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Spes: An intense source of Neutron-Rich Radioactive Beams at Legnaro

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Abstract. The Isotope Separation On-Line (ISOL) method for the production of Radioactive Ion Beams (RIB) is attracting significant interest in the worldwide nuclear physics community. Within this context the SPES (Selective Production of Exotic Species) RIB facility is now under construction at INFN LNL (Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Legnaro). This technique is established as one of the main techniques for high intensity and high quality beams production. The SPES facility will produce n-rich isotopes by means of a 40 MeV proton beam, emitted by a cyclotron, impinging on a uranium carbide multi-foil fission target. The aim of this work is to describe the most important results obtained by the study of the on-line behavior of the SPES production target assembly. This target system will produce RIBs at a rate of about 10^{13} fissions per second, it will be able to dissipate a total power of up to 10 kW, and it is planned to work continuously for 2 week-runs of irradiation. ISOL beams of 24 different elements will be produced, therefore a target and ion source development is ongoing to ensure a great variety of produced isotopes and to improve the beam intensity and purity.

1. Introduction

The SPES facility has the primary goal of producing intense exotic beams, as described in [1], [2]. The radioactive nuclei will be produced by the interaction of a 40 MeV proton beam, at currents up to 200 μ A, with a properly designed target. The specific radioactive ion beam (RIB) will be selected making use of the isotope separation on-line (ISOL) method and delivered to several experimental halls in which nuclear physics experiments will be performed. The C70 H- cyclotron of Best Cyclotron Systems, with a maximum current of 0.750 mA rowing two exit ports will be used as a proton driver accelerator with variable energy (35-70 MeV) [2]. Two proton beams can be delivered at the same time, sharing the total current of 0.750 mA. In an ISOL-based facility, the fission fragments are generated inside the grains of the ceramic material constituting the target [3]. They subsequently diffuse towards the surface of the grains; once there, they move towards the ion source by random transport in high vacuum (effusion). In order to facilitate both the diffusion and the effusion mechanisms, the temperature of the target is kept as high as possible, in the order of 2000 °C. In order to manage a target with up to 10 kW





Figure 1. The SPES Target-Ion Source Unit, without the water cooled aluminum cover.

power deposition, the development of new techniques for the target production and handling are necessary [4]. For this reason, the SPES target design has been optimized in order to dissipate the foreseen beam power and maximize the release efficiency and at the same time to make use of devices (typically ion sources) developed in collaboration with other laboratories. The Target-Ion Source assembly (TIS), see figure 1, incorporates many of the engineering features used in other ISOL RIB facilities design. The SPES target-ion source chamber is indeed designed for easily removal or reconnection to the beam transport system, to allow for both the substitution of the target material and ion source maintenance, as required in a high radioactive environment. The unit is coupled to the RIB line and to the proton driver beam by means of two quick connectors and two pumping ports which can be sealed off with valves. The handling system must be designed in order to move the target chamber unit, housed in a lead container, into the area where the target will be irradiated, and to connect it to the beam lines. After the irradiation stage, the target chamber must be removed from the beam lines, stored in the lead container and finally sent out of the hot area for further handling and long term storage.

The ions produced with the ion sources are accelerated towards the ion extraction electrode by a potential up to 40 kV. After passing through a High-Resolution Mass Separator (HRMS), the selected isotopes will be stopped inside a charge breeder and extracted with increased charge (n^+). A final mass selector will be installed before reaching the PIAVE-ALPI re-accelerator [5], to clean the beam from the contaminations introduced by the charge breeder itself. The re-accelerator complex will deliver ion beams at energies of 10 AMeV and higher, for masses in the region of $A = 130$ amu, with an expected rate on the secondary target of 10^8 pps. The aim of this paper is to describe the main devices of the SPES RIB source: the general design of the target assembly, the target material, the ion sources and the TIS handling system.

2. Target and Ion Source complex

The Target Ion Source (TIS) system constitutes the working core of the facility [4]. It converts the 40 MeV, 200 μ A proton beam coming from the cyclotron into a radioactive ion beam. The TIS system is constituted by the production target and the ion source devices, linked together by

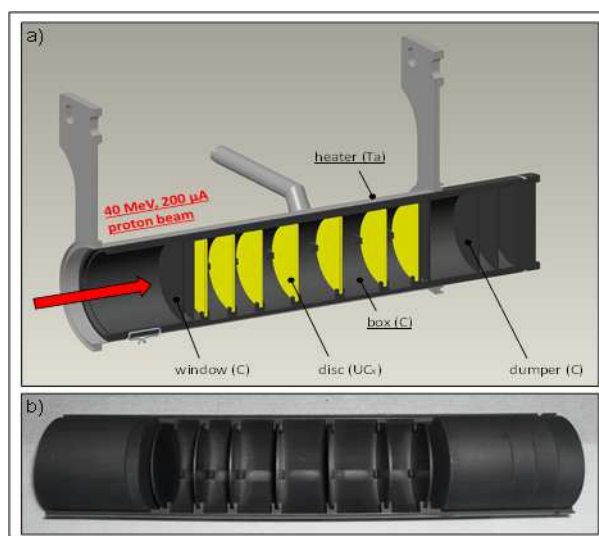


Figure 2. a) The SPES production target. b) Picture of the graphite box containing the discs and both the window and the dumper assemblies.

means of a tubular transfer line made of tantalum [6]. All the aforementioned components work in general at very high temperatures, close to 2000 °C. The SPES production target (see figure 2) is composed of 7 uranium carbide discs characterized by a diameter and a thickness of 40 and 1.3 mm, respectively. They are spaced in the axial direction in order to dissipate by thermal radiation the power of the primary beam passing through them. Two thin graphite windows are positioned at the proton beam entrance, preventing the undesired loss of radioactive isotopes and an excessive temperature drop for the first and the second target discs. Four circular graphite dumpers, with thickness ranging from 0.8 up to 10 mm, stop the proton beam at the rear side of the production target. All the discs, windows and dumpers are closed inside a tubular graphite box, that is located under vacuum inside a water-cooled chamber and has to maintain the average temperature of 2000 °C. All the SPES TIS systems presented in figure 2 are closed inside a water-cooled vacuum chamber, capable to dissipate the amount of power associated to both the target and the ion source, and to guarantee a vacuum level of approximately 10^{-6} mbar. By means of commercial fast couplings, it provides the water for the cooling system and the electrical current needed to heat by Joule effect the production target and the ion source.

3. The SPES Ion Sources

In this section the ionization mechanisms that will be implemented in the SPES ion sources, that are surface ionization, laser ionization and electron impact ionization are described. They correspond to three different ion sources, that define, as a consequence, three different TIS systems, as reported in figure 3. The SPES Surface Ion Source (SSIS) [7] is a tubular hot-cavity ion source capable to produce efficiently 1^+ ions for the elements with ionization potential smaller than 7 eV, mainly for the alkali and the alkaline earth metals (such as Rb, Cs, Sr and Ba). It is composed of a Re tubular ionizing cavity connected to one side to a tantalum support and to the other side to the transfer line. During operation both the SSIS and the transfer line are resistively heated at temperature levels close to 2000 °C by the same power supply. The geometry of the SPES Laser Ion Source (SLIS) [8] is similar to the SSIS, but in this case the material used to manufacture the hot-cavity is tantalum, characterized by a lower work function value respect to rhenium, in order to reduce the undesired contaminants coming from the surface

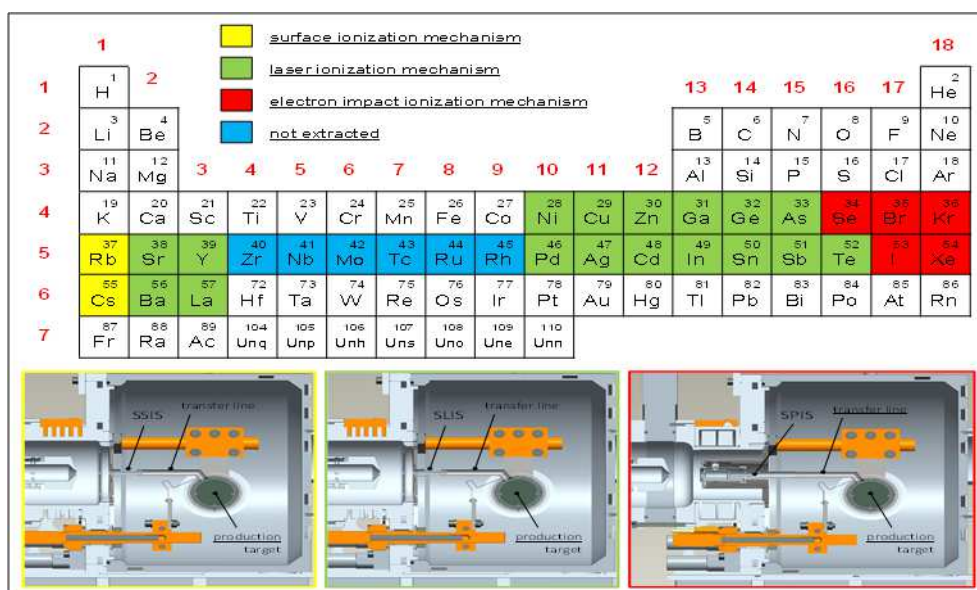


Figure 3. Main fission products in the SPES production target and representation of the three main target ion source systems.

ionization. In the resonant laser ionization process atoms are stepwise-excited leading finally to continuum. It typically consists of two or three steps, everyone characterized by a precise absorption energy level for the atom, i.e. a precise emission wavelength for the lasers. This ionization process is chemically selective and it can produce an extremely pure ion beam. The laser beams enter the beam line thanks to a view port positioned at the first mass separator magnet. The SPES Plasma Ion Source (SPIS) [9], [10] is a Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source. It is a non-selective device, and is particularly used for the ionization of noble gases. The two main components of the SPIS are the cathode and the anode, made of tantalum and molybdenum, respectively. The former is heated at high temperature by Joule effect, allowing the production of electrons by thermionic emission on the surface facing the anode, whereas the latter is kept at approximately 150 V with respect to the rest of the source, confining the plasma from which the beam is extracted.

4. Target discs production

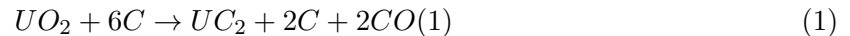
The properties required for the SPES target material [11], as in the case of other ISOL facilities, are directly related to the efficiency of the processes undergoing between the isotopes production and their release, which can be divided into two distinct phases:

- The diffusion of the isotopes, generated inside the ceramic material grains, towards their surface. This mechanism is governed by Ficks laws.
- The effusion in high vacuum towards the ion source, consisting of random walks and bounces on the surrounding surfaces, each one characterized by a specific sticking time which contributes to the overall delay.

The obtainment of a fast release of isotopes depends on a large number of parameters, both relative to the material properties and to the target operative conditions. The characteristics required for a material to work with a high efficiency as an ISOL target can be summarized as [12]:

- A sufficiently high cross-section for the reaction between the target constituting atoms and the primary beam.
- The target material must be able to work for a sufficient amount of time at high temperatures in high vacuum.
- The material should exhibit high thermal emissivity and conductivity.
- The target should be highly porous to favor the release of isotopes towards the ion source.

The research on materials for the SPES target represents an important part of the entire facility development, both in terms of material structural properties and target behavior under irradiation in specifically designed on-line tests. The most used ISOL target material is by far uranium carbide, since it fulfills all of the requisites above highlighted. The most common type of uranium carbide produced, tested and used in ISOL facilities is commonly referred to as UC_x , indicating it is composed of different phases: uranium dicarbide (UC_2), graphite (C), and a minor amount of uranium monocarbide (UC). In the last years, the synthesis and characterization of uranium carbide thin discs have been successfully carried out, and the production methodology can be considered ready to be used to produce real UC_x targets when SPES will be operative. The synthesis is based on the reaction between a proper uranium source, typically uranium dioxide, and graphite:



which is made to occur at high temperature (up to 1800 °C) in high vacuum (10^{-6} mbar). In order to characterize the target behavior during irradiation, two target prototypes, constituted by seven UC_x thin discs, with the same layout of the SPES target but with scaled dimensions were tested at the OLTF (On-Line Test Facility) of Oak Ridge National Laboratory (ORNL) [13], [14], [15]. The on-line irradiation tests performed at OLTF with a 50 nA, 40 MeV primary proton beam demonstrated the capability of the SPES target prototypes to produce and release a set of more than 75 isotopes, with half-lives ranging from seconds up to few hours.

5. The TIS Handling system

The target handling system consists of three devices: in one hand there is the coupling table positioned on the front-end apparatus which is in charge of coupling and uncoupling the target chamber to the beam lines. On the other hand, there are two independent handling devices (called vertical and horizontal devices) that will move the target chamber to and from the irradiation bunker zone. The horizontal one will be used as the primary handling device while the vertical one is intended as a backup solution. Figure 4 shows the location of each device on the facility layout. The coupling table is located inside the bunker chamber where a high level of radiation is present. The system is operated using only electro-pneumatic actuators, mechanical switches and passive linear potentiometers. Four pneumatic motors with screw-type transmission system will move the chamber, the protonic beam line vacuum pipe and two vacuum valves in order to perform the coupling and uncoupling operations.

The horizontal handling device is formed by an Automatic Guide Vehicle (AGV) that will move the target chamber to and from the bunker area and a cartesian handling system, located on the top of the AGV, that will move the target chamber to and from the coupling table once the AGV is in position. The Cartesian device is implemented using a screw type system and electrical motors. A PLC will be installed on the AGV in order to perform the operation, and it will communicate with a user interface using wireless communication. The whole system will be operated on batteries. Therefore, the system will work in a completely wireless way.

The vertical handling device will access the bunker through a hole on the bunker roof. It will

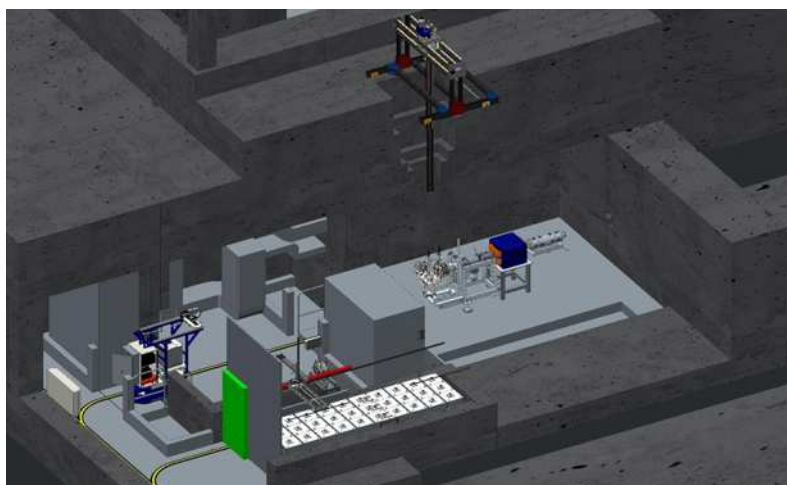


Figure 4. Layout of the SPES target chamber handling system.

grab the target chamber using an interface tool placed on top of the chamber.

The control of the whole system will be completed automatized using PLCs (Programmable Logic Controllers). In order to increase its reliability, the control system is designed using redundancy as much as possible. Furthermore, the system will allow the switch over to manual operation, in case an operator should intervene in case of emergency or failure on the automatic system.

6. Conclusions

The SPES project at INFN-LNL is one of the main nuclear physics developments in Italy for the next years. It is organized as a wide collaboration among the INFN Divisions and Laboratories, Italian Universities. SPES is a second generation ISOL facility and is an up to date project in this field with a very competitive throughput representing a step forward for the implementation of the European project EURISOL. The relevance of the project is not only related to nuclear physics research but also to astrophysics and applied physics. The main field of applied research is the possible production of radiopharmaceuticals for medicine. The ability to simultaneously operate the ALPI Linac and the two-exit-port Cyclotron will result in a large improvement in the research capabilities at LNL. The first exotic beam at SPES is expected within 2019.

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