Nuclear Instruments and Methods in Physics Research B 541 (2023) 236–239

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, B

journal homepage: www.elsevier.com/locate/nimb

Low energy radioactive ion beams at SPES for nuclear physics and medical applications

A. Andrighetto[a], L. Centofante[a,*], F. Gramegna[a], A. Monetti[a], M. Ballan[a], A. Zenoni[b], S. Corradetti[a], G. Lilli[a], M. Manzolaro[a], T. Marchi[a], A. Arzenton[a,c], O.S. Khwairakpam[a,c], D. Scarpa[a], A. Donzella[b], E. Mariotti[c], G. Meneghetti[d], P. Colombo[d], L. Biasetto[e], R. Oboe[e], M. Lunardon[f], D. Rifuggiato[g]

[a] INFN, Laboratori Nazionali di Legnaro, Viale dell'Università, 2, 35030 Legnaro, Italy
[b] Dipartmento di Ingegneria Meccanica e Industriale Università degli Studi di Brescia, Via Branze 38, 25123 Brescia, Italy
[c] Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente and INFN Siena, Via Roma 56, 53100 Siena, Italy
[d] Dipartimento di Ingegneria Industriale, Università di Padova, Via Venezia 1, 35131 Padova, Italy
[e] Dipartimento di Tecnica e Gestione dei Sistemi Industriali, Università di Padova, Stradella S. Nicola, 1, 36100 Vicenza, Italy
[f] Dipartimento di Fisica ed Astronomia, Università di Padova, Via Marzolo 5, 35122 Padova, Italy
[g] INFN, Laboratori Nazionali del Sud, Via S. Sofia, 62, 95123 Catania, Italy

ARTICLE INFO

Keywords:
SPES project
ISOL facility
Radioactive beams
ISOLPHARM

ABSTRACT

Over the past decades many accelerator facilities have been built in order to produce radioactive nuclei. Among the falcility under construction, SPES (Selective Production of Exotic Species) is the Italian ISOL (Isotope Separation On Line) facility in the installation phase in these years in the Laboratori Nazionali di Legnaro. The innovative aspect of this facility is that the radioactive beam produced by fission induced by the proton beam, produced by a high power cyclotron, interact with a multi-disks uranium carbide target. The formed RIB will be sent directly to the low energy experimental area and, afterwards, to the post-acceleration complex. Currently the installation program concerning the SPES RIB source provides the set-up of the apparatus around the production bunker. The main objective of SPES project is to provide, in the next years, the first low-energy radioactive beams for beta decay experiments using the b-DS (beta Decay Station) set-up and for radiopharmaceutical applications by means of the IRIS (ISOLPHARM Radioactive Implantation Station) apparatus. In this work, all the specific issues related to the SPES RIB and the Low Energy beam lines will be reported. The main RIB systems, such as ion source systems, target-handling devices and the installation of low energy transport line, will be presented in detail.

1. Introduction

Modern nuclear research relies heavily on the availability of radioactive isotopes as a vehicle both for fundamental studies and for many applications in various fields of science. A large number of facilities for the production of radioactive ion beams (RIBs) already in operation or under construction employ the so-called ISOL (Isotope Separation On-Line) technique [1]. This technique is generally based on a primary beam impinging on a thick target. The production atoms diffuse and effuse from the target material and find their way to an attached ion source where they can be ionized. Finally, the ions are electrostatically accelerated, by means of a platform voltage and mass separated into appropriate electromagnetic elements. The fact that the isotopes are produced at rest makes the ISOL method ideally suitable either for low energy experiments and also for post acceleration using well-established acceleration techniques. Moreover, the production of radioactive isotopes for medical use (mainly radiopharmaceuticals) and other applications with unprecedented purity and high specific activity becomes possible.

SPES is a second generation nuclear facility for the production of radioactive ion beams based on the ISOL technique. It is currently in the advanced construction phase at the Laboratori Nazionali di Legnaro of INFN (Istituto Nazionale di Fisica Nucleare). The Radioactive Beam Production (RIB) production method is based on a proton beam of about

* Corresponding author.
E-mail address: lisa.centofante@lnl.infn.it (L. Centofante).

https://doi.org/10.1016/j.nimb.2023.05.044
Received 25 January 2023; Received in revised form 11 May 2023; Accepted 11 May 2023
Available online 26 May 2023

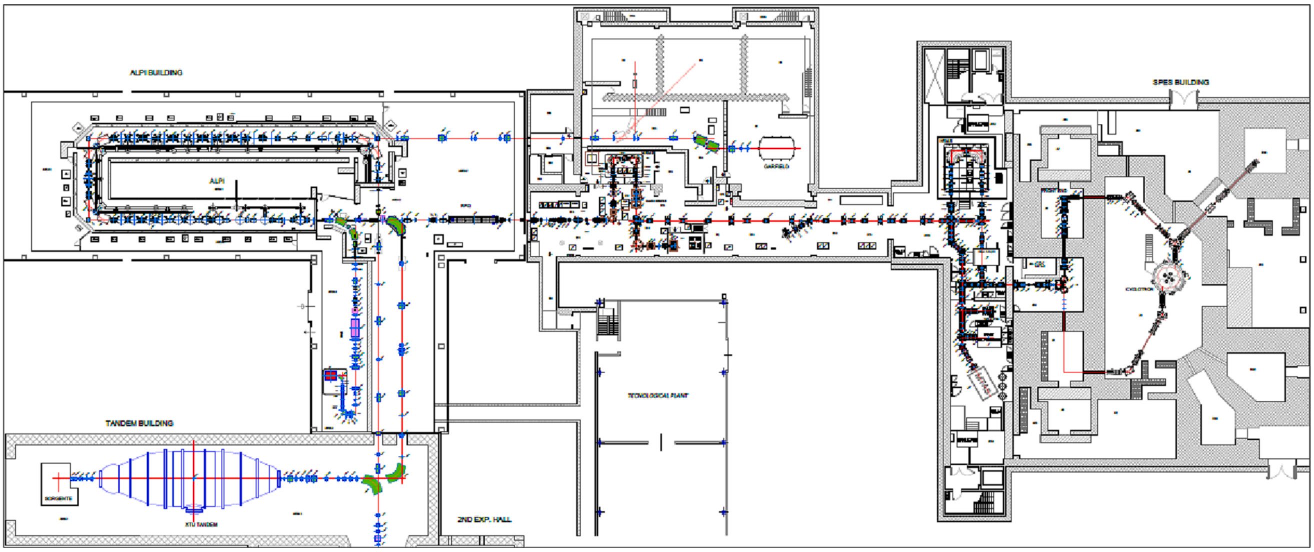

Fig. 1. The whole accelerator SPES complex.

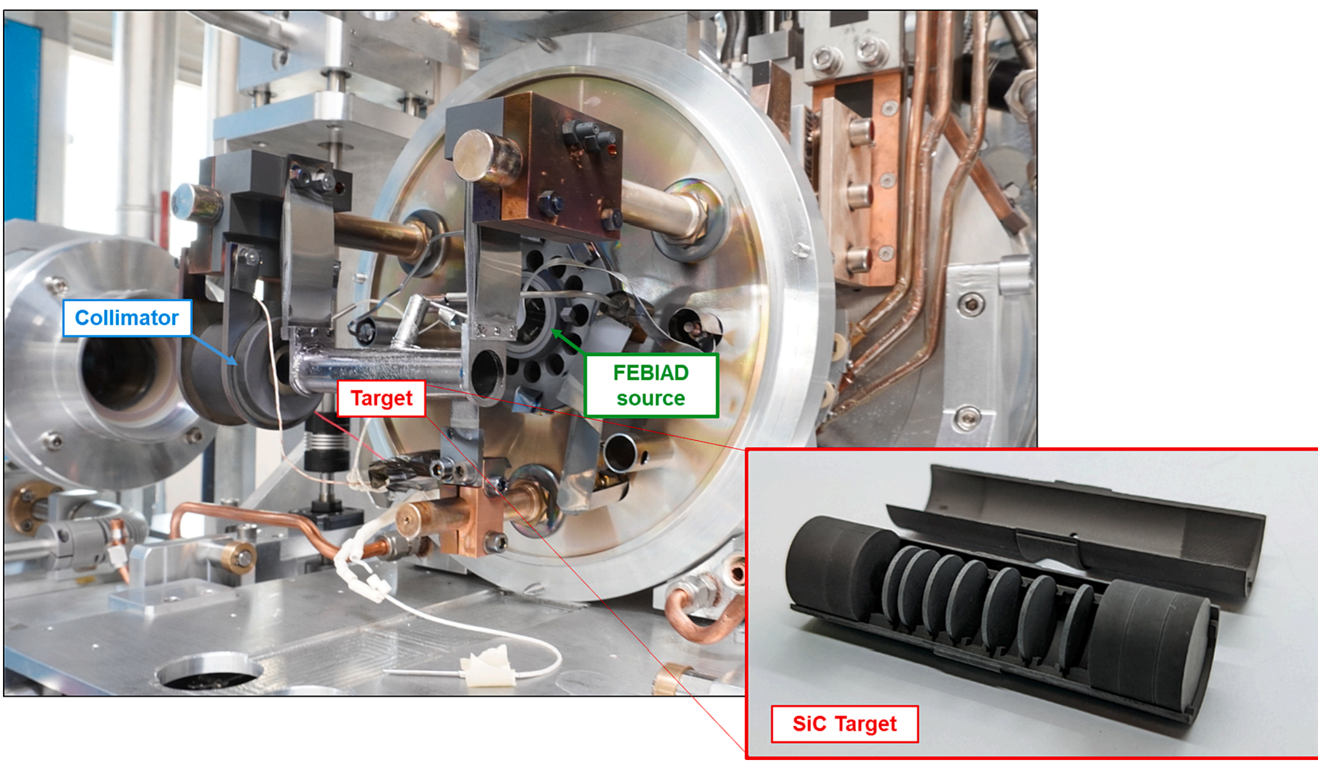

Fig. 2. Picture of the SPES TIS unit tested at high temperature for two weeks.

40 MeV energy and 200 μA current, produced by a high intensity cyclotron, which interacts with a Uranium Carbide (UC_x) target. Radioactive neutron-rich isotopes are produced by nuclear fission induced on uranium at a rate of about 10^{13} fission/s. The primary driver is a commercial cyclotron produced by the Best Cyclotron Systems Inc. The proton beam can be delivered in the 35–70 MeV energy range with a maximum of 750 μA total current. The machine accelerates H- ions provided by an external multi-cusp ion source via an axial injection line and an electrostatic inflector. Protons are extracted by stripping the electrons in a thin graphite foil. The layout of the facility complex is shown in Fig. 1, together with the existing accelerator complex, Piave-Tandem – Alpi, which, at present, delivers stable beams at LNL.

2. The target ion source complex

The SPES Target and Ion Source (TIS) unit has been developed at Legnaro National Laboratories since 2006. In particular, the SPES Uranium Carbide target is designed to dissipate the important amount of power deposited by the 40 MeV 200 μA primary proton beam, and to release in an efficient way the produced radioisotopes [2]. A surface ionization source [3] can be coupled with the target, with the possibility to implement resonant laser ionization in its tubular hot-cavity. As an alternative, a plasma ion source (FEBIAD type) can be used. As specified in the following paragraph, a SiC target will be used for the SPES facility commissioning. In this phase the proton beam intensity will be

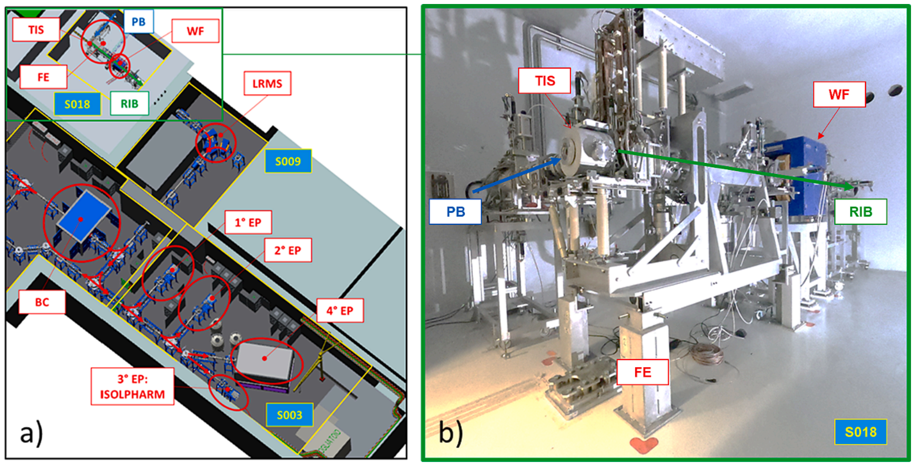

Fig. 3. Overview of the SPES ISOL facility (a) and current status of S018, the SPES target irradiation bunker (b).

consistently reduced (5–10 μA) and a scaled target version will be adopted (13 mm disks in diameter instead of the nominal 40 mm). The scaled SiC target coupled with a FEBIAD source has been tested at high temperature, together with all its auxiliary components such as type C thermocouples and gas injection tubes for the ion source (Fig. 2). A lot of constructive details have been consolidated during the last years and the TIS unit is now ready for the first irradiation at the SPES facility.

The research activities on target materials have been focused in recent years on three different materials [4,5], representing the three different stages of the SPES facility operation: silicon carbide, titanium carbide and uranium carbide (in order of use). Silicon carbide (SiC) is the first material that will be used in the SPES facility commission and in early stages of its operation with pilot beams such as ^{26}Al. This material has been extensively studied in recent years, especially focusing on its thermal and thermo-mechanical properties [6]. Detailed emissivity measurements have been carried out and, most recently, commercial SiC materials in the form of disk have been thoroughly characterized, the focus being on their high temperature thermal conductivity and thermo-mechanical resistance.

Uranium carbide (UC_x) is by far the most used material in ISOL facilities. After using SiC for the facility commissioning, most of the foreseen experimental campaigns at SPES will use UC_x as a target. In many years of research, different recipes have been developed to produce targets with optimized release properties. These targets have been optimized in terms of microstructure (nano grain size) and porosity (open interconnected pores). Porosity is particularly important since it helps in releasing isotopes produced inside the target, in particular very short-lived ones. In the framework of SPES, in the last ten years some target production and testing activities have been conducted in collaboration with universities and research centers. It is important to underline that in most cases, these uranium carbides contain a certain amount of dispersed residual carbon, with the aim of improving thermal properties. The choice of the type and amount of carbon is an aspect which was thoroughly investigated in recent years, for example by making use of graphite, nanotubes, graphene. Titanium carbide (TiC) has recently been studied and characterized in detail for different applications in ISOL facilities. At SPES, this target material could be a choice for the production of medically relevant isotopes of scandium in the framework of the ISOLPHARM project. Many different approaches are being explored for the production of porous TiC-carbon composites with optimized properties at the nanoscale. These involve the use of alternative carbon sources such as phenolic resin or sucrose and the use of sol–gel approaches in place of traditional production techniques based on dry methods (powder mixing and pressing). These innovative methods allow to have a better control on the final materials properties, particularly in terms of type and amount of porosity [7].

3. Target handling

The TIS unit is planned to be irradiated on the SPES Front-End for a two-week period. It is then left at rest within the ISOL hall for a first steep radioactive decay in the following two weeks. The significant expected gamma dose rate, mainly due to the TIS unit activation, extraction electrode surface isotope deposition, and residual activation of the SPES Front-End promoted the development of a set of automated systems, referred to as the SPES Remote Handling framework [8]. Different systems have been designed to meet the TIS unit life cycle, with the ultimate goal of reducing staff exposure to ionizing radiation. The TIS unit journey starts from the Supply Point, an automated loading bay where it is manually positioned once assembled. From this point, the unit management hands over to the main transport vehicle, named Horizontal Handling Machine (HHM), in charge for the remote transfer of fresh and activated TIS units among the various production and storage stations. A fresh TIS unit is subsequently installed on the SPES Front-End within the ISOL hall for irradiation. Before the next irradiation cycle begins, activated TIS unit is moved (thanks to the HHM) to a dedicated long-term storage site. The standard TIS unit replacement procedure concludes with the installation of a new TIS unit on the SPES Front-End. The Temporary Storage System (TSS) can house up to 54 activated TIS units for radioactive decay before dismantling.

4. The low energy beam lines

The first part of the Front-End is constituted by an axial movable extractor electrode which can apply a difference of potential of about 40 kV. Subsequently the accelerator includes two couple of steerers for each transversal plane, followed by a triplet for beam focusing. A preliminary separation stage is provided by a Wien Filter that was installed in the SPES bunker, able to reject more than 99% of the contaminants into the vertical plane. Finally, a triplet focuses the beam out of the SPES bunker. The current status of the SPES target bunker hall is presented in Fig. 3. The ground plants are now being installed and the completion of the bunker is expected soon.

The subsequent beam line out of the SPES bunker is composed by in-house developed components, in particular electrostatic triplets and 90° benders. They are always interposed by steerers, to correct beam misalignment, and diagnostics, composed by Faraday Cup and Beam Profilers for the tuning with a pilot beam. A Low Resolution Mass Spectrometer was installed in the second hall to increase the resolution of the Wien Filter ($m/\Delta m = 300$) and provide to the user a beam with the desired mass number. The beam can be then delivered following various paths, together the main components of the beamline. Either the beam can be sent to the low energy experimental points (EP) or to the post-

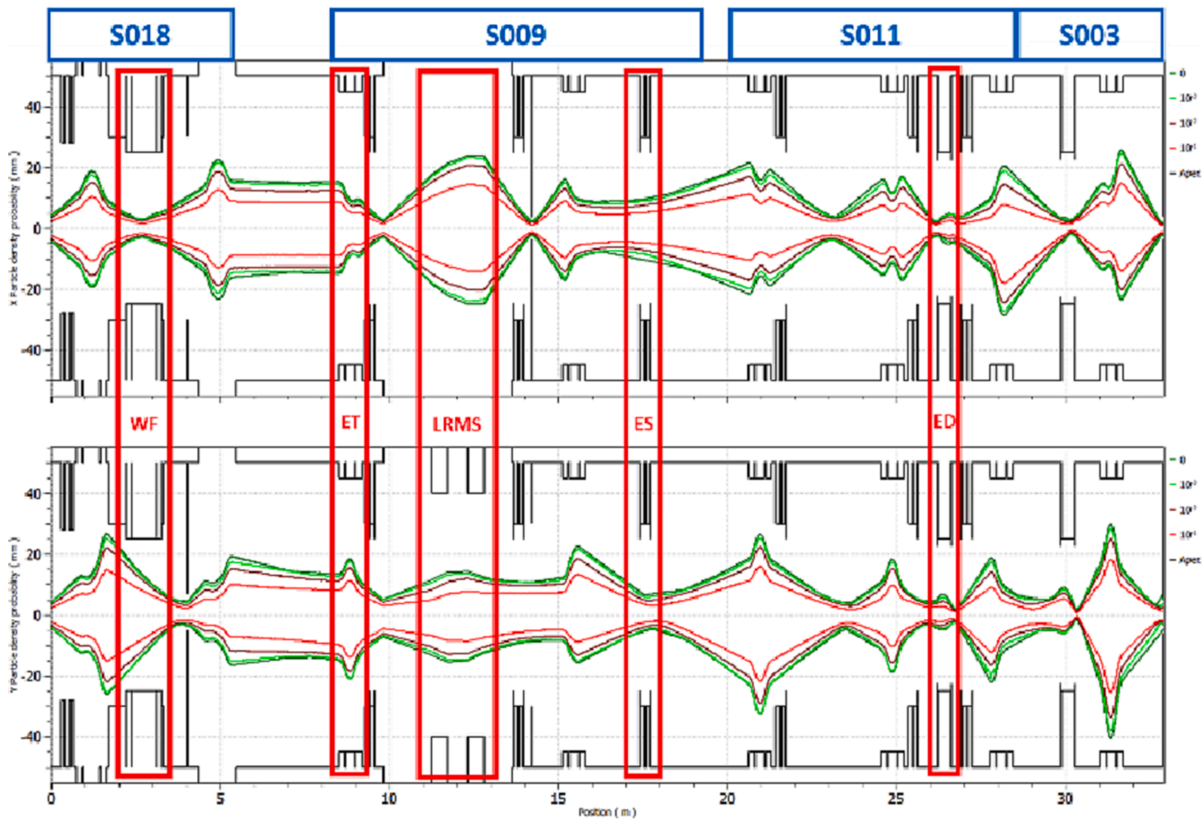

Fig. 4. Beam transport calculation up to the first Experimental Point, highlighting the main optical elements.

acceleration. In both cases, if the isobaric mass separation is requested, the beam can be injected into a section of the beamline including a beam cooler followed by the High Resolution Mass Spectrometer. The transport beam line has been designed to handle beam in the energy range from 20 keV up to 45 keV, even if the nominal energy is 40 keV. In Fig. 4, the multi-particles simulation by using TraceWin [17] of the complete beamline up to the first experimental point is presented. An increase of the emittance of about 10% on the x-plane and 30% on the y-plane is foreseen, mainly caused by the dispersion introduced by the separating magnets, and by the sharp focusing performed at the last triplet to before the experimental point. Currently, four different experimental points have been foreseen. The first is common a Tape Station that will be used both to characterize the Radioactive Beam and for experiment. The second is another beta Decay Station (beta-DS) coupled with SLICES (Silicon for Conversion Electrons), which requires a particular sharp focusing. The third experimental point was reserved for ISOLPHARM [9], a new project under development at LNL, aimed at the research on innovative radiopharmaceutical exploiting the high purity radionuclides producible with the SPES ISOL facility.

5. Conclusions

SPES is the project for the production of reaccelerated exotic beams by ISOL technique. The system, presented in this article and currently in advanced installation phase at LNL, will allow to obtain in the next years, the first low-energy radioactive beams for beta-decay experiments and for radiopharmaceutical applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] T. Nilsson, European RIB facilities – status and future, Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms 317 (Part B) (2013) 194–200, https://doi.org/10.1016/j.nimb.2013.06.037.

[2] A. Monetti, A. Andrighetto, C. Petrovich, M. Manzolaro, S. Corradetti, D. Scarpa, F. Rossetto, F. Martinez Dominguez, J. Vasquez, M. Rossignoli, M. Calderolla, R. Silingardi, A. Mozzi, F. Borgna, G. Vivian, E. Boratto, M. Ballan, G. Prete, G. Meneghetti, The RIB production target for the SPES project, Eur. Phys. J. A 51 (10) (2015), https://doi.org/10.1140/epja/i2015-15128-6.

[3] M. Manzolaro, F. D'Agostini, A. Monetti, A. Andrighetto, The SPES surface ionization source, Rev. Sci. Instrum. 88 (9) (2017) 093302.

[4] S. Corradetti, M. Manzolaro, S.M. Carturan, M. Ballan, L. Centofante, G. Lilli, A. Monetti, L. Morselli, D. Scarpa, A. Donzella, A. Zenoni, A. Andrighetto, The SPES target production and characterization, Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms 488 (2021) 12–22.

[5] A. Gottberg, Target materials for exotic ISOL beams, Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms 376 (2016) 8–15, https://doi.org/10.1016/J.NIMB.2016.01.020.

[6] M. Manzolaro, S. Corradetti, M. Ballan, R. Salomoni, A. Andrighetto, G. Meneghetti, Thermal and mechanical characterization of carbides for high temperature nuclear applications, *Mater (Basel, Switzerland)* 14 (2021), https://doi.org/10.3390/MA14102689.

[7] A. Zanini, S. Corradetti, S.M. Carturan, P. Colombo, A. Andrighetto, G. Franchin, Sucrose-based sol-gel synthesis of microporous titanium carbide as target material for the production of radioisotopes, Microporous Mesoporous Mater. 337 (2022), 111917, https://doi.org/10.1016/J.MICROMESO.2022.111917.

[8] G. Lilli, L. Centofante, M. Manzolaro, A. Monetti, R. Oboe, A. Andrighetto, Remote handling systems for the Selective Production of Exotic Species (SPES) facility, Nucl. Eng. Technol. 55 (1) (2023) 378–390, https://doi.org/10.1016/j.net.2022.08.034.

[9] F. Borgna, et al., Early evaluation of copper radioisotope production at ISOLPHARM, Molecule 23 (10) (2018) 2437, https://doi.org/10.3390/MOLECULES23102437.