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CHARGE BREEDING TIME STUDIES WITH SHORT PULSE BEAM INJECTION

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Abstract

Investigations on the Charge Breeding (CB) time have been done with the PHOENIX ECR Charge Breeder. The traditional measurement method consists of generating a 1+ ion beam rising front and measuring the time to reach 90% of the final N+ ion beam intensity. In order to study the possible self-consistent effects of the accumulation of injected ions in the plasma and to better understand the 1+N+ process, short Rb^{+} pulses were injected and the time resolved N+ beam responses were measured. The new short pulse CB time method and the experimental results are presented. The effects of several parameters such as the amplitude and the width of the pulse are studied. Calculation methods are proposed for the efficiency and CB time in pulse mode. Compared with the traditional values, the efficiencies are found to be equivalent and CB time shorter by -10% in the case of short pulse injection; showing that the accumulation effect is low in the studied configuration.

The short pulse method was used to study the influence of B_{min} on the plasma behaviour. An increase of B_{min} leads to an increase of the Rb^{19+} efficiency that is found to be caused by a higher ion confinement time. The results are also used to estimate the 1+N+ efficiencies in the case of Radioactive Ion Beam (RIB) species, showing how the RIB efficiency is reduced as a function of the half-life and charge state.

INTRODUCTION

ECR charge breeders (ECR CB) are used in ISOL facilities to increase the charge state of a Radioactive Ion Beam (RIB) from 1+ to N+. They operate in continuous mode and can accept the injection of high particle flux, more than 10^{13} pps. They are mainly characterized by 3 parameters.

The first one is the Charge Breeding Time τ_{CB} of the charge state of interest N. It is traditionally measured by switching ON the injected beam and measuring the 90 % rise time of the N+ response [1-4]. In order to improve the signal over noise ratio, the time response is averaged over several measurements, the 1+ beam being pulsed ON / OFF at low frequency (about 0.5 Hz) with a duty cycle of 50%. This method is called here Long Pulse Injection (LPI). Figure 1 illustrates the principle of the τ_{CB} measurement with LPI.

The second is the ionization efficiency. It is the ratio between the extracted particle current of charge state N and the injected particle current. Using the LPI, the N+ particle current is determined taking into account the background level (1+ beam OFF).

The third parameter is the contaminant rate defined as the percentage of contaminants included into the N+ response measurement. It depends on the charge breeder cleanness, the RIB production yield and the resolution of the downstream spectrometer. In the case of low RIB production yield (10^2 to 10^6 pps) and low spectrometer resolution (ΔM/M of about 1/200), the beam of interest may represent a fraction that can be very small (some %), which has dramatic consequences for the physics experiments [5].

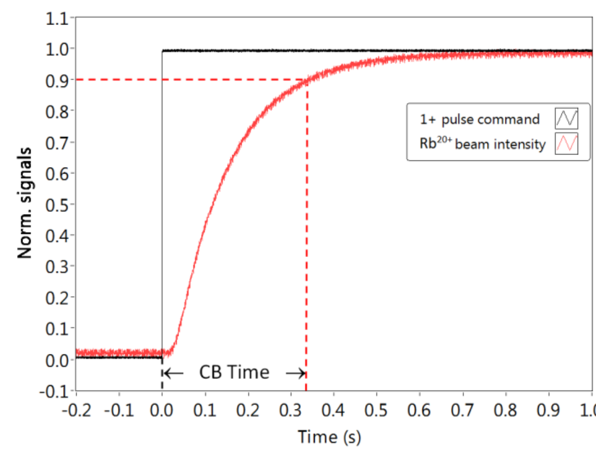

Figure 1: Principle of the traditional τ_{CB} measurement. The dashed lines are the references of the pulse start (black) and 90% level of the Rb^{20+} beam intensity (red).

Motivations for Short Pulse Injection

Previous experiments have shown that the 1+ beam injection can i) modify the CB plasma Charge State Distribution (CSD) [6] and ii) trigger instabilities in a time scale comparable to the CB Time [7].

In addition, the LPI method can appear to be ambigu-ous because the rise of the N+ response is simultaneously affected by the injection and capture of the 1+ ions and the extraction of the N+ ions.
Finally, large discrepancies were reported in the τ_{CB} measurements [8] with only small variations of CB parameters.

For these reasons it was proposed to measure τ_{CB} inject-ing the 1+ beam with very short pulses [9]. This method is called here the Short Pulse Injection (SPI).

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EXPERIMENTAL SETUP

The SPI was tested with the PHOENIX Charge Breeder on the LPSC 1+N+ test bench. The 1+ ion beam was generated by an ion gun source [10] and the pulse timing system was based on a signal generator to ensure a pre-cise pulse duration and triggering.

The charge breeder wasn't in the configuration offering the best efficiencies [11]. At injection it was equipped with a large diameter decelerating electrode, the HF blocker electrode [12] while the additional soft iron plug that increases the injection axial magnetic field peak was removed [11]. In this configuration, the maximum axial magnetic field was 1.2 T at injection (injection coil current of 1200 A), and 0.9 T at extraction (extraction coil current of 800 A). The charge breeder was equipped with a permanent magnet hexapole generating a 0.8 T radial magnetic field at plasma chamber wall.

Similar to the LPI, the 1+ and N+ beam intensities were measured with 1+ and N+ mass analysed Faraday cups.

RESULTS

N+ Response

The SPI method was tested injecting a Rb^{+} beam into an He plasma. The CB was configured as follows. The microwave power level was 510 W. The injection, minimum and extraction axial magnetic field strengths were simulated to be 1.19 T, 0.44 T and 0.84 T, respectively (injection, median and extraction coils were set to 1185 A, 320 A and 726 A respectively). The pulse duration was reduced until the temporal N+ response becomes constant in shape. Figure 2 shows the Rb^{19+} time response corre-sponding to a 2.5 ms SPI together with the integral of this signal i.e. the cumulative distribution function.

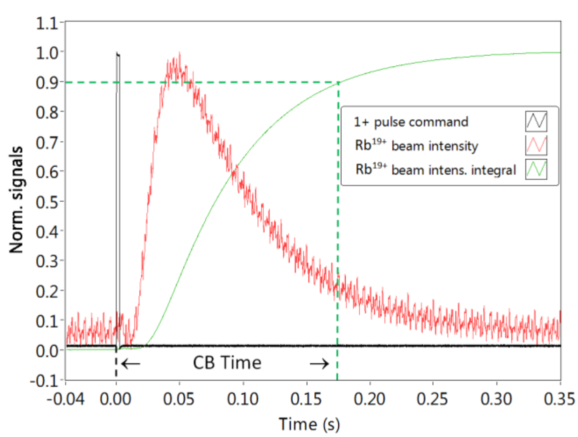

Figure 2: Rb19+ response to a 2.5 ms injected pulse and the corresponding integral function. The dashed lines are the references of the pulse start (black) and 90% level of the Rb19+ integral function (green).

With the SPI method, the efficiency is defined as the ratio between the number of injected particles over the number of extracted particles. It can be calculated by integrating both the 1+ and N+ signals.

The CB Time is defined as the time between the rise front of the 1+ pulse and the necessary time to extract 90% of the N+ ions (Fig. 2).

To compare the values, the Rb^{19+} efficiency and CB time were measured with both the LPI and SPI methods. The efficiency was found to be the same with both methods at 4.8 %. The CB Time with SPI (178 ms) was found to be shorter than with LPI (191 ms) by -10%, which means that the accumulation effect of the 1+ ions injection into the CB plasma is low in this configuration. Moreover, it can be seen that the N+ pulse is strongly asymmetric, which implies that a large fraction of the ions are produced and extracted at significantly shorter time.

Effect of the 1+ beam intensity

The influence of the 1+ beam intensity on the N+ response was studied in the range of 177 – 644 nA, the other experimental conditions (CB tuning, pulse duration…) being unchanged with respect to the previous measurement. The normalized N+ responses corresponding to several 1+ beam intensities are compared in Fig. 3.

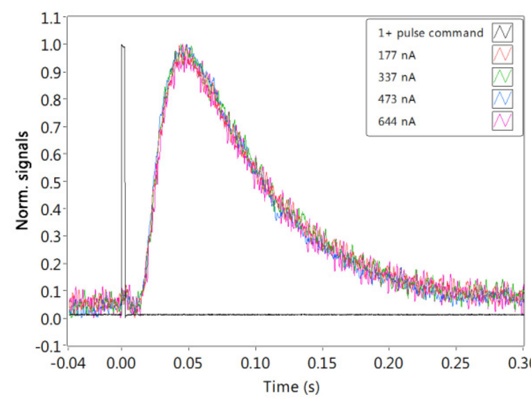

Figure 3: 1+ injection pulse and Rb^{19+} normalized signal responses to several 1+ beam pulse intensities.

In the studied beam intensity range, the N+ responses are the same, which means that the perturbation caused by the 1+ beam injection on the CB plasma is relatively small.

Influence of the N+ Charge State

Keeping the same configuration and with the same pulse duration, several N+ responses were measured for Rb charge states between 4+ and 19+. The time responses are plotted in Fig 4. These measurements illustrate the step by step ionisation process existing in ECR ion sources plasmas.

Similar results were obtained by several laboratories injecting short pulses of neutrals [13-16]. The goal of these earlier experiments was to study the plasma behaviour and estimate some plasma parameters (ion temperature and density, electron temperature and density…) by using 0 dimension model simulations.

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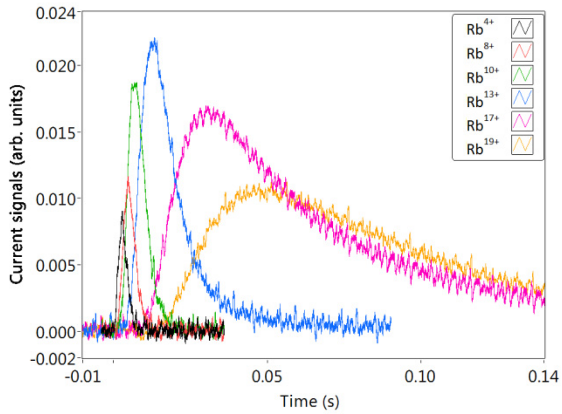

Figure 4: Rb^{4+}, Rb^{8+}, Rb^{10+} Rb^{13+}, Rb^{17+} and Rb^{19+} beam intensity responses to a 2.5 ms injection pulse.

Plasma Behaviour Study Example with B_{min}

Similar to the neutral injection, the SPI can be used to study the CB plasma behavior. As an example, this was done by varying B_{min}. During the experiments, it was noticed that a linear variation of B_{min} in the range 0.432 - 0.444 T induced a linear variation of the Rb^{19+} efficiency. N+ responses were measured for several intermediate B_{min} values, see Fig. 5.

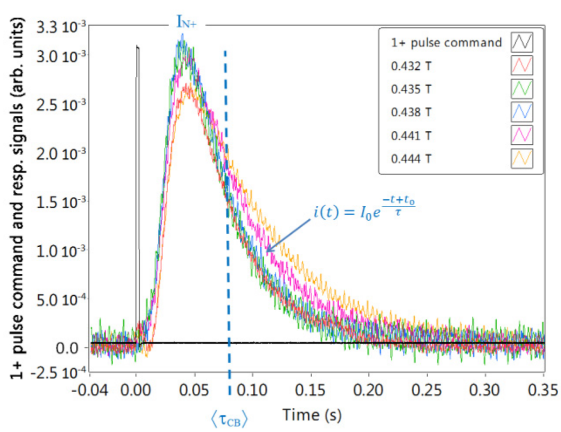

Figure 5: Rb^{19+} signal responses at several median coil currents.

From the N+ response, some parameters can be de-fined:

i) I_{N+} which is the beam intensity peak value ii) $<\tau_{CB}>$ which is the time average of the N+ response and iii) τ which is a time constant when fitting the N+ response decay with a function of the form $i(t) = I_0 e^{-t+t0/\tau}$. Figure 6 shows the relative evolution of these parameters together with the LPI and SPI efficiencies as a function of B_{min}.

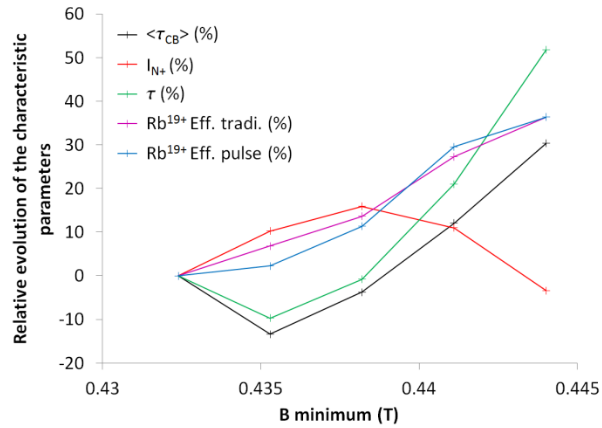

Figure 6: Variation of the time characteristics, maximum current and Rb^{19+} efficiency as a function of the median axial field.

In the studied range, the LPI and SPI efficiencies are the same. I_{N+} passes by a maximum value at the middle of the range (+16% at B_{min} = 0.438 T) when $<\tau_{CB}>$ and τ first experience a decrease of about 10% before substan-tial increase of respectively 30% and 50%. Since the decay time can be considered to be directly related to the confinement time of the high charge state ions [17], the result implies that at stronger B-minimum the ion con-finement is improved.

IMPLICATION ON THE RIB CB EFFI-CIENCY

Efficiency as a Function of the Half-life

For stable elements, the SPI N+ response can be pro-vided during preliminary RIB experiments done with the stable isotope or by earlier CB characterization measure-ments. If the RIB population decay is considered to be of the form of $N(t) = N_0 e^{-t/\tau_1}$ with $T_{1/2} = \tau_1 * \ln(2)$ and $T_{1/2}$ being the half-life, it becomes possible to estimate the actual RIB efficiency with the stable SPI N+ response more accurately than with the LPI method. This was done for Rb isotopes from ^{93}Rb ($T_{1/2}$ 5840 ms) to ^{99}Rb ($T_{1/2}$ 50.3 ms), using the $^{85}Rb^{19+}$ SPI N+ response shown above. Figure 7 shows the evolution of the Rb^{19+} RIB efficiency over Rb^{19+} stable efficiency ratio as a function of $T_{1/2}$.

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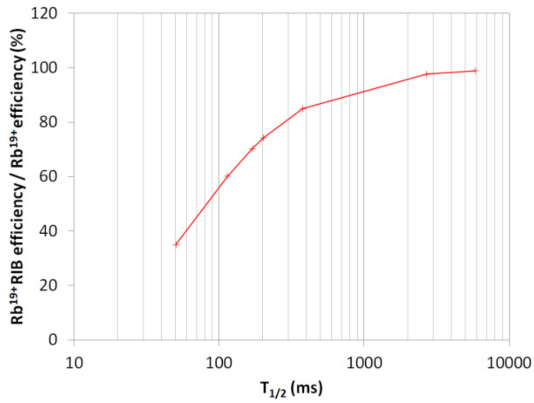

Figure 7: Evolution of the Rb^{19+} RIB efficiency over Rb^{19+} stable efficiency ratio as a function of $T_{1/2}$.

Down to a half-life of about 380ms, corresponding to $^{95}Rb^{19+}$, the reduction of efficiency is limited to about 15% but at shorter half-lives the CB efficiency starts decreasing rapidly for this charge state. An efficiency reduction of 65% is estimated for $^{99}Rb^{19+}$ in this case.

Efficiency As a Function of the Charge State

N+ responses are different depending on the charge state (Fig. 4). The RIB efficiency estimation can be done for each charge state like done in the previous section for Rb^{19+}. Figure 8 shows the estimated efficiency CSD of the radioactive Rb isotopes between ^{93}Rb and ^{99}Rb together with the stable ^{85}Rb one.

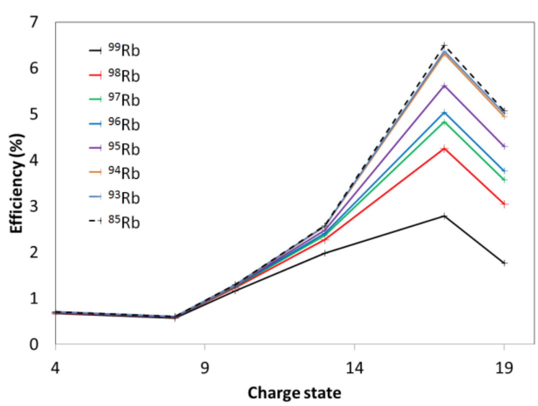

Figure 8: Rb isotope efficiencies as a function of the charge state.

From Fig. 8, it can be seen that the high charge state RIB ions are more affected by decay losses than lower charge state ones leading to a shift of the CSD toward lower charge state. It is clearly visible by plotting the average charge state as a function of $T_{1/2}$, see Fig. 9.

In the presented configuration, the mean charge state shift is of -1.6 when comparing ^{99}Rb with ^{85}Rb.

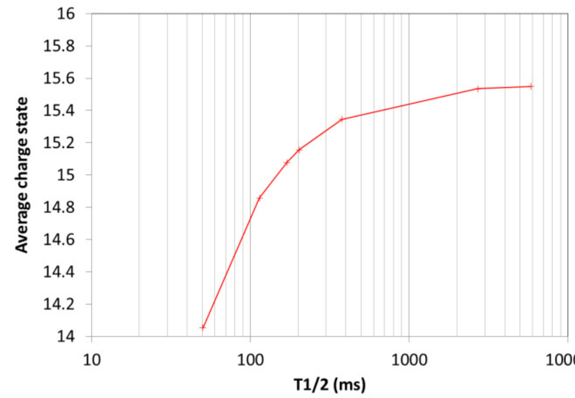

Figure 9: Evolution of the average ion beam charge state as a function of the half-life.

CONCLUSION

Using the SPI method, the temporal distribution of the N+ beam extracted from the CB was measured. The efficiencies in SPI and LPI were compared and found equivalent. The CB Time with SPI was found shorter than with LPI by -10%.

SPI N+ responses provide information on the plasma behavior and this method will be of interest to study the influence of the different CB parameters on the efficiency and charge breeding time and more generally on the ECR plasma behavior.

Finally, the N+ response curves will allow more precise estimation of RIB efficiency as a function of the half-life and charge state which is crucial for ISOL facilities. The method of predicting the RIB efficiencies could be vali-dated by RIB experiments.

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