STATUS OF FAR-TECH'S ELECTRON-CYCLOTRON-RESONANCE CHARGE-BREEDER SIMULATION TOOLSET; MCBC GEM AND IONEX *

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Abstract

The status of FAR-TECH's electron-cyclotron-resonance charge-breeder simulation toolset (MCBC, GEM and IonEx) is described. FAR-TECH, Inc. has been building a suite of comprehensive numerical tools for end-to-end Electron Cyclotron Resonance (ECR) charge breeding (CB) modeling [1]. They consist of the Monte Carlo Beam Capture (MCBC) code [2,3], the Generalized ECRIS Modeling (GEM) code [3,4], and the Ion Extraction (IonEx) code [6,7]. We present the main progresses since our last status presentation [1]. This progress includes upgrades in GEM to 2D and IonEx to 3D.

INTRODUCTION

In ECR "charge breeders" a beam of low (+1 or +2) charged ions is injected into an ECRIS plasma and charge bred to produce higher charge-state ions. The charge breeders are particularly useful for radioactive ion beam (RIB) production. Future large, expensive ion sources will require modeling and diagnostics for optimal and efficient design.

FAR-TECH, Inc. has been building a suite of comprehensive numerical tools for end-to-end Electron Cyclotron Resonance (ECR) Charge Breeder (CB) Ion Source (IS) modeling [1]. The tool consists of three modules, each representing distinctive physical processes. First, the Monte Carlo Beam Capture (MCBC) code [2,3] traces injected ions until they are captured by being slowed down to a speed less than the background ion thermal speed, lost to the walls, or pass through the extraction holes. Second, the Generalized ECRIS Modeling (GEM) code [4,5] calculates the charge state distribution (CSD) of an ECR ion source plasma including the captured injected beam ions. Finally, the Ion Extraction (IonEx) code [6,7] calculates extracted ion trajectories utilizing the phase space ion distributions obtained from GEM. The link between MCBC and GEM are in place, and the link between GEM and IonEx will be carried out in the near future.

Since our last status report [1], our main progress has been with GEM2D and IonEx upgrades. The 2D (r,z) spatial extension of GEM from 1D (z) allows more realistic modeling of the rf resonance, which is a key ingredient for ECRIS performance. Through GEM2D, the ellipsoidal shaped rf resonance surface can be modeled. For typical ECR plasmas GEM2D simulations indicate hollow profiles of electron density and temperature, consistent with experimental observations at ATOMKI [8], resulting in hollow profiles of extracted ion sources [9]. As for IonEx, while a user-friendly GUI is being built, a 3D spatial extension is being made. IonEx utilizes a meshfree technique, which uses points or nodes not cells, and an innovative meshfree technique called PICOP (particle-in-clouds-of-points) [6], not PIC (particle-in-cell). Generation and adaptation of points are easier than those of meshes and particularly for handling a complicated geometry and highly non-uniform problems (e.g., multi-scale problems like a plasma meniscus).

Next, we present a summary of these three modules.

SUMMARY OF MCBC, GEM, IONEX MODULES

As presented previously, GEM models ECR ion source plasmas by fluid ions and bounce averaged Fokker Planck electrons [5,10]. The MCBC code simulates beam slowing down dynamics in a plasma due to Coulomb collisions, and atomic processes which includes ionization due to hot electrons and charge exchange. MCBC provides ion source profiles to GEM, which in turn provides ion flux profiles to IonEx. Next we briefly describe the status of each of these modules.

MCBC

The full 3D3V Monte Carlo particle tracking code models Coulomb collisions, and atomic processes in a plasma. The Coulomb collisions are implemented by the Boozer model [11], after modifying the collision formula to ECR plasmas. The modified Boozer model and atomic processes modeled in the code can be found in our previous paper [1].

GEM

We made improvements in two main areas with GEM. The first area is in the convergence of the GEM1D code using the up-wind scheme for the ion contintuity equations. The second area is the extension of GEM to 2D. The 2D modeling allows for the resonant layer to be at finite radius as well as at finite axial locations. As rf heating is a main ingredient for producing ECR plasmas,

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accurate modeling of the resonance region is important. The 2D grids of GEM represent the ECR plasma by a uniform axial grid and radially nested flux tubes. The radially nested flux tubes are obtained by averaging the magnetic fields azimuthally. The main GEM modeling remains the same; fluid ions with the same axial velocity due to strong collisions between them but with independent radial velocities, Fokker-Plank bounce averaged electrons at each flux tube, and particle balance neutrals. The detailed model of GEM2D is given by Zhao [12,13].

IonEx

Although there are several ion extraction codes commercially available [14,15], we have been developing our own extraction module for the following reasons: (1) An ion extraction code requires initial particle conditions, which should be obtained from plasma simulations such as GEM more realistically. (2) The plasma meniscus should be resolved, where the plasma meniscus region is many orders of magnitude smaller than the device size.

IonEx is being developed using our innovative numerical technique, Particle-In-Cloud-Of-Points (PICOP) [6]. It uses a meshless technique. Meshless computation does not require cells or meshes, rather it uses points. This feature allows easier handling of complex boundaries and easier adaptation where required, thus is suitable for multiple scale problems. As our technique is based on computational points rather than meshes or cells, we developed a new algorithm which we call Particle-In-Cloud-Of-Points (PICOP) as appose to Particle-In-Cell (PIC). The PICOP algorithm is a key element in IonEx. The 2D version is benchmarked, and the 3D version is close to being ready. The 3D computational point generation, adaptation, refinement and de-refinement of points, and the 3D PICOP algorithm, are all individually tested. The 3D IonEx is close to completion. Next we describe the basic modeling of IonEx.

THE IONEX MODEL AND BENCHMARKING

The IonEx module simulates steady state solutions of extracted ion trajectories from plasmas. The ions are treated kinetically and electrons as Boltzmann massless fluid. Steady state solutions are obtained by iterating solutions for field and particles alternately until a converged solution is found.

The fields are governed by the nonlinear Poisson's equation; $\varepsilon_0 \nabla^2 \phi = -\rho_i + \rho_e$ where ε_0 is permittivity of free space, and ρ_e and ρ_i are electron and ion charge densities respectively. IonEx solves the equation after normalization,

$$\lambda_D^2 \nabla^2 \Phi = -\rho + \exp(\Phi)$$

where λ_D is the Debye length, the normalized potential is $\Phi = -e(\phi_P - \phi)/T_e$ with ϕ_P being the plasma potential, and the normalize ion charge density is $\rho = \rho_i / en_{e0}$ with $n_e = n_{e0} \exp\left[\frac{e(\phi - \phi_0)}{T_e}\right]$.

This nonlinear equation for the potential is solved by the Newton's iteration method except for the first couple of iterations using the Gauss-Seidel method. The Newton's iteration scheme is $F\Phi^{n+1} = -\rho + (1 - u^n)\exp(\Phi^n)$, with $A\Phi^{n+1} = -\rho + \exp(\Phi^n)$, and $F = A - \exp(\Phi^n)$. Here, the matrix **A** is a discrete (meshless) analog of the Laplacian. The solution to this equation typically converges within a few iterations.

Once the field is solved, macro ions are tracked in the electric fields calculated from potentials at neighborhood points of the field solutions, and in the given static magnetic fields. Once ion trajectories are obtained, charge densities are distributed over "neighborhood" of points. The charge deposited to computational points is used to update the field solutions. By iteration between field solutions and particle traces, steady state macro ion trajectories are obtained in self-consistent electrostatic fields and static magnetic fields.

As the simulation evolves the trajectories are updated. Computational point locations and the number of points are adapted based on density and potential gradients to obtain self-consistent, steady state solution, accurately and fast. Some of the 2D IonEx results in the absence of magnetic fields were presented before [7], including a benchmark with IGUN [14]. Since then, we implemented magnetic field effects in IonEx. IonEx conserves total energy and the canonical momentum. A benchmark simulation is obtained for the parameters given in the parameters given in Eq.(1) and the magnetic field in Eq.(2), where $z_0 = 0$. The results are shown in Fig. 1 on the left for IonEx and on the right for IGUN.

$$\begin{aligned} &n_0 = 2.24 \times 10^{17} m^{-3}, \quad T_e = 20\, eV, \quad m_i = 1\, amu \\ &Z_i = 1, \quad U_i = 20\, eV \\ &\phi_0 = 60063\, V, \quad \phi_1 = 65000\, V, \quad \phi_2 = 0\, V \end{aligned} \qquad (1)$$

$$\vec{B}(T) = 140 r (z - z_0)\hat{r} + (1 - 140((z - z_0)^2 - r^2/2))\hat{z} \qquad (2)$$

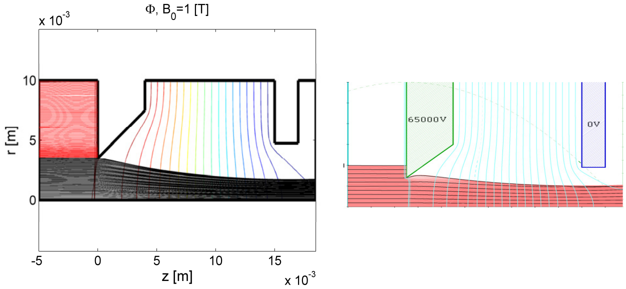
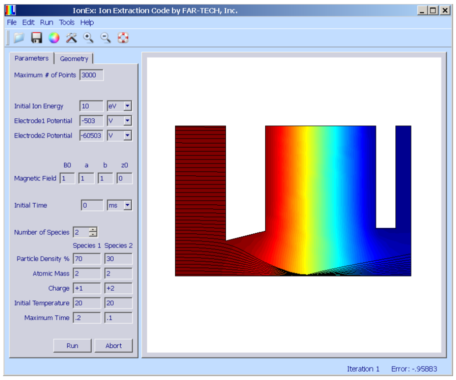


Figure 1. A benchmark run showing the results of IonEx on the left with IGUN on the right.

INTEGRATION OF THE MODULES AND GUI

The strength of our toolset is that it could provide end-to-end simulation to assist ECR CB optimization. If the current of injected beam ions is small enough so that they do not affect the background plasma, MCBC and GEM can be run in series only once to obtain CSD. From MCBC we obtain the steady state ion sources by the beam ions, and then GEM can use that information to obtain CSD. If the current of input beam ions is significant enough to affect background plasma, the two modules need to be run one after the other, and iterated until convergence. This iteration process is implemented. From MCBC and GEM simulations, we obtain density and velocity profiles of each ion species at the extraction aperture. This phase space information distribution of each ion species at the extraction aperture will be the input to IonEx. This link is being implemented. Since GEM is a 2D2V code, the phase space information at the extraction has only r, z, υ_r, and υ_z information. GEM2D can provide much information we need to understand and optimize ECR CB plasmas. If necessary, 3D effects that includes the dependence in azimuthal direction could be examined within our model in a parametric manner.

We have started a GUI implementation for the IonEx module to ease the use of the code as shown in Fig. 2x. Ultimately the GUI will be extended to other modules and to integrate them.



Maximum # of Points 3000

Initial Ion Energy 10 eV
Electrode1 Potential -503 V
Electrode2 Potential -60503 V

	B0	a	b	z0
Magnetic Field	1	1	1	0

Initial Time 0 ms

Number of Species 2

	Species 1	Species 2
Particle Density %	70	30
Atomic Mass	2	2
Charge	+1	+2
Initial Temperature	20	20
Maximum Time	.2	.1

Iteration 1 Error: -.95883

Figure 2. A screen capture of an initial GUI panel for IonEx.

DISCUSSION

Our ECR charge breeder simulation toolset has begun to produce results and some understanding of ECR plasma performance. However, more upgrades are needed before the toolset can fully provide a robust performance.

In addition to code performance such as speed and convergence, some model upgrades can be made in the future. As plasma is a complex system, much aspect of the GEM code is based on physics models. Therefore, it is important to understand the validity of the module and the assumptions used the model. One particular area that needs special attention is the rf heating. GEM uses the quasi-linear diffusion model [16] for rf heating.

Typical ECRIS plasmas operate at densities so that their ECR frequencies are below the cutoff frequency. Thus, rf waves penetrate as far as they can until absorbed by electrons, which occur at the resonance region where near rf frequency = eB/mc. However, an ECR plasma device is a cavity and has cavity modes. The cavity modes may alter the rf-absorption characteristics. The experimental evidence of sensitivity with respect to rf frequency is an indication of the cavity mode effect [17]. The effects of cavity mode to ECR heating has not been implemented in GEM.

A few other areas of needed implementations are as follows. First, when ions hit the walls, they either stick to the wall or a neutral may be coming out of the wall. The latter recycling effect is not implemented in MCBC. Second, while recombination is negligible compared to ionization in the plasma with hot electrons, it could play a role at the injection side as low charged ions have to traverse cold region before they reach the central hot electron zone. In fact, we plan to simulate beam ions starting at a little distance before they enter the ECR device. This way a more complete simulation of injected beam dynamics and beam capture will be simulated. It would also provide the possibility of simulating the effect of backstreaming ions on the injected ion beams before they enter the plasma, which has not been investigated.

REFERENCES

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

[2] J.S. Kim, C. Liu, D.H. Edgell, and R. Pardo, Rev. Sci. Instrum., 77, 03B106 (2006).

[3] J.S. Kim, L. Zhao, B.P. Cluggish, and R. Pardo, Rev. Sci. Instrum. **78**, 103503 (2007)

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

[5] D.H. Edgell, J.S. Kim, S.K. Wong, R.C. Pardo, and R. Vondrasek, Phys. Rev. ST Accel. Beams, 2, 123 502 (1999).

[6] S. A. Galkin, B. P. Cluggish, J. S. Kim, and S. Y. Medvedev, Proc. of the Pulsed Power and Plasma Science Conference 2007. Section 8B6, Albuquerque, NM, 17-22 June, 2007.

[7] B.P. Cluggish, S.A. Galkin, J.S. Kim, TUPAS077, Proc. of the Particle Accelerator Conference, Albuquerque, NM, June 25-29, 2007

[8] S. Biri, A. Valek, and T. Suta, E. Takacs and Cs. Szabo, L. T. Hudson, B. Radics, J. Imrek, B. Juhasz, and J. Pa linkas, Rev. Sci. Instrum., Vol. 75, (2004)

[9] J.W. Stetson and P. Spadtke, Proceedings of PAC07, Albuquerque, NM, FROBAB02, (2008)

[10] Girard, K. Serebrennikov, C. Lécot, G. Melin, D. Hitz, L. Sun, 15th International Workshop on ECR

Ion Sources, June 12-14, 2002, University of Jyväskylâ, Finland
[11] A. H. Boozer, Phys. Plasmas 9, 4389 (2002)
[12] L. Zhao, J.S. Kim, B.P. Cluggish, TUPAS079, Particle Accelerator Conference, Albuquerque, NM, June, 2007
[13] L. Zhao, J.S. Kim, B.P. Cluggish, Presented to this conference, at the 18th ECR Ion Source workshop, Chicago, IL September 15-18, 2008
[14] http://www.egun-igun.com/
[15] P. Spadtke, Rev. Sci. Instrum., 75, 1643 (2004)
[16] T.H. Stix, Waves in plasmas, AIP press, (1992)
[17] L. Celona, G. Ciavola, F. Consoli, S. Gammino, F. Maimone, D. Mascali, P. Spädtke, K. Tinschert, R. Lang, J. Mäder, J. Roßbach, S. Barbarino, and R. S. Catalano, Rev. Sci. Instrum, 79, 023305 (2008)