LPSC PHOENIX ECR CHARGE BREEDER BEAM OPTICS AND EFFICIENCIES

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Abstract

The PHOENIX ECR charge breeder characteristics (efficiency and charge breeding time) were measured at CERN-ISOLDE and at the Laboratoire de Physique Subatomique et de Cosmologie (LPSC), they were considered as sufficient to allow its setup on various facilities (TRIUMF - Canada / GANIL - SPIRAL2 and SPIRAL1 – France / SPES/INFN). The developments performed at the Argonne National Laboratory (ANL) have shown that the ECR charge breeder efficiencies could be much higher than the ones obtained with the LPSC PHOENIX, without major differences between the two devices. We have tried to study the possible reasons of such different results in order to improve the PHOENIX charge breeder characteristics. The transmission value of the n+ beam line has been measured to be as low as 30%. Emittances of the total beam extracted from the source and of some analysed beams (after the magnetic spectrometer) have been measured and will be presented. Simulations have shown a too low vertical acceptance at the center of the magnetic spectrometer. Simulations and experimental results will be presented, they show how an additional Einzel lens, inserted just before the dipole, has drastically improved the beam transmission. The impact of this new beam transport on charge breeding efficiencies will be presented.

ANL AND LPSC CHARGE BREEDERS CHARACTERISTICS

The ANL charge state breeder has been extensively described in [1]. It is a modified ECRIS allowing the injection and slowing down of an ion beam close to the axis, through a 25.4 mm internal diameter movable transfer tube. Like performed at LPSC, the injection plug has been modified in order to symmetrize the magnetic field at the injection side [2]. The recent configuration and results are presented in [3]. The pressure in this charge state breeder is about 2×10^{-8} mb, the axial magnetic field values at the injection, in the middle plane and at the extraction of the source, are respectively B_{inj} = 1.16 T, B_{min} = 0.27 T and B_{ext} = 0.83T.

Concerning the LPSC PHOENIX charge state breeder a few modifications have been performed since 2008. For example, the plasma chamber was modified in order to have the possibility to insert a liner (no internal diameter change) and has been equipped with two waveguide ports. The magnetic field, at the injection, has been slightly increased and fully symmetrized by the addition of iron parts around the plasma chamber [4]; finally, the grounded transfer tube has been removed allowing a more stable operation of the source. The pressure at the injection is about 6×10^{-7} mb and the axial magnetic field values are equal to B_{inj} = 1.21T, B_{min} = 0.42T and B_{ext} = 0.82T.

Both the ANL and LPSC charge breeders have two waveguide ports, at ANL the plasma is excited by a 2kW, 10.44GHz klystron plus a 500W, 11 to 13GHz TWTA. At LPSC we use a 2kW, 14GHz klystron and performed experiments (in collaboration with the INFN Laboratori Nazionali di Legnaro, Padova-Italy) with an additional 500W, 13.75 to 14.5 GHz TWTA [5].

This description of the two charge breeders shows that their characteristics are very close, some results presented in 2011 by both laboratories [3], [6] are compared in Table 1 below.

Table 1: Some Performances of the ANL and LPSC Charge Breeders

Laboratory	Ion	Yield (%)	Global yield (%)
ANL	$^{129}Xe^{25+}$	13.4	64
LPSC	$^{132}Xe^{18+}$	6.31	Not measured
ANL	$^{85}Rb^{19+}$	13.7	77
LPSC	$^{85}Rb^{15+}$	6.5	32

We can see that the performances of the ANL charge breeder are much better in term of yields and charge states. Unfortunately, the final number of radioactive ions being the convolution between the charge breeding time and the efficiency, it is difficult to make a valuable comparison due to the lack of data concerning charge breeding times. However, the difference in the yields results is sufficient to expect an improvement of the characteristics of the LPSC charge state breeder. The next paragraphs of this publication will discuss the LPSC charge breeder setup characteristics.

N+ BEAMS CHARACTERIZATION AND BEAM LINE OPTICS AT LPSC

Extraction Conditions and Beam Line

A photo of the PHOENIX charge breeder extraction beam line is shown Fig. 1. The extraction holes diameters of the source are 8 mm for the plasma electrode and 18 mm for the puller, the distance between them is 42mm. The n+ ions are extracted at 20 kV, they enter a 120° magnetic spectrometer through a beam line equipped with

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an X-Y magnetic steerer and a Faraday cup (Extraction Faraday cup), the analysed ion beams are characterized in a 1.3 m long n+ beam line equipped with X and Y emittance scanners and a N+ Faraday cup.

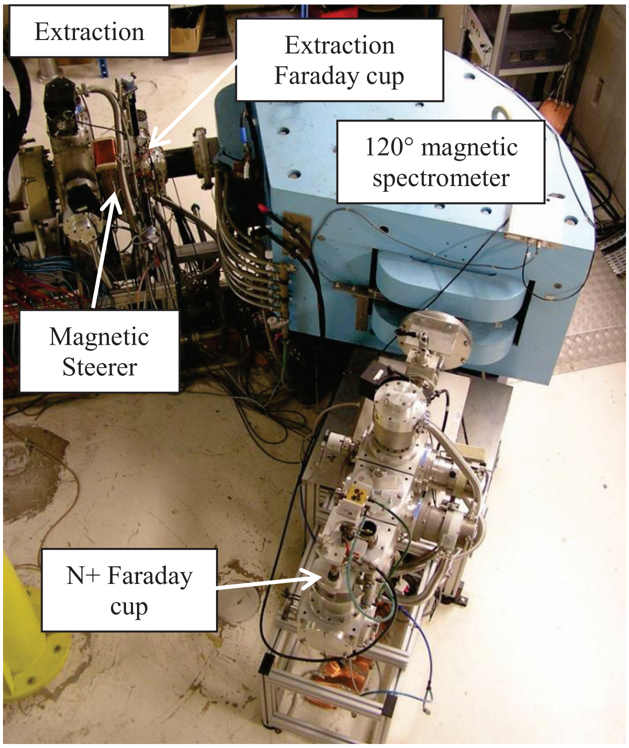

Figure 1: The LPSC charge breeder extraction beam line.

Last year, we noticed, on the LPSC PHOENIX ECR charge breeder, an excess of high voltage drain current with regard to the total current of a spectrum performed in the n+ Faraday cup. After, we disconnected the the 1+ source and the charge breeder ancillary equipment (to be sure that no parasitic current was flowing out), the excess drain current was still existing. This latter may have a few origins like: electrons produced at the extraction and accelerated towards the source; a transmission problem between the ion extraction and the final faraday cup placed after the magnetic spectrometer; for charge breeders, another origin of this current excess is due to the plasma leak occurring at the opened injection side, unfortunately this flow has not been carefully measured.

Let us consider three quantities: T_{glob}, T_{ext}, T_{tr} being defined as follows:

$$T_{glob} = \frac{\sum_i I_i}{I_{HV}}. \quad (1)$$

Where I_i is the ionic current of each peak analysed by the magnetic spectrometer and measured in the n+ Faraday cup, I_{HV} the drain current of the high voltage power supply,

$$T_{ext} = \frac{I_{axis}}{I_{HV}}. \quad (2)$$

Where I_{axis} is the total ionic current measured in a Faraday cup (Extraction Faraday cup on Fig. 1) placed just after the puller electrode before the magnetic spectrometer, and finally,

$$T_{tr} = \frac{\sum_i I_i}{I_{axis}}. \quad (3)$$

Even if we consider that the major part of the ions are extracted at the extraction side, to rigorously measure the global transport T_{glob}, one has to avoid the plasma leak at the injection side, this is performed by closing the plasma chamber, at the injection side, with a flange at the source voltage. In this configuration, we measured a global transport $T_{glob} \approx 0.3$ which is a low value potentially decreasing the measured 1+ → n+ efficiencies.

Diagnostic

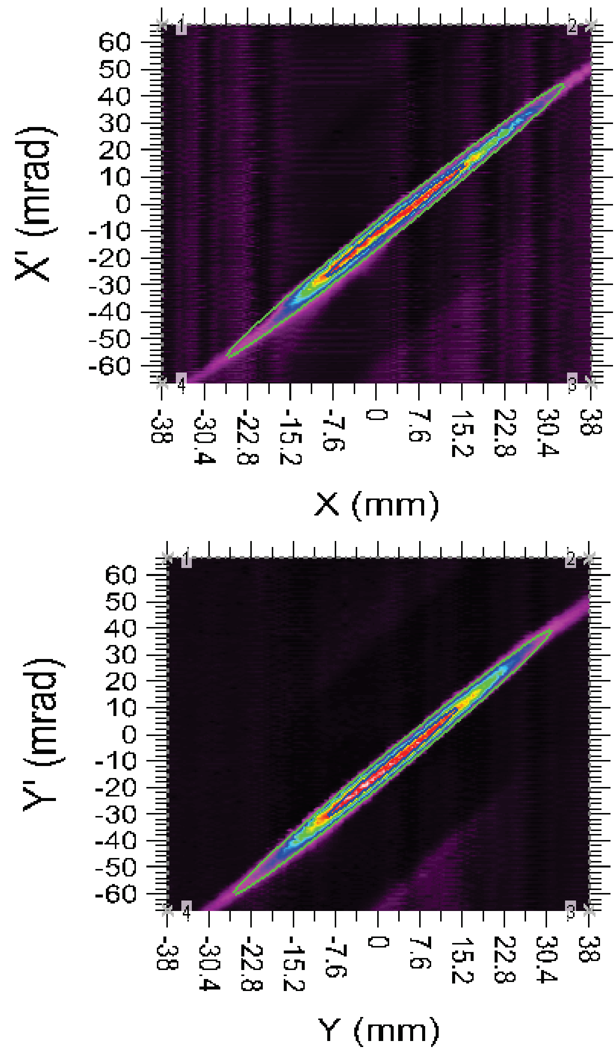

Figure 2: Horizontal (top) and vertical (bottom) emittances plots.

In order to determine the origin of this low global transmission, we have first characterized the total beam

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extracted before its entrance in the spectrometer, then we have measured its transmission through the 120° spectrometer. We have measured the two quantities T_{ext} and T_{tr}, to be respectively 0.91 and 0.32. These measurements clearly show that there is no electron production excess at the extraction itself, and that 70 % of the ions extracted from the charge breeder (when operated as a normal source) are lost in the magnetic spectrometer or the n+ beam line.

To characterize better this problem, and in order to have realistic experimental data input for N+ beam line optics simulations, we have measured the horizontal and vertical emittances of the total beam at the extraction of the charge breeder, these plots are presented Fig. 2. The emittance values are about 25 π.mm.mrad (RMS).

TRANSPORT SIMULATIONS IN THE N+ BEAM LINE

Initial Configuration Simulation

First we used the TRANSPORT code [7] and plotted X and Y beam envelopes (1σ), with the beam line acceptance on the same graph. The result is that the X envelope tangents the dipole vacuum chamber at its entrance and exit, and that the Y envelope is much bigger than the vertical size of this vacuum chamber all along the dipole.

In order to evaluate the transmission through the dipole we have used the SIMION code [8]. The model was simply composed of the vacuum chamber at the extraction (we did not simulate the beam extraction), the two magnetic poles of the dipole and a disc representing the Faraday cup. The experimental emittances were used to fly a 'realistic' beam of O^+ ions (during the emittance measurement, the average charge state was low), the space charge was neglected. The magnetic field has been computed using 'magnetic charges' on inclined surfaces (the magnet having a horizontal focalization index), and manually adjusted in order to direct the extraction axis ions at the center of the Faraday cup. With this simulation, we observed that about 50% of the ions were hitting the Faraday cup, the other ones being splashed on the upper and lower dipole vacuum chamber walls. The obtained trajectories are shown Fig. 3. With such a simple model, we find a difference with the experimental value T_{tr} = 0.32, but we have the confirmation of the loss in the vertical plane in the spectrometer.

Figure 3: Ion beam trajectories in the magnetic spectrometer after the extraction.

Technical Choice for Transport Improvement

We have planned to improve the charge breeder beam adaptation to the n+ beam line adding a lens just after the extraction. The use of a Glaser lens was discarded because it couldn't be easily implemented: modification of the extraction to insert the coil, installation of a power supply… So, as a first approach, we have installed a kind of Einzel lens, by inserting an 80 mm diameter and 135 mm long cylindrical electrode into the extraction chamber, using the vertical walls of the chamber as the grounded electrodes.

Einzel Lens Effect on the Simulated Beam

The electrode was added in the SIMION simulation and we checked if the assembly was acting as an Einzel lens. We plotted the focal length of the lens as a function of the cylindrical electrode voltage and deduced that the electrode setup was close to an Einzel lens configuration. By varying the cylindrical electrode voltage, we looked for the optimal beam transport to the Faraday cup and found an optimum value of 0.9 for T_{tr}, at -27kV and +15kV values.

IMPLEMENTATION

The cylindrical electrode was installed on an insulated support into the extraction chamber, no alignment system was present to help placing the electrode (see Fig. 4). In this configuration, we measured a global transport T_{glob} = 0.75 that could be optimized up to 0.82 using the magnetic steerer in the vertical plane. Finally, the magnetic steerer acting differently on different m/Q, its current intensity has been automatically adjusted to be optimized for each ion beam selected by the magnetic spectrometer. This latter servo control allowed us to reach a global transport T_{glob} = 0.84. With T_{ext} = 0.91, it gives a transport coefficient $T_{tr} = \frac{T_{glob}}{T_{ext}} = 0.92$. This value being close to 1 (and much higher than 0.32!), it has been decided to evaluate the impact of this improvement on the charge breeding efficiencies. So, the flange at the injection of the charge breeder was removed and the test bench reconfigured in the charge breeding configuration.

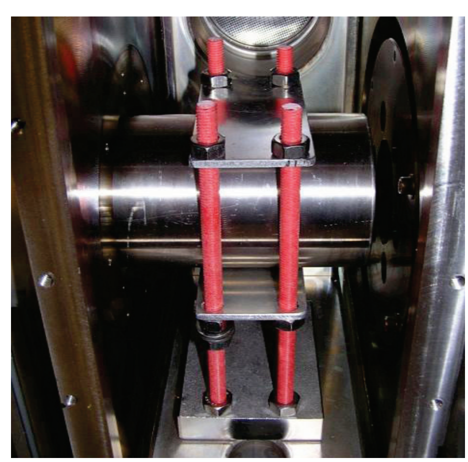

Figure 4: High voltage cylindrical electrode.

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EXPERIMENTAL RESULTS

Argon and Xenon

To test the new configuration, we first measured argon charge breeding. A 1µA Ar^+ current was produced by the COMIC ion source [6] and injected into the charge breeder. With a usual charge breeder tuning, we obtained a maximum yield of 16.2% for $Ar^{1+} \rightarrow Ar^{8+}$, with a global capture of 75% (see Fig. 5) and a charge breeding time of 78ms (about 10ms per charge). For Ar^{8+}, it represents an increase of 17% compared with the previous maximum of 13.4% measured in April 2012, values reported in blue (Fig. 5).

When injecting a $^{132}Xe^+$ beam, we obtained a maximum yield of 10.9% for $^{132}Xe^{20+}$ with a global capture of 80% and a charge breeding time of 252ms for Xe^{21+} (12 ms per charge).

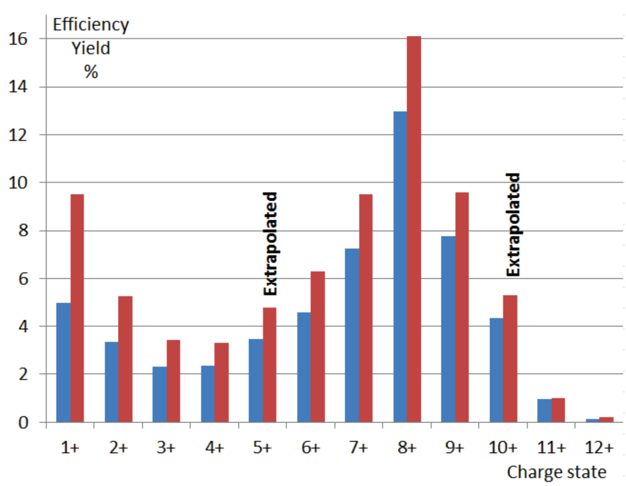

Figure 5: Argon charge state distribution extracted from the LPSC charge breeder.

Rubidium

To produce $^{85}Rb^+$, the COMIC source was replaced by a new 1+ ion thermo-ionic source based on the use of an alumina-silicate emitter. We designed a simple extraction optics formed by a set of three electrodes to produce the beam (Fig. 6).

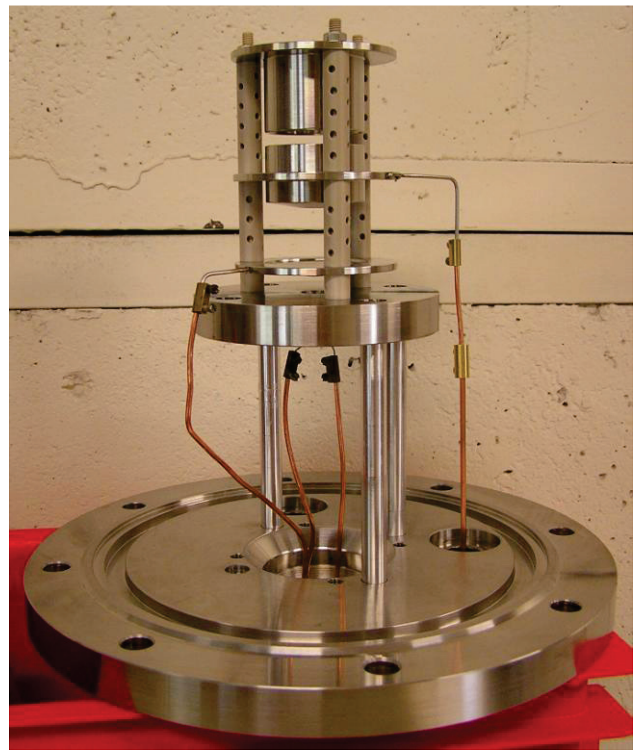

Figure 6: ion gun with its set of three electrodes.

The source was able to deliver a 300 nA $^{85}Rb^+$ beam within an horizontal emittance of about 2 π.mm.mrad, which is a reasonable value, even if much higher than the one get with the former source (0.6 π.mm.mrad) that was equipped with a sophisticated set of five electrodes. The tuning of the charge breeder led us to find a yield of 7.5% for $^{85}Rb^+ \rightarrow {}^{85}Rb^{17+}$ with a charge breeding time of 226 ms (about 13 ms per charge). The charge state distribution is shown Fig. 6, the charges marked as extrapolated are superimposed with impurities, the 16+ is approximated to 8% in order to get a rather normal distribution, this leads to a global capture of about 55%. For this experiment with rubidium, it is more difficult to say that the efficiency yields increases are due to the transport improvement. One can see (with respect to our previous experimental data plotted as the blue bars Fig. 7), that the charge state distribution is shifted towards higher charge states, certainly due to an improvement of the pumping, leading to a lower pressure in the charge breeder.

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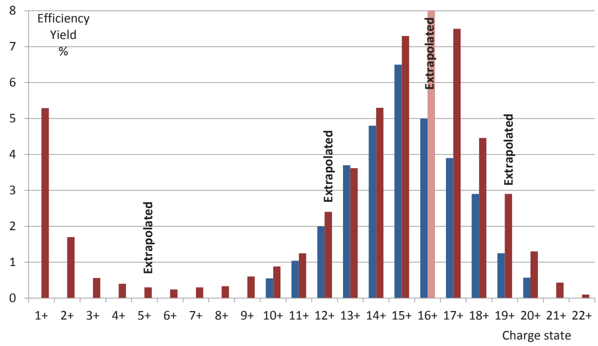

Figure 7: Rubidium charge state distribution extracted from the LPSC charge breeder.

Conclusion

The maximum efficiency yields obtained by the LPSC charge breeder have been improved by at least 15% after having solved a transmission problem observed in the vertical plane of the n+ line vertical plane. All the results we give are obtained with a charge breeding time of about 10 ms per charge, in order to avoid possible plasma modifications observed when tuning the charge breeder in a long confinement time configuration. This plasma modification systematically observed could lead to overestimated results. The improvement of the vacuum level clearly shows a shift of the charge state distribution and an improvement of the efficiencies, certainly due to a better confinement and a decrease of the charge exchange effect.

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