SPES BEAM DYNAMICS

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Abstract

At LNL INFN is under construction a Rare Isotope Facility (SPES) based on a 35-70 MeV proton cyclotron, able to deliver two beams with a total current up to 0.5 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).

In this talk will be described the elements between the production target and the experiments, like the selection system, the ECR charge breeder, the second separation system and the new CW RFQ (80 MHz, 714 keV/u, internal bunching).

The problems that have been solved during the design phase are partly common to all RIB facilities, like the necessity to have an high selectivity and high transmission for a beam of a very low intensity, plus the specific challenges related to the use of ALPI (with a reduced longitudinal acceptance) and related to the specific lay out.

At present the design phase has been finalised, and the procurement procedure for the charge breeder, the transfer lines and the RFQ are in an advanced state and will start in the next months. The main beam dynamics aspects of the transfer lines (including magnetic selections) and the linac ALPI will be discussed in detail.

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, in order to perform nuclear physics experiments, which will require beams above Coulomb barrier.

The main functional steps of the facility are shown in Fig.1, namely the primary beam from the cyclotron, the beam from the fission target (up to 10^{13} fission/second), the beam cooler, the spectrometers, the charge breeder and the accelerator, the existing ALPI with a new RFQ injector.

The use of the continuous beam from the +1 source (LIS, PIS, SIS) maximizes the RNB efficiency but needs a CW post accelerator (RFQ and ALPI); this layout also needs a charge breeder chosen to be an ECR that woks in continuous.

The energy on the transfer lines are determined by the chosen RFQ input energy (w_{RFQ}=5.7 keV/u); namely, all the devices where the beam is approximately stopped (production target, charge breeder and RFQ cooler) lay at a voltage:

$$eV = (A/q)w_{RFQ} \tag{1}$$

The charge state range ($3.5 \leq A/q \leq 7$) is bounded by the RFQ field level for the upper limit and by the minimum voltage on q=1 transport line (overall space charge from the source and contaminants separations).

The beam preparation scheme satisfies various requirements:

1. the zone with worst radiation protection issues is reduced by means of the first isobar selection (resolution R=1/200).
2. after that with an RFQ cooler the beam energy spread and transverse emittance are reduced both for further separation and to cope with the charge breeder acceptance (about 5 eV).
3. HRMS and MRMS (high and medium resolution mass spectrometers, R=1/40000 and R=1/1000 respectively) are used to select the RNB (with good transmission) and to suppress the contaminants from the charge breeder source.
4. Both the HRMS and the MRMS are installed on a negative voltage platform, to decrease the beam geometrical emittance, the relative energy spread and to keep the dipole field in a manageable range (>0.1 T).
5. The 7 m long RFQ has an internal bunching and relatively high output energy; this easies the setting and allows 90% transmission into ALPI longitudinal acceptance (constraint deriving from quite long ALPI period, 4 m).
6. An external 5 MHz buncher before the RFQ will be available for specific experiments.
7. The dispersion function is carefully managed in the various transport lines; where possible the transport is achromatic, otherwise the dispersion is kept low (in particular at RFQ input D=0, D' is about 50 rad).

Radiation Containment

RIB facilities require special radiation protection. The SPES building itself is designed in order to reduce the radiation exposure. From the beam dynamic design point of view, the separation of the nominal beam from its contaminants (nA nominal current respect to μA contaminants) in safety areas is mandatory. In this prospective, the low separation stage is placed inside radiation containment walls (see Fig. 2); at the same time such boundary conditions impose restrictions on the beam dynamics design.

As far as the HRMS is concerned, it is important to clean the nominal species from contaminants in order to reduce radioactive species implantation inside the CB.

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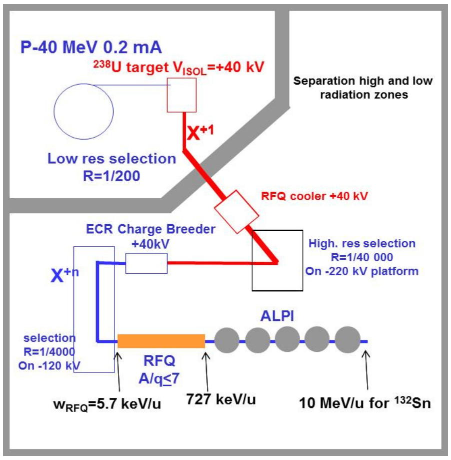

Figure 1: functional scheme of the SPES facility. There are two main areas: the 1+ line (red) and the n+ line (blue), where 1+ and n+ indicates the beam charge state.

METHOD FOR SIMULATIONS

The main software used for the simulation is TraceWin [1] a 3D multiparticle tracker, capable of field map usage. Thus, it is possible to take into account fringe field and all non-linear effects of the line elements. Moreover, it can perform static or dynamic errors for all beam line devices.

This is useful for the complex devices like the Wien Filter and the high-resolution spectrometers, which may diverge from the linear behaviour.

The simulations will be benchmarked with different programs such as GIOS and TRACK.

Moreover, the TraceWin software with full field maps capability is ordinary used to set all beam line for the runs: this kind of commissioning was demonstrated successful for the setting of LINAC ALPI cavities [2].

BEAM DYNAMIC SIMULATIONS

General Layout

Figure 2 shows the actual layout of the SPES facility. The main areas are shown: the cyclotron area, the target room, the 90˚ magnetic, the beam cooler and HRMS spectrometer dipole zone in the new building under construction (at the right hand side); the CB and the MRMS area, the RFQ and ALPI and the experimental rooms.

The position of the new building was forced by various constraints. In particular the technological plant is placed in front of the MRMS complex and the experimental rooms. As a result the space that the RIBs have to travel from the production source to ALPI is quite long. Moreover the beam distribution line network from ALPI to the experiments in the third experimental hall have been rebuilt to leave the beam tunnel reserved to RIBs.

The layout leaves space for some additional use (low energy beam lines) and future expansions (like a new stable beam source and an EBIS charge breeder).

Low Resolution Section

The low resolution section is the part of the line between the target and the beam cooler. The current produced by the target (up to some μA) needs to be clean from its contaminants.

Two mass spectrometers are inserted between the target and the beam cooler. The first device is the Wien Filter, which acts as a pre-mass separator with a resolution of about 1/50-1/75 in mass. The second element is a 90˚ magnetic dipole which achieve a separation in mass of 1/200: this resolution is sufficient in order to select the isobars.

Two focussing triplets match the Wien Filter output beam with the 90˚ magnetic dipole.

The selection of the isobars before the beam cooler is an important aspect because it allows the device to work in a low current regime about less than 25 nA, i.e. with reduced space charge effects. In such a way it is possible to boost the beam cooler performances: a first reasonable estimation shows the possibility to reduce the energy spread of the source down to 1 eV [3] and the transverse geometric emittance down to 10 times the input emittance [4]. The estimated transmission is about 60% [3] in the worst case.

The reference beam is chosen to be the ^{132}Sn , extracted at 40 kV at the end of the target extraction system. With q=19 after the charge breeder i.e. A/q= 6.9, it is possible to test the maximum required electromagnetic fields of the line elements of the facility.

The input Twiss parameters used for calculations were measured during an off-line test of the target extraction system: $\alpha_{x,y}$ = -1, $\beta_{x,y}$ = 0.66 mm /π mrad. The normalized rms emittance is chosen to be $\varepsilon_{n,rms}$ = 0.007 π mm mrad, with an equivalent geometric emittance at 99% of $\varepsilon_{geo,99\%}$ = 70.18 π mm mrad.

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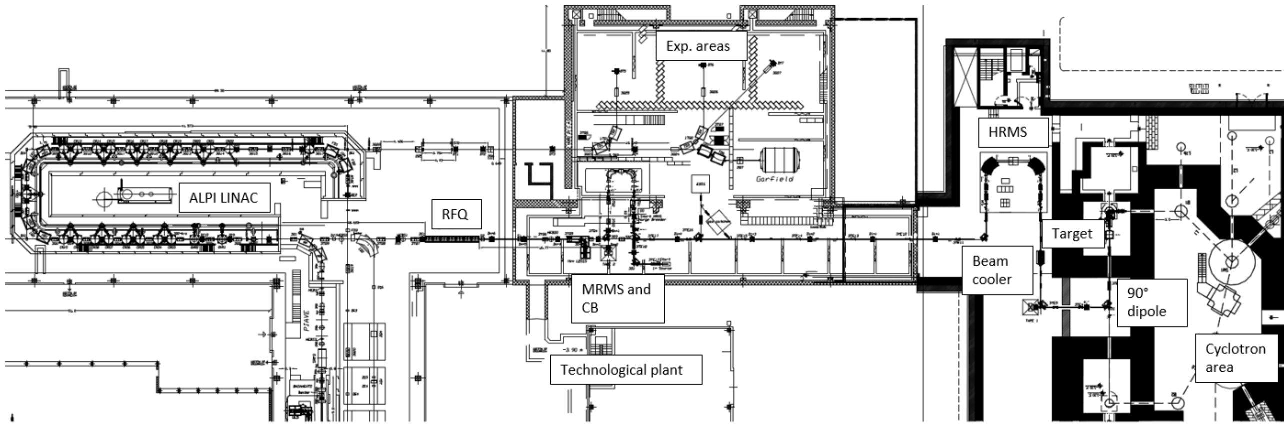

Figure 2: Full SPES layout with main areas.

The transverse spatial distribution is Gaussian-like, truncated at three sigma. As far as the longitudinal space is concerned, it follows a uniform distribution: the beam phase is included between $\pm 180^0$, while the energy spread $\Delta W = \pm 20$ eV. The number of macro particles simulated was 10^5.

The first elements met by the beam after the extraction system is an electrostatic triplet. A field map of this element was calculated with COMSOL.

A horizontal defocusing quadrupole is placed before the 90˚ magnetic dipole, in order to have a better control of the resolution.

The dispersion function between the two mass spectrometers is arranged in order to maximize its value at the dipole slits, while it is matched at the entrance of the beam cooler. The multiparticle beam envelopes are shown in Fig. 3.

The magnetic spectrometer is modelled via hard edge; the curvature R_{edge} of the edge angle is included with a zero-length exapole of field A_{exa} using the formula expressed by Brown in [5]. The transverse emittance growth after the spectrometer is less than 7%.

Many beam species are expected to be handed, each one with its custom extraction voltage. Although, lower kinetic energy led to a larger relative energy spread term.

In order to check the resolution power of the system, different ion species (ranging from A/q=7 to A/q=4) were tested: the input for dynamic calculation was made with three beams of same emittances (i.e. 0.007 π mm mrad), masses and Twiss parameters, separated of 0.25% in $\Delta p / p$ (i.e. 1/200 in mass). The slits at waist were left in the same position as for the reference case. The total separation is achieved.

The High and Medium Resolution Sections

Two different spectrometers, HRMS an MRMS are provided for the SPES project. The HRMS is used to obtain the ions of interest, because it removes isobar ions coming from the source, the MRMS is used to clean the nominal beam from contaminants introduced by charge breeder. The first separation stage is represented by HRMS placed on a 260 kV platform, this separator is constituted by six quadrupole lens, two exapole lens, two dipole and one multipole lens placed in the symmetry plane of the system to fix the high order aberration.

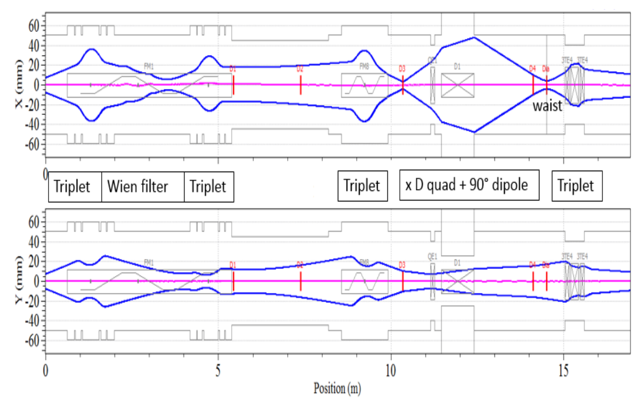

Figure 3: beam multiparticle envelopes in vertical (y) and horizontal direction (x).

The reference beam is $^{132}Sn^{1+}$ with normalized emittance in both planes equal to 0.0014 π mm mrad. The HRMS is able to separate different isobar with ΔM/M=1/20000 and ΔW= ±5eV (Fig. 4).

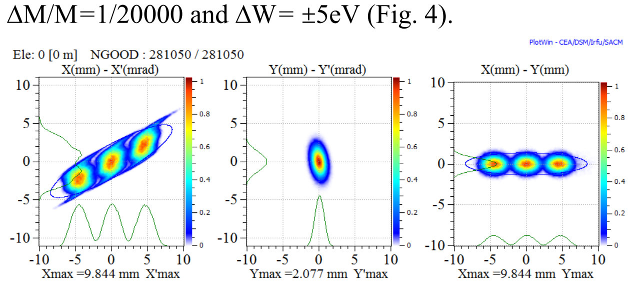

Figure 4: phase spaces at the HRMS dipole slits. The three beam separated of 1/20000 in mass.

After the charge breeder, the next spectrometer is the MRMS, placed on a 120 kV platform.

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The reference beam is $^{132}Sn^{19+}$ with normalized emittance equal to 0.1 π mm mrad in both planes. The goal in resolving power of this spectrometer is 1000 is achieved (Fig.7).

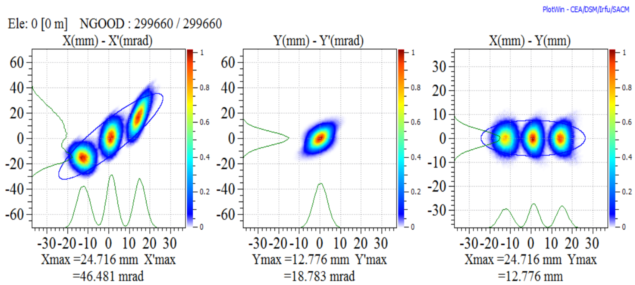

Figure 5: phase spaces at the MRMS slits. The three beam separated of 1/1000 in mass.

This separator is composed by four quadrupole lens, two dipole and one multipole lens placed in the symmetry plane of the system to fix the high order aberration.

The MRMS parameters are listed: bending angle 90˚, bending radius 0.75 m, edge angles 33.35 ˚, width ±35^0; sextupole correction is provided by entrance and exit poleface curvature, the magnetic induction field for the test case is 0.203 T. The below Table 1 shows the mass spectrometers parameters and dipoles features.

Table 1: Medium and High Spectrometer Performances

Parameter	MRMS	*HRMS*
Input norm. emittance rms [mm mrad]	0.1	0.0014
Emittance growth	10%	3%
Resolution at 99% $\Delta W = 0$	1/2000	1/60000
Res. at 99% $\Delta W = \pm 5$eV	1/1000	1/20000

The transfer line for the MRMS connects the CB to the RFQ via MRMS. The input Twiss parameters used for the beam dynamic calculation were obtained via a simulation of the Charge Breeder extraction system; KOBRA3d, as described in [6].

The beam input is spatially Gaussian distributed, while an energy spread of $\Delta W = \pm 5$ eV is implemented. The beam charge is equal to +19 with an A/q= 6.9. The Twiss parameters and emittances are set as follows: $\alpha_{x,y} = -3.23$, $\beta_{x,y} = 0.07$ mm/ π mrad; the normalized rms emittance is chosen to be $\varepsilon_{n,rms} = 0.1$ π mm mrad, with an equivalent geometric emittance at 99% of $\varepsilon_{geo,99\%} = 230.9$ π mm mrad.

The beam injection from the charge breeder extraction to the object point is given by a solenoid and a magnetic triplet. The HV platform ensures a low beam divergence and reduces the effect of the ΔW/W term. After the selection (1/1000), the beam is matched in transverse planes and dispersion to the RFQ via a magnetic dipole, a set of triplets and two solenoids. The magnetic dipole is used in order to keep under control the dispersion generated at the MRMS.

The accelerator columns were modelled via field map, in order to take into account their focusing and defocusing effect.

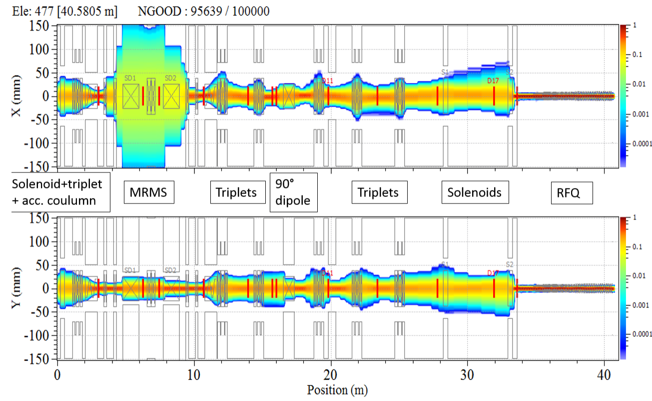

Figure 6: beam multiparticle envelopes in vertical (y) and horizontal direction (x).

An emittance growth occurs after the medium separation stage, and it is equal to 10%.

In order to check the beam transmission to ALPI, the normal conductive RFQ [7,8] were modelled via TOUTATIS. The total nominal beam losses at the exit of the RFQ are about the 7.6%. The longitudinal rms emittance at the exit of the RFQ is $\varepsilon_{long,rms} = 0.69$ π MeV deg, the entry kinetic energy is 760 keV, while the exit energy is 93.9 MeV.

In order to test the transfer line focusing elements sensibilities, an error study was performed. The input beam errors and the MRMS' dipole sensibilities were analysed separately. The set of error applied for the triplets are shown in Table 2.

Each error follows an independent uniform distribution between the values expressed in Table 2. 2000 runs ensure the needed statistic. The final average output longitudinal emittance at the exit of the RFQ resulted $\varepsilon_{long,rms} = 0.78$ π MeV deg with a standard deviation of 0.030 π MeV deg. The resulted beam losses are shown in Fig. 9. The average losses are 7.56%, and the standard deviation is 0.98%.

Table 2: Quadrupole Magnet Errors

Error type	Value
Translation in transverse plane	±100 μm
Tilt in transverse plane	±0.15˚
Gradient error	±0.3%
Multipolar component	±0.6%

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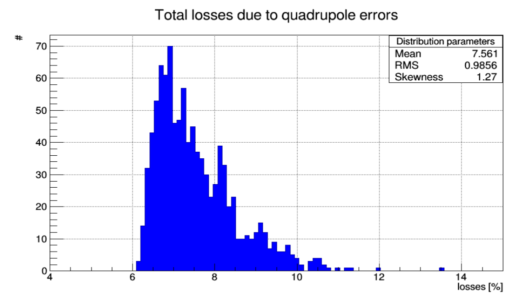

Figure 7: Total beam losses after the RFQ due to quadrupole errors define in Table 3.

A 5 MHz buncher, which will be coupled with a chopper system, is foreseen in order to perform certain experiments: its effect and position were studied. The voltage applied is VT= 325 V. Table 3 reports the results.

Table 3: Buncher Performances.

Set up	transmissions	$\varepsilon_{long,rms}$ [π MeV deg]
Buncher off	92.4%	0.69
Buncher on	40.6%	0.16

The Acceleration Section

The MEBT line connects the output beam from the RFQ to the LINAC ALPI. A $^{132}Sn^{19+}$ beam was simulated, with an A/q = 6.9.

The simulation was performed with the field maps of the quarter wave's cavies, in order to take into account their vertical misalignment effect on the beam. [9]

The beam can be boosted to the maximum energy with 76 QWR cavities at the maximum field. All cavities work with the maximum performance: QWR1- QWR 2=4 MV/m; CR03- CR 18=4.5 MV/m; CR 019- CR 20=6.5 MV/m. However, to reduce field of the bending magnet at the exit of structure last two cryostats from twenty should be off. The final energy in this case will be 9.04 MeV/A. Maximum limit of gradient of the quadrupole is 30 T/m. Maximum used gradient was < 25 T/m. Losses obtained in calculations are lower than 3% (mainly located at the first part of ALPI).

CONCLUSIONS

SPES post accelerator beam design has involved the study of many critical devices, and the overall optimization to distribute the criticality. The beam transport lines from CB to ALPI are now specified and we are tendering the magnets.

The mechanical design of RFQ and HRMS will be completed during 2015, and procurement procedure will follow.

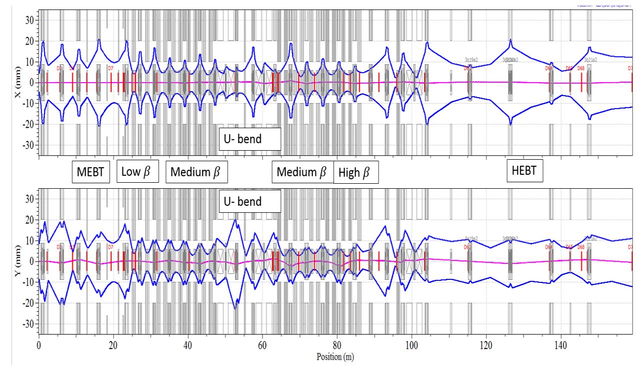

Figure 8: beam multiparticle envelopes in vertical (y) and horizontal direction (x) in the MEBT and ALPI LINAC section.

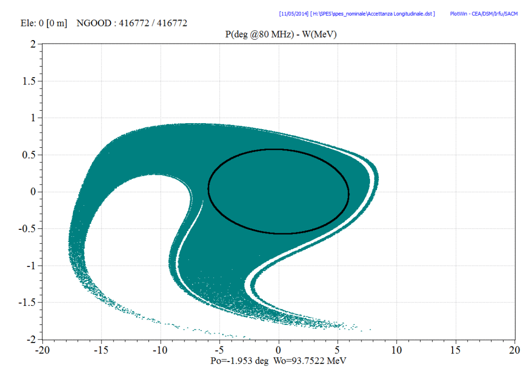

Figure 9: ALPI LINAC longitudinal acceptance.

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