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EXPERIMENTAL ACTIVITIES WITH THE LPSC CHARGE BREEDER IN THE EUROPEAN CONTEXT*

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Abstract

One of the Work Packages of the "Enhanced Multi-Ionization of short-Lived Isotopes at EURISOL" NuPNET project focuses on the ECR charge breeding. The LPSC charge breeder is used for experimental studies in order to better understand the fundamental processes involved in the 1+ beam capture by a 14 GHz ECR plasma. Some improvements, like symmetrisation of the magnetic field at the injection side and higher pumping speed, have been carried out on the PHOENIX charge breeder. The impact of these modifications on the efficiencies and charge breeding times are presented. In the same time, the new LPSC 1+ source developments performed in order to ease the efficiency measurements with various elements are presented.

CONTEXT

In Europe, several high energy radioactive ion beams (RIB's) facilities are under design, construction, or upgrade. At CERN (Geneva, Switzerland), the HIE-ISOLDE project (which uses an EBIS as a charge breeder) has the objectives to increase the energy and the beam intensity of the REX-ISOLDE facility by 2017 [1]. At GANIL (Caen, France), the SPIRAL2 phase2 aiming to produce high energy intense RIB's has been stopped for the moment; however, an upgrade of the SPIRAL1 facility will allow the delivery of new light condensable elements, by 2016, using a modified PHOENIX ECRIS charge breeder whose initial version was developed at LPSC [2].

At the 'Laboratori Nazionali di Legnaro' (Legnaro, Italy) of the Istituto Nazionale di Fisica Nucleare (INFN), the SPES facility (Selective Production of Exotic Species) [3] is under construction; its completion is foreseen in 2017. It will deliver mainly heavy radioactive ions up to an energy of 11 MeV/u, and will be equipped with a LPSC PHOENIX ECRIS charge breeder [4].

For long term science with accelerated radioactive ion beams, the EURISOL project aims to produce high intensities (10 to 100 times higher than the present facilities under construction) and should be equipped with an EBIS and an ECRIS charge breeder. ECR charge breeders with their high intensity acceptance, their fully cw or pulsed operation, are suitable to increase the charge state of the monocharged radioactive ions, as a beam line component located far from the highly radioactive environment of the production targets. LPSC, where ECR charge breeding has been first developed, has taken the responsibility of the design, the construction, and of the experimental qualification of European charge breeders.

Within the same time, the laboratories, authors of this publication, have gathered their research and development activities related to charge breeding in a collective project named '**E**nhanced **M**ulti-**I**onization of short-**L**ived **I**sotopes at **E**URISOL (EMILIE)', funded by the **E**uropean **R**esearch **A**ctivities - **NET**work for Nuclear Physics Infrastructures (NuPNET).

LPSC ACTIVITIES RELATED TO ECRIS CHARGE BREEDERS

SPIRAL2

A detailed mechanical design of the ECR charge breeder has been performed including the modifications studied at LPSC (for example, the suppression of the grounded tube for the slowing down of the 1+ beam). The definition of the operating conditions have been characterized on the LPSC test bench allowing the highest efficiencies maintaining a short charge breeding time (typically 10 ms per charge). The radioactive environment has been taken into account by optimizing the troubleshooting procedures of contaminated parts, allowing to respect the "**A**s **L**ow **A**s **R**easonably **A**chievable" principle. For the moment the SPIRAL2 phase 2 project has been suspended, so the LPSC charge breeding activities for this project, too.

SPIRAL1 Upgrade

The SPIRAL1 facility, after its upgrade including a modified ECR PHOENIX charge breeder, will have to deliver new light condensable radioactive elements. In this context, we have performed experiments with the original charge breeder to compare the charge breeding efficiencies of carbon ions when injecting either $^{13}C^+$, $^{13}CO^+$ or $^{13}CO2^+$ beams extracted from the miniaturized 2.45 GHz COMIC [5] source (see Fig. 1). The detailed

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*Work supported by the ERA-NET NuPNET

results of these experiments [6] show that the best charge breeding efficiencies are obtained when injecting $^{13}CO2^{+}$ into the charge breeder and confirm the interest of using molecules, when available, to "make heavier" the atoms to be charge bred.

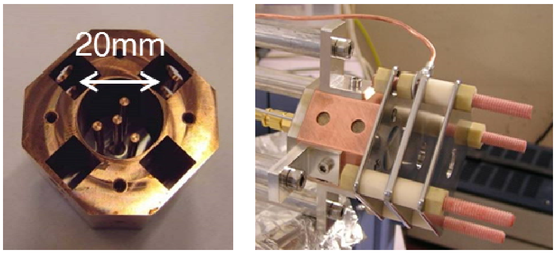

Figure 1: The 2.45 GHz COMIC source.

The next step, before the final setup of the upgrade at GANIL, will be the qualification of the SPIRAL1 charge breeder including its specific optics on the LPSC test stand, this should be performed in 2015.

SPES

The Physics case of the SPES project is detailed on the SPES website [7]. The main goal of the SPES Project is to produce neutron-rich radioactive nuclei with mass in the range 80-160 up to 11 MeV/u for A=130. The 1+ ion sources close to the production target will deliver beams with an emittance in the range 5÷50 π.mm.mrad extracted at a maximum voltage of 40kV. The charge breeder (CB) extraction voltage upper value will be 40 kV as well, the multi-ionization efficiencies on a specific ion with A/q<7 will be 10-15% for gaseous ions and 5-10% for metallic one [4]. In order to get rid of most of the impurities superimposed to the n+ beams, a -120 kV high voltage platform will be equipped with a spectrometer with a resolving power of ΔA/A~1/1000 at 10% of the peak's intensity (see Figure 2).

LPSC is in charge of the final design, the construction and the experimental qualification of the charge breeder which will be delivered to LNL in April 2015.

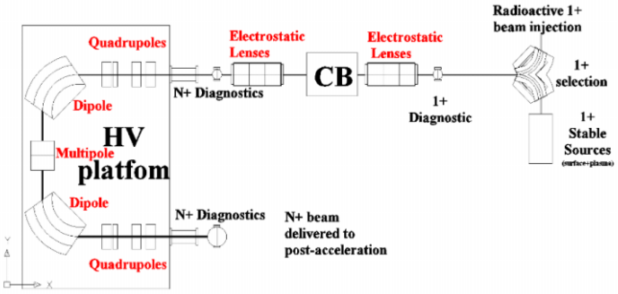

Figure 2 : Scheme of the charge breeding part of SPES

EUROPEAN R&D ACTIVITIES WITH THE ECR PHOENIX CHARGE BREEDER

Activities of The "EMILIE" Project

In a far future, the EURISOL facility may be equipped with both EBIS and ECRIS charge breeders which have been shown as complementary devices [8]. The R&D activities of the EMILIE project has the objectives of improving both Charge Breeding methods. Concerning ECRIS, we have the objective to improve the PHOENIX charge breeder. The main goals are to increase the breeding efficiency keeping the charge breeding times in the range of 4 to 10 ms/charge, to study the wall recycling effects and the possibilities to reduce the stable background mixed with the low intensity multicharged radioactive ion beams extracted from the charge breeder, and finally, to establish the reproducibility of the performances.

Until now, extensive and accurate experiments to evaluate the transmission, the capture, the charge breeding efficiencies and the charge breeding times, have been performed with Ar^{+}, Kr^{+}, Na^{+}, Rb^{+}, Cs^{+} beams. The influence of the support gas flux and nature, the benefits of fine frequency tuning and double frequency heating have been evaluated. The development of a hot 1+ source has been performed to evaluate wall recycling effects. In the following paragraphs different studies performed within the collaboration are presented.

Studies Performed

Wall recycling effects in low charge ion sources

We have developed a hot version (650°C) of the 2.45 GHz COMIC source to produce 1+ alkali ion beams with high stability and low emittance. The objective is to study its efficiency dependence with the temperature. This may give information about the interest of developing a charge breeder with a hot plasma chamber.

In order to control their temperature, the FeNdB permanent magnets have been installed in a water cooled support independent from the hot cavity (Fig. 3). The design criteria were to reproduce the magnetic field and the electric field of the COMIC source. RADIA-Mathematica and ANSYS allowed simulating magnetic field, RF coupling and thermal characteristics. The magnetic field induction is shown in Fig. 4 and the electric field intensity in Fig. 5

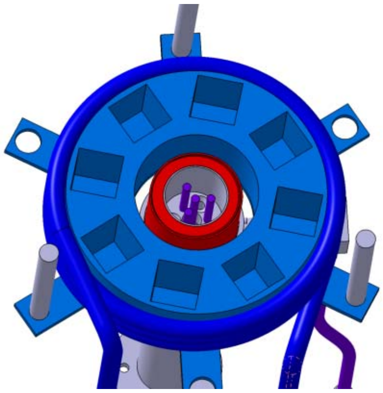

Figure 3 : Mechanical design of the hot COMIC source, purple: HF couplers, red: hot plasma cavity, blue: water cooled magnets support

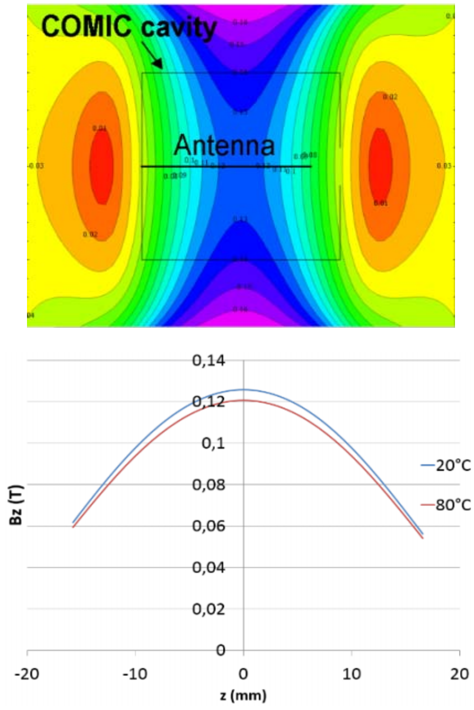

Figure 4: Magnetic field of the hot COMIC source (top: iso-B in the plasma cavity, bottom: magnetic induction on the axis).

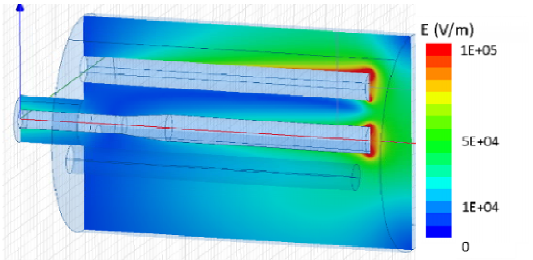

Figure 5: Electric field magnitude into the hot COMIC plasma cavity.

The source has been built (Fig. 6) and will soon be tested. A second version will be developed to reach 1200 °C, in order to extend the operation to metallic ion beams.

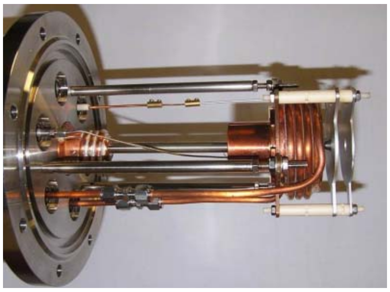

Figure 6: Hot 2.45 GHz COMIC ion source.

LPSC PHOENIX charge breeder improvements

- Vacuum improvement

The charge breeding efficiency is known to be highly dependent on the vacuum level [9]. We have added a 1000 l/s turbo molecular pump on the LPSC test stand, allowing reaching 3 E-07 mbar. Fig. 7 shows, for two different gas fluxes, the production efficiencies of argon charge states obtained with a specific tuning. The total efficiency (sum of the efficiencies for each charge state) drastically decreases with increasing pressures (from 60% at 3.3 E-07 to 20% at 6E-07 mbar).

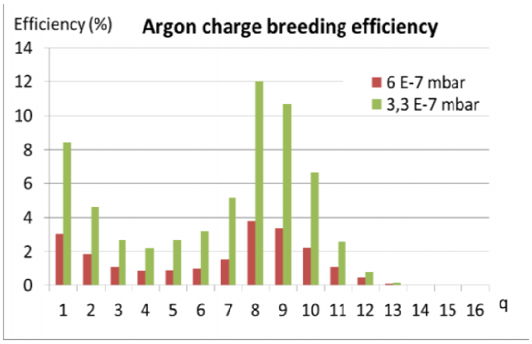

Figure 7: Efficiency for charge bred argon at different gas fluxes.

- Magnetic field symmetrization at the injection

The LPSC charge breeder has two HF ports in order to study the effect of double frequency heating, the electromagnetic waves being injected radially into the plasma chamber at 90° one from each other. The soft iron magnetic plug at the injection has two grooves (Fig. 8) to allow the passage of the two WR62 waveguides with water cooling tubes. These grooves produce a non-symmetric axial magnetic field at the injection, the region where the 1+ beam is decelerated.

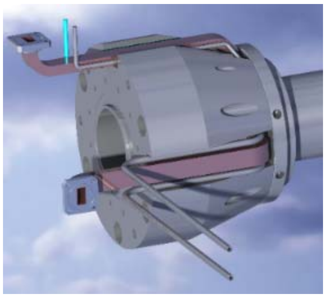

Figure 8: Magnetic plug with cuttings.

We have simulated the 3D trajectories of a 20 keV $^{85}Rb^{+}$ beam injected into the charge breeder with such a magnetic configuration and at a potential of 19.99 kV. The initial condition is composed of 1000 ions in the emittance of the 1+ beam measured on the test stand, $\varepsilon(1\sigma) = 2\pi$.mm.mrad. The 3D magnetic field map has been calculated with RADIA-Mathematica and used in SIMION 3D in order to get the ions trajectories. In Fig. 9, that shows a cut view of the result of the simulation, the green rectangles are the positions of the two WR62 waveguides. One can see an important deflection of the beam on the opposite side of the two soft iron cuttings that may lead to a lack of capture of the 1+ beam by the plasma.

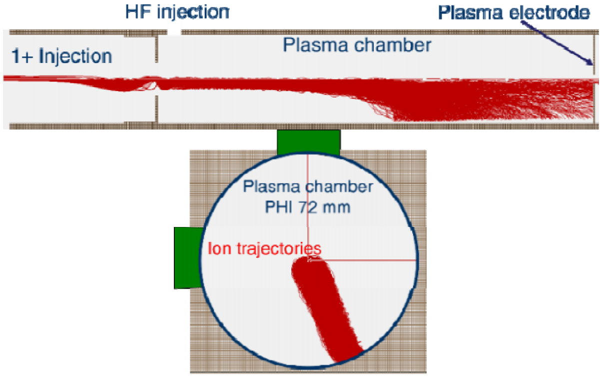

Figure 9: SIMION3D trajectories in the dissymmetric magnetic field ($^{85}Rb^+$, 20 keV, $\varepsilon(1\sigma) = 2\pi$.mm.mrad, charge breeder potential: 19990 V).

The injection magnetic plug was symmetrized by machining two additional grooves like shown in Fig. 10. The beam experiments with sodium have shown, for high charge states, a significant efficiency increase (see Table 1) maintaining the charge breeding time to 6 ms/charge. Moreover, we have experimentally noticed that the optics tuning was easier after the symmetrization and that there was no efficiency increase for rubidium.

Table 1: Sodium efficiencies measured before and after the symmetrisation of the magnetic field at the injection

Ion	Before sym.	After sym.
$^{23}Na^{6+}$	3%	3.7%
$^{23}Na^{7+}$	1.47%	3%
$^{23}Na^{8+}$	--	2.6%

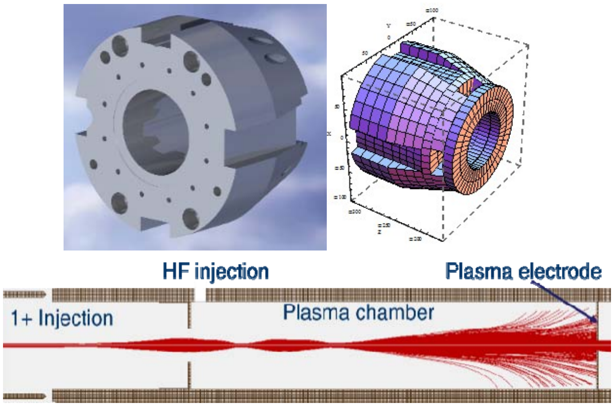

Figure 10: Symmetrized injection magnetic plug and its RADIA model, SIMION 3D trajectories.

- Magnetic field gradient modification

In the PHOENIX charge breeder, the axial magnetic field gradient can be adjusted by moving two soft iron rings placed around the hexapole. Since many years, various modifications were applied to the charge breeder,but the influence of the magnetic field gradient on the efficiencies was not checked. The position of the iron rings was changed, pushing them toward the extraction side. The initial position, the final one, the iso-B plots and the axial magnetic field for the two positions are shown in Fig. 11. We can see that the 14.5 GHz resonance zone (pink curve on the iso-B plots) is shifted towards the extraction and slightly deformed, however the magnetic field at the injection is almost unchanged.

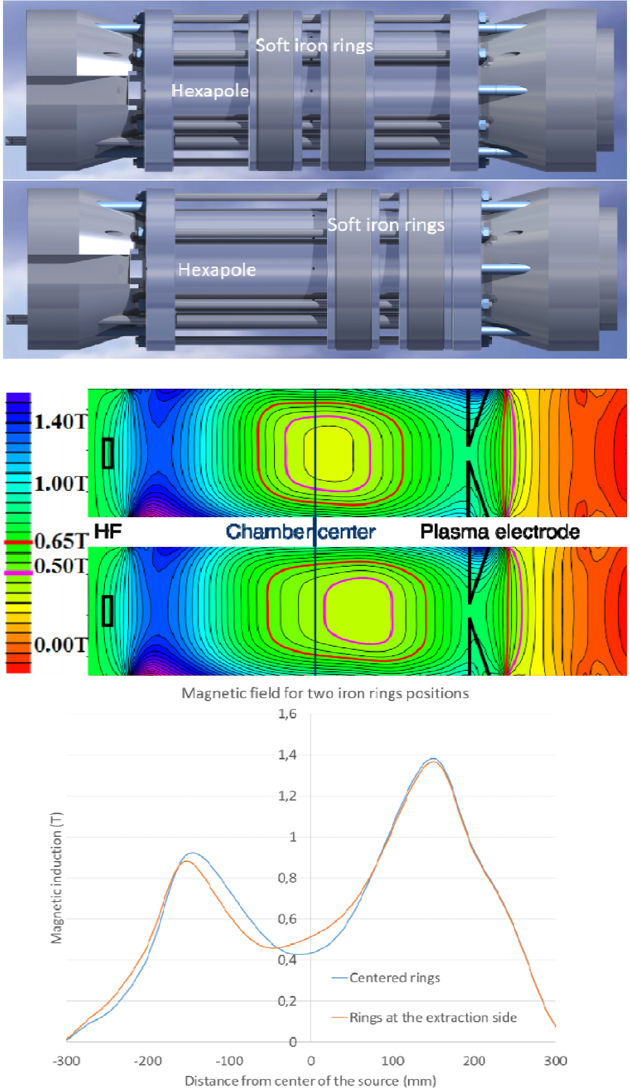

Figure 11: Magnetic field induction on axis for two different positions of the movable soft iron rings.

The efficiency yields have been measured for sodium beams. Results are shown in Table 2, one can see a significant improvement of the efficiencies for the multi-ionization of sodium to high charge states.

Table 2: Sodium efficiencies for two magnetic field gradients

Ion	Rings centered	Rings shifted towards extraction
$^{23}Na^{6+}$	3.7%	3.8%
$^{23}Na^{7+}$	3%	3.7%
$^{23}Na^{8+}$	2.6%	3.2%

Double frequency heating and fine frequency tuning in conventional and charge breeder ECRIS's

- Double frequency heating

Double Frequency heating has been tested with the JYFL 14 GHz ECRIS and the PHOENIX charge breeder. Ar, Kr and Xe have been used for these studies. The results have been published in [10]. It has been shown the same effect in both sources, double frequency heating improves the production efficiency of high charge states. Moreover, despite an axial magnetic field, at the injection, much lower in the charge breeder than in the conventional ECRIS (1.2 T versus 2.2 T), and despite the absence of bias disk, the ionization efficiency and the charge state distribution (CSD) of each source are very close one to each other.

- Fine frequency tuning

We have tested the fine frequency tuning in the LPSC charge breeder and compared the Ar^{11+} production efficiencies obtained when using a Traveling Wave Tube Amplifiers (TWTA) to vary the ECR frequency, or a klystron with a fixed frequency of 14.521 GHz. With the TWTA, we have noticed for some specific frequencies huge variations of the multi-ionization efficiency, and important plasma instabilities preventing us from measuring correct values. In any case, the klystron has given the best results with a highest value of 8.4% for Ar^{11+}. Even for other charges and ion species the best efficiencies have always been obtained with the klystron.

Our interpretation of this fact is like the one developed in [11]. The charge breeder has a direct injection of the microwaves into the plasma chamber through a WR62 waveguide brazed on it. When the plasma is established in the large volume of the plasma chamber, the coupling optimization is not effective due to multi-mode behavior and to the plasma absorption. In 'CAPRICE-like' sources, we have a waveguide to coaxial mode transition which is extremely sensitive, so in this later case, fine frequency tuning surely optimizes the transmission of waves through the transition.

New charge breeding results and potential application to ECR plasma physics

- Cesium

The 1+ beam was produced by a commercial ion gun (Heat Wave Labs) with an extraction optics simulated and designed at LPSC (Fig. 12).

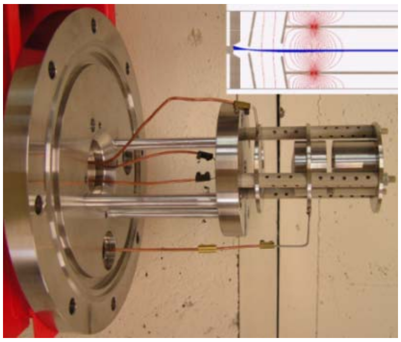

Figure 12: LPSC ion gun with its extraction optics.

We have studied the charge breeding efficiencies for the different charge states of cesium, varying the 1+ beam intensity between 50 nA up to 1.15 μA. In the range between 50 nA and 500 nA, the emittance (1σ) of the 1+ beam, increases from 1.7 to 2.7 π.mm.mrad and presents a plateau for higher intensities. The results are shown in Fig. 13. Except for the lowest 1+ beam intensity injected (~50 nA), where the highest multi-ionization efficiency is obtained (9.5% for $^{133}Cs^{27+}$), the CSD are peaked on the $^{133}Cs^{26+}$. They exhibit two maxima in the ranges from 1+ to 3+ and from 21+ to 31+. The 1+ charge breeding efficiency is the proportion of the incident 1+ beam which is not captured, propagating through the plasma. The 2 and 3+ ones have two components, one due to subsequent multi-ionization after capture, and one contribution of direct in-flight ionization without capture. Additional data supporting the given interpretation will be presented in a future publication.

In terms of breeding efficiency variation with the injected intensity, there are two kinds of behaviors depending on the charge state domain. For charge states in the range 4+ to 20+, there is almost no efficiency variation when increasing the 1+ intensity, whereas for the 1+ to 3+ and the 21+ to 31+ ranges, we observe a decrease of the efficiencies, more important for low charges. If we look at the sum of the efficiencies in the different charge states ranges (lower plot Fig.13), the decrease of the global capture is essentially due to the high charge states that decrease like the 1+ beam intensity transmitted by the plasma.

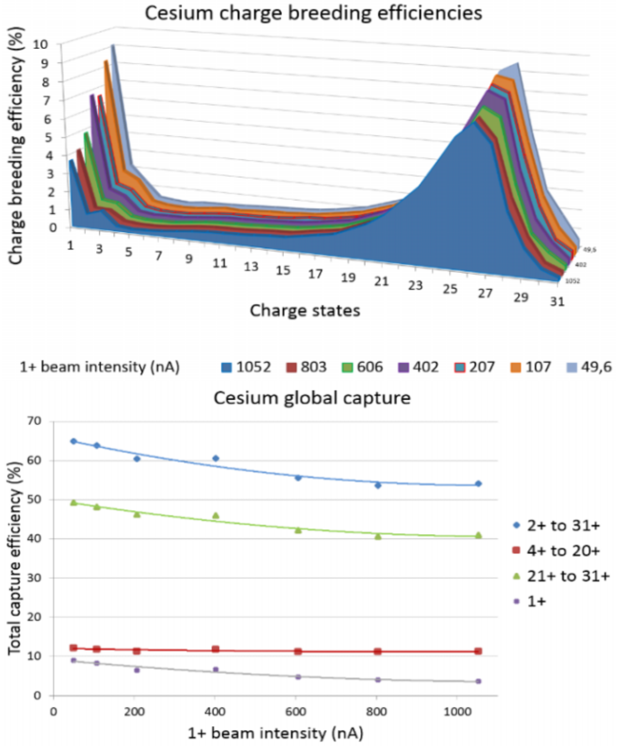

Figure 13: Charge breeding efficiencies for cesium charge states and global capture in different domains of charge states as a function of the 1+ beam intensity.

These results seem to show that the injection of the 1+ beam has a great influence on the plasma characteristics or on its electronic population. The high charge state decrease suggests that the high intensity 1+ capture reduces the ion confinement time or increases the neutral density in the chamber.The ΔV plots (Fig. 14) show the efficiencies for various charge states as a function of the incident 1+ beam energy. It is interesting to note that the high charge states are clearly obtained after the capture of the 1+ beam, that occurs in a narrow 1+ energy range, when the 2+ plot has almost the same behavior than the 1+ transmitted through the plasma, so we may consider that the majority of the 2+ is directly ionized in flight when crossing the plasma.

- Sodium

We have extensively studied the charge breeding of sodium to try to better understand the difficulty to capture light ions. The best efficiencies obtained have been detailed in the previous sections of this publication. Figure 15 shows the ΔV plots for ^{23}Na^{+}, ^{23}Na^{2+} and ^{23}Na $^{6+}$. It is very interesting to note that the 2+ plot seems to have two contributions, a similar shape to the 1+ plot for high energies (high negative values), but a maximum at the energy corresponding to the optimum of the 1+ capture (close to the 6+ which is obviously obtained after the capture process.). This result can be interpreted as follows: at low energy, 2+ ions are produced subsequent to a capture process, while at high energies, they are mainly in-flight ionized. Such effect (dual-peak) is not observed with heavier elements because the charge state distribution of the captured ions does not overlap with the low charge states being ionized in-flight.

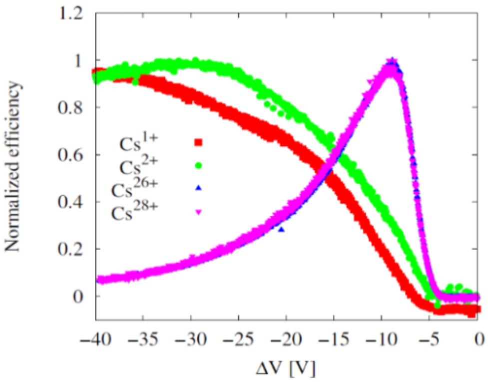

Figure 14: Relative efficiencies for cesium charge breeding as a function of the DeltaV.

The charge breeding times measurements (Fig. 16) for different charge states (1+, 2+, 3+, 6+) for ΔV= -11.4V, allowing the optimization of the capture, shows a classical behavior with a charge breeding time of about 10 ms/charge. If we set ΔV= -23 V, value outside of the 1+ beam energy capture window, we measure for the 2+ (green plot) a faster signal much closer to the 1+ one. This clearly shows that, in this condition, we have access, quantitatively, to the small part of the Na^{2+} which is directly produced during the flight of the uncaptured 1+ beam.

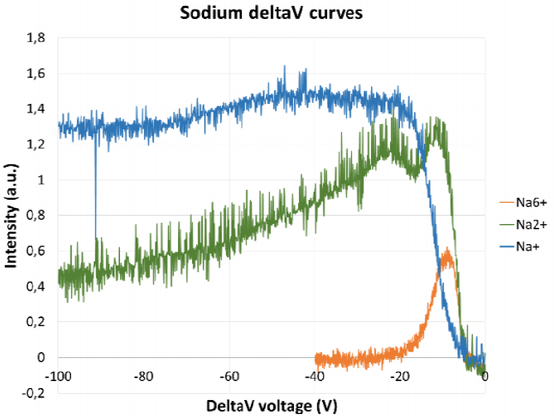

Figure 15: Relative efficiencies for sodium charge breeding as a function of the DeltaV

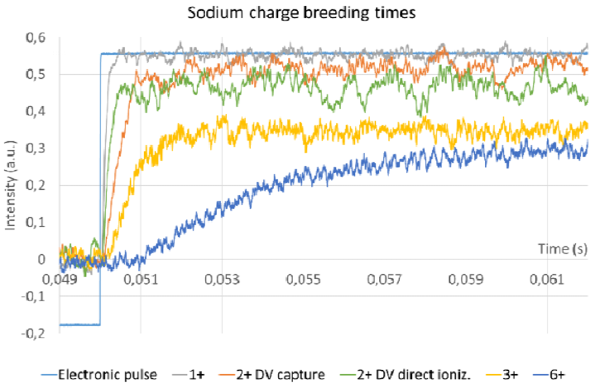

Figure 16: Charge breeding times for 1+, 2+, 3+ and 6+ charge states, two 1+ beam injection energies for the 2+.

- Plasma-beam interaction physics

We have seen, in the previous paragraphs, that the injection of a low intensity (with respect to the total current extracted) 1+ heavy ion beam into a dense ECR plasma may affect this latter. Such an effect was shown in [12] when injecting a Xe^{+} beam. We have performed the same experiment injecting a Cs^{+} beam, varying its intensity. We have measured the intensity variation of the buffer gas ions (oxygen) during the injection. The results are reported in Fig. 17. We see a huge decrease of the intensity, especially for multicharged ions and a slight increase of the monocharged ones. A plausible interpretation of the result could be based on momentum transfer in ion-ion collisions, often referred as ion cooling. In such a process, the average energy of the lighter ion species (O) increases due to Coulomb collisions with the heavier one (Cs). The increased energy in turn implies a shorter confinement time, which shifts the charge state distribution of the buffer gas towards lower charge states. Further experiments and/or simulations are required to confirm this hypothesis. The possible charge exchange process is not a dominant effect, the low charge ions being not repopulated significantly. So only a modification of the plasma equilibrium could be the cause of such an important phenomenon.

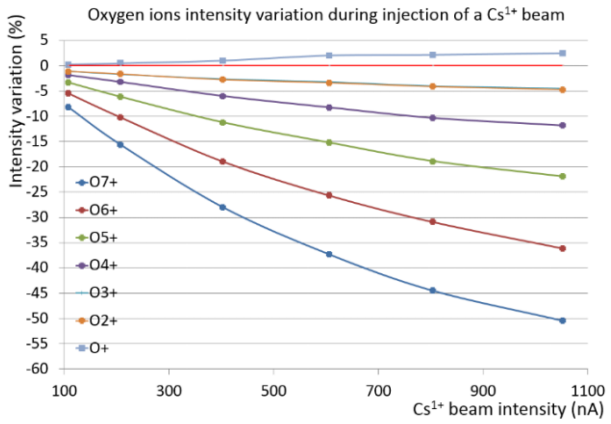

Figure 17: Intensity variation of buffer gas ions when injecting different Cs^{1+} beam intensities.

PROSPECT

The next stages of our activities will be the support of the present construction projects (SPES, SPIRAL1) and the reinforcement of fundamental studies of plasma physics made possible by the charge breeding method. We will soon explain, in a new publication, how powerful this method can be.

AKNOWLEDGEMENT

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