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An EBIS for charge state breeding in the SPES project

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Abstract. The 'charge state breeder', BRIC (breeding ion charge) is in construction at the INFN section of Bari (Italy). It is based on EBIS scheme and it is designed to accept radioactive ion beam (RIB) with charge state +1 in a slow injection mode. This experiment can be considered as a first step towards the design and construction of a charge breeder for the SPES project.

The new feature of BRIC, with respect to the classical EBIS, is given by the insertion, in the ion chamber, of a rf-quadrupole aiming at filtering the unwanted masses and then making a more efficient containment of the wanted ions. In this paper, the breeder design, the simulation results of the electron and ion beam propagation and the construction problems of the device will be reported.

Keywords. EBIS; charge state breeder.

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1. Introduction

SPES will be a Legnaro National Laboratory (LNL) facility that will use an ISOL technique for the radioactive ion beam production [1]. With this technique two beam acceleration stages are used. The primary accelerator is intended to provide the light ion beam incident on the target. The produced radioactive species have to be ionized, elevated in charge state and mass separated. The secondary stage is intended to accelerate the radioactive ions at the desired energy before they reach the experimental area. After the production, the radioactive species enter the ion source to be ionized. Then the singly charged ion beam is injected into a charge state breeder device to enhance the ion charge state at high level. This increases the total efficiency of the beam transmission and lowers the cost of the secondary accelerator. For efficient acceleration by compact LINAC's, charge to mass ratios greater than 1/10 are required and a value between 1/9 and 1/4 seems to be a good choice for SPES [1]. At the present state of art, other than the usual stripping technique, two source types seem useful for charge state breeding: the electron cyclotron resonance ion source (ECRIS) and the electron beam ion source (EBIS). The literature on the argument is very large, and several meetings (see for example [2,3]) and review articles (see for example [4]) have been dedicated to the performances of these two ion sources.

In the framework of the LNL SPES project, our INFN group in Bari is involved in the development and testing of a *charge state breeder* device based on an EBIS source type: BRIC. In the SPES project, the foreseen accelerated radioactive atoms will have, most probably, masses lying in the range 80–150 a.m.u. Then, as already noticed, a charge breeding technique will give a more efficient RIB post-acceleration.

In an EBIS source, the ion charge state enhancement is obtained through the interaction with an external electron beam. In a typical scheme of the source, the electron gun, the ion chamber and the collector are coaxial and the ions are injected and extracted from the same side of the set up. The injected ions are trapped in a longitudinal potential well where they remain until the extraction. Two injection modes for the ion beam considered up to now [4] are:

- *fast injection mode*: where the ions are decelerated before the injection, enter the breeder through the collector and are finally trapped by raising the potential barrier on the collector side. The ions must be injected in a pulse whose length has to be shorter than the round trip time in the potential well.
- *slow injection mode*: where the ions have an energy higher than the potential barrier on the collector side and enter the chamber continuously during the confinement time. They reach a higher charge state during one round trip time and then remain trapped in the confinement area.

For the fast injection mode the continuous ion beam must be pre-bunched and so a trap for accumulation, cooling and bunching is required (as in REX-ISOLDE (CERN)). However, the number of particles that can be accumulated in a Penning source is limited. On the contrary, for the slow injection mode no trap is required, but the electron space charge force can be directly used to transversely contain the ions during the charge state breeding. The number of ions that can be contained in an EBIS depends on the electron beam current I_{e} and energy U_{e}, on the confinement length λ and on the reachable fraction of space charge compensation k, which could reach about 50%. This number, N_q^+, can be obtained by the following relation:

$$N_q^+ \leq k\sqrt{\frac{m_{\mathrm{e}}}{2e^3}}\frac{\ell}{q}\frac{I_{\mathrm{e}}}{\sqrt{U_{\mathrm{e}}}}. \tag{1}$$

In the BRIC device an rf-quadrupole will be inserted in the ionization region to increase containment efficiency through a selection of rf parameters in such away to obtain motion stability only for the element of interest. Then, in principle, in BRIC the k value of (1) could increase up to about 1. This increase should have more importance in the breeding device for the RIB application, where the desired element to be ionized and then accelerated for the experiment, is produced, in general, together with other species. On the other side, during the development of the EBIS sources a similar idea of using rf fields to improve the yield of wanted ions has been presented already in the past [5]. In this paper the status report of the project with the main construction problems faced up to now will be presented and shortly discussed.

2. BRIC experiment

The breeding ion charge (BRIC) experiment, funded by the INFN agency, will test an EBIS slow injection breeding scheme. As mentioned before, in BRIC the EBIS design has been

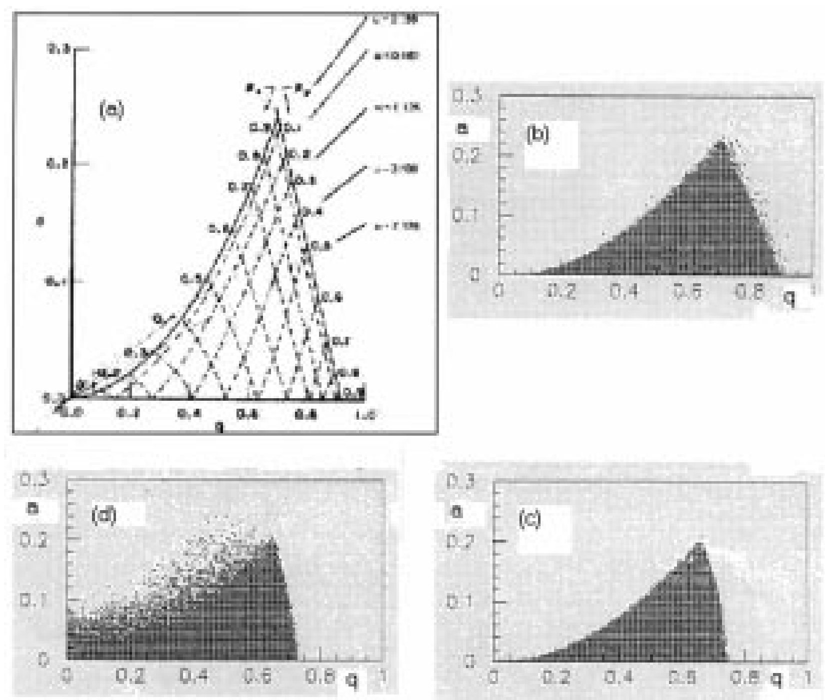

Figure 1. Ion first stability zones obtained from: (**a**) analytical solutions of Mathieu equations (without solenoidal and space charge field); (**b**), (**c**), (**d**), ion distribution in the (a, q) domain after a length trap of about 1 m, obtained from numerical solutions of eq. (2) for $B_z = 0$ and $I_e = 0$ (**b**); numerical solutions for $B_z = 0.18$ T and $I_e = 0$ (**c**); numerical solutions for $B_z = 0.18$ and $I_e = 10$ mA (**d**). The other parameters used in the simulations are: Ion mass $A = 110$ a.m.u., $\omega_{\rm rf} = 1$ MHz, ion charge state $Z = 4$.

modified by adding, in the region of the drift tubes, an rf-quadrupolar field with the aim to increase the breeding containment efficiency. Preliminary simulations were in order to verify that the typical selective rf containment is not lost by the effect of the simultaneous presence of rf, solenoidal and electron beam space charge fields on the ions.

The theory of the rf-quadrupole has been already completely developed (see for example [6,7]). The particle motion equations can be expressed in both the transverse coordinate planes, through two Mathieu equations. The theoretical results of the Mathieu equations show that the motion is stable only when the coefficients a and q are chosen within the 'stability regions' for both the transverse planes. In the mass filter theory the stability region of interest is restricted to a small quasi-triangular zone in the positive (a, q) plane (see figure 1a). The ratio $u = a/q = 2U/V$ is only dependent on the DC and AC components of the radio-frequency. For a fixed charge state, the points corresponding to the particle-given masses are all on the working line corresponding to the chosen U and V components. The intersection of this line with the stability region determines the stable masse range (see figure 1a). The slope of the line, and consequently the range of the stable masses, can be changed by varying the value of U and V.

When the longitudinal magnetic field of the solenoid and the electron beam space charge force are taken into account, the stability diagram is quite modified. Namely, the new equations of the ion motion in the plane (x,y), now depend also on two other coefficients accounting for the magnetic field and the electron beam space charge.

Since within the ion chamber the electron beam can be roughly assumed as of cylindrical shape of constant radius r_b, owing to the solenoid magnetic field, a simple model can be assumed to evaluate the space charge effect. Thus, by neglecting the slight scallop effect, the new trajectory equations, in substitution of the Mathieu ones, can be written as:

$$\begin{cases} \frac{\mathrm{d}^2 x}{\mathrm{d}\tau^2} - b\,\frac{\mathrm{d}y}{\mathrm{d}\tau} + \left(a_x + c - 2q_x \cos 2(\tau - \tau_0)\right) x = 0 \\ \frac{\mathrm{d}^2 y}{\mathrm{d}\tau^2} - b\,\frac{\mathrm{d}x}{\mathrm{d}\tau} - \left(a_y + c - 2q_y \cos 2(\tau - \tau_0)\right) y = 0 \end{cases} \quad \text{for } r < r_b \tag{2}$$

$$\begin{cases} \frac{\mathrm{d}^2 x}{\mathrm{d}\tau^2} - b\,\frac{\mathrm{d}y}{\mathrm{d}\tau} + \left(a_x + c\left(\frac{r_b^2}{r^2}\right) - 2q_x \cos 2\left(\tau - \tau_0\right)\right) x = 0 \\ \frac{\mathrm{d}^2 y}{\mathrm{d}\tau^2} - b\,\frac{\mathrm{d}x}{\mathrm{d}\tau} - \left(a_y + c\left(\frac{r_b^2}{r^2}\right) - 2q_y \cos 2\left(\tau - \tau_0\right)\right) y = 0 \end{cases} \quad \text{for } \geq r_b \tag{3}$$

where $\tau = \frac{1}{2}\omega t$, $a_x = -a_y = 4q_i U/m_i\omega^2 r_0^2$, $q_x = -q_y = 2q_i V/m_i\omega^2 r_0^2$, and with the two new parameters, $b = 2q_i B/m_i\omega$ and $c = (1/4\pi\varepsilon_0)(8q_i/m_i\omega^2 r_b^2)(I_e/v_e)$ added to the usual Mathieu equations, where the first one is related to the solenoid field B, whereas the latter takes into account the electron beam space charge force: I_e is the beam current intensity and v_e the electron velocity.

Until now no analytical solutions have been found for eq. (3). Furthermore, the necessity to follow the charge state evolution of the ions during the interaction with the electron beam imposed to develop an appropriate numerical package (BRICTEST) to take into account all the physical problems involved. The developed routines allow to evaluate both the solenoid and electron beam space charge effect on the trapped ions. Furthermore, a routine that takes into account the ion charge state evolution due to ion–electron interaction has been recently added.

In figure 1b, c and d, the BRICTEST simulation results show what is the final ion distribution in the (a,q) domain, after that a uniform distribution in the (a,q) plane has been propagated for an ion trap of about 1 m long. In figure 1a the stability region derived from the analytical results of the Mathieu equation is shown as reference for the BRICTEST results of figure 1b, where the case without magnetic field and space charge effect is presented.

The axial magnetic field of the BRIC solenoid is added to the rf-quadrupolar field in the case of figure 1c, where the stability region, obtained from the simulations, decreases from the region of higher q. On the other hand, when the eb space charge effect has also been taken in account, simulations of figure 1d, the stability region enlarges leaving, anyway, the possibility to obtain a selective containment for a chosen e/m. In conclusion, it seems that the magnetic field and the electron beam space charge act in opposite way: the first one tends to reshape and reduce the stability region area, whereas the latter tends to increase the stability area, due to the enhancement of the transverse containment force of the ions.

Although the simulation tests carried out up to now show that the mass separation is still possible in our device, the complexity of the parameter interconnection push us to continue the study to better understand their behavior. Furthermore, the recent addition, in

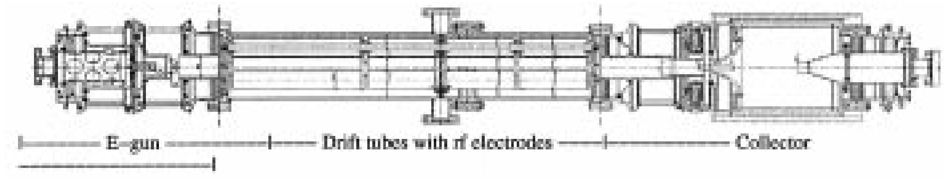

Figure 2. BRIC set-up assembly, without solenoids.

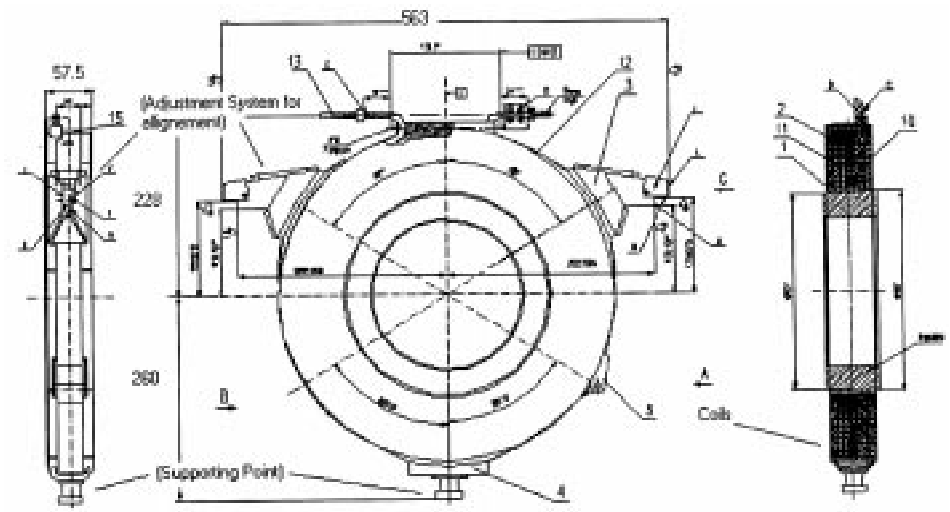

Figure 3. Coil mechanical design. The main parts of the coil with the its global size are also indicated.

the BRICTEST code, of the charge state evolution makes more stringent a deeper insight in understanding how the ion masses of interest can be elevated at the highest charge states and remain contained by appropriate dynamic rf-quadrupole parameter change. Simulation in this directions are under way and will be presented as soon as possible.

The BRIC experimental set up is, in the test assembling, practically the same as a classical EBIS. The general scheme of the breeder is shown in figure 2.

The detailed design of the device has been already presented in ref. [8]. Here, for the sake of clarity, we will show again, shortly, the device to put in evidence some changes adopted during the construction to solve the problems faced. From the same figure 2, it can be seen, inside the drift chamber, the rf electrodes which will give ion selective containment and longitudinal entrapment.

The BRIC electron gun has no Pierce electrode. In fact, the new electron gun design is the same as the original one except for the Pierce focusing electrode that has been eliminated. This choice is due to relatively low solenoid magnetic field that can be reached with the funds available for this purpose. With the axial magnetic field obtainable (see figure 3b), the designed current density (about 10 A/cm^2) can be reached by increasing the perveance of the electron gun by the removal of the Pierce electrode and by using only the axial magnetic field to focus the beam.

In the electron gun, a dispenser cathode with $\emptyset \approx 5$ mm, providing a current up to 1.5 A, has been mounted on a metallic disc with a diameter of 1 cm. The output energy can be raised up to 10–15 keV. The transverse dimensions of the beam are maintained practically constant (immersed flow configuration) along the drift tube up to the collector by the axial magnetic field of the solenoids placed on ion chamber. Actually, the solenoids are made of coils designed in an appropriate way to be mounted together to form a solenoid (see figure 3 for mechanical design). This technique has been successfully used by the BINP institute of Novosibirsk to construct the solenoid for the E-Cooling system of GSI. The magnetic field configuration obtained by these coils should maintain slight beam scallop throughout the ion drift chamber with a current density greater than 10 A/cm^2. The tail of the solenoid field have to be cut on the collector zone in order to increase the efficiency of the electron beam collection and to avoid the electrons to come back towards the ion chamber and towards the gun.

The collector (see figure 1) allocates, at the end, an ion extraction electrode which has also the task to repel the electrons by opening them further and focus the ions at the exit hole where there is another electrode that can be used to give the start and stop signal for the TOF system that will be placed at the end of the BRIC to analyze the ion charge states.

The ion chamber (figure 4) has been designed to allocate the drift tubes, the barrier electrodes for the longitudinal ion trapping and the rf-quadrupole. All the feed troughs for dc voltage and rf power supply, diagnostics and so on, have been inserted in the central zone of the chamber.

The overall chamber (110 cm length) is immersed in the longitudinal magnetic field of two solenoids formed by 20 coils. The current in the winding coils can be greater than 130 A and the maximum field that can be obtained on the axis with this current is about 2.0 kG.

Note, as already previously mentioned, that a high magnetic field is important to ensure the highest possible electron beam current density, J, and then to reduce the ion-beam containment time, τ_c, to reach the required charge state. This means that a much higher magnetic field intensity should be required (more than 1 T) to reach higher ion charge state at the same τ_c. However, this can be obtained with corresponding major cooling problems and cost.

The chosen field value on the axis, compatible with the fund obtained by INFN for the experiment, permits to obtain a value of $J \approx 10$ A/cm^2.

Following the SPES project requirements, if an ion of mass about 100 a.m.u. and a charge state of 10 (charge over mass ratio = 1/10) is considered, a 'breeding parameter' [9] $J \cdot \tau_c \approx 3 \div 4 [A \cdot \text{sec/cm}^2]$ can be obtained by using the Lotz formula [10] as ionization cross section. The resulting containment time τ_c, for electron beam current density J of the order of 10 A/cm^2, is in the range 100÷300 ms.

Figure 4 shows the transverse section of the BRIC ion drift chamber together with the rf-quadrupole electrodes. The quadrupole has been designed by choosing a value for the parameter η, defined as r/r_0 (where r is the cylinder radius and r_0 is the distance of the cylinder from the axis) in such a way as to obtain the best approximation of a pure quadrupolar field by using cylindrical shaped electrodes. Currently, the value of η is fixed at the so called 'magic number' $\eta = 1.145$. However, more recently, it has been demonstrated that the best quadrupolar field approximation is obtained by choosing $\eta = 1.1$ [11]. Our quadrupole has been designed by taking into account this last assumption. In fact the values $r = 2$ cm and $r_0 = 2.2$ cm have been chosen.

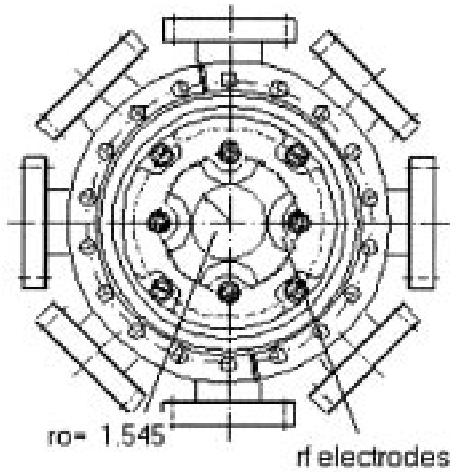

Figure 4. Transverse view of the ion drift chamber with the cylindrical shaped rf electrodes (r_0 is in cm).

3. Work in progress and conclusion

BRIC experiment will be carried out in two stages. The first one, the test of BRIC device as a stand alone highly charge state ion source, and in the latter, the same device will be used as charge breeder of an ISOL facility based on the CN accelerator located at LNL called ISOL-T/S [12]. Now we are involved in the first stage.

The electron gun and the collector were built in the beginning of the last year. The complex gun plus collector has been mounted and the vacuum-tight successfully tested. Furthermore, the electron gun perveance, P, has been measured at two levels of anode voltage: at low voltage (few hundreds of Volt), $P = 0.8\ \mu$P and at high anode voltage (few kV), giving $P = 0.53\ \mu$P. The latter is in agreement with simulation results value and it seems to be the real value of the perveance. In fact, at low voltage the current emitted by the metallic surface around the cathode (see e-gun design, figures 2 and 3) is high enough to perturb the current emitted by the cathode emitter surface that, in this case, is low and then comparable with the one emitted outside the cathode. To recover the current extracted by the gun on the collector, two home made coils has been used. These two coils are allowed to recover all the current extracted from the gun (about 60 mA) on the collector.

Today, all the parts of the BRIC device have been built and mounted, as shown in figure 5, except for the coils that will form the 2 solenoids.

By mistake the rf cylindrical shaped electrodes have been built with $r = 1.7$ cm, instead of the designed 2 cm. Then, to preserve the η value to 1.1 the value of r_0 also has been changed appropriately (see figure 4).

A test of vacuum-tight of all the structure has been already done. A vacuum of about 2×10^{-8} Torr has been reached without heating the ion drift chamber. The ion drift chamber heating to reach higher vacuum level is under way.

Another test with electron beam at low power, is foreseen in the next weeks. All the coils that will form the solenoids which give the designed magnetic field is now under construction at BINP of Novosibirsk and should be ready by next June.

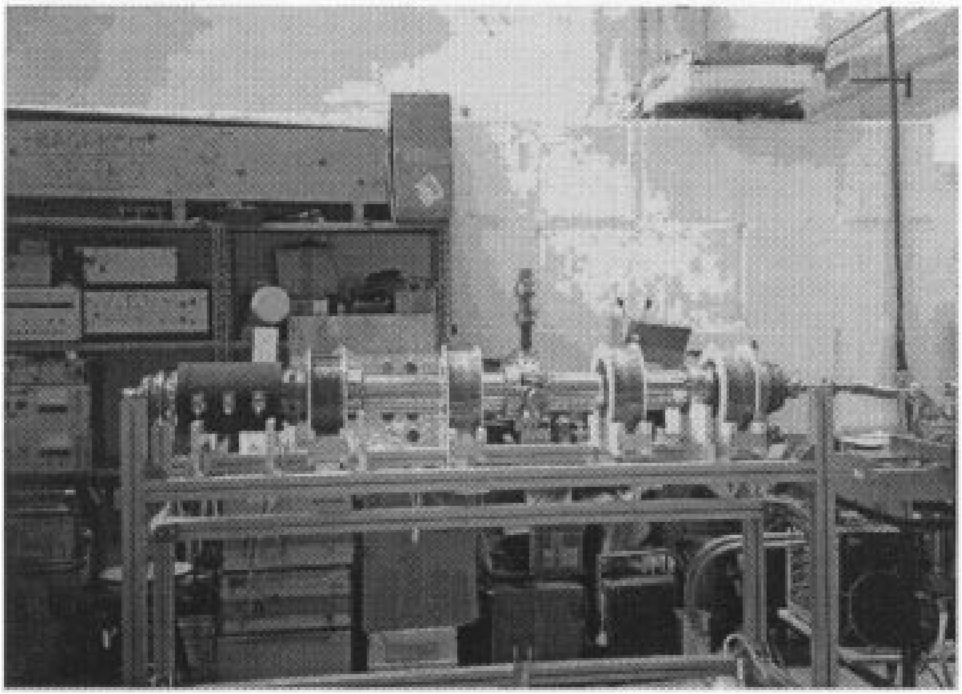

Figure 5. BRIC device mounted in vacuum ready for the low power test. The home made coils for the electron beam transport at low power are already placed.

We think that by next summer the coils forming the solenoids will be mounted and aligned on the BRIC structure and then we will start with experimental measurements without rf power on the electrodes. By the end of the year the rf power also will be transferred to the electrodes and then the eventual increased efficiency will be estimated. The second stage of the experiment, that is, the use of BRIC as charge breeder device for ISOL-T/S at LNL is foreseen for the next year.

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