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SPES low-energy beamline status and development of ISOLPHARM Radionuclide Implantation Station (IRIS)

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ABSTRACT

SPES (Selective Production of Exotic Species) is a second-generation ISOL (Isotope Separation On-Line) facility to produce Radioactive Ion Beams (RIBs), under completion stage at the Laboratori Nazionali di Legnaro of the Istituto Nazionale di Fisica Nucleare (LNL-INFN), Padua, Italy. ISOLPHARM (ISOL technique for radioPHARMaceuticals), within the SPES medical production program, is a research activity dedicated to developing innovative radiopharmaceuticals exploiting the high purity radionuclides produced using the ISOL technique. Within this scope, ISOLPHARM Radionuclide Implantation Station (IRIS) is designed to be coupled with the SPES low-energy beamline to handle the collection of medical radionuclides. In this paper, a detailed description on the design of collection substrates and IRIS components is reported. The on-site commissioning comprising the reliability tests and offline calibration tests of the detection system is also presented. IRIS is expected to begin operation with initial experiments at SPES facility in the near future.

1. Introduction

The ISOL (Isotope Separation On-Line) technique, originally devoted to the production of radioactive ion beams for nuclear physics studies [1], has in recent years been established as a promising method to produce medical radionuclides [2]. Examples of operative and future ISOL facilities that have medical radionuclides production programs can be found in Europe [3–7] and worldwide [8]. Among these, the new and close-to-operation SPES (Selective Production of Exotic Species) ISOL facility at Legnaro National Laboratories of INFN will be partly employed for medical radionuclides production. This facility [9] is based on a cyclotron (BEST 70p [10]) which will provide protons of energy up to 70 MeV and intensity up to 750 μA. A primary target will be bombarded by protons to generate neutron-rich fission fragments (when using uranium carbide as a target) [11] or proton-rich radionuclides (when using non-fissile materials as targets) [12–14]. The produced radionuclides will be extracted from the target, ionized [15] and subsequently accelerated at energies up to 50 keV and mass separated to form high quality Radioactive Ion Beams (RIBs), to be employed in nuclear physics and medicine experiments and studies [16]. A Wien Filter and a Low-Resolution Mass Separator (LRMS) system provide selections of $\Delta M/M \sim 1/150$ and 1/200 respectively. At this stage, only RIBs without post acceleration are considered for experiments in the low-energy experimental area. An additional beamline is dedicated to

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further purification through the High-Resolution Mass Separator (HRMS), with a design specification of $\Delta M/M \sim 1/20000$ [9]. An overview of the layout of the SPES-RIB production area is shown in Fig. 1. The low-energy experimental area is foreseen to be hosting four different experimental points, of which one is a tape station for beam quality assessment, and one is a beamline pertaining to the ISOLPHARM (ISOL technique for radioPHARMaceuticals) project. ISOLPHARM is one of the medical research programs in the framework of SPES, employing the ISOL technique to produce high-specific-activity radionuclides to be used for research on innovative radiopharmaceuticals [17]. It is part of the so-called "SPES-γ" framework, in which all the medical production activities with the SPES cyclotron are included [18].

In this work, the focus will be on the ISOLPHARM Radionuclide Implantation Station (IRIS), the device designed to collect mass separated radionuclides coming from the SPES target by depositing them on appropriate substrates [19], to assess their quality by measuring their radioactivity and to make them available for the subsequent steps of chemical purification into radiopharmaceutical precursors. A few representative implantation stations are currently available in ISOL facilities with medical isotope production programs, including ISAC Implantation Station (IIS) in TRIUMF [20] and the implantation station operating at CERN in the MEDICIS facility [4]. After a general introduction on the SPES and ISOLPHARM projects, this paper will describe the IRIS device in detail, from collection substrates to mechanical and control systems development.

2. SPES at INFN-LNL and ISOLPHARM project

SPES is a second generation ISOL facility now being fully commissioned at INFN-LNL. It is designed to provide experimental users with both low-energy and reaccelerated radioactive ion beams [9]. To do so, it will make use of protons coming from a recently installed cyclotron supplied by BEST Cyclotron Systems. The masses of the obtained radionuclides will span from 60 to 170 (elements from manganese to terbium), depending on the chosen target materials. The non-reaccelerated radioactive beam will be sent out of the production bunker and after other mass separation, beam steering and focussing stages, to a low-energy experimental area, shown in Fig. 2. In this part of the facility, different experimental setups will be placed, to both perform beam quality measurement using a tape station and carry out experimental activities, mainly of nuclear physics and medicine [9,21].

In this area, the ISOLPHARM project will carry out experimental research activities on nuclear medicine. ISOLPHARM is a multidisciplinary and collaborative project between several INFN sections and university departments [22,23]. It foresees the production of innovative and highly pure radionuclides to be used in nuclear medicine research as radiopharmaceutical precursors, with ^{111}Ag being one of the main radionuclides of interest for ISOLPHARM. The idea behind this project is to make use of the SPES ISOL facility, which includes mass separation, to produce isobaric radioactive ion beams and to collect radionuclides of interest depositing them on a substrate [17,19]. This substrate can then be chemically treated to eliminate isobars of the radionuclide of interest [24]. This approach, combined with the potentialities of laser ionization in selecting elements to be ionized [25], is very promising to obtain high-specific-activity radionuclides, currently difficult if not impossible to obtain with traditional production methods [22].

To be able to collect radionuclides on the substrate and to quantify them right after the collection, the IRIS experimental setup has been designed, constructed and installed in the low-energy experimental area (ISOLPHARM beamline in Fig. 3). This setup will host several substrates, and it will be able to load them, align them with the radioactive ion beam to perform radionuclides collection, unload them to perform quantitative measurements and transport them for the subsequent stages of purification. The work done in recent years on substrates and on the IRIS machine itself will be discussed in the following sections.

3. Collection substrates

The development of collection substrates is a fundamental step in the process of radionuclide production via the ISOL technique.

Many aspects have to be taken into account when choosing a proper substrate material, such as: chemical compatibility with the deposited radionuclides, minimization of contamination, impact and friction resistance and self-sputtering. The latter occurs when the radioactive ion beam impinges on a substrate that has already a deposit of radionuclides on its surface, which can cause sputtering of radionuclides out of it,

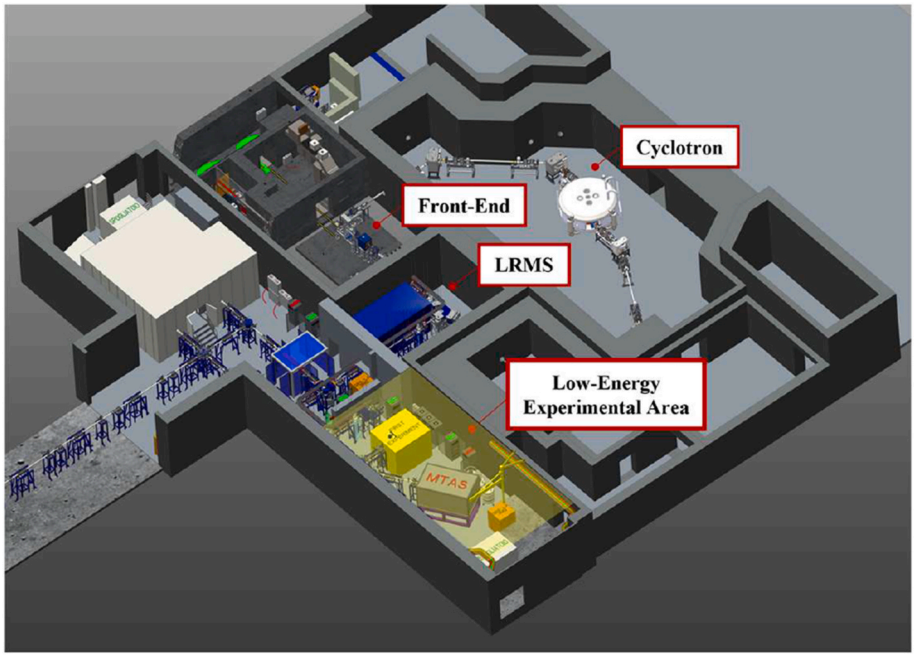

Fig. 1. Layout of SPES-RIB production area, indicating the cyclotron, front-end, Low-Resolution Mass Separator (LRMS) and low-energy experimental area. The ISOLPHARM beamline is located in the low-energy experimental area.

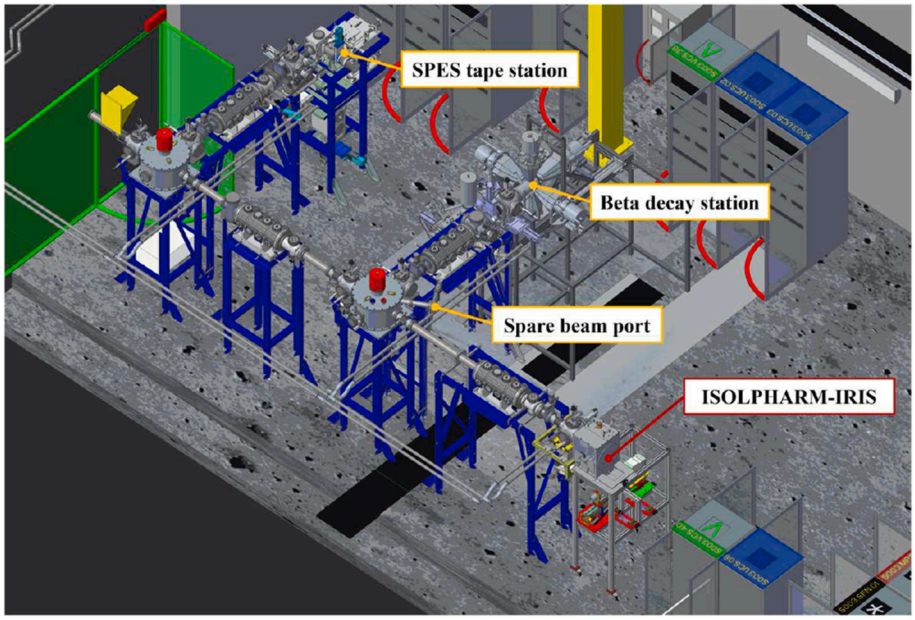

Fig. 2. Layout of low-energy experimental area, hosting four experimental points: SPES tape station, SPES beta decay station, ISOLPHARM beamline and a spare beam port for experiments in the future.

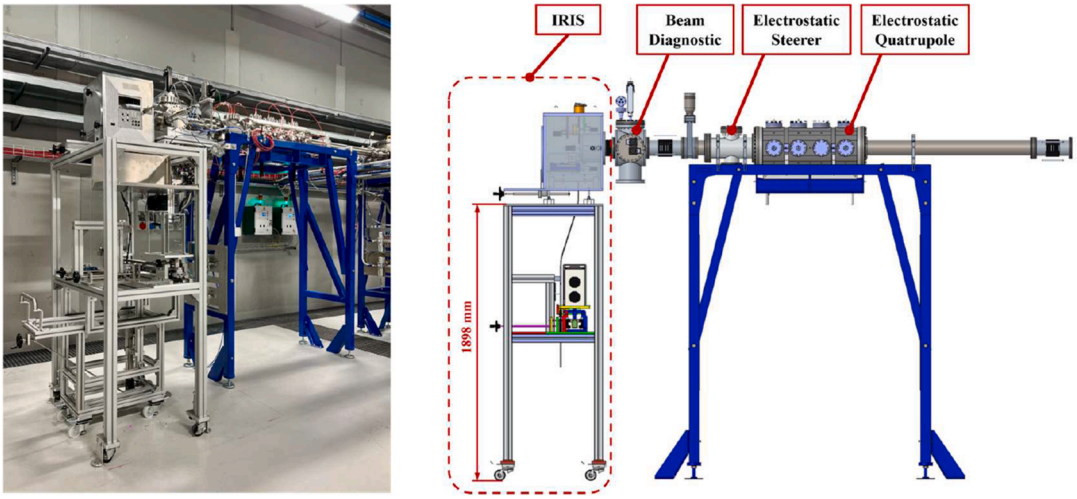

Fig. 3. Composition of ISOLPHARM beamline.

resulting in reduced efficiency of the production and in possible radioactive contamination issues.

Materials used for radionuclide deposition in existing facilities include thin metal foils of zinc and aluminum, and salt layer coated aluminum foil [26–28]. As for SPES, early experiments with stable beam made use of inorganic substrates composed of either sodium chloride or sodium nitrate. They were effective in collecting stable ions of strontium, yttrium, copper and silver. However, reactivity issues or the presence of elements and ions which could alter and make difficult the quantification of the deposited nuclides was found to be unavoidable [17,19,22,23]. In the case of deposition tests with stable iodine, activated carbon/polyvinyl alcohol substrates were developed, in order to avoid contamination from iodine present in sodium chloride and to be able to efficiently trap iodine in the substrate matrix (iodine is in gaseous state at the working pressure of 10^{-5}-10^{-6} mbar) [22]. The quantification of the deposited amounts of strontium, copper and silver was carried out using Graphite Furnace Atomic Absorption Spectroscopy (GF-AAS), whereas deposited yttrium and iodine were quantified by means of Inductive Coupled Plasma Optic Emission Spectroscopy (ICP-OES) and titration, respectively. After the preliminary tests with the materials above mentioned, substrates made of pharmaceutical grade materials were produced and tested. This was motivated by the necessity of minimizing the amount of metallic contamination and at the same time ensuring that the substrates are resistant to impact and friction caused by their handling before and after irradiation. The developed pharmaceutical grade materials include water-soluble dextrates (sugars) and insoluble cellulose-based polymers [19,29], which proved to be useable to deposit and recover silver in several tests with stable beam. The use of light organic materials has also the advantages of mitigating the risks of incurring in self-sputtering, as reported in Ref. [27]. Furthermore, the implantation depth calculations performed with different nuclides of interest indicated results below 60 nm for all the mentioned materials when using a low-energy beam (40 keV), confirming that they are suitable for the employment in ISOLPHARM experiments [19].

Taking into account the factors described above and the deposition

tests performed before, the materials applied for the substrate handling with IRIS were dextrates, which were chosen as baseline substrates due to their capability of retaining radionuclides while minimizing contaminants, easy dissolution and compatibility with separation chemistry. The use of different materials for future on-line tests is however not excluded.

4. IRIS components and commissioning

The IRIS framework is composed of different subsystems designed to fulfil the specific requirements in each phase of the substrate life cycle (illustrated in Fig. 4). The process begins with external substrate loading and proceeds at the Implantation Station (IS), which performs substrate loading, alignment, and unloading after irradiation. The Offline Detection System (ODS) is meant for on-site spectroscopic characterization, playing a critical role in product quality control. At the end of the operation, a shielded trolley transports the irradiated samples to the designated experimental area for chemical processing. In addition, a high-vacuum system is implemented to maintain the vacuum level consistent with the other part of the SPES beamline, which operates at $\sim 10^{-6}$ mbar. A diagnostic chamber and an electrostatic beam deflector are implemented before IRIS to adjust the beam path. The details of these subsystems are presented in the following sections.

4.1. Implantation station (IS)

After the substrates are manufactured and prepared for RIB implantation, they are transferred to the Implantation Station (IS) shown in Fig. 5 (a), which is composed of a vacuum chamber and a motion system designed for automated substrate handling. A leakage rate of below 1×10^{-12} mbar L/s was reached in the preliminary test for the vacuum chamber, measured using a Leybold Phoenix Vario leak detector with the helium tracer gas method under atmospheric pressure. A system consisting of a Faraday cup and collimator, controlled by a linear driver, is integrated with the chamber at a distance of ~40 mm from the substrates, as shown in Fig. 5 (b). The system prevents the unwanted irradiation on the substrate holder and is designed to alternatively insert the Faraday cup and the collimator in correspondence of the beam axis. The IRIS Faraday cup is inserted when the substrate is positioned at the irradiation point and is removed only when the beam optics are properly tuned to focus the beam on the substrate. Conversely, during the target irradiation, the collimator is positioned in front of the target providing a 10 mm aperture, which is sufficiently transparent for the expected beam size, normally around 7–8 mm. In case of beam misalignment, or beam defocusing during the irradiation, some beam current is collected by the collimator, providing instantaneous feedback to the operators running the experiment, that can refocus properly the beam by inserting the beam profiler equipped in the preceding diagnostic box. Additionally, the prevention of the contamination of the substrate holder is ensured, which is essential to preserve the purity of the collected nuclides.

The motion system, as illustrated in Fig. 6, consists of three separated parts dedicated to loading, irradiation and unloading procedures that are all assembled within a cubic frame. The design prioritizes modular flexibility for the convenience during maintenance while enabling a reasonable number of implantation experiments to be conducted within a single beam cycle. A longitudinal motor is connected to the back panel of the vacuum chamber, with the central buffer mounted on it, to provide forward and backward motion. This motor enables chamber coupling and positions the back panel for loading and unloading operations.

The IS operation process features remote handling once substrates are loaded into the system, minimizing personnel exposure. In a real operational scenario, following motors homing, substrates are firstly fed into the system, ensuring a sufficient quantity for the experiments programmed according to the beam schedule. The loading guide can accommodate up to 12 substrates. The loading buffer then receives the substrates and facilitates their descent through loading guide to the central buffer. As the critical element in implantation process, the central buffer is designed to hold up to three substrates, which can be allocated to three five-day RIB depositions within a 15-day irradiation beam cycle. The final yield of the RIB beam has been previously estimated with Monte Carlo simulations [30]. Each cell in the central buffer is sealed by a spring-loaded mechanism: substrates can only be loaded when the buffer rotates to the designated position and the entrance is actuated open by a solenoid. Once the loading process is complete, the back panel of the vacuum chamber couples with the front cap, initiating the chamber evacuation and irradiation. Substrates are sequentially rotated to the beam centre position for depositing RIBs. Upon the completion of an experimental cycle, the substrates are unloaded thanks to a structure similar to the loading system. At the end of the process, the substrates descend individually from the unloading setup to the detection system through a bent plastic guide by gravity. The motion process of the implantation station is demonstrated in Appendix A, Video A.1.

To enhance the fault tolerance and ensure the repeatability in the entire process from loading to unloading, extensive tests were conducted during the commissioning stage. Key optimizations were implemented to prevent critical errors that could lead to system blockage and to increase system redundancy in mechanical structure and control software:

- The compatibility between the dimension of the entire passage and the substrate was investigated using substrates of different thicknesses, the optimal thickness was determined to be 1.35 ± 0.04 mm.

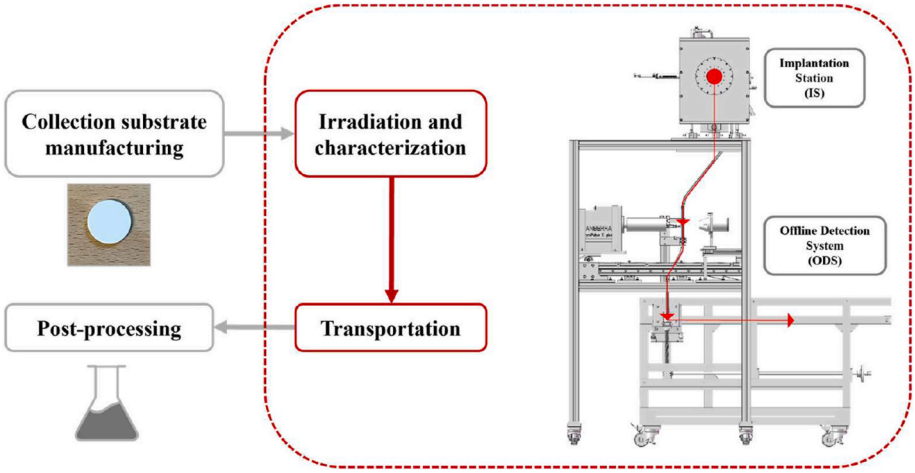

Fig. 4. Collection substrate life cycle.

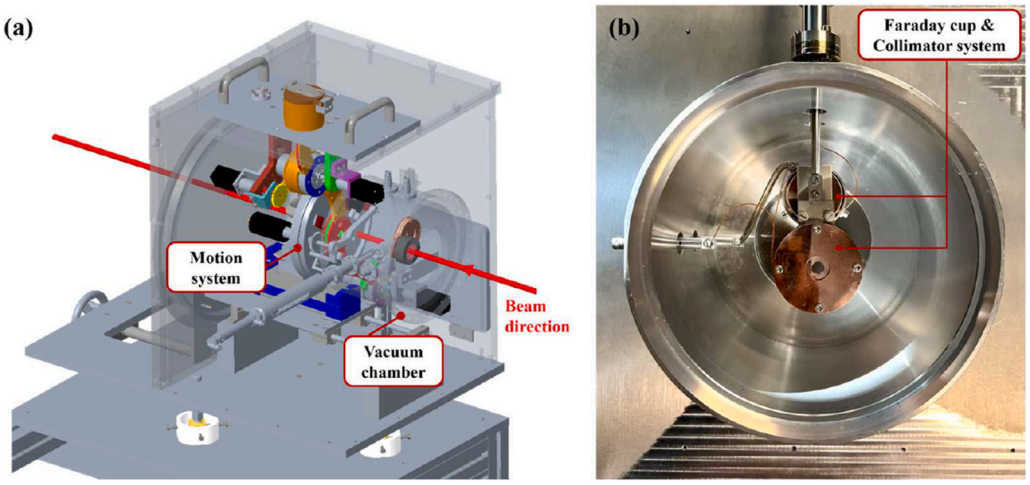

Fig. 5. (a) Inner view of the implantation station, including the motion system and the vacuum chamber. (b) Inner view of the vacuum chamber, with the collimator and Faraday cup system installed.

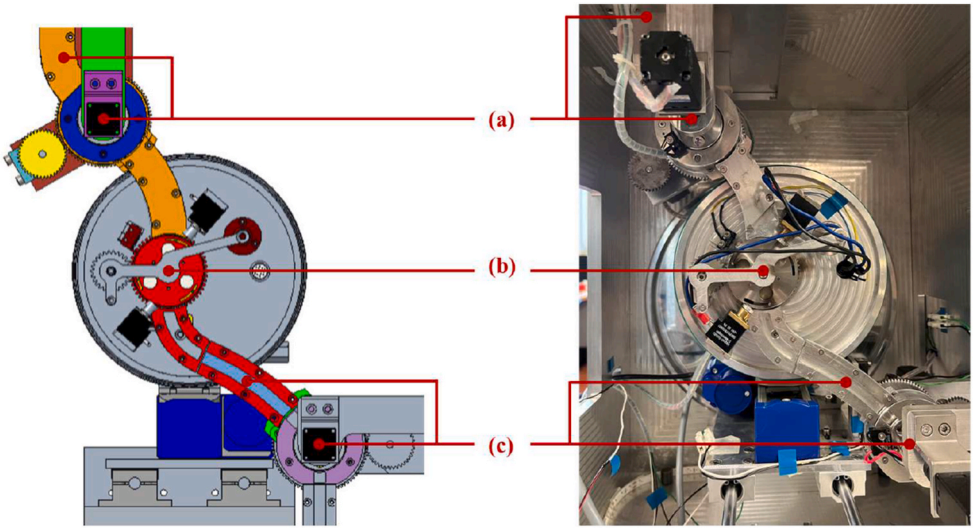

Fig. 6. Front view of motion system, consisting of (a) loading buffer and guide, (b) central irradiation buffer and (c) unloading buffer and guide, the back panel of the vacuum chamber is positioned to perform loading and unloading operations.

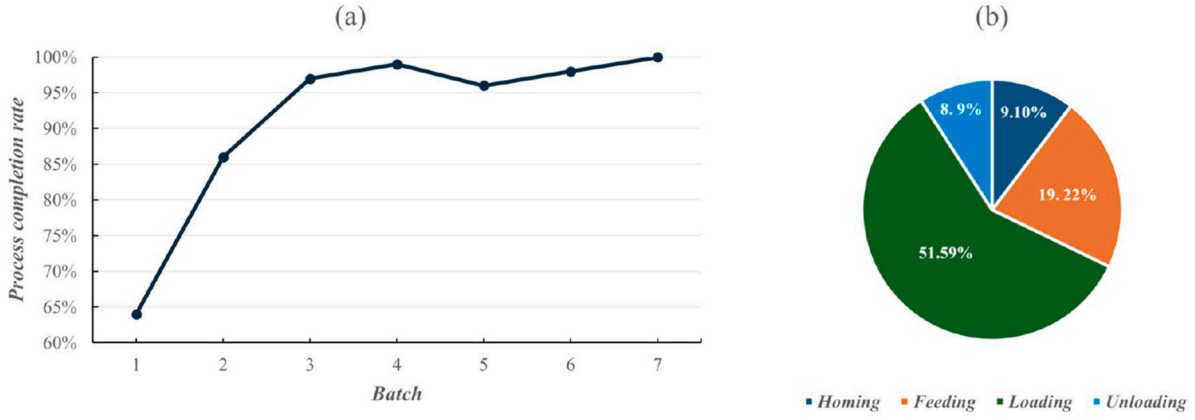

Fig. 7. (a) Completion rate of operating cycles over batches (100 cycles per batch). Each cycle consists of homing, substrate feeding, loading and unloading. (b) Proportion of system failures caused by different operational procedures.

Given that the diameter is fixed by the mold (13 mm), the raw material used for substrate manufacturing should be approximately 200 mg.

- At each interface between guides and buffers, a funnel-shape entrance was applied to ensure the smoothness of substrate passing through. In particular, an adjustable holder was designed to adapt the bent plastic guide to the unloading setup.
- Additional swing movements of loading and unloading guide were introduced by adding correction steps to the motors. The adjustments serve to compensate for the misalignment caused by routinely operational vibrations, and allow unloaded substrates to fall off the guide, preventing fatal obstructions within the system.

As shown in Fig. 7, the rate of the process completion over one hundred repeatability tests increased from 64 % to 100 % after the refinements. Most of system failures occurred during the loading stage, where indeed the majority of significant optimizations were implemented.

4.2. Offline Detection System (ODS)

As indicated by the International Atomic Energy Agency (IAEA), radiopharmaceuticals intended for human administration must undergo strict Quality Control (QC) measures before release [31]. In particular, radionuclidic purity tests are essential for the purpose of preventing unnecessary radiation exposure to patients [31,32]. To meet the requirements, the ODS is built for the spectroscopic characterization of irradiated samples, enabling the quantification of overall yield and contamination levels while guiding the subsequent chemical separation process. Due to the mass separation technique employed in RIB production, the contaminations would primarily consist of isobars of target isotopes. For example, ^{111}Cd would be a major contaminant when using UCx target to produce ^{111}Ag.

The setup of the detection system is shown in Fig. 8. An actuator inserts or retracts a plate in the transport plastic guide to stop substrates for measurement or permit passage. Two detectors are installed in an opposite-facing configuration for gamma spectroscopic characterization. One of them is a High Purity Germanium (HPGe) detector, GR3021 provided by Mirion Technologies. This model offers a relative efficiency greater than 30 %, with a full width at half maximum (FWHM) of 1.2 keV at 122 keV and 2.1 keV at 1.3 MeV. Given its specifications, the HPGe detector features good energy resolution over a broad energy range, allowing the discrimination of even low-energy X rays emitted by radionuclides. The Cryo-Pulse® 5 Plus is selected to cool the HPGe detector. As an electrically powered and maintenance-free system once installed, it is appropriate for the on-site characterization application. The geometric efficiency depends on the actual distance of the detector from the source. In fact, the setup is mounted on a rack that allows positioning the endcap of the detector at 100–1000 mm from the irradiated sample.

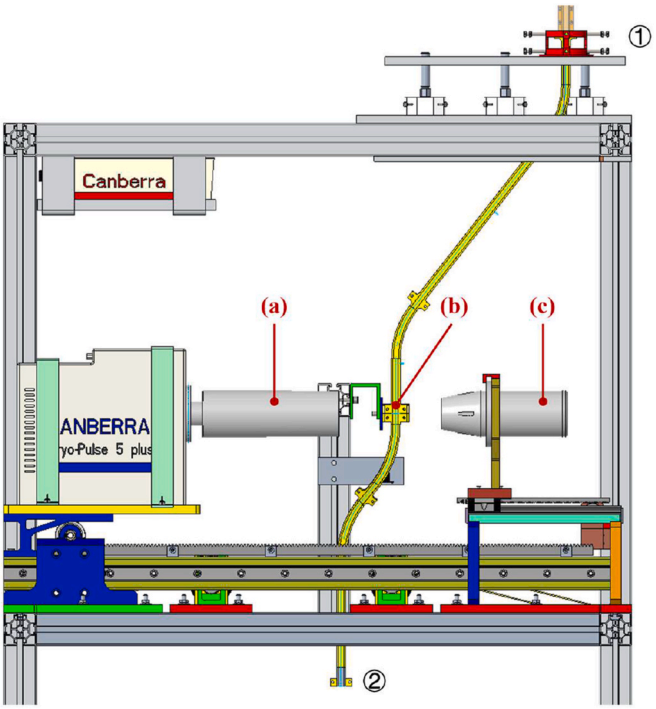

Fig. 8. Offline Detection System setup composed of (a) a Germanium detector, (b) the measurement point where a movable plate blocks the substrate for detection or allows it to pass and (c) a LBC detector. Unloaded substrates pass through the plastic guide from the implantation station (①) to the transportation trolley (②).

Opposite the HPGe detector, a scintillator detector is placed to provide complementary measurements, verifying the scintillator's performance and cross-checking the characterization results of implanted radionuclides. A LaBr3:Ce (LBC) crystal manufactured by SCIONIX was selected. This detector presents a fast anode signal (~100 ns) and negligible dead-time effects below 50 kHz. The crystal, encapsulated in a dedicated aluminium case against its hygroscopicity, has a cylindrical shape with a diameter of 1.5 inches and a height of 1.5 inches. It is coupled with a tube assembly - Hamamatsu H15265-100-01, which comprises an R6231 photomultiplier tube (PMT) and a Super Bialkali (SBA) photocathode. The entire assembly is enclosed within a customized light-shielding plastic case, designed for easily coupling with a similar rack structure as the HPGe detector: the adjustable distance is 100–320 mm.

The data acquisition system for both detectors was built using a CAEN DT-5725 digitizer and a CAEN-DT5780 Multi Channel Analyzer (MCA). The anode signal from the LBC detector is directly fed to DT-5725, while the pre-amplified signal of the HPGe detector is digitized with DT-5780. The two modules are interconnected to ensure consistent data acquisition. In addition, the DT-5780 served as the high-voltage power supply for both detectors. Control of acquisition parameters and voltage settings is managed through the CAEN-CoMPASS software.

To ensure an optimal performance in terms of energy resolution and full-energy peak efficiency, the detectors were characterized in an offline bunker at LNL using different gamma-ray sources (^{22}Na, ^{133}Ba, ^{60}Co, ^{137}Cs, ^{241}Am). To ensure accurate results, background spectra were also recorded and subtracted from the measured data. The spectra obtained with two different detectors are shown in Fig. 9. As expected, the HPGe detector exhibited better energy resolution, while the LBC detector showed higher absolute efficiency. The HPGe will serve as the primary detector for precise characterization of implanted radionuclides in initial online experiments. The LBC detector, currently installed to evaluate the performance of this home-built prototype, has been validated using calibration sources. Its performance for implanted species will be further verified in future online experiments, where its fast response time may make it particularly suitable for high-activity applications.

4.3. Transportation trolley

At the end of the collection substrate life cycle, a trolley is used to transport all irradiated substrates to the designated laboratory for post-processing, as shown in Fig. 10. The trolley remains coupled with the IRIS frame during the entire irradiation stage. The system is based on a cart on which a substrate container is installed, it houses a fixed vial for accommodating the substrates as they descend from the offline detection system. A screw jack assembly enables the operator to adjust the container's vertical position at 50 cm from the irradiated sample. Thanks to this feature, the operator's presence in the experimental area is limited to a short time, enhancing both safety and operational efficiency.

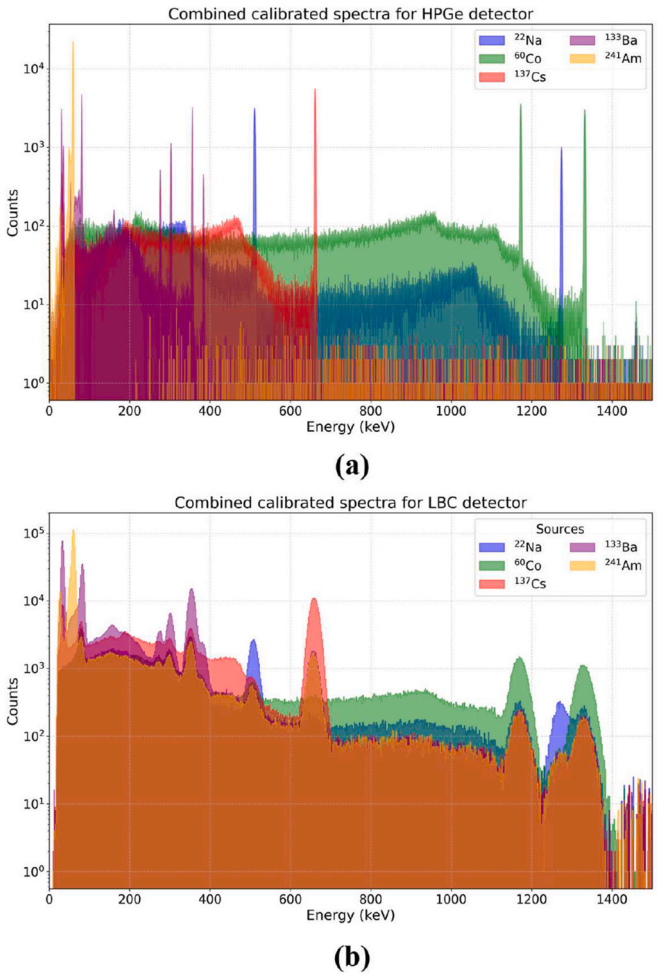

Fig. 9. Combined calibration spectra for different gamma-ray sources obtained with (a) HPGe detector and (b) LBC detector. The distance between the detectors and the sources was approximately 5 cm.

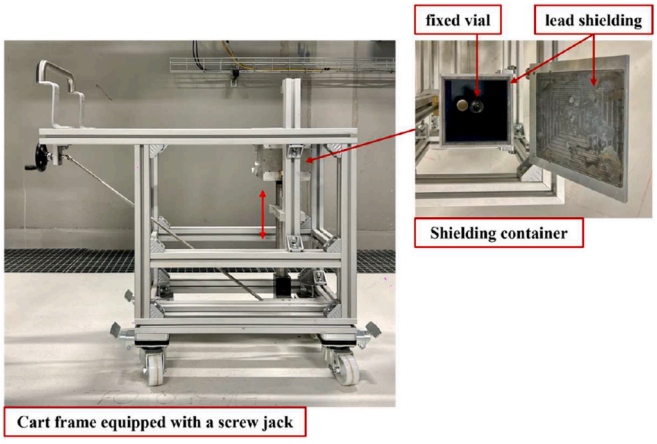

Fig. 10. Transportation trolley coupled with the shielding container. See text for details.

As the core component of the trolley, modular lead shielding with a thickness of 5 mm is attached to the inner surface of the container for protecting operator from radiation exposure. A Monte Carlo (MC) simulation was performed using FLUKA [33] to verify that the current shielding design complies with the requirements for the first collection of radionuclides produced from the SiC and TiC primary targets, in

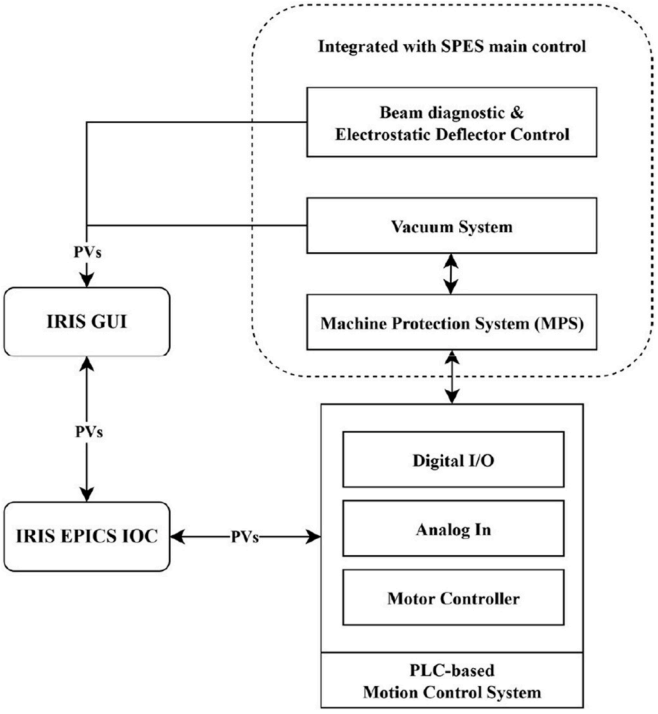

Fig. 11. Global control architecture of IRIS.

accordance with the experiment agenda. The calculation results show that at a handling distance of 50 cm from the irradiated sample, the ambient dose equivalent rate drops below the regulatory limit of 100 μSv/h within 10 min after irradiation for radionuclides of interest, suggesting that the current shielding design is sufficient for transportation shortly after irradiation. The simulation settings for a representative case are provided in Appendix B. Additional shielding layers can be easily incorporated due to the modular configuration, allowing for flexibility in adapting to different experimental requirements.

5. IRIS control system and safety architecture

With the focus to provide a solution fully integrated in the main SPES control system, an EPICS-based control system was developed. EPICS is a toolset to establish servers and client applications in distributed architecture, to achieve a flexible and robust control system for scientific instruments [34]. The network communication between clients and servers is standardized using the TCP/IP-based Channel Access (CA) protocol, which provides high-speed operation, bandwidth and reliability. For IRIS control, the EPICS-based system is responsible for the following tasks:

- Drive the motion of the IS and the ODS as described above according to programmable parameters such as moving speed, number of steps and so on, which involves multiple stepper motors, limit switches and solenoids.
- Coordinate the movement according to information from SPES subsystems, such as vacuum system and beam diagnostic system.
- Interact with the SPES Machine Protection System (MPS) through hardware and software interlocks, to ensure the safety of the entire beamline during the operation stage.
- Provide a global user-friendly interface that is capable of executing the aforementioned tasks and monitoring the data acquired via the subsystems.

The control scheme is based on using a single EPICS server to manage the motion within the IS and to communicate with the SPES main

control through EPICS Process Variables (PVs). The Graphic User Interface (GUI) was realized with the Control System Studio (CSS) application, to be consistent with all the other interfaces for the apparatus controlled within the EPICS frame in the SPES facility. The design architecture of the IRIS control is shown in Fig. 11.

The motion control system is the crucial part of the IRIS self-contained tasks. A Programmable Logic Controller (PLC)-based architecture was adopted. A Finite-State Machine (FSM) was established to automatically perform the procedure described in section 4, which is based on LASAL CLASS 2 platform provided by Sigmatek. The FSM checks its current state every time an input or output PV changes and, if the conditions allow it, the code of the specific state is executed. The IRIS FSM remains in the idle state till the user starts the specific procedure; once the procedure is launched, the FSM executes the step-by-step movements following the instructions given from the GUI. Users can also manually set the moving speed and number of steps of stepper motors and monitor the running state via the GUI. A detailed description of IRIS GUI is provided in supplementary data. In the event of hardware failure such as motor overcurrent or overtemperature, the control system triggers a safe configuration in which the FSM enters the stop state, commanding all actuators to stop and power off. The system remains in this state until an external reset is applied.

The SPES MPS, part of the SPES main control, is responsible for the safety of the machine, avoiding dangerous states that could damage critical components, and for the coordination of interactions between subsystems within the SPES facility [35]. With this scope, it is interconnected with all the systems in the facility and permits the exchange of mutual software interlocks to preserve its integrity. For the IRIS system, the main component involved in MPS is the vacuum chamber where the RIBs implantation would be performed. The MPS determines whether chamber motion is permitted and isolates the IRIS control system from the beamline vacuum system to avoid misoperation. A request must be sent to the MPS to enable chamber movement before operating IRIS, if conditions are favorable, the MPS returns an acknowledgment signal, allowing chamber coupling and evacuation. Once the chamber is coupled, a field signal is sent to the MPS to reset the acknowledgment state. After the chamber vacuum is consistent with the other parts of the beamline and the beam is aligned using the electrostatic system, feedback from the SPES main control is transferred via an EPICS PV to indicate the initiation of the implantation process. During irradiation, the collimator current is transferred through a dedicated EPICS PV and monitored as a safety indicator, where the detection of any current prompts operator intervention for beam refocusing. At the end of irradiation and venting, another request is sent for decoupling the chamber. In case of a software interlock failure or vacuum anomaly, the gate valve isolates IRIS from the rest of the beamline, serving as a hardware interlock managed by the SPES MPS. The automated operation procedures involving MPS are shown in Fig. 12.

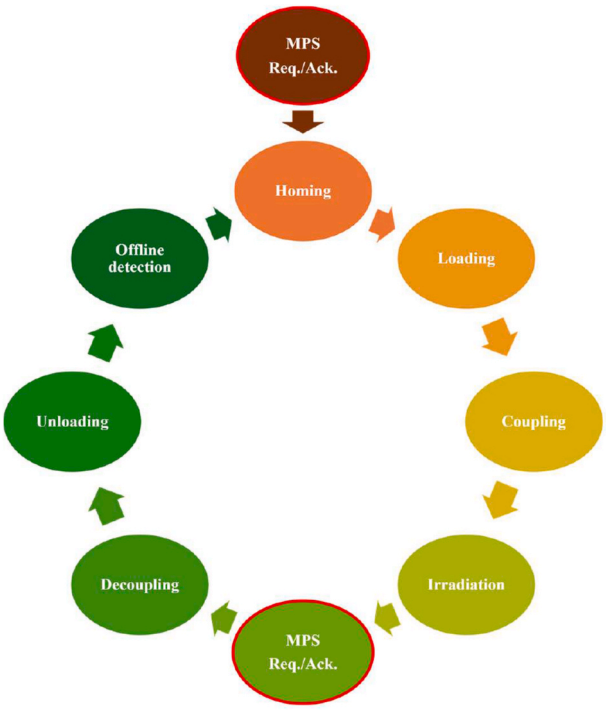

Fig. 12. IRIS automated operation process, the SPES MPS is interlocked to permit vacuum chamber movements.

6. Summary and future work

The SPES facility is currently in the completion stage. Within the low-energy experimental area, the ISOLPHARM beamline has been constructed as part of SPES medical production activities.

For substrates used to collect medical radionuclides of ISOLPHARM interest, dextrates have been determined to be appropriate candidates owing to their chemical compatibility, mitigation of contamination and mechanical robustness during handling operations. At the core of this study, a dedicated ISOLPHARM Radionuclide Implantation Station (IRIS) is developed, to meet the specific requirements of periodical Radioactive Ion Beams (RIBs) implantation and automated handling in an access-control area. The proposed system configuration and commissioning activities have been presented. In particular, reliability tests were performed on Implantation Station (IS) to optimize the performance from the aspects of mechanics and software control. In terms of the Offline Detection System (ODS), the HPGe detector, confirmed by calibration tests to have better energy resolution, is chosen to be primarily used for quality control of irradiated samples, while the energy resolution of the LBC detector will be further evaluated in future online experiments.

Regarding the future work, the IRIS system will be optimized to adapt the SPES phase two operational program using a high-power proton beam and the UCx target. The optimization will include dedicated shielding for the detection system, enhanced shielding measures during substrate transportation. In addition, a detailed calibration of the offline detection system is currently being performed to better determine the detection limits regarding the expected implanted activities, the results will be comprehensively discussed in future work. Furthermore, the integration of beta detection is also foreseen, which aims to improve the capability of implanted species identification.

An experimental campaign using the SPES tape station for RIBs characterization is currently ongoing: the results and operational experience can be referred by the further development and optimization of IRIS, particularly the spectroscopic characterization activities concerned with the offline detection system. The comprehensive IRIS performance within online radionuclide collection experiments will soon be evaluated.

CRediT authorship contribution statement

Daiyuan Chen: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis. **Stefano Corradetti:** Writing – original draft, Resources, Investigation, Funding acquisition. **Davide Serafini:** Writing – review & editing, Validation, Project administration, Investigation. **Aurora Leso:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Massimo Giuseppe Martello:** Software, Investigation. **Alberto Arzenton:** Writing – review & editing. **Michele Ballan:** Validation, Resources, Methodology, Conceptualization. **Antonietta Donzella:** Writing – review & editing. **Anselmo Margotti:** Validation, Resources. **Alberto Monetti:** Resources. **Marcello Lunardon:** Supervision, Resources. **Emilio Mariotti:** Supervision, Resources, Funding

acquisition. **Alberto Andrighetto:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Stefano Corradetti reports financial support was provided by Italian Ministry of University and Research. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.nima.2025.171151.

Appendix A. Motion process of Implantation station

Video A.1. Motion process of implantation station.

Appendix B. FLUKA simulation settings for the shielding assessment with M = 28 u radionuclides

Implantation of radionuclides with M = 28 u was selected as a representative case for the shielding assessment of the container coupled with the transportation trolley. This configuration is expected to be applied in the first online implantation activity, where ^{28}Mg is considered for its potential theranostic applications. The settings adopted for the assessment are summarized in Table B.1. The ambient dose equivalent rate was calculated to be 34 μSv/h at a distance of 50 cm from the irradiated sample at 10 min after the end of irradiation, complying with the regulatory limit.

Table B.1
Parameters used in the FLUKA simulation for the shielding assessment with M = 28 u radionuclides

Target	Proton beam	Implanted radionuclides	Total ion intensity	Irradiation time
SiC	40 MeV, 200 μA	^{28}Mg,^{28}Al,^{28}P	1.50×10^9 nuclei/s	5 days

Data availability

Data will be made available on request.

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