Progress in the design and construction of SPES at INFN-LNL

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ABSTRACT

INFN-LNL is constructing an ISOL (Isotope Separation On Line) facility delivering neutron rich ion beams at 10 A MeV or beyond, making use of the linear accelerator ALPI as the secondary accelerator. The facility includes a direct ISOL target based on UC_x and able to reach 10^{13} fissions/s. In parallel, an applied physics facility will be developed, with applications in medicine and neutron production. The SPES project is a national facility, approved and funded. Commissioning with the first exotic species is expected in 2019. The primary accelerator is a commercial cyclotron, which will send a 40 MeV, 200 μA proton beam onto an UC_x target, connected to SIS, PIS and LIS ion sources. The extracted beam is purified through a Low Resolution Mass Separator (LMRS, i.e. a Wien filter and a dispersive dipole), a beam cooler and a High Resolution Mass Separator (HRMS) and sent to an ECR charge breeder to boost the exotic beam charge state. The highly charged exotic beam is further separated in a MRMS (Medium Resolution Mass Separator) and injected into a 100% duty cycle RFQ and into the existing superconducting linac ALPI, which will be refurbished and upgraded to be an efficient exotic beam accelerator. The upgrade of ALPI will give ~10 A MeV energy to $^{132}Sn^{19+}$, taken as the reference ion beam. The paper presents the status of the design and construction of the SPES facility.

1. Introduction

SPES (Selective Production of Exotic Species) is a being built ISOL type facility taking root on the existing superconducting linac ALPI (Acceleratore Linear Per Ioni) [1]. The ALPI linac, which accelerates highly charged ions up to $8 \div 11$ A MeV (for $A/q = 7 \div 5$) and is employed for stable beam operation since 1994, will be used as the Radioactive Nuclear Beam (RNB) accelerator. The SPES primary accelerator is a commercial cyclotron [2], designed for $30 \div 70$ MeV and 750 μA, shared between two exit ports, thus allowing simultaneous operation of two proton beams. For exotic beam generation, the machine will be operated at 40 MeV and a 200 μA, i.e. at the maximum power (8 kW) which the UC_x target can withstand. Around 10^{13} fissions/s will be generated at the target and effusing-diffusing exotic species will be driven to either surface ionization (SIS), plasma (PIS) or LASER (LIS) ion sources and extracted. The purification process of the nuclear species of interest takes several steps of increasing selectivity. After charge state increase in an ECR-based charge breeder (SPES-CB) [3], the beam is once again purified from the contaminants introduced in the breeding stage and then sent to ALPI through a new full duty cycle RFQ. Fig. 1 shows the area, in the chart of nuclides, which is expected to be populated by mostly n-rich SPES beams, created by the nuclear fission of 40 MeV proton beams on the SPES UC_x target.

Several existing or upgraded detectors will be available for the experimental campaigns, such as the PRISMA spectrometer [4], the recently commissioned GALILEO [5] gamma array, or the complex detectors which are being built in a European collaboration framework (AGATA [6], NEDA [7], PARIS [8] and FAZIA [9]). From the several physics workshops which are being carried out, with the

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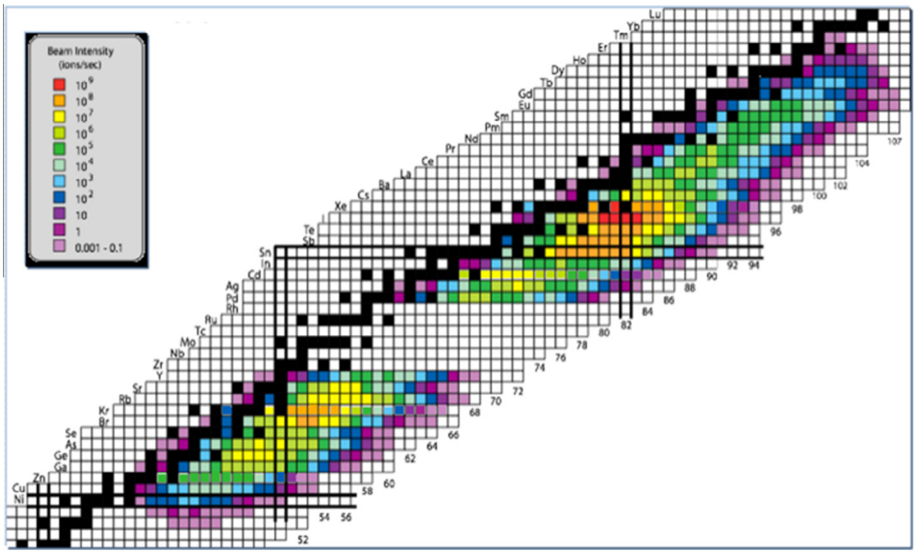

Fig. 1. Expected beam intensity (particle/s), at the TIS stage, in the SPES project by nuclear fission of a 40 MeV, 200 μA proton beam on the multi-slice UC_x target.

primary scope of shaping the first experimental phase at SPES, the most highly requested beam is ^{132}Sn, which gives the possibility to investigate the shell evolution around the magic numbers $Z = 50$ and $N = 82$.

The double extraction capability of the cyclotron will leave ample margins to use the primary accelerator for application purposes, in primis the production of radioactive nuclides for medical purposes. In this context, INFN plans to share the use of the facility with an industrial partner, for the production and commercialization of radioisotopes such as ^{82}Sr and $^{64/67}$Cu, and to dedicate a properly equipped experimental area for research investigations of future radioisotopes for the same purpose (LARAMED project)

At the end of 2014, INFN secured funding for the realization of the entire facility for exotic beam generation and acceleration, whereas medical research facilities were so far partially funded by the Italian government among the so called Progetti Premiali (Award Projects of national interest).

Despite the funding is at national level, the development of SPES relies on collaborations not only with various INFN units (LNS in Catania above all) and universities, but also with European and worldwide ones. Indeed, together with HIE-Isolde at CERN [10] and SPIRAL2 [11] in Ganil (F), SPES paves the way – as a second generation ISOL facility under the coordination of NuPECC – to the realization of EURISOL [12], a facility aiming at 10^{15} fissions/s and 150 A MeV exotic beam energy, the construction of which might start around year 2025.

Fig. 2 shows the layout of the entire SPES facility, where the main components are described in the caption.

This paper reviews the status and the latest developments on the proton driver and the exotic beam production area (chapter 2), as well as the design and realization activities for beam preparation to reacceleration in ALPI and the upgrade steps on ALPI itself (chapter 3 and 4)

2. Exotic beam production

SPES is an ISOL-type [13] facility, which will concentrate on fission fragments induced by the 40 MeV 200 μA proton beam on a thick target.

While the UC_x target and the associated Front End (FE), largely inspired by the CERN-Isolde setup, have been the subject of an intense multi-disciplinary research and optimization effort along several years, the proton driver is a commercial prototype product from the company Best Cyclotron System Inc. (Canada). Capable of a beam energy between 35 and 70 MeV, the cyclotron can accelerate an H^- beam and extract, via beam stripping, a 250 ÷ 500 μA proton current, out of two exit ports simultaneously, which shall allow the nuclear physics experimental program to be overlapped, at any time, with the application one.

The cyclotron was delivered in April 2015 and will be fully commissioned by the supplier, at the INFN-LNL site, within early spring 2016. Fig. 3 shows a photo of the cyclotron and the beam line delivering the beam to the UC_x target station, during its assembly stage.

Fig. 4 shows the layout of the SPES FE, the apparatus which couples the incoming primary beam to the UC_x target [14]. It consists of 7, properly spaced, UC_x discs (Ø = 70 mm, l = 1.3 mm) followed by a graphite beam dump. The discs are housed in a graphite box, surrounded by a hollow tungsten ohmic heater. The release of exotic species from the target, by thermal motion diffusion and effusion, is sustained by the high temperature (2000 °C) of the target itself, the transfer tube and the ionizing cavity (in the case of a SIS).

The 1+ ionized particles are then extracted at a 20 ÷ 40 kV extraction voltage as a low-energy exotic beam.

Such beams are, in general, submerged by an overwhelming fraction of contaminants, created by the same proton-target interaction, of sometimes very similar mass values. Primary separation may be applied in the SIS or LIS by selective element ionization. Elements with high ionization potential, e.g. rare gases, require a PIS, which, however, provides no selectivity whatsoever.

The SPES Target-Ion-Source (TIS) is described, together with the latest developments and tests, in Ref. [15].

Intense experimental activities are being carried out, in dedicated off-line laboratories, both to optimize the target with its ancillary devices, including the various kinds of ion sources, and to design an on-line FE suitable to operate in a high radiation environment.

The production area (target bunker) was also deeply investigated, with respect to the activation of the target itself, air and cooling water in the target bunker, concrete shielding and the soil. Once extracted from the TIS system, the exotic beam requires subsequent purification stages, including that after the charge state breeder, prior to its acceleration by the new RFQ and ALPI.

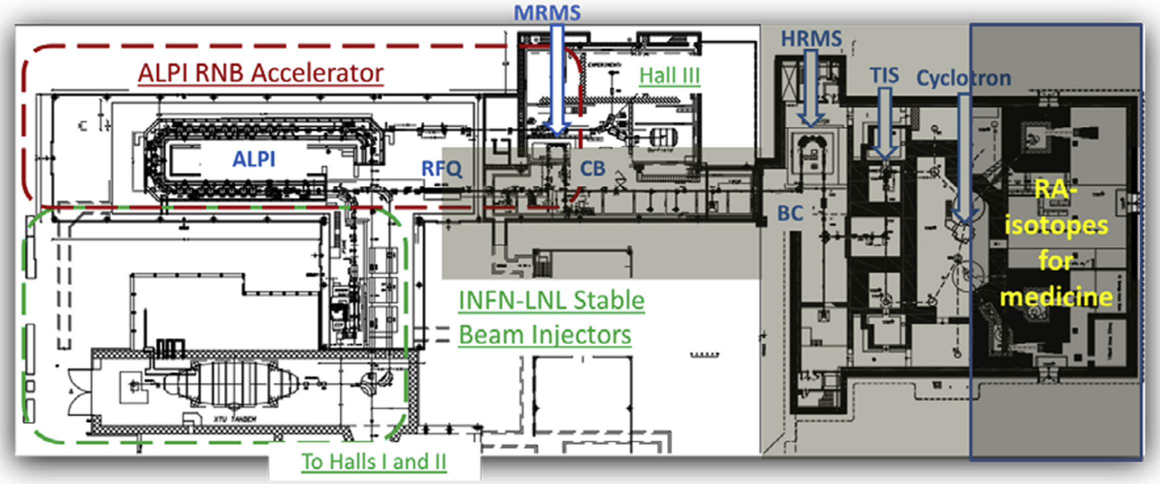

Fig. 2. Layout of the SPES facility. On the left hand side the existing facility, with ALPI, the SC linac which will serve as RNB accelerator, at present injected by either a 15 MV Tandem or by PIAVE, an injector based on superconducting RFQs. On the right hand side, the new building, hosting the cyclotron, two target-ion-source stations and the mass selection stage, i.e. a Beam Cooler (BC) and a High Resolution Mass Separator (HRMS). In the middle, part of present experimental hall III will be occupied by the beam transfer section, including a charge boosting device (ECR-based charge breeder) and a Medium Resolution Mass Separator (MRMS) downstream, plus a new CW RFQ structure in the ALPI building. On the very right, the areas dedicated to exploitation of cyclotron beams for radioisotope production of medical interest are shown.

Fig. 3. Photo of the SPES cyclotron and beam line during installation.

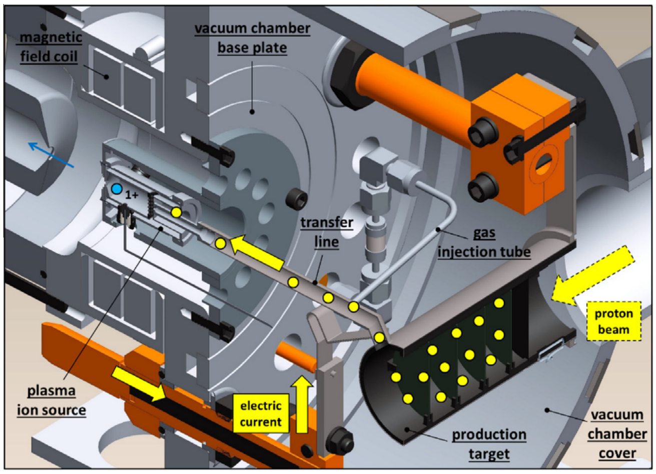

Fig. 4. Pictorial view of the SPES Front End, with the multislice target structure receiving the proton beam and producing exotic species, thermally led, through the transfer tube, to the ion source and its extraction system, forming the beam.

3. RNB selection and preparation for post-acceleration

Following the TIS system, a Wien filter (still inside the target bunker) and a magnetic dipole provide a mass separation of resolution $R = \Delta M/M \sim 1/200$, which is far from being sufficient for most n-rich beams of scientific interest.

Indeed, if we plot the calculated beam intensities produced by the uranium fission in the p-UC$_x$ reaction, we note that a resolution $R \sim 1/10{,}000$ would not be sufficient to separate the ^{132}Sn isotope (reference isotope for beam optics calculations) from the closest contaminants, above all ^{132}Cs, whereas this goal is reached if a resolution $R \sim 1/20000$ is achieved.

Such mass resolution is achieved with the HRMS [16] (Fig. 2). The HRMS is located on a HV platform, where the 1+ ion energy is increased from 40 to 260 kV. This has at least two advantages: the physical emittance is reduced by the higher energy; the dipole magnets can be operated at a field which is not too low, thanks to the increased beam rigidity.

HRMS beam dynamics calculations are shown in Fig. 5. It must be pointed out that the desired resolution is achieved as the result of an error analysis, running Tracewin [17] simulations, spreading among them uniformly distributed errors with an given maximum range in component misalignment (±0.5 mm), tilt (0.1°) and field (0.05%). The simulation where all such sources of errors are taken into account, albeit halving their maximum range, shows that 1/20,000-far-in mass isotopes are quite clearly separated at 1% of their peak yields (Fig. 6).

It should be emphasized that such resolution is achievable only if the horizontal rms emittance and the energy spread are decreased, with respect to what is supplied by the exotic beam ion source: $\varepsilon_{\rm rms} = 0.68$ mm mrad and $\Delta E = \pm 1$ eV are assumed in the calculation (a factor of 5 and 10 reduction respectively). To achieve such phase space shrinkage, a beam cooling device [18] was prototyped and will be extensively tested prior to its application on the SPES beam, upstream the HRMS. This design of the HRMS is still under optimization.

After the HRMS and a long transfer line, the beam is injected into the SPES-CB, which has the goal of boosting the charge state

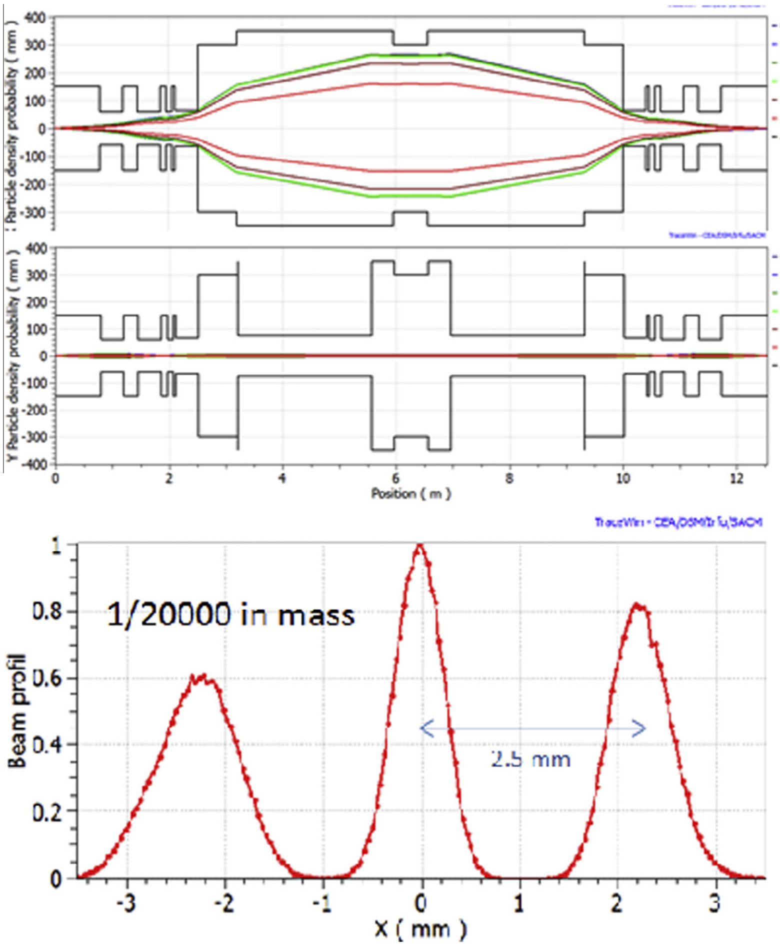

Fig. 5. Horizontal and vertical beam envelopes and the horizontal spectrum of three 1/20,000 separated masses in the diagnostics station at the spectrometer image. HRMS element errors are not included in the simulations.

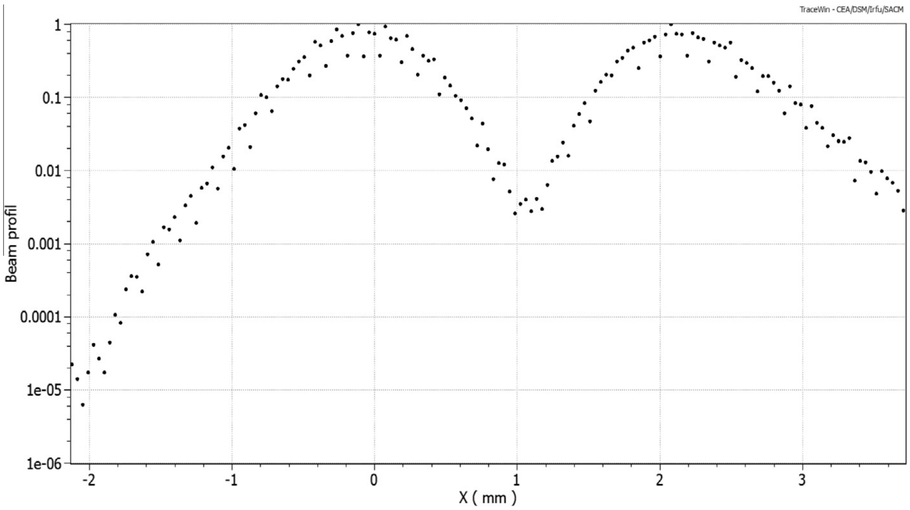

Fig. 6. Two beams, separated in mass by $\Delta A/A = 1/20{,}000$, at the image point of the HRMS. Errors are included in the simulations. Taking into consideration the log-scale on the *Y* axis, the two peaks turn out to be well separated.

of the exotic species prior to their acceleration in ALPI, used as a RNB accelerator.

The SPES CB (Fig. 7) [3] was developed by IN2P3-LPSC (Grenoble, F), as an updated version of the Phoenix booster [19], which is operational since about 20 years.

It is a 2nd generation ECR source, usually operating at ~14.5 GHz. Completed in February 2015, the SPES-CB fulfilled the validation tests at LPSC between March and April 2015 [20], with very encouraging results in terms of breeding efficiencies of the selected species, which in several cases surpassed the best ever corresponding results obtained on the Phoenix booster.

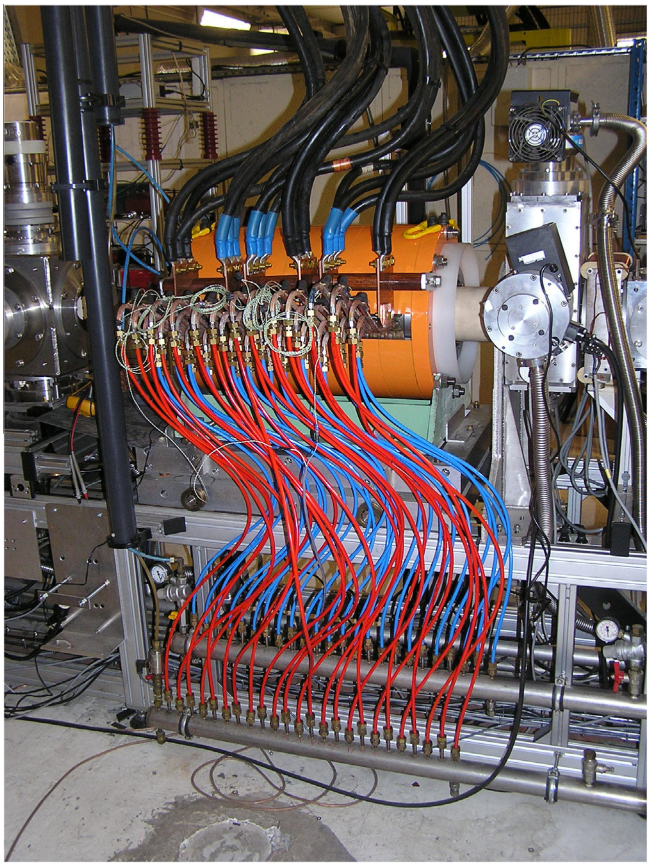

Fig. 7. Photo of the SPES charge breeder.

As mentioned above, ECR-based charge breeders unavoidably mix the extracted charge-bred exotic beam with contaminants, mostly originating from the support gas or emitted by the surfaces exposed to plasma. Such contamination may be mitigated by proper vacuum treatments of the chamber itself (as foreseen for the SPES CB). Residual contamination will be separated by a Medium Resolution Mass Separator (MRMS) on a 160 kV platform downstream of the CB.

Beam dynamics through the MRMS of the desired $^{132}Sn^{19+}$ exotic beam ($I = 10^5$ particles/s, $\varepsilon_{in,n,rms} = 0.1\ \pi$ mm mrad) and two contaminant beams with $\Delta(A/q)/(A/q) = \pm 1/1000$, was carried out, with an error study assuming realistic deviations in the position, angle and gradient of the lenses, as well as errors in the beam initial energy and position. The three beams were well separated after the MRMS, with an overall emittance increase of ~10% only (the value of ε_{in} in the calculation is, conservatively, a factor 4 higher than the one measured during the test phase of the SPES CB).

SPES shall be the only facility ensuring such level of selectivity on a charge boosted ion beam, which is expected to alleviate the most serious drawback of ECR-type charge breeders versus EBIS-type ones.

Upstream the charge breeder, a stable 1+ source and a complete beam line will allow the characterization of this device during the commissioning phase, and “pre-tuning” during operation.

4. RNB acceleration

As shown in Fig. 2, the charge-bred well-selected exotic species will be characterized at a tape station following the MRMS. Then they will be sent to the entrance of a new RFQ injector for ALPI, i.e. a CW RFQ [16] with internal bunching. The RFQ will match the beam energy at the exit of the HV platform (5.7 A keV for an $A/q = 7$) with the optimum energy at the entrance in the ALPI SC linac (727.3 keV/A, still for an $A/q = 7$).

The RFQ, the 3D model of which is shown in Fig. 8, is an 80 MHz 4-vane structure with an RF power up to 100 kW. Its mechanical design, similar to the Spiral2 one, takes advantage of the design and technological experience acquired by the LNL team with the IFMIF RFQ [21].

The RFQ shall be preceded by a double-drift double-frequency beam buncher (5–10 MHz) for experiments requiring the corresponding beam time structure. Transmission inside the RFQ is calculated to be larger than 93% in case of a CW injected beam, dropping to 65% (with respect to 3% for plain chopping) for a bunched beam. Mechanical and RF design of this low frequency buncher is under final definition.

It is to be noted that the RFQ will be designed for a beam current as high as 100 μA, so as to potentially serve in the future as a new stable beam injector, of higher current, for ALPI.

The SPES RFQ and ALPI will be matched through a new beam line, comprising both magnetic lenses for transverse focusing and two 80 MHz normal conducting bunchers to preserve the quality of the beam longitudinal phase space. The SPES beam line will merge with the present stable beam line inside the bent 90° dipole, driving the tandem beam into ALPI. The PIAVE stable beam injector will be preserved, but the two cryomodules (CM) with low-beta superconducting resonators will be moved to ALPI, in position CR01 and CR02, thus becoming available for both stable and unstable beams.

The ALPI layout shall be upgraded also with the addition of two higher beta cavity CM’s, with Nb/Cu sputtered resonators (expected accelerating field $E_a \sim 5.5$ MV/m). This will enhance the final energy of the exotic species to the 9 ÷ 12 A MeV range ($A/q = 7 \div 5$) as required by the users.

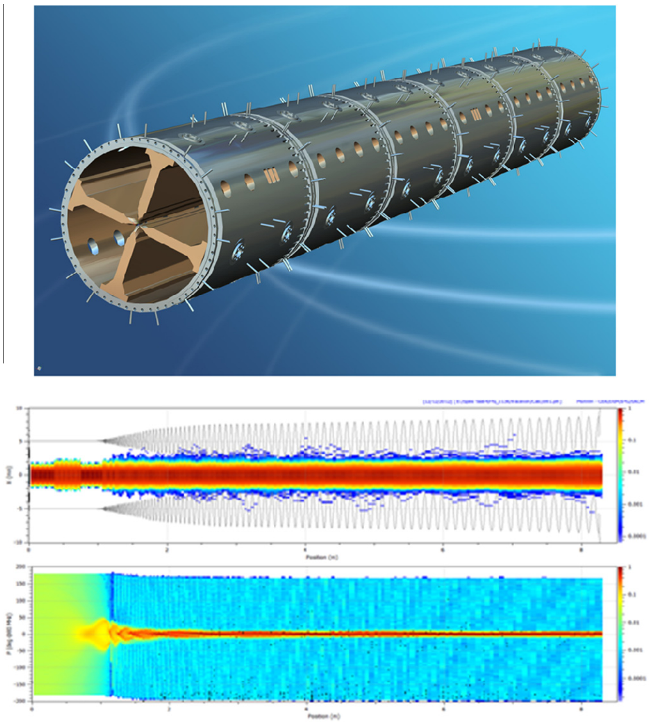

Fig. 8. 3D model of the SPES RFQ (above), and x, y beam multiparticle tracking along it.

Further upgrades of ALPI, aiming at increasing transmission of the very low current beam to the experiments, are worth mentioning.

The first one is intrinsically related to the linac layout, the period of which (CM-triplet lens-CM-instrumentation box) was appropriate when the maximum field of the SC cavities was around 3 MV/m only (Pb/Cu cavities), as in the original design. With the upgrade to sputtered Nb/Cu resonators, the average accelerating field almost doubled and the coupling between the longitudinal and the transverse phase spaces introduced unavoidable losses. Such losses will be reduced by increasing the focusing field of the quadrupole triplets (from 20 to 30 T/m) at least in the lower energy branch of ALPI, where the sensitivity to this measure is higher.

Higher beam transmission will be granted also by better component alignment (an alignment campaign in 2012–2013 resulted in a much improved – 95% – transmission of a CW beam) and a more precise definition of the resonator phases, with the development of digital controllers, replacing the present analog devices (prototype tests of the new controllers are foreseen for early 2016) [22].

5. Conclusion

With the overall SPES budget for the exotic beam facility secured in fall 2014, the present project schedule foresees beam commissioning in 2019. It must be noted, however, that the addition of a few experimental lines for low energy nuclear physics experiments – recently proposed for additional funding by the Italian government – might slightly interfere with such plan and possibly induce some delay.

Beam commissioning will be done in several stages. First of all, after the cyclotron Site Acceptance Tests (SAT), planned for spring 2016, the exotic beam target bunker shall be equipped with the online FE, and the first tests of exotic beam production, extraction and low resolution separation will be carried out in 2017. Meanwhile, a provisional beam line to the second target bunker will be set up for radioisotope production, in collaboration with an industrial partner (end of 2016). In parallel with the above, measures are being taken to set up the RNB accelerator injector (from the CB to the RFQ input) in the third experimental hall, with the purpose of anticipating its commissioning with a careful setup of the charge breeder and the MRMS.

References

[1] G. Fortuna et al., The ALPI Project at the Laboratori Nazionali di Legnaro, in: Proceedings of the 5th Int. Conf. on Electrostatic Accelerator and Associated Booster, Strasbourg-Heidelberg, NIM A 287, 1990, p. 253.

[2] A. Lombardi et al., Proceedings of Cyclotrons, Vancouver, BC, Canada, 91, 2013.

[3] A. Galatà et al., The SPES-Charge Breeder (SPES-CB) and its beam line at INFN-LNL, Nucl. Instr. Meth. B. http://dx.doi.org/10.1016/j.nimb.2015.12.031.

[4] A.M. Stefanini et al., Nucl. Phys. A 701 (2002) 217.

[5] Calin A. Ur, J. Phys. 366 (2012) 012044.

[6] E. Farnea et al., The AGATA Collaboration, Nucl. Instr. Meth. A 621 (2010) 331–343.

[7] G. Jaworski et al., NIM A673 (2012) 64.

[8] A. Maj et al., The PARIS project, Acta Phys. Pol. B 40 (2009).

[9] <http://fazia.in2p3.fr/Fazia/fazia.htm>.

[10] W. Venturini et al., Proceedings of LINAC2014, 795.

[11] R. Ferdinand et al., Proceedings of IPAC2013, Shanghai, China, 3755.

[12] <www.eurisol.org>.

[13] M. Lindroos, Proceedings of EPAC 2004, Lucerne, Switzerland, 45.

[14] M. Ballan et al., A combined experimental and numerical approach for the monitoring of the SPES target status during operation at high temperature, Nucl. Instr. Meth. B. http://dx.doi.org/10.1016/j.nimb.2016.01.038.

[15] A. Andrighetto, C.M. Antonucci, S. Cevolani, C. Petrovich, M. Santana Leitner, Multifoil UC_x target for the SPES project – An update, Eur. Phys. J. A 30 (2006) 591–601.

[16] A. Pisent et al., SPES Beam Dynamics, TUO4AB01, HB2014, East-Lansing, MI, USA, 2014.

[17] D. Uriot, N. Pichoff, TraceWin, CEA Saclay, 2014.

[18] M. Maggiore, Proceedings of HIAT 2012, Chicago, IL USA, 68, 2012.

[19] J. Angot et al., Proc. of ECRIS12, Sydney, Australia, 167.

[20] A. Galatà et al., The new ECR charge breeder for the selective production of exotic species project at INFN-Laboratori NAzionali di Legnaro, presented at ICIS-2015, NY (USA).

[21] A. Pepato et al., Proceedings of LINAC2014, Geneva, Switzerland, 257.

[22] S. Barabin, G. Bassato, Proc. of ICALEPCS2011, Grenoble, France, 2011, pp. 174–176.