The SPES facility at Legnaro National Laboratories

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Abstract. Worldwide efforts to tackle the nature of exotic nuclei comprise the construction of new-generation Radioactive Ion Beam facilities. The Italian community is deeply involved in the process and the construction of SPES at Legnaro National Laboratories (INFN) is progressing. This contribution describes the layout of SPES in all its flavours, from Nuclear Physics to Applications in Nuclear Medicine and Neutron Physics. In particular, the status of the SPES-β ISOL facility, together with some of the relevant physics cases and the associated equipment are described.

1. Introduction

The development of new experimental techniques is one of the main drivers for progress and new discoveries in any field of science. In Nuclear Physics, the playground is set by the Nuclear Chart and today’s challenge is its exploration towards the limits of nuclei’s existence (drip lines) both in the neutron-rich and neutron-deficient sides as well as in the super-heavy frontier. A recent review by M. Thoennessen [1] shows how the development of new technologies and techniques can be directly related to the number of nuclei that have been discovered and more deeply studied along the last century. The analysis also shows that any technique unavoidably leads to a saturation that is typically overcome by the introduction of new concepts. This is the case of heavy-ion fusion-evaporation reactions that led to a peak in the number of nuclides discovered per year in the 1960’s. The same is true, in the following decades, for target or projectile fragmentation/disintegration reactions that have been used to produce on-line or in-flight Radioactive Ion Beams (RIBs). The same argument clearly holds for acceleration and detection techniques. On one hand, the basic features like nuclide’s lifetime, ground state properties...
or first excited state properties can be accessed even if a very limited number of rare ions is available and already provide interesting physics output [2]. On the other hand, complete spectroscopic information and precise reaction-cross section datasets can be collected only if a sufficiently intense (larger than $10^5$-$10^6$ pps) and pure beam is available. So, for the next step, the main keywords of the next-generation RIB facilities are beam intensity and beam purity. Within this endeavor, SPES (Selective Production of Exotic Species) at Legnaro National Laboratories (LNL, INFN, Italy) is designed as a second-generation RIB facility using the Isotope Separation On-Line (ISOL) technique. A thick target (normally Uranium Carbide, UCx) is bombarded with a high intensity (up to 250 µA) primary proton beam ($E_p \sim 30$-$70$ MeV) to induce up to $10^{13}$ fissions/s. The radioactive ions produced in the target are then extracted, ionized and selected to provide a post-accelerated beam to the experiments. In the case of SPES, the post accelerator is the existing ALPI superconducting linear accelerator, already operational at LNL. In addition, the availability of a high-intensity proton driver triggered the development of several parallel projects in different fields of applications.

The next paragraph will provide a global overview of SPES in all its facets while paragraph 3 will focus on the basic Nuclear Physics Research plans and the related instrumentation.

2. The SPES project

SPES is conceived as a multidisciplinary facility. The project is organized in four main phases: alpha, beta, gamma, delta. SPES-α is the primary proton driver and represents the beating-heart of the full system. SPES-β is the laboratory for the production and post-acceleration of Radioactive Ion beams using the ISOL technique. Its focus is on basic research in Nuclear Physics and related disciplines. SPES-γ aims at producing radionuclides for applications, mainly in the medical sector, and at the development of new related techniques. SPES-δ will to produce secondary neutron beams for science and applications.

![Figure 1. Layout of the SPES facility coupled to the existing heavy-ion accelerator complex at LNL. See text for details.](image)
The layout of the facility is shown in Figure 1, together with the existing Tandem-Piave-ALPI complex that is already functioning at LNL. The components of SPES-β are indicated in green and comprise the ISOL source, the High-Resolution Mass Separator (HRMS), the Charge Breeder (CB) and a new Radiofrequency Quadrupole (RFQ) injector for ALPI. The halftone red screened area indicates the SPES-γ part of the facility with separate bunkers for Applied Research in Nuclear Medicine and others for routine Radioisotope production. The halftone orange part denotes the SPES-δ area.

2.1. SPES-α

The primary driver is a commercial cyclotron produced by the Best Cyclotron Systems Inc. [3]. The proton beam can be accelerated in the 35-70 MeV energy range with a maximum of 700 µA total current. The machine offers simultaneous double extraction from two exit ports on opposite sides. It is an Azimuthally Varying Field (AVF) compact cyclotron with four sectors. The main magnet is energized by resistive coils. Two delta shaped electrodes, each fed by 55 kW of RF power (56 MHz, 4th harmonic mode) can reach a 70 kV voltage. 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 H⁺ electrons in a thin graphite foil. Figure 2 shows a picture of the machine installed at LNL. Transport, setup and successful commissioning were accomplished in 2015-2017, driving the beam to a home designed and built beam dump. The latter was made of two cooled copper plates, tilted by 10°, in order to reduce the maximum power density to less than 200 W/cm².

Stability and reliability tests were conducted [4]. During a 5 days run at 40 MeV, the average beam current was 201.18±0.97 µA. Tests were then extended to 70 MeV - 500 µA with good stability and repeatability. Dual extraction was proven as well.

The machine is now being maintained and the second extraction beam line construction is being finalized.

2.2. SPES-β

As anticipated, SPES-β is dedicated to the production of RIBs for Nuclear Physics studies. It represents the most peculiar and challenging part of the whole SPES project starting from the design and construction of the Target-Ion Source (TIS) system [5] to the High-resolution mass purification and RIB injection into ALPI. The core is an ISOL source built to sustain up to 8 kW of proton beam power on the target. The design phase of the TIS profited from the expertise gained at HRIBF (Oak Ridge, TN, USA) [6] and ISOLDE (CERN) [7] that pioneered the technique at lower proton current (~10 µA) and
in a different energy regime, respectively. The SPES TIS was optimized for a 40 MeV proton primary beam 200 µA current on a thick UCx target. Other composite targets have been studied like SiC [8] or B₄C [9]. At SPES, the beam power is directly released on the thick production target that was divided in several slices to increase power dissipation and extraction efficiency (see Figure 3). The target material is heated up to 2000°C. Specific tests on the TIS system have been performed and have demonstrated the capability of the sliced SPES target to produce extra yields with respect to the bulk configuration, which was originally used at HRIBF.

Figure 3. The SPES-b front-end and target ion source.

The TIS is integrated in the Front End (FE), a custom designed piece of instrumentation that will be installed inside the production bunker. One offline FE version has been used in the R&D phase and for testing purposes. The final version is now procured and ready to be installed in one of the SPES-β production bunkers. The FE is used to couple the cyclotron beam to the TIS itself through the proton entrance channel. The proton beam impinges on the TIS at 90 degrees with respect to the extracted RIB, interacts in the UCx target and finally stops in the last part of the target set-up (beam dump), which consists of a series of graphite disks. In order to satisfy different needs, three kind of TIS have been developed: a Surface Ion Source (good efficiency and selectivity for elements like Rb, Cs, Ba); a Plasma Ion Source (necessary to ionize elements with high ionization potential, though with very poor selectivity); a Laser Ion Source (which is based on the laser resonant photoionization and it is very powerful and highly selective) [10,11].

Following the extraction from the TIS, the ions are directed towards a Wien Filter, still located in the production bunker, which can provide a selection of ΔM/M ~ 1/150. Outside the bunker, a first series of elements (a Magnetic Dipole plus a series of electrostatic elements) will complete the selection reaching a resolution of ΔM/M about 1/200. This block is called Low-Resolution Mass Separator system (LRMS).

At this stage, the ions are pre-selected, slightly ionized (1+) and accelerated at 40 kV that is the FE high-voltage platform potential. This allows to transport the non-reaccelerated RIBs using electrostatic elements towards one of the following stages:
   a) the Tape Station for beam diagnostic;
   b) the experimental areas requiring non-reaccelerated beams;
   c) the post acceleration.

A detailed view of the full scheme is given in Figure 4. It is worth mentioning that the lines are designed to allow, only if needed, the beam purification through the High-Resolution Mass Separator (HRMS) [12] that has a design specification of ΔM/M=1/20000. Such performance is possible only if the beam transverse emittance is reduced to few π mm mrad. At this purpose, a dedicated Beam Cooler has been developed [13] and will be installed as injector for the HRMS.

The diagnostic Tape Station is designed both for the TIS development/optimization and for the beam characterization before the delivery to the final users.
In the case of post-accelerated beams, the ions are then directed towards the “ADIGE” section, which is made of a Charge Breeder [14], a medium mass resolution separator (MRMS) and the RFQ injector [15], before reaching the ALPI accelerator. The installation of the Charge Breeder, the MRMS and its High Voltage platform and a pilot beam stable-ion source are in an advanced stage of completion.

The SPES performances in terms of production beam intensities and, for post accelerated RIBs, at the secondary target position (experiment) have been evaluated with MCNPX and reported on the LNL website (see figure 5). Users can download the Beam Tables together with the description of the system from the web page. A sketch of the expected beams with a realistic estimate of the expected intensities is shown in Figure 5.
2.3. SPES-γ
The availability of an intense proton primary beam immediately calls for its exploitation in several fields of application. SPES-γ is the part of the project that deals both with the R&D on new radioisotopes for Nuclear Medicine research and with radioisotopes routine production. On the first topic there are two main initiatives running: the LARAMED and the ISOLPHARM projects. The systematic production will be managed by a private company.

LARAMED [16] aims at developing innovative medical radionuclides, those that are presently unavailable for the scientific and clinical community. Although the research facility is yet to become fully operative, the LARAMED team has already started working on the cyclotron production of conventional medical radionuclides, such as Tc-99m, and on emerging radionuclides of high potential medical interest, such as $^{65}$Cu, $^{47}$Sc-47, and $^{52}$Mn-52. LARAMED summarizes a series of initiatives, all sharing the conventional thick target approach. In those cases, the R&D on target production and post-irradiation processing, together with integral reaction cross section experimental measurements take most of the scientific efforts.

ISOLPHARM aims at using the already developed ISOL target technique to collect the radioisotopes after on-line separation and purification. This allows, in some cases, to collect very high and pure specific activities. The ISOLPHARM technological challenges are shifted towards an efficient extraction and purification and efficient collection, closer to the SPES-β case. The production yields must be carefully evaluated and experimentally determined. ISOLPHARM is an INFN international registered patent.

2.4. SPES-δ
The cyclotron’s proton beam can be used to produce neutron fluxes. Two main irradiation points have been proposed: one with a standard Be target followed by moderator blocks for providing reactor-like neutron fluxes, the other one using a rotating Pb-Be target with variable thickness. In the latter, the different energy loss of the proton beam inside the target allows to shape the outgoing neutron energy to the desired spectrum shape (e.g. terrestrial neutron flux simulation) or to obtain a quasi-monoenergetic neutron flux using a thin target and selecting the proper incoming proton energy. Together with a direct proton irradiation facility, SPES-δ will be a completely new Italian facility for irradiation in applied science.

3. Nuclear Physics with exotic beams at SPES
The Nuclear Physics program exploiting the beams produced at SPES-β is quite broad and was established in a series of thematic workshops and International Conferences [17]. The Scientific Advisory Committee of SPES endorsed a large number of letter of intents (more than 40). The main items are connected to the study of Nuclear Structure, both single particle and collective properties, using different techniques that couple gamma-ray spectroscopy and particle (or neutron) detection. The effects of exotic structures on reaction dynamics and collective modes of excitation are also of interest, together with reaction mechanisms related to Astrophysical processes or super heavy element’s production.

The three main resident detection setups already installed at LNL are being maintained and upgraded to ensure optimal performances when SPES beams will be available. All of them require post-accelerated beams. GALILEO [18] is an array of gamma-ray detectors for in-beam spectroscopy. It can be coupled to several ancillary detectors like: silicon arrays for charged particles detection [19], neutron multiplicity filters like NEDA [20], the PLUNGER device for lifetime measurements [21], large volume crystals for high-energy gamma-ray detection [22,23] or recoil filter detectors for evaporation residues [24]. PRISMA is a large acceptance magnetic spectrometer [25]. It is used standalone or coupled to other particle detectors to provide high resolution particle spectroscopy in single-particle or multinucleon transfer reactions or in fusion reactions. PRISMA was coupled to the AGATA demonstrator and the present plan is to couple it again with the AGATA array [26,27] for the
forthcoming campaigns. GARFIELD [28] is a high granularity $4\pi$ detector for charged particles and heavy fragments, it can detect in coincidence all the particles emitted in high multiplicity events (e.g. six alpha particles from the $^{24}\text{Mg}^*$ decay [29]).

Other setups are expected to run experiments at SPES. In addition to the already mentioned AGATA and NEDA, arrays like FAZIA [30], FARCOS [31] and PARIS [32] are discussed in the Letters of Intent presented. In addition, the construction of an Active Target for SPES (ATS) is ongoing. This work is carried on in synergy with the ACTAR TPC collaboration [33,34].

It is worth mentioning that, according to the present time-schedule, the first Nuclear Physics experiments available at SPES will be carried out using the non-reaccelerated beams. In addition to the one for beam characterization, a new Tape Station for Nuclear Physics experiments is under development at INFN [35]. It will be equipped, at the implantation point, with plastic detectors for the identification of the emitted electron/positron and HPGe detectors to define the de-excitation scheme following the parent’s decay. It will allow to study beta decays in a large range of lifetimes (few tens of ms up to hours) and is planned to be flexible in order to host detectors for lifetime measurements (LaBr$_3$:Ce fast detectors), conversion electrons (Si(Li) detectors), beta-delayed neutrons (NEDA detectors) and high-energy gamma rays (LaBr$_3$:Ce detectors). An off-line decay chamber will serve as a second measuring point. It will be equipped with HPGe detectors and a nitrogen-cooled Si(Li) detector to complement the measurements with E0 and electron-conversion. The design status is shown in Figure 6. Drawings for the mechanics and electronics for the movement control of the tape station were finalized in collaboration with the ALTO Facility and iThemba-Labs. The mechanics of the tape rolling cassette is ready for vacuum-leak tests. A prototype of the motors and actuators has been built and the final design fixed. High- and low-level control interface has been developed within the EPICS environment in order to be fully compatible with the SPES control system. The design of the beam pipe and decay chamber and the best configuration of the detectors are in progress.

![Figure 6. A 3D view of the beta decay station for SPES.](image)

The low-energy experimental area at SPES will be able to host a larger number of setups, in addition to the Tape Station here described. A dedicated working group is defining the layout of the experimental area and the required services. New Users are encouraged to present requests through the LNL Users Board.

4. Conclusion

The SPES facility is under construction at Legnaro National Laboratories. The project is organized in four main parts. SPES-$\alpha$ consists in the procurement and installation of a commercial primary proton driver with two exit ports. The task is completed and the cyclotron has been commissioned up to the
nominal maximum energy (70 MeV) with a peak current of 500 µA. SPES-β is the ISOL Radioactive Ion beam facility with post-acceleration, where the big challenges are the design of an 8 kW TIS and all the following beam-purification and post-acceleration tools (HRMS, Charge Breeder, RFQ injector). The TIS and the full FE are now ready for installation in the completed production bunker. The Charge Breeder is installed and the RFQ injector is being produced. The HRMS is in an advanced design stage.

An important part of the project is represented by the several applications of the high intensity proton beam. Several projects (grouped as LARAMED and ISOLPHARM) are developing new techniques for radioisotopes production and studying the use of new isotopes for medical applications. The routine production of radioisotopes for Nuclear Medicine in collaboration with private companies, is also foreseen. Neutron fluxes and direct proton irradiation will complete the facility in a later stage.

A wide physics program has been defined in several thematic workshops and by collecting a large number of Letters of Intent. Interesting physics cases that can be studied with non-reaccelerated beams recently emerged. Those will be the first experiments able to be performed as soon as all the SPES-β components will be installed and commissioned.

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