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CHARACTERIZATION OF THE ECR ION SOURCE LEGIS EXTRACTION SYSTEM AND ITS LOW ENERGY BEAM TRANSPORT LINE AT LEGNARO NATIONAL LABORATORIES

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Abstract

At INFN-Legnaro National Laboratories the heavy ions accelerator complex is fed with beams produced by a permanent magnet Electron Cyclotron Resonance ion source called LEGIS (LEGnaro ecrIS). Although suitable intensities and charge states to fulfill the requests of the users are normally guaranteed, the first part of the Low Energy Beam Transport line (LEBT) downstream of the ion source suffers from non-negligible losses and a lack of scalability when switching between ions with different mass-over-charge ratios, thus leading to a machine preparation time longer than would be desirable. These criticalities called for a deep characterization of the beam coming out from the ion source, especially in the case of high charge states heavy ions production, normally showing the lowest intensities. This contribution describes the numerical studies performed on the extraction system of the LEGIS source and its LEBT. The physics case used is a $^{208}Pb^{31+}$ beam produced for a nuclear physics experiment in fall 2022. As will be shown, the results shed light on the reasons for the bad reproducibility and transmission, mostly due to aberrations induced on the extracted beam by the first optical elements.

INTRODUCTION

Electron Cyclotron Resonance Ion Source (ECRIS) [1] extraction systems for highly charged heavy ions beams necessitate of detailed studies, since they have to manage several ion species with different intensities, while ensuring the proper beam quality for the injection in the accelerators. Indeed, the beam quality directly affects the global acceleration line in terms of transmission, while the charge states are important in relation with the final beam energy.

At INFN–Legnaro National Laboratories (LNL) the PIAVE-ALPI [2–4] heavy ions accelerator complex is fed with highly charged heavy ions by a 2nd generation ECRIS called LEGIS (LEGnaro ecrIS) [5]. It is a full permanent magnet source of the Supernanogan type produced by the Pantechnik company [6], with an operating frequency range between 14 and 14.5 GHz. In order to match the optimum $\beta = v/c$ for the injection into PIAVE, LEGIS and the first part of the LEBT are installed on a high voltage platform (maximum voltage 400 kV).

Suitable intensities for the requests coming from the nuclear physics community are normally produced. Despite that, operational experience evidenced a not satisfactory transmission in the LEBT line installed on the platform, as well as a lack of scalability of the values of the steerers mounted in the downstream fixed-β magnetic beam line towards PIAVE.

To shed light on the above-mentioned criticalities, we carried out numerical simulations of beam extraction from LEGIS and its transport in the first part of the LEBT line, taking as case study the production of a lead beam for a nuclear physics experiments performed in fall 2022 at LNL.

This paper describes the results coming out from the simulations, drawing some conclusions on the possible explanations for the criticalities observed and the actions could be undertaken to solve them.

LEGIS AND THE LNL ACCELERATOR COMPLEX

The LEGIS source can produce heavy ions beam currents of the order of µA for the PIAVE-ALPI accelerator complex. Its extraction system consists of four electrodes (see Fig. 1): the plasma electrode, with a 7 mm extraction aperture and a voltage of 24 kV (voltage V_s always fixed), a puller (maximum operational voltage $V_p = -6$ kV), an electrostatic lens named focus (max voltage $V_f = 1$ kV) and a ground electrode. It is directly coupled to the analysis dipole, characterized by a maximum field of 0.5 T, a bending radius of 500 mm, a pole gap of 80 mm and edge angles of 28.3°, both at the entrance and at the exit. A selection slit (10 mm opening usually) and a Faraday cup are mounted more or less at its image point: this first part of the LEBT, installed on the high voltage platform (as shown in Fig. 1), is generally used to characterize the LEGIS' performances and is the part of the line object of the studies presented in this paper.

The line on the platform continues with a double Einzel lens (max operational voltage $V_{ein} = 10$ kV) that focuses the selected beam into the accelerating column, followed by an electrostatic triplet (max voltage $V_{trip} = 4$ kV) outside of the platform. From this point, the line continues with a fixed-β magnetic beam line for the injection in the PIAVE-ALPI accelerator complex.

PIAVE (Positive Ion Accelerator for Very-low Energy) is a positive ions linear accelerator preceded by a three harmonic buncher (40, 80, 160 MHz) and consisting of two 80 MHz superconducting RFQs, with β equal to 0.0089 and 0.0035 at the RFQs entrance and exit, respectively. The RFQs are

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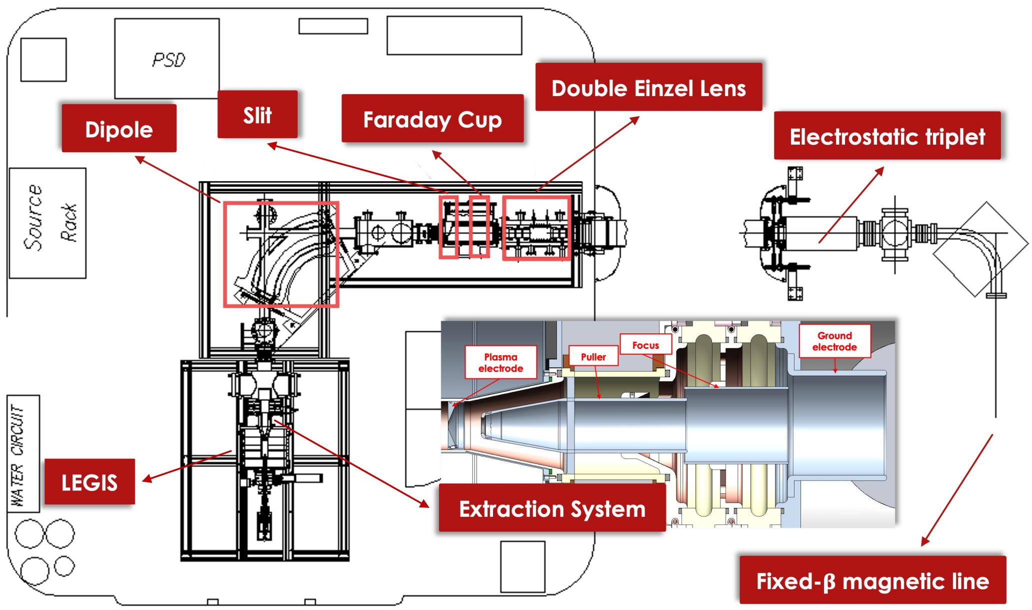

Figure 1: Schematic representation of the LEGIS extraction system and the first part of the downstream LEBT.

characterized by maximum operational accelerating field of 27.10 MV/m and 25.49 MV/m (for $^{238}U^{32+}$).

ALPI (Acceleratore Lineare Per Ioni) is the superconducting booster consisting of 20 cryostats, each containing 4 quarter-wave resonators (QWRs) and operating at 80 MHz (first 6 low-β cryostats) and 160 MHz (the others high-β cryostats), with a maximum accelerating field of 5 MV/m. Beams can reach 10 MeV/A of energy for a mass-over-charge ratio of 7.

SIMULATIONS OF BEAM EXTRACTION AND TRANSPORT

The operational experience with LEGIS revealed some criticalities, in particular: a transmission to the Faraday Cup on the platform not higher than 50 %; the fact that the steerers' values in the fixed-β magnetic line downstream of the LEBT line do not scale following the mass-over-charge ratio as expected. To find possible explanations, we carried out extensive numerical simulations of the beam extracted from LEGIS and its transport through the first part of the LEBT.

The case study considered is a ^{208}Pb beam produced by means of a resistive oven for a nuclear physics experiment scheduled in fall 2022 at INFN-LNL. All the parameters have been optimized to deliver the charge state 31^+ with a suitable intensity: Table 1 shows the main ones relevant for the studies presented in this paper.

The extraction from LEGIS has been simulated for the first time by using the code IBSimu [7], considering a total beam current of 1.9 mA and a space charge compensation at 98 %. The input distribution consisted of ions from Pb^{14+} to Pb^{32+} and from O^{1+} to O^{4+}, resembling the spectrum acquired during the experiment. Figure 2 shows the simulated Pb^{31+} horizontal emittance: it can be seen that the

Table 1: Main Parameters Used for the Production and Transport of the $^{208}Pb^{31+}$ Beam

P [W]	f [GHz]	I_{tot} [μA]	$I_{Pb^{31+}}$ [μA]	V_{plat} [kV]
304	14.328	1900	2.7	224.68
V_s [kV]	**V_p [kV]**	**V_f [kV]**	**V_{ein} [kV]**	**V_{trip} [kV]**
24	-1	1	6.4, 4	4

beam has a limited divergence and, above all, a normalized rms emittance of 0.039 64 mm·mrad, well within the limit of acceptance expected for PIAVE (0.1 mm·mrad).

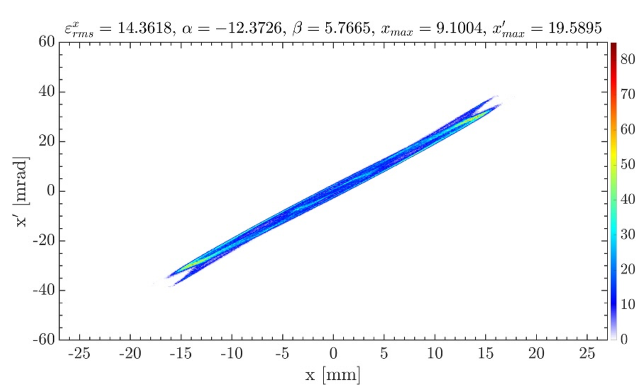

Figure 2: Phase space distribution of the Pb^{31+} numerically obtained by means of the code IBSimu.

The extraction simulation results have been the input to simulate the beam transport through the first part of the LEBT installed on the platform, using the TraceWin software [8]. As a first step, the beamline acceptance was evaluated for each ion considered for the simulations: it has been

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found that it exists a significant mismatch with the beam emittance at the entrance of the line, being more evident for the O^{4+} shown in Fig. 3. As a confirmation of this effect, the calculated transmission of the O^{4+} revealed to be the lowest one (~23 %).

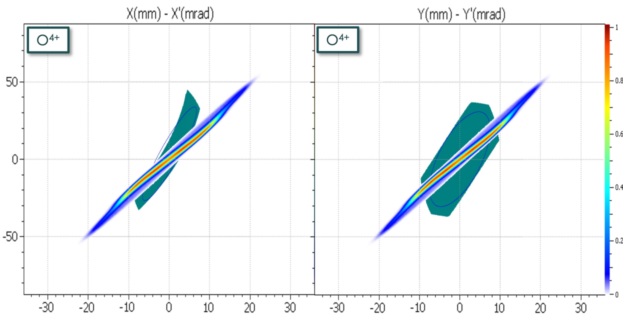

Figure 3: Emittance-acceptance mismatch with the LEBT for the O^{4+}.

This first outcome of the simulations gave us already a possible explanation for the low transmission to the Faraday cup experimentally observed.

The study proceeded by evaluating, for all the ions, the density levels along the LEBT: Figure 4 shows the results in the direction corresponding to the bending plane for the lowest (among all ions) and highest (for lead) mass-over-charge ratio. It is evident that both beams, initially centered (in position and distribution) on the nominal trajectory, emerge off-centered after passing through the dipole, with the focus well preceding or following the slit position.

These aberrations can be explained by the non-linear effects induced by the dipole magnetic field depending on the beams' width with respect to the bending radius in the middle of the analysis dipole. In addition to the beam losses, these lead to the distortion of the distributions.

Indeed, the $^{208}Pb^{31+}$, whose dynamics is closer to the nominal one, suffers from fewer losses since its smaller width and intensity allowed a beam focusing closer to the slit, as shown in Fig. 5, favoring consequently the transmission.

In addition, the evaluation of the transmission along the global line confirmed that the losses are not only due to the cuts at the slit, but are observed all along the beam-line.

The influence of the nonlinear contributions on the beam quality can be verified comparing the beams emittance computed at the entrance and exit of the LEBT. We observed two different trends for lead and oxygen ions: for the former, the emittance increases due to the not suitable optics; for the latter, beam losses are dominant and lead to an overall decrease of the emittance.

More interesting results emerged by comparing the emittances of the transported beams and those computed at the beam line entrance for the same beams' percentage of the transmitted one (Fig. 6). In this case all beams show an emittance deterioration, up to a factor more than 3 for the Pb^{31+}. However, as we can see, that did not prevent the injection in PIAVE, since the emittance values (all <0.08 mm·mrad) are

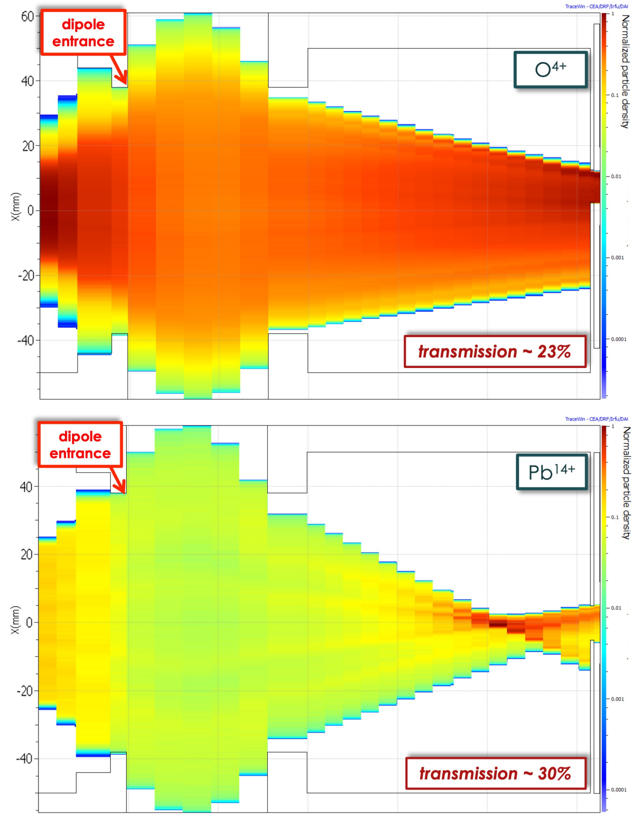

Figure 4: Density levels in the bending plane of the O^{4+} and Pb^{14+} beams.

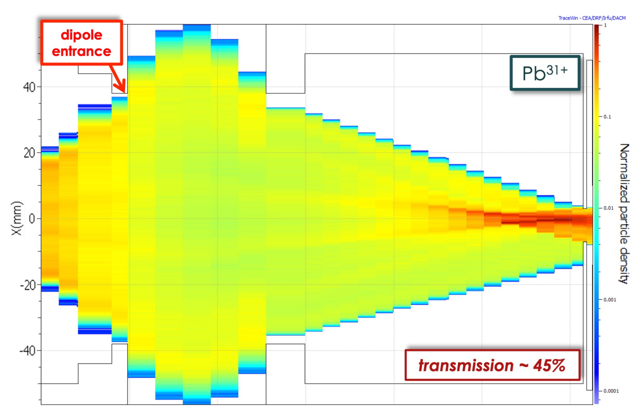

Figure 5: Density levels in the bending plane of the optimized Pb^{31+}.

still within the acceptance limit expected for its RFQs. As a proof, the experimentally measured transmission of $^{208}Pb^{31+}$ through PIAVE turned out to be close to the nominal one.

All these evidences can be also observed in the phase space distributions' deformation at the end of the line with respect to those at the beginning (see Fig. 7), which led to the emittances deterioration and confirmed the presence of non-linear forces in the dipole.

Finally, as shown in Fig. 8, a complete misalignment of the centroid of each beam, with specific values for each ion,

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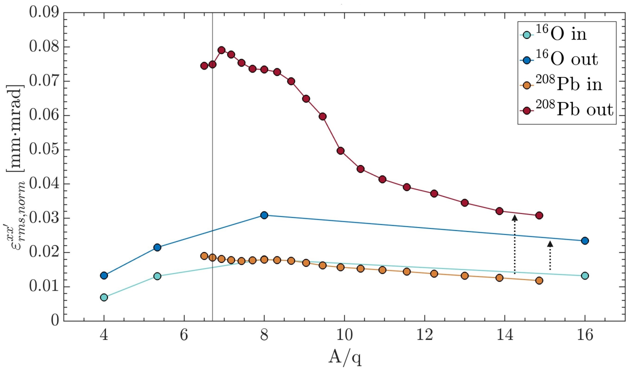

Figure 6: Comparison between input and output emittances of the same beam percentage.

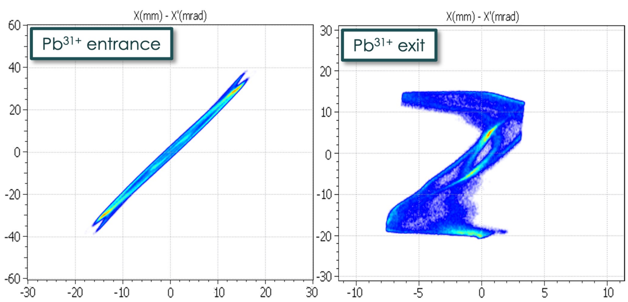

Figure 7: Comparison between the Pb^{31+} emittance distributions in the phase space at the LEBT entrance and exit.

came out from the evaluation of the average position and divergence as a function of the mass-over-charge ratio.

As a consequence, the steerers in the fixed-β magnetic line towards PIAVE have to deal not only with eventual mechanical misalignments (normally fixed), but also with those induced by the transport process. It is an important result that can explain the experimental observation according to which steerers values exhibit deviation of up to 60 % from expectations based on the theoretical scaling with the mass-over-charge ratio.

CONCLUSIONS AND PERSPECTIVES

Beams extracted from LEGIS has been simulated for the first time thanks to IBSimu. These have allowed to carry out many simulations of the beams transport along the LEBT, that shed light on the reasons for the experimentally observed criticalities. In particular, the almost 50 % losses could be traced back to an emittance-acceptance mismatch in the LEBT line. In addition, an optic not suitable for transport through the dipole has been found, that leads to the beam quality deterioration due to non-linear effects. This brought to off-centered average positions and divergences of each beam centroid, with different values for each mass-over-charge ratio, thus explaining the steerers non-scalability in the fixed-β magnetic line towards PIAVE, as experimentally expected.

From these results some possible solutions have been identified. Firstly, the modification of the LEBT line layout by installing the source closer to the dipole or by interposing a lens between them, in order to improve the matching between the beams' emittance and the acceptance of the LEBT. Secondly, the design of a new extraction system to produce beams with more suitable qualities.

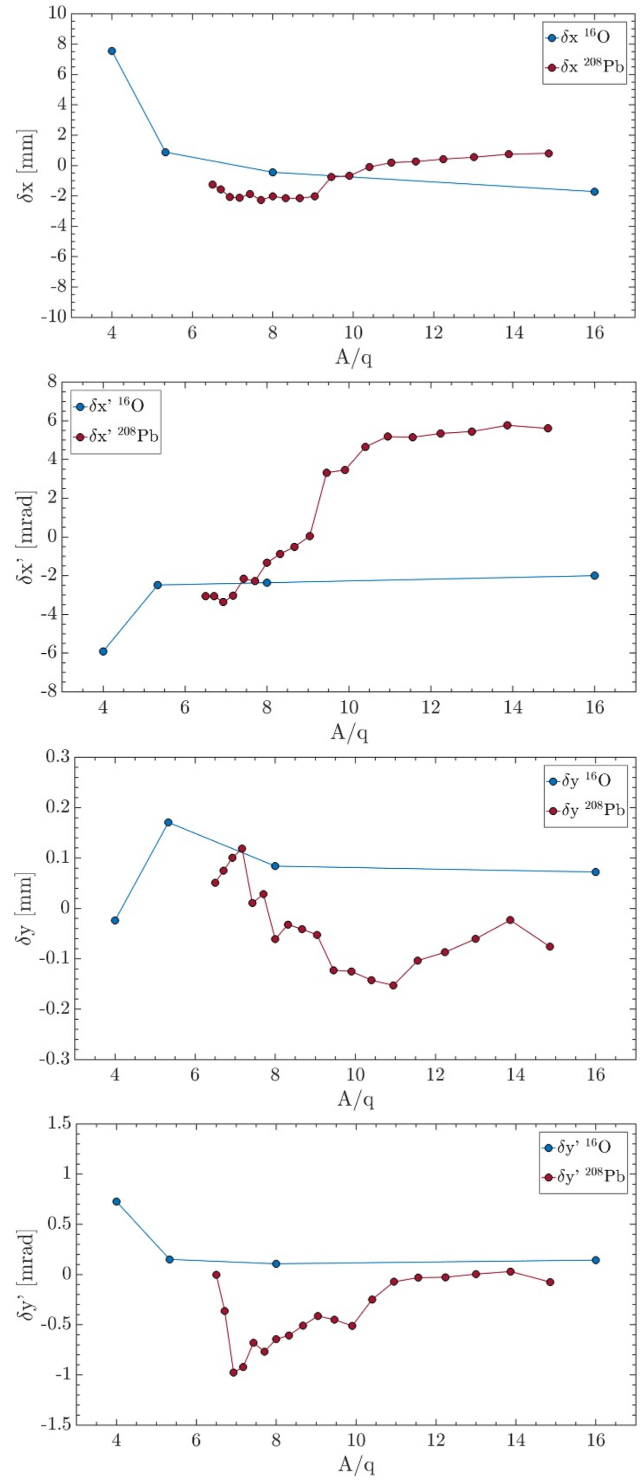

Figure 8: Average position and divergence in the transverse plane of the centroid of each beam as a function of the mass-over-charge ratio.

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