Recent developments and results of the LPSC PHOENIX type ECR charge breeder

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Abstract. Four models of the PHOENIX ECR charge breeder have been manufactured for ISOL application. Two are currently under operation at TRIUMF (ISAC) and GANIL (SPIRAL 1) while the SPES one is being installed on the facility. The last model is set on the LPSC 1+N+ test bench where a R&D program is ongoing to improve its performances. The last modifications consisted in improving the beam line vacuum and the alignment. Commissioning experiments showed an improvement of the charge breeder performances for all the tested species. The global CB efficiency is close to 100% for Cs when correcting the measurements with the beam transmission. Na and K efficiencies have increased significantly to reach 18.7% for Na^{8+} and 22.7% for K^{9+}. In parallel, the charge breeder plasma was studied injecting short pulses of 1+ ions and using a zero-dimension model to estimate the plasma parameters. These experiments have provided a better understanding of the performance improvement. The last developments of the LPSC Charge Breeder together with the experimental results are presented.

1. Introduction

The PHOENIX type Electron Cyclotron Resonance Charge Breeder (ECRCB) has been developped at LPSC since the early 2000s [1]. Several versions have been manufactured for TRIUMF, ISOLDE, GANIL and SPES facilities. At LPSC, one model, installed on the 1+N+ test bench, is used to continue R&D and improve the charge breeding performances. One of the objectives is the reduction of the co-extracted contaminants, in the frame of the LNL-LPSC-GANIL collaboration [2] and on the basis of a previous agreement signed between LNL and LPSC in 2018. To perform the contaminants reduction experiments in the best possible conditions, the 1+N+ beam line was upgraded to improve the vacuum and the alignment of the optics and instruments.

The LPSC ECRCB is a 14.5GHz PHOENIX type ion source [2], with 3 coils to generate the axial magnetic field and a hexapole providing 0.8 T radial field on the poles at the plasma chamber wall surface, corresponding to a diameter of 72 mm. Two movable soft iron rings are set around the hexapole to act on the axial magnetic field gradients on the resonance surface. The objectives of the last major modifications were i) to improve the 1+ beam injection by making the injection soft iron plug symmetric and modifying the injection electrode shape [3, 4] and

ii) enhancing the plasma confinement by adding a soft iron plug under vacuum at injection to increase the axial magnetic field and tuning the position of the two soft iron rings surrounding the hexapole [5]. These modifications allowed to gradually improve the ECRCB single Charge State (CS) and the total efficiencies, while keeping the rise time short.

The LPSC PHOENIX ECRCB is qualified on the 1+N+ test bench [6], which is composed of a beam line that generates the 1+ beam to be injected into the ECRCB and another one that analyses the beams extracted from the charge breeder. Each beam line is equipped with a mass spectrometer, beam optics and diagnostics (Faraday cup (FC), horizontal and vertical Allison type emittance scanners) after the mass spectrometer. Two types of 1+ sources are used to produce the 1+ beams i) the COMIC source for gaseous elements and ii) the surface ionisation ion gun for alkali species. An electrostatic deflector is placed in front of the 1+ spectrometer to pulse the 1+ beam and measure the background for the efficiency calculations. On the N+ beam line, a removable FC is mounted between an Einzel lens and the mass spectrometer, to measure the total extracted beam intensity. The test bench configuration allows operation at 20kV maximum source potential. A high voltage supply is used to polarize the 1+ source. Another precision power supply sets the voltage difference (ΔV) between the ECRCB and the 1+ source.

In parallel to the charge breeder qualification experiments, the 1+N+ test bench was used for plasma studies [6, 7, 8]. Recently, a new method, based on short pulse 1+ injection of metal ions, was developed to estimate the ionisation, charge exchange and confinement times together with the plasma energy content and triple product [9]. This Consecutive Transient (CT) method, was applied to the LPSC ECRCB, injecting K^+ ions into an He plasma.

2. 1+N+ test bench upgrade

To prepare the contaminants reduction experiments, the 1+N+ test bench was upgraded in the period of 2018-2019, as described in detail elsewhere [2]. In summary, all the vacuum chambers were modified or replaced to be compatible with Ultra High Vacuum (UHV) techniques. The vacuum pumping configuration was also deeply modified and the turbo pumps were either refurbished by the manufacturer or replaced by new ones. The FCs were replaced together with the double Einzel lens at the ECRCB injection and the Einzel lense at the extraction. The emittance scanners were enhanced for UHV environment. Modifications were also done to the mass spectrometers to create view ports on each axis for the alignment of the beam line devices. Following the assembly, a vacuum leak detection was systematically performed on each section. After the upgrade, the vacuum level was measured to be between 3 to 6×10^{-8} mbar, which is one order of magnitude better than previously.

After this upgrade, qualification experiments were carried out to validate the assembly and check the effect on the charge breeder performances.

3. Commissioning experiments

Following the extraction Einzel lens replacement and the alignment, the N+ beam line transmission was checked. The charge breeder was operated with a H_2 plasma in a configuration optimized for potassium (K) charge breeding. The transport efficiency of the N+ beam line was measured to be 83% by comparing the total extracted N+ current and the sum of all mass analysed N+ ions.

Na, K, Rb and Cs were chosen for the commissioning of the PHOENIX ECR CB in the new 1+N+ test bench configuration. The source (microwave power, coils currents, support gas ...) and beam optics parameters were optimized to maximize the 1+N+ efficiency yield for each species. Table 1 compares the former (2017) and new (2020) results and tunings. The ECRCB efficiency Charge State Distributions (CSD) are plotted in Fig. 1.

Table 1: The former (2017) and new (2020) performances (optimum charge state, efficiency, total efficiency and rise time) and tuning (support gas, injection - minimum - extraction axial magnetic field, microwave power and pressure at injection) of the LPSC ECRCB obtained for Na, K, Rb and Cs injected species. The 1+ (fly-through ions) efficiency is not included for the total efficiency calculation.

	Na 2017	Na 2020	K 2017	K 2020	Rb 2017	Rb 2020	Cs 2017	Cs 2020
Charge state	8+	8+	10+	9+	19+	18+	26+	26+
Eff. (%)	12.9	18.7	11.7	22.7	10.4	11.3	13.0	14.1
Total Eff. (%)	54.1	59.9	63.4	78.7	63.9	85.08	71.9	91.8
Rise time (ms/q)	12.9	26.8	8.2	13.5	29	16.7	44.2	12.8
Support gas	He	He	He	H_2	He	He	O_2	He
Binj (T)	1.57	1.56	1.57	1.58	1.57	1.58	1.57	1.56
Bmin (T)	0.47	0.46	0.44	0.45	0.45	0.46	0.46	0.47
Bext (T)	0.83	0.84	0.83	0.83	0.88	0.85	0.86	0.84
MW power (W)	486	770	290	520	480	700	500	670
Pinj ($\times 10^{-8}$ mbar)	46	5	44	14	40	5	52	4

4. Discussion

An increase of the total efficiency can be noticed for all the species and could be explained by a better capture (we see a decrease of the 1+ and 2+ charge state efficiencies in Fig. 1) and a better transport in the beam lines. The Cs total efficiency is 91.8%. Taking into account the N+ beam line transmission, the total capture efficiency is in fact very high and close to 100% for Cs. For Na and K, certain high charge states (Na^{10+}, $Na^{11+}$and K^{13+}) cannot be measured because the resolving power of the N+ spectrometer does not allow a good separation from contaminant beams. Therefore, the given total capture is underestimated for Na and K. For every species, an increase of the efficiency for the optimum charge state is noticed, the CSD efficiency being shifted toward lower charge states for K and Rb as clearly visible in Fig. 1. The rise times are longer for Na and K with respect to the former measurements. The new results were all obtained at lower pressure measured at injection and at higher microwave power.

For K, a great improvement is obtained with an efficiency increasing from 11.7% for K^{10+} to 22.7% for K^{9+}. After the upgrade, the first experiments were carried out with the same support gas (He) and the obtained performances were close to the former ones. Changing the support gas to H_2 seems to explain the increased efficiency in these measurements. To better understand this, short pulse measurements were done with H_2 and He plasmas, the tuning being optimized for K^{10+} and K^{9+}, respectively. The CT method was applied to the measured N+ responses to compare the plasma parameters. This study is described in detail elsewhere [10]. Table 2 summarizes the tunings and Fig. 2 compares the efficiency CSDs obtained during the short pulse experiments. The same trend is observed in Fig. 2 as in Fig. 1 b. The efficiency CSD modification and the high increase of K^{9+} efficiency can be explained by a change of the ionisation, charge exchange and confinement times and by an optimisation on K^{9+} which corresponds to a closed shell configuration [10]. The production of K^{9+} beam is favoured by a decrease of the charge exchange time for high charge states, a decrease of the ionisation time for the low charge states and a decrease of the K^{9+} confinement time. The ionisation time is inversely proportional to the electron density and to the ionisation rate coefficient [9]. The charge exchange time is inversely proportional to the neutral density and to the charge exchange rate coefficient.

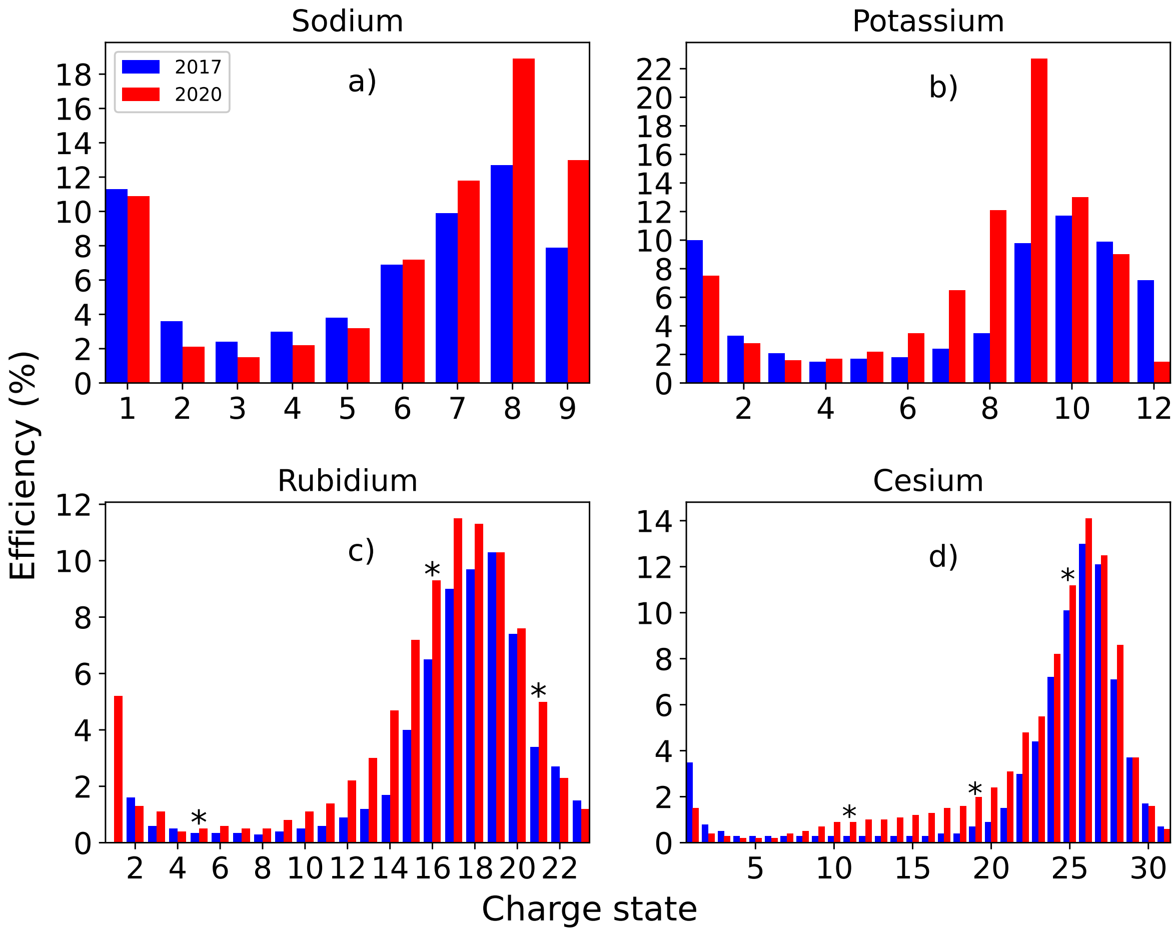

Figure 1: a) Na, b) K, c) Rb, d) Cs efficiency CSD comparison between former (blue) and new (red) results. CS efficiencies marked with * were extrapolated from adjacent charge states.

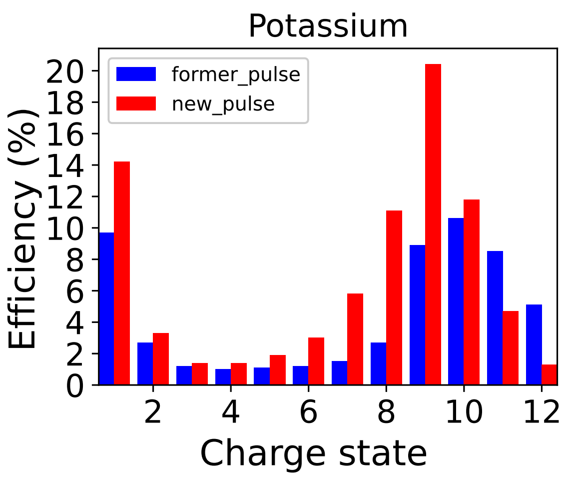

Figure 2: K efficiency CSD comparison for the pulse mode experiments with H_2 (red) and He (blue) support gas.

	K with He	K with H_2
Charge state	10+	9+
Eff. (%)	10.6	20.4
Total Eff. (%)	44.5	66.1
Rise time (ms/q)	13.2	14.6
Support gas	He	H_2
Binj (T)	1.58	1.57
Bmin (T)	0.45	0.44
Bext (T)	0.83	0.84
MW power (W)	500	530
Pinj ($\times 10^{-8}$ mbar)	9	13.5

Table 2: The performances and tuning of the LPSC ECRCB for the pulse mode experiments with K obtained with He and H_2 support gas. The 1+ efficiency is not included for the total efficiency calculation.

In the new configuration, the electron density and the plasma energy content are found to be higher, which could in part be explained by a slightly higher microwave power. A higher neutral density and a higher relative speed between the ions and neutrals could explain the charge exchange time decrease. The higher relative speed between the ions and the neutrals is very likely due to the use of H_2 as support gas, instead of heavier He.

Regarding the charge breeding times, this value also depends on the plasma characteristic times (ionisation, charge exchange and confinement) but also on the different steps of ionisation and charge exchange experienced by the ions before their extraction; the confinement time represents a cumulative value from the charge state 1+ [10]. The rise time increase, from 9 to 13.5 ms/q, observed along with the decrease of most of the characteristic times would be due to a larger number of ionisation and charge exchange steps before extraction.

For Na, Rb and Cs, the modification of the ECRCB tuning led to different efficiency CSD and rise times. Na^{8+} efficiency also greatly increased from 12.9% to 18.7%. Short pulse measurements and CT method analysis for each species could help understanding the evolution of the performances, which is difficult based only on the efficiency CSD and rise time measurements.

5. Conclusion

The qualification experiments after the 1+N+ beam line upgrade showed an increase of the total efficiency and an increase of the efficiency per charge state for all the studied species. In addition to the alignment and vacuum improvements, some parameters of the ECRCB, such as the support gas species, microwave power and coil currents were optimized to obtain these results. A shift to lower charge states in the efficiency CSD was measured for K and Rb together with longer rise times for Na and K. A high efficiency increase was obtained for Na^{8+} and K^{9+}, this latter being now greater than 20%. For K, the short pulse measurements and the CT method allowed to better understand the influence of the support gas change on the plasma parameters and on the change of the efficiency CSD. The ECR plasma studies will continue, in particular based on the use of the CT method, to estimate the influence of the source parameters on the charge breeding performances. The next step of the LPSC PHOENIX ECRCB R&D program will consist in optimizing the magnetic structure and increasing the plasma chamber volume.

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