LATEST DEVELOPMENTS IN ECR CHARGE BREEDERS

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Abstract

The basic principles of the ECR charge state breeder (CSB) are recalled, special attention is paid to the critical parameters allowing the optimization of the ECR charge breeders characteristics (efficiency yield, charge breeding time, capture potential deltaV). An overview is given on the present ECR charge breeders situation and results worldwide. Possible means to increase the 1+ ion beam capture for light ions is presented. In the context of radioactive environment, possible technological improvements and/or simplifications are suggested to facilitate the maintenance and to reduce the human intervention time in case of a subsystem failure.

INTRODUCTION

The Electron Cyclotron Resonance (ECR) charge breeding, developed at Laboratoire de Physique Subatomique et de Cosmologie in Grenoble has been studied and setup (or is under development) in many laboratories worldwide (CERN/ISOLDE - Switzerland, KEK TRIAC - Japan, TRIUMF - Canada, Argonne National Laboratory - United States of America, Texas A&M University - United States of America, SPIRAL2 - France). These developments allow the cross check of the different experimental results and allow improvements of the method and of the technologies.

BASIC PRINCIPLES OF ECR CHARGE BREEDERS

An ECR charge state breeder (CSB) is a classical ECRIS where the injection side is opened in order to inject a 1+ beam. The 1+ beam is suitably decelerated in order to optimize its capture by the ECRIS plasma where the multi ionization process takes place before the extraction (Fig. 1).

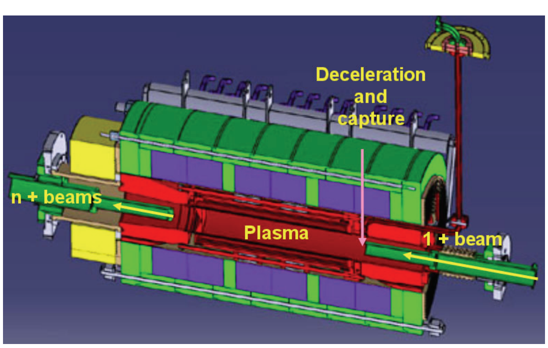

Figure 1: Cut view of the PHOENIX ECR charge breeder.

The main characteristics of an ECR charge breeder for a radioactive ion beam facility are efficiency, fastness, purity and quality of the beams delivered, tuning possibilities, reliability and easy maintenance. The critical parameter for the capture efficiency is the final energy of the decelerated beam that should be equal to the energy of the ions of the plasma (a few eV). Different behaviours can be seen for gaseous and non gaseous ions on the delta V plots which show the n+ ion intensity evolution when varying the potential of the ECR charge breeder (Fig. 2). At too low energies (right side of the curves), the beam is reflected by the plasma, then, when decreasing the voltage of the charge breeder, the 1+ beam begins to get captured and multi ionized; at too high energies (left side of the curves), the metallic ions go to the wall and are lost, the gaseous ones are still available for the multi ionization process because they can be reflected by the walls.

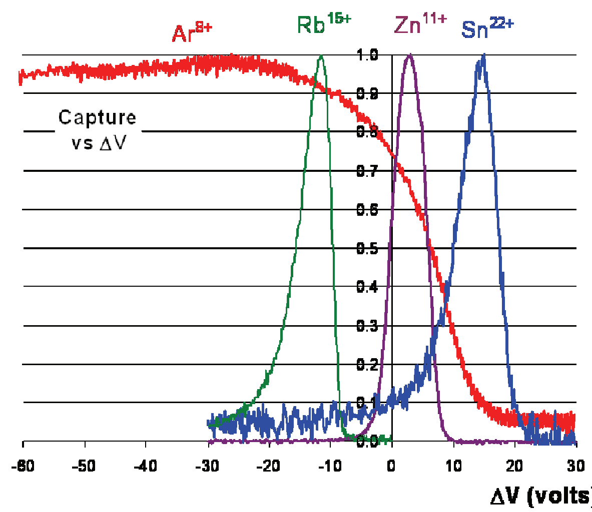

Figure 2: Normalized ΔV plots for various elements and 1+ sources.

EXPERIMENTAL AND OPERATIONAL ECR CHARGE BREEDERS WORLDWIDE

CERN-ISOLDE

The LPSC-PANTECHNIK PHOENIX charge breeder bought by CRLC Daresbury has been installed at ISOLDE as an experiment (IS397) just after the General Purpose Spectrometer. The purpose was to investigate the charge breeding process with 1+ beams produced by a realistic and well known ISOL facility. This experiment has been unfortunately stopped in 2008 due to insufficient manpower; however, it has produced a lot of interesting and/or preliminary results detailed in [1]. To summarize, stable and radioactive ions have been injected, the efficiency yields measured are within the range of the results obtained at LPSC, the charge breeding times are roughly 10 ms/charge which is consistent with the ones obtained at LPSC. The injection of a cocktail of radioactive beams delivered by one ion source, like: ^{142}Xe ($T_{1/2}$ = 1.22s) + ^{142}Cs ($T_{1/2}$ = 1.689s) + ^{142}Ba ($T_{1/2}$ = 10.6 min) + ^{142}La ($T_{1/2}$ = 91.1 min), show when analysing the gamma rays emitted by the n+ ions, that the xenon and the caesium ions are present with their own ΔV plots giving the evidence of the capture process explained in the previous paragraph. The injection of molecules has been performed (i.e., LaO^+) and it has been experimentally proven that these molecules are broken in the charge breeder (an efficiency of 3.5 % has been measured for the production of $^{139}La^{23+}$ with such process).

KEK – TRIAC

The KEK-TRIAC ECR charge breeder [2] is basically of the same kind as the LPSC one but with a higher injection magnetic field (1.6 T with respect to 1.2 T). The efficiency yields obtained on one charge, for a 18 GHz operation, are typically in the range 7-10% for gaseous elements, and 1-2 % for non-gaseous ones. A promising treatment method of the plasma chamber walls [3] has been proposed in order to decrease the background superimposed with the low level radioactive n+ beams. To understand the low efficiencies observed with non gaseous ions better, a very interesting study has been performed to measure the repartition of the remaining activity in the plasma chamber. It shows that the main part of the activity is isotropic at the extraction side of the source [4].

TRIUMF - ISAC

At TRIUMF, many experiments have been performed on a test stand with a modified LPSC-PANTECHNIK PHOENIX charge breeder including two steps deceleration and extraction systems. The source operates at 14.5 GHz, helium is used as buffer gas. For alkali ions the efficiencies obtained are nominal, for gaseous ones a bit lower than in other laboratories certainly due to the n+ transmission that was not fully optimized. The charge breeding times are much higher than the ones usually observed, it could be due to the use of helium as buffer gas [5]. n+ impurities have been significantly decreased by the setup of an additional electrostatic bender just after the magnetic separation [6]. The ECR charge breeder has been setup on the ISAC facility and a first radioactive ion beam (^{80}Rb) has been charge bred and accelerated [7]. Additional results will be presented at the 2009 International Conference on Ion Sources at Gatlinburg (Tennessee-USA).

ANL - CARIBU

In the frame of the ATLAS superconducting linear accelerator upgrade, the CARIBU project will permit the production and the charge breeding of neutron rich ions. The ECR charge breeder has been designed and setup by modifying an existing ECR ion source. Stable Rubidium and caesium 1+ ion beams have been successfully charge bred with good efficiencies. It has been recently shown that the vacuum improvement of the ECR charge breeder shifts the charge state distribution towards higher charge states and improves the efficiency yields. Let us note that very good results have been obtained on this project within a tight schedule. For more details see [8].

Texas A&M University

In the frame of the upgrade of the K500 superconducting cyclotron facility, in order to reaccelerate radioactive ion beams by 2011, an ECR charge breeder has been designed and built by Scientific Solutions (San Diego, USA) [9]. It is a ‘classical’ ECR charge breeder based on the AECR-U magnetic configuration [10], but innovative concepts have been applied with respect to other charge breeders: the 1+ beam injection is performed through a little hole, the microwaves are injected axially into an almost closed plasma chamber leading to an expected better HF coupling. A first plasma test has been performed into the device, charge breeding experiments are planned by the end of year 2009.

CHARGE BREEDING SIMULATION

Some theoretical work has been and is still performed with more or less sophisticated methods.

At the Laboratori Nazionali di Legnaro, M. Cavenago has developed a 3D model of the full process in the PHOENIX ECR charge breeder (axial and radial magnetic fields and ambipolar potential including pre-sheath and hexapolar distorsion). It is based on a 3D Monte Carlo simulation where random kicks, at each time step, simulate the collision from the background, including ionization and recombination models [11], [12].

At Institute of Particle and Nuclear Studies - KEK, S. C. Jeong has calculated the stopping efficiency [13] for a 10 eV incident Ar^+ ion beam injected into a uniform plasma of N^{2+} (n_i= 5x10^{11}/cm^3, T_i=1 eV), the model includes ion-ion collisions and magnetic field.

At FAR-TECH Inc., J. S. Kim is developing a suite of codes modelling successively the capture process, the physics of the ECR plasma leading to the charge state distribution, and then the extraction. Each code is based on a specific model like Monte Carlo simulations for capture, Fokker-Planck equation resolution for ECR physics and a specific mesh less method for the extraction (Particle In Cloud Of Points) [14, 15].

All these theoretical works can help to a better understanding of the processes and may permit to improve the characteristics of the method.

ECR CHARGE BREEDER IMPROVEMENTS

Efficiency Increase

The efficiency of a ECR charge breeder (CSB) for a specific charge state n+ is the ratio of the ionic current of this n+ ion beam relative to the 1+ beam current injected.

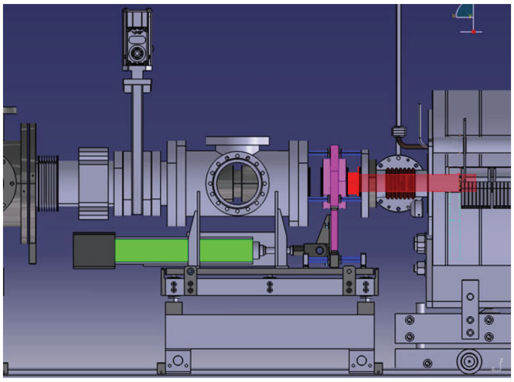

Figure 3: Mechanical setup for the movement of the grounded tube.

Depending on the tuning of the device, the charge state distribution can be peaked on different charge states. The efficiency, generally given on the most abundant charge state, is about 10 % for gaseous elements and a factor 3 less for metallic or alkali ones. Due to the electrostatic configuration of a CSB, with a grounded tube on the injection side, a proportion of the n+ ions are extracted in the backward direction. In order to confidently compare different CSB setups, one should first control the transmission of the n+ line (ratio of the sum of the n+ ion beam currents measured after the analysis device with respect to the total current extracted measured just after the extraction of the source). This must be performed as a preliminary stage of the characterization of a CSB, closing it at the injection side as a normal ECRIS (equipotential).

Deceleration of the 1+ ion beam is considered as a critical phase of the process that should lead to the optimal velocity of the 1+ ions entering the plasma in order to maximalize their capture. Even if theoretical studies have been performed in order to better understand this process, 3D magnetic field, decelerating electric field, plasma sheath, and final slowing down of the 1+ ions have to be included in such simulations, the ECR semi-empiric experimental method is often preferred for the optimization. The decelerating optics has been optimized by a two electrode system at TRIUMF and a multi electrode one has been setup at the KEK [16] charge breeder without obvious efficiency increase with respect to the direct deceleration taking place at the extremity of the grounded tube in the LPSC charge breeder. This tube, acting like an extraction system on the injection side and establishing the decelerating electric field, may be of crucial importance for the interface between the 1+ ion beam and the ECR plasma. Specifically, light ions (A<40), which have a higher speed than heavier ones in the CSB, are difficult to capture and their charge breeding efficiency is lower. The best result obtained at LPSC for sodium is an efficiency of 1.4 % for $^{23}Na^{6+}$ (using He gas) with a charge breeding time of 50 ms. In such conditions, it has been shown that the injection of NaO^{+}, available from the thermo ionization source producing the Na^{+} beam, permitted to immediately increase the efficiency to 1.9 %, showing that the plasma capture may effectively depend on the speed of the 1+ ions during deceleration. At LPSC, we have developed a system permitting to move the decelerating tube, like as shown in Fig. 3, with the idea that for light ions a higher deceleration distance would be needed.

The green part is a hydraulic jack moving the pink part guided by the blue tubes and supporting the grounded tube in red. The available range is 40 mm.

Simulations of the 1+ ion trajectories have been performed with SIMION for different positions. The simulation includes the full 3D magnetic field calculated with RADIA [17]. On Fig. 4, two sets of trajectories are shown. On the first one, the grounded tube ends in front of the HF power input, on the second one, the grounded tube is moved backward by a distance of 30 mm. The initial conditions for the 1+ ions have been reconstructed from the emittance measurement of a real rubidium beam extracted from a thermo-ionization source, supposing a Gaussian beam. The blue vertical line is the entrance of the hexapole, the green one is the axis of the HF wave guide. These plots show that when moving the tube, the focus point of the 1+ beam is moved along the axis and that the interface between the 1+ beam and the plasma can be drastically changed. This movement can be an additional tuning to the classical double Einzel lens optics and may help to adapt the 1+ beam to the plasma entrance, especially for light ions which are too fast to be efficiently captured.

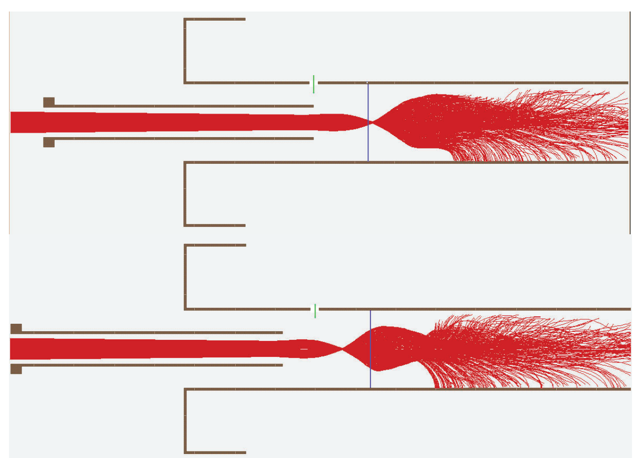

Figure 4: 1+ trajectories during deceleration for two positions of the grounded tube.

Suppression of the Grounded Tube

In a radioactive environment, especially when using high intensities, one should facilitate the maintenance of the system in order to limit potential contamination and personal exposition to radiations. Due to the configuration of the ECR charge breeder, with the grounded tube at the injection and the puller electrode at the extraction which are supported by the injection and extraction vacuum chambers, it is not easy to find the best mechanical design and an easy procedure to remove the booster from the beam line, unless the two tubes are motorized and axially moveable. The best solution at the injection would be to fix the grounded tube into the body of the booster itself, but due to the high voltage configuration, the ground has to be brought from the injection vacuum chamber. However, if the 1+ beam were able to enter the charge breeder without a grounded tube, it would be extremely interesting. Without the red grounded tube of Fig. 3, it would be possible to partially close the CSB. A disk (with a hole permitting the injection of the 1+ beam) can be inserted into the plasma chamber at the entrance of the hexapole, the present HF injection (perpendicular to the grounded tube) could be modified to an axially injection in a fully equipotential plasma chamber like in standard ECR ion sources (see Fig. 5).

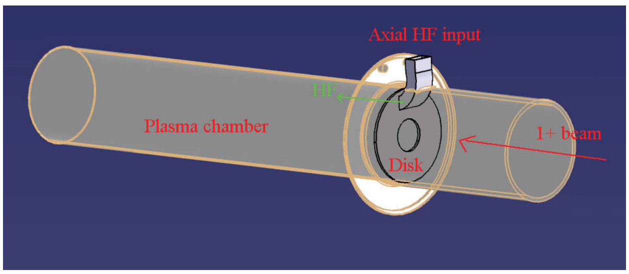

Figure 5: HF and 1+ beam injections in the plasma chamber without decelerating tube.

The benefits of such configuration are:

- The decrease of the HF leaks towards the injection side
- A more efficient coupling of the HF to the plasma
- The disappearance of the extraction of n+ beams towards the injection side

Depending on the optical characteristics of the 1+ beam entrance in the charge breeder, the charge breeding efficiency may be increased significantly. Simulations of the 1+ trajectories have been performed for such a configuration, and show that modifying the double Einzel lens tunings, thanks to the magnetic field, it is possible to enter the charge breeder despite the deceleration at its entrance. The mechanics of this concept is rather simple and is planned to be designed and tested at LPSC.

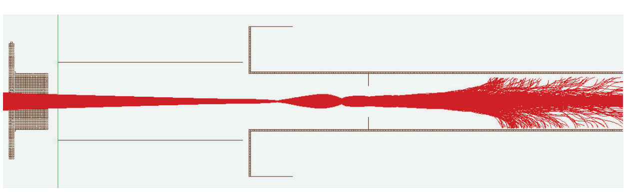

Figure 5: 1+ trajectories without decelerating tube.

Charge Breeding Time Decrease

Efficiency, when charge breeding radioactive ions, is not the only parameter to improve. Depending on the half-life of the isotope, a compromise should be found between the efficiency and the charge breeding time, in fact, each radioactive ion beam should have its specific tuning depending on its half-life. For example, we have published in [18] an efficiency of 5.5 % with a charge breeding time of 225 ms ('slow charge breeding'). Recently, we could find a different tuning, lowering the confinement magnetic field, leading to a lower efficiency (3.6 %) but with a much lower charge breeding time of 70 ms ('fast charge breeding'). If we apply these results to the charge breeding of ^{74}Rb ($T_{1/2} \approx 64.9$ ms), and ^{82}Rb ($T_{1/2} \approx 76$ sec), the final number of ions available for physics will be higher when using the fast charge breeding tuning (but lower efficiency) for the ^{74}Rb, when it will be the opposite for the ^{82}Rb. In order to further improve the method, the reproducibility and the parameters influencing the charge breeding time should be better theoretically and experimentally characterized.

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