BRICTEST: A CODE FOR CHARGE BREEDING SIMULATIONS

V. Variale, INFN sezione di Bari

M. Claudione, T. Clauser, A. Raino’, Dipartimento di fisica Universita’ di Bari e infn sezione di Bari

Abstract

In the framework of the SPES project, funded by INFN at the LNL (Padua), for Radioactive Ion Beam (RIB) production, an R&D experiment of a charge breeder device, BRIC, is in progress at Bari INFN section. BRIC is an EBIS type ion charge state breeder in which a radio frequency (rf) quadrupolar field has been superimposed in the trapped ion region to introduce a selective containment with the aim to increase the wanted ion trapping efficiency. A code that studies the motion and the ion charge state evolution in the trap region of the BRIC device has been, recently, developed in Bari. That code should allow of choosing the rf quadrupole parameters to optimise the ion charge breeding efficiency. In this paper the main feature of the code, named BRICTEST, and the simulation test will be presented and shortly discussed.

1 INTRODUCTION

The increasing interest in nuclear astrophysics and nuclear structure studies has led many laboratories, in the world, to project and build ISOL facilities for the production of RIB accelerated up to several MeV/u [1]. 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. Up to now, two type of charge state breeders have been considered: One is based on ECR sources and the other one on EBIS sources [2]. Recently, in the INFN section of Bari, an R&D experiment placed in the framework of the SPES project of LNL (Padua) is developing a new type of charge breeder based on EBIS source BRIC [3]. The new feature of BRIC with respect to the classical EBIS is given by the insertion of an rf quadrupole in the ion drift chamber. The quadrupolar field has the aim of filtering the unwanted masses to obtain a more efficient containment of the desired ions.

2 THE CODE BRICTEST

The theory of the RF Quadrupole has been already completely developed (see for example [4,5]). 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 (see below eq.s 2) 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 fig. 1 (a)). 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 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. The slope of the line, and consequently the range of the stable masses, can be changed by varying the value of U and/or 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:

$$\begin{cases} \dfrac{d^2 x}{d\tau^2} - b\dfrac{dy}{d\tau} + \left(a_x + c - 2q_x \cos 2(\tau - \tau_o)\right)x = 0 \\ \dfrac{d^2 y}{d\tau^2} - b\dfrac{dx}{d\tau} - \left(a_y + c - 2q_y \cos 2(\tau - \tau_o)\right)y = 0 \end{cases} \tag{1}$$

for $r < r_b$

$$\begin{cases} \dfrac{d^2 x}{d\tau^2} - b\dfrac{dy}{d\tau} + \left(a_x + c\left(\dfrac{r_b^2}{r^2}\right) - 2q_x \cos 2(\tau - \tau_o) \right)x = 0 \\ \dfrac{d^2 y}{d\tau^2} - b\dfrac{dx}{d\tau} - \left(a_y + c\left(\dfrac{r_b^2}{r^2}\right) - 2q_y \cos 2(\tau - \tau_o) \right)y = 0 \end{cases} \tag{1'}$$

for $r \geq r_b$

where:

$$\tau = \frac{1}{2}\omega t;\; a_x = -a_y = \frac{4q_i U}{m_i \omega^2 r_o^2}; q_x = -q_y = \frac{2q_i V}{m_i \omega^2 r_o^2}; \tag{2}$$

and with the two new parameters: $b = \dfrac{2\, q_i\, B}{m_i\, \omega}$ and $c = \left(\dfrac{1}{4\pi\varepsilon_o}\right)\dfrac{8q_i}{m_i\omega^2 r_b^2}\dfrac{I_e}{v_e}$ added to the usual Mathieu eq.s, where the first one is related to the solenoid field B, whereas the latter, c, take into account the electron beam space charge force. In fact, I_e is the beam current intensity and v_e the electron velocity.

Until now no analytical solutions have been found for eq.s (1). Furthermore, the necessity to follow the charge state evolution of the ions during the interaction with the electron beam has imposed the development of 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. The Main of those routines follows the ion motion in the trap region.

In fig. 1 (b), (c), (d), the BRICTEST simulation results show what is the final ion distribution, in the (a,q) domain, after that a uniform distribution of ion, in the (a,q) plane, has been propagated for an ion trap of about 1 m long. In fig. 1 (a) the stability region derived from the analytical results of the Mathieu eq.s is shown as reference for the BRICTEST results of fig. 1 (b), 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 fig. 1 (c), where the stability region, obtained from the simulations, decreases from the region of higher q. On the other side, when also the eb space charge effect has been taken in account, simulations of fig. 1(d), 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 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 behaviors. More recently, the routine that takes into account the ion charge state evolution, due to ion-electron interaction, has been added to the code to make our simulation of the ion motions in the trap more close to the reality. Furthermore, the addition in the BRICTEST code of the charge state evolution makes more stringent a deeper insight in the understanding how the ion masses of interest can be elevated at the highest charge states and remain contained by changing in an appropriate way the rf quadrupole parameters. Simulations in this direction are under way and will be presented as soon as possible.

The charge state evolution, in BRICTEST, is described by the following equation system:

$$\frac{dn_i}{d(j_e t)} = \frac{j_e}{e}\left[n_{i-1}\sigma_{ion,i-1\to i}(Ee) - n_i\sigma_{ion,i\to i+1}(E_e) + n_{i+1}\sigma_{RR,i+1\to i}(E_e) - n_i\sigma_{RR,i\to i-1}(E_e)\right] \tag{3}$$

where n_i is the ion density with charge state i, j_e the electron current density, e the electric charge and E_e the electron beam energy. Furthermore, $\sigma_{ion,i}$ and $\sigma_{RR,i}$ indicate, respectively, the ionization to the charge state i and the radiative recombination cross sections.

For the ionization cross section has been used the empirical Lotz formula given by [6]:

$$\sigma_{ion,i\to i+1}(E_e) = 4.5\cdot 10^{-14}\,\frac{\ln\{E_e / E_i\}}{E_e \cdot E_i}$$

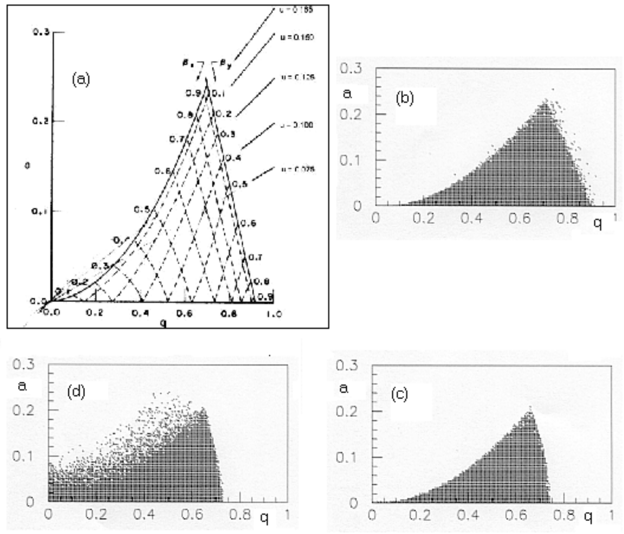

Figure 1: Ion first stability zones obtained from: (a) analytical solutions of Mathieu eq.s (without solenoidal and space charge field); (b), (c), (d), ion distribution in the (a, q) domain after a length trap of about 1 m, obtained by numerical solutions: (b) for B_z= 0 and I_e= 0; (c) for B_z= 0.18 T and I_e= 0; (d) for B_z= 0.18 and I_e= 10 mA. In these simulations : A = 110 Amu, ω_{rf} = 1 MHz, Z = 4.

while, for the recombination cross section has been used the Kim and Pratt formula [7]:

$$\sigma_{RR,i\to i-1} = \frac{8\pi}{3\sqrt{3}}\alpha\lambda_e^2\chi\ln\left\{1 + \frac{\chi}{2(n_0)_{eff}^2}\right\}$$

where α is the fine structure constant, λ_e is the Compton electron wavelength, the parameter χ is defined as

$$\chi = 2Z_{eff}^2 I_h / E_e$$

and the effective quantum number is given by

$$(n_0)_{eff} = n_0 + (1 - W_{n_0}) - 0.3$$

with n_0 valence shell number and W_{n_0} the ratio between the occupied state number and the available state number in the shell with the valence n_0.

At the initial conditions all the radioactive ions injected in the BRIC will have charge state *+1* (*N*(number of ions) = n_1). Then, once the rf parameter has been chosen in such a way to obtain stable conditions, as described in fig.1, the ion +1 motion will be followed inside the rf trap region by the main of the code. However, in that region, the ion +1 will interact with the electron beam and after a while the initial ion distribution will change as described by the equation system (3). After a preset time step Δt, the control of the program will go to the routine that computes the new charge state distribution and then again to the Main to follow the ion motion in the trap region with the new charge state distribution obtained after Δt.

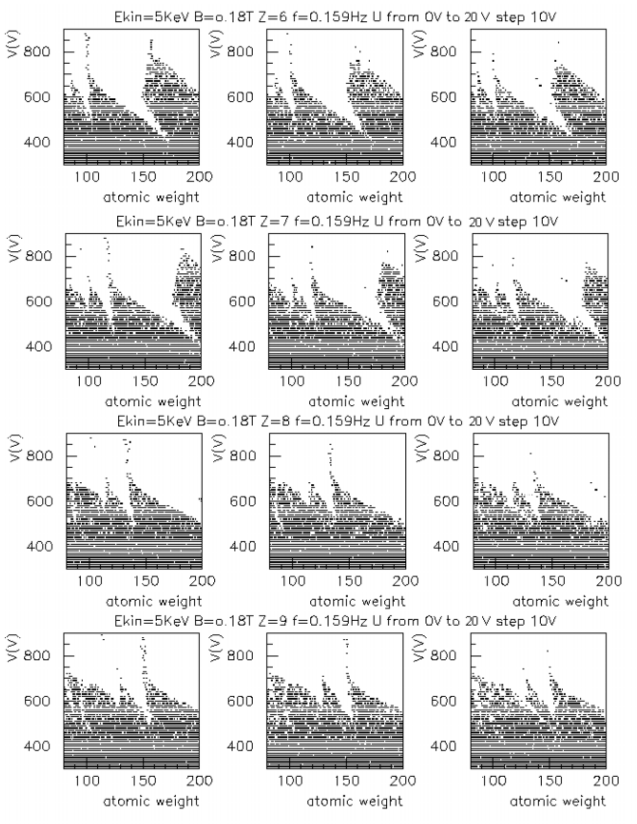

Figure 2. Stability regions for ion masses in the region 80 – 200 Amu in function of the rf amplitude V for different ion charge state. The space charge term is obtained by an I_e = 100 mA, ν=159 kHz and B=0.18 T.

To obtain a parameter set that can produce stable motion for the ions with the desired charge state, a scanning of the ion masses in the range of interest can be done with BRICTEST. In this way the stability of the motion for each ion mass can be tested by varying the rf amplitude V at fixed frequency. The simulation results of this scanning test can be shown as in fig.2. In the graphs of that figure when the ion motion results to be stable up to the end of the trap region a dot is placed at the value of ion mass considered with the used V. Furthermore this stability test can be done for different ion charge states and U values.

From the simulation results shown in fig. 2, it can be seen that for low V voltages all the ion masses with different charge states and U values have a stable motion. Regions of instable motion for some ion masses start to be present for V values greater than 500 V. This value will depend, of course, on the space charge force given by electron beam current, in this case 100mA. For higher beam current higher values of V will be needed to have instable motion regions. Furthermore, from the results of fig. 2 it can be seen as the stability patterns change for different ion charge state and U values. Then through a proper choice of the voltages U and V motion stable conditions can be obtained for the wanted ions.

However, it must be noticed that for higher electron beam currents the instable regions of fig. 2, in a first moment, can disappear because of deeper transverse potential wells due to space charge. Then, as the space charge compensation start to take place and the transverse well depth, as consequence, decrease too, those instable regions reform as in fig. 2. The evolution of the space charge compensation , then, has to be taken into account to simulate in a more realistic way the ion motion. The inclusion of the space charge compensation, in BRICTEST code, is underway.

3 CONCLUSION

A code package to simulate the ion with different charge state and mass in the BRIC device has been developed to check the if a selective containment can occur in it. The selective containment has been confirmed by the simulation. Furthermore, the simulations have shown (see fig. 2) that by a proper choice of the rf, V, and DC, U, amplitudes a stability region for an ion mass with the desired charge state can be found. Since the charge state of the desired ions will increase in the time, because of the interaction with the electron beam, those same ions could enter an instability region. To keep the stability conditions of the desired ions, also as the charge state increases, a proper adjustment of the U and V values should be operated during their motion. As the space charge compensation becomes more important the selectivity of the device will increase too. The implementation of the space charge compensation in the code is underway.

REFERENCES

[1] See, for example, SPES "Project Study", LNL - INFN (REP), 145/99.

[2] U. Köster, O. Kester and D. Habs, Rev. Sci. Instrum., 69 (1998) 1316.

[3] G. Brautti et al., “BRIC:An EBIS Design For Charge State Breeding In RIB Applications”, Proc. Of 8th International Symposium EBIS/T 2000, Upton, New York (2000) p. 74.

[4] Dawson P. H., “*Quadrupole Mass Spectrometry and Its Applications*”, Elsevier, Amsterdam, 1976.

[5] Murch R. E. and Hughes R. J., “*Quadrupole Storage Mass Spectrometry*”, John Wiley & Sons, New York, 1989.

[6] W. Lotz, Z. Phys. 206 (1967) 205.

[7] Kim, Prat, Phys. Rev. A 27 (1983) 2913.