ION CHARGE STATE INCREASE 1+ → N+ FOR THE ACCELERATION OF ALKALI AND METALLIC RADIOACTIVE IONS

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Abstract

The forward injection of a 1+ beam into an Electron Cyclotron Resonance Ion Source (ECRIS) is an efficient way to obtain n+ radioactive ion beams suitable for particle acceleration.

Two different methods have been developed depending on the type of accelerator (c.w. or pulsed one): the 1+ → n+ charge breeder and the Electron Cyclotron Resonance Ion Trap (ECRIT) breeder buncher.

New results are given for the efficiency yield of the 1+ → n+ method (3.5% for $Zn^{1+} \rightarrow Zn^{9+}$, 4.2 % for $Pb^{1+} \rightarrow Pb^{24+}$, 5% for $Rb^{1+} \rightarrow Rb^{15+}$). Different ion sources have been used to study the variation of the efficiency as a function of the energy of the 1+ primary beam. Charge state distributions are especially measured for Pb and Rb ions.

A new mode of operation, the Electron Cyclotron Resonance Ion Trap (ECRIT) breeder/buncher, permitting to trap and bunch the n+ ion beam is demonstrated and experimentally verified. The injection of a 400 nAe Rb^{1+} ion beam leads to a 11.5 µAe peak current of the Rb^{15+} ion beam extracted during the first ms. The temporal evolution of the cumulated particle transformation and trapping efficiency is measured in the case of Rb^{15+}.

The impact of these results on the ability to produce valuable accelerated radioactive ion beams is discussed.

1 INTRODUCTION

The production of high energy Radioactive Ion Beams [1] require the ability of transforming, with the best efficiency, 1+ ions into n+ ions which are suitable for acceleration.

Depending on the type of accelerator (cyclotron, linac, synchrotron) c.w. or pulsed n+ ion beams have to be produced. In this latter case the bunching of the n+ beams is of great interest in order to lose as few radioactive ions as possible.

We developed two methods which permit to expect high n+ ion production efficiencies:

- the 1+ → n+ charge breeder [2-4]
- the ECRIT breeder buncher [5-6]

2 THE 1+ → N+ CHARGE BREEDER

We developed a DC charge breeder method (1+ → n+) for radioactive ion beams (RIB) based on the injection of a 1+ ion beam into an n+ Electron Cyclotron Resonance Ion Source (ECRIS) [7], MINIMAFIOS-10GHz. The 1+ ions are captured by the plasma and are consequently multi-ionized.

The breeder efficiency for one given charge is defined as:

$$\eta = \frac{\text{number of (n+) ions extracted/sec}}{\text{number of (1+) ions injected/sec}}$$

2.1 Efficiency yield

Different 1+ ion sources (ECRIS, hollow cathode, thermoionisation) have been used to produce rare gas, metallic and alkali ions, the n+ charge states given in the Table 1 are those which have been optimised in the MINIMAFIOS source.

Table 1: Breeder efficiencies for various ions

1+ Ion	n+ ion	η
Kr	Kr^{9+}	9.2 %
Ar	Ar^{8+}	9%
Zn	Zn^{9+}	3.5%
Pb	Pb^{24+}	4.2%
Rb	Rb^{15+}	5%

2.2 Charge spectra

Charge spectra obtained by the 1+ → n+ method have been measured in the case of Pb and Rb.

For example in the case of an incident beam intensity of 65nA of Pb^{1+} the n+ beam has been tuned on the 24+ charge state (Fig.1), in the case of a 135 nA Rb^{1+} ion beam, we optimised the 15+ charge state (Fig.2). Let us notice that the overall particle efficiency for all the spectrum is about 30 % for Pb and 35% for Rb, these values are very close to the 43 % efficiency when feeding the MINIMAFIOS ECRIS with gas. These charge distributions are one of the best we could obtain with MINIMAFIOS, different optimisations have been done on lower charge states, higher charge states could be obtained in a high performance ion source.

2.3 Energy acceptance

The 1+ sources we used have different energy spreads δV (i.e. ≈ 0.1 eV for the thermoionic one, of the order of a few eV for the ECRIS). The 1+ and the n+ sources are brought to a main potential (i.e.: 18 kV), an additional voltage supply permits to slightly vary the potential of the n+ source (i.e.: +/- 60V) in order to optimise the capture of the 1+ ions by the plasma of the n+ source. The potential difference between the two sources is called ΔV.

The relative efficiency of the 1+ $\rightarrow$ n+ process is a function of the ΔV (Fig.3). One can note that the width of the curves is almost the same ≈ 10 eV. Due to the fact that the global particle efficiencies are of the same order (i.e. 30-35%), one can consider that the energy acceptance of the process is independent of the 1+ sources we used.

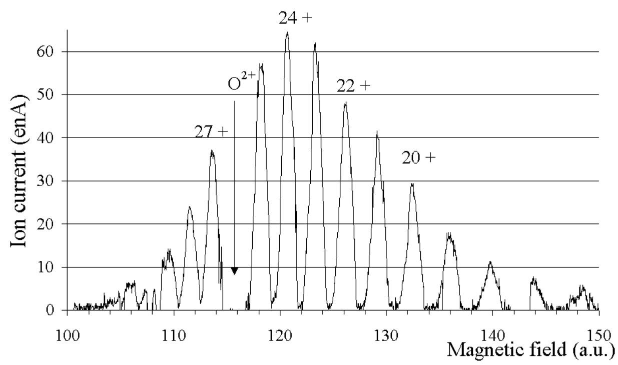

Figure 1: Pb^{n+} spectrum for a 65 nAe Pb^{1+} injected beam

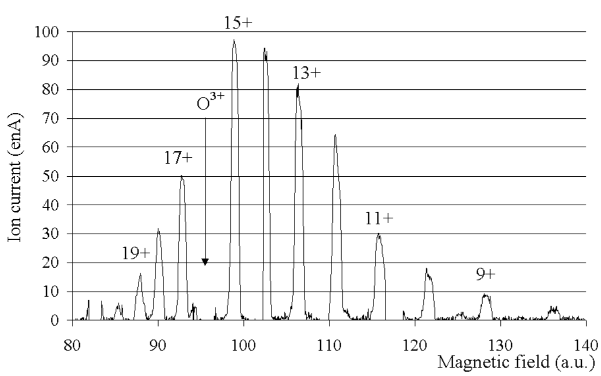

Figure 2:Rb^{n+} spectrum for a 135 nAe Rb^{1+} injected beam

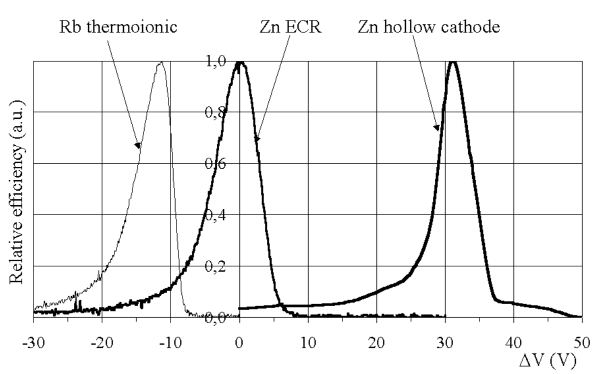

Figure 3: Variation of the relative efficiency versus ΔV

3 THE ECRIT BREEDER/BUNCHER

3.1 The ECRIS compromise

In order to produce more intense n+ beams, the ECRIS tuning always requires a compromise between ion confinement and ion extraction. To obtain the higher charge states, the ion confinement time must be increased (because of the step by step ionisation process between the ions and the electrons of the plasma). On the opposite, the decrease of the ion confinement increases the ion intensities extracted from the ECRIS. This compromise is not applied in the ECRIT mode.

3.2 Characteristics of the ECRIT mode

The ECRIT mode consists of optimising the trapping of the 1+ ions. During the trapping time, n+ ions are created by multi-ionisation and are trapped too. They are therefore ready to be extracted using the afterglow process [8].

In this way, it is possible to independently accumulate ions in the source and extract them in a pulsed mode, like in the 1+ injection systems presently used in slow injection EBIS. This extraction must be very fast to obtain as many particles as possible in a short pulse (of the order of a few ms), a process which can be achieved by a sudden increase of the plasma mirror loss cone obtained by the abrupt cancellation of the R.F. power (afterglow process).

3.3 Experimental procedure of the ECRIT mode

A pulsed Rb^{1+} ion beam of intensity 550 enA is injected into the n+ source during the time t_{inj}. The RF power, which is pulsed too, is cancelled after a Δt time following the end of the Rb^{1+} pulse. During Δt, the Rb^{1+} ions are multi-ionised and trapped in the plasma, and then, they are brutally extracted by the cancellation of the RF power (Fig. 4).

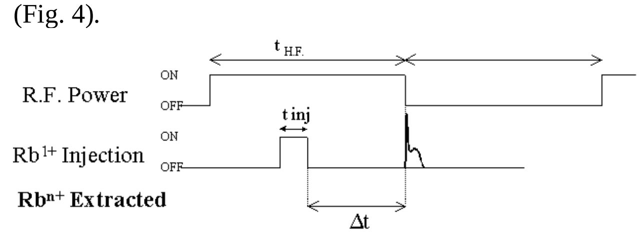

Figure 4: Time structure of the ECRIT mode

3.4 Trapping time of the ECRIT

Let us assume that the time to reach the charge states equilibrium (~ 20ms) is significantly shorter than the confinement time(> 300 ms). So we consider that the Rb^{1+} ions injected in the ECRIT are almost instantaneously transformed in Rb^{15+}. The evolution of the number of Rb^{15+} ions in the plasma, as a function of the time between the end of the Rb^{1+} injection and the afterglow, $n_{Rb15+}(t)$, is given by the equation :

$$n_{Rb15+}(t) = Ae^{-\frac{t}{\tau_{conf}}} \qquad (1)$$

where τ_{conf} is the Rb^{15+} confinement time in the plasma and A an experimentally determined constant.

A very good fit between the experimental values and the equation (1) is obtained with an average confinement time of τ_{conf}=520 ms (Fig.5) and we found that the number of Rb^{15+} ions extracted is :

$$n_{Rb15+ext}(t) = 9.3\times10^{8}\, e^{-\frac{t}{520}} \qquad (2)$$

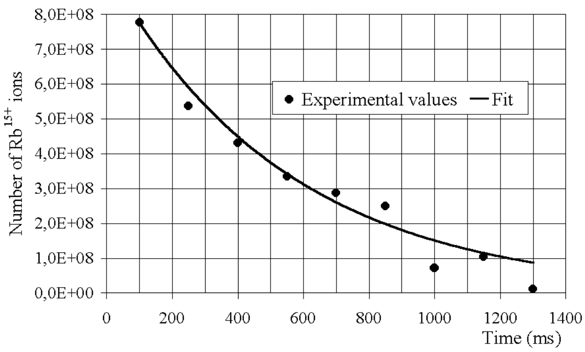

Figure 5: Rb^{15+} confinement time of 520 ms

3.5 Efficiency and charge capacity of the ECRIT

Experiments have been performed by observing the Rb^{15+} which is the most abundant charge state extracted from our ECRIS – Minimafios 10 Ghz. The Rb^{1+} beam has an intensity of 400 nAe. When the Rb^{1+} ions and RF power are injected with the same frequency 0.5 Hz, and the same phase (i.e. $t_{H.F} = t_{inj}$ =1000 ms and Δt=0), the Rb^{15+} afterglow signal measured has a maximum peak intensity of 11.5 μAe (Fig. 6). During 20 ms following the RF power cancellation 2.4×10^{10} particles of Rb^{15+} are extracted, corresponding to a total number of Rb ions extracted greater than 10^{11} for the whole charge spectrum. The charge capacity of the ECRIT is orders of magnitudes higher than the one obtained with EBIS systems [9]. The cumulated efficiency is shown Fig. 7 which is the integrated efficiency at a given time after the beginning of the afterglow process.

The integration of the afterglow signal during 20 ms after the RF cancellation gives a $Rb^{1+}\rightarrow Rb^{15+}$ transformation efficiency of 2.2%.

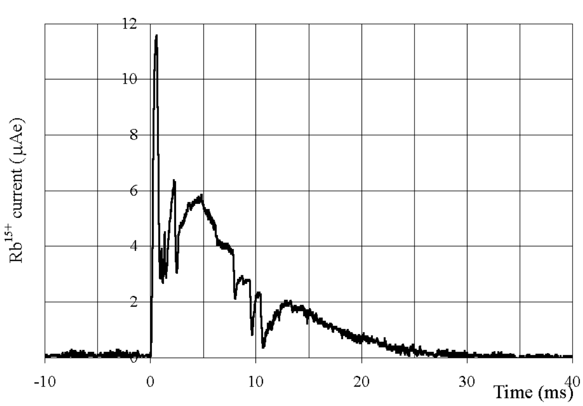

Figure 6: 400 nA Rb^{1+} injected; 11.5 μAe Rb^{15+} extracted

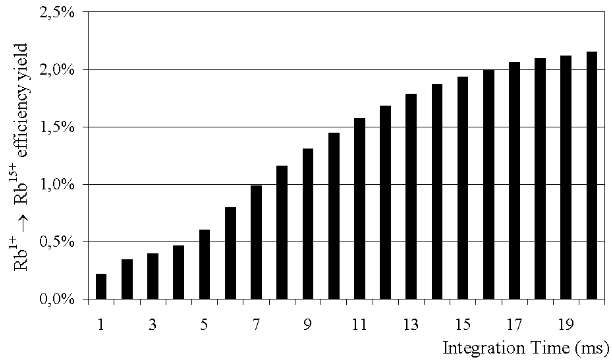

Figure 7: $Rb^{1+}\rightarrow Rb^{15+}$cumulated efficiency

4 CONCLUSION

When using a 1+ ion beam with an energy spread less than a few eV and an emittance less than 50 π.mm.mrad, the charge breeder 1+ → n+ efficiency is proved to be independent of the incoming beam. Its global particle efficiency yield is very close to the gas efficiency when using a MINIMAFIOS 10 GHz ECRIS. It is therefore a very efficient method to produce high energy radioactive ion beams when using a c.w. accelerator.

The new ECRIT mode is one of the most powerful charge breeder/buncher existing at this time. Its charge capacity is higher than the EBIS systems, its efficiency yield is still interesting, a specific high performance ion source could still improve its characteristics especially considering the highest charge state obtained. It will permit to feed pulsed accelerators at a reasonable cost.

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