PHYSICAL DESIGN OF THE SPES FACILITY

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Abstract

SPES (Selective Production of Exotic Species) is the Italian project for a rare isotope beam (RIB) facility based on a cyclotron as primary accelerator and on the existing superconducting linac ALPI as post accelerator. The cyclotron, energy up to 70 MeV and total current of 0.75 mA, shared on two exits, is in construction in the industry. The production of neutron-rich radioactive nuclei, with ISOL technique, employs the proton induced fission on a direct target of UCx; the fission rate expected with a proton beam of 40 MeV and 0.2 mA, is 10^13 fissions/s. The main goal of physical design of the SPES facility is to provide an accelerator system to perform forefront research in nuclear physics by studying nuclei far from stability, in particular neutron-rich radioactive nuclei with masses in the range of 9–160.

The final RIB energy on the experimental target will be up to 10 MeV/A for A = 130, with an intensity in the range of 10^7–10^9 pps.

INTRODUCTION

The SPES strategy is to develop a facility for Nuclear Physics research together with a facility for applied Physics based on the same technology and infrastructure.

SPES [1] is designed to provide neutron-rich radioactive nuclear beams (RIB) of final energies in the order of 10 MeV/A for nuclei in the A= 9-160 mass region. The radioactive ions will be produced with the ISOL technique using the proton induced fission on a Direct Target of UCx [2] and subsequently reaccelerated using the PIAVE-ALPI accelerator complex [3]. A Uranium fission rate of 10^13 fission/s is foreseen.

A Cyclotron with a maximum current of 0.750 mA rowing two exit ports will be used as proton driver accelerator with variable energy (30-70 MeV).

Two proton beams can be operated at the same time sharing the total current of 0.750 mA. To reach a fission rate of 10^13 fission/s a proton beam current of 200 µA (40MeV) is needed; the second beam, up to 500 µA 70MeV, will be devoted to applications; mainly neutron production for material research and study of new isotopes for medical applications.

The expected rate of fast neutrons is estimated to be 10^14 n/s at the target output using a Pb target (mean energy 1MeV).

The ISOL technique for radioactive beam production is based on a driver accelerator which induces nuclear reactions inside a thick target. The reaction products are extracted from the target by thermal process, ionized 1+, isotopically selected, ionized n+ and injected into a re-accelerator. In order to produce neutron-rich isotopes it is mandatory to perform fission reactions in Uranium or other actinide targets using protons, deuterons, neutrons or gammas. The SPES choice is to use a proton beam to induce fission on a UCx target (Direct Target).

Fig. 1 shows schematically the SPES main elements located at underground level, a second floor at ground level hosting laboratories and services is not shown.

The driver is the proton cyclotron delivering beam on different targets. Two production ISOL targets are planned to be installed. The production target and the first mass selection element will be housed in a high radiation bunker. Before the High Resolution Mass Spectrometer (HRMS) a cryopanel will be installed to prevent the beam line to be contaminated by radioactive gasses and a RFQ cooler to reduce the input emittance of the HRMS. After passing through the HRMS, the selected isotopes will be stopped inside the Charge Breeder and extracted with increased charge (n+). A final mass selector will be installed before reaching the PIAVE-ALPI accelerator, to clean the beam from the contaminations introduced by the Charge Breeder itself.

Two facilities for applied physics are planned: a neutron facility that make use of the proton beam to produce neutrons and an irradiation facility for production and study of radioisotopes for medical use.

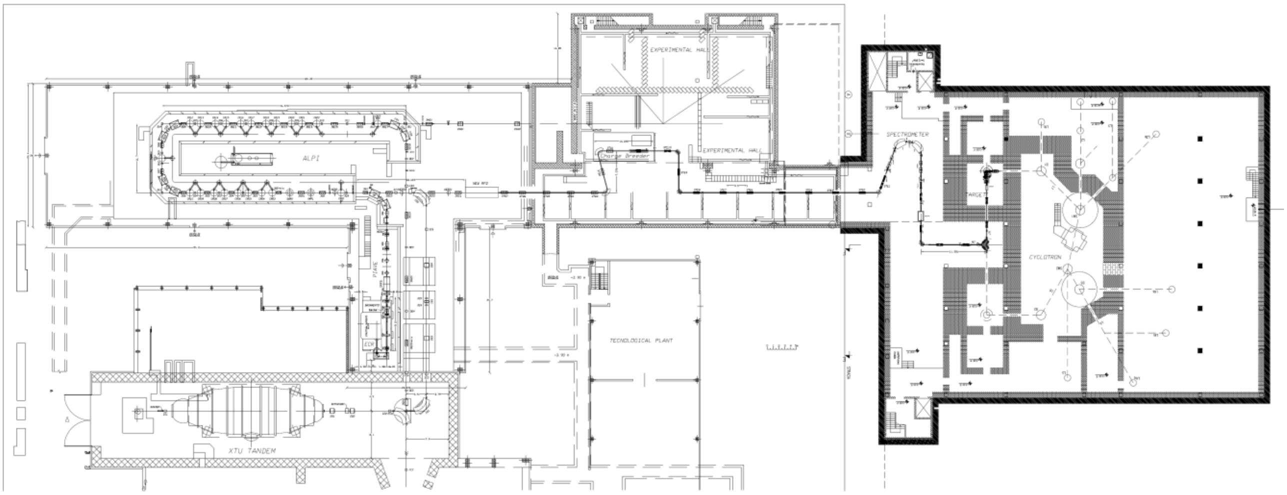

Figure 1: Layout of the SPES and ALPI facility; the dark black part on right is the new Cyclotron area.

THE CYCLOTRON

Within the SPES project, during the 2010 the tender for supply of the Cyclotron, the transport beam line up to the ISOL target and the ancillary systems, was accomplished out. The INFN assigned the contract to BEST Theratronics Ltd. (Canada). The contract foresees the delivery to LNL and the commissioning of the accelerator and the beam line, within 3 years from the assignment [4]. The BEST cyclotron is a compact four straight sector machine, see figure 2, energized by a pair of room temperature conducting coils. The cyclotron is able to accelerate H beam, provided by an external multi-cusp ion source, up to the energy of 70 MeV. Since the proton extraction is done by the stripping process, the final energy varies within 35-70 MeV. Two independent extraction channels placed at 180° one respect to the other provide the simultaneous extraction of two beams. The maximum beam current deliverable is estimated to be 700 µA. The table 1 shows the main parameters of the machine.

Table 1: Main Cyclotron parameters

Main Magnet	Bmax field: 1.6 T Coil current: 127 kAT 4 sectors, deep valley Hill sector angle: 50° Varying hill gap: 6-4.69 cm
RF cavity	Frequency: 58 MHz Harmonic: 4th Dissipated power: 28 kW Dee voltage: 60-81 kV Dee angle: 36°
External ion source and injection line	Multi-cusp H-, 15-20 mA DC Beam current: 700 µA Injection Energy: 40 keV Spiral inflector
Vacuum	Ion source: <1x10^{-5} torr Main tank: < 1x10^{-7} torr
Extraction	Simultaneous dual beam 2 stripping multi-foil carousels Variable energy 35-70 MeV

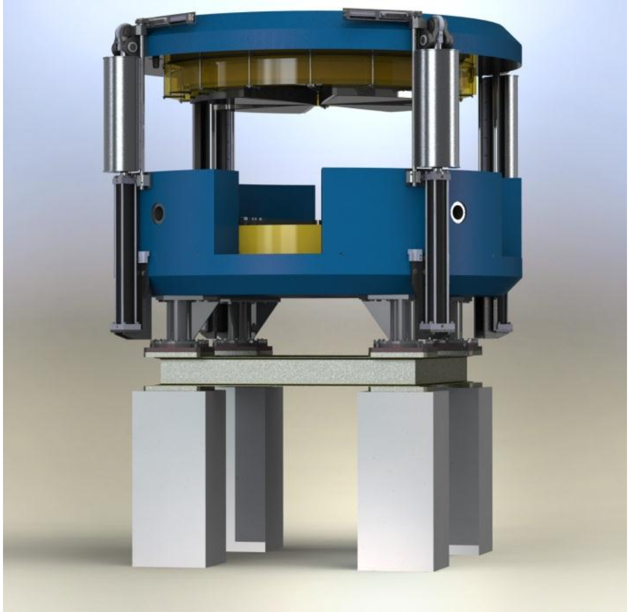

Figure 2: Best Theratronics 70p model.

THE MULTI FOIL DIRECT TARGET

In an ISOL facility, like SPES, the working core is constituted of the production target and the ion source [2]: they have to be carefully designed and optimized in order to obtain the desired high production rate of RIBs. Due to the low pressure of the environment, the power deposited by the proton beam in the target by means of electromagnetic and nuclear interactions can be removed only by thermal radiation towards the surrounding container box. In order to optimize both heat dissipation and fission fragments evaporation, the SPES target consists of seven, 40 mm diameter and 1.3 mm thick, co-axial disks housed in a cylindrical graphite box, see figure 3. In choosing the target material, which should stand the highest possible beam current, it is crucial to optimize the beam-target combination with respect to the highest production cross section and lowest amount of contaminants. UCx, uranium dicarbide dispersed in an excess of graphite, is widely recognized as the reference material for the production of neutron-rich radioactive beams. The preparation of the SPES UCx disks is based on the carbon-thermal reduction of UO2 powders in excess of graphite. The powders are mixed and ground in order to obtain a homogeneous mixture; these powders are uniaxial cold pressed. Finally the heat treatment is performed in a dedicated vacuum furnace. The final bulk density of the disks turns out to be about 3 g/cm3, while the U:C atomic ratio is close to 1:4. The calculated in target fission rate in all the 7 disks approaches 10^13 fps. The distribution of the fission products is shown in Figure 4. The isotope in-target production for some interesting isotopes (Ag, Sn, Cs) reaches values up to 10^11 aps. The 132Sn isotope, being a double-magic nucleus, is one of the radioactive nuclei of interest and the in-target production yield is here estimated to be 10^10 aps. The output emittance from the target will be in the order of 30 mmrad at 40 kV [5]. An off-line front-end of the thin target is fully operational at LNL, see figure 5.

The beam transport of the radioactive beam is started from the target; see figure 6, with a first rough mass separation made by a Wien filter, after that the beam is transported to the RFQ cooler, figure 7.

The TraceWin simulation [6] is performed at first order, but includes the transfer matrix of the Wien Filter, as custom element. The mass resolving power achieved by the dispersive effect of the Wien Filter and the 90° analyzing dipole is more than 300.

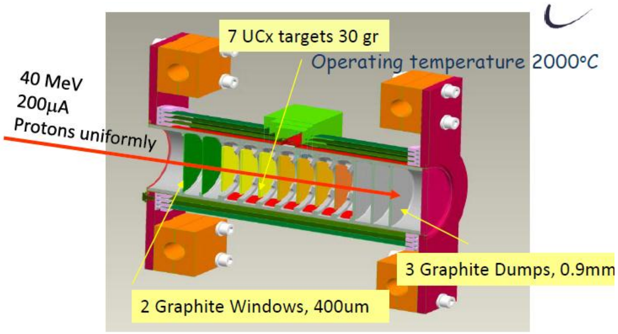

Figure 3: The SPES thin target model.

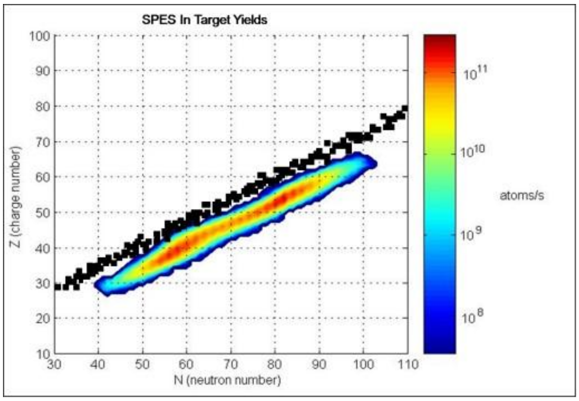

Figure 4: The in-target isotope yields.

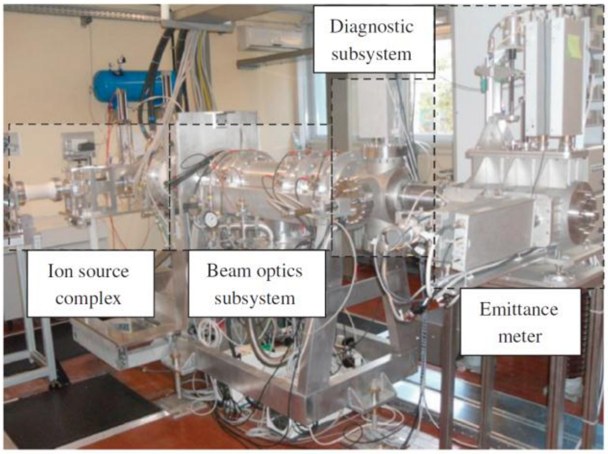

Figure 5: The offline front-end: fully operational at LNL.

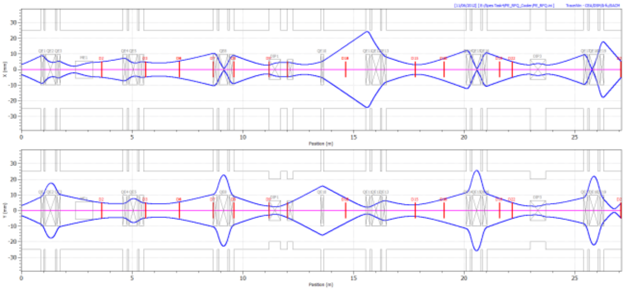

Figure 6: Envelope of the line from the Front-end to the RFQ cooler, from left to right.

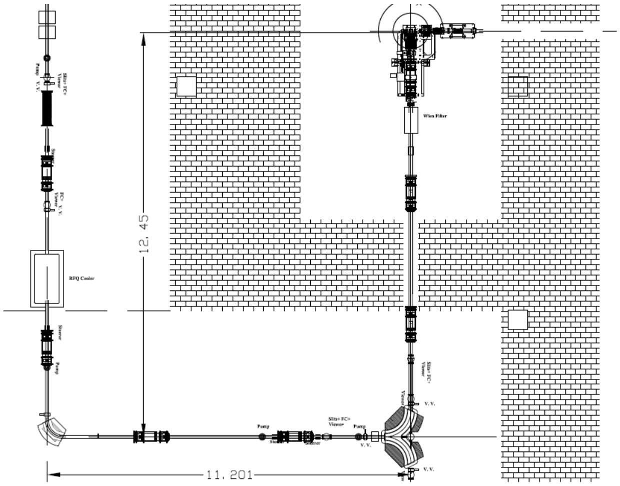

Figure 7: Layout from the Target Front-End to the RFQ-Cooler.

THE RFQ COOLER

In the framework of the SPES project, the radioactive ion beams transport is under study in order to evaluate the transmission efficiency and the final quality of the delivered beams in terms of mass resolution and longitudinal energy spread. In particular the high resolution mass spectrometer needs a beam emittance of the order of 3π mm mrad and an energy dispersion of about 1 eV to get the minimum resolving power of 20’000. These requirements will be fulfilled with the radio frequency quadrupole (RFQ) beam cooler device [7].

The gas-filled, RFQ is a device whereby a previously decelerated, low energy (E<100eV) beam is thermalized via successive collisions with an inert buffer gas. This process allows to decrease, by the energy exchanging with the gas molecules, the radial momentum and the longitudinal energy dispersion of the ions passing through the RFQ.

The preliminary design of the device is carrying on at LNL since 2011, see table 2, and the feasibility study is funded by V committee of INFN in the framework of REGATA experiment, see figure 8.

Table 2: RFQ Cooler main parameters

Mass Range	9 – 200 amu
Tr. Emit. injected beam	30 mmmrad (40 keV)
Emittance reduction factor	10 (max)
Buffer gas	He (293 K)
Beam intensity	50 – 100 nA (10^11 pps)
Energy spread	<5 eV
RF voltage range	0.5 – 2.5 kV
RF frequency range	1 – 30 MHz
RFQ gap radius (R0)	4 mm
RFQ length	700 mm
Pressure buffer gas (HE)	0.1 – 2.5 Pa
Ione energy	100 – 200 eV

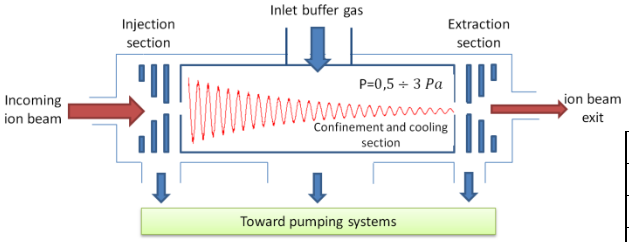

Figure 8: RFQ cooler layout.

THE HIGH RESOLUTION SPECTROMETER

A crucial task for the experimental use of radioactive beams is not only the beam intensity but also the beam quality. Special efforts have been dedicated to design a mass spectrometer with an effective mass resolution of at least 1/20000. Such design takes advantage of the 260 keV beam energy obtained with the HV platforms. Such high selectivity results in an advantage also for the safety issue, reducing the problems of contaminations along the beam transport areas and in the target location, see figure 9.

The design of the SPES spectrometer is a scaled up version of the separator designed at Argonne. The first order design mass resolution is about 40.000 to reduce the tails of contaminant with higher yields, see figure 10 and table 3.

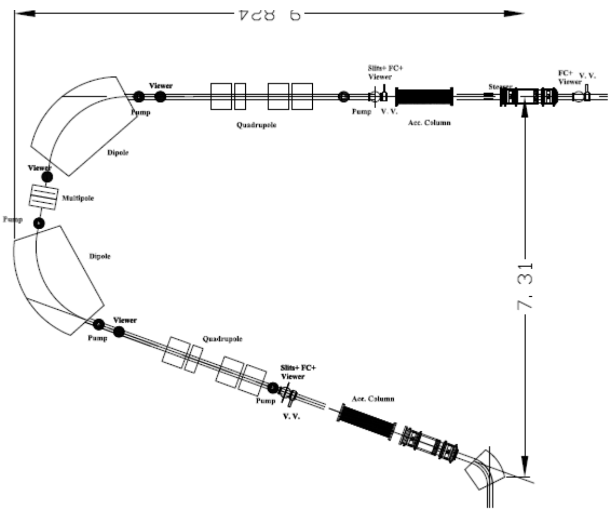

Figure 9: Spectrometer Layout from the RFQ cooler to the transport line to the Charge breeder.

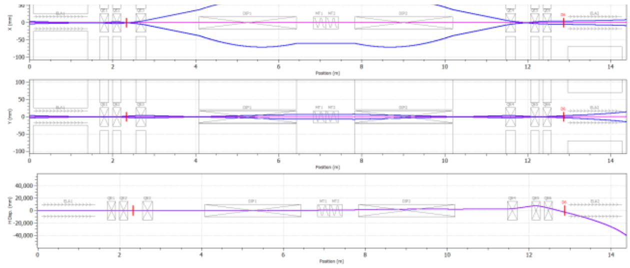

Figure 10: Envelope design of the spectrometer.

Table 3: Spectrometer main parameters

Mass Resolution	1/40000
Dipole Bending Angle	80 deg
Dipole Bending radius	1.5 m
Dipole Edge	28 deg
Dipole max field	1.2 T
Energy (1/132)	260 keV
Multipole element	Sextupole
Input tr. Emittance RMS norm.	0.00171 mmmrad

THE TRANSPORT LINE TO THE CHARGE BREEDER

From the High resolution beam spectrometer to the charge breeder is necessary to transport the beam for about 34 meters in a carefully way to avoid beam losses This periodic line is made by using electrostatic triplets with a period of about 3.6 meters; the total length of the line so may be changed by adding a period or removing a period, table 4 and figure 11.

Table 4: Transport line to the Charge breeder main parameters

Ion	1/132
Electrostatic Triplet lengths (mm)	200+70+400+70+200
Electrostatic Triplet radius	60 mm
Electrostatic max voltage	4.03 kV
Dipole Radius	500 mm
Dipole max field	0.67 T
Energy (1/132)	40 kV
Total number of triplets	10
Transvers Emittance RMS norm.	0.02 mmmrad

In figure 12 is reported the layout of the transport line and the maximum envelopes in X and Y.

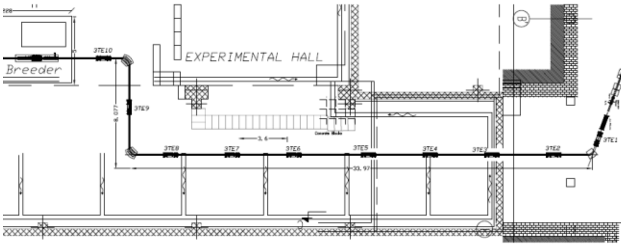

Figure 11: Layout from the Spectrometer to the Charge Breeder in the experimental hall 3 from right to left.

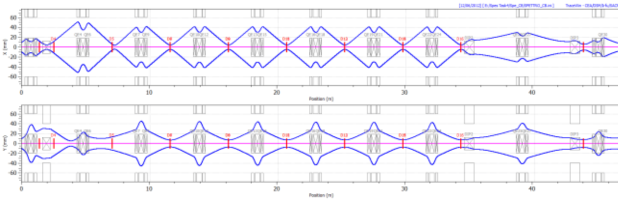

Figure 12: Max Envelope from the Spectrometer to the Charge Breeder from left to right.

THE CHARGE BREEDER

In 2010 an agreement was signed between the SPES and the SPIRAL2 projects in the framework of the LEA-COLLIGA aiming at sharing know how in the field of radioactive beam production and manipulation, see table 5 and figure 13. The agreement foresees the development of the neutron converter for SPIRAL2 by INFN and the development of an ECR-based charge breeder by LPSC. During 2010 some experimental activities on charge breeding (the so called 1+/n+ method) were performed at LPSC with the Phoenix booster aiming at improving the capture efficiency by means of fine frequency tuning of the microwave injected and checking the plasma characteristics variations measuring the plasma potential.

When a characterized 1+ ion beam is injected into a plasma and then all the ion species are extracted and analyzed , one could expect some information about the characteristics of the plasma itself: its ability to capture 1+ ions and its ability to multi ionize the 1+ ions injected (i.e. plasma temperature and density). The 1+/n+ method developed for radioactive ion beams could be considered as a kind of non perturbative probe because the number of ions injected is exactly known (1+ beam intensity measurement), and extremely low with respect to the initial number of ions present in the plasma, even if some effects on the plasma were observed during the experiments performed at LPSC, like the partial destruction of the high charge states of oxygen without a corresponding increase of the current of the lowest ones.

Some studies have been performed in a frequency sweep mode: however due to the variation of the net power coupled to the plasma during a sweep and the limited reflected power sustainable by the TWTA that amply and feed microwave into the plasma chamber, the influence of the fine frequency tuning could not be properly deduced. Further studies are mandatory to verify the usefulness of this technique.

The joined team INFN-LNL/LNS is also involved as deputy coordinator in a European project called EMILIE (Enhanced Multi-Ionization of short-Lived Isotopes at EURISOL) approved in 2011 by the NuPNET [8]. In the framework of this project the INFN team will investigate numerically two important aspects concerning the ECR-based charge breeding: the microwave coupling to plasma chamber of the Phoenix charge breeder installed at LPSC Grenoble and the study of the capture of the 1+ beam by the ECR plasma. The work will lead from one side to a conceptual design of an optimized plasma chamber for the Phoenix charge breeder; on the other side a numerical code (developed at LNS) describing the ECR-plasma dynamics will be adapted to deeply study the capture process in order to understand how to improve it, especially in the case of condensable elements.

Table 5: Charge Breeder main parameters

Frequency	14.5 GHz
Power Max	1000 W
Magnetic Field Injection	1.5 T
Magnetic Field Extraction	1.0 T
Magnetic Field Radial	1.35 T
Efficiency for gas	8-10 %
Efficiency for metals	3-5 %
Charge breeding time	From 3 to 15 ms/q
Output emittance RMS	0.1 mmmrad

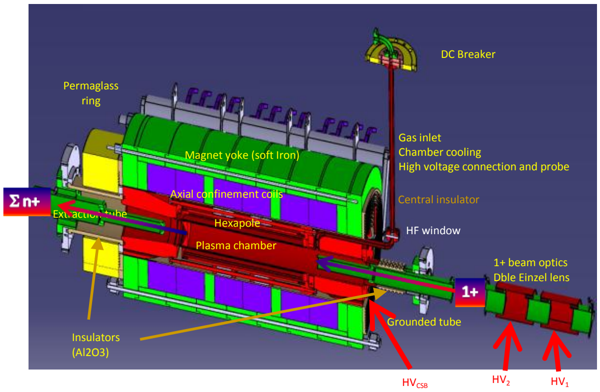

Figure 13: Layout of the Charge Breeder.

A transport line of about 20 meters is necessary to transport the beam from the Charge Breeder to the new RFQ, see table 6; this line is made by using 7 magnetic triplets, with a gradient 3.3 T/m at maximum but with a quite large aperture, this is done for avoid beam losses. This line should also be able to separate ion mass within

1/1000, see figure 14. This beam line also prepares the beam input condition for the new RFQ.

The triplets and doublets used are of the same type of the PIAVE-LEBT magnetics elements.

In figure 15 is reported the layout of the line from the charge breeder to the RFQ and the maximum envelopes in X and Y.

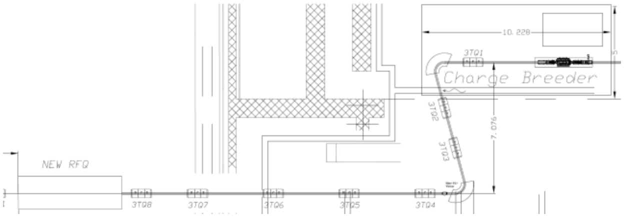

Figure 14: Layout form the Charge Breeder to the new RFQ from right to left.

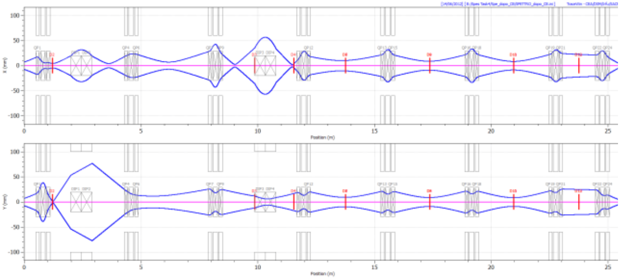

Figure 15: Maximum Envelopes from the Charge Breeder to the injection into the new RFQ from left to right.

Table 6: Transport to the new RFQ main parameters

Ion	132Sn19+
Magnetic Triplet lengths (mm)	150+50+200+50+150
Magnetic Triplet radius	60 mm
Magnetic max integrated gradient	0.5 T
Dipole Radius and angle	500 mm 105 deg
Dipole max field	0.15 T
Energy (132Sn19+)	0.76 MeV
Total number of triplets	8
Transvers Emittance RMS norm.	0.1 mmmrad

THE NEW RFQ INJECTOR

The injection to the ALPI Linac is based on the use of a new Radio Frequency Quadrupole, with the adiabatic bunching inside. In this way a high voltage platform can be avoided, and a higher overall transmission could be achieved.

The new RFQ will operate in a CW mode (100% duty factor) at a resonant frequency of 80MHz. This frequency is the same as that of the lowest energy ALPI superconducting structures. The injection energy of ions was set to 5.7 keV/u. This choice is a compromise between the desire to reduce the ion energy to simplify the LEBT and RFQ bunching section design and the need to increase the injection energy to reduce space charge effects. The extraction energy was set to 727 keV/u, higher than the output of PIAVE RFQ, to optimize the beam dynamics of the SRF linac. Table 7 summarizes main RFQ parameters.

Table 7: Principal RFQ parameters

Operational mode	CW
Frequency (MHz)	80.
Injection Energy (keV/u)	5.7 (β=0.0035)
Extraction Energy (keV/u)	727 (β=0.0395)
Accelerated beam current (μA)	100
Charge states of accelerated ions (Q/A)	7 – 3
Internal bunching section	Yes

The design goals were to minimize the longitudinal and transverse emittances and to optimize the RF losses and transmission of the RFQ structure. The RFQ cells were created using the program CORTO, used for the design of CERN linac3 RFQ, PARMTEQM code package and Toutatis in an iterative cell-by-cell procedure. With this design the RF power consumption is minimized, while a ramped voltage profile allows the RFQ to accelerate the beam more effectively at higher velocities and achieve higher output energy. Figure 16 shows the density plot along the RFQ while Table 8 lists parameters of the RFQ structure. The RFQ transmission is more than 94%, the final RMS normalized longitudinal emittance is 0.05 mmrad, i.e. 4.4 keVdeg/u, see figure 17.

Table 8: RFQ design parameters

Parameter (units)	Design 1
Inter-vane voltage V (kV, A/q=7)	63.8 – 120
Vane length L (m)	5.56
RF power (kW, four vanes structure)	180
Average radius R_0 (mm)	5.03 – 9.574
Vane radius ρ to average radius ratio	0.8
Modulation factor m	1.0 – 3.16
Total number of cells	293
Synchronous phase (deg.)	-90 – -20
Focusing strength B	5.28 – 2.8
Peak field (Kilpatrick units)	1.7

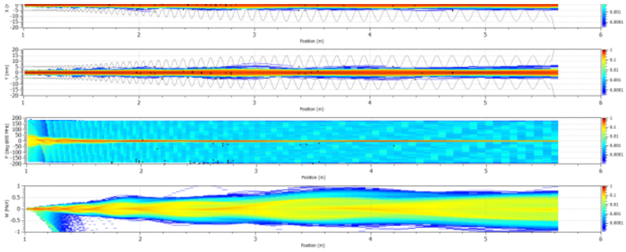

Figure 16: Multiparticles of the new RFQ.

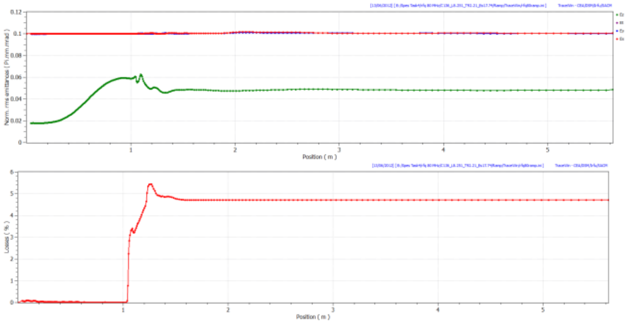

Figure 17: Emittance and losses plot along the new RFQ.

THE ALPI LINAC UPGRADE

The present configuration of the Legnaro super-conducting accelerator complex (PIAVE injector and ALPI main accelerator) fits the requirements for SPES post acceleration too. Nevertheless an upgrade of its performances both in overall transmission and final energy is needed and a solution which minimizes the impact on the present structures [3].

The super-conducting linac ALPI is injected either by a XTU tandem or by the s-c PIAVE injector. The linac (at the present 64 cavities and a total voltage of 48 MV) is build up in two branches connected by an achromatic and isochronous U-bend (Fig. 1). ALPI period consists in one triplet and 2 cryostats (4 cavities in each cryostat), and a diagnostic box (profile monitor and Faraday cup) in between.

The PIAVE-ALPI complex is able to accelerate beams up to A/q = 7. Higher A/q ions suffer from too low injection energy to the medium-β cryostats, where the RF defocusing is too strong and the beam gets easily lost onto the cavity beam ports for this purpose a new RFQ injector will be used. In the last years the average cavity accelerating field has been enhanced by more than a factor of two with respect to the original design value [9], see figure 18. The strength of the focusing lenses on the other hand, has remained the same (20 T/m). Therefore, even for 6 < A/q < 7 it is hard to design a proper longitudinal beam dynamics such that it will not cause problems on the transverse plane, see figure 19. To fully exploit the available acceleration gradient, some improvements are required in the layout of ALPI.

For SPES, the Radioactive Ion Beam at 727 keV/A will be injected into ALPI by means of the QWRs actual present into PIAVE, see figure 20 and the envelopes in figure 21, by using this layout and with the help of the new RFQ the losses in the ALPI linac are reduced at about 20%: 10% in the first branch of the linac and the other 10% in the high energy branch of the ALPI linac.

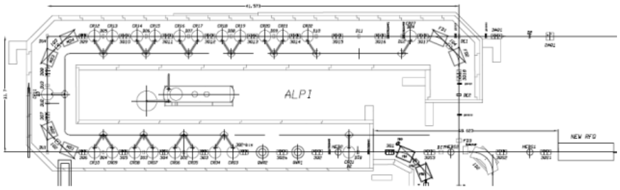

Figure 18: Layout of ALPI with the new RFQ as Injector.

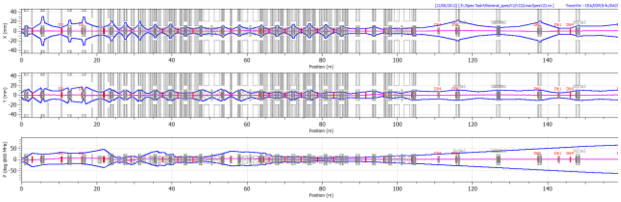

Figure 19: Multiparticles envelopes of the ALPI, with the beam coming out from the new RFQ, from left to right.

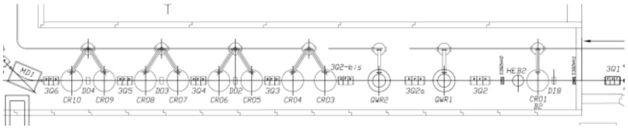

Figure 20: Layout of the new low energy ALPI branch.

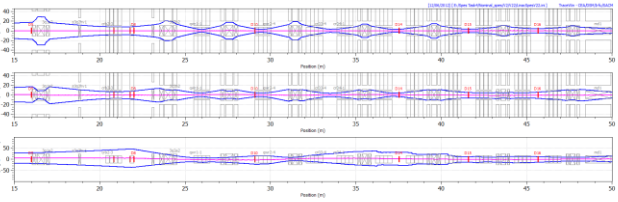

Figure 21: Multiparticles envelope of the new low energy branch, from left to right.

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