

PROGRESS IN THE REALIZATION AND COMMISSIONING OF THE EXOTIC BEAM FACILITY SPES AT INFN-LNL

G. Bisoffi, A. Andrichetto, P. Antonini, L. Bellan, D. Benini, J. Bermudez, D. Bortolato, M. Calderolla, M. Comunian, S. Corradetti, L. De Ruvo, A. Facco, E. Fagotti, P. Favaron, A. Galatà, F. Galtarossa, M. Giacchini, F. Gramegna, A. Lombardi, M. Maggiore, M. Manziolaro, D. Marcato, T. Marchi, P. Mastinu, P. Modanese, M. F. Moisisio, A. Monetti, M. Montis, A. Palmieri, S. Pavinato, D. Pedretti, A. Pisent, M. Poggi, G. Prete, C. Roncolato, M. Rossignoli, L. Sarchiapone, D. Scarpa, D. Zafiroopoulos, INFN/LNL, Legnaro, Italy, M. Bellato, INFN - Sez. di Padova, Padova, Italy
V. Andreev, ITEP, Moscow, Russia, A. Mendez, ORNL, Oak Ridge, Tennessee, USA

Abstract

SPES (Selective Production of Exotic Species) is an ISOL type facility for production and post-acceleration of exotic nuclei for forefront research in nuclear physics. Radioactive (RA) species ($A=80\div 160$) will be produced by fissions induced by a proton beam impinging on an UCx target: the proton beam will be delivered by a commercial cyclotron with a 40 MeV maximum energy and a 0.25 mA maximum current. The RA species, extracted from the Target-Ion-Source system as a $1+$ beam, will be cooled in a RFQ (radiofrequency quadrupole) beam cooler (RFQ-BC) and purified from the isobars contaminants through a High Resolution Mass Separator (HRMS). Post-acceleration will be performed via an ECR-based charge breeder, delivering the obtained $q+$ RA beam to a being built CW RFQ and to the being upgraded superconducting (sc) linac ALPI (up to 10 MeV/A for a mass-to-charge ratio $A/q=7$).

INTRODUCTION

The SPES project was fully funded in 2012 and the cyclotron proton driver was commissioned in 2017. The schedule foresees first experiments with a low energy exotic ion beams in 2020, and with post-accelerated ones in 2021. The HRMS ($\Delta M/M \sim 1/20000$) will be made available for experiments in 2023. This paper reports on the status of the project, with an overview on the progress on the different parts of the facility.

EXOTIC BEAM PRODUCTION

The proton beam is accelerated by a $35\div 70$ MeV, 700 μ A commercial cyclotron C70 (Best Cyclotron Systems Inc.). It offers simultaneous double extraction from two 180° apart exit ports, to be used for both fundamental nuclear science and medical and material research.

C70 is an Azimuthally Varying Field (AVF) compact cyclotron with four sectors, with the main magnet 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 and accelerate H⁻ ions provided by an external multi-cusp ion source via an axial injection line and an electrostatic inflector. Protons are extracted by H⁻ stripping the electrons in a thin graphite foil. Installation and successful commissioning were accomplished in 2015-2017, driving the beam to a home designed and built beam dump. The latter was made out of two cooled copper plates,

tilted by 10° , so as to reduce the maximum power density to less than 200 W/cm². Stability and reliability tests of C70 were conducted: e.g. in a 5 days long run at 40 MeV, the average I_{beam} was $201.18 \pm 0.97 \mu\text{A}$ (Fig.1). Tests were then extended to 70 MeV - 500 μA with good stability and repeatability. Dual extraction was proven as well.

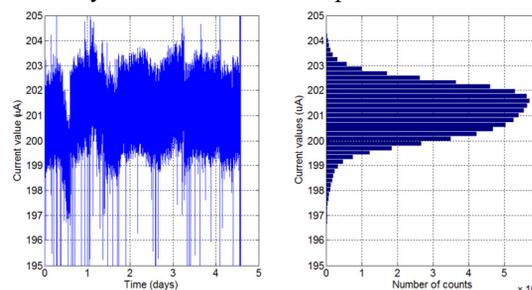


Figure 1: Result of the 5-days-long beam current stability tests with the C70 cyclotron.

The overall transport efficiency was in excess of 99%. This implies low beam line activation, allowing maintenance in the cyclotron vault only 24 hours after beam acceleration, following 9-days operation at 40 MeV-200 μA . During operation, a remotely controlled scanning radiation survey will be provided, so as to reduce operator exposure: scans will exhibit plots similar to the one shown in Fig. 2, where the point with the maximum dose rate (2 mSv/h), at a few cm distance from the cyclotron extraction exit slits, is shown.

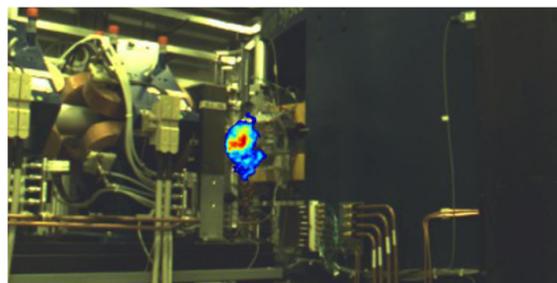


Figure 2: Radiation scan at a few cm from the cyclotron extraction slit (2 mSv/h maximum value).

The beam dump in the bunker will be replaced in 2019 by the Target Ion Source (TIS) system [1] consisting, in its final layout, of a multi-foil uranium carbide target and the related ion source, linked together by a Ta tubular transfer line.

Content from this work may be used under the terms of the CC BY 3.0 licence © 2018. Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

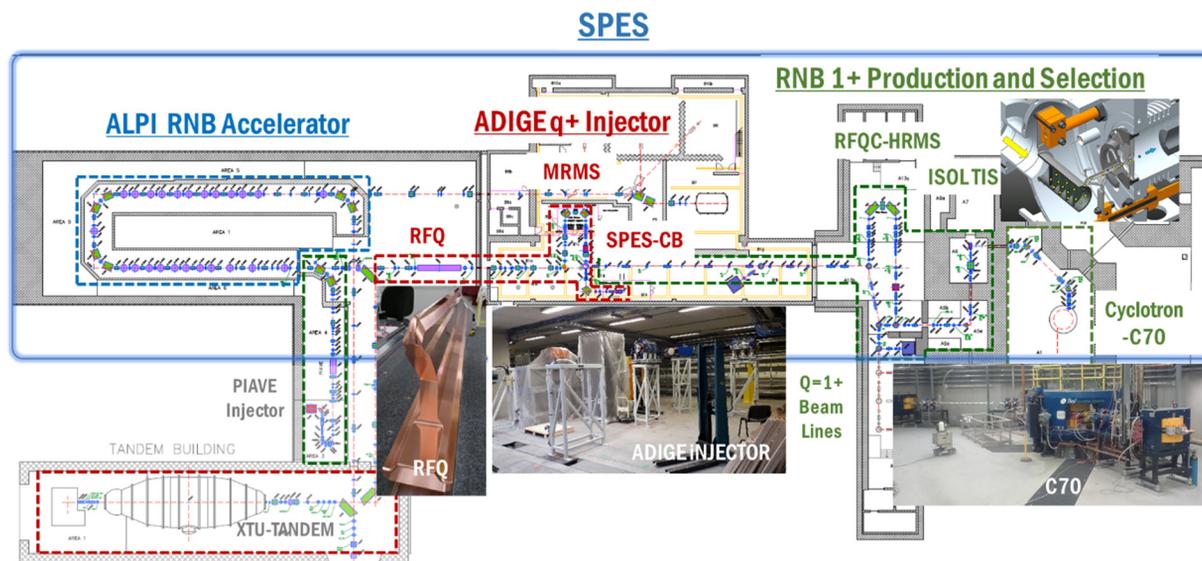


Figure 3: SPES Layout, with photos of facility parts (from right to left: cyclotron, TIS, ADIGE injector, RFQ).

The SPES layout is shown in Fig.3. A 40 MeV, 200 μ A proton beam, accelerated by the C70 cyclotron, will impinge the production target (7 properly spaced UCx discs, 40 mm diameter, 0,8 mm thick), generating $\sim 10^{13}$ fissions/s. RA isotopes produced by the ^{238}U fissions are delivered to the 1+ ion source where they are ionized and accelerated to 20÷42 keV.

The target box must be kept at $T_{\text{ave}} = 2000\div 2200$ °C in vacuum to enhance RA isotope mobility, extraction and ionization. This temperature is achieved by combining the 8 kW proton beam and Joule heating. Surface (SIS), plasma (PIS) and LASER (LIS) ionization sources will be used, aiming at maximum ionization efficiency, since the production rate of specific nuclei can be extremely low.

Once extracted and pre-accelerated, the desired beam species is preliminarily selected inside the target bunker by a quadrupole electrostatic triplet and a Wien Filter, where most contaminants are separated to minimize radioactivity along the beam line. Then the beam can either be driven to the re-acceleration stage, through the HRMS if required, or directly to experimental stations for low-energy experiments. This beam line was modelled to the 3rd order using GIOS [2]. After the bunker, a Low Resolution Mass Separator (LRMS, made out of two 45° magnetic dipoles) is foreseen, with a $\Delta M/M \sim 1/300$ resolution.

BEAM PURIFICATION AND REACCELERATION

Following the LRMS, the exotic beam can be sent to the HRMS and then to charge breeding and pre-acceleration stage, or straight to the latter, by-passing the HRMS.

The HRMS [3] has to provide, for the SPES-reference ^{132}Sn ion beam, mass selectivity $\Delta M/M \sim 1/20000$, with a $\Delta V \leq \pm 1$ eV energy spread, and beam transmission $T \geq 95\%$. The separator, to be installed on a -260 kV platform, will consist of two magnet dipoles ($R=1.5$ m, $\Theta=90^\circ$), 3 electrostatic multipoles, and 6 electrostatic quadrupoles.

To obtain the desired separation, it shall have to be preceded by a RFQ-BC, to be built by LPC (Laboratoire de Physique Corpusculaire, Caen, F), able to shrink transverse emittance and energy spread, each by around a factor 10. A review on the RFQ-BC-HRMS system is foreseen in fall 2018, followed by detailed design and construction. Assembly will be done in 2022 and first highly resolved beams will be available in 2023.

After the HRMS, the RA beam is conducted to the charge breeder through a long electrostatic focusing channel. To increase the exotic beam charge state for efficient post-acceleration, we chose an Electron Cyclotron Resonance (ECR)-based charge breeder (SPES-CB), which was developed by LPSC (Grenoble, F) and delivered to LNL in late 2015, after completion of the acceptance tests [4]. The downstream beamline was designed to characterize the device with stable beam and for regular operations with RA ions. The high charge state exotic beam injector ADIGE [5] consists of three main sections: ADIGE-1 is an electrostatic 1+ beam line aimed at full SPES-CB input beam characterization; ADIGE-2 is a q+ beam line from the SPES-CB to the RFQ, with a Medium Resolution Mass Separator (MRMS, $\Delta M/M \sim 1/1000$) on a -120 kV platform in between. The MRMS is an important development of the SPES project: it will ensure post-acceleration of clean RA beams from the SPES-CB contaminants. In 2017 an intense work was carried out to set up the ADIGE beam line: the 1+ source and the SPES-CB were positioned; a small 40 kV platform, in a Faraday cage, was designed and built in order to house all the devices necessary to run the 1+ source; HV power supplies were delivered, and related infrastructures were designed; in July 2017, the construction of the MRMS platform started, factory acceptance tests being scheduled within April 2018, and delivery to LNL for early June. All optical elements and power supplies of ADIGE-1 and ADIGE-2, off the high voltage platform, were delivered and installed and are being connected

to electrical and cooling plants. We expect to run the 1+ beam line from June 2018, while the completion of the rest of the beam line, up to the RFQ injection point, is scheduled for the end of 2018.

ADIGE-3 includes the RFQ and the matching line to the ALPI sc linac. The SPES RFQ, to be located in the ALPI building, is designed to accelerate exotic isotopes in CW mode with $A/q = 3\div 7$ [6]. It is composed of six 1.2-m-long modules, made of a stainless steel tank and four OFE Cu electrodes (obtained by brazing of two subassemblies). The tank inner surface is Cu-plated and a spring joint between tank and electrode seals the RF. After extensive prototyping [7] the RFQ is in its construction phase: 20 out of 24 electrodes were finished, and tight mechanical accuracies were within specifications. The tank machining tender was completed and its construction shall start in June 2018. Support and alignment frames were meanwhile designed.

After the RFQ, a transport line, including 2 normal conducting quarter wave resonators (QWR) for longitudinal matching, delivers the exotic beam to the existing sc linac ALPI. Several upgrades are being implemented, to improve both the performance (in final energy and current values) and the reliability of ALPI. The complete refurbishment of the cryostats and cryogenic plant control systems was completed in 2017 and tested with success. During 2018, two important milestones are planned: replacement of 10 magnetic lenses with 50% higher gradient ones, expected to improve beam transmission along the machine; displacement of 2 QWR cryostats from the PIAVE stable beam injector to ALPI, to make them available to both stable and exotic beams. In 2020, we plan to add two fully new cryostats at the end of ALPI, so as to achieve the final energy of 10 MeV/A for the reference SPES beam ^{132}Sn .

All along the facility, proper beam instrumentation for both pilot and exotic beam must be provided: beam current will be measured via normal Faraday cups, equipped with low noise amplifiers; position and transverse profiles via wire grids and MCP-based electron monitors; emittances via wire-grid and Allison scanners. The first series of boxes will be completed in 2018 for the ADIGE injector and the low-energy exotic beam transport line. Tape stations, based on γ -ray spectroscopy of the β -decaying RA nuclei, will be located after the LRMS, after the HRMS and at the end of ALPI, to identify the beam isotopic composition and intensity.

CONTROL, SAFETY AND RADIOPROTECTION ASPECTS

SPES features a full fledged, network-based control system. Its infrastructure is a campus-wide fiber-based 10 Gb/s Ethernet network that covers the accelerators plants with more than 40 switch racks. All the control system software is EPICS-based, built with bottom up approach to accommodate both the needs of the new components of the SPES complex and the existing linac, largely refurbished in the last 3 years. The endpoints of EPICS client software is commercial (Beckhoff, Schneider, Siemens, NI) and custom-made hardware (for Beam Diagnostic system, Low

Level RF, Machine Protection System), exploiting state-of-the-art FPGA technology for fast and closed-loop controls. A local computing center hosts servers, which centralize common services and run soft-IOCs communicating with hardware on the field. Distributed intelligence was kept to a minimum to ease maintenance. All graphical user interfaces are being developed in CSS (Control System Studio) and deployed via a network file system on thin-client machines. A project for the construction of a centralized control room for all accelerators of the LNL complex is being envisaged.

By the end of 2019, before beam commissioning with exotic beams can start, SPES must be equipped with a safety system compliant with the Italian regulatory framework. Safety goals were defined, harmonizing national law on radiation exposure with real hazards of the various processes. The safety analysis is being assisted by a specialized company. Risk evaluation was performed using HAZOP (HAZard Operability) analysis, identifying all plant deviations; with the LOPA (Layer Of Protection Analysis) technique, for each initiating event all independent protection layers are recognized and assessed for failure probability. Detailed analysis of safety instrumented functions and requirement specifications are in progress. Installation and commissioning of the whole system will be carried out in 2019.

A licensing procedure is being completed for: use of fissile targets to generate and reaccelerate exotic beams at 40 MeV and 200 uA; use of $q=1+$ exotic beams for low energy experiments; production of radioisotopes for radiopharmaceuticals labelling. Finally, besides analyzing general aspects of workers' radioprotection, potential dose increment to the public and the environment was studied, through atmospheric dispersion models and environmental transport through any possible pathways. Both normal and accidental scenarios were considered, to analyze consequences of both chronic and acute radioactivity release.

REFERENCES

- [1] A.Monetti *et al.*, "The RIB Production Target for the SPES Project", *Eur. Phys. J. A* 51, 128, Oct. 2015.
- [2] H.Wollnik, J.Brezina and M.Berz, "GIOS BeamTrace", NIMA258, 408, 1987.
- [3] M.Comunian *et al.*, "Design of High Resolution Mass Spectrometer for SPES", presented at IPAC'18, Vancouver, Canada, Apr.-May 2018, paper THPAK021, this conference.
- [4] A.Galatà *et al.*, "Status of the SPES-charge breeder (SPES-CB) and its beam line at INFN-LNL", NIMB376, 329, 2016.
- [5] A.Galatà *et al.*, "ADIGE: the radioactive ion beam injector of the SPES project", *Journal of Physics Conference Series*, doi:10.1088/1742-6596/874/1/012052
- [6] L. Ferrari *et al.*, "Thermomechanical Calculations for the SPES RFQ", in *Proc. HIAT'15*, Yokohama, Japan, Sep. 2015, pp. 219-221.
- [7] L. Ferrari *et al.*, "RF Mechanical Design and Prototyping of the SPES RFQ", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 4166-4168.