THE SPES PROJECT AT LNL: STATUS OF THE PROJECT, TECHNICAL CHALLENGES, INSTRUMENTATION, SCIENTIFIC PROGRAM*

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for the SPES Collaboration

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Several technological innovations and challenges are foreseen for SPES (Selective Production of Exotic Species), the INFN project for a Nuclear Physics facility with Radioactive Ion Beams (RIBs). The project is in advanced construction in Legnaro. It will provide mostly neutron-rich exotic beams, derived by the fission fragments (10^{13} fiss/s) produced in the interaction of an intense proton beam (200 μA) on a direct UCx target. The expected SPES beam intensities, their quality and, eventually, their maximum energies (up to 11 MeV/A for $A = 130$) will permit to perform forefront research in nuclear structure and nuclear dynamics, studying a region of the nuclear chart far from stability. By coordinating the developments on the accelerator complex and those of the experimental set-ups,

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a successful program can be obtained. A huge upgrading of the Linac ALPI post-accelerator is being performed. For what it concerns the instrumentation, some apparatuses are already installed at the Legnaro National Laboratory and they are regularly upgraded. Moreover, new developments are under study and construction, which are very innovative and challenging. The new instrumentation development is well inserted in international collaborations, where it was agreed to make them available for the experimentation at SPES. Several Letter of Intents have been presented to the Scientific Advisory Panel during the 2^{nd} SPES International Workshop (May 26–28, 2014). The presented themes represent a quite large and up-to-date scientific program to be discussed and studied in the forthcoming years.

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1. Introduction

The SPES facility is under construction at the Legnaro National Laboratory (LNL) in Italy [1].

The full project is divided into four different phases, with separate financial budgets, in order to complete them independently:

— the α-phase: *(i)* for the construction of the new building; *(ii)* for the development, set-up, installation and commissioning of the proton-driver; *(iii)* for the development and installation of the RIB production target areas and set-ups [2];

— the β-phase, related to the RIBs transport and post-acceleration performed with the upgraded ALPI Linac post-accelerator;

— the γ-phase, related to medical applications and radioisotope production, so-called LARAMED [3].

— the δ-phase, which is dealing with a dedicated area for proton and neutron beam irradiation facilities.

2. The SPES project

The main part of the project is related to the production of a Radioactive Ion Beam (RIB) facility. In particular, SPES is an ISOL facility devoted to the production of neutron-rich element by means of fission induced by protons on uranium: an intense proton beam (of the order of few hundreds of μA) is directly sent onto a sliced UCx target, with the final aim to produce up to 10^{13} fiss/s [2].

2.1. The driver

The SPES facility proton driver bases on a commercial, newly designed, 70 MeV Cyclotron produced by the BEST Theratronics Company [4]. The chosen accelerator is a very innovative cyclotron able to produce quite intense proton beams (up to 750 μA beam current), with variable energy ranging between 35 and 70 MeV. The cyclotron is a four-sector machine, quite compact, which is energized by a pair of room temperature conducting coils. It can deliver two beams simultaneously through two independent extraction channels, which are positioned at 180° one to another: this fact gives the opportunity of performing nuclear physics studies with the RIBs using one exit, while studying and performing interdisciplinary physics activities and appliance with the second beam. The only limitation is related to the fact that the same cyclotron energy has to be used, while the intensity may be modulated between the two exits, despite the fact that the sum of the two beam currents is maintained lower than 750 μA.

An external ion source provides the H^- beam. The source has to deliver a current up to 15–20 mA, in order to obtain the 750 μA maximum designed current at the exit of the cyclotron.

The accelerator is about to be completed and under final test in Ottawa (Canada). A view of the cyclotron main magnet is shown in figure 1. The driver will be transported and commissioned at LNL between the end of 2014 and the beginning of 2015, depending on the Factory Acceptance Tests (FAT), which are in progress.

Fig. 1. The main magnet of the cyclotron lodging the tested RF resonators.

2.2. The layout

The proton beam dedicated to the RIBs production will be sent onto a direct multi-foil target (mainly UCx). The produced species will be ionized and extracted using different Target-Ion Sources (TIS) systems, as it will be described in the following. The TIS system, together with the extraction electrode, a couple of diagnostic boxes and, finally, a Wien Filter selector, which is used for a first selection stage, are part of the so-called Front End System, which is shown in figure 2. The transport line will then pass through different dipoles and short triplets magnets before reaching the High Resolution Mass Spectrometer (HRMS) and being transported towards the Charge Breeder and, finally, to the post acceleration stage in ALPI.

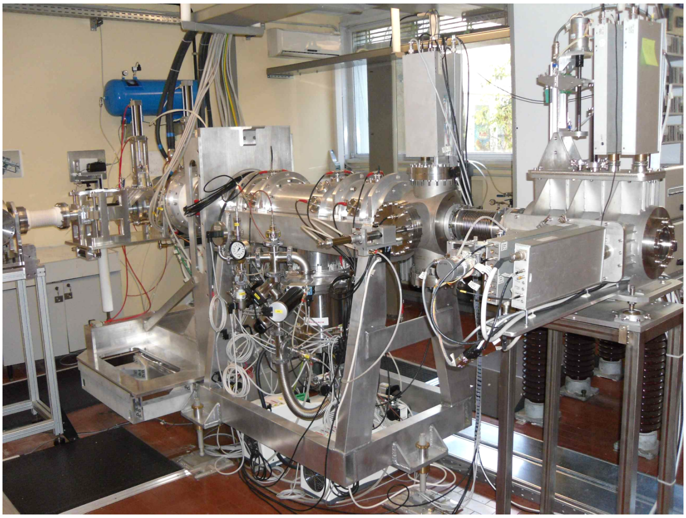

Fig. 2. Off-line Front End System working at LNL.

A cross section of the SPES layout is displayed in figure 3: the Cyclotron area is shown on the right part. The re-accelerated beams will be delivered in three experimental halls, the third of which is also shown in the same figure.

Applications will be mainly devoted to material analysis, neutron production and medical appliances as in the case, for example, of radio-isotope production [3]. The area dedicated to applications, is also visible on the very right part of the layout, while the two RIB target bunkers are displayed on the left side of the Cyclotron area as shown in figure 4.

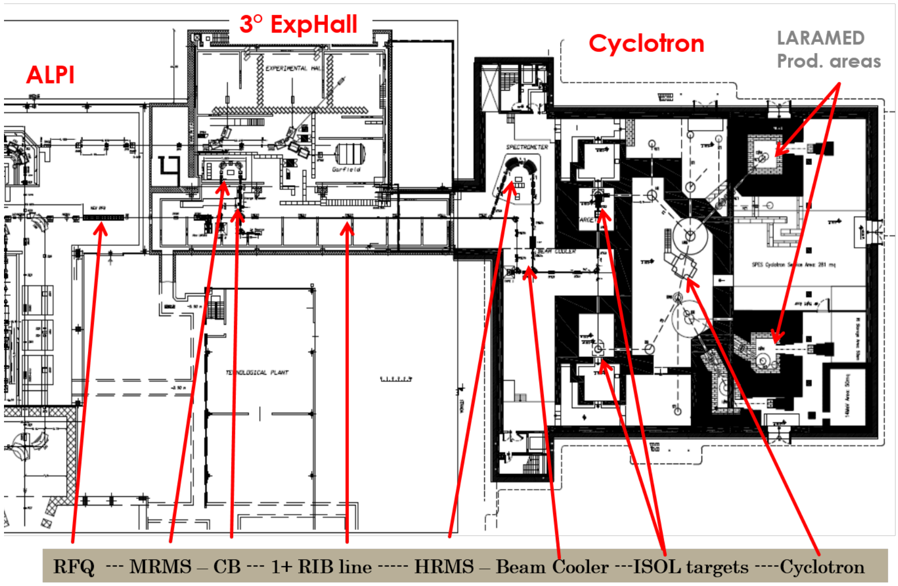

Fig. 3. SPES layout: the arrows refer respectively to the LARAMED production areas, the Cyclotron, the two ISOL production target bunkers, the Beam Cooler (BC), The High Resolution Mass Spectrometer (HRMS), the 1^+ transport line, the Charge Breeder (CB), the Medium Resolution Mass Spectrometer, the Radiofrequency Quadrupole (RFQ) in the ALPI area.

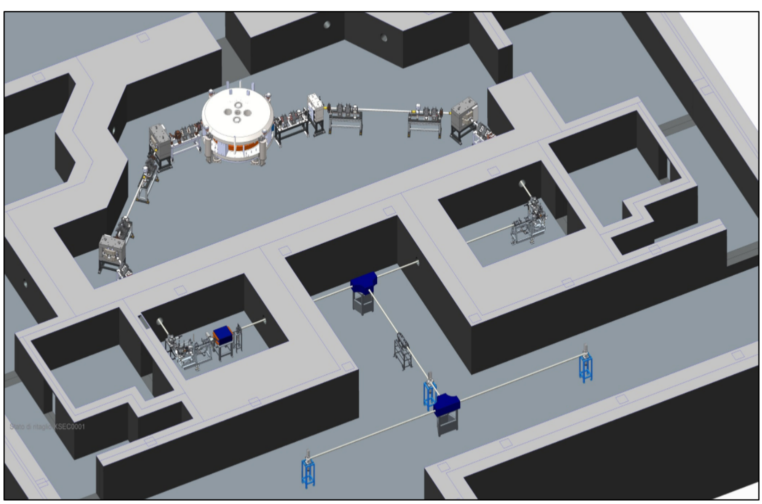

Fig. 4. 3D design of the cyclotron area plus the two bunkers for the production targets.

2.3. The target on source system

It is clear that the TIS system is a key element for the RIB project, since its behaviour will strongly affect the final intensity of the desired RIB and its contaminants: the SPES design of the production target is based on a multi-foil structure made by seven thin UCx disks for a total of 30 g of uranium, followed by three thin disks of graphite used as a beam dump. The UCx target installed in the vacuum chamber is shown in figure 5 together with the heating system. Considering a 40 MeV highly intense proton beam (200 μA), the total power on target is 8 kW. The resulting power density on target is such to maintain the temperature well under the UCx melting point (2350°C) [5].

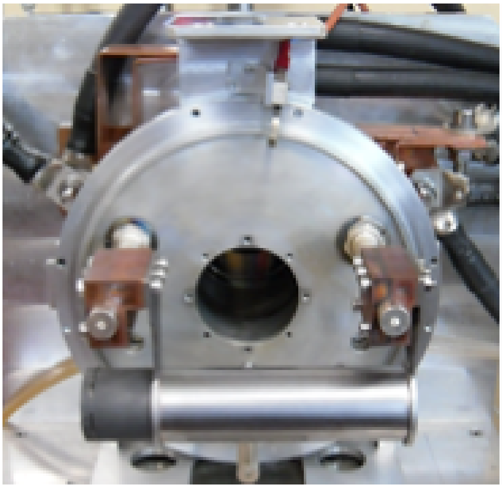

Fig. 5. Target and heating system installed in the vacuum chamber.

The proposed target geometry have demonstrated to support much higher currents with respect to the compact configuration [6]. Several test on target materials have been previously performed at ORNL (Tennessee, USA) [7] and, at present, at iTHEMBA Lab (CapeTown, South Africa) [8]. A complete SPES configurated target has been tested at iThemba Lab, where a 66 MeV 60 μA proton beam was delivered, bringing up to 4 KW on target. Check on the stability of vacuum and temperature were performed and the measurement was completely satisfactory. Some more tests are planned in the next future. The test configuration used at iThemba Lab is shown in figure 6.

Several target materials (SiC, B_4C, ZrC, Al_2O_3, CeS, LaCx, TaC, *etc.*) are under development besides UCx. They are studied in order to produce even some neutron deficient beams, which are listed in the available beam list [9].

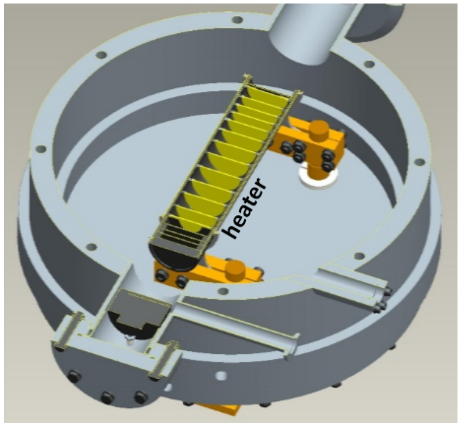

Fig. 6. Test configuration for the SPES UCx target at iThemba Lab (May 2014).

In order to produce the RIBs, the production target is coupled to different ionization sources, forming the so-called Target-Ion Source system (TIS). At SPES, the Surface Ionization Source (SIS), the Plasma Ion Source (PIS) and the Laser Ionization Source (LIS) are being developed. The SPES hot-cavity ion source has been designed and constructed according to the ISOLDE specifications [10]. The three different sources can be used according to their specificities: in particular, the Surface Ion Source has good efficiency and selectivity for the elements as Rb, Cs, Ba. Using a similar hot cavity cell, the laser resonant photo-ionization, is a powerful method to achieve sufficiently selected exotic beams for most of the elements [11]. However, in order to ionize elements with high ionization potential like the rare gases, the plasma source is needed: even though this source easily ionize many elements, it has the drawback of not being selective at all. Both surface and plasma sources have been developed and in operation at the off-line test-bench laboratory. The laser ionization technique is under development aiming at producing the most pure beams as possible (chemical selectivity) also for metal isotopes. For this purpose, a new laser laboratory has been installed at the LNL.

2.4. The beam selection and transport

The isotopes produced in the target and ionized in the source are extracted and directed towards the first selective element of the SPES accelerator, that is a Wien Filter able to select isotopes up to $\simeq \Delta M/M = 1/80$. Then, a first series of dipoles and short triplets magnets complete the first selection reaching a value of $\Delta M/M = 1/200$. The transfer line is then designed to pass through a Beam Cooler stadium, which is necessary to properly inject the beam into a High Resolution Mass Spectrometer. The Spectrometer (HRMS) is conceived to reach an effective mass resolution of at least $\Delta M/M = 1/20000$. In order to reach this goal, the HRMS physics design in the SPES configuration is made so to reach a resolution of $\Delta M/M = 1/40000$, value which is constrained by values of 3π mm mrad in emittance and 1.3 eV in energy spread. A by-pass line is also foreseen with the double aim either to by-pass the high resolution stadium, when required, or to transport back the exotic beams to the low energy area. At the exit of the HRMS or after the by-pass, the transport line continues towards the Charge Breeder, after which a further selection is provided by a Medium Resolution Mass Spectrometer MRMS ($\Delta M/M \simeq 1000$). This is necessary to clean up the beam from contamination deriving by the breeding stadium. A new normal conductive RFQ injector is being designed to properly inject the RIBs into the Linac ALPI for the post-acceleration: the RFQ injection energy is 5.7 keV/u and the exit energy is 727 keV/u. The ALPI post accelerator is undergoing a major upgrading in terms of transmission properties, *i.e.* intensities, and maximum energies. A re-alignement of the ALPI accelerators and of the main experimental lines has been performed using a laser tracker, thus obtaining a major reliability in the beam transport, which is necessary when dealing with weak RIBs. Finally, the selected exotic beam will be allowed to reach three experimental areas, where the secondary targets will be provided by the user, together with the dedicated instrumentation.

Fig. 7. SPES construction site.

The new building is in an advanced phase of construction as shown in figure 7, nearly ready to lodge the cyclotron. The operation of the cyclotron has already been authorized, comprehensive of the extraction and interaction of 5 μA proton beam on UCx target, for the first-day experimental activity.

A major aspect, when dealing with RIB facilities, is related to the safety and security items. A procedure is undergoing in Legnaro National Laboratory in order to handle all safety aspects both from the radioprotection point of view and from the standard risk framework. All procedures and technical design aspects will be certified under a Quality and Safety Management System (QSMS) in order to minimize errors and to afford and overcome all possible expected risks through proper and organized procedures.

3. SPES instrumentation and scientific program

The SPES performances in terms of beam intensities at the production/extraction point (after the ionization source 1^+) and at the secondary target (experiment) position (post-accelerated intensities) have been evaluated and they are reported in [12].

The SPES scientific program is under discussion based on the long-standing experience in nuclear structure and dynamics studies of the LNL and LNS international user communities. In particular, one of the traditional fields is the study of nuclei under extreme conditions, that is the study of the evolution of nuclear structure towards the region far from stability in terms of excitation energy (decay and behaviour of hot nuclei), high spin states (highly rotating nuclei), and, finally, high isospin (high N over Z ratio). Large efforts are devoted to the upgrading of installed experimental set-ups (PRISMA [13], GARFIELD [14], *etc.*). The developments of new instrumentation (AGATA [16], NEDA [19], FAZIA [18], GALILEO [15], ATS_ACTAR [17], PARIS [20], TRACE [21], *etc.*) are also performed within international collaborations in order to carry out up-to-date experimentation at SPES, as it was recently discussed in the 2$^{\rm nd}$ International SPES Workshop (May 26–28, 2014), where about 40 Letters of Intents have been presented and discussed with the Scientific Advisory Commitee [22].

4. Conclusions and outlook

The SPES facility is under construction at the Legnaro National Laboratory. Both nuclear physics scientific programs and all connected applications will give to the international community a great opportunity to further improve in knowledge and technology development. International collaborations are renewed around the α- and β-phases of this facility developing new up-to-date instrumentation in order to afford studies of nuclear structure and reaction dynamics in an unknown region of the chart of nuclides.

In the meanwhile, the opportunity given by the further two phases of the project will permit on the one hand to be inserted in the innovative production process for new radio-isotopes needed in medicine (γ-phase) and on the other hand (δ-phase) in the development of a dedicated area for proton and neutron beam irradiation facilities of interest for material science and radiation damage purposes.

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