IL NUOVO CIMENTO **46 C** (2023) 32
DOI 10.1393/ncc/i2023-23032-y

Colloquia: SOGIN 2023

Remote handling of radioactive targets at the SPES facility

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received 7 March 2023

Summary. — SPES (Selective Production of Exotic Species) is a new facility being developed by Legnaro National Laboratories of INFN. Once operational, it will be able to generate high-intensity RIB (Radioactive Ion Beams) for research in the field of nuclear physics, and investigate medical applications through the ISOLPHARM project. The interaction of a 40 MeV 200 μA primary beam produced by a cyclotron proton driver with a multi-foil uranium carbide target leads to the production of the radioactive isotopes of interest. Collisions take place within the Target Ion Source (TIS) unit, which is the core of the SPES project. During the operation, a periodic replacement of the TIS unit is required to maintain process efficiency. Automated systems can perform critical tasks under such highly radioactive conditions, including handling, transporting, and storing the TIS unit without human intervention. For this reason, a remote handling framework is currently being developed to meet the functional and safety requirements of the project. In this paper, the SPES target area is presented. Here, remote handling systems ensure the proper operation of the facility, preventing staff from being exposed to high dose rates or contamination problems.

1. – Introduction

The availability of radioactive isotopes as a vehicle for basic studies and many applications in various scientific areas is essential to modern nuclear research. Legnaro National Laboratories of INFN (Istituto Nazionale di Fisica Nucleare) are now engaged in the advanced construction phase of a second-generation nuclear facility known as SPES, or Selective Production of Exotic Species [1]. The plant will employ the Isotope Separation On-Line (ISOL) technique to produce Radioactive Ion Beams (RIB). This method typically relies on the collision between a Primary Proton Beam (PPB) with a thick target. The heating of the target assembly enables the effusion and diffusion of the fission products. As they move away from the target, the released isotopes reach an ion source where they are ionized. The ions are then electrostatically accelerated and mass separated along the RIB line using various electrostatic components. The primary driver of SPES is a high-intensity cyclotron, which generates a 40 MeV 200 μA PPB. Radioactive isotopes are produced as a result of the proton beam's interaction with a Uranium Carbide (UCx) target. By employing the ISOL technique, SPES will develop into a valuable asset for both low-energy and post-acceleration experiments, as well as for the production of radioactive isotopes with potential medical applications.

2. – The SPES project

The SPES project is divided into four major phases (α, β, γ, δ), which refer to the development of a nuclear physics experimental area (RIB facility) on one hand, and the commissioning of a facility for applied research on the other (beams for medicine and neutrons for applied science) [2]. The building's construction and the acquisition of the cyclotron are the objectives of SPES-α, while the primary goal SPES-β is to commission the facility to produce and post-accelerate radioactive ion beams using the ISOL method. The focus in this case is on fundamental research in nuclear physics and related disciplines. SPES-γ aims at the production radionuclides for medical applications, and at the development of innovative related techniques. Finally, SPES-δ will investigate secondary neutron beams for scientific and industrial applications. Figure 1 depicts the SPES accelerator complex, which is located within the context of the existing accelerators at LNL.

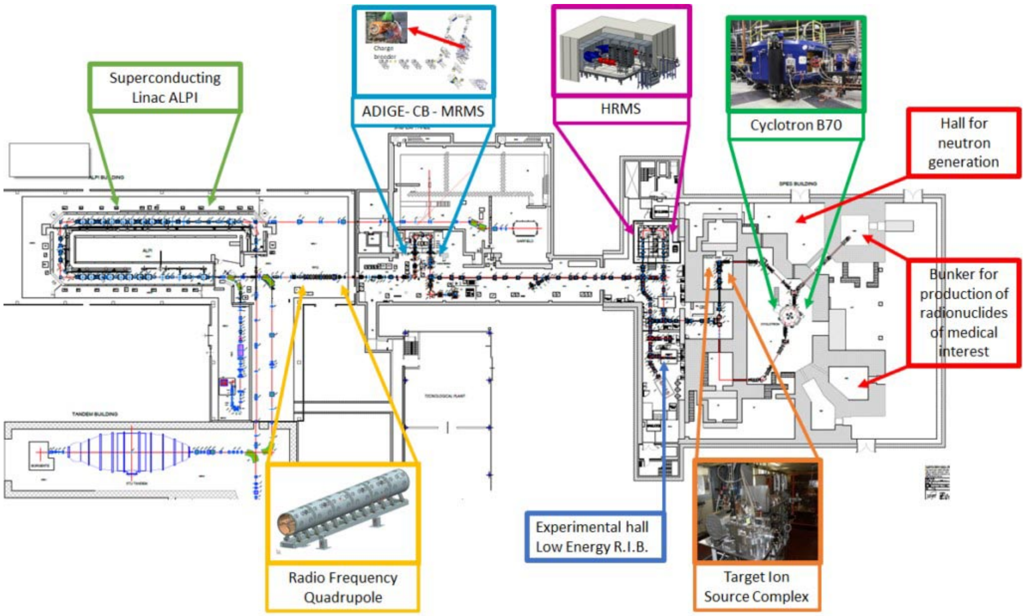

Fig. 1. – Global view of the LNL accelerator complex. The SPES new building is visible on the right, the existing TANDEM-ALPI facility is shown on the left.

2˙1. *SPES as RIB facility.* – The primary driver of SPES is a commercial cyclotron manufactured by Best Cyclotron Systems Inc®. The proton beam can be delivered with an energy range of 35-70 MeV and a total current of up to 750 μA. Two exit ports on opposite sides of the machine provide simultaneous double extraction. An axial injection line and an electrostatic inflector are used by to accelerate H$^-$ ions coming from an external multi-cusp ion source. Protons are extracted by stripping electrons in a thin graphite foil. Transport, setup, and successful commissioning were completed in recent years, driving the beam towards a high-power beam dump designed and built by LNL. Stability and reliability testing have been performed with an average beam current of about 200 μA. The system has then been verified in a 70 MeV - 500 μA configuration, showing good reproducibility and stability. Dual extraction was finally demonstrated. The Best® 70p Cyclotron installed at SPES is visible in fig. 2.

SPES-β is devoted to the production of RIB for fundamental physics. In this context, the most challenging task is the Target Ion Source (TIS) design and construction. To ensure the most effective ionization of the target atoms, prevent their loss, and ensure their efficient diffusion and effusion, this process necessitates a thorough understanding of a broad range of scientific principles. Following the extraction from the ion source, the ions are directed towards a Wien Filter, which can provide a selection of ΔM/M $\sim$ 1/150. Additional elements, such as a magnetic dipole placed outside the production bunker, enable an improved selection, with a resolution of ΔM/M $\sim$ 1/300. The described system is known as Low-Resolution Mass Separator system (LRMS). This enables the RIB transport, through electrostatic elements, towards the beam diagnostic Tape Station, the experimental beam lines or the post-acceleration complex. The diagnostic Tape Station is intended for both TIS development/optimization and beam characterization prior to delivery to end users. If necessary, the combined action of a Beam Cooler and a High-Resolution Mass Separator (HRMS) can further purify the beam up to a resolution

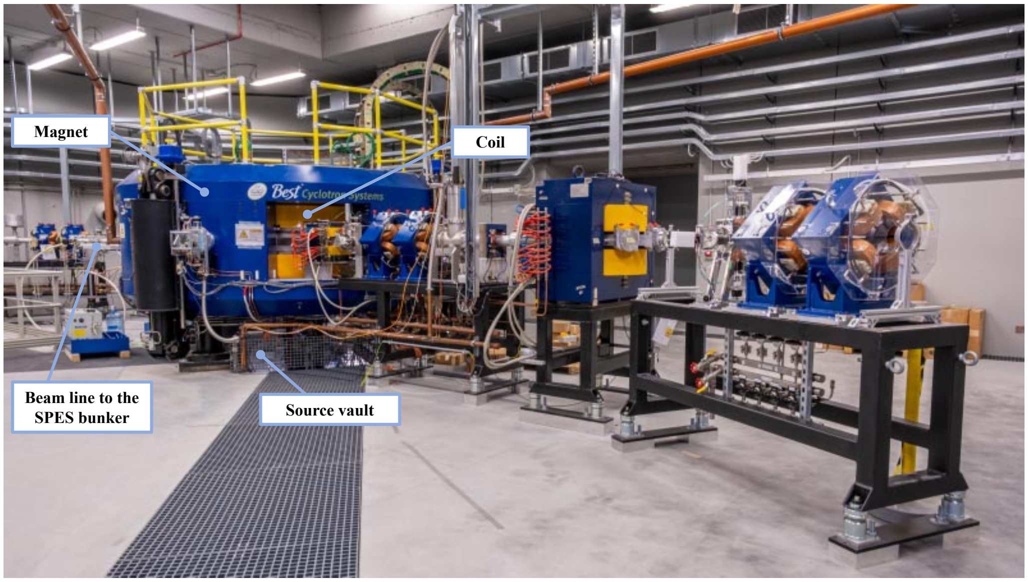

Fig. 2. – View of the Best® 70p cyclotron: the SPES primary driver.

of $\Delta M/M \sim 1/20000$. The beam line is divided at the HRMS exit, sending the highly resolved RIB either back to the low-energy area or towards the post-accelerator. In this second case, the charge state must be changed from 1+ to n+ prior to injection into the ALPI superconducting linac. The RIB is therefore routed through a long electrostatic focusing channel to an ECR Charge Breeder. A RFQ pre-accelerator will then increase the beam energy to match the ALPI acceptance. This element is intended to accelerate exotic isotopes in CW mode with $A/q = 3\div 7$. At this point, the beam will subsequently be reaccelerated in the ALPI linac and directed toward high-energy experimental areas.

2·2. *SPES as application facility.* – The SPES-γ stage focuses on both radioisotope production techniques and research and development of novel radioisotopes for use in Nuclear Medicine. In the second area of interest, LARAMED and ISOLPHARM are the two primary ongoing projects. On one hand, LARAMED seeks to produce novel medical radionuclides using conventional technology, with a particular emphasis on those that are not currently available on the market. On the other hand, the goal of the ISOLPHARM project is to exploit the SPES ISOL facility to produce a wide spectrum of radioisotopes for medicinal applications. In this context, ISOLPHARM intends to conduct a feasibility study on a novel method for producing radionuclides with extraordinarily high-specific activity as radiopharmaceutical precursors [3, 4]. ISOLPHARM has been registered as international patent by INFN.

Another use for the SPES cyclotron PPB is to generate intense neutron fluxes. SPES-δ will be the first Italian neutron facility for irradiation in applied research. The project will employ two different irradiation points: a spinning Pb-Be target with adjustable thickness, and a Berillium target followed by moderator blocks for delivering reactor-like neutron fluxes.

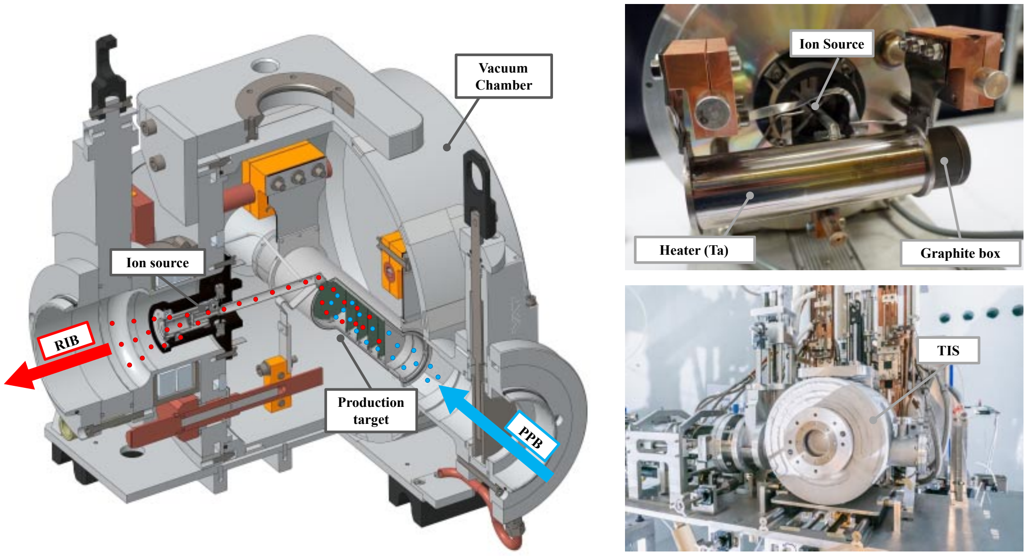

Fig. 3. – Section view of the SPES Target Ion Source (TIS) unit (on the left), and actual system under test installed on the SPES Front-End (on the right).

3. – The Target Ion Source unit

Legnaro National Laboratories has been working on the development and optimization of the SPES TIS unit since 2006. Figure 3 shows a section view of the assembly on the left and depicts the actual system on the right. In this context, SPES targets have been especially designed to dissipate the 8 kW power deposited by the PPB and to efficiently release the generated radioisotopes [5]. The SPES TIS unit architecture was optimized for a 40 MeV proton primary beam 200 μA current on a thick UCx target, relying on the knowledge gathered in other International Labs (ISOLDE [6], HRIBF [7]). The SPES target is made up of seven disks that are designed to improve power dissipation and extraction efficiency. The target material is heated to a temperature of 2300 °C. As visible in fig. 4, specific tests at LNL demonstrated the sliced SPES target's ability to produce higher yields than the bulk configuration [8]. Figure 5 shows the internal architecture of the SPES sliced target (on the bottom) and a target disk exposed to thermal gradients during a measurement, simulating the power deposition due to the primary beam (on the top left). The proton beam impinges on the TIS at a 90-degree angle with respect to the extracted RIB, interacting with the production target, and finally stops within a graphite beam dump located within the target assembly. Isotope ionization is enabled by different types of ion sources, developed and coupled to the target in order to meet specific needs. The SPES Surface Ion Source (SSIS) [9] offers good efficiency and selectivity for alkali and alkaline earth metals. The SPES FEBIAD Ion Source can ionize alogens and noble gases, albeit with a limited selectivity [10]. Finally, the Resonance Ionization Laser Ion Source (RILIS), which is based on laser resonant photoionization [11], can be used for the remaining elements [12]. During the commissioning phase, the SPES facility will operate with a decreased proton beam intensity ($5 \div 10$ μA). A custom target assembly composed of Silicon carbide (SiC) [13] target disks will be exploited in these conditions. Following this stage, the planned experimental campaign at SPES will make

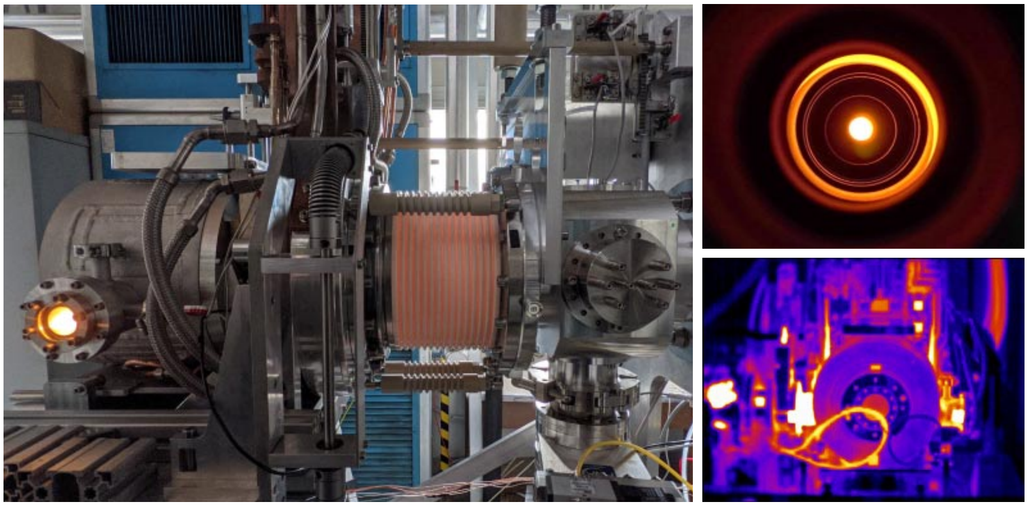

Fig. 4. – Thermal tests of the SPES TIS unit during the precommissioning phase at LNL. TIS unit installed on the test station (on the left), target disks at 2300 °C (top right), thermography of the assembly (bottom right).

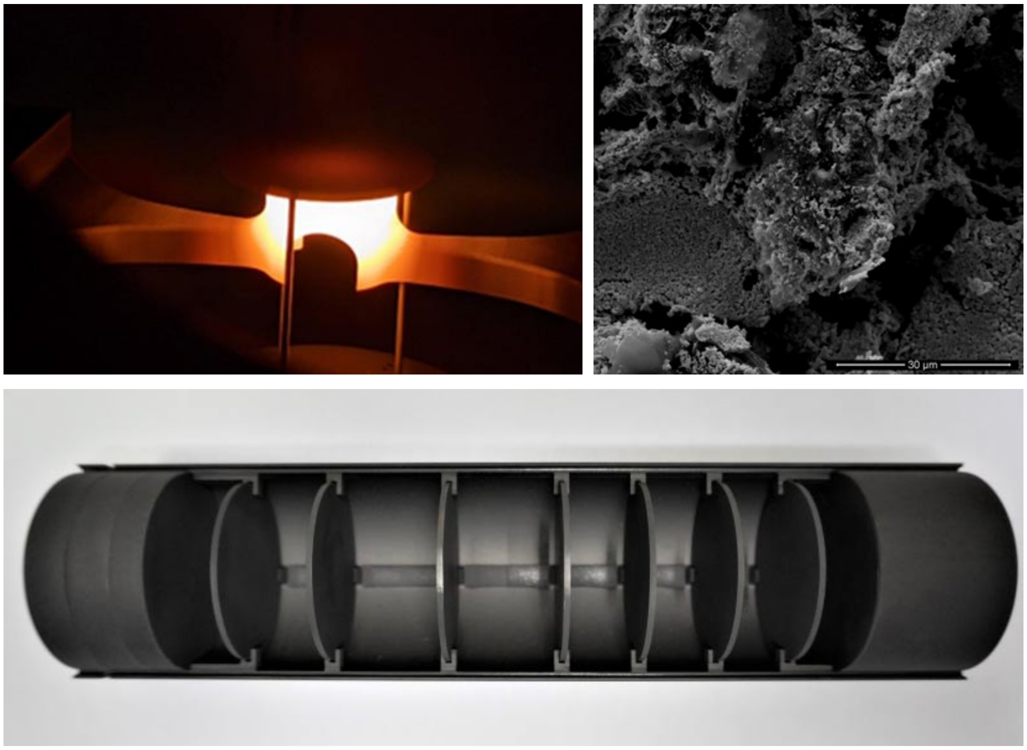

Fig. 5. – The target assembly including 7 UCx disks within a graphite container (on the bottom). A SiC target disk exposed to thermal gradients (top left), microstructure of uranium carbide containing carbon nanotubes (top right).

use of Uranium carbide (UCx) targets. Over the past few years, improvements have been made to the target microstructure and porosity in order to enhance the isotope release properties [14]. These uranium carbides typically include some dispersed residual carbon in an effort to improve their thermal characteristics. Recent years have seen extensive research into the choice of the kind and quantity of carbon, for instance by using graphite, nanotubes, and graphene. Figure 5 shows a SEM (Scanning Electron Microscope) of the microstructure of a porous uranium carbide containing carbon nanotubes. In addition to standard UCx targets, the use of Titanium carbide (TiC) disks [15] at SPES may be advantageous for the production of medically relevant isotopes in the context of the ISOLPHARM project [16].

4. – Remote handling

The irradiation of the TIS unit at the SPES Front-End will last for two weeks. During this phase the target is impinged by the PPB for the production of rare isotopes. Thereafter, the unit will cool down in the ISOL hall for the following two weeks for a rapid radioactive decay. The SPES operational schedule has been drafted based on the need for periodic replacement of the unit due to numerous aging signs experienced in both target and ion source, leading to a reduction in global performance. The contribution from the target and ion source assembly, together with the isotope deposition on the extraction electrode [17] and the residual activation of to the SPES Front-End [18] are the primary sources leading to a predicted significant gamma dose rate. To address this issue, the SPES remote handling framework is currently being developed [19]. A variety of automated systems have been designed to reduce staff exposure to ionizing radiation while ensuring the remote handling process. The operational area of the described Remote Handling systems is shown in fig. 6.

The journey of a TIS unit starts at the supply point, an automated loading dock where it is positioned manually after the assembly and offline tests performed in the production laboratory. The primary transport vehicle, known as the Horizontal Handling Machine (HHM), is then in charge of the remote transportation of fresh and activated TIS units between the various irradiation and storage locations. The HHM consists of an AGV-based system (Automated Guided Vehicle) following an optical track on the ground, while a cartesian manipulator is fitted to the top for pick-up and removal tasks. The system includes three linear axes used for the longitudinal and vertical displacement of a pneumatic clamp and a shielded case in which the unit is placed during transportation. The HHM vehicle under development at LNL is visible in fig. 7 (on the left). In the ISOL hall, the new TIS unit is remotely positioned on the SPES Front-End for irradiation by the HHM. Here, it is coupled to the primary and secondary beam lines through four lead-screw axes operated by radiation-tolerant pneumatic motors. Two mechanical switches and a linear potentiometer operate in parallel to provide precise position detection in every coupling direction. Once connected to the plant, a variety of connections are used to maintain vacuum, electrical power supply, water cooling, gas, and signal exchange throughout the irradiation phase. Preliminary simulations have estimated the TIS unit activity reached at the end of this stage, showing a level of approximately $3 \cdot 10^{13}$ Bq [5]. The subsequent cooling period of two weeks reduces the equivalent dose rate of

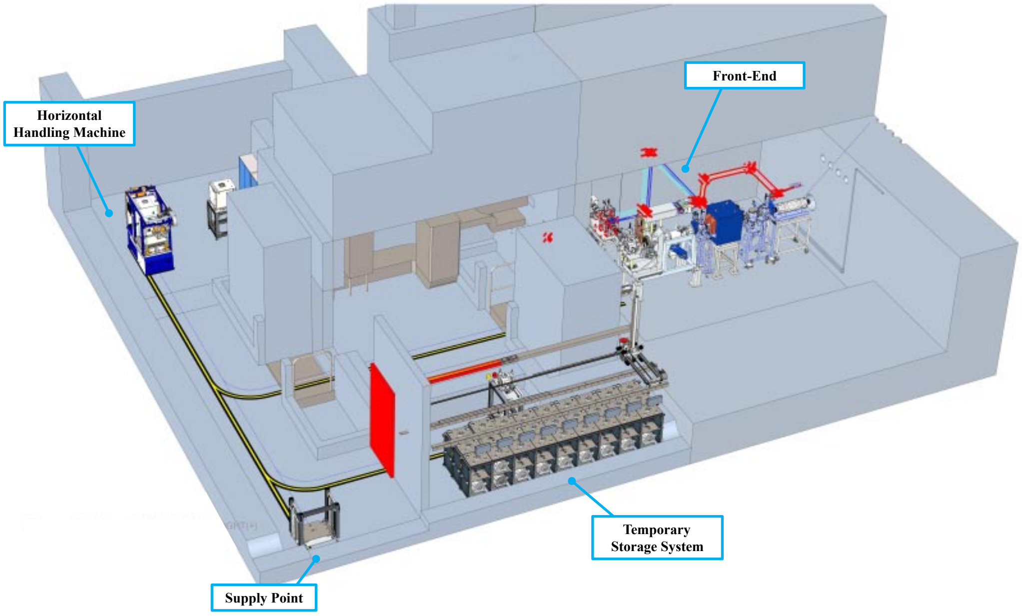

Fig. 6. – Overview of the SPES remote handling systems operational area.

about two orders of magnitude, leading to a safer operation. The HHM relocates the activated TIS unit to a designated long-term storage location before the next irradiation cycle starts. The installation of a new TIS unit on the SPES Front-End completes the standard TIS unit replacement procedure. Up to 54 activated TIS units can be stored in the Temporary Storage System (TSS) for radioactive decay before being dismantled. The system capacity covers more than five years of nominal plant operation, at a rate of 10 irradiation cycles per year. The highly radioactive TIS units are positioned in the internal storage locations of the TSS rack, made up of 9 adjacent shielded modules, each containing 6 cells on 2 layers. Over time, the storage arrangement is gradually reconfigured, moving lower dose sources to external positions. The proposed storage strategy minimizes the contribution of the TSS to the external ambient dose. A cartesian manipulator, sliding over of the rack, permits the opening and closing of the shielding lids on the top of the storage locations and the subsequent lowering of the TIS unit. The handling of the different components benefits from a standardized gripping interface. Following a decay process lasting between 2 and 5 years, exhausted TIS units are withdrawn from the TSS and transported to a dedicated Hot Cell where they can be safely disposed of. As shown in fig. 7 (center, right), the TSS is currently being manufactured, and it will shortly be installed in its final location inside the SPES plant. Successful completion of remote handling procedures requires solid coordination and interaction by means of physical and fieldbus interlock signals, which are exchanged with external systems as the SPES Access Control System (ACS) and the Machine Protection System (MPS). The above-mentioned partners are respectively responsible for the safety of personnel and the operating machines. High-level monitoring and control of the running tasks is possible via a dedicated Graphical User Interface (GUI) and thanks to a set of Pan Tilt Zoom (PTZ) surveillance cameras. The SPES Remote Handling framework's design phase benefited from the knowledge acquired in other laboratories, such as TRIUMF [20] and CERN [21].

Fig. 7. – The Horizontal Handling Machine (HHM) during the tests in the SPES remote handling laboratory (left), the Temporary Storage System (TSS) during the construction phase prior to the installation (center, right).

5. – The low-energy beam lines

The SPES RIB line begins with an electrode, which is part of the Front-End and is used to extract ions from the TIS unit via a 40 kV potential difference. Moving away from the source, the RIB line includes two transversal plane steerers and a triplet for beam focusing. A Wien Filter installed in the SPES bunker provides a preliminary separation stage, rejecting more than 99% of contaminants into the vertical plane. The RIB leaving the SPES bunker is finally focused by a triplet. A Low-Resolution Mass Separator system has been installed outside the production bunker to improve the Wien Filter's resolution and provide the user with a beam of the desired mass. The transport beam line was designed to handle beams with energies ranging from 20 keV to 45 keV. The layout of the experimental hall has been conceived planning four distinct experimental points. The first is a standard tape station that will be used for both the characterization of the radioactive beam and conducting experiments. The second is a beta Decay Station (b-DS) paired with SLICES (Silicon for Conversion Electrons), which calls for particularly sharp focussing. A third experimental point has been dedicated to the ISOLPHARM Radionuclide Implantation Station (IRIS), while the space designated for a fourth experimental point has been reserved for upcoming upgrades to the facility.

6. – Conclusions

The SPES facility's remote handling strategy for the transportation and storage of radioactive targets has been described in this contribution. The proposed solutions employ different automated systems that collaborate to perform unmanned operations in a critical area in order to minimize worker exposure to ionizing radiation. The planned facility commissioning phase will provide an opportunity to demonstrate the effectiveness and reliability of the described framework.

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