A QUASI-3D MODEL OF ELECTRON CYCLOTRON RESONANCE ION SOURCE*

L. Zhao[a)], B. Cluggish[b)], J. S. Kim, FAR-TECH, Inc., San Diego, CA 92121, U.S.A.

Abstract

FAR-TECH, Inc. is developing a hybrid, quasi-three dimensional (Quasi-3D) model to simulate charge breeding of a test 1+ or 2+ ion beam in an electron cyclotron resonance ion source (ECRIS). The model is a combination of three dimensional (3D) mapping of the plasma background calculated by a 1D Generalised ECRIS Model (GEM-1D) [1] and 3D tracking of the ion trajectories with Monte Carlo Charge Breeding Code MCBC [2]. The background plasma on axis that is calculated self-consistently in GEM-1D is mapped to 3D space using the conservation laws of energy and magnetic moment. The test beam ions are then tracked in the plasma using MCBC which includes Coulomb, ionization and charge exchange collisions. The exact ion trajectories in the plasma and steady state 3D ion distribution at the extraction aperture are predicted and compared with the experiments on rubidium (Rb) charge breeding at Argonne National Laboratory (ANL).

INTRODUCTION

In an ECR charge breeder device, a beam of lower charge state ions (typically 1+) are injected to an ECRIS plasma. The injected ions are then trapped and ionized to higher charge states due to Coulomb collisions and ionizations with the background plasma. An ECR charge breeder can produce large, steady state currents of high charge-state ions of all natural elements and is highly suited as a source for heavy-ion accelerators used in nuclear and high-energy physics research.

One of the challenging aspects of ECR ion sources is the complicated, three dimensional structure of the magnetic field. A numerical model of the ECRIS plasma that could predict the asymmetric distribution of the extracted beam ions would be extremely useful to ECRIS users.

FAR-TECH, Inc. has developed a hybrid, quasi-three-dimensional ECRIS modelling tool to simulate a test ion beam charge breeding in an ECRIS plasma. This code combines the 3D tracking of the ion trajectories using a test particle Monte Carlo method with a 3D mapping of a 1D background plasma which is calculated by a self-consistent ECRIS model, GEM-1D. By calculating the plasma dynamics self-consistently, the code only relies on experimental parameters. Also, the simulation tool is able to provide realistic, 3D distributions of ion trajectories at the extraction aperture, which can be compared to experimental results and allow users to analyze and optimize the extracted beam.

* Grant supported by DOE office of Nuclear Physics
[a] zhao@far-tech.com
[b] Working at General Atomics now.

This paper will describe this Quasi-3D simulation tool using a test simulation to a Rb charge breeding experiment on ECRCB [3] at ANL. The modeling details are presented and discussed.

SIMULATION SETUP

As an example application, we have used Quasi-3D ECRIS model to simulate Rb charge breeding experiments in ECRCB device at ANL. The plasma in the device is heated by a RF and confined by a mirror field and a hexapole field shown. A beam of +1 Rb ions are injected from the injection end. The ions with high charge states are collected at the extraction end as the output of the charge breeder. The basic operation parameters in the experiment are listed in Table 1.

Table 1: Operation Parameters

Parameters	Values
Rf power	270 W
Rf frequency	10.44 GHz
Supporting gas	oxygen
Gas pressure	1.2e-7 Torr
Length	29 cm
Radius	4 cm
B field ratio	4.3 and 3.0

DESCRIPTION OF THE QUASI-3D MODEL

With the parameters given in Table-1, we can simulate charge breeding experiments using the Quais-3D model. The standard simulation procedure is divided into 4 steps: 1) analytically calculating the magnetic field on a give 3D grid; 2) generating a 1D axial background oxygen plasma using GEM-1D; 3) mapping the 1D plasma to 3D space based on the conservation laws and the assumption that ions "follow" the electrons through quasi-neutrality and ambipolarity; 4) tracking injected 1+ Rb ions until the ions are either lost or extracted. The output of the simulation is the ion distribution at the extraction aperture. The procedure will be described in detail in the following paragraphs.

Magnetic Field

The magnetic field on the ECRCB is composed of a mirror field and a hexapole field. The measured on axis mirror field is fitted to a polynomial and extrapolated to 3D based on $\nabla\cdot\vec{B}=0$ and $\nabla\times\vec{B}=0$. The hexapole

Copyright © 2011 by PAC'11 OC/IEEE — cc Creative Commons Attribution 3.0 (CC BY 3.0)

field is also fitted from experimental measurements using following approximation formula:

$$B_r(r,\theta) = B_a\left(\frac{r}{r_a}\right)^2 \sin 3\theta$$
$$B_\theta(r,\theta) = B_a\left(\frac{r}{r_a}\right)^2 \cos 3\theta \qquad (1)$$

where θ is the azimuthal angle, B_a and r_a are fitting parameters. Combining the mirror field with the hexapole field, we can calculate magnetic field vector everywhere in space. The contour plots of the magnetic field on different cross-sections are shown in Fig. 1. The ECR resonance surface (B_{res}=0.37T in Fig. 1) is clearly showing complicate 3D features.

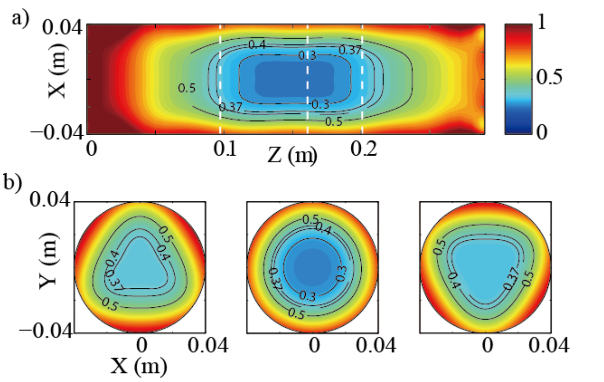

Figure 1: Contour plots of the minimum-B field (in T) configuration on an ECRIS. a) field contour at y-z plane. b) field contours at x-y plane at, from left to right, z~0.1, 0.15 and 0.2 m.

1D Background Plasma by GEM-1D

GEM-1D is a 1D hybrid model for ECRIS plasma modelling. It calculates electron distribution function (EDF) by solving a bounce-averaged Fokker-Planck equation and calculates cold ions using a fluid model because ions are highly collisional. Electrons and ions are balanced through quasi-neutrality and ambipolarity.

Since the bouncing frequency of electrons is much greater than the collision frequency, EDF on mid-plane is able to be mapped axially along the magnetic flux surface through electron energy (E) conservation and magnetic moment (μ) conservation:

$$E = \frac{1}{2}m_e v_\parallel^2 + \frac{1}{2}m_e v_\perp^2$$
$$\mu = \frac{m_e v_\perp^2}{2B} \qquad (2)$$

where $v_\parallel$ and $v_\perp$ are the electron velocities. As we can see from Eq. 2, EDF, $f(v_\perp, v_\parallel)$, is only a function of B. Ions are calculated by solving 1D fluid continuity equation with the assumptions that all ion species are moving at one fluid velocity and total ion flow equals total electron flow. Also quasi-neutrality is satisfied and Bohm condition is imposed for the ions at the device walls. The converged solution is a quiet 1D ECRIS plasma along the axis. GEM-1D has obtained simulation results consistent to the experiments [1].

Mapping 1D Plasma to 3D Space

The Quasi3D model is based on the fact that electrons bounce back and forth along the magnetic fields while drift across the fields and thus cover a large area almost ergodically. In this region, EDF can be well described as functions of B. As noted, although the electron density, temperature, etc. are not solely functions of the magnetic field but a good approximation. For example, the plasma density $n_e(z)$ that is calculated by GEM-1D is obviously a function of B (the function is written as $n_e(B)$) within the assumption stated above. Then $n_e(x,y,z)$ for any given point (x,y,z) can be obtained if B at that point is given. The resultant 3D electron density contours are shown in Fig. 2 on the same planes shown in Fig. 1. The contours have similar shapes compared to those of magnetic fields, which they should be.

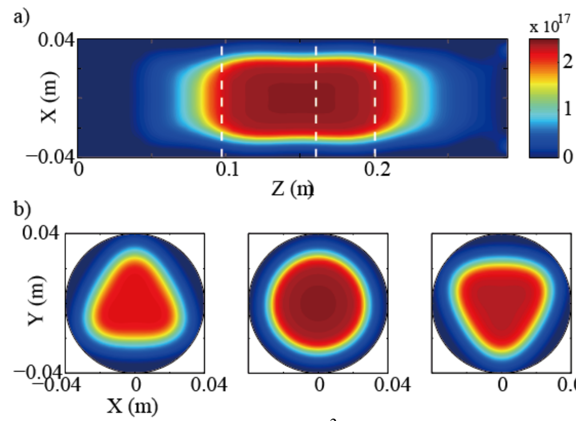

Figure 2: Electron density (in m^{-3}) contours in 3D space. a) X-Z n_e contour; b) X-Y n_e contours are at the positions marked as white dotted line on X-Z contour (a).

Ions are not expected to cover most of the phase space within a typical ECRIS confinement time. We mocked up oxygen ion distributions in ECRIS by applying a similar mapping technique used for electrons. One justification, however, is that applying such mapping to ions provides a solution that matches GEM-1D on axis. With that, we applied the same 3D mapping technique to oxygen related plasma parameters such as plasma potential (ϕ), neutral density (n_0), effective ion charge (Z_{eff}), ion density (n_i) and ion temperature (T_i).

Track Test Ions using Steady State MCBC

We used MCBC, developed by FAR-TECH, to simulate the trajectories of 10k Rb ions injected into the ECRIS for charge breeding. MCBC is a Monte Carlo charge breeding code that simulates 3D ion trajectories in an ECRIS. It tracks the ions and simulates the effects of Coulomb, ionization, and charge exchange collisions. In

Copyright © 2011 by PAC'11 OC/IEEE — cc Creative Commons Attribution 3.0 (CC BY 3.0)

steady state MCBC, each ion particle that is injected into the plasma is tracked until it leaves the plasma, either by hitting the wall then sticking to it or going out from the extraction aperture. The tracking time for this simulation lasts ~ 4ms until all the injected Rb ions leave the plasma. MCBC has implemented Boris leapfrog pushing algorithm which conserves the energy for large time scales and treat each test particle as a beam-let that enables ion charge, density and velocity being deposited onto the grids like PIC codes do. This way, the Quasi3D model is able to provide 3D information of the extracted ions. Fig. 3 shows the profile of extracted Rb ions, peaking at every 120 degrees azimuthally, as has been observed experimentally.

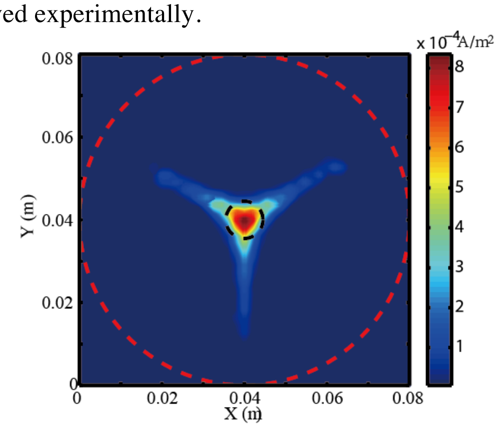

Figure 3: Ion charge distribution on the extraction end. The black dotted line marks the position of the extraction aperture. The red dotted line is the device boundary.

The confinement times of ion charge z can be estimated by the ratio between the total charge (Q_z) of each ion charge state in ECRIS and the loss current (I_z) of each charge state,

$$\tau_Z = \frac{Q_Z}{I_Z}. \tag{3}$$

Fig. 4 shows Rb ion confinement time for different charge states for the test run. For lower charge states, the ion confinement time is increasing with ion charge states. The peak confinement time is ~3 ms, which is consistent with theoretical calculations [4]. For higher charge states, the confinement time curve drops because higher charge states are not well confined in current numerical model.

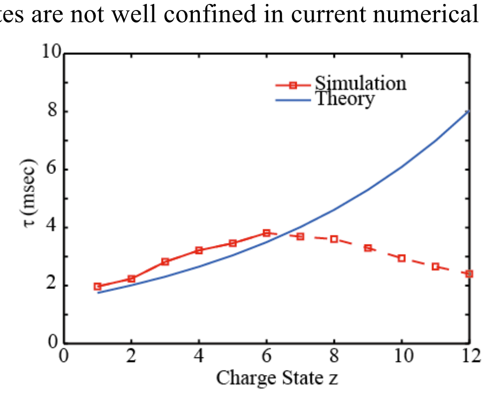

Figure 4: Predicted ion confinement times are compared with a 0D collisional confinement theory [4].

The charge state distribution (CSD) of extracted Rb ions is obtained with the Quasi3D model. The results are shown in Fig. 5. The results are similar to that of GEM-1D, with the CSD peak at a lower charge state than the experiment [3].

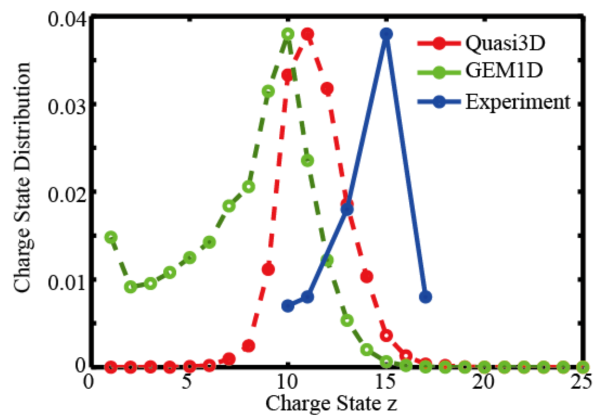

Figure 5: Predicted CSD (red dash, no unit) and comparisons with the experiments (blue solid), simulation results using previous GEM-1D (green dash).

One major discrepancy with the experiments may be that our model does not include wall recycle. Observed from the simulation, the majority of ions are leaving the system once they hit the radial wall. In experiments, the ions should be neutralized at the wall and back into the system. Inclusion of wall recycling in the model will increase the ion and electron populations in the device, as the wall recycled neutrals become ionized. This should make the peak of CSD at a higher charge state.

DISCUSSION AND CONCLUTIONS

The Quasi-3D ECRIS model has been able to track test ions in a 3D background plasma. Full 3D features of ion distribution have been obtained. The comparisons with the experiments and theory are showing reasonably good consistence. Future improvements will be focused on modelling background plasma ions self-consistently instead of 3D mapping approximation. Also the wall effect will be implemented to confine ions for a longer time.

REFERENCES

[1] D. H. Edgell, J. S. Kim, I. N. Bogatu, R. C. Pardo, and R. C. Vondrasek, Rev. Sci. Instrum. 73, 641 (2002).

[2] J. S. Kim, L. Zhao, B.P. Cluggish, I.N. Bogatu, and R. Pardo, Rev. Sci. Instrum. 79, 02B906 (2008).

[3] R. C. Vondrasek, R. Scott, J. Carr, and R. C. Pardo, Rev. Sci. Instrum. 79, 02A901 (2008).

[4] G. Melin, A.G. Drentjie, A. Girard, and D. Hitz, Journal of Applied Physics, Vol. 86, No. 9 (1999).

Copyright © 2011 by PAC'11 OC/IEEE — cc Creative Commons Attribution 3.0 (CC BY 3.0)