VALIDATION AND APPLICATION OF GEM (GENERAL ECRIS MODELING)*

L. Zhao#, J. S. Kim, B. Cluggish, FAR-TECH Inc., San Diego, CA 92121, U.S.A.
Richard Pardo, Richard Vondrasek, ANL, Argonne, IL 60439, U.S.A.

Abstract

GEM [1,2], developed by FAR-TECH Inc, is a self consistent hybrid code to simulate general ECRIS plasma. It calculates EDF (electron distribution function) using a bounce-averaged Fokker-Planck code and calculates the ion flow using a fluid code, which has been modified to implement new boundary settings including fixed boundary ion velocities or fixed sheath potentials at both ends of the device. Extensive studies on the convergence and performance of the code have been performed. Also, GEM has been connected to MCBC (Monte Carlo beam capture) code and the validations of the code using ANL ECR-I charge breeding data and other published experiments are underway. The typical converged solutions of GEM and the comparisons with the experiments are presented and discussed.

INTRODUCTION

Electron Cyclotron Resonance (ECR) charge breeders (ECRCB) are an efficient method of producing highly-charged rare ions. In an ECRCB, lower charge state ions (typically 1+) are injected to an ECRIS plasma which is confined by a mirror field and a multipole field. The injected ions are then slowed down and charge bred to higher charge states due to Coulomb collisions and ionizations with electrons in ECRIS plasma. The high charge state ions are then extracted from the plasma for use in experiments.

To model ECRCB experiments efficiently, FAR-TECH, Inc. has been developing a suit of codes, GEM and MCBC and IonEx [3]. This paper utilizes only GEM and MCBC. The MCBC code uses a Monte-Carlo method to track the test beam ions that have been injected into the ECRIS plasma, which is given by GEM. The code follows the trajectories of the injected ions under the influence of the magnetic and electric fields in the ECRIS plasma, including the effects of Coulomb collisions, ionization, and charge exchange until the ions are captured or lost. The output of MCBC is the spatial profile of captured ions which can be used as ion source term in later GEM calculation.

GEM is an advanced hybrid code that can predict steady state ECRIS plasma self-consistently. It uses only experimental knobs as input, such as rf power, rf frequency, gas pressure, and device configurations to calculate non-Maxwellian EDF (electron distribution function) of hot electrons using a bounce-averaged Fokker-Planck code and solve the flow of the cold ions using ion fluid model. Since the applications of GEM to ECRCB and beam extraction simulations require both axial and radial plasma profiles, GEM has been extended to 2D while simulating the complicate magnetic field in ECRIS and ECR heating zone in 2D configurations. It has obtained some numerical results consistent with experiments.

This paper presents the simulation results of recent ECRCB experiments on ECR-I in ANL using MCBC and GEM2D codes described above. The comparisons with experimental data are also presented and discussed.

CHARGE BREEDING EXPERIMENTS

The experimental results which we discuss here were recently reported at the ECRIS08 meeting and in [4]. In the experiments, singly charged rubidium (Rb) and cesium (Cs) ion beams were injected into the ECR-I device (Fig. 1) at ANL. The ions were captured and charge-bred to high charge states before being extracted. The Rb^{+1} and Cs^{+1} beams were generated using thermionic ion emission sources, which have very low energy spread. During the experiments, ECR-I was floated at approximately the same voltage (10 kV) as the injected ion source. The operating parameters of charge breeding experiments for the Rb beam are shown in Table 1. Parameters for the Cs experiments were very similar. Oxygen was used as the support gas in both cases. The total extracted current was 0.48 mA.

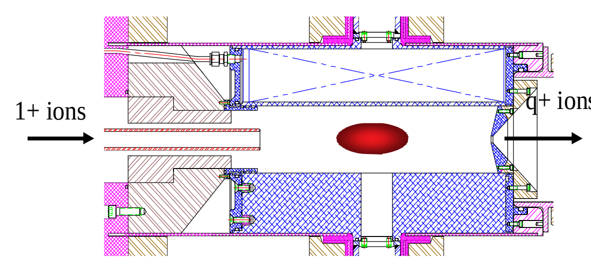

Figure 1: ANL ECR-I [5] device which is used as a charge breeder. The coils and the multicusp magnets provide min-B configuration for the plasma confinement

The voltage difference between the injection ion source and the ECR-I was adjusted to optimize the charge state distribution (CSD) of the charge-bred ions. For Rb, the extracted current of Rb^{+15} was maximized when ECR-I was 18 V below the ion source; for Cs, 35 V was found to maximize the current of Cs^{+20}.

* Work Supported by US DOE SBIR program (Nuclear Physics Division)
# zhao@far-tech.com

Table 1: Operating parameters for charge breeding experiments on ECR -I

Parameters	Values
rf power (W)	270
rf frequency (GHz)	10.44
Gas pressure (torr)	1.2×10^{-7}
Plasma	Oxygen
Length	29 cm
Radius	4 cm
B field ratio	4.5 and 3

CHARGE BREEDING SIMULATION

Three steps are required to simulate charge breeding experiments:

- Calculation of oxygen plasma profiles using GEM2D.
- Modeling of beam ion capture using MCBC.
- Calculation of charge breeding using MATLAB.

The details and simulation results of three steps will be discussed in the following paragraph.

GEM2D

To calculate the profiles of the oxygen plasma, the GEM2D code is using the parameters shown in Table 1. The magnetic field on ECR-I is fitted from axial and radial fields that are calculated using POSSON SUPERFISH input file provided by ANL. The field is then averaged azimuthally for 2D ECRH modeling. The 2D field lines are obtained by averaging the 3D field lines whereas the ECR heating surface is obtained by averaging the magnitude of the field. The first is independent of the multipole field whereas the second is not. Profiles are shown in Figure 2. The radial grids of GEM2D calculation are fixed on these field flux surfaces. The ECR resonance surface is a closed surface which is distributed on both radial and axial directions. Note that GEM2D can model the ECR heating surface with fairly good accuracy compared with the full 3D ECR resonance surface while GEM1D has to ignore the radial dependence of ECR heating. The radial dependence of the later GEM2D results is mainly from this 2D feature of the ECR heating.

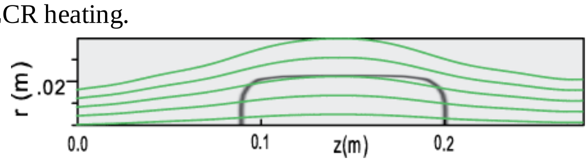

Figure 2: Radial grids that are tied onto the magnetic field lines. The closed shape in the center is the ECR heating surface.

GEM2D runs in MPI (message passing interface) configuration until it gets converged solution. The profiles of electron density, temperature, ion density and ion fluxes that are predicted by GEM2D modeling are showing clear radial dependence due to the spatial distribution of ECR heating in Fig. 2. For example, the predicted electron density profile shown in Fig. 3 is a hollow profile with the density peaked at the ECR resonance surface which is 2 cm away from the device center. The hollow profile of ECRIS plasma has also been observed in the experiments. GEM simulation results and the experimental results are showing that the plasma density peaks around the ECR heating surface.

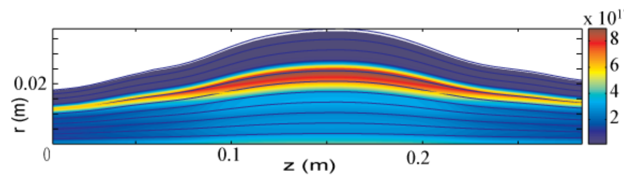

Figure 3: The contour plot of the plasma density (in m^{-3}) modeled by GEM2D.

Fig. 4 shows the 2D potential profile in the plasma. The potential profile shows a "dip" in the center of the plasma, as has been previously predicted. This dip confines the ions in both the axial and radial directions.

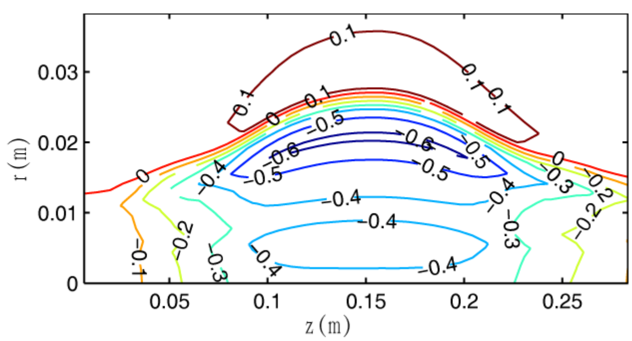

Figure 4: The contour plot of the plasma potential modeled by GEM2D. Potential is in volts.

MCBC

Once the plasma profiles were calculated, the injection and trapping of the Rb and Cs beams were simulated by the MCBC code. All particles were started at the $z = 0$ axial location, where the axial magnetic field is maximum. The beam was assumed to be mono-energetic (E_{Rb}=18eV, E_{Cs}=35 eV), and distributed evenly on the 1mm radius injection aperture.

Each particle was tracked until it was "captured" or hit the wall, with "capture" being defined as having energy less than the 1 eV temperature of the oxygen ions. The locations at which the beam ions were captured were then grouped into 2D bins as shown in Fig .5 for Rb charge breeding.

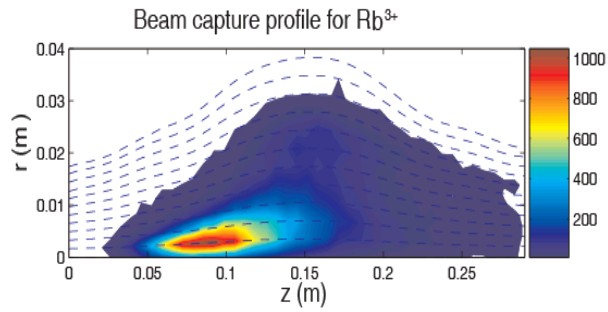

Figure 5: An example profile of captured Rb^{3+} ions in ECR-I plasma.

CSD

Once the ion capture source profiles are calculated by MCBC, we can calculate the charge state distribution of the extracted, charge-bred ions. Because the current of the injected beam (100 nA) is small compared to the total extraction current from ECR-I (~ 1 mA), the injected ions should not perturb the plasma. A MATLAB routine was used to solve the steady state continuity equations (Eq.1) for each charge state, using the beam capture source profiles calculated by MCBC and the electron distribution function calculated by GEM. The continuity equation for charge state q is

$$\frac{\partial n_q}{\partial t} + \frac{1}{A}\frac{\partial}{\partial z}(An_q u_q) = S_q + \sum_j n_j \nu_{jq} - n_q \sum_j \nu_{qj} \quad (1)$$

where n_q and u_q are the density and flow velocity of charge state q, S_q is the rate at which ions of charge state are captured in the plasma, and ν_{qj} is the rate at which ions of charge state q are ionized into charge state j. By solving Eq. 1 on reach radial grids, we have 2D ion charge state distribution (Fig. 6) of highly charged ions at the extraction end. The peak of CSD is on axis and at Rb^{15+}. For Cs charge breeding, the beam capture profile and charge state distribution are similar to what have been shown in Fig. 5 and Fig. 6 for Rb.

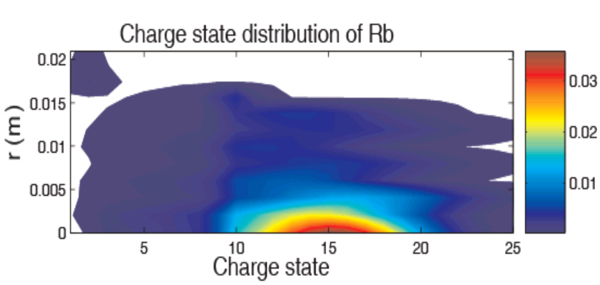

Figure 6: Predicted charge state distribution of charge bred Rb beam.

By integrating the 2D CSD profile shown in Fig. 6 from r=0 to r=0.45cm (radius of the extraction), we have the output charge state distribution and the comparisons between simulation and experiments are shown in Fig. 7. The peak of CSD is correctly predicted. The predicted charge breeding efficiency is within a factor of 2. The shape of CSD is different from the measurements might due to the fact that Lotz ionization rate used in the simulations are different from the real ionization rates or non-Maxwellian EDF prediction is off.

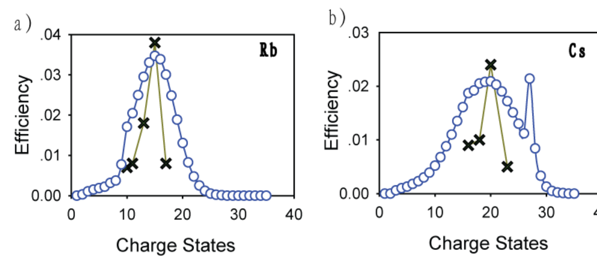

Figure 7: a) Extracted ion charge state distribution for Rb. The circles are the points predicted by GEM and the crosses are the experimental measurements. b) Similar plot for Cs charge breeding.

DISCUSSION AND CONCLUSIONS

GEM2D is an advanced ECRIS plasma modelling tool which can simulate ECRIS plasma in both radial and axial directions. The results of charge breeding simulation using GEM2D and MCBC are consistent with recent ANL charge breeding experiments within a factor of 2 without factoring the injection beam emission and faraday cup efficiency at the extraction end.

Future work of GEM will be focused on more validation of GEM2D using other available experimental data, preferably argon ECRIS plasma which has more accurate ionization rates available and improve the algorithm of both MCBC and GEM.

REFERENCES

[1] L. Zhao, J. S. Kim, B. Cluggish, "Modeling ECRIS Plasma Using 2D GEM," ECRIS08 workshop, Chicago, IL, September 2008.

[2] D. H. Edgell, J. S. Kim, I. N. Bogatu, R. C. Pardo and R. C. Vondrasek, Review of Scientific Instruments, Vol. 73, No. 2, p. 641-643, (February 2002).

[3] J. S. Kim, L. Zhao, B.P. Cluggish, I.N. Bogatu, S. Galkin, L. Grubert and R. Pardo, ECR Ion Source Workshop, Chicago IL Sept 2008

[4] R. Vondrasek, "ECR Charge Breeder and High Voltage Platforms," presented at CARIBU Annual Progress Review, Feb. 3-4, 2009.

[5] Richard C. Pardo, Guy Savard, Sam Baker, Cary Davids, E. Frank Moore, Rick Vondrasek, and Gary Zinkann , Nuc. Instrum. Methods B. 261, 965 (2007)