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PROGRESSES IN THE INSTALLATION OF THE SPES-CHARGE BREEDER BEAM LINE

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Abstract

Since fall 2017, the ADIGE (Acceleratore Di Ioni a Grande carica Esotici) injector of the SPES (Selective Production of Exotic Species) project entered the installation phase. The injector includes an Electron Cyclotron Resonance (ECR)-based Charge Breeder (SPES-CB) and its complete beam line, as well as a newly designed RFQ, to allow the post-acceleration of the radioactive ions produced in the so-called target-ion source-system. The injector has different peculiarities, deriving from particular needs of SPES: a complete electrostatic beam line equipped with a 1+ source for test purposes, and a unique Medium Resolution Mass Spectrometer (MRMS, R~1/1000), mounted downstream the SPES-CB, to clean the radioactive beam from the contaminants induced by the breeding stage. This contribution reports about the status of the installation of the injector, describing the various technical solution adopted, and giving a realistic planning for the commission and following operation of its main parts.

INTRODUCTION

SPES [1] (Selective Production of Exotic Species) is an INFN project with the aim at developing an Isotop Separation On Line (ISOL) Radioactive Ion Beam (RIB) facility as an intermediate step toward EURISOL. The SPES project is under construction at the INFN-Laboratori Nazionali di Legnaro (LNL): the main goal is the production and post-acceleration of exotic beams to perform forefront research in nuclear physics by studying nuclei far from stability. The project is concentrating on the production of neutron-rich radioactive nuclei with a mass range A=80–160: they are fission fragments that will be produced by delivering a proton beam on a UC_x target developed at LNL. The proton driver will be a commercial cyclotron [2] with a variable energy (30–70 MeV) and a maximum current of 0.75 mA (upgradeable to 1.5 mA), with the possibility to split the beam on two exit ports. The accelerator was installed in a new dedicated building in 2016 and the factory acceptance tests were succesfully carried out in 2017. The radioactive species produced will be extracted as a 1+ beam from dedicated sources [3], cooled in a RFQ-cooler [4] and purified from the isobars contaminants through a High Resolution Mass Spectrometer (HRMS) presently in the design phase. In order to allow post-acceleration with the LNL booster ALPI (up to 10 MeV/A for A/q = 7), the project will employ an Electron Cyclotron Resonance (ECR)-based charge breeding technique [5]: the Charge Breeder will be equipped with a complete test bench totally integrated with the SPES beam line. This part of the post-accelerator, together with the newly designed RFQ [6], composes the so-called ADIGE (Acceleratore Di Ioni a Grande carica Esotici) injector [7], whose layout is shown in Fig. 1. Since fall 2017, the injector entered the installation phase: this paper will describe its main components, the various technical solutions adopted, and will report on the status of the installation, giving a realistic planning for the commissioning and following operation of its main parts.

BEAM LINE DESCRIPTION

The ADIGE injector consists of a 1+ beam line producing stable beams for test purposes, and a N+ beam line to deliver the beams extracted from the Charge Breeder to the post-acceleration. Those parts will be described in separated sub-sections.

The 1+ Beam Line

Depending on the particular element to be charge bred, two kind of sources will be employed (alternatively), sharing the same vacuum chamber: a surface ionizaion source (SIS) or a plasma ionization source (PIS). Those sources are semplified copies of the ones which will be installed in the target-ion source-system of SPES and are described elsewhere [3]: the ionization machanisms employed will allow the production of beams from most of the elements of the periodic table, except for the refractory metals. The stable 1+ ions produced will be extracted by applying a positive high voltage between 20 keV and 40 keV to the common vessel through a 3 mm hole, and placing a movable electrode at ground potential, in order to optimize the electric field depending on the extracted intenisty. The beam will pass through two couples of X-Y electrostatic steerers (±2 kV max) that will correct possible beam misalignments, and will then be focused by an electrostatic quadrupoles triplet (5 kV max, total length 848 mm) to the first beam instrumentation box, equipped with a faraday cup, two beam profile monitors (one for each transversal plane) and selection slits. Such box is mounted at the object point of the 1+ selection dipole: it is a 90°, 750 mm radius magnet, with entrance

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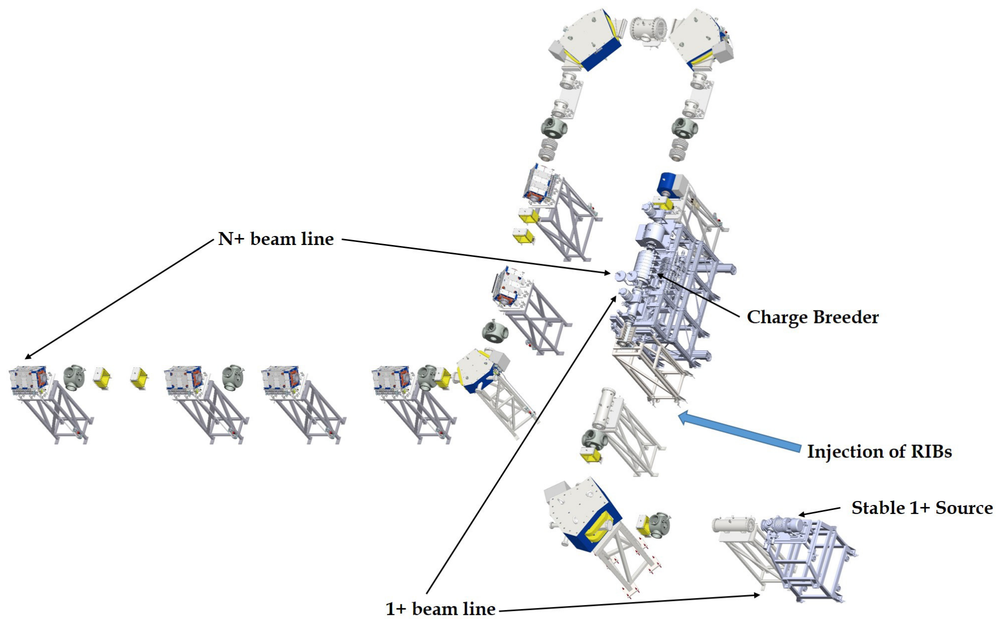

Figure 1: Prospective view of the ADIGE injector with its 1+ beam line (from the 1+ Source to the Charge Breeder) and N+ beam line (from the Charge Breeder on). The position where the 1+ beam line for RIBs will be connected is also shown.

and exit angles of 26.6° and a pole gap of 110 mm. Another beam instrumentation box is placed at the image point of the dipole, and a further electristatic quadrupoles triplet will focus the beam to the emittance measurement device: it consists of two slit-grid systems, with a spatial resolution of 0.2 mm and minimum and maximum measurable divergence of, respectively, 1.8 and 68 mrad. Finally, the 1+ beam will be injected into the Charge Breeder through a double Einzel Lens (20 kV max). Along the beam line, magnetic steeres will give the possibilty to correct possible misalignments.

The N+ Beam Line

Charge breeding at SPES will be based on the ECR technique: in particular, the model adopted (SPES-CB) derives directly from the PHOENIX Charge Breeder installed at the Laboratoire de Physique et de Cosmologie [8]. The SPES-CB was delivered to LNL at the end of 2015, after succesfull acceptance tests carried out between March and April [5]. Highly charged ion beams in the range $4 \leq A/q \leq 7$ will be extracted from this device through a three electrodes extraction system designed at LNL [9], and initially focused by two solenoids (effective length 325 mm, maximum field B=1.5 T). It is well known that the breeding stage 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) [5]. For the second one, a Medium Resolution Mass Spectrometer (MRMS) was designed with an expected resolving power of $R=\Delta(M/q)/(M/q)=1/1000$ and will be installed downstream the charge breeder: a prospective view is shown in Fig. 2. Its main elements are: four electrostatic quadrupoles (EQ in Fig. 2, 12 kV max), an electrostatic multipole up to 12° pole order (MUL in Fig. 2, 3 kV max), and two bending dipoles (BD in Fig. 2, radius 750 mm, edge angles 33.35°, field homogeneity $\Delta B/B=10^{-4}$); selection slits are foreseen at the object and image points of the spectrometer. To compensate the larger part of the sextupole aberration, the edges of the dipoles were designed with a curvature of 1474 mm and 828 mm at, respectively, the entrance and the exit of the spectrometer: to ensure the desired resolution, it will be mounted on a -150 kV high voltage platform, connected to the beam line through two accelerating columns (ACC in Fig. 2), in order to reach a beam energy of 23 keV/A. An analysis of the expected perfomances of MRMS was carried out supposing a gaussian shape of all the transported beams, and considering all possible contaminants induced by the breeding stage both from gaseous sources (gas fed, ougassing) and from the surfaces-plasma interaction (AISI 316L for the plasma chamber, AU4G for the extraction electrode), i.e.: C, N, O, Mg, Al, Si, P, S, Ar, Cr, Fe, Mn, Ni, Co, Cu, Zn and Mo; all the isotopes of the considered elements were taken into account. The parameters considered in the analysis are: the dispersion D of the spectrometer (D=8000 for the MRMS), the distance d between the peaks of the nominal beam and the contaminants and the slits aperture s; this last two parameters are expressed in units of σ, the width of the gaussian peaks. Instead of considering two beams with different A/q ratios, we considered the same beam (in our

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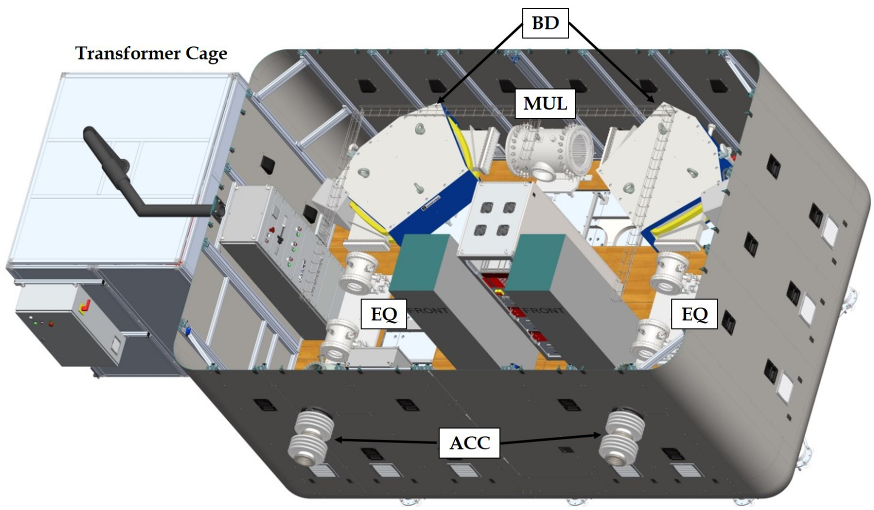

Figure 2: Prospective view of the Medium Resolution Mass Spectrometer installed on its high voltage platform: it consists of four electrostatic quadrupoles (EQ), an electrostatic multipole (MUL) and two bending dipoles (BD). The platform is connected to the rest of the beam line through two accelerating columns (ACC).

case the RIB $^{132}Sn^{19+}$), one with the nominal momentum p (nominal beam) and the second with a momentum p+Δp (non-nominal beam): a separation Δ(M/q)/(M/q)=1/1000 is, in fact, equivalent to a relative difference in momentum Δp/p=1/2000. Considering this value for Δp/p and the value of the dispersion D, the MRMS should be able to separate two peaks at d=4σ. Clearly, if the two peaks were "δ-Dirac-shaped", the contaminaton would be 0% for any value of d≠0, but the gaussian shape changes this scenario, because the tail of the distribution of the non-nominal beam can contaminate the nominal one: this picture is made clearer by looking at Fig. 3, showing two gaussian peaks with the same amplitude, separated by a distance d=2σ and with the slits aperture s=2σ. In this case the spectrometer would keep

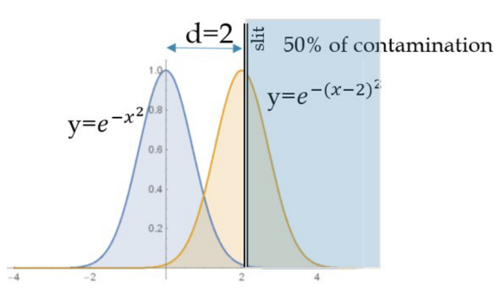

Figure 3: Contamination of the nominal beam (in blue) by the non-nominal one (in yellow) for a separation d=2σ and a slits aperture s=2σ.

the 95% of the nominal beam, but it would be contaminated by the 50% of the non-nominal one. Defining the relative amplitude A=$I_{non-nom}/I_{nom}$ between the non-nominal and the nominal beam, Fig. 4 shows the expected contaminaton level as a function of the relative amplitude for different values of d, and for a slits aperture s=d/2. It has to be observed that, for example, for d=4 (the case of the MRMS), even if the evaluation forsees a contamination level of 20% for a relative amplitude A=10^2, the numerical simulations carried out with the TraceWin gave a level of 10% instead; this is due to the fact that the real beam shape is not exactly gaussian. In order to be conservative, the simulations considered beams with an energy spread ΔE=15 eV and a normalized emittance ϵ=0.1 π mm mrad, about twice the one measured during the acceptance tests [5]. It is interesting to see the effect of the

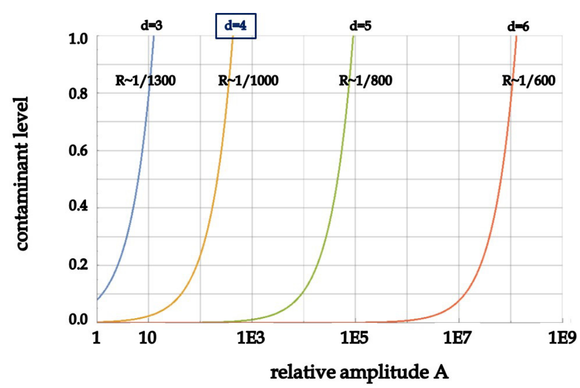

Figure 4: Expected contamination as a function of the rela-tive amplitude A=$I_{non-nom}/I_{nom}$ between the non-nominal and the nominal beam for different values of d and s=d/2; the MRMS corrsponds to d=4.

slits aperture on the contamination for a given value of d: Fig. 5 shows the contamination level as a function of the relative amplitude, for d=4 and different slits aperture. It can be seen that, by reducing the slits aperture to s=1.3, the contamination level can be kept belowe 10% even for a realtive amplitude A=10^3, at the expenses of the 20% of the nominal beam. Further considerations revealed that, increasing the separation to d=5 (equivalent to consider a sligtly worse resolution Δ(M/q)/(M/q)=1/800), for a slits aperture s=2 (95% of the nominal beam kept) a non-nominal beam such that A=10^3 would be totally removed, while for A=10^4 the

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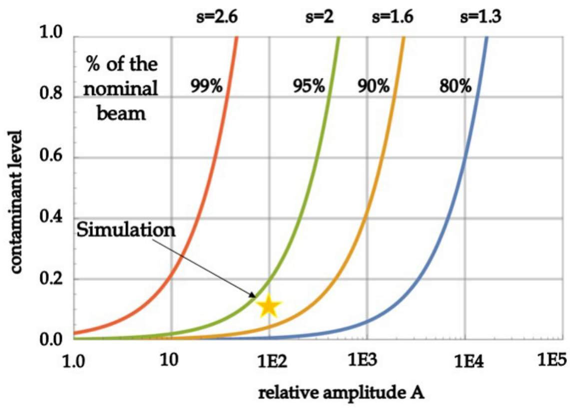

Figure 5: Expected contamination as a function of the relative amplitude A=$I_{non-nom}/I_{nom}$ between the non-nominal and the nominal beam for different values of s and d=4. Simulations gave better risults compared to the estimation made considering the gaussian shape of the two peaks.

contamination would be 10%. By reducing further s to 1.6 (90% of the nominal beam kept), the contamination would be 0% for A=10^4 and only 10% for A=10^5. Following those last considerations, and taking into account all the possible contaminants mentioned above, table 1 lists the charge states of typical RIBs expected at SPES that could be accelerated with a very limited contamination.

Table 1: Charge states of typical RIBs expected at SPES that should be free from contamination after passing through the MRMS.

Species	Charge States
^{94}Rb	15+,16+,21+
^{130}Sn	19+,29+
^{132}Sn	19+,21+,23+
^{134}Te	27+,31+
^{133}Cs	20+,22+,23+,26+,28+,30+,31+

Finally, the beam coming out from the MRMS will be focused by magnetic quadrupoles triplets (gradient 1.97 T/m and effective length 237 mm for each quadrupole) and characterized in a beam instrumentatation box equipped with an emittance measurement device of the Allison scanner type (not shown in Fig. 1). A further 90° dipole (radius 500 mm, edge angles 26.6°) will bend the beam towards the injection line into the new RFQ (horizontal line in Fig. 1). More or less 30% of the future users at SPES will request beams bunched at 5 MHZ instead of the usual 80 MHz of the LNL accelerating structures: to satisfy those requests, two low energy bunchers (LEB) will be installed in the final part of the ADIGE beam line. The bunchers consists of a two harmonic bunching system, known as "double drift method of bunching", totally equivalent to a triple harmonics system and with a bunching efficiency of at least 60-65%. Two double gap resonant structures will be installed in the beam line and separated by a distance of about 1m: the first buncher will operate at 5 MHz, while the second one at 10 MHz. The gap voltage is about 1 kV for the two resonantors and both will be equipped with movable tuners for a fine tuning of the resonant frequency.To simplify as much as possible the manufacturing of the two resonantors, they share most of the components, except for the drift tubes and the spirals: table 2 summarize their technical specifications.

Table 2: Technical specifications of the two harmonic bunchinng system

	5 MHz	10 MHz
Central tube length [mm]	102	50
Gap length [mm]	2	2
Tube outer radius [mm]	68	68
β_{opt}	0.003515	0.003515
Resonant frequency [Mhz]	5	10
Max surface E-field [Mv/m]	0.296	0.350
Q	900	780

STATUS AND FUTURE PLANS

All optical elements and power supplies of the ADIGE beam line were delivered by the end of 2017 and installed in the III experimental hall of LNL in the first months of 2018 (except for those of the MRMS), togheter with the 1+ source and the Charge Breeder. Then, the work for the preparation of the electrical and water cooling plants started in March: the main electrical board feeding electricity to the power supplies of the coils and some ancillary systems of the Charge Breeder and to the insulating transformer of the 1+ source was installed and connected. The rest of the power supplies were connected to busways already present in the area, while other electrical boards will be delivered, installed and cabled within Autumn 2018. All the power supplies necessary to operate the 1+ source are referred to its high voltage: a rack containing all those devices is installed on a small high voltage platform designed at LNL and already put in its final position. For safety reasons, this area is shielded by a Faraday cage designed at LNL and constructed by an external company: the access to this area will be managed by a PLE safety level system, designed at LNL and validated by the PILZ company (in charge of the safey system of different parts of SPES); its main components were already mounted. The water cooling system is divided in branches connected to groups of utilities: each branch is equipped with pneumatic valves at the main inlet and manual valves at the inlet and outlet of each utility, togheter with flow and temperature sensors. Oxygen, conductivity, pH and pressure sensors were installed and will monitor continuously the status of the cooling water. The main cooling circuit of the 3^{rd} experimental hall is a closed circuit with very low conductivity water (~0.2 μS/cm) and a maximum allowed pressure drop of 4-5 bar, and is compliant with almost all the devices installed: the only exceptions are the cooling of the 1+ source (two separated circuits), the plasma cham-

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ber of the Charge Breeder and its coils (necessary pressure drop Δp=10 bar). For those utilities, a special cooling skid was designed in collaboration with the Technical Division of the LNL and already installed. The skid consists of a pump, raising the water pressure to the value necessary for the coils circuit, followed by two branches equipped with manual and pneumatic valves: each branch is then split in two sub-branches, two for the 1+ source, one for the plasma chamber of the Charge Breeder and the other for its coils. In those sub-branches, where the very high pressure is not necessary, pressure regulaturs will lower it to usable values. All the utilities were connected to the main manifold and first tests of the circuits are expected within September 2018.

All the beam instrumentation boxes and the emittance measurements device of the 1+ beam line are already in their final position: the vacuum system of this part of the line is installed, while the installation of the vacuum tubes is almost completed. Leak tests on the already available parts of the beam line gave positive results. The other beam instrumentation boxes are in the construction phase and should be available by the end of 2018: their installation will start at the beginning of 2019, followed by the installation of the vacuum system of the N+ beam line. The construction of the high voltage platform housing the MRMS has been commissioned to the Pantechnik company: the factory acceptance tests were partially carried out before Summer 2018 and will be completed in the middle of September. The delivery and installation is expected for middle of October, together with all the power supplies necessary to operate the MRMS. The ADIGE control system design is complete and is currently under construction. It is based on the Experimental Physics and Industrial Control System (EPICS) framework, and can be described using a three layer model: the graphical user interface (GUI), the Middle-ware and the Hardware. The GUI is implemented using the Control System Studio (CSS) and connects to the MIddle-ware layer using the EPICS Channel Access protocol: it can be based on software infrastructure running on Virtual Machines (EPICS IO controllers) or standard PLCs depending on the device to be controlled. In both cases, this layer represents the intelligent/autonomous part of the system, does not depend from the GUIs and provides all the basic functionalities and automatic procedures. The Harware is the lowest level, directly connected to the devices to be controlled and used by the Middle-ware layer. For this reason, it can be considered, depending on the device: (i) the device itself if it directly supports an Ethernet-based protocol. This is the case of many high level instrumentation (signal generators, gauge controllers etc); (ii) industrial Standard IO devices (analog/digital), as in the case of simple devices like solenoids, valves, motors, analog references etc. These devices are usually controlled by the middle-ware layer using standard Ethernet protocols or other standard industrial field-buses; (iii) custom hardware, as in those cases where an Industrial Standard peripheral is not available or it is too expensive. At LNL a generic DAQ board has been developed and tested to acquire all the Beam Instrumentation data of the SPES facility: it is based on the Industrial Com Express standard module, and it can be used with or without μProcessor unit, and so considered part of the Middle-ware or used as a simple IO pheripheral depending on the needs.

The planning for the ADIGE injector forsees to start the operation with the 1+ source within the end of 2018: the first tests will be carried out with the SIS and will continue with the PIS. Both kind of sources will be completely characterized in terms of emittance, intensity and beam stability: such experimental activity will continue in 2019 without interfering with the completion of the rest of the ADIGE beam line, due to the absence of Radiation Protection issues and to the proper shielding adopted for the high voltage parts. After the insallation of the rest of the beam instrumentation boxes and the vacuum system, the N+ beam line should be avilable from the middle of 2019: the first tests will be carried out with the Charge Breeder in “source-mode”, that is without injecting the 1+ beam. This will allow to continue the characterization of the 1+ sources and, at the same time, to verify the resolving power of the MRMS: to this scope, the Charge Breder will operate producing a plasma of oxygen mixed with xenon. The relatively high mass of xenon and the high number of stable isotopes will allow the verification of different level of resolution: as an example, the separation of $^{136}Xe^{25+}$ from $^{131}Xe^{24+}$ (R=1/300), $^{129}Xe^{19+}$ from $^{136}Xe^{20+}$ (R=1/620), or $^{132}Xe^{32+}$ from $^{128}Xe^{31+}$ (R=1/1000). The tests will proceed with the injection of the first 1+ beams in the Charge Breeder and will continue in 2020, with the entire beamline up to the injection of the RFQ operational.

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