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Recent improvements of the LPSC Charge Breeder

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Abstract. LPSC has developed the PHOENIX electron cyclotron resonance Charge Breeder since 2000. The performances have been improved over time acting on the 1+ and N+ beam optics, the base vacuum and the 1+ beam injection. A new objective is to update the booster design to enhance high charge state production and 1+ N+ efficiencies, reduce the co-extracted background beam and improve the ion source tunability. The first step, consisting in increasing the peak magnetic field at injection from 1.2 T to 1.6 T was implemented and significant improvement in 1+N+ efficiencies are reported: 12.9% of $^{23}Na^{8+}$, 24.2% of $^{40}Ar^{8+}$, 13.3% of $^{132}Xe^{26+}$ and 13% of $^{133}Cs^{26+}$. The next steps of the upgrade are presented: modification of the axial magnetic structure, significant increase of the plasma chamber radius (72 to 90 mm), plasma heating at 18 GHz (instead of 14 GHz), reduction of chemical elements composing the plasma chamber wall and the surrounding beam line.

CONTEXT

In Europe, two Isotope Separation On Line (ISOL) facilities are based on the use of a PHOENIX type ECR charge breeder (CB) : the SPIRAL1 upgrade is about to start in operation [1] at GANIL (Caen, France), the SPES facility is under construction [2] at LNL (Legnaro, Italy). In order to improve the CB operation in these two facilities, the LPSC continues the R&D on the PHOENIX charge breeder. In the context of beam production for physics, the reduction of the radioactive beams contamination is crucial, and is one of the main limitation for the use of ECR charge breeders, some recent work has shown that plasma instabilities may drastically increase this contamination [3]. Concerning the PHOENIX charge breeder, simulations have shown that the magnetic structure has some deficiencies that may affect the performances. The base vacuum is also a critical point and efforts have to be done on the mechanical structure to reduce it by, at least, one order of magnitude. Finally, the ease of tuning and the repeatability are also important factors.

PHOENIX CB INJECTION MAGNETIC FIELD INCREASE

The PHOENIX charge breeder was designed with a modular structure [4], this feature allows testing different configurations by modifying only certain parts at a time, reducing modification cost. The maximum magnetic field intensity on axis at the injection side that can be reached in its initial configuration was 1.2 T, whereas at 14.5 GHz a field of at least 1.6 T (3x B_{ECR}) would be necessary to ensure a good confinement according to the empirical laws of ECR sources [5]. In order to increase the field at injection, we have designed an additional soft iron plug under vacuum in lieu of the HF blocker electrode [6]. Its shape has been defined by magnetic simulations done with Radia [7] and Mathematica, the simulated axial magnetic field is shown **FIGURE 1 (a)**. Since this part was screening the waveguide port, a rectangular groove has been machined to route the microwaves to the plasma chamber cavity,

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redirecting them toward the plasma. To remove the steering effect and ensure a good 1+ beam injection [8, 9], additional grooves have been machined to obtain a symmetrical magnetic field design. Two additional grooves have also been machined on the external diameter surface to create a path for the support gas. The simulated longitudinal magnetic force has been calculated and is about 6500 N in static mode. Therefore, particular attention has been paid to the plug clamping. The additional plug has been machined at LPSC and mounted on the charge breeder in July 2016. In the PHOENIX CB, two movable soft iron rings surround the hexapole and can influence the magnetic field gradient and the ECR zone length when changing their longitudinal position. Until now, their positions were set by default at the extraction side following an experiment done in 2013 [8], a new optimization has been performed like described in the next section.

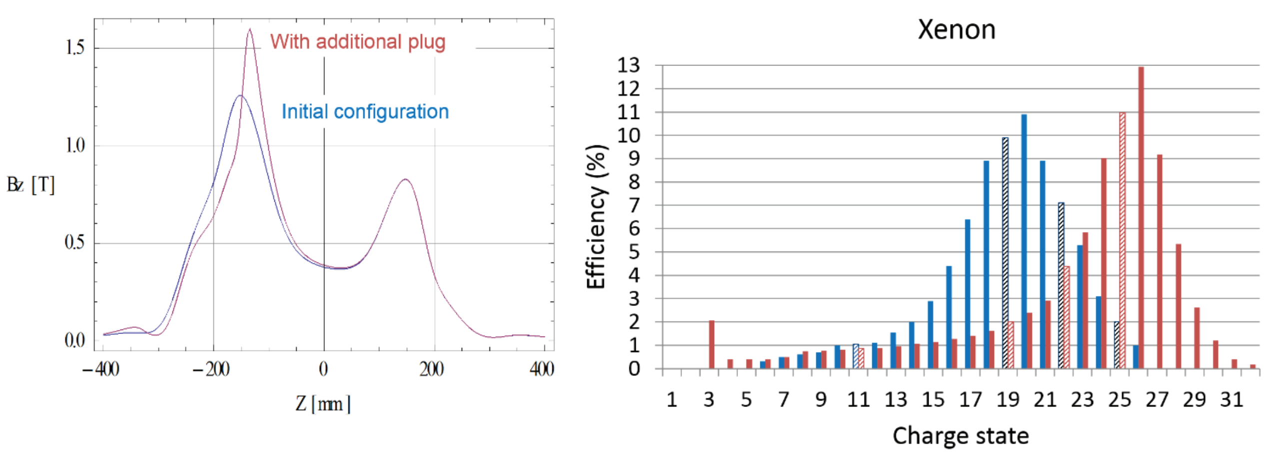
RESULTS AND DISCUSSION

The charge breeder was first run as a conventional ECRIS to produce oxygen high charge state beams. In this configuration, the O^{6+} beam intensity was optimized as a function of the soft iron rings positions. The optimum positions were found to be respectively -100 mm and 116 mm for the extraction and injection rings, from the center of the source to the center of the rings. A 182 eμA O^{6+} beam intensity was reached whereas a maximum of 120 eμA was obtained in the initial CB configuration. The modification of the magnetic configuration predominantly increased the ECR resonance zone length and the injection magnetic field gradient.

In the 1+N+ mode, the charge breeder was tested with the 1+ COMIC (COmpact MIcrowave and Coaxial) source [10] delivering successively Ar, Kr and Xe beams. Then the 1+ ion gun [8] was used to produce Na, K, Rb and Cs beams. For Xenon, the difference of the charge state spectra and efficiencies in both configurations is shown **FIGURE 1 (b)**. The rise times and the results obtained for all the studied beams are summarized in **TABLE 1**. The optimum microwave power was found in the same range i.e. 400 to 500 W. The rings positions were retuned at the beginning of the alkalis charge breeding experiments: the $^{39}K^{10+}$ efficiency was then increased from 9.9% to 11.7% by moving the injection and extraction rings at respectively -106 mm and 112 mm from the center.

For each element, a clear improvement is noticed, all efficiencies are now higher than 10%. The largest improvement concerns light ions with an increase from 3.8% of $^{23}Na^{7+}$ to 12.9% of $^{23}Na^{8+}$. For higher masses, a shift of the peak charge state to higher charge state is noticed, for example $^{132}Xe^{20+}$ to $^{132}Xe^{26+}$. These results have been obtained with a base vacuum at injection and extraction of about 3.10^{-7} mbar. It has been shown that the base vacuum is essential for high charge state charge breeding [8, 13, 14] and the measured efficiencies may be affected by this parameter. A base vacuum in the 10^{-8} mbar range is targeted in the future.

Concerning the rise time, no clear trend can be extracted from the results, the values are not directly correlated to the efficiencies. For Cesium, a very long rise time of 44.2 ms/q has been measured when getting the maximum efficiency, on the 26+ charge state.



(a) (b)

FIGURE 1. Initial configuration (blue) and with an additional magnetic plug installed under vacuum (red) : (a) Comparison of the axial magnetic field of the PHOENIX charge breeder; (b) Experimental charge breeding Xenon spectra in both configurations

TABLE 1. Comparison of the LPSC ECR charge breeder performances in the initial and additional plug configurations.

Species	Initial configuration: Efficiency (%)	Initial configuration: Rise time (ms/q)	Initial configuration: Total efficiency (%)	Additional plug configuration: Efficiency (%)	Additional plug configuration: Rise time (ms/q)	Additional plug configuration: Total efficiency (%)
$^{40}Ar^{8+}$	16.2	9.8	75	24.2	8.6	84
$^{40}Ar^{12+}$				14.2	28.4	78
$^{86}Kr^{15+}$				11	8.2	
$^{86}Kr^{18+}$				11.3	14.6	
$^{132}Xe^{20+}$	10.9	12	80			
$^{132}Xe^{26+}$				13.3	5.9	
$^{23}Na^{8+}$	3.3	8.6	19	12.9	12.9	65
$^{23}Na^{7+}$	3.8		19			
$^{39}K^{10+}$				11.7	8.2	73
$^{85}Rb^{17+}$	7.5	13.3	55			
$^{85}Rb^{19+}$				10.4	29	66
$^{133}Cs^{26+}$	11.4			13	44.2	75

A systematic recording of rise time and efficiency has been done for all the stable tunings of the charge breeder in order to find a faster regime. An efficiency of more than 7% has been measured with a rise time lower than 10 ms/q.

In order to understand if the efficiencies improvement were caused by an electron density increase, the efficiencies of 1+ and 2+ charge states have been compared to the initial charge breeder configuration results for Na and Rb. They represent the fractions of the 1+ beam that are not captured by the plasma and their yield can be linked directly to the plasma density and ionization rate [15, 16]. The values obtained in the two configurations have been found comparable which implies that the electron density has not been modified significantly.

In the future, additional experiments are planned to see if the plasma confinement was affected by the soft iron plug insertion. An ambitious experimental program will now be implemented until 2020 allowing full optimization of the magnetic field, even suitable for 18 GHz operation, lower base vacuum, and bigger volume of the plasma chamber.

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