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CHARGE BREEDING SIMULATIONS IN A HOLLOW GUN EBIS

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Abstract

Charge breeding technique is used for Radioactive Ion Beam (RIB) production in the Isotope Separation On Line (ISOL) method in order of optimizing the re-acceleration of the radioactive element ions produced by a primary beam in a thick target. That technique is realized by using a device capable of increase the radioactive ion charge state from +1 to a desired value +n. In some experiments a continuous RIB of a certain energy could be required. Recently, a charge breeding device based on a hollow gun EBIS that in principle could reach a Continuous Wave (CW) operation, has been proposed1). Although, in principle, the hollow in the electron beam produced by that EBIS can be reduced up to zero by an enough high focussing solenoid magnetic field, a reduction on the ion charge state increase efficiency should be expected. In order to study that problem, a code already developed for studying the ion selective containment in a EBIS with RF quadrupoles, BRICTEST2), has been implemented. In this paper, the ion charge state breeding decrease due to the hollow electron beam has been studied by simulating the ion motion inside the hollow gun EBIS with the implemented BRICTEST code

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1 INTRODUCTION

Radioactive ion beams (RIBs) are an important tool for experiments at the foremost frontier of nuclear physics. Recently, the final report of the design study of the European project EURISOL has been published$^{3)}$. In that report the design of a European ISOL type facility capable of producing RIBs with intensities several order of magnitude greater than those available today has been presented. An important problem studied in the EURISOL design was how to reach higher efficiency in the RIB post-acceleration. In fact, 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 for the RIB can sensitively lower the accelerator cost. That high ion charge state can be realized by using an appropriate device capable of increasing, before of the post-acceleration, the radioactive ion charge of the elements that have to be accelerated.

The EURISOL design study report has also confirmed that the 'charge breeding' technique used to increase the ion charge state of the produced radioactive ions can be based on two different type of ion sources: the Electron Beam Ion Sources (EBIS) and the Electron Cyclotron Resonance Ion Sources (ECRIS)$^{3)}$. The Rex-ISOLDE experiment, in fact, had already shown that the charge breeding of radioactive beams is possible with efficiency, typically, up to *10%* in one charge state and breeding times of *~50 ms* for light beams and *~150 ms* for heavy beams. In order to become comparable in the overall efficiency with the 'classical' more expensive stripper scheme, all the steps of the breeding process have to be optimized. The possibility of optimizing the charge breeding process trough several techniques had been also explored in the European project EURONS-JRA3$^{4)}$. Furthermore, also in ref.$^{4)}$, a comparison between the two types of 'charge breeders', the EBIS and the ECR based, has been shown. In that work it has been pointed out the advantages and the drawbacks of both devices and has been shown as one of the main problem of an EBIS based 'charge breeder', for high RIB intensities, it is the impossibility to be operated in CW. In ref.$^{1)}$ a kind of EBIS that at least in principle, could reach the CW operation has been proposed and built for a test experiment. Practically, it consisted of a typical EBIS which had an electron gun with hollow cathode. That kind of e-gun, in fact, would allow a continuous injection of 1+ ions from the e-gun side and, as usual, the extraction of the n+ ions from the electron collector side.

Although, in principle, the hollow radius, r_h, in the electron beam of that EBIS could be reduced up to zero by an enough high focussing solenoid magnetic field, also a reduction on the ion charge state increase efficiency should be expected. Since the charge breeding efficiency is very important for an efficient RIB acceleration, in this paper, the study of the ion charge state breeding decrease due to the hollow electron beam (*eb*) has been performed by simulating the ion motion inside the hollow gun EBIS. Those simulations have carried out by using the code BRICTEST$^{2)}$, already developed for studying the ion selective containment in a EBIS with RF quadrupoles. In order to take into account the hollow effect in the charge breeding, an implementation to the code that is shortly presented below, has been done too.

2 THE BRICTEST CODE IMPLEMENTATION

The BRICTEST code, developed in Bari INFN section few year ago$^{2)}$ to study the ion motion stability inside a test EBIS device (BRIC$^{5)}$) which had rf quadrupole electrodes for selective containment, can be also used for studying our problem of ion charge breeding efficiency in presence of an ionising *eb* with a small hollow inside. The ion motion equations shown in ref.$^{2)}$, in fact, are still valid when we put the quadrupole electrode voltages, V (rf voltage) and U (dc voltage), to zero. However the space charge term, already present in the eq.s, had to be modified to take into account of the eventual *eb* hollow having a radius r_h. The motion equations, however, can be written again as in ref.$^{2)}$:

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

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

Where, also here:

$$\tau = \frac{1}{2}\omega t;\ a_x = -a_y = \frac{4q_iU}{m_i\omega^2 r_o^2};\ q_x = -q_y = \frac{2q_iV}{m_i\omega^2 r_o^2}; \qquad (2)$$

and with the same parameter: $b = \dfrac{2q_i B}{m_i\,\omega}$, related to the solenoid field B, while this time we have a new space charge parameter: $c = \left(\dfrac{1}{4\pi\varepsilon_o}\right)\dfrac{8q_i}{m_i\omega^2(r_b^2 - r_h^2)}\dfrac{I_e}{v_e}$, where r_h is, as mentioned above, the hollow radius inside the *eb* .

Notice that in eq.s 2 we put a_x and q_x zero because we use $U = V = 0$ (no more RF field electrodes) and that the parameter τ it is continued to be used instead of the time t for 'historical reason' (the code has been developed for rf selective containment). Furthermore, we have to notice also that in the region where $r<r_h$ no space charge force is felt by the ions. In that region, then, only the solenoid magnetic field needed for eb focusing acts on the ions.

The BRICTEST code, other than to follow the ion motion in the EBIS trap, computes the ion charge state breeding evolution through the following equation system :

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

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.

In general, the 'charge breeding' calculation is carried out simply by assuming fixed the 'overlapping' region between the electron and the ion beam. Notice that in the eq.s (3) it is assumed a complete 'overlapping'. In the case of a no complete overlapping, instead, each term of eq.s (3) has to be multiplied by a factor (F_{ov}) that takes into account the part of the ion beam cross section that it is not hit by the electrons. To evaluate that factor we consider a transverse *eb* section size given by $S_b=\pi r_b^2$ and assume $S_b=S_i$ (ion beam transverse size), if we call S_h the hollow surface inside the *eb*, the mentioned factor will be given by $F_{ov}= S_h/S_b$. In term of the radii, being $S_h=\pi(r_b^2-r_h^2)$, $F_{ov}=(1-r_h^2/r_b^2)$. Then for $r_h/r_b= 0.2$ we will have $F_{ov}=96\%$ (a reduction of 4%).

The assumption of a fixed 'overlapping' can be a good approximation when the +1 ion beam is injected in the *eb* with practically the same radius and with a low transverse velocity as it is usual. In the our case, however, the *eb* has a hollow inside, then, the above approximation is no more a good one and the charge breeding calculation has to take into account that the ions oscillate in the *eb* potential well. Then, for a while, they will move also in the hollow region where they cannot increase their charge state because they are no more hit by the electrons. In order to make more accurate calculations the code, in some way, had to take into account the above mentioned transverse oscillating ion motion.

The original code BRICTEST, actually, had already the possibility to follow the ion motion and check if their positions were outside the *eb* transverse size. In that case, those ions were not considered for charge breeding in the eq.s (3), where to this purpose the initial ion density n_i was properly updated. To take into account also the effect of the hollow region inside the *eb* for the ion charge state evolution calculation, the code has to check when the ions are inside the hollow region and, in that case, exclude them, again, for the charge state increase calculation. Furthermore, we have to add that since the code could not follow the motion of too many ions otherwise the calculation time became too long, only part of them had be followed in their motion, typically 4000. That number seemed enough big to understand ion behaviors in the EBIS trap but it was too low, for statistical reason, to be used for the calculation of n_i in the eq.s (3). For that reason, each ion, followed by the code through the eq.s (1) in its motion, has been multiplied by a factor N (typically, 5000 seem enough), when the n_i are computed through the eq.s (3). Then the total number of ions for which is computed the charge state evolution used in the eq.s (3) is, typically, of about $2x10^7$.

In short the implemented code acts in this way. It generates a 1+ ion distribution, flat in transverse positions and velocities, with the max transverse position given by r_b and the max transverse velocity that can be chosen through the factor *vfac* for which the longitudinal ion velocity is divided to get the transverse one. After that, it checks what are the ions inside the *eb* hollow and excludes them to be considered for charge state evolution by updating the n_i in eq.s (3). Then , it propagates all the ions by means of the eq.s (1) in the EBIS trap and after each integration step it performs a new check on the ion positions in order to properly re-update the n_i of eq.s (3) and then it computes the correct new ion charge state distribution.

Another implementation that has been done to the BRICTEST code with respect to description done in the original paper, has been the inclusion of the space charge compensation as reported in ref.6).

3 SIMULATION RESULTS

In the simulation results shown in fig. 1, the charge state evolution with a fixed 'overlapping' of *96%*, corresponding to an r_h of *20%* with respect to r_b (a reference value for our E-gun design1)), has been considered for comparison with the case of the ion charge state distribution evolution of an *eb* without hollow. From that figure it can be seen that although r_h is not so small, only a very slight difference can be noticed between the two ion charge state simulations. However, as already above noticed, in the case of the presence of a hollow in the *eb*, the fixed 'overlapping' assumption could to be a very rough approximation. A more accurate ion charge state distribution evolution calculation can be carried out by using the new features of the code described in the previous paragraph. However, before of that, test simulations has to be done in order to verify if the modified code still give reliable results. To this purpose, test particles, for which are stored the trajectories for all the simulation time, have been introduced. Through the test particle trajectories one can monitor if the ion motion is consistent with the involved forces.

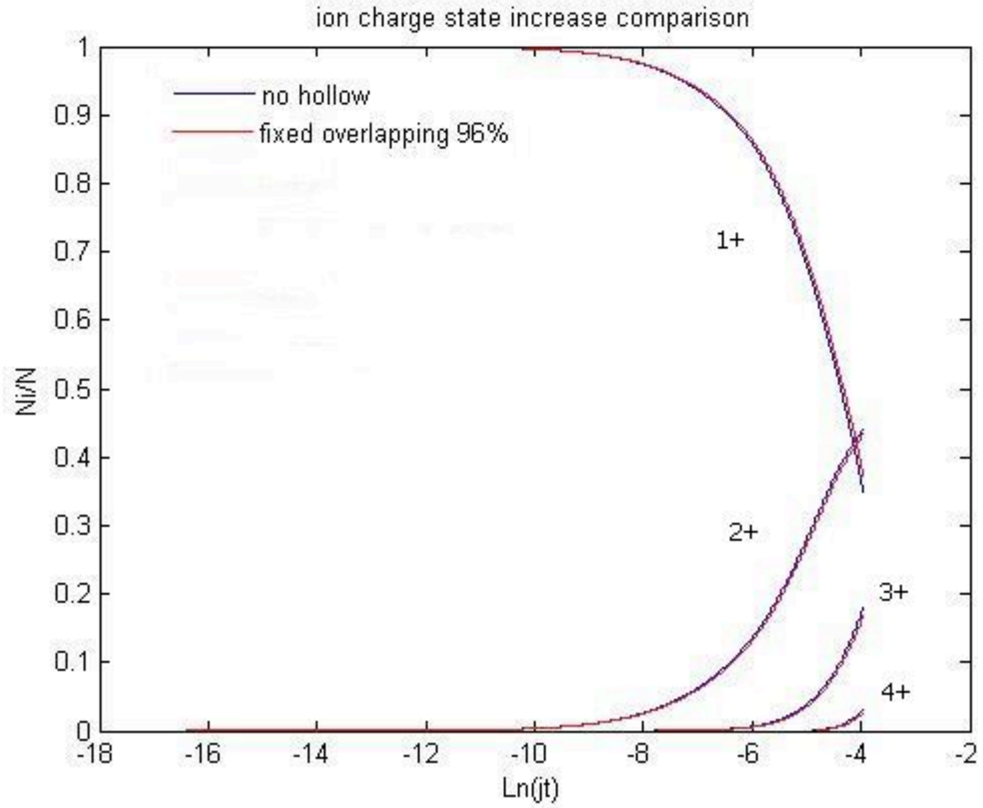

Figure 1 - Ion charge state evolution for the 96% fixed 'overlapping' case. The simulation results shown are so close that the curves can be hardly distinguished.

The routine used to solve the motion equations (1)[2)] could no more work when all the force terms, except the solenoid field, are put to zero. As first test, then, we have verified that the 1+ ion motion was correctly simulated also in the *eb* hollow region where only the solenoid magnetic field acts.

In fig 2, the simulation results of the test particle transverse positions, x and y (a) and their transverse velocities, v_t (b) *vs Ns* (integration step number) are shown. From the simulation results of fig.2, it can be noticed that test ion motion is consistent with the forces involved. In fact, they oscillate in the *eb* potential well, placed in the centre of the pipe ($x=y=0$), and solenoid field but when they move in the hollow region, where only the solenoid field acts, they have a constant radial velocity (see fig. 2 b)) as it has to be since the magnetic field does not change the velocity module. That means the routine solving motion eq.s (1) works well also in the new conditions with no rf field.

The simulation results of the ion charge state evolution given by the implemented code described before are shown in fig. 3 where the same case of fig. 1 is presented. In those simulations, however, the fixed 'overlapping' of 96% assumed before has been modelled by considering, inside the *eb*, a cylindrical shaped hollow with a section having a radius $r_h=0.024$ *cm* corresponding to a *20%* of r_b. From the results of fig. 3, it can be seen that, this time, the case of *eb* without hollow shows a sensitive difference with respect to the case of the *eb* with a hollow on the contrary of the results seen in the 'fixed overlapping' simulation of fig.1. The more accurate simulations obtained by taking into account the ion motion in the *eb* hollow, then, show a sensitive slow down of the charge breeding rate that can be better understood by observing the test particle ion motion behaviour for all the simulation time (*~1.5 ms*) as it will be discussed later. Before of that, however, we have to mention an unexpected behaviour in some test ion motion when observed all along the simulation time

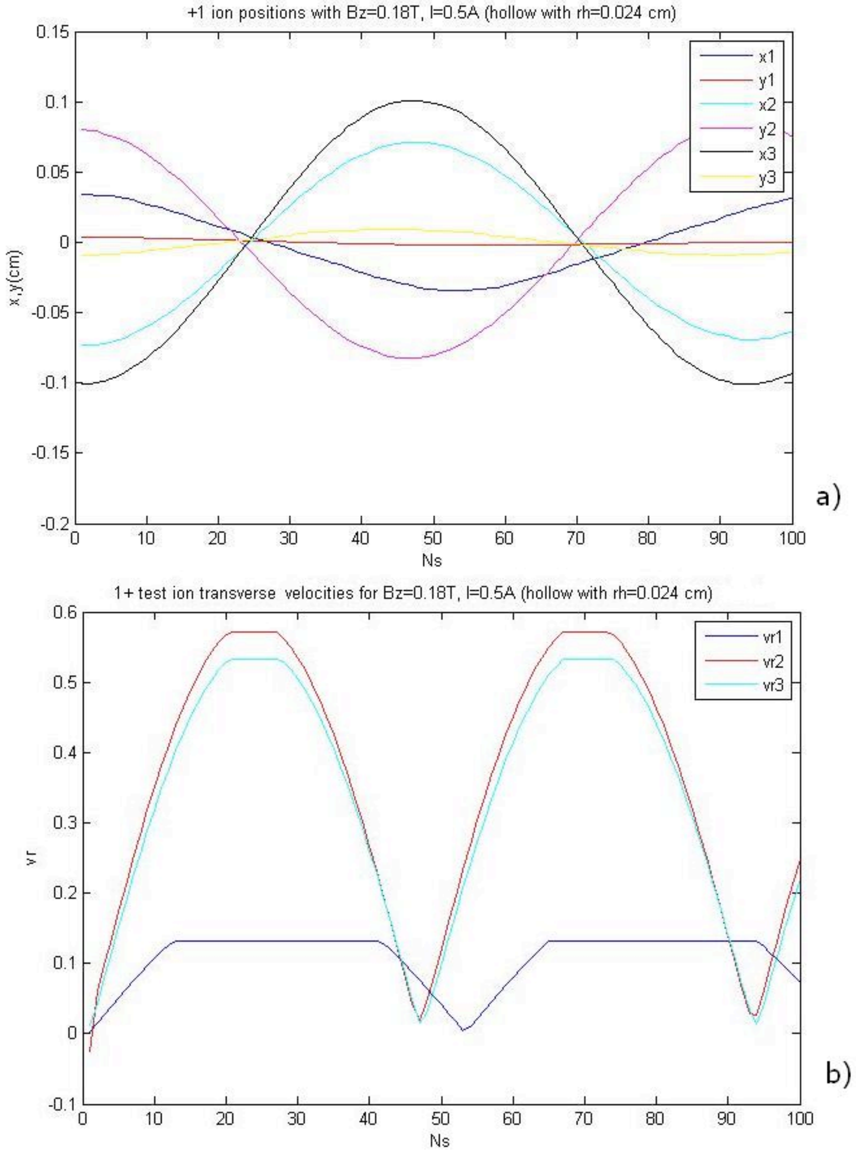

Figure 2 - a) Test particle transverse position vs integration step number Ns (with step length l_s*=0.0004μs); b) test particle transverse velocities. For the simulation a hollow of radius* r_h*=0.024cm has been used. The numbers 1,2,3 refer to different test particles.*

The test particle transverse velocities for all the simulation time are shown in fig.4a). There, actually, the transverse velocities of the test particle *1* and *2* present the expected results, that is, ions oscillating with constant amplitudes. In fact, although at the beginning of the simulation it can be seen decreasing amplitude oscillations, which are due to the space charge compensation that takes place during the ionization process[6], after that, those amplitudes remain practically constant. That is the correct ion motion behaviour since in the motion equations considered above are present only conservative force terms. The *3* test particle transverse velocity simulation, however, presents damped oscillating amplitudes. More precisely, its amplitude decreases up to a small constant value different from zero in about *1ms* and then it remains constant. The oscillating amplitudes of the *3* test particle, in fact, reduces up to a minimum of a value about r_h and after that it continues its motion only in presence of the solenoid field and then its velocity remains constant.

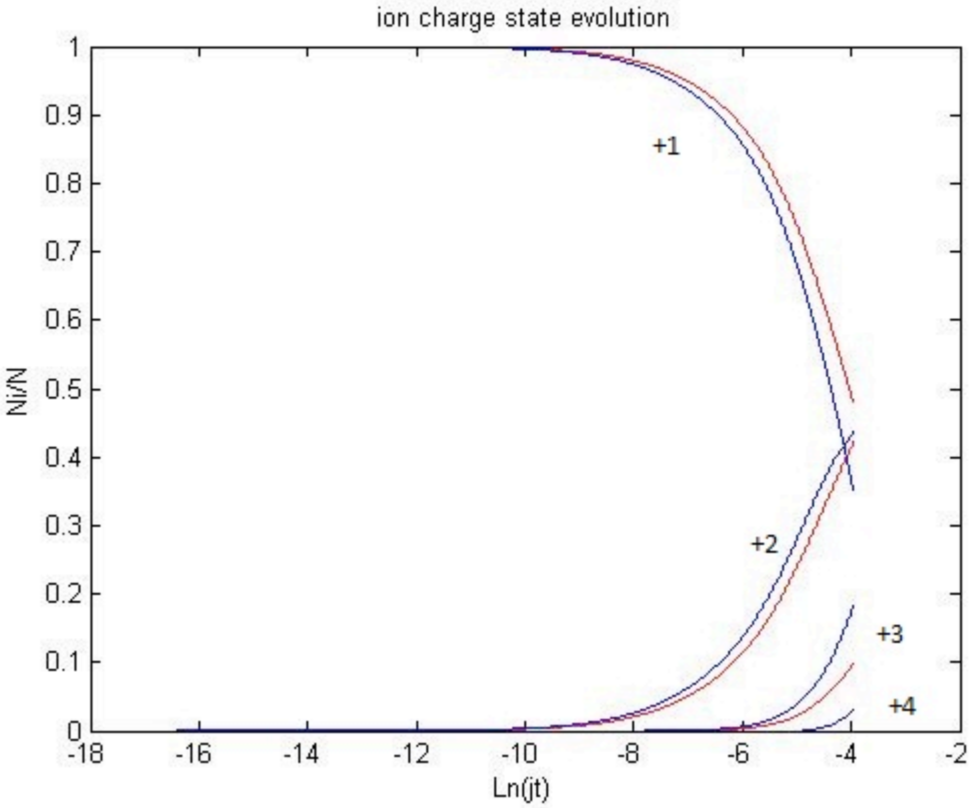

Figure 3 - Ion charge state distribution evolution for r_h=0.024cm (being r_b=0.12) corresponding to an overlapping of 96% (the redline refer to rh=0.024, the blue line to rh=0.0)

The *3* test ion motion behaviour cannot be explained by the only conservative forces present in the motion eq.s (1). However, since this kind of damping motion it is found only in the presence of a hollow in the *eb*, it can be thought that it is the same hollow inside the *eb* potential well that could induce a kind of 'out of phase' parametric resonance effect in the motion of some ions (see below). Furthermore, on the other hand, in figure 4b), where the initial and final transverse ion position distributions are shown, it can be noticed that in the right final ion distribution (case with r_h=*0.024 cm*) there are particles placed at a very far distance from the potential well centre and then out of the *eb* cross section. Those positions are indicative of ions having had an oscillating motion with increased amplitudes (compare with the left figure where no hollow is present in *eb*). That increase, on the contrary of what observed before, can be due to an 'in phase' parametric resonance effect.

In conclusion, it seems that in the simulations with a hollow *eb* some ions decrease their oscillating amplitude up to remain trapped inside the hollow and some other increase their oscillating amplitudes. Both those types of ions, of course, will contribute to slow down the charge breeding rate of the device as it has been confirmed by the results shown in fig. 3 where, as already mentioned, the ion charge state distribution evolution for an r_h=*0.024* cm have been presented together to the case without hollow. Also the ions with increasing oscillation amplitudes, in fact, since stay outside the *eb* for an increasing fraction of time will contribute to slow down the charge state increase rate.

Just for comparison with fig. 4a), in fig 5 it is shown the simulation of the test particle transverse velocities for the case of an *eb* without hollow. In that figure, as expected, nor dissipation or excitation in the oscillating motion can be observed and all the ions, after the charge space compensation process, oscillate inside the *eb* potential well with constant amplitudes until the end of the simulation time.

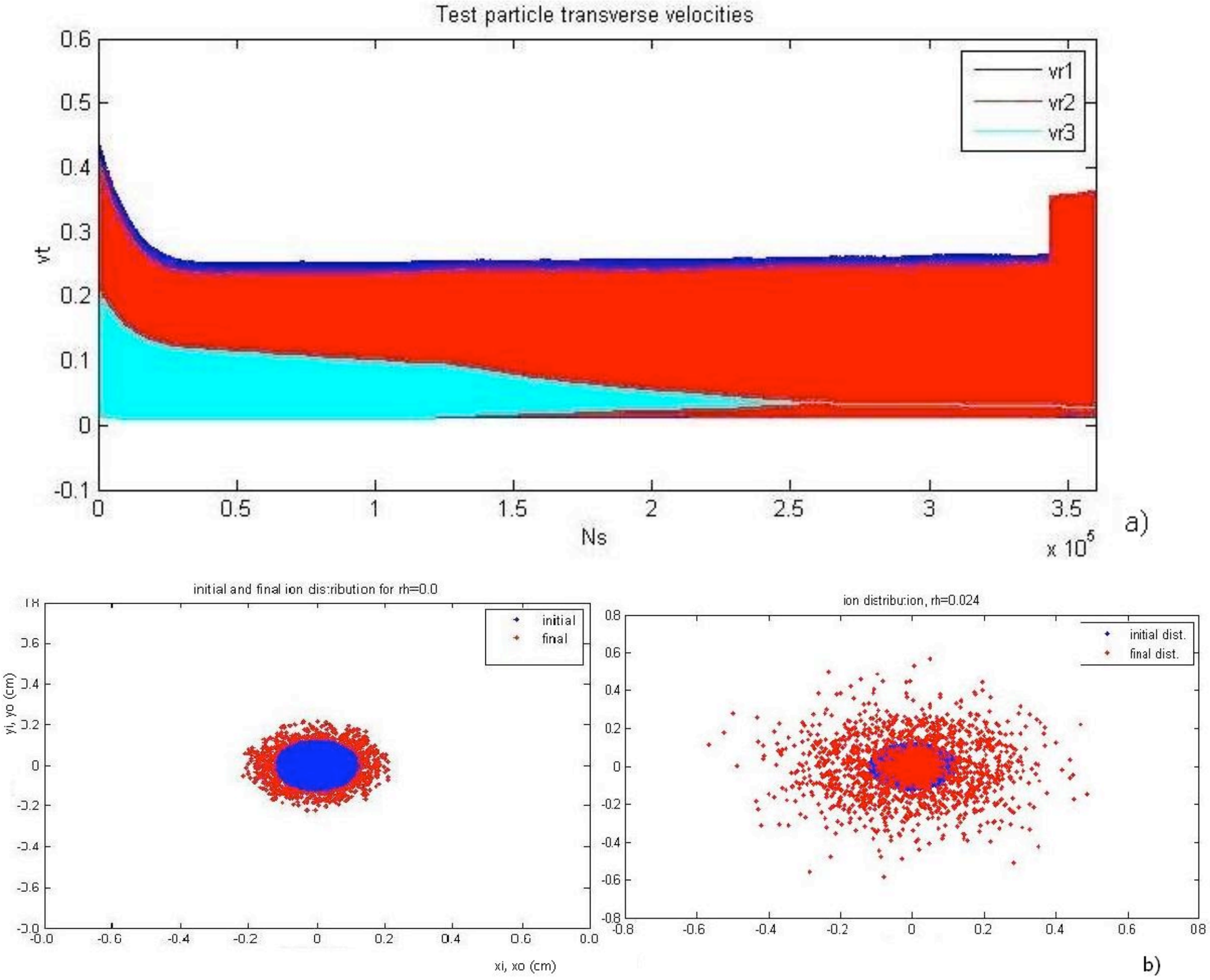

Fig.4. a) Test particle transverse velocities. Notice that the oscillating periods (see fig. 2) are very small with respect the simulation time (1.5 ms). The vr_2 *sharp increase, that can be noticed almost at the end of simulation time, is given by the charge state increase of test particle 2. b) Initial an final transverse ion position distribution: on the left, the case* $r_h=0.0$ *and on the right, the case* $r_h=0.024$.

All the simulation carried out until now to study the ion charge state breeding in presence of a hollow in *eb* has confirmed that some test particles could manifest the unexpected motion behaviour described before. Although the above observation could explain the simulation results of fig. 3, it remains yet to understand the mechanism that causes damped or increased oscillation amplitudes of the ions. In fact, as already observed above, from the motion eq.s (3) it can be seen that on the ions are applied only the *eb* potential well and a focusing constant, longitudinal, magnetic field, which are both conservative forces. It is well known that in the presence of only conservative forces no damped or increasing ion oscillating motion should happen. Further simulations, then, are under way in order to better study and clarify the mechanism inducing oscillations with damping or increasing amplitudes.

However, from the simulations carried out up to now, it can be guessed that the presence of a hollow in the *eb* introduces discontinuities in the space charge potential well which seems to be felt by the ions, in that place, as an extra force that perturbs their motion. that force seems to act with different strengths on different oscillating ions then it seems to have resonant features as it is when parametric resonances occur. In fact, since in the ion motion equation solution are used finite integration step length, l_s, it could happens that some ions, during their motion, could see a potential well depth slightly different in each period. More specifically, when the transverse starting ion position is inside the *eb* cross section and the final transverse position results in the hollow region, that ion is treated as if it was subjected to the potential well for all the step, while, once inside the hollow region, no more electric field would act on it.

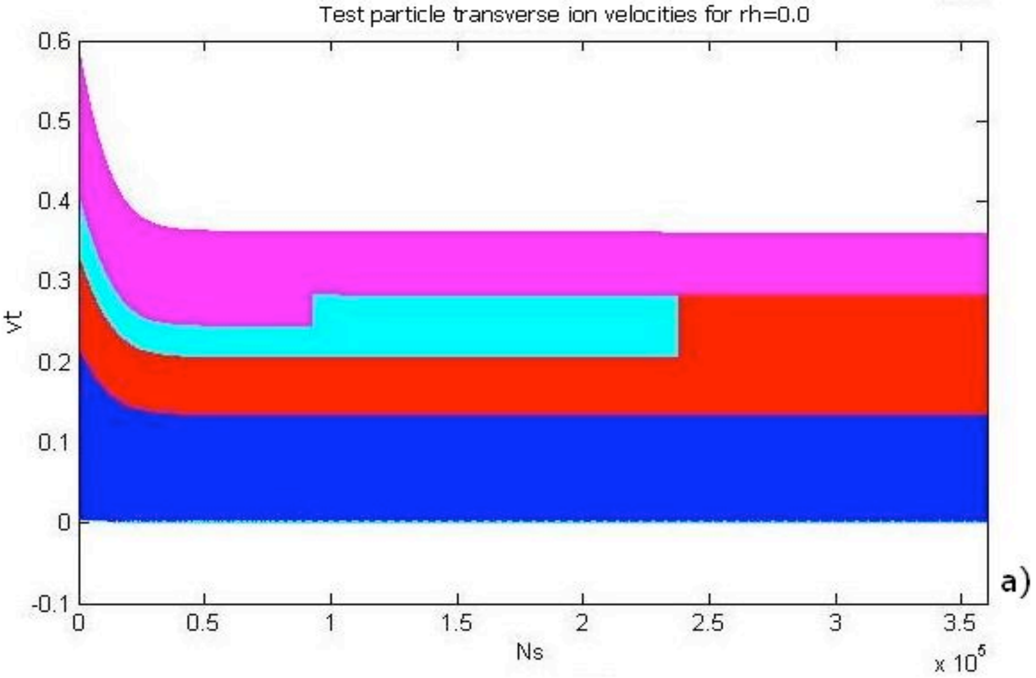

Fig. 5. transverse velocities different colours refer to different test particles. Jumping in the curves refer to ion charge state changes. Different colours refer to different test particles. The initial oscillation amplitude decrease undergone by all the test particles is due to space charge compensation.

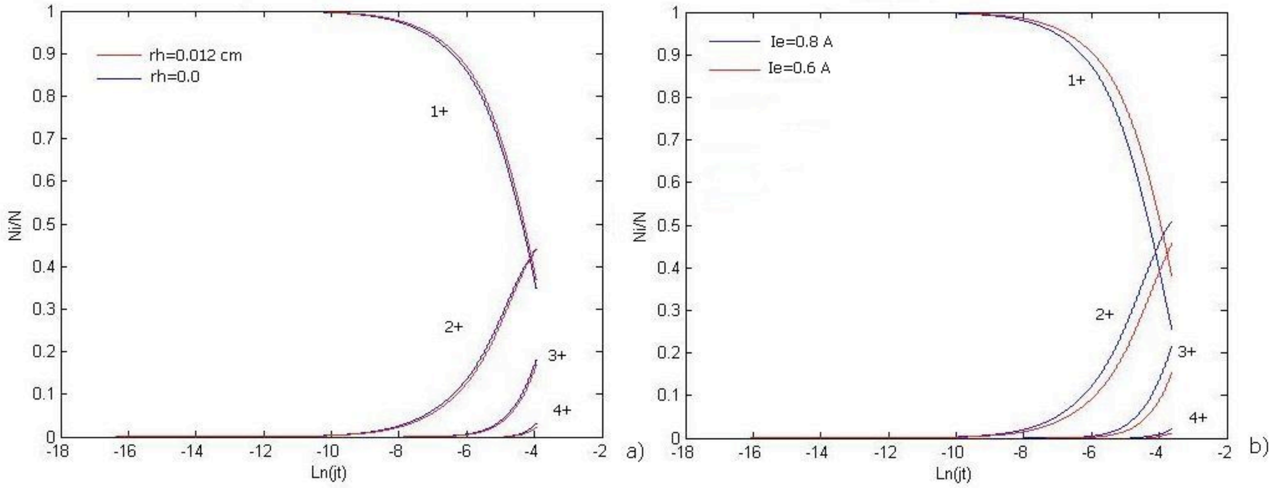

Fig. 6. Ion charge state distribution evolution : a) case of comparison with no hollow and r_h=0.012 cm; b) case of rh=0.024 cm with different eb currents.

Furthermore, we have to notice that the finite step length, l_s, used to integrate the motion eq.s (1), in correspondence of the sharp potential discontinuity due to hollow, could result to be, in any case, too long for giving correct calculation results. The above ion motion anomalies could be, then, due to the rough way of the code to take into account the discontinuity between the potential well and the hollow region where null space charge field is present. On the other hand, however, when we tried l_s shorter than *0.004 μs* (value used in all the simulations shown above) we did not observe significant modifications on the ion motion behaviour.

In practice, then, it is still not clear if the anomalies noticed on the ion motion behaviour in our EBIS trap with the hollow *eb* is a physical or numerical effect due to approximate calculations. Further simulations are under way in order to better understand the mechanism which causes amplitude increasing or damping in the ion oscillating motion. In any case, the experimental results would clarify the dilemma.

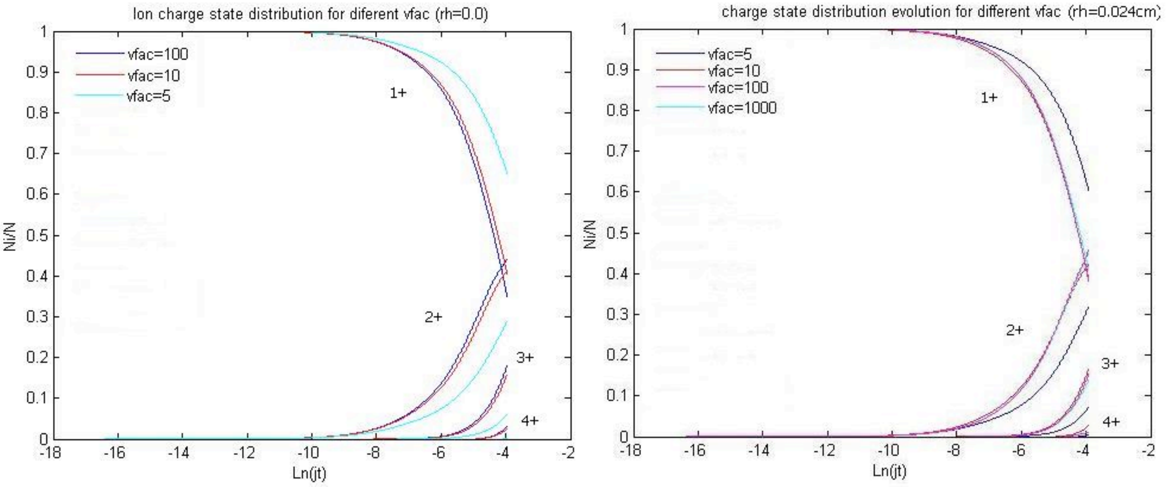

Fig. 7. Ion charge state distribution for different vfac. On the left it is shown the case with r_h=0.0, on the right the case r_h=0.024cm.

Finally, in order to understands as different parameters can affects the ion charge state increase rate, simulations with a r_h*=0.012cm* and an other with I_e*=0.8A* have been carried out and the related results are shown in fig. 6. Form those results, it can be seen how a r_h reduction from *20%* to *10%* with respect to r_b could improve very sensitively the ion charge state increase rate. Furthermore, also a relatively small increase (*0.2A*) of the *eb* current can further improve the rate (see 6 on the left). An other important parameter that can affect the ion charge state breeding rate is the ion transverse velocity. A high ion transverse velocity, in fact, can induce large amplitude oscillations with a proportionally large fraction of ion motion spent outside the *eb* transverse section and that imply a reduction of the ion charge state increase rate. In fig. 7 are shown the simulation results of the ion charge state distribution evolution for different ion transverse velocities factor, *vfac*, for both cases with and without hollow in *eb*. From the ion charge state distribution evolution simulations shown in that figure it can be seen that for *vfac* values in the range *10 ÷ 100* the results are very similar but when we used a value of *5*, that is, an ion maximum transverse velocity *1/5* of their longitudinal velocity (corresponding to a kinetic energy of about *4 keV*) the charge breeding rate became very slow. Then, it can be concluded that, although the trapped ion transverse velocities should remain as low as possible, transverse velocities as high as up to 1/10 of their longitudinal velocity can be accepted without any significant slow down of the charge breeding rate.

4 CONCLUSION

The code package BRICTEST developed to simulate the ion charge state evolution in the BRIC device where rf field was used for selective containment could be used, after small modification, also for studying the ion charge state increase rate in an hollow gun EBIS.

The simulation results have shown that the rough approximation with ‘fixed overlapping’ between *eb* and ion beam transverse sizes gave improper results. More accurate simulations, in fact, show that the ion charge state increase rate slow down sensitively with respect of the ‘fixed overlapping’ case when an enough long interaction time was considered. Some ‘anomalies’, as the unexpected increased or damped oscillation amplitudes manifested in the ion motion behaviour when an hollow *eb* was used.

Further simulations are underway to better understand if the ion motion anomalies, noticed in the simulation results, are related to parametric resonance effects and then real or not. In any case a proper e-gun design with enough strong magnetic field could reduce the hollow radius r_h practically to zero and then avoid a sensitive slow down of the ion charge state increase rate. Of course, the experiment, now in phase of mounting[1)] would also help to clarify the above problem.

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