Test Measurements On The RF Charge Breeder Device BRIC

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Abstract. The "charge state breeder" BRIC (BReeding Ion Charge) is based on an EBIS source and it is designed to accept Radioactive Ion Beam (RIB) with charge state +1, in a slow injection mode, to increase their charge state up to +n. BRIC has been developed at the INFN section of Bari (Italy) during these last 3 years with very limited funds. Now, it has been assembled at the LNL (Italy) where are in progress the first tests as stand alone source and where, in the future, with some implementation, it will be tested as charge breeder at ISOL/TS facility of that laboratory. BRIC could be considered as a solution for the charge state breeder of the SPES project under study also at the LNL. The new feature of BRIC, with respect to the classical EBIS, is given by the insertion, in the ion drift chamber, of a Radio Frequency (RF) - Quadrupole aiming to filtering the unwanted masses and then making a more efficient containment of the wanted ions. In this paper, the first ion charge state measurements and analysis and the effect of the RF field applied on the ion chamber will be reported and discussed. The first RF test measurements seem confirm, as foreseen by simulation results carried out previously, that a selective containment can be obtained. However, most accurate measurements needed to study with more details the effect. For this reason, few implementations of the system are in order to improve the accuracy of the measurements. The proposed modifications of the BRIC device, then, will be also presented and shortly discussed.

INTRODUCTION

The physics with energetic Radioactive Ion Beams (RIB) represents one of the foremost frontiers in Nuclear Physics. For this reason, many laboratories in the world have start to project and build new facilities for the production of RIB accelerated up to several MeV/u [1]. Among them can be mentioned the SPES project which is in an advanced phase of study at the Legnaro National Laboratory (LNL) (Padua, Italy). This kind of project is based on the ISOL technique. With this technique, two beam acceleration stages are used. The primary accelerator is intended to provide a proton, or a light ion, beam incident on a target to induce nuclear reactions. Then radioactive species will be produced inside. These radioactive elements need to be ionised for acceleration and then a secondary stage is intended to accelerate the radioactive ions at the desired energy before they reach the experimental area. Since the cost of an accelerator is roughly related to the inverse of the charge state of the beam to be accelerated, a higher ion charge state beam can allow a sensitive lowering of the accelerator cost. This problem can be solved by using, before the post-acceleration of RIB, an appropriate device capable of increase the charge ion state of the radioactive
element that must be accelerated. In the framework of the LNL SPES project, our
INFN group, in Bari, has been involved in the development and testing of a "charge
state breeder" device based on an EBIS source type: BRIC. The BRIC features have
been presented in a detailed way in ref. [2,3]. The main feature of BRIC is the using of
a RF quadrupolar field to obtain a selective containment of the wanted ions to reach,
in this way, a more efficient high charge state ion production.

The original purpose of the experiment was to test the selective containment due to
the RF quadrupoles and study the charge breeding in connection to the ISOL/TS
facility of LNL. However the limited fund obtained until now and, above all, the very
few FTE researchers available to work in this experiment have induced us, for the
moment, to modify our previous goal. In fact the present aim is to test the BRIC
device only as stand alone high charge ion source to verify the idea of the RF selective
containment and then study its effect in the ion production. In this paper, therefore, the
test of the selective containment of the BRIC and the first measurement results will be
presented and discussed together with small device modification in order to improve
the measurement quality.

THE CHARGE BREEDER BRIC

As mentioned before, the detailed design of the device has been already presented in
ref. [2,3]. However, for sake of clarity, a shortly description of the device here will be
done to recall its main features. As can be seen from fig.1, the BRIC experimental set
up is practically the same of a classical Electron Beam Ion Source (EBIS). In fact, in
that figure, as in an usual EBIS, the electron gun, the ion drift chamber and the typical
electron collector with the hole for the ion extraction are put in evidence.

The main difference between BRIC and a usual EBIS can be observed from the
inside of the ion drift chamber shown in fig.1. In the chamber, RF electrodes of
cylindrical shape, placed around the symmetry axis in such a way to form a
quadrupolar RF field, are shown. The RF field, which is added to the electron beam
space charge potential, can give the above mentioned transverse selective containment
to the wanted ions. The anode and the electrode placed at the end of the cylindrical
shaped RF electrodes are used to create the longitudinal trap for the ions, needed for
the ion charge state breeding, before that they could be extracted.

![FIGURE 1. BRIC mechanical design without electron focusing solenoid.](image)

To find out whether the RF quadrupolar field could be used to obtain a selective ion
containment also in the presence of the electron beam space charge force and of the
axial magnetic field, needed for the electron beam focusing, a simulation code
package called BRIC has been developed [4]. The simulation results obtained by using
BRIC-code have shown both that the electron beam is not significantly perturbed by
the RF and that the selective ion containment could be possible also when to the RF
quadrupolar field is added also the axial magnetic field and the electron beam space charge force [4]. However, since many approximations are used to simplify the calculations of the ion motion in the BRIC device a test experiment is required to confirm the simulation results.

Although the funds obtained from our agency INFN and the FTE researcher that could be involved in the BRIC project were not enough for the construction and the generation of a real charge breeder connected to the ISOL/TS facility of the LNL, they are enough to test the existence of the selective RF containment effects on the ions, which was the main feature of the BRIC original project and, eventually, study the ion motion stability behavior. The goal of our experiment, then, as mentioned in the introduction, remains the test of the RF selective containment.

The initial BRIC design parameters were a current density, $J_e$, of about 10 A/cm$^2$ and an electron beam energy of about 5 keV [5]. For this current density (following the SPES project requirements), if an ion mass of about 100 a.m.u. and a charge state of 10 (charge over mass ratio = 1/10) is considered, a “breeding parameter” [6]: $J_e \tau_c \approx 3 \div 4$ [A•sec/cm$^2$] can be obtained by using the Lotz formula [7] as ionization cross section. Then, to reach a ion charge state of 10, confinement times of about 300 ms had to be required. In the actual experimental conditions, as will be shown in the following, an electron density current of about 2 A/cm$^2$ with an energy of about 2 keV can be reached.

For the electron beam focusing system are used two short solenoids made of special coils suitable to be mounted together in such a way to form a solenoid [5]. These coils have been designed and built by the BINP institute of Novosibirsk.

The magnetic field precision reached with this system has been of about $5 \times 10^{-4}$. However, the mounting of the water cooling system for the coils (see Fig. 2) has spoiled the solenoid coil alignment and a further adjustments on the beam pipe axis have been needed (together with the action of steering coils) to collect the electron beam in the collector with a recovery efficiency greater than 99%. The water cooling system operation allows to supply a current of 150 A without any increase of the coil temperature, then a maximum magnetic field of 1.4 kG has been reached on the axis of the solenoid.

FIGURE 2. BRIC device with the coil system of the solenoid and TOF for the ion charge state analysis.
RF Test Experiment

Experimental set-up

The experimental set-up used for our measurements is shown in the scheme of fig. 3. The power supply used for the electron beam recovery (taken by another experiment) can deliver a current of 0.5 A at a voltage of 1.25 kV. Those values limit the electron current that we could extract from the cathode to a value of about 0.2 A with a kinetic energy of about 2 keV.

FIGURE 3. Experimental set-up (before the adding of the RF field). On the top of the figure there is the Faraday Cup that collect the ion pulse at the end of the TOF line and in the bottom is shown the Electron Gun. In the boxes are indicated the main features of the devices used.
Since the axial magnetic field obtained from our solenoid could give a $B_{\text{max}}$ of 1.4 kG, the obtainable density current, $j_e$, is then less than 2 A/cm$^2$. These kind of parameters allow very low charge state ions (Z should be about +3) [7]. However, preliminary measurements of the RF effect on the trapped ions could be the same carried out. In fact, simulations carried out with BRIC code have been useful to find out what are the RF parameters that give stable motion conditions for the wanted ions (in our case Ar ions) with the aim of improve the containment efficiency. As described in the ref. [5], once fixed the element of interest, BRIC code can be used to find the stability region in the plane $(q,a)$.

The parameter $q$ and $a$ are typically used in the theory of the RF quadrupole spectrometry and are defined as:

$$a = a_x = -a_y = \frac{4eU}{m \omega^2 r_0^2}$$

$$q = q_x = -q_y = \frac{2eV}{m \omega^2 r_0^2}$$

here $\omega$ is the pulsation of the RF signal used and $V$ its amplitude, $U$ is the DC component, $r_0$ is the distance from the axis to the RF electrodes and $e/m$ is the charge over mass ratio of the element considered. The simulation results are shown in fig. 4.

FIGURE 4. a) Stability (dotted) regions for different charge states of Ar ions, the parameters used are: RF frequency $\nu_{rf}=1.5$ MHz, $I_e=0.2$ A and SCC 98%; b) stability (dotted) regions of Ar+3 ions for different SCC values, the parameters used are: RF frequency $\nu_{rf}=1.0$ MHz, $I_e=0.2$ A.
From that figure, it can be seen that, at least in principle, it could be chosen a working point of the (a,q) plane in such a way to obtain stable motion only for ion $\text{Ar}^{+3}$. However, further simulations of stability regions for $\text{Ar}^{+3}$ for different electron beam Space Charge Compensation (SCC) (see the 96%, 97%, 98% and 99% cases in fig. 4b) show that the stability zones are very sensitive to SCC value and when the value is too low (less than 90% for our $I_e=0.2$ A) almost all the plane (a,q) becomes stable. Since the SCC effect on the ion motion is taken into account from the BRIC code in a very rough way [4], it becomes very difficult to make some prediction on the measurement results on the basis of the simulations done. Then, only the experimental test with the RF field could show if the foreseen selective containment can be possible.

The time needed to reach the electron beam SCC can be roughly evaluated by the relation [8]:

$$\tau_e = 7.5 \times 10^4 \frac{E_e^{1/2} I_e}{n \ln (E_e / I_e)}$$

where $n$ is the residual gas density, $E_e$ the electron energy and $I_e$ the ionization potential. In our case, the vacuum reached in the ion chamber was not so high, $P=10^{-8}$ Torr, and then we got a low value of about 10 ms (being $E_e=2\text{keV}$). Then, in our measurements a $\tau_e$ greater than 10 ms will be used to be sure to reach the maximum SCC.

**Test Measurements**

As first step, the ion beam pulse measurement extracted by the ion chamber has been detected without the application of the RF quadrupolar field. In fig. 5a is shown the ion pulse measured on the extraction electrode placed in the electron collector.

![FIGURE 5](image)

a) ion pulse on the extraction electrode; b) ion analysis of the pulse at Faraday Cup (FC) on the end of the TOF line. The different curves refer to different delay time between the ion trap emptying pulser and the TOF start pulser.
The parameter used in the measurements shown in fig. 5 are shortly described in the following. The power supply connected to the collector, that recovers the electron beam extracted from the cathode, is insulated from the ground (see fig.3) and it was set to, $V_{\text{coll}}=1.25 \text{ kV}$. Since the cathode potential was, $V_k=-1.8 \text{ kV}$ the collector was placed to $-530 \text{ V}$ with respect to the ground. The electron extraction electrode potential was, $V=+1.8 \text{ kV}$ and the anode potential was placed to the ground. The electron current recovered on the collector has been about 180 mA with an efficiency of 99.7% and the ion extraction electrode placed in the collector had a voltage of about $-2 \text{ kV}$. The ion trap emptying pulses (see fig. 3) are given with a frequency of 70 Hz allowing a $\tau_c$ of about 14 ms.

The TOF start pulser provided a pulse with an amplitude of about $-2 \text{ kV}$ and a width of about 200 ns. Furthermore, an Einzel lens at a voltage of $-2.5 \text{ kV}$ has been used before to detect the ion pulse on the FC at the end of the TOF (see fig. 3).

In fig. 5b, although with a not so good resolution, the peaks referring to the residual gas ions with different $e/m$ values can be seen clearly. However the start position on the oscilloscope time axis was not very well-defined. A more accurate determination of the TOF for each value of $e/m$ can be obtained by considering that the residual gas composition in the ion chamber is for 85% of H$_2$ (or H) and the rest is given by CO and N$_2$ (same masses). The first two peaks of fig. 5b, then, refer to H$^+$ and H$_2^+$ respectively and by Assuming that all the ions have the same kinetic energy, knowing the TOF base, the TOF of H$^+$ can be given by $\tau_{H^+} = \Delta \tau/(\sqrt{2}-1)$, where $\Delta \tau$ is the time distance between the first 2 peaks. From this value can be scaled the TOF values of the all other ions with different $e/m$ values. The ion pulse of fig. 5a have to travel for about 50 cm (see fig. 3) before to reach the electrode where is applied the TOF start signal. Since it is composed of ions with different $e/m$ values, it will spread on the arriving to the TOF start electrode. Precisely, the ions with smaller $e/m$ values will be on the head of the pulse and those ones with higher $e/m$ values on its tail. To take into account all ions coming from the trap a time delay scan of the TOF start signal on all the length of the trap ion pulse is needed. The different curves of fig. 5b show that with increasing time delay the peaks corresponding to smaller $e/m$ values decrease while those ones with greater $e/m$ values increase. The delay time between the ion trap emptying pulse and the TOF start pulse is realized by a synchronized signal with a delay time generator (see fig. 3).

After the first measurements shown in fig. 5 we have added Ar in the ion chamber and then we try new measurements also with the adding of the RF quadrupolar field.

![FIGURE 6](image-url). TOF ion analysis with and without the RF field for $\tau_d=50 \text{ } \mu\text{s}$. The yellow curve refer to the case in which the RF field has been applied. The RF parameters used are: $f_{ rf}=2 \text{ MHz}$, $V_{ rf}= 20 \text{ V}$, $V_{ dc}= 5 \text{ V}$. 
FIGURE 7. TOF ion analysis for $\tau_d=5$ $\mu$s: a) without RF field application; b) with RF field application, $v_{rf}=1$ MHz, $V_{rf}=90$ V, $V_{dc}=0$ V. In both figures is shown the TOF start pulse.

In fig. 6 are shown the results of those measurements. As it can be seen from the figure, it seems that the application of the RF field has given an effect of ion selective containment as foreseen from the simulations. In fact, when the RF field is applied to the ion chamber with increasing RF amplitude $V_{rf}$, the decreasing of the peaks referring to smaller e/m values (corresponding to $\text{Ar}^{+2} \div \text{Ar}^{+3}$) can be observed up to the complete disappearance while the peak corresponding to $\text{Ar}^+$ remain there practically unperturbed. However, further increase of $V_{rf}$ (a few hundreds of Volts) could cause also the lost of the electron beam and, then, of the all trapped ions. In the measurements of fig. 6, the peaks corresponding to the ions $\text{H}^+$ and $\text{H}^{2+}$ coming from the trap are not shown because of the very high time delay used ($\tau_d=50$ $\mu$s). Then, further measurements, without the adding of Ar, have been carried out, successively, at $\tau_d=5$ $\mu$s. The results of those measurements are shown in fig. 7. The RF field application has produced, also in this case, the decreasing of the peaks corresponding to the ions $\text{H}^+$, $\text{H}^{2+}$ and of the other ions with greater e/m values.
CONCLUSION

The preliminary experiment results have shown that ions in BRIC trap can be selectively contained when an appropriate RF field is applied to the quadrupole electrodes. However, the charge state analysis carried out with the present experimental set-up are still very rough. Furthermore, the power supply used for the electron beam recovery in this first experiment allow an electron beam current not greater than 0.2 A. For that reason we could have a $j_e \tau_e$ parameter which gave, for the Ar ions, a very low value of maximum charge state reachable (Z=3).

Further experiments are underway to confirm and better characterize the selective containment given by the RF quadrupolar field applied to the BRIC ion trap. However, to obtain more clear measurements results, few experimental set-up implementations are in order to solve the existing problems. One of the main problems of these measurements has been the low pumping efficiency that allowed a not very high vacuum level of about $6 \times 10^{-9}$ Torr (before the electron beam extraction). This problem was due to the using of an old ion pump placed necessary far from the ion chamber that had to be evacuated. That ion pump will be replaced by 2 new smaller ion pumps, already bought, that can be placed very close to the ion chamber. The electron beam recovery power supply will be replaced by a new more powerful one capable to recovery a current of about 0.5 at higher voltage (2 kV) and then to give a $j_e \tau_e$ parameter allowing higher charge state ions. On the last, but not the least, some modification on the TOF system will also be done.

A new start electrode will be placed very close to the ion extraction electrode doubling in this way the TOF base. Furthermore, the FC on the end of the TOF line will be replaced by a microchannel plate detector and the signal given by the ion pulse mass spectra will be analyzed by a MultiChannel Scaler (MCS) [9]. In fact, an MCS records the counting rate of events as a function of time. Precisely, at the end of a preselected dwell time the MCS advances to the next channel of its digital memory. In this way, we think that a better resolution in the ion charge state analysis could be obtained.

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