

STATUS OF THE SPES EXOTIC BEAM FACILITY

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Abstract

At Legnaro National Laboratories of INFN it is under construction a Rare Isotope Facility called "Selective Production of Exotic Species" (SPES) based on a 35-70 MeV proton cyclotron, able to deliver two beams with a total current up to 0.75 mA, an ISOL fission target station and an existing ALPI superconducting accelerator as a post accelerator (up to 10 MeV/u for $A/q=7$). The paper will cover notably: the high-resolution mass separator, the CW RFQ (80 MHz, 727 keV/u, with internal bunching), the 1+ low energy transfer line and the injection line from Charge Breeder to ALPI under installation.

INTRODUCTION

SPES, acronym of Selective Production of Exotic Species, is a CW radioactive ion beam facility under construction at LNL INFN in Italy. It will produce and accelerate neutron-rich radioactive ions, to perform nuclear physics experiments, which will require beams above Coulomb barrier [1].

The main functional steps of the facility are shown in Fig. 1: the primary beam delivered by the cyclotron, the beam from the fission target (as an example, up to 10^{13} particle/s of ^{132}Sn), the beam cooler, the separators, the charge breeder and the accelerator (the existing ALPI with a new RFQ injector). The use of the continuous beam from the +1 source, which can use different configuration types LIS, PIS, SIS, maximizes the RNB efficiency but need a CW post accelerator (RFQ and ALPI). The beam is prepared for the post-accelerator stage with a charge breeder device. The energy from 20 to 40 kV on the transfer lines are determined by the chosen RFQ input energy (5.7 keV/u); for this reason, all the devices where the beam is approximately stopped (production target, charge breeder and RFQ cooler) lay at a voltage proportional to the ratio A/q . The charge state range ($3.5 < A/q < 7$) is bounded by the RFQ field level for the upper limit and by the minimum voltage on $q=1$ transport line.

THE CYCLOTRON AS PRIMARY DRIVER FOR SPES AND TARGET

The proton beam is accelerated by a 35-70 MeV, 700 μA 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 [2].

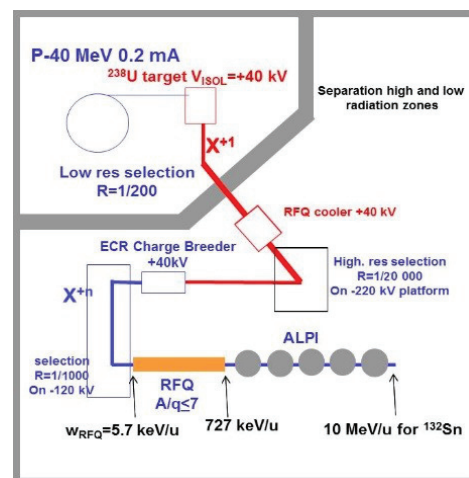


Figure 1: functional scheme of the SPES facility. There are two main areas: the 1+ line and the n+ line, where 1+ and n+ indicates the beam charge state.

C70 is an Azimuthally Varying Field (AVF) compact cyclotron with four sectors, with the main magnet energized by resistive coils.

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.

Stability and reliability tests of C70 were conducted: e.g. in 5 days long run at 40 MeV, the average beam current was $201.18 \pm 0.97 \mu\text{A}$. Tests were then extended to 70 MeV - 500 μA with good stability and repeatability. Dual extraction was proven as well.

The cyclotron will impinge the production target (7 properly spaced UCx discs, 40 mm diameter, 0.8 mm thick), generating about 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 20-40 keV.

The target box must be kept a temperature of $2000 \pm 2200^\circ\text{C}$ in vacuum to enhance RA isotope mobility, extraction and ionization. This temperature is achieved by combining

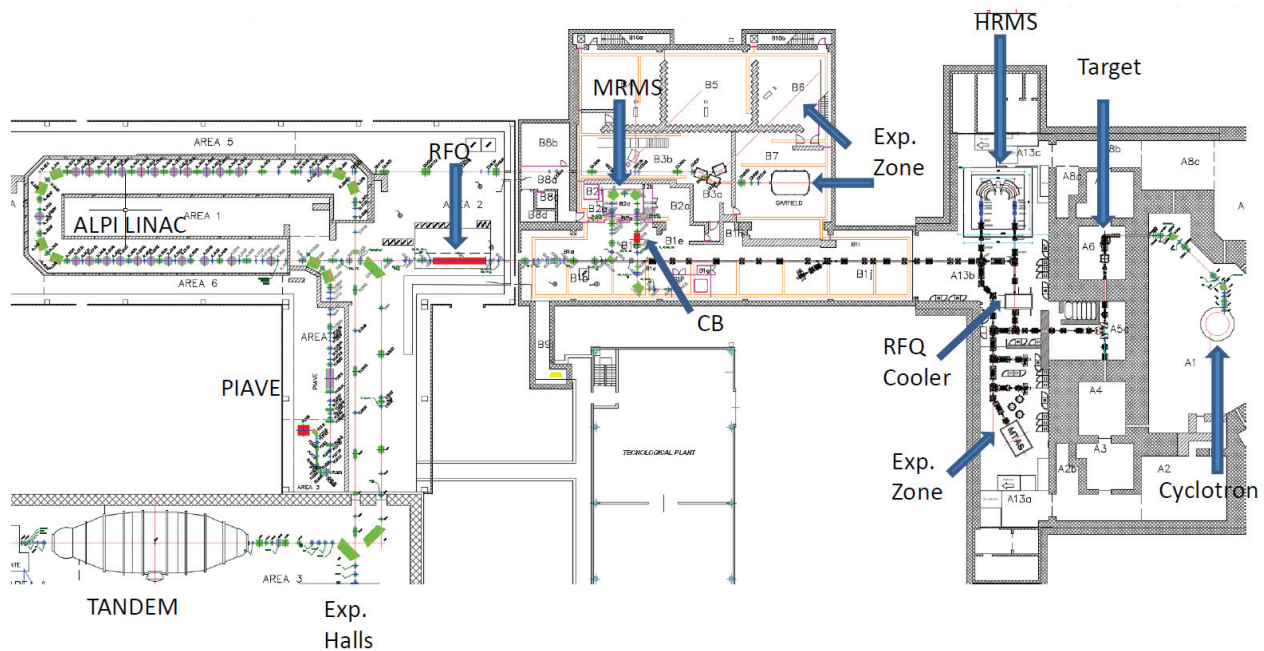


Figure 2: General SPES layout with main areas.

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.

THE SEPARATION STAGES

The general layout of the SPES facility is presented in Fig. 2.

The reference beam for the beam dynamics simulations is chosen to be the ^{132}Sn , extracted at 40 kV at the end of the target extraction system. It has been chosen a $q=19$ after the charge breeder i.e. $A/q=6.9$, in such a way to test the maximum required electromagnetic fields of the line elements of the facility.

There are three normalized rms emittance regimes: after the target, it is chosen to be $\epsilon_{n,rms}=0.007$ mm mrad, with an equivalent geometric emittance at 99% of $\epsilon_{geo,99\%}=64$ mm mrad, assuming a gaussian distribution cut at 4σ . Then, the beam cooler prepares the beam to the high mass resolution stage, reducing the emittance down at least by a factor 5 and the energy spread by a factor 10 at the level of ± 1 eV rms. After the CB, the emittance for the BD calculation is assumed to be $\epsilon_{n,rms}=0.1$ mm mrad. As far as the longitudinal phase space is concerned, a uniform distribution between ± 10 eV is considered. After the CB, the energy spread is set to ± 15 eV. The low-resolution section (LRMS) is the part of the line between the target and the beam cooler. Two mass spectrometers are placed between the target and the beam cooler: the Wien Filter and a 90° dipole. The overall resolution is of 1/200 in mass, enough to separate the isobars from the other isotopes. Two similar type of spectrometers, the High-Resolution Mass Spectrometer (HRMS) and the Medium Resolution Mass Spectrometer (MRMS) are provided for the SPES project. Both are composed by two 90° magnet with a multipole

(up to 12° order pole) between them, placed onto platforms.

The HRMS is a full ions separator used to obtain the ions of interest, because it removes isobar ions coming from the source and the MRMS is used to clean the nominal beam from high intensity contaminants introduced by charge breeder [3].

After the 1/200 isotopes separator, the isobars separation is represented by HRMS placed on a -220 kV platform (the effect is a reduced divergence and energy spread). This separator is constituted by six quadrupole lens, two hexapole lens, two dipoles and one multipole lens placed in the symmetry plane of the system to fix the curvature aberration. The HRMS can separate different isobar with $\Delta M/M=1/20000$ and $\Delta W/W=\pm 1$ eV (this so low energy spread is due to the beam cooler) like shown in Fig. 3 below. The optics improvement is still ongoing, but it shows a fully resolving capability of isobars separated of 1/20000 in mass. An option to reduce the platform voltage for the HRMS down to -120 kV, like the MRMS, is ongoing. The code used for the design of HRMS/MRMS is TraceWin from CEA [4], and a full benchmark has been done, with the same results, by using COSY [5].

It is important to consider that the HRMS performance depend strongly on the beam cooler efficiency [6][7]. After the charge breeder, the next spectrometer is the MRMS, placed on a -120 kV platform (for the same reasons of the HRMS). The goal in resolving power of this spectrometer is 1/1000 with the interest beam in A/q fully separated. The Table 1 shows the overall capabilities of the two spectrometers. After the selection, the beam is sent to the CB through a periodic transport line.

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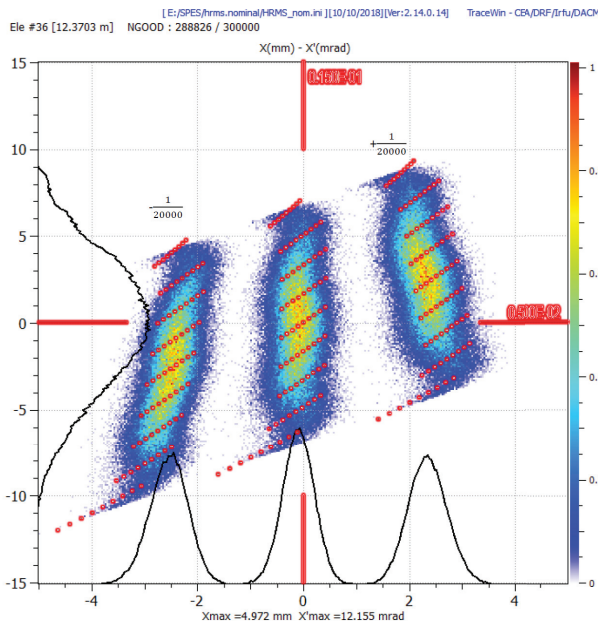


Figure 3: Phase Space (X, X') at HRMS image point of three beams separated of $1/20000$ on mass with $\pm 1\text{eV}$ RMS energy spread, with overlapped the results of COSY 5° order simulation, as red dots.

Table 1: Medium and High Spectrometer Performances

Parameter [units]	MRMS	HRMS
RMS Emit. nor. [mrad]	0.1	0.0014
Beam Energy [keV]	160	260
Nominal Resolution	1/1000	1/20000
RMS Energy Spread [eV]	± 15	± 1
90% Geom. Emit. [mrad]	56	2.8
(Geom. Emit.)/Resol.	56000	56000

THE CHARGE BREEDER

Charge breeding at SPES will be based on the ECR technique: the model adopted (SPES-CB) derives directly from the PHOENIX Charge Breeder installed at the Laboratoire de Physique et de Cosmologie. The SPES-CB was delivered to LNL at the end of 2015, after successful acceptance tests carried out at LPC [8].

Highly charged ion beams in the range $3.5 < A/q < 7$ will be extracted from this device through a three electrodes extraction system designed at LNL [9], and initially focused by two solenoids. It is well known that the breeding can introduce contaminants in the extracted beam, coming from two main sources: impurities present in the gas fed into the plasma chamber (normally oxygen),

or deriving from the outgassing of the surfaces exposed to vacuum, and the release of particles from the materials constituting the vacuum chamber due to their interaction with the plasma. To face with the first problem, special attention was paid to the surface treatments, in particular of the stainless steel plasma chamber and the iron plug at extraction (ARMCO). For the second one, a Medium Resolution Mass Spectrometer (MRMS) was designed with an expected resolving power of $\Delta(M/q)/(M/q)=1/1000$ will be installed downstream the charge breeder. Figure 4 show the installation zone of charge breeder.



Figure 4: Charge Breeder installation.

THE SPES RFQ

The SPES RFQ is designed to accelerate beams with A/q ratios from 3.5 to 7 from the Charge Breeder through the MRMS and the selection and injection lines up to the MEBT. The main parameters of the RFQ are listed in Table 2. The RFQ is composed of 6 modules about 1.2 m long each. Each module is basically composed of a Stainless-Steel Tank (AISI LN 304) and four OFE Copper Electrodes [10]. In Fig. 5 the transverse beam dynamics through the RFQ is show.

A copper layer will be electrodeposited on the tank inner surface and a spring joint between tank and electrode is used to seal the RF.

Table 2: Main RFQ Parameters

Parameter [units]	Design value
Operational mode	CW
Frequency [MHz]	80
In/out. Energy [keV/u]	5.7-727 ($\beta=0.0035-0.0359$)
Vane length L [m]	6.95
RF Power [kW] (+30%)	98

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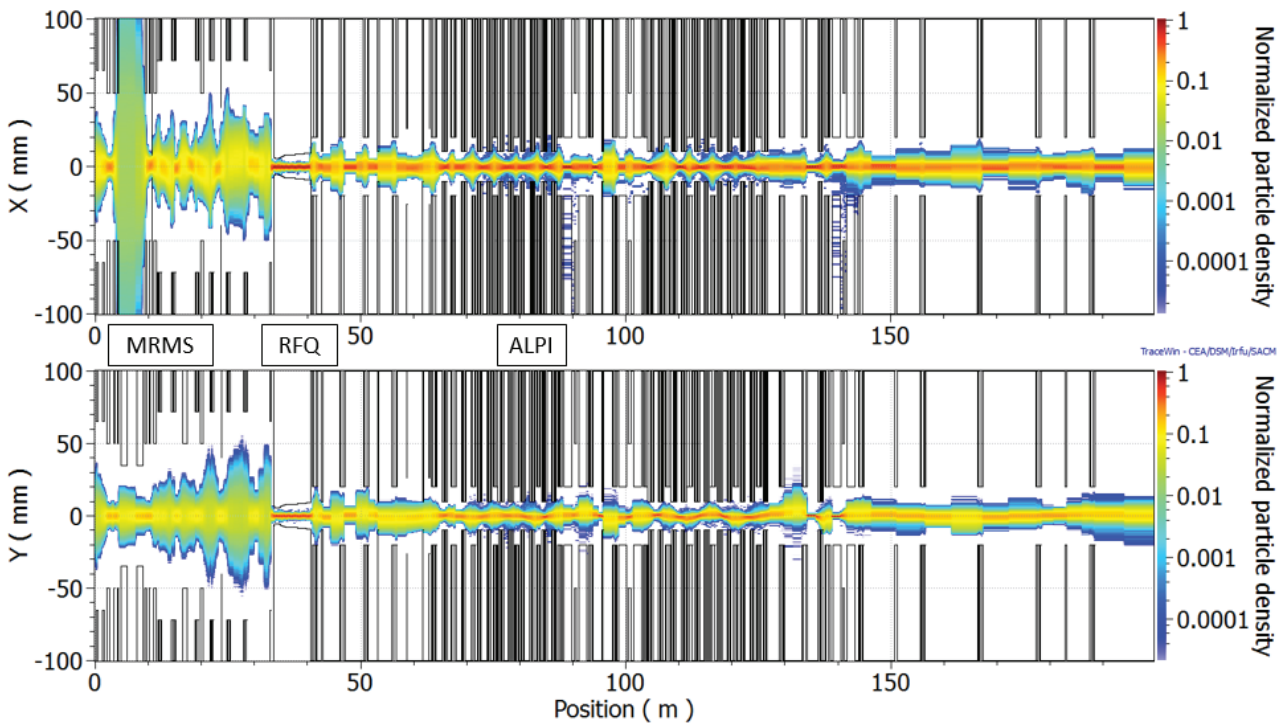


Figure 5: Multiparticle normalised-densities y and x of the whole line CB-RFQ-ALPI- Experimental hall.

The RFQ voltage law is a linear function along z $V(z)=V(0)+a \cdot z$ with $a=3.177$ kV/m and $V(0)$ depending on the A/q of the ion to be accelerated. Such law is implemented by designing the RFQ to obtain a constant TE_{21} cut-off frequency $f_c=79.5$ MHz along the structure and by properly shaping the vane undercuts at the Low and High Energy Ends of the RFQ. The compensation of the R_0 variations, is made with the capacitive region that is varied along the RFQ. The electrode thickness is equal to 48 mm and the tank inner radius R is equal to 377 mm.

The RFQ is in its construction phase: 20 out of 24 electrodes were finished, and tight mechanical accuracies were within specifications. Almost all scanned profiles of each electrodes follow tolerance on best fitted curve profiles (0.04mm) except for some small spot (Outliers <1 % of measured points). In Fig. 6 is show the RFQ electrode under measurements.

The tank machining tender was completed, and its construction is started. Support and alignment frames were meanwhile designed.

THE ALPI LINAC FOR SPES

After the SPES 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 [11] [12]. The complete refurbishment of the cryostats and cryogenic plant control systems was completed in 2017 and tested with success.

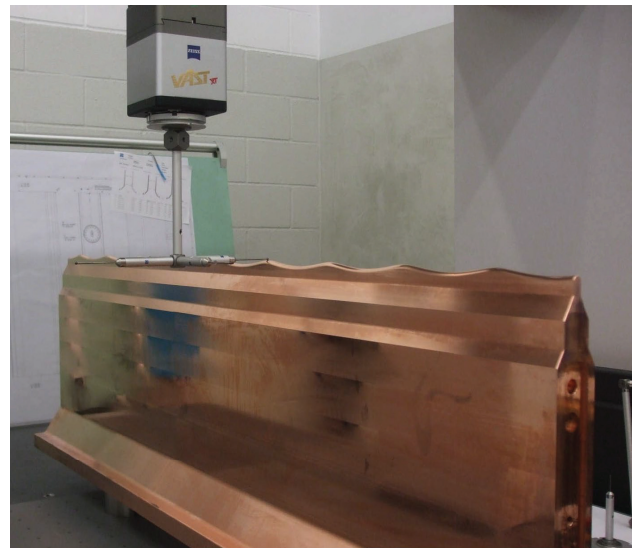


Figure 6: SPES RFQ electrode under measurements.

During 2018, several important milestones are planned: the 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 and 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, the 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 new SPES 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.

An end-to-end simulation from the CB to the end of ALPI has been performed by using TraceWin. The beam travels from the CB to the third hall. The final kinetic energy is 1.2 GeV ($\Delta E/E < \pm 0.4\%$) with total losses of 14% in the nominal case. In Fig. 5 the multiparticle densities are shown for the x and y coordinates.

CONCLUSIONS

Several highlights of the SPES project were shown. The high-resolution mass separator is under refinement while the WF and the LRMS are under procurement. The MRMS is going to be installed and the RFQ is under construction. An end to end simulation of the line from the CB to the experimental hall was done, showing an overall transmission >85% in the nominal case.

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