (hemispherical total emissivity)
!
!Experimental data

!Istituto Nazionale di Fisica Nucleare

!Laboratori Nazionali di Legnaro

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	950.,	1000.,	1050.,
MPTEMP,	4,	1100.,	1150.,	1200.,
MPTEMP,	7,	1250.,	1300.,	1350.,
MPTEMP,	10,	1400.,	1450.,	1500.,
MPTEMP,	13,	1550.,	1600.,	1650.,
MPTEMP,	16,	1700.,	1750.,	1800.,
MPTEMP,	19,	1850.,	1900.,	1950.,
MPTEMP,	21,	2000.,	2050.,	2100.,
MPTEMP,	24,	2150.,	2200.,	2250.,
MPTEMP,	27,	2300.,	2350.,	2400.,

!Emissivity table [-]

MPDATA,EMIS , TaAMab	, 1,	1.8147E-01,	1.8866E-01,	1.9631E-01,
MPDATA,EMIS , TaAMab	, 4,	2.0426E-01,	2.1305E-01,	2.2217E-01,
MPDATA,EMIS , TaAMab	, 7,	2.3164E-01,	2.4125E-01,	2.5177E-01,
MPDATA,EMIS , TaAMab	, 10,	2.6206E-01,	2.7328E-01,	2.8507E-01,
MPDATA,EMIS , TaAMab	, 13,	2.9700E-01,	3.0907E-01,	3.2113E-01,
MPDATA,EMIS , TaAMab	, 16,	3.3320E-01,	3.4526E-01,	3.5800E-01,
MPDATA,EMIS , TaAMab	, 19,	3.7074E-01,	3.8347E-01,	3.9621E-01,
MPDATA,EMIS , TaAMab	, 21,	4.0900E-01,	4.2179E-01,	4.3459E-01,
MPDATA,EMIS , TaAMab	, 24,	4.4738E-01,	4.6017E-01,	4.7456E-01,
MPDATA,EMIS , TaAMab	, 27,	4.8896E-01,	5.0335E-01,	5.1774E-01,

!-----

!DENSITY

!

!NOTE 1 - Data are calculated from the linear expansion.

!

!NOTE 2 - the S.I. system of units is used.

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	0.,	100.,	200.,
MPTEMP,	4,	300.,	400.,	500.,
MPTEMP,	7,	600.,	700.,	800.,
MPTEMP,	10,	900.,	1000.,	1100.,
MPTEMP,	13,	1200.,	1300.,	1400.,
MPTEMP,	16,	1500.,	1600.,	1700.,
MPTEMP,	19,	1800.,	1900.,	2000.,
MPTEMP,	22,	2100.,	2200.,	2300.,
MPTEMP,	25,	2400.,	2500.,	2600.,

!Density table [kg/m³]

MPDATA,DENS , TaAMab	, 1,	1.6606E+04,	1.6574E+04,	1.6542E+04,
MPDATA,DENS , TaAMab	, 4,	1.6509E+04,	1.6475E+04,	1.6441E+04,
MPDATA,DENS , TaAMab	, 7,	1.6406E+04,	1.6371E+04,	1.6336E+04,
MPDATA,DENS , TaAMab	, 10,	1.6300E+04,	1.6264E+04,	1.6227E+04,
MPDATA,DENS , TaAMab	, 13,	1.6190E+04,	1.6152E+04,	1.6113E+04,
MPDATA,DENS , TaAMab	, 16,	1.6072E+04,	1.6031E+04,	1.5987E+04,
MPDATA,DENS , TaAMab	, 19,	1.5942E+04,	1.5894E+04,	1.5843E+04,
MPDATA,DENS , TaAMab	, 22,	1.5789E+04,	1.5731E+04,	1.5668E+04,
MPDATA,DENS , TaAMab	, 25,	1.5601E+04,	1.5528E+04,	1.5448E+04,

!-----

!SPECIFIC HEAT

!

!NOTE 1 - Data are taken from:

!I. Barin, Thermochemical Data of Pure Substances, pub. VCH, Weinheim (1993)

!

!NOTE 2 - the S.I. system of units is used.

!-----

MPTEMP ! erase previous table

MPTEMP,	1,	20.,	100.,	200.,
MPTEMP,	4,	300.,	400.,	500.,
MPTEMP,	7,	600.,	700.,	800.,
MPTEMP,	10,	900.,	1000.,	1100.,
MPTEMP,	13,	1200.,	1300.,	1400.,
MPTEMP,	16,	1500.,	1600.,	1700.,
MPTEMP,	19,	1800.,	1900.,	2000.,
MPTEMP,	22,	2100.,	2200.,	2300.,
MPTEMP,	25,	2400.,	2500.,	2600.,

!Specific heat table [J/kg·C]

MPDATA,C , TaAMab	, 1,	1.4046E+02,	1.4229E+02,	1.4429E+02,
MPDATA,C , TaAMab	, 4,	1.4603E+02,	1.4759E+02,	1.4902E+02,
MPDATA,C , TaAMab	, 7,	1.5039E+02,	1.5174E+02,	1.5312E+02,
MPDATA,C , TaAMab	, 10,	1.5457E+02,	1.5613E+02,	1.5782E+02,
MPDATA,C , TaAMab	, 13,	1.5967E+02,	1.6169E+02,	1.6388E+02,
MPDATA,C , TaAMab	, 16,	1.6627E+02,	1.6883E+02,	1.7157E+02,
MPDATA,C , TaAMab	, 19,	1.7448E+02,	1.7753E+02,	1.8070E+02,
MPDATA,C , TaAMab	, 22,	1.8416E+02,	1.8836E+02,	1.9285E+02,
MPDATA,C , TaAMab	, 25,	1.9751E+02,	2.0257E+02,	2.0853E+02,

!-----

!COEFFICIENT OF THERMAL EXPANSION

!

!NOTE 1 - Data are taken from:

!Thermophysical Properties of Matter, v12, Y.S. Touloukian, R.K. Kirby,
! R.E. Taylor & P.D. Desai, 1975, IFI/Plenum, NY, NY.

!

!NOTE 2 - 3% error below 1100K, 5% from 1100-2100K, 10% above 2100K.

!

!NOTE 3 - the S.I. system of units is used.

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	0.,	100.,	200.,
MPTEMP,	4,	300.,	400.,	500.,
MPTEMP,	7,	600.,	700.,	800.,
MPTEMP,	10,	900.,	1000.,	1100.,
MPTEMP,	13,	1200.,	1300.,	1400.,
MPTEMP,	16,	1500.,	1600.,	1700.,
MPTEMP,	19,	1800.,	1900.,	2000.,
MPTEMP,	22,	2100.,	2200.,	2300.,
MPTEMP,	25,	2400.,	2500.,	2600.,

!Secant coefficient of thermal expansion [1/°C]

MPDATA,ALPX ,TaAMab	, 1,	6.2542E-06,	6.5206E-06,	6.7324E-06,
MPDATA,ALPX ,TaAMab	, 4,	6.8984E-06,	7.0274E-06,	7.1281E-06,
MPDATA,ALPX ,TaAMab	, 7,	7.2093E-06,	7.2797E-06,	7.3481E-06,
MPDATA,ALPX ,TaAMab	, 10,	7.4233E-06,	7.5140E-06,	7.6289E-06,
MPDATA,ALPX ,TaAMab	, 13,	7.7769E-06,	7.9666E-06,	8.2069E-06,
MPDATA,ALPX ,TaAMab	, 16,	8.5065E-06,	8.8741E-06,	9.3186E-06,
MPDATA,ALPX ,TaAMab	, 19,	9.8486E-06,	1.0473E-05,	1.1200E-05,
MPDATA,ALPX ,TaAMab	, 22,	1.2040E-05,	1.2999E-05,	1.4089E-05,
MPDATA,ALPX ,TaAMab	, 25,	1.5316E-05,	1.6690E-05,	1.8220E-05,

!-----

!ELASTIC MODULUS

!

!NOTE 1 - Data are taken from:

!R. Farraro and R.B. McLellan, Metall. Trans., vol 10A, p1699, (1979);

!above 2100K P.E. Armstrong and H.L. Brown, Trans. AIME, v230, p962 (1964).

!

!NOTE 2 - fully annealed; 3% error.

!

!NOTE 2 - the S.I. system of units is used.

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	0.,	100.,	200.,
MPTEMP,	4,	300.,	400.,	500.,
MPTEMP,	7,	600.,	700.,	800.,

MPTEMP,	10,	900.,	1000.,	1100.,
MPTEMP,	13,	1200.,	1300.,	1400.,
MPTEMP,	16,	1500.,	1600.,	1700.,
MPTEMP,	19,	1800.,	1900.,	2000.,
MPTEMP,	22,	2100.,	2200.,	2300.,
MPTEMP,	25,	2400.,		

!Elastic modulus [Pa]

MPDATA,EX ,TaAMab	, 1,	1.8328E+11,	1.8220E+11,	1.7904E+11,
MPDATA,EX ,TaAMab	, 4,	1.7240E+11,	1.6647E+11,	1.6216E+11,
MPDATA,EX ,TaAMab	, 7,	1.5946E+11,	1.5813E+11,	1.5689E+11,
MPDATA,EX ,TaAMab	, 10,	1.5563E+11,	1.5434E+11,	1.5302E+11,
MPDATA,EX ,TaAMab	, 13,	1.5167E+11,	1.5030E+11,	1.4890E+11,
MPDATA,EX ,TaAMab	, 16,	1.4890E+11,	1.4602E+11,	1.4453E+11,
MPDATA,EX ,TaAMab	, 19,	1.4302E+11,	1.3980E+11,	1.3472E+11,
MPDATA,EX ,TaAMab	, 22,	1.3472E+11,	1.2030E+11,	1.1097E+11,
MPDATA,EX ,TaAMab	, 25,	1.0024E+11,		

!-----

!POISSON'S RATIO

!

!NOTE 1 - Data are taken from:

!calculated from Elastic modulus and Shear modulus: errors may be large.

!

!NOTE 2 - values above 600°C are kept constant to match the temperature table
!used for the Elastic Modulus (this is a constraint imposed by ANSYS)

!

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	0.,	100.,	200.,
MPTEMP,	4,	300.,	400.,	500.,
MPTEMP,	7,	600.,	700.,	800.,
MPTEMP,	10,	900.,	1000.,	1100.,
MPTEMP,	13,	1200.,	1300.,	1400.,
MPTEMP,	16,	1500.,	1600.,	1700.,
MPTEMP,	19,	1800.,	1900.,	2000.,
MPTEMP,	22,	2100.,	2200.,	2300.,
MPTEMP,	25,	2400.,		

!Poisson's ratio [-]

MPDATA,PRXY ,TaAMab	, 1,	2.7745E-01,	2.7760E-01,	2.7778E-01,
MPDATA,PRXY ,TaAMab	, 4,	2.7797E-01,	2.7816E-01,	2.7835E-01,
MPDATA,PRXY ,TaAMab	, 7,	2.7853E-01,	2.7868E-01,	2.7868E-01,
MPDATA,PRXY ,TaAMab	, 10,	2.7868E-01,	2.7868E-01,	2.7868E-01,
MPDATA,PRXY ,TaAMab	, 13,	2.7868E-01,	2.7868E-01,	2.7868E-01,
MPDATA,PRXY ,TaAMab	, 16,	2.7868E-01,	2.7868E-01,	2.7868E-01,

MPDATA,PRXY,TaAMab,19,2.7868E-01,2.7868E-01,2.7868E-01,
MPDATA,PRXY,TaAMab,22,2.7868E-01,2.7868E-01,2.7868E-01,
MPDATA,PRXY,TaAMab,25,2.7868E-01,

Appendix G.9 Tantalum additively manufactured (polished)

!-----1-----2-----3-----4-----5-----6-----7-----8

!-----

!Tantalum AM

!-----

!Version 1.1 (Aug 24) by

!Giacomo Voltan

!Proprietà AM

!Resistività elettrica

!Conducibilità termica calcolata con legge di Wiedemann-Franz

!Emissività provini con finitura polished

!-----

/prep7

TaAMp=25 !Material number in the ANSYS library

MPDELE,all,TaAMp

!-----

!ELECTRICAL RESISTIVITY

!

!Experimental data

!Istituto Nazionale di Fisica Nucleare

!Laboratori Nazionali di Legnaro

!

!NOTE 3 - the S.I. system of units is used.

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP, 1, 950., 1000., 1050.,

MPTEMP, 4, 1100., 1150., 1200.,

MPTEMP, 7, 1250., 1300., 1350.,

MPTEMP, 10, 1400., 1450., 1500.,

MPTEMP, 13, 1550., 1600., 1650.,

MPTEMP, 16, 1700., 1750., 1800.,

MPTEMP, 19, 1850., 1900., 1950.,

MPTEMP, 21, 2000., 2050., 2100.,

MPTEMP, 24, 2150., 2200., 2250.,

MPTEMP, 27, 2300., 2350., 2400.,

!Electrical resistivity table [ohm m]

MPDATA,RSVX , TaAMp , 1, 5.9032E-07, 6.0945E-07, 6.2859E-07,

MPDATA,RSVX , TaAMp , 4, 6.4772E-07, 6.6686E-07, 6.8599E-07,

MPDATA,RSVX , TaAMp , 7, 7.0513E-07, 7.2247E-07, 7.4340E-07,

MPDATA,RSVX , TaAMp	, 10,	7.6254E-07,	7.8167E-07,	8.0081E-07,
MPDATA,RSVX , TaAMp	, 13,	8.1995E-07,	8.3908E-07,	8.5822E-07,
MPDATA,RSVX , TaAMp	, 16,	8.7735E-07,	8.9649E-07,	9.1563E-07,
MPDATA,RSVX , TaAMp	, 19,	9.3476E-07,	9.5390E-07,	9.7303E-07,
MPDATA,RSVX , TaAMp	, 21,	9.9217E-07,	1.0113E-06,	1.0304E-06,
MPDATA,RSVX , TaAMp	, 24,	1.0495E-06,	1.0687E-06,	1.0878E-06,
MPDATA,RSVX , TaAMp	, 27,	1.1069E-06,	1.1261E-06,	1.1452E-06,

!-----

!THERMAL CONDUCTIVITY

!

!Data calculated using Wiedemann-Franz law

!Istituto Nazionale di Fisica Nucleare

!Laboratori Nazionali di Legnaro!

!

!NOTE 4 - the S.I. system of units is used.

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	950.,	1000.,	1050.,
MPTEMP,	4,	1100.,	1150.,	1200.,
MPTEMP,	7,	1250.,	1300.,	1350.,
MPTEMP,	10,	1400.,	1450.,	1500.,
MPTEMP,	13,	1550.,	1600.,	1650.,
MPTEMP,	16,	1700.,	1750.,	1800.,
MPTEMP,	19,	1850.,	1900.,	1950.,
MPTEMP,	21,	2000.,	2050.,	2100.,
MPTEMP,	24,	2150.,	2200.,	2250.,
MPTEMP,	27,	2300.,	2350.,	2400.,

!Thermal conductivity table [W/m°C]

MPDATA,KXX , TaAMp	, 1,	5.0639E+01,	5.0934E+01,	5.1228E+01,
MPDATA,KXX , TaAMp	, 4,	5.1523E+01,	5.1817E+01,	5.2111E+01,
MPDATA,KXX , TaAMp	, 7,	5.2406E+01,	5.2700E+01,	5.2995E+01,
MPDATA,KXX , TaAMp	, 10,	5.3289E+01,	5.3584E+01,	5.3878E+01,
MPDATA,KXX , TaAMp	, 13,	5.4172E+01,	5.4467E+01,	5.4761E+01,
MPDATA,KXX , TaAMp	, 16,	5.5056E+01,	5.5350E+01,	5.5644E+01,
MPDATA,KXX , TaAMp	, 19,	5.5939E+01,	5.6233E+01,	5.6528E+01,
MPDATA,KXX , TaAMp	, 21,	5.6822E+01,	5.7116E+01,	5.7411E+01,
MPDATA,KXX , TaAMp	, 24,	5.7705E+01,	5.8000E+01,	5.8294E+01,
MPDATA,KXX , TaAMp	, 27,	5.8589E+01,	5.8883E+01,	5.9177E+01,

!-----

!EMISSIVITY (hemispherical total emissivity)

!

!Experimental data

!Istituto Nazionale di Fisica Nucleare

!Laboratori Nazionali di Legnaro

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	950.,	1000.,	1050.,
MPTEMP,	4,	1100.,	1150.,	1200.,
MPTEMP,	7,	1250.,	1300.,	1350.,
MPTEMP,	10,	1400.,	1450.,	1500.,
MPTEMP,	13,	1550.,	1600.,	1650.,
MPTEMP,	16,	1700.,	1750.,	1800.,
MPTEMP,	19,	1850.,	1900.,	1950.,
MPTEMP,	21,	2000.,	2050.,	2100.,
MPTEMP,	24,	2150.,	2200.,	2250.,
MPTEMP,	27,	2300.,	2350.,	2400.,

!Emissivity table [-]

MPDATA,EMIS ,TaAMp	, 1,	7.4202E-02,	7.8827E-02,	8.3664E-02,
MPDATA,EMIS ,TaAMp	, 4,	8.8717E-02,	9.3991E-02,	9.9490E-02,
MPDATA,EMIS ,TaAMp	, 7,	1.0522E-01,	1.1146E-01,	1.1767E-01,
MPDATA,EMIS ,TaAMp	, 10,	1.2442E-01,	1.3172E-01,	1.3933E-01,
MPDATA,EMIS ,TaAMp	, 13,	1.4715E-01,	1.5528E-01,	1.6321E-01,
MPDATA,EMIS ,TaAMp	, 16,	1.7119E-01,	1.7917E-01,	1.8714E-01,
MPDATA,EMIS ,TaAMp	, 19,	1.9512E-01,	2.0310E-01,	2.1207E-01,
MPDATA,EMIS ,TaAMp	, 21,	2.2105E-01,	2.3103E-01,	2.4101E-01,
MPDATA,EMIS ,TaAMp	, 24,	2.5098E-01,	2.6096E-01,	2.7094E-01,
MPDATA,EMIS ,TaAMp	, 27,	2.8192E-01,	2.9289E-01,	3.0487E-01,

!-----

IDENSITY

!

!NOTE 1 - Data are calculated from the linear expansion.

!

!NOTE 2 - the S.I. system of units is used.

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	0.,	100.,	200.,
MPTEMP,	4,	300.,	400.,	500.,
MPTEMP,	7,	600.,	700.,	800.,
MPTEMP,	10,	900.,	1000.,	1100.,
MPTEMP,	13,	1200.,	1300.,	1400.,
MPTEMP,	16,	1500.,	1600.,	1700.,
MPTEMP,	19,	1800.,	1900.,	2000.,
MPTEMP,	22,	2100.,	2200.,	2300.,
MPTEMP,	25,	2400.,	2500.,	2600.,

!Density table [kg/m³]

MPDATA,DENS ,TaAMp	, 1,	1.6606E+04,	1.6574E+04,	1.6542E+04,
MPDATA,DENS ,TaAMp	, 4,	1.6509E+04,	1.6475E+04,	1.6441E+04,
MPDATA,DENS ,TaAMp	, 7,	1.6406E+04,	1.6371E+04,	1.6336E+04,
MPDATA,DENS ,TaAMp	, 10,	1.6300E+04,	1.6264E+04,	1.6227E+04,
MPDATA,DENS ,TaAMp	, 13,	1.6190E+04,	1.6152E+04,	1.6113E+04,
MPDATA,DENS ,TaAMp	, 16,	1.6072E+04,	1.6031E+04,	1.5987E+04,
MPDATA,DENS ,TaAMp	, 19,	1.5942E+04,	1.5894E+04,	1.5843E+04,
MPDATA,DENS ,TaAMp	, 22,	1.5789E+04,	1.5731E+04,	1.5668E+04,
MPDATA,DENS ,TaAMp	, 25,	1.5601E+04,	1.5528E+04,	1.5448E+04,

!-----

!SPECIFIC HEAT

!

!NOTE 1 - Data are taken from:

!I. Barin, Thermochemical Data of Pure Substances, pub. VCH, Weinheim (1993)

!

!NOTE 2 - the S.I. system of units is used.

!-----

MPTEMP ! erase previous table

MPTEMP,	1,	20.,	100.,	200.,
MPTEMP,	4,	300.,	400.,	500.,
MPTEMP,	7,	600.,	700.,	800.,
MPTEMP,	10,	900.,	1000.,	1100.,
MPTEMP,	13,	1200.,	1300.,	1400.,
MPTEMP,	16,	1500.,	1600.,	1700.,
MPTEMP,	19,	1800.,	1900.,	2000.,
MPTEMP,	22,	2100.,	2200.,	2300.,
MPTEMP,	25,	2400.,	2500.,	2600.,

!Specific heat table [J/kg·C]

MPDATA,C ,TaAMp	, 1,	1.4046E+02,	1.4229E+02,	1.4429E+02,
MPDATA,C ,TaAMp	, 4,	1.4603E+02,	1.4759E+02,	1.4902E+02,
MPDATA,C ,TaAMp	, 7,	1.5039E+02,	1.5174E+02,	1.5312E+02,
MPDATA,C ,TaAMp	, 10,	1.5457E+02,	1.5613E+02,	1.5782E+02,
MPDATA,C ,TaAMp	, 13,	1.5967E+02,	1.6169E+02,	1.6388E+02,
MPDATA,C ,TaAMp	, 16,	1.6627E+02,	1.6883E+02,	1.7157E+02,
MPDATA,C ,TaAMp	, 19,	1.7448E+02,	1.7753E+02,	1.8070E+02,
MPDATA,C ,TaAMp	, 22,	1.8416E+02,	1.8836E+02,	1.9285E+02,
MPDATA,C ,TaAMp	, 25,	1.9751E+02,	2.0257E+02,	2.0853E+02,

!-----

!COEFFICIENT OF THERMAL EXPANSION

!

!NOTE 1 - Data are taken from:

!Thermophysical Properties of Matter, v12, Y.S. Touloukian, R.K. Kirby,
! R.E. Taylor & P.D. Desai, 1975, IFI/Plenum, NY, NY.
!
!NOTE 2 - 3% error below 1100K, 5% from 1100-2100K, 10% above 2100K.
!
!NOTE 3 - the S.I. system of units is used.
!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	0.,	100.,	200.,
MPTEMP,	4,	300.,	400.,	500.,
MPTEMP,	7,	600.,	700.,	800.,
MPTEMP,	10,	900.,	1000.,	1100.,
MPTEMP,	13,	1200.,	1300.,	1400.,
MPTEMP,	16,	1500.,	1600.,	1700.,
MPTEMP,	19,	1800.,	1900.,	2000.,
MPTEMP,	22,	2100.,	2200.,	2300.,
MPTEMP,	25,	2400.,	2500.,	2600.,

!Secant coefficient of thermal expansion [1/°C]

MPDATA,ALPX ,TaAMp	, 1,	6.2542E-06,	6.5206E-06,	6.7324E-06,
MPDATA,ALPX ,TaAMp	, 4,	6.8984E-06,	7.0274E-06,	7.1281E-06,
MPDATA,ALPX ,TaAMp	, 7,	7.2093E-06,	7.2797E-06,	7.3481E-06,
MPDATA,ALPX ,TaAMp	, 10,	7.4233E-06,	7.5140E-06,	7.6289E-06,
MPDATA,ALPX ,TaAMp	, 13,	7.7769E-06,	7.9666E-06,	8.2069E-06,
MPDATA,ALPX ,TaAMp	, 16,	8.5065E-06,	8.8741E-06,	9.3186E-06,
MPDATA,ALPX ,TaAMp	, 19,	9.8486E-06,	1.0473E-05,	1.1200E-05,
MPDATA,ALPX ,TaAMp	, 22,	1.2040E-05,	1.2999E-05,	1.4089E-05,
MPDATA,ALPX ,TaAMp	, 25,	1.5316E-05,	1.6690E-05,	1.8220E-05,

!-----

!ELASTIC MODULUS

!

!NOTE 1 - Data are taken from:

!R. Farraro and R.B. McLellan, Metall. Trans., vol 10A, p1699, (1979);

!above 2100K P.E. Armstrong and H.L. Brown, Trans. AIME, v230, p962 (1964).

!

!NOTE 2 - fully annealed; 3% error.

!

!NOTE 2 - the S.I. system of units is used.

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	0.,	100.,	200.,
MPTEMP,	4,	300.,	400.,	500.,
MPTEMP,	7,	600.,	700.,	800.,

MPTEMP,	10,	900.,	1000.,	1100.,
MPTEMP,	13,	1200.,	1300.,	1400.,
MPTEMP,	16,	1500.,	1600.,	1700.,
MPTEMP,	19,	1800.,	1900.,	2000.,
MPTEMP,	22,	2100.,	2200.,	2300.,
MPTEMP,	25,	2400.,		

!Elastic modulus [Pa]

MPDATA,EX , TaAMp	, 1,	1.8328E+11,	1.8220E+11,	1.7904E+11,
MPDATA,EX , TaAMp	, 4,	1.7240E+11,	1.6647E+11,	1.6216E+11,
MPDATA,EX , TaAMp	, 7,	1.5946E+11,	1.5813E+11,	1.5689E+11,
MPDATA,EX , TaAMp	, 10,	1.5563E+11,	1.5434E+11,	1.5302E+11,
MPDATA,EX , TaAMp	, 13,	1.5167E+11,	1.5030E+11,	1.4890E+11,
MPDATA,EX , TaAMp	, 16,	1.4890E+11,	1.4602E+11,	1.4453E+11,
MPDATA,EX , TaAMp	, 19,	1.4302E+11,	1.3980E+11,	1.3472E+11,
MPDATA,EX , TaAMp	, 22,	1.3472E+11,	1.2030E+11,	1.1097E+11,
MPDATA,EX , TaAMp	, 25,	1.0024E+11,		

!-----

!POISSON'S RATIO

!

!NOTE 1 - Data are taken from:

!calculated from Elastic modulus and Shear modulus: errors may be large.

!

!NOTE 2 - values above 600°C are kept constant to match the temperature table

!used for the Elastic Modulus (this is a constraint imposed by ANSYS)

!

!-----

!Temperature table [°C]

MPTEMP ! erase previous table

MPTEMP,	1,	0.,	100.,	200.,
MPTEMP,	4,	300.,	400.,	500.,
MPTEMP,	7,	600.,	700.,	800.,
MPTEMP,	10,	900.,	1000.,	1100.,
MPTEMP,	13,	1200.,	1300.,	1400.,
MPTEMP,	16,	1500.,	1600.,	1700.,
MPTEMP,	19,	1800.,	1900.,	2000.,
MPTEMP,	22,	2100.,	2200.,	2300.,
MPTEMP,	25,	2400.,		

!Poisson's ratio [-]

MPDATA,PRXY , TaAMp	, 1,	2.7745E-01,	2.7760E-01,	2.7778E-01,
MPDATA,PRXY , TaAMp	, 4,	2.7797E-01,	2.7816E-01,	2.7835E-01,
MPDATA,PRXY , TaAMp	, 7,	2.7853E-01,	2.7868E-01,	2.7868E-01,
MPDATA,PRXY , TaAMp	, 10,	2.7868E-01,	2.7868E-01,	2.7868E-01,
MPDATA,PRXY , TaAMp	, 13,	2.7868E-01,	2.7868E-01,	2.7868E-01,
MPDATA,PRXY , TaAMp	, 16,	2.7868E-01,	2.7868E-01,	2.7868E-01,

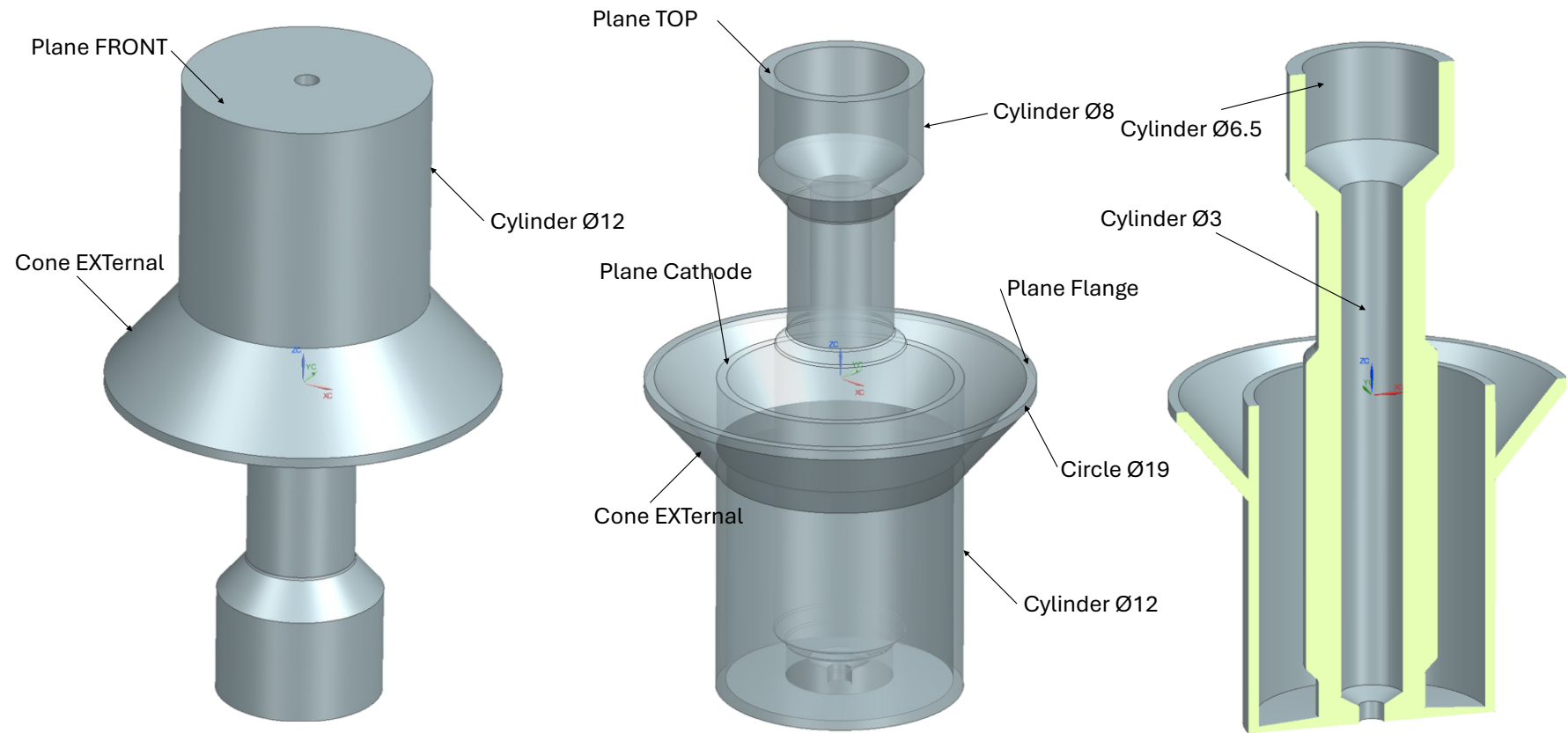
MPDATA,PRXY,TaAMp , 19, 2.7868E-01, 2.7868E-01, 2.7868E-01,
MPDATA,PRXY,TaAMp , 22, 2.7868E-01, 2.7868E-01, 2.7868E-01,
MPDATA,PRXY,TaAMp , 25, 2.7868E-01,

Appendix H CMM measurements

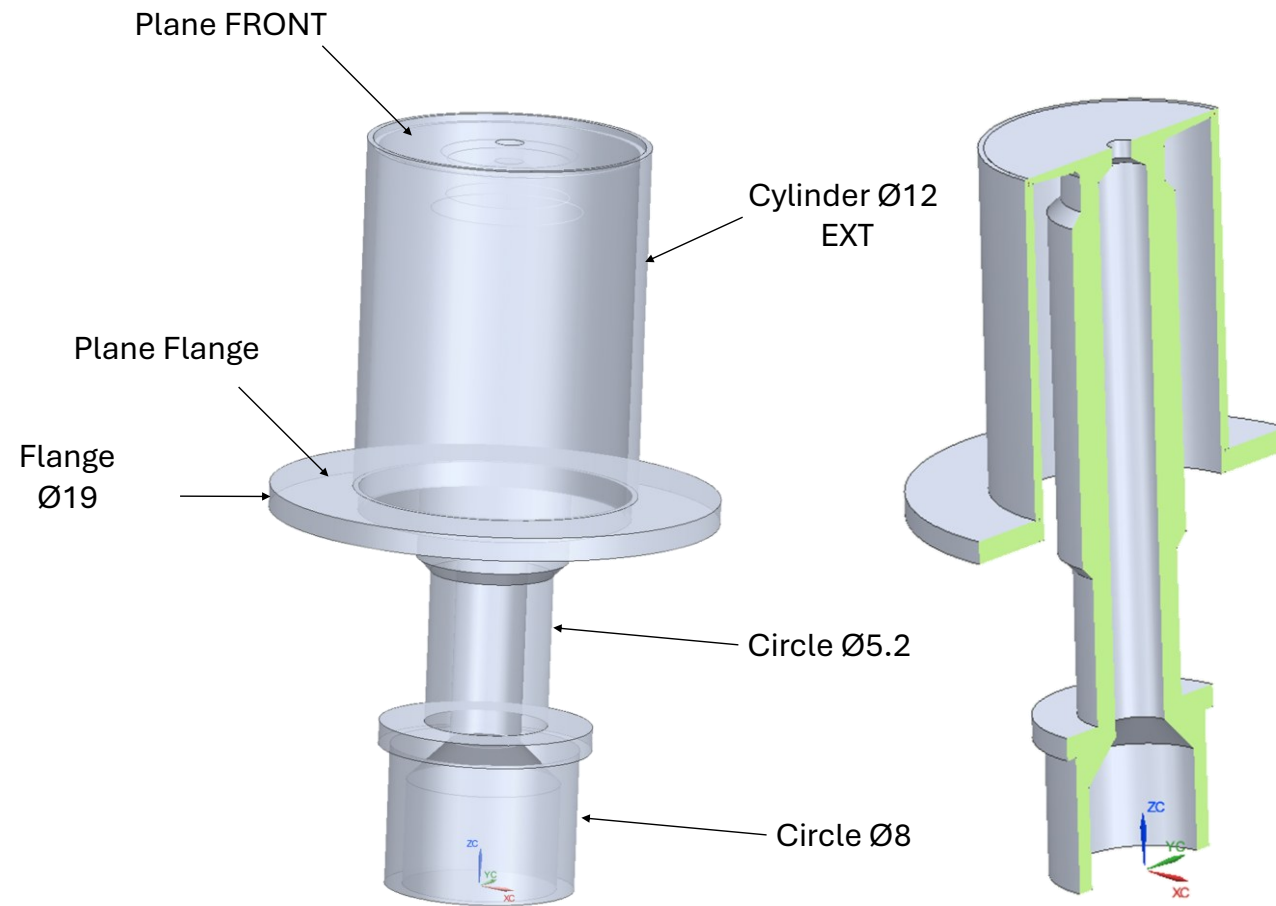
Appendix H.1 Comparison between STD and LPBF_conv cathodes

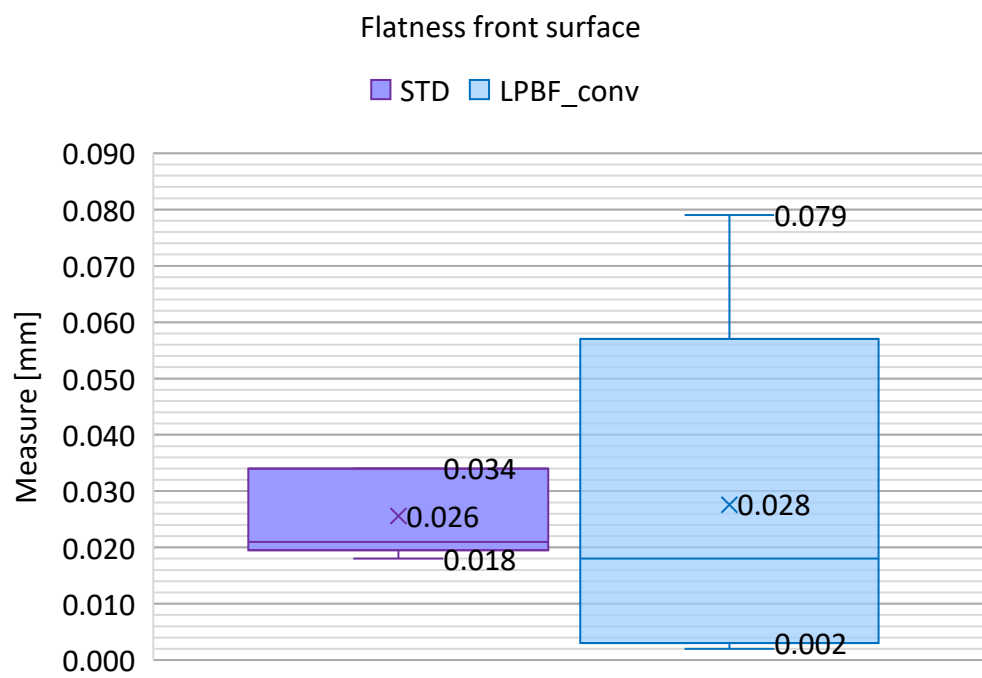
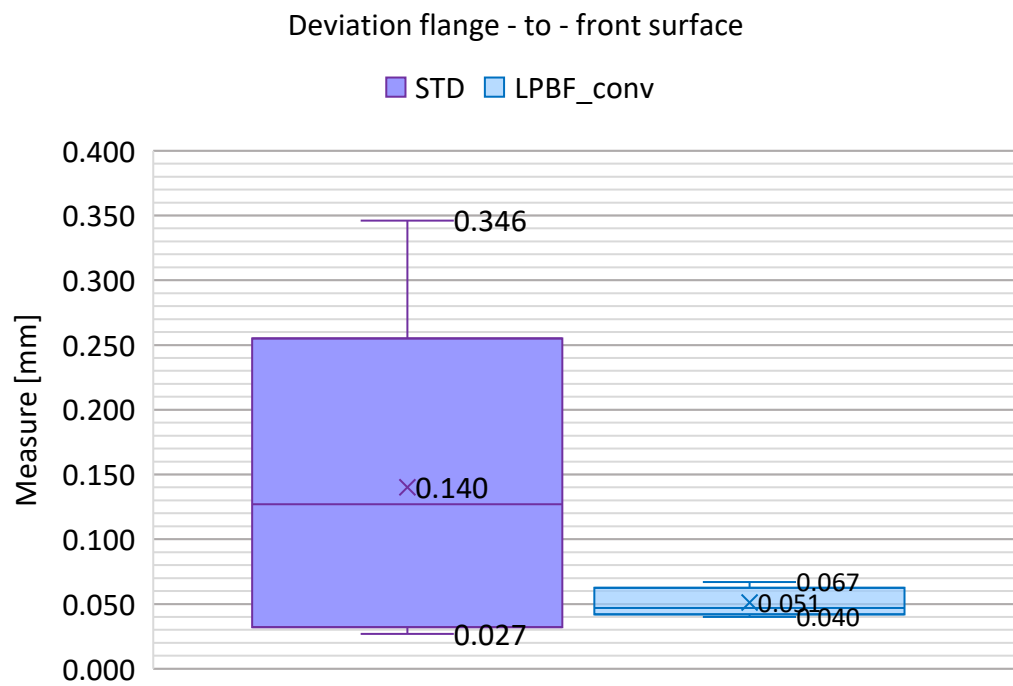
Feature	LPBF					STD				
	Cathode 0	Cathode 1	Cathode 2	Cathode 3	Cathode 4	Cathode 0	Cathode 1	Cathode 2	Cathode 3	Cathode 4
Diameter cylinder Ø3	2.933	2.938	2.875	2.943	2.944	-	-	-	-	-
Diameter cylinder Ø6.5	6.436	6.468	6.440	6.437	6.448	-	-	-	-	-
Diameter cylinder Ø8	8.010	7.973	7.992	8.005	7.999	-	-	-	-	-
Diameter cylinder Ø12	12.021	12.014	11.989	11.993	11.988	12.016	12.036	12.016	12.029	12.034
Deviation cylinder Ø12	0.021	0.014	-0.011	-0.007	-0.012	0.016	0.036	0.016	0.029	0.034
Diameter cylinder Ø19	19.016	19.002	18.977	19.002	18.996	-	-	-	-	-
Roundness cylinder Ø19	0.041	0.038	0.026	0.035	0.042	0.033	0.051	0.053	0.110	0.041
Cylindricity cylinder Ø12	0.029	0.020	0.026	0.020	0.028	0.039	0.030	0.039	0.052	0.019
Concentricity Ø19-Ø8	0.032	0.030	0.525	0.039	0.125	0.058	0.108	0.057	0.035	0.068
Flatness flange	0.034	0.035	0.109	0.027	0.033	0.154	0.031	0.043	0.045	0.103
Flange to front distance	16.044	16.067	15.960	16.047	15.942	15.027	15.037	14.836	15.127	15.346
Displacement flange to front distance	0.044	0.067	0.040	0.047	0.058	0.027	0.037	0.164	0.127	0.346
Flatness front	0.004	0.002	0.079	0.018	0.035	0.021	0.034	0.018	0.021	0.034
Perpendicularity front - cyl Ø12	0.036	0.005	0.029	0.012	0.040	0.210	0.168	0.057	0.034	0.068
Cone angle	79.64	79.46	79.63	79.84	79.98	-	-	-	-	-

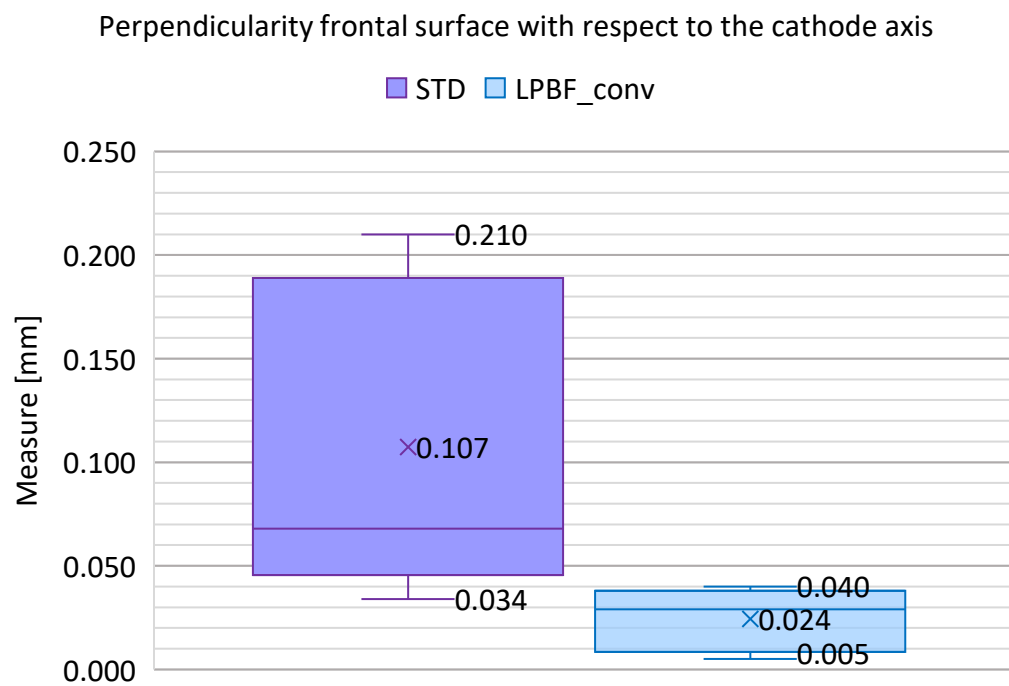
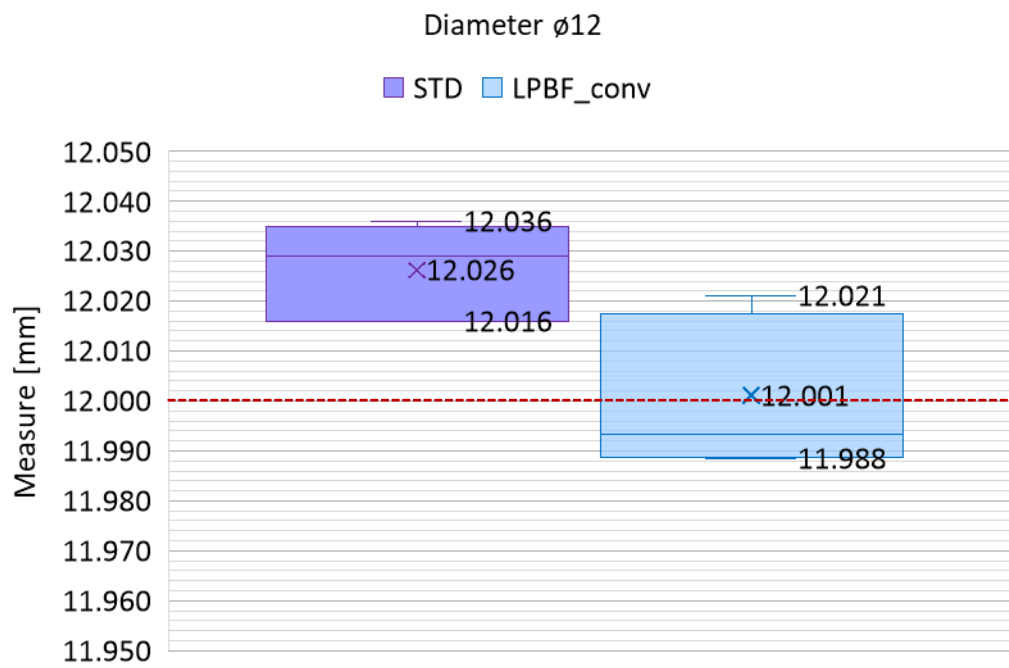
LPBF_conv cathode

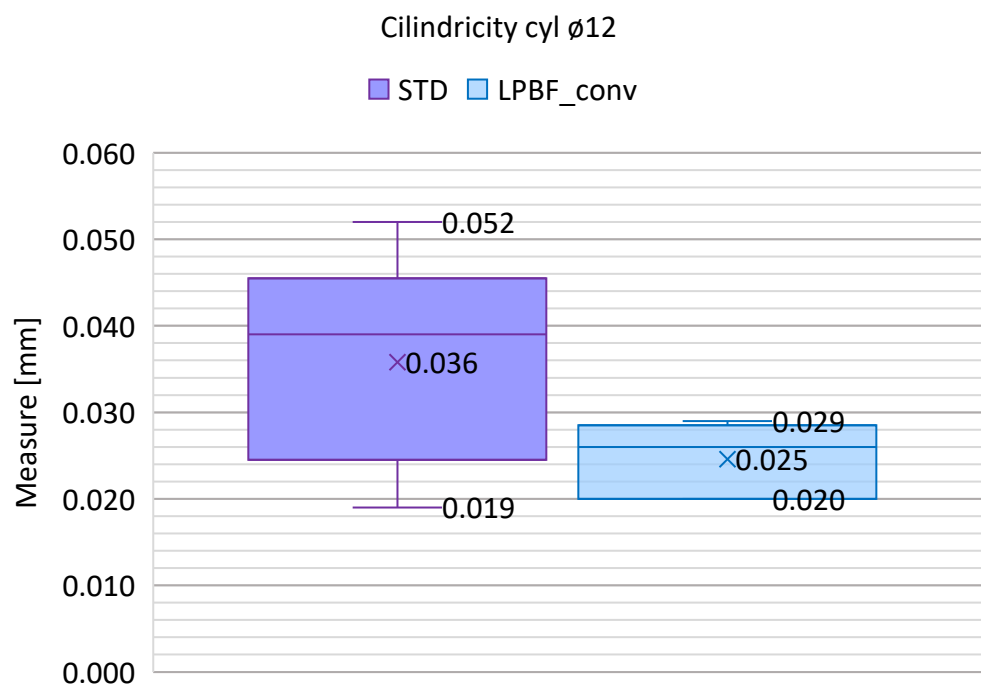


STD cathode



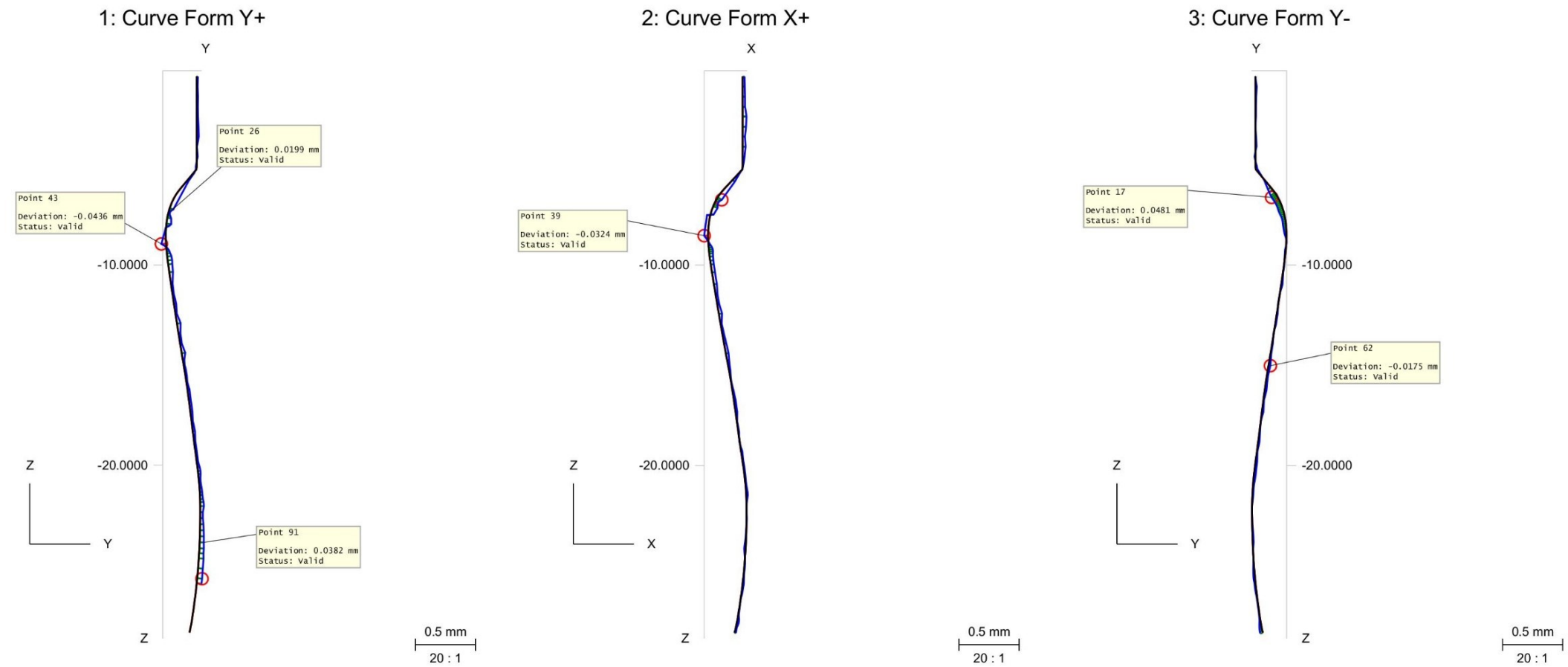






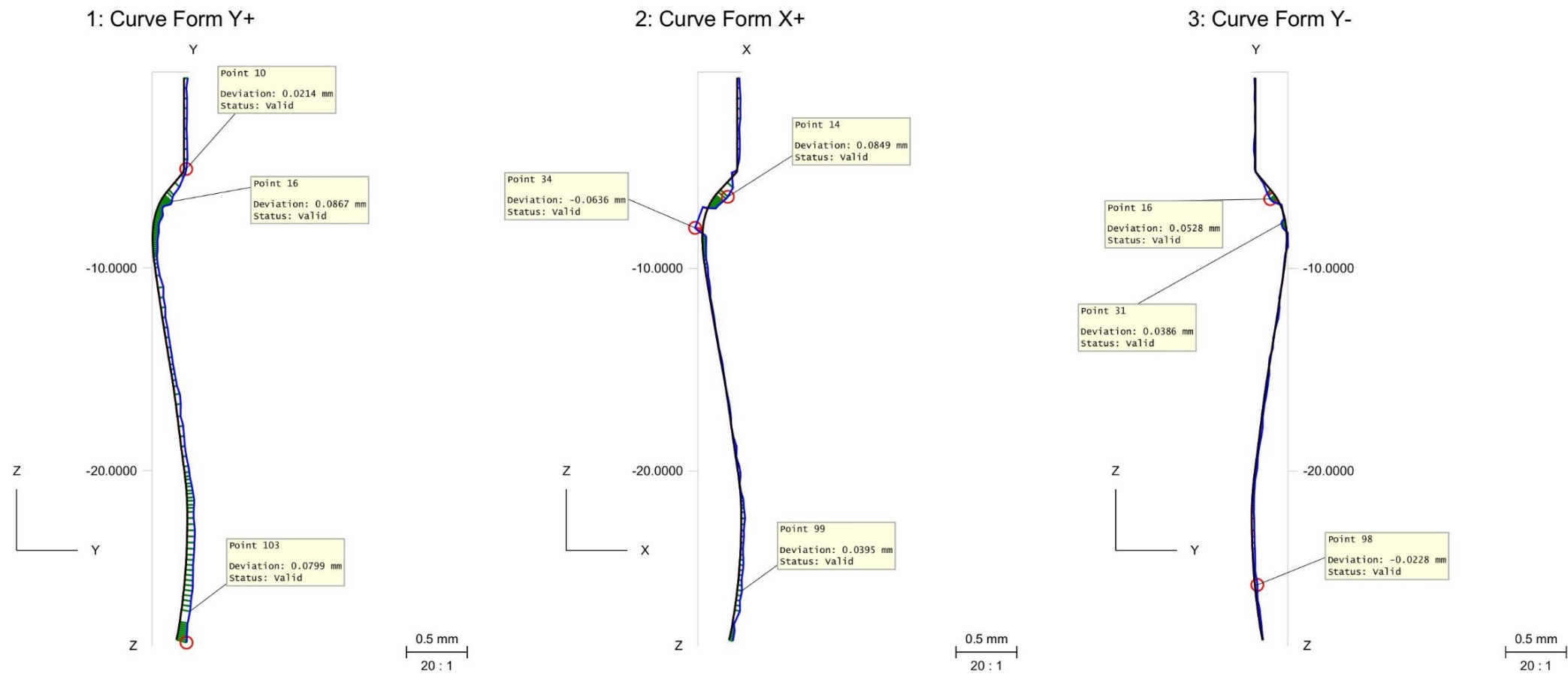
Appendix H.2 LPBF_OPT central body profile measurement

	Calypso 7.0.16	Carl Zeiss	Date Order	December 19, 2023
Part Number 1	CMM Type ACCURA_MASS	Drawing No.	Department: Operator	Master
Meas. Plan Name	Cathode corpo centrale 1		Signature:	



No	Identifier	Sigma [mm]	Form [mm]	Number of Points	Lower Tol. [mm]	Upper Tol. [mm]	MinInd	Min Dev. [mm]	MaxInd	Max Dev. [mm]	Best Fit	X [mm]	Y [mm]	Z [mm]		X	Y	Z
1	Curve Form Y+	0.0251	0.0884	77	0.0000	0.0000	23	-0.0436	76	0.0447	Translation	0.0000	0.0000	0.0000	Rotation	0.0000	0.0000	0.0000
2	Curve Form X+	0.0171	0.0719	96	0.0000	0.0000	22	-0.0324	14	0.0395	Translation	0.0000	0.0000	0.0000	Rotation	0.0000	0.0000	0.0000
3	Curve Form Y-	0.0193	0.0656	113	0.0000	0.0000	62	-0.0175	17	0.0481	Translation	0.0000	0.0000	0.0000	Rotation	0.0000	0.0000	0.0000

 Calypso 7.0.16		Carl Zeiss		Date Order	December 19, 2023
Part Number 1		CMM Type ACCURA_MASS		Drawing No.	
Meas. Plan Name Cathode corpo centrale 2				Department: Operator Signature:	Master

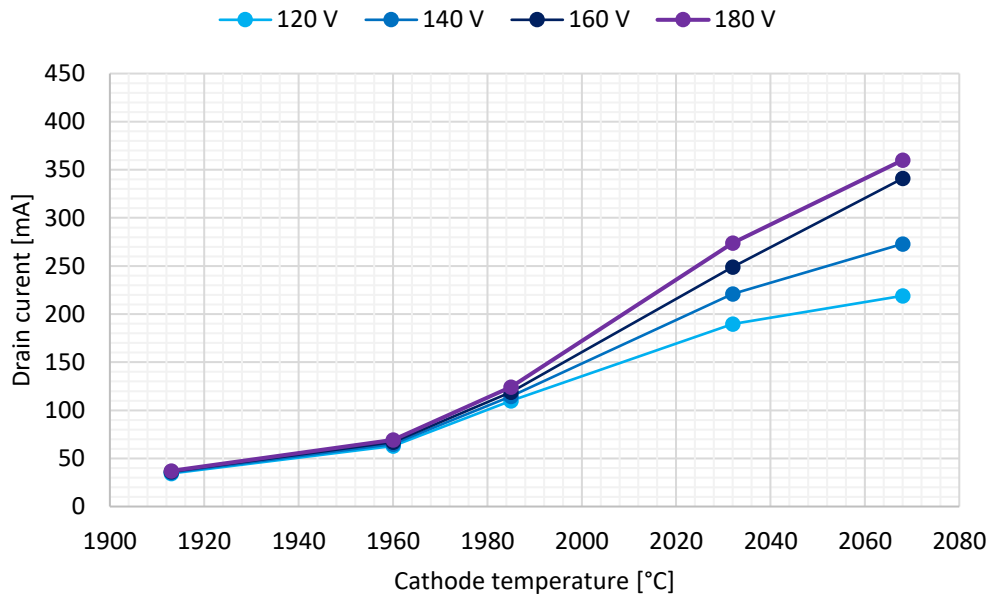


No	Identifier	Sigma [mm]	Form [mm]	Number of Points	Lower Tol. [mm]	Upper Tol. [mm]	MinInd	Min Dev. [mm]	MaxInd	Max Dev. [mm]	Best Fit	X [mm]	Y [mm]	Z [mm]		X	Y	Z
1	Curve Form Y+	0.0562	0.0952	113	0.0000	0.0000	10	0.0214	113	0.0952	Translation	0.0000	0.0000	0.0000	Rotation	0.0000	0.0000	0.0000
2	Curve Form X+	0.0320	0.1485	104	0.0000	0.0000	25	-0.0636	14	0.0849	Translation	0.0000	0.0000	0.0000	Rotation	0.0000	0.0000	0.0000
3	Curve Form Y-	0.0183	0.0755	98	0.0000	0.0000	83	-0.0228	16	0.0528	Translation	0.0000	0.0000	0.0000	Rotation	0.0000	0.0000	0.0000

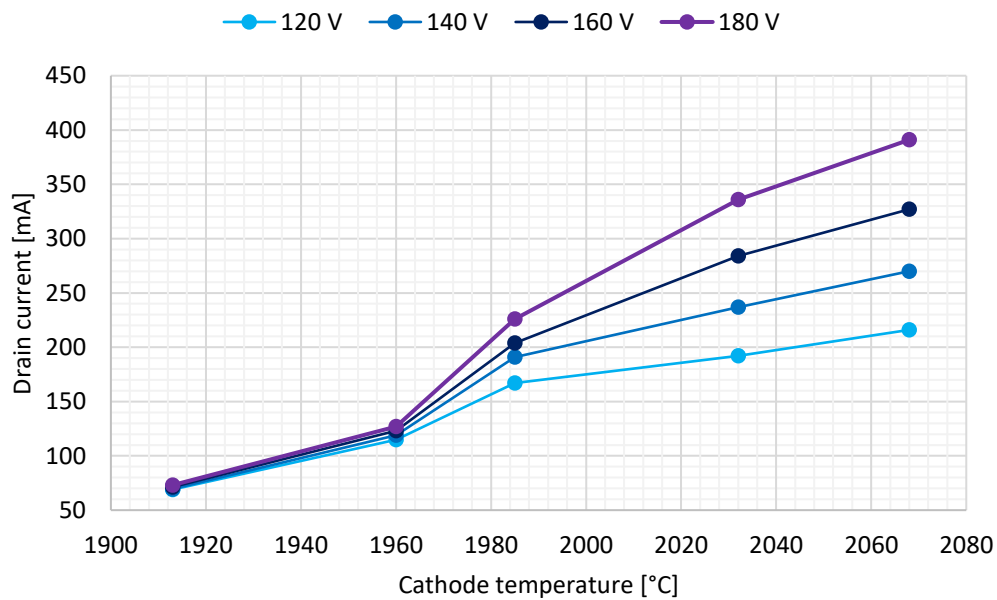
Appendix I CERN-ISOLDE ionisation test

Appendix I.1 LPBF Ta anode configuration drain current analysis

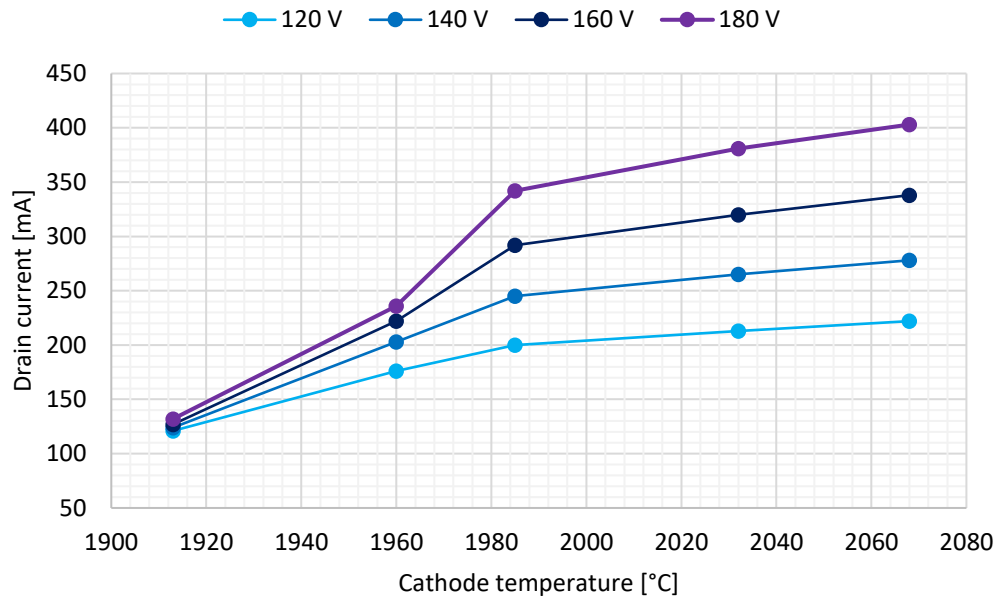
Time: 0h operation



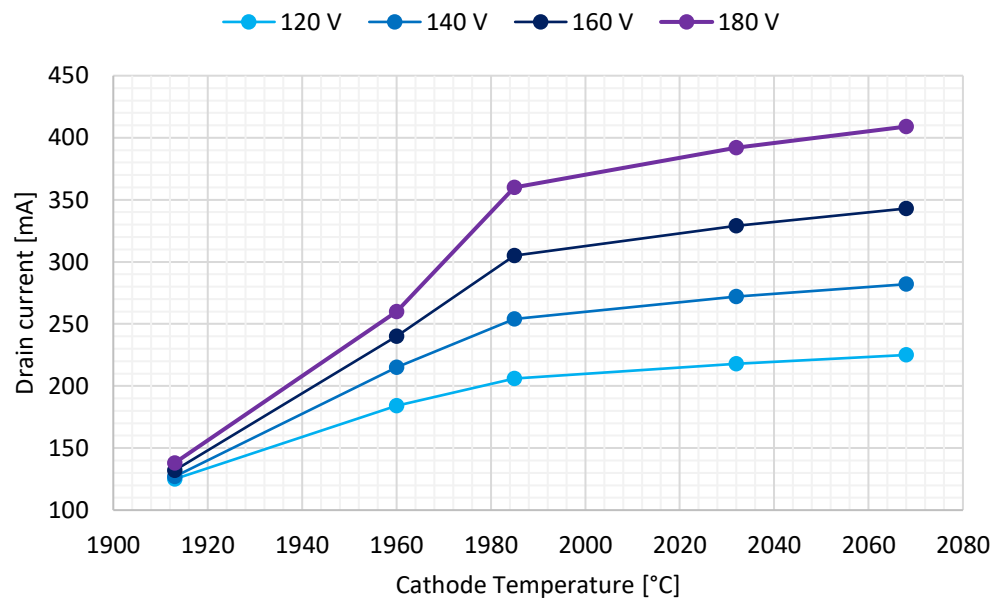
Time: 13h operation



Time: 86h operation

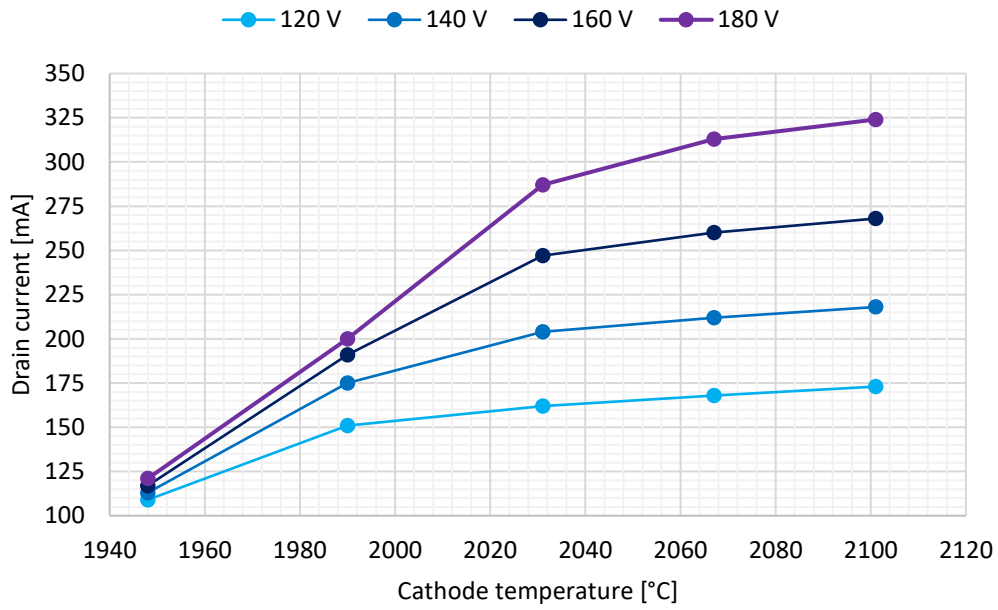


Time: 146h operation

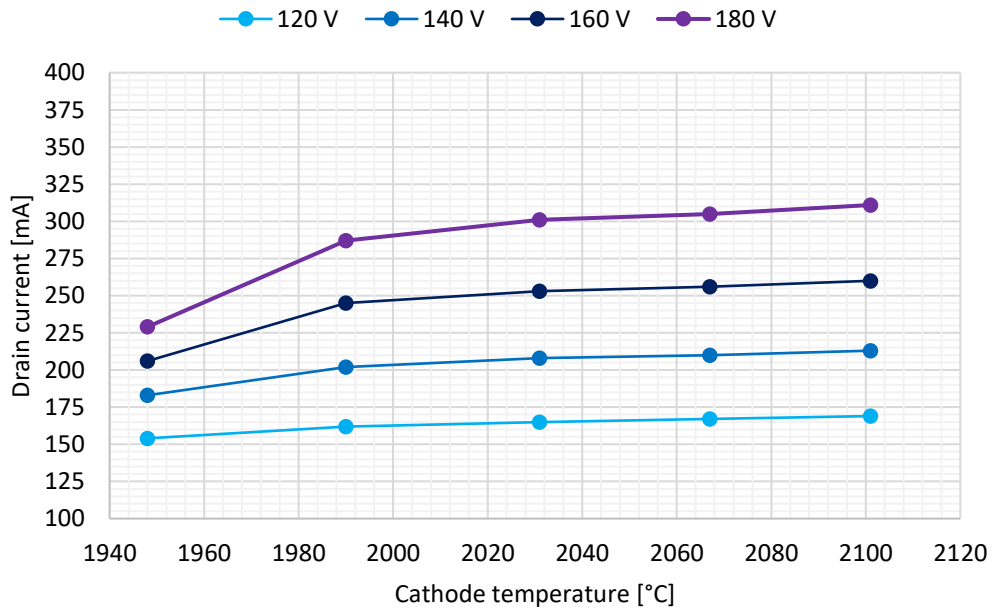


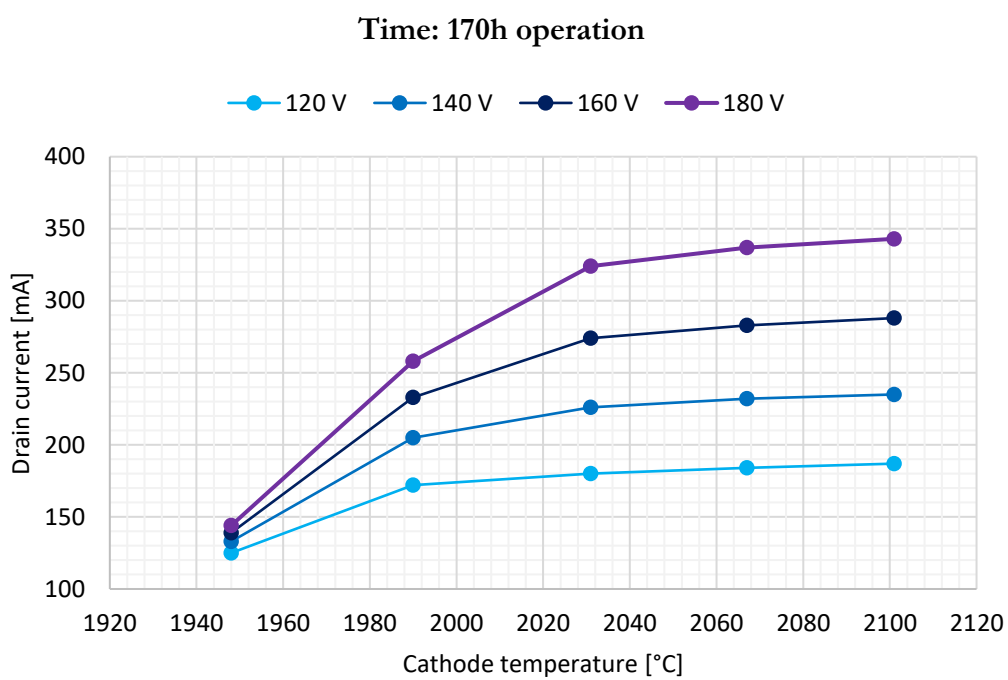
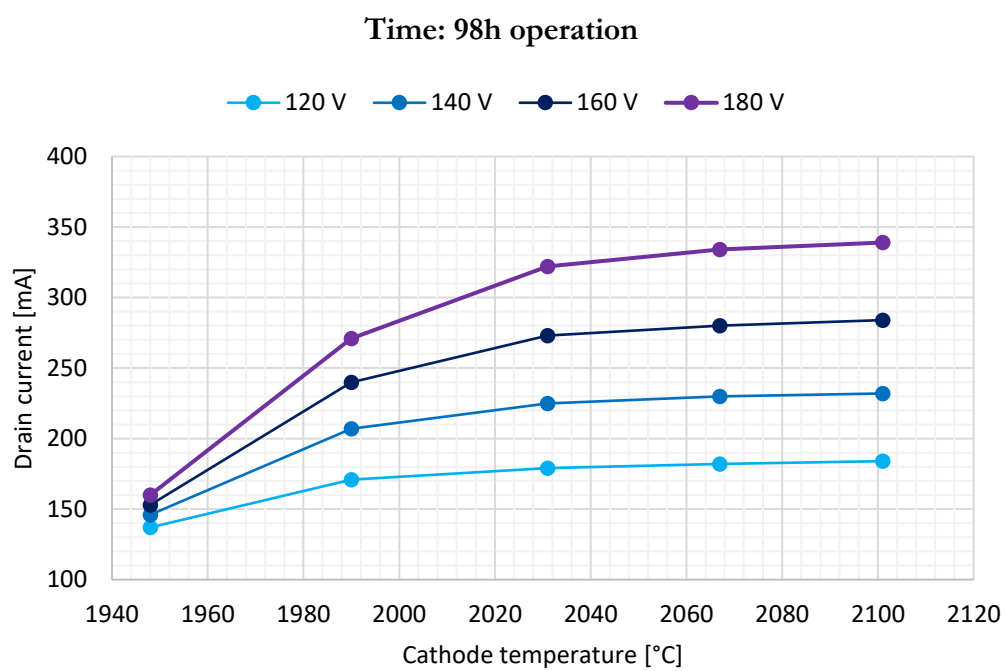
Appendix I.2 LPBF Mo anode configuration drain current analysis

Time: 0h operation



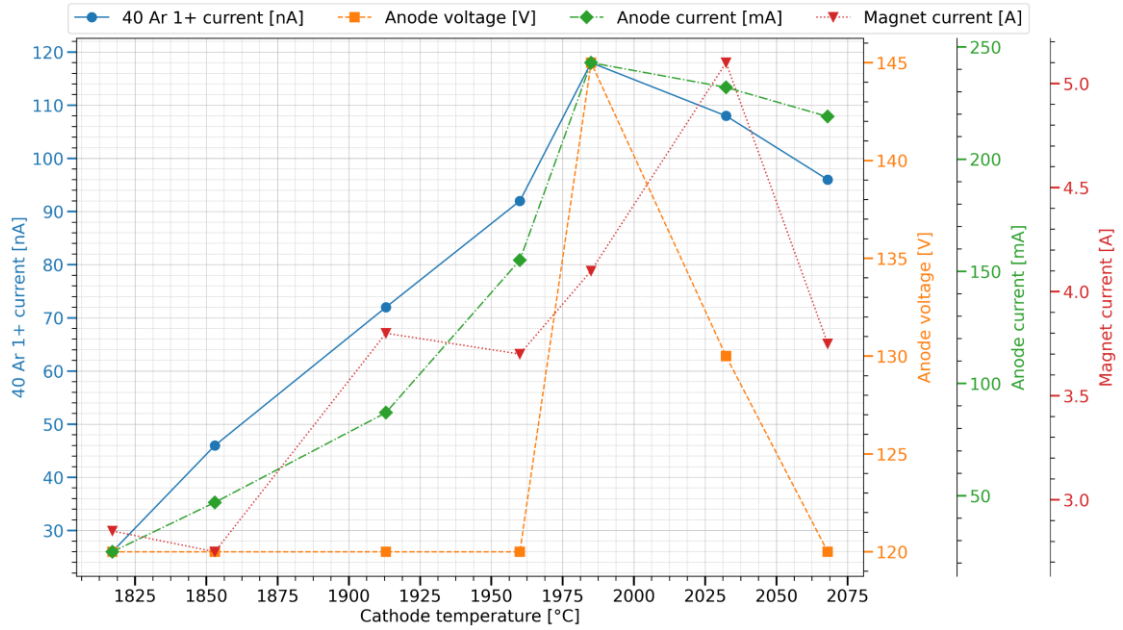
Time: 41h operation





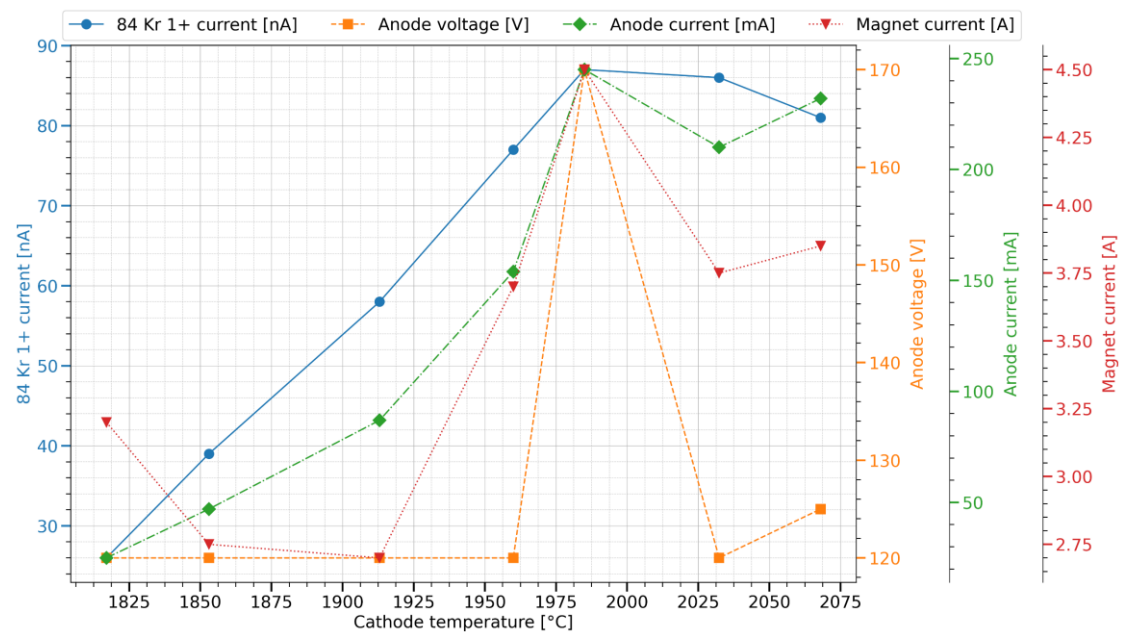
Appendix I.3 Ionisation efficiency – LPBF Ta anode configuration

40 Ar¹⁺ beam current measurement



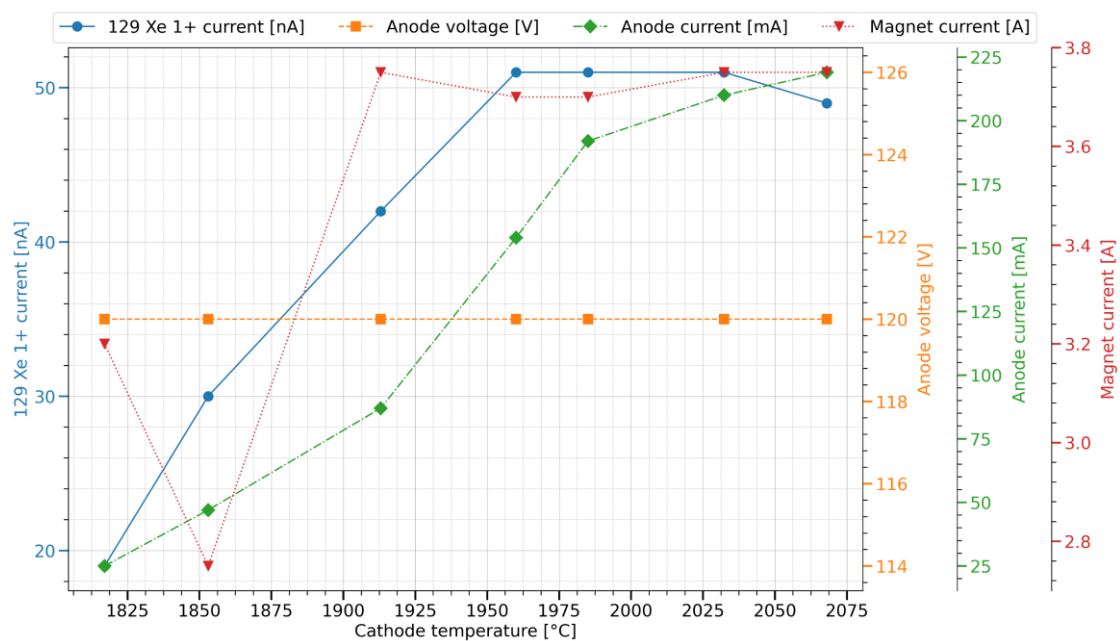
Cathode temperature [°C]	40 Ar ¹⁺ current [nA]	Anode voltage [V]	Anode current [mA]	Magnet current [A]
1817	26	120	25	2.85
1853	46	120	47	2.75
1913	72	120	87	3.8
1960	92	120	155	3.7
1985	118	145	243	4.1
2032	108	130	232	5.1
2068	96	120	219	3.75

84 Kr ¹⁺ beam current measurement



Cathode temperature [°C]	84 Kr ¹⁺ current [nA]	Anode voltage [V]	Anode current [mA]	Magnet current [A]
1817	26	120	25	3.2
1853	39	120	47	2.75
1913	58	120	87	2.7
1960	77	120	154	3.7
1985	87	170	245	4.5
2032	86	120	210	3.75
2068	81	125	232	3.85

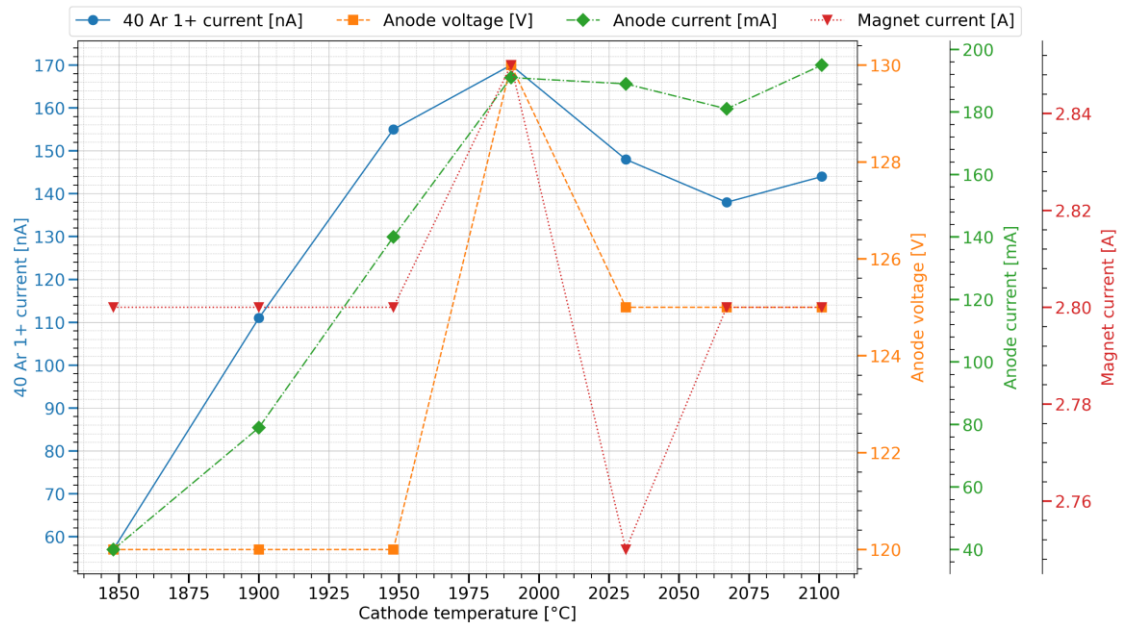
129 Xe ¹⁺ beam current measurement



Cathode temperature [°C]	129 Xe ¹⁺ current [nA]	Anode voltage [V]	Anode current [mA]	Magnet current [A]
1817	19	120	25	3.2
1853	30	120	47	2.75
1913	42	120	87	3.75
1960	51	120	154	3.7
1985	51	120	192	3.7
2032	51	120	210	3.75
2068	49	120	219	3.75

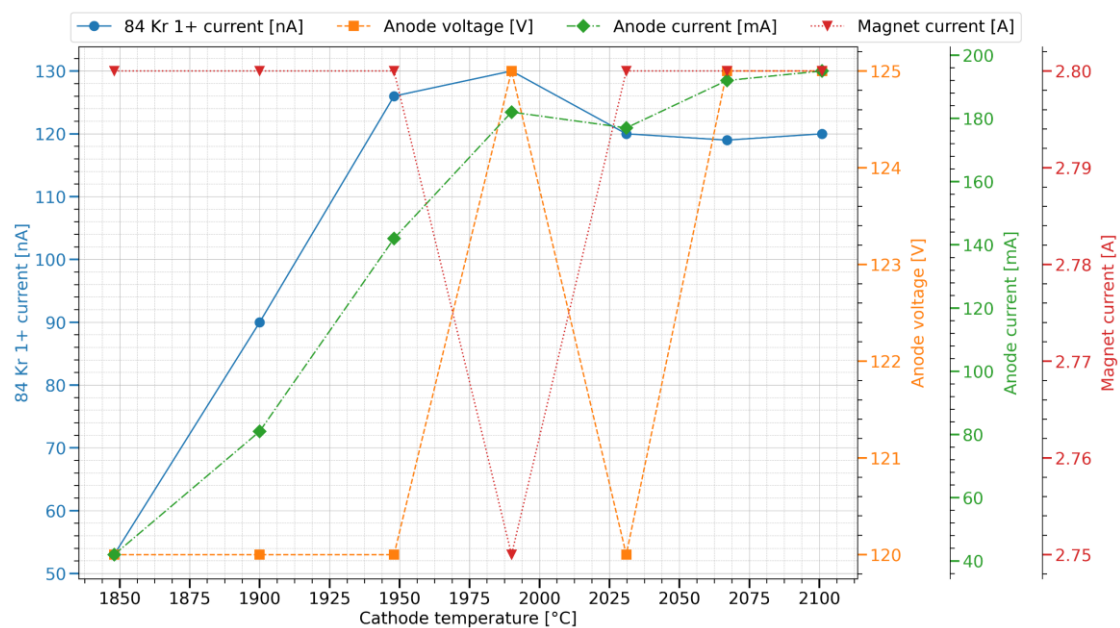
Appendix I.4 Ionisation efficiency – LPBF Mo anode configuration

40 Ar¹⁺ beam current measurement



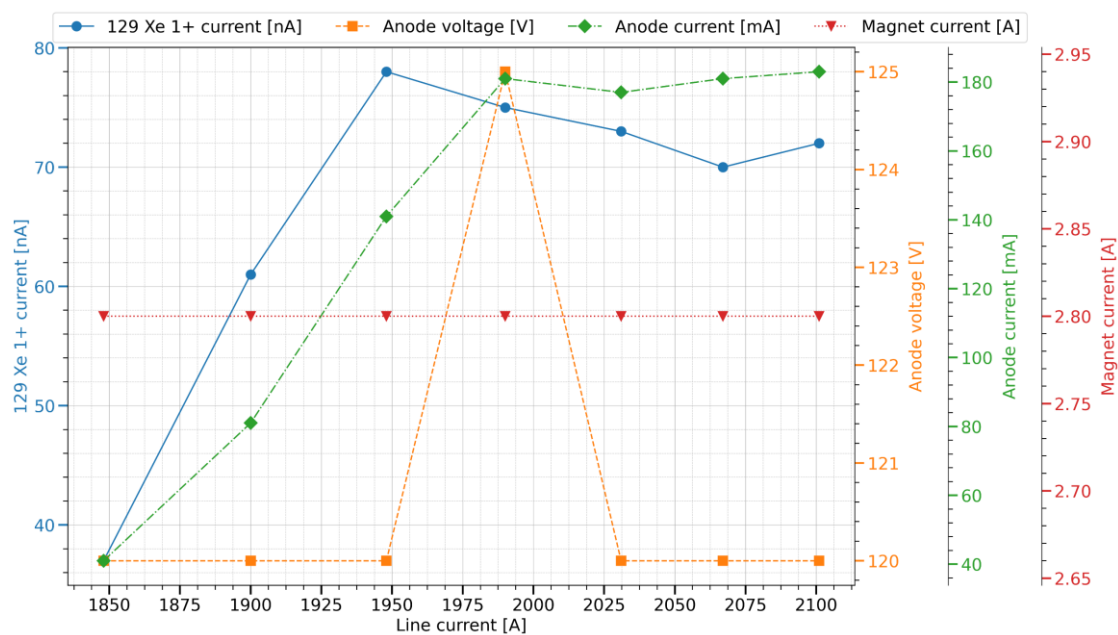
Cathode temperature [°C]	40 Ar ¹⁺ current [nA]	Anode voltage [V]	Anode current [mA]	Magnet current [A]
1848	57	120	40	2.8
1900	111	120	79	2.8
1948	155	120	140	2.8
1990	170	130	191	2.85
2031	148	125	189	2.75
2067	138	125	181	2.8
2101	144	125	195	2.8

$^{84}\text{Kr}^{1+}$ beam current measurement



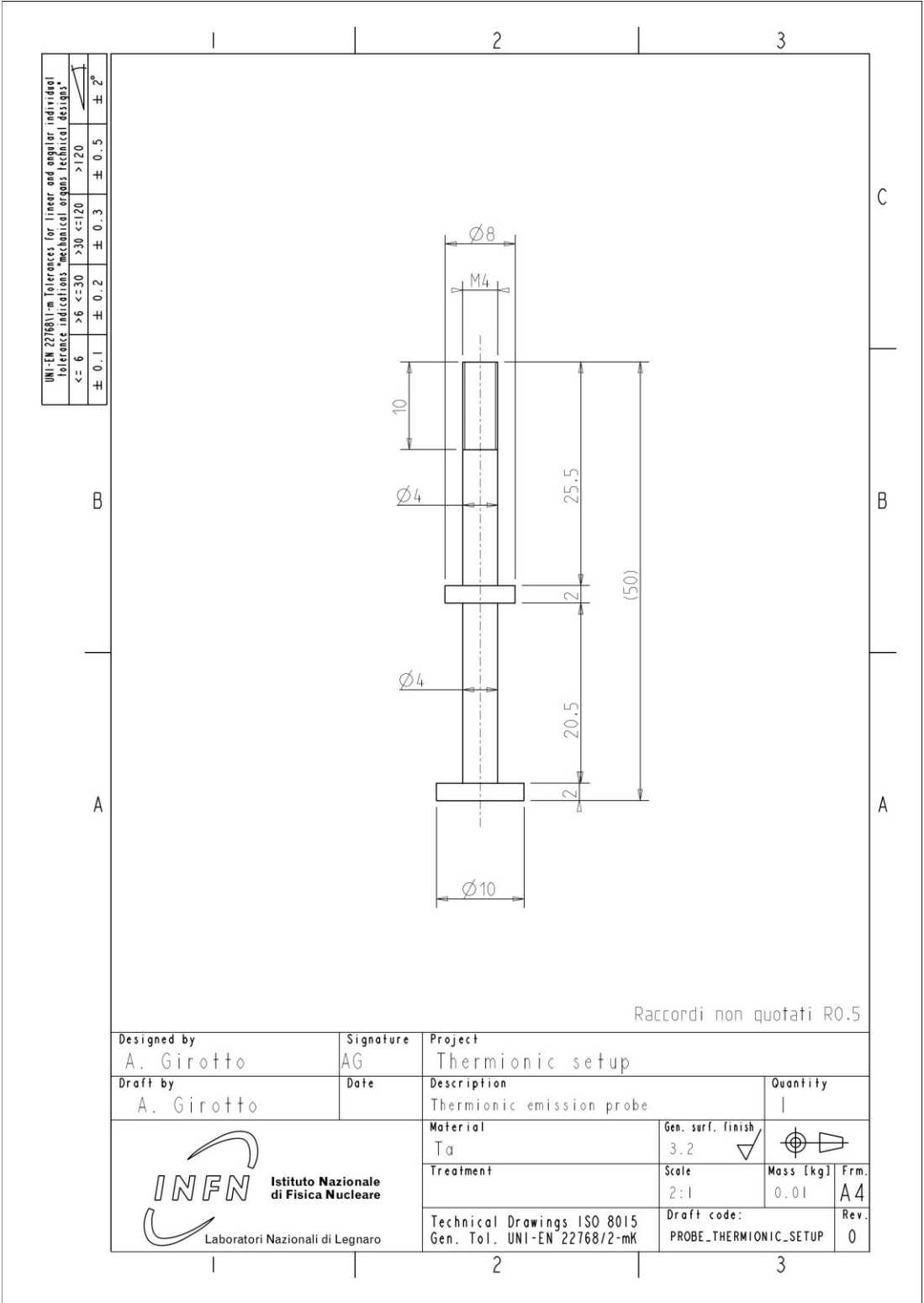
Cathode temperature [°C]	$^{84}\text{Kr}^{1+}$ current [nA]	Anode voltage [V]	Anode current [mA]	Magnet current [A]
1848	53	120	42	2.8
1900	90	120	81	2.8
1948	126	120	142	2.8
1990	130	125	182	2.75
2031	120	120	177	2.8
2067	119	125	192	2.8
2101	120	125	195	2.8

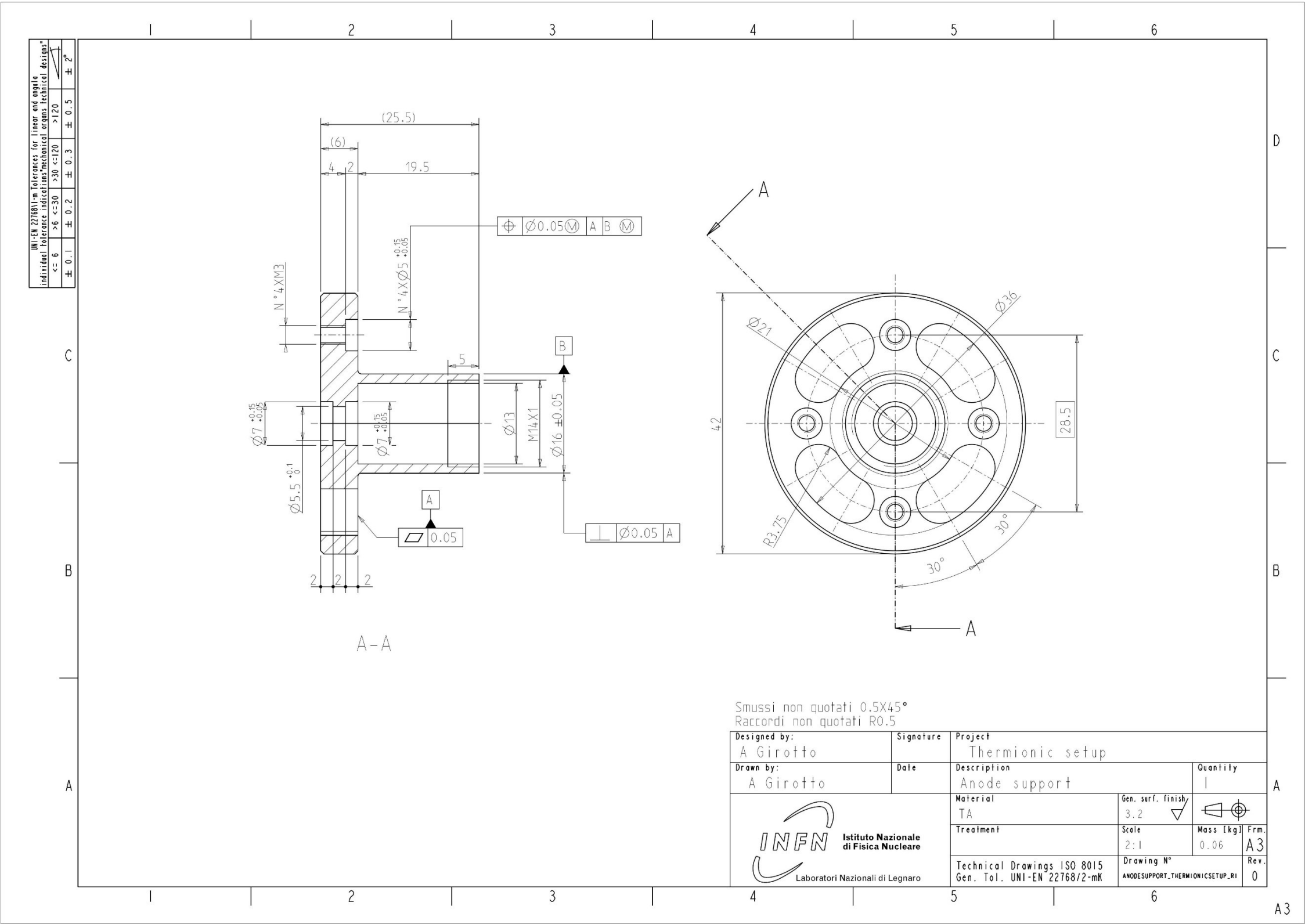
129 Xe 1+ beam current measurement



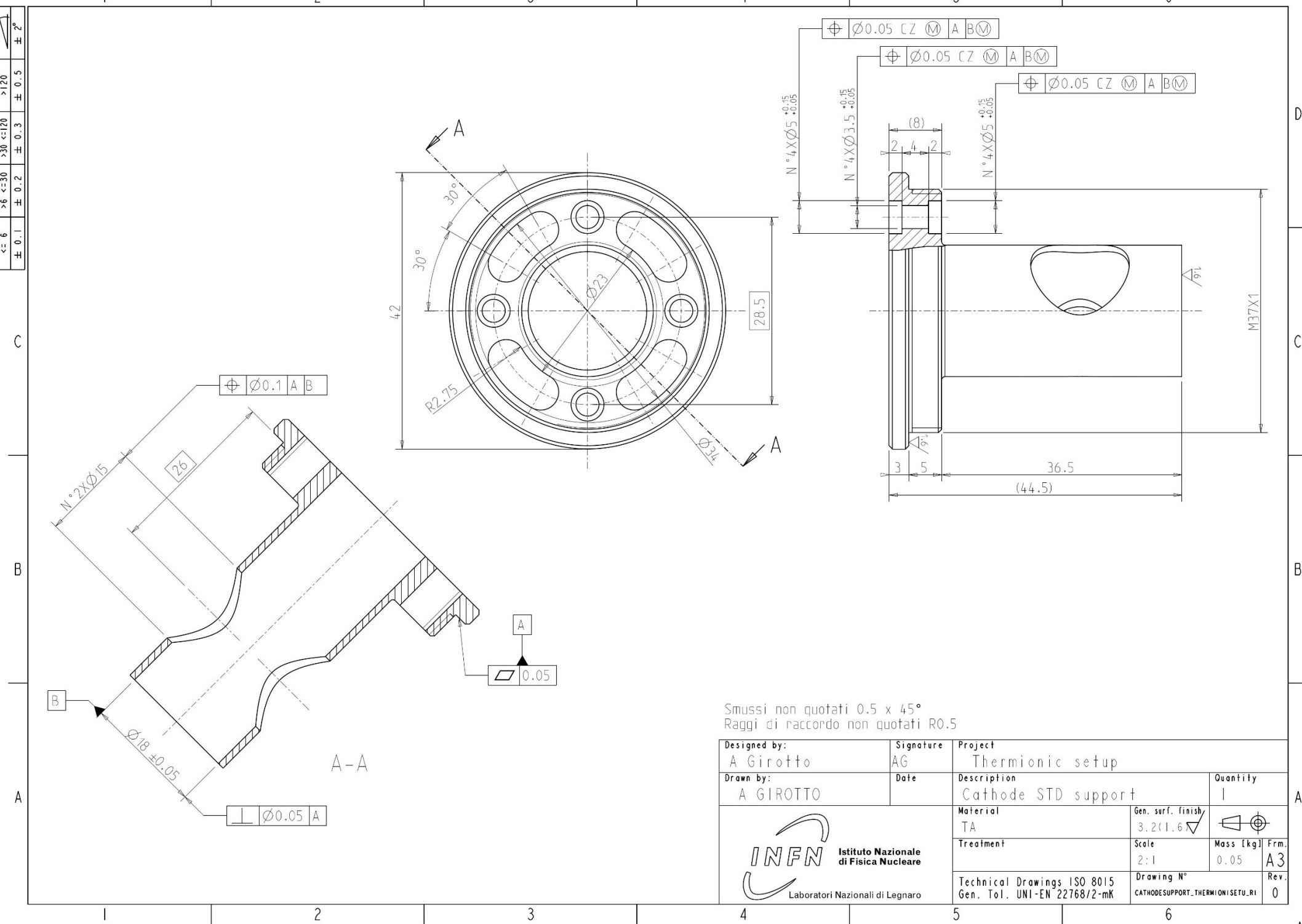
Cathode temperature [°C]	129 Xe 1+ current [nA]	Anode voltage [V]	Anode current [mA]	Magnet current [A]
1848	37	120	41	2.8
1900	61	120	81	2.8
1948	78	120	141	2.8
1990	75	125	181	2.8
2031	73	120	177	2.8
2067	70	120	181	2.8
2101	72	120	183	2.8

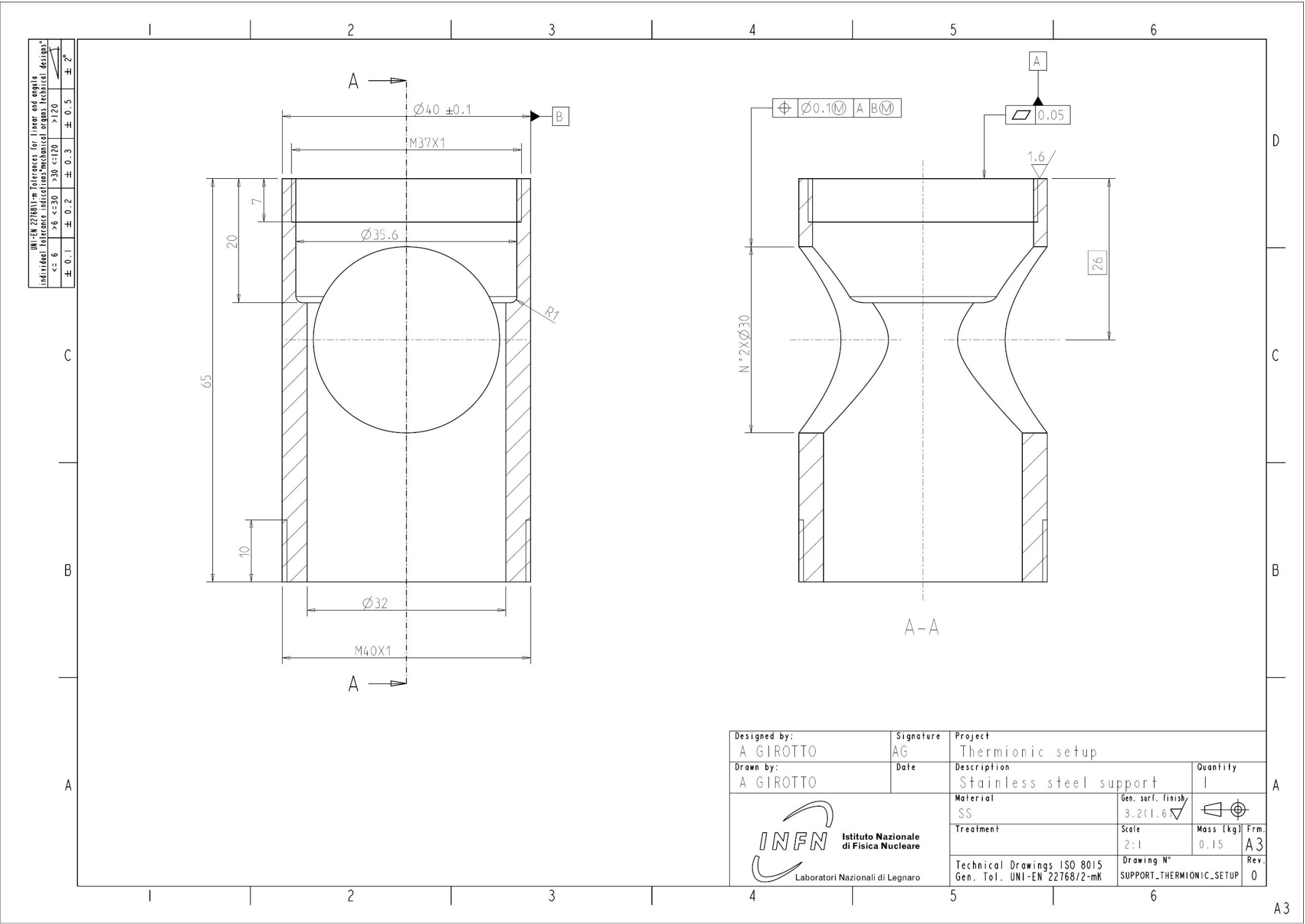
Appendix J Thermionic emission setup technical drawings

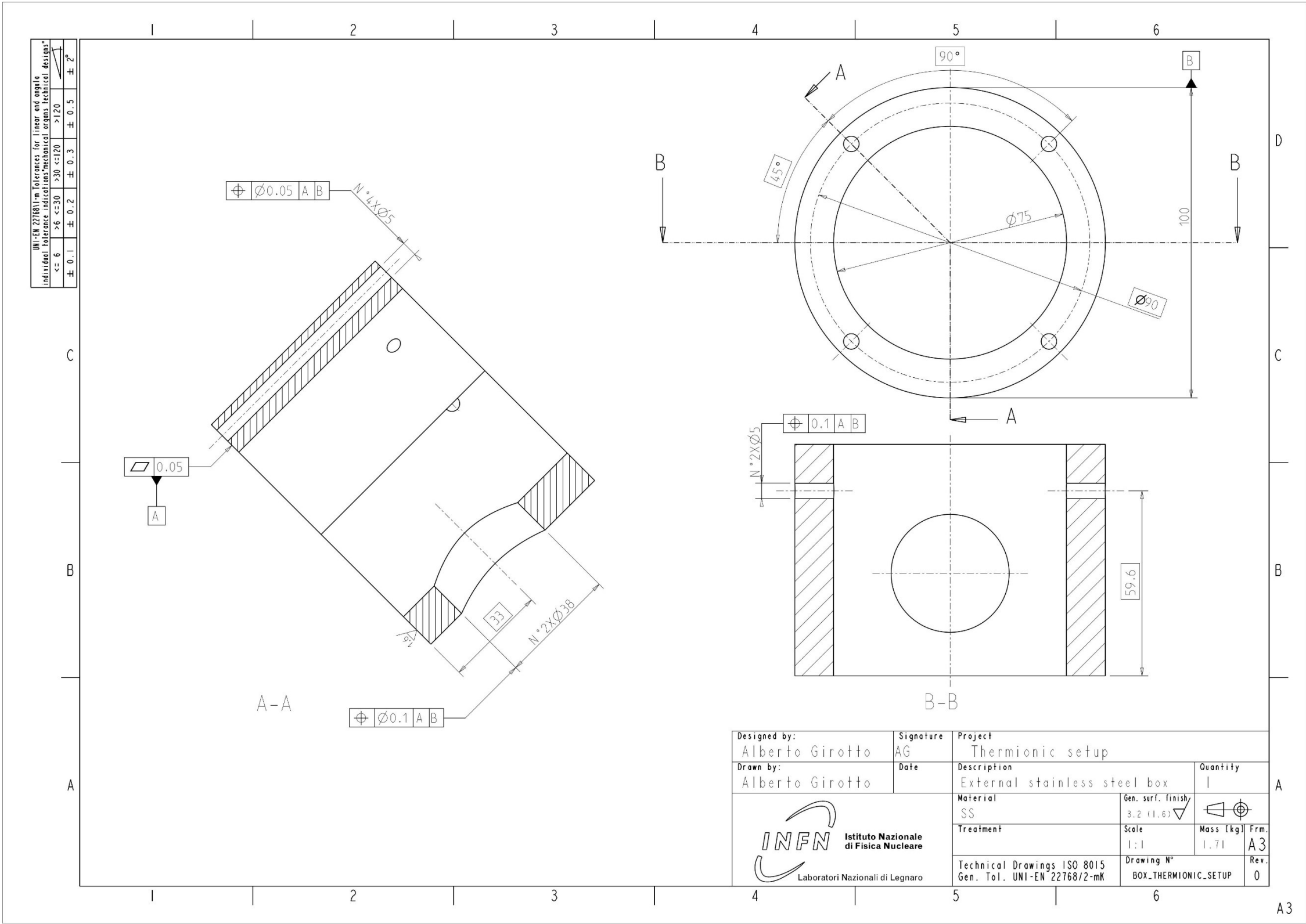


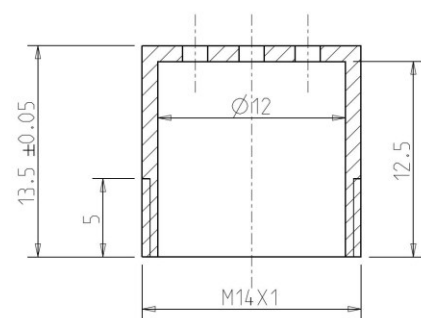


UNI-EN 227681-m Tolerances for linear and angular individual tolerance indications "mechanical organs technical designs"			
≤ 6	$> 6 \leq 30$	$> 30 \leq 120$	> 120
± 0.1	± 0.2	± 0.3	± 0.5
			$\pm 2^\circ$



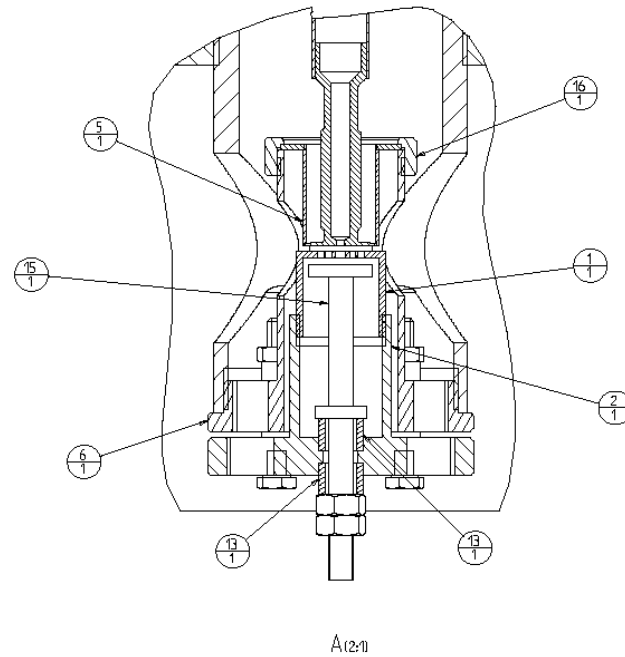
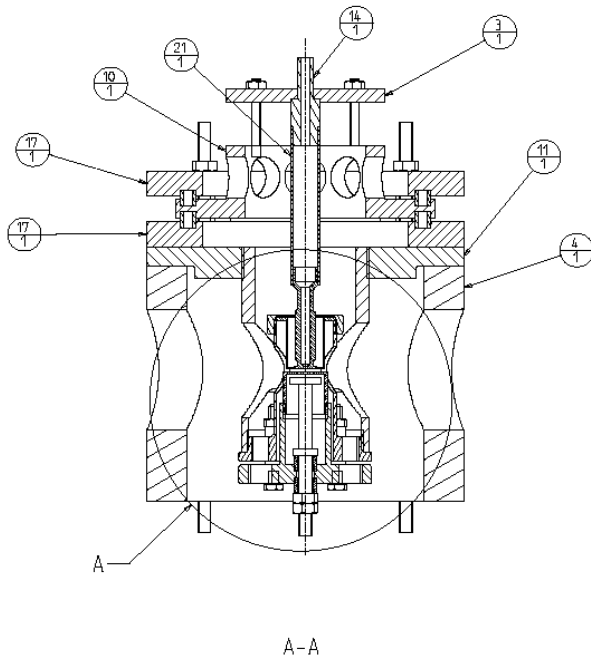
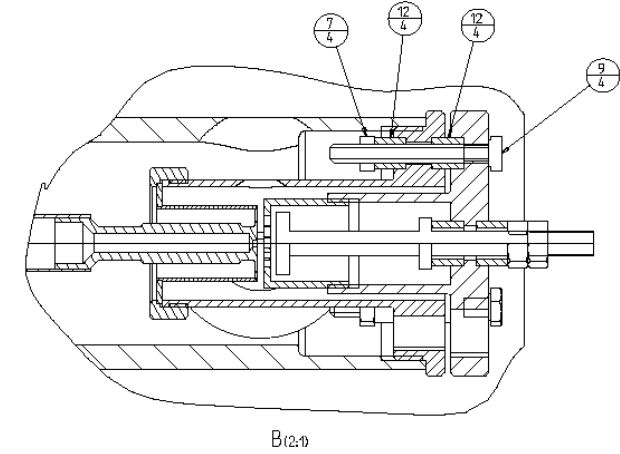
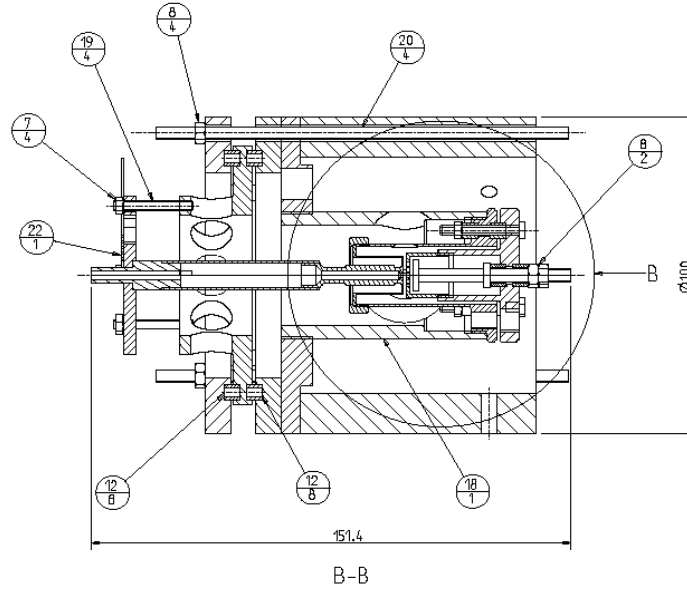
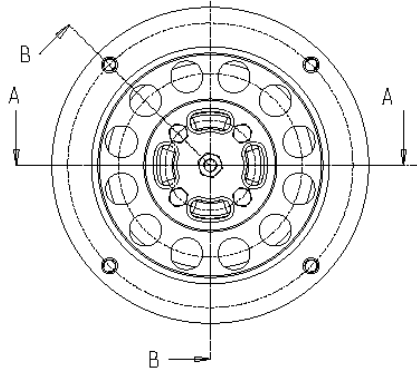




A
$$A - A$$


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UNI-EN 22381-6: Technical file (user and compiler)
Individuals: Parameters indicating technical aspects (technical designs)



ITEM	COMPONENT	MATERIAL	MASS (kg)	QTY
1	ANODE_GROD_THERMIONIC_SETUP	TA	0.005	1
2	ANODESUPPORT_THERMIONICSETUP_R1	TA	0.060	1
3	BLOCK_TLINE_THERMIONIC_SETUP	MD	0.070	1
4	BXD_THERMIONIC_SETUP	SS	1.711	1
5	CATHODE_THERMIONIC_SETUP		0.000	1
6	CATHODESUPPORT_THERMIONICSETU_R1	TA	0.059	1
7	DADD_DIN934_M3	SS	0.000	8
8	DADD_DIN934_M6	SS	0.001	6
9	DIN933_A2_M3X25	SS	0.006	4
10	FLANGE_TLINE_THERMIONIC_SETUP	SS	0.247	1
11	FLANGE_THERMIONIC_SETUP	SS	0.317	1
12	INSULATOR_SPM_THERMIONIC_SETUP	ALUMINA	0.000	24
13	INSULATOR_BM_THERMIONIC_SETUP	ALUMINA	0.000	2
14	PERNO_TRANSFERLINE	TA	0.008	1
15	PROBE_THERMIONIC_SETUP	TA	0.007	1
16	RETAINER_NUT_THERMIONIC_SETUP	TA	0.009	1
17	SUPPORT_TLINE_THERMIONIC_SETUP	SS	0.273	2
18	SUPPORT_THERMIONIC_SETUP	SS	0.154	1
19	THREADED_BAR_SPM_THERMIONIC_SET	SS	0.001	4
20	THREADED_BEAMS_THERMIONIC_SETUP	SS	0.013	6
21	TRANSFERLINE_ANSYS	TA	0.006	1
22	TRANSFERLINE_SUPPORT	SS	0.004	1

Designed by A GIROTTO	Signature AG	Project Thermionic setup		
Draft by A GIROTTO	Date	Description Thermionic setup	Quantity 1	
 INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Legnaro		Material Treatment	See surf. finish Scale 1:1	 M22 (tg) Tru. 3.309 A
		Technical Drawings G01 001 UNI-EN 22789/2-2	Draft code: THERMIONIC.SETUP	

Acknowledgement

Quando iniziai il percorso di dottorato ero consapevole che non sarebbe stato tutto facile, lineare, privo di ostacoli. Fortunatamente, in questi tre anni, ho avuto accanto tantissime persone che mi hanno permesso di svolgere le attività di ricerca con determinazione, rendendo quelle che per me erano montagne impervie da scalare delle soffici colline facilmente percorribili. Se dovessi dimenticarmi qualcuno, chiedo venia: chi mi conosce, sa che a volte la mia memoria può essere incerta.

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