SIMULATION OF ELECTRON AND ION DYNAMICS IN AN EBIS*

L. Zhao[#], J. S. Kim[+], E. G. Evstatiev, FAR-TECH, Inc., San Diego, CA 92121, USA
E. Beebe, A. Pikin, BNL, Upton, NY 11973, USA

Abstract

To model the dynamics and charge state distribution (CSD) of the ions in an Electron Beam Ion Source (EBIS), a time-dependent, self-consist particle-in-cell Monte Carlo code (EBIS-PIC) has been developed by FAR-TECH, Inc. The energetic background electron beam is modelled by PBGUNS by dividing the long beam path into several segments to resolve the big length-to-radius spatial scaling problem. The injected primary ions and ionized neutral gas ions are tracked using Monte Carlo method which includes the ionization, charge-exchange and Coulomb collisions with the electron beam. The potential well is calculated by solving the Poisson equation each time step. EBIS-PIC calculates the spatial and velocity space distributions and the evolution of the charge state distribution of trapped ions in EBIS devices operating in fast or slow trapping mode. The physical model of EBIS-PIC and the simulations of the experiments on the Test EBIS at BNL are described. The results are in good agreement with the experimental measurements.

INTRODUCTION

In an EBIS, a high current electron beam created by an electron gun is compressed to high density as it enters a strong solenoidal magnetic field (Figure 1). The beam is stopped by an electron collector after passing through a series of drift tubes and exiting the solenoid. The injected primary ions are confined in the radial direction by the potential well created by the space charge of the electrons, and in the axial direction by positive potential barriers on the drift tubes at the two ends of the device. Ions are then ionized to high charge states by electron impact and extracted as the output beam. EBIS are one of the best candidates for producing highly charged radioactive ions.

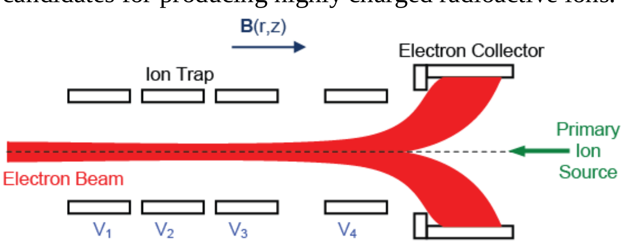

Figure 1: Diagram of EBIS device. The electron beam travels to the right until stopped by the electron collector. The primary ion source is to the right of the collector.

FAR-TECH has developed a numerical tool, EBIS-PIC, to simulate ion dynamics and charge breeding in an EBIS. The tool has modules to model various physics in the EBIS. The initial electron beam is simulated by PBGUNS [1] by dividing the beam path into several segments. The injected primary ions and ions from neutral gas are tracked using a time dependent Monte Carlo method which includes Coulomb collisions and ionizations with background electron beam and charge exchange with neutrals. The electrostatic potential is updated by solving Poisson's equation. The EBIS-PIC has been used to simulate Cs 1+ charge breeding experiments on Test EBIS [2, 3] at BNL. The basic parameters of Test EBIS are listed in Table 1. We use the Test EBIS as an example device to illustrate the simulation of electron beam and ions.

Table 1: Operation Parameters of Test EBIS

Parameter	Value
Trap length	0.7 m
Drift tube radius	1.5 cm
Max magnetic field	5 T
Drift tube voltages	12, 6, 9 kV
Ion Specie	Cs
Ion Current	15 μA
Ion Energy	9kV
Pressure	5×10^{-10} Torr

ELECTRON BEAM MOELING

In EBIS operation, the electron beam propagates several meters from the cathode to collector through drift tubes. The length to radius ratio could be from 200 to 1000. To resolve such big spatial scaling issue, the electron beam is simulated by PBGUNS in several regions to increase accuracy. The PBGUNS code uses relaxation techniques to solve the Poisson's Equation for the potentials on a large, rectangular array of squares, alternately computing potentials and trajectories. It is modified to be able to perform the simulation of the long electron beam path in sections with different grid settings to achieve required accuracy. The sectional simulations were linked continually from the gun to the collector by passing the beam conditions, including the radial distribution of beam energy, angle and spin velocities, and ensuring a steady state in all the sections.

A full electron beam simulation for Test EBIS was performed in 4 regions with their boundaries shown in Figure 2b as vertical dashed lines. The steady state electron beam (shown in Figure 2b) travels ~ 3 meters from the gun to the electron collector in the magnetic field shown in Figure 2a. The electrostatic potential along

*Grant supported by DOE Office of Nuclear Physics
#zhao@far-tech.com
+kim@far-tech.com

the axis is shown in Figure 2c. Here the cathode voltage was set as zero. The trap region is from around 1m to 2m along the z axis where the magnetic field is 5 T. The simulated electron beam current is about 2A and the beam radius is about 0.75mm in the trap region.

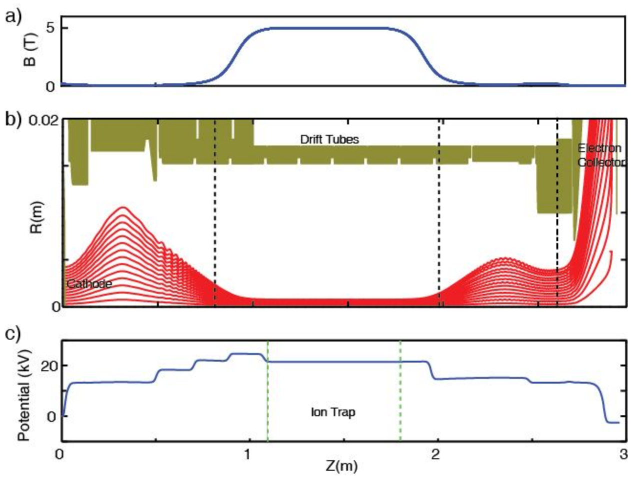

Figure 2: PBGUNS simulation. a) Axial magnetic field; b) electron beam simulated by PBGUNS in 4 sections indicated by the dashed lines; c) the simulated electric potential along the axis. The ion trap region is indicated by the dashed lines.

The 3D view of the electrostatic potential obtained from the PBGUNS simulation is shown in Figure 3. The potential well shown is from the trap region to the electron collector. Due to the negative space charge of the electron beam, the potential well is ~1700 V in the trap region.

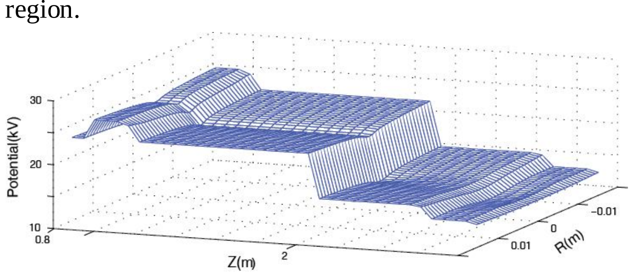

Figure 3: 3D plot of electrostatic potential, for R<2 cm, from trap to electron collector.

The axial profiles of the electron beam in the trap region are shown in the left column in Figure 4. From top to bottom shown are the axial profiles of axial-magnetic field (without the beam), the electron density, axial kinetic energy of the electron beam, and the electrostatic potential. The radial profiles of the electrostatic potential up to 1.5 cm and electron density up to 1.5 mm are shown in the right column. The radial beam profile is convex near the axis, showing increased density in radius with a sharp drop at the beam edge. When ions are injected and trapped in the electron beam, the space charge potential will be modified according to Poisson's equation and the electron density will also be updated while keeping the total electron current constant.

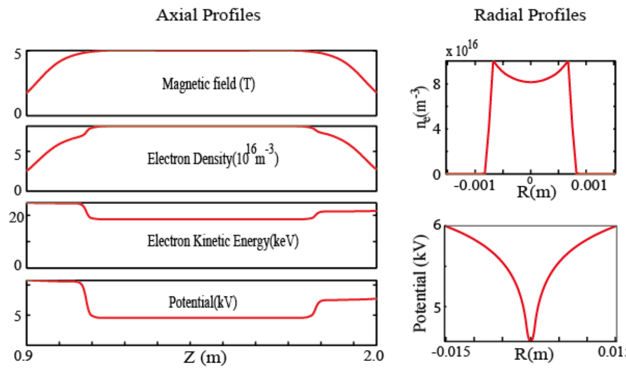

Figure 4: Left column: from top to bottom shown are axial profiles of the magnetic field (T), electron density ne (m-3), electron kinetic energy (keV), and electrostatic potential (kV). Right column: electron density, r only up to ~1.5 mm and radial profile of electrostatic potential up to r =~1.5cm.

ION DYNAMICS

In EBIS, the ion dynamics is governed by both the electrostatic potential (shown in Figure 3) and the magnetic fields (in Figure 2a). The orbit of an ion is the combination of gyro-motion and the oscillation motion in radial direction. Experimentally, ions are injected meters away from the trap region (Figure 1). It is important to understand the ion dynamics from beam injection plane, where the initial beam emittance is measured, to the trap.

The orbit of an ion injected from outside of electron collector is shown in Figure 5. From the projections of the orbit (Figure 5a and 5b), one can see that the ion is oscillating mostly in the y-plane due to the electric field generated by the electron beam, and slowly rotates as the ion enters the trap as the magnetic field increases and starts acting on the ion, as seen in Figure 5c. In the trap, where magnetic field is strong, ions rotate fast around the axis, and at the same time they oscillate radially close to simple harmonic oscillation due to the almost linearly increasing radial electric field. Once being trapped, ions will bounce back and forth between the voltage barriers until they are extracted or lost to the wall due to electron heating.

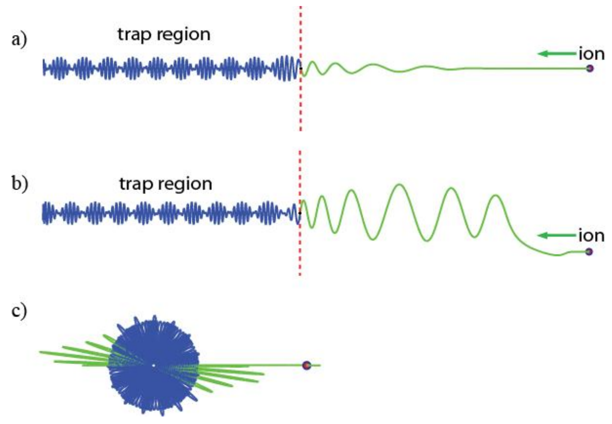

Figure 5: An orbit of a primary ion that is injected from outside of the electron collector into the trap. Shown are the projections of the orbit onto x-z plane (a), y-z plane (b), and x-y plane (c). The dot is the initial point of the orbit.

The acceptance of the ion beam is an important factor to determine the efficiency of EBIS operation. The acceptance is estimated when the ion trajectory is completely within the electron beam in the trap region. To study the acceptance of the ion beam with respect to the electron beam in the trap region, ions with different pitch angles and radial positions are launched from the plane at the same initial position as shown in figure 5. Figure 6 shows an X-X' phase space acceptance plot for the ions that are launched from the electron beam dump. Ions with initial conditions inside the outer dashed ellipse overlap with the electron beam over 50% (the inner solid ellipse is for ions with 100% overlapping) in the trap. The estimated acceptance is about 100π mm mrad which is about the same as other predictions [3].

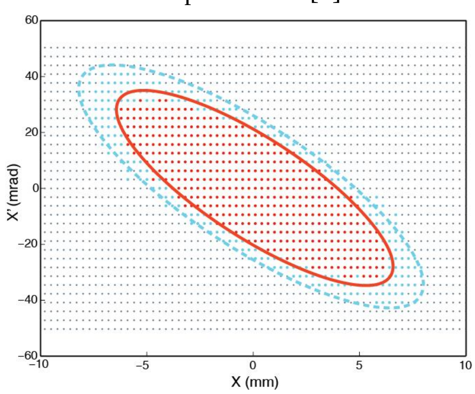

Figure 6: Estimated acceptance of the ion beam in Test EBIS. Ions with initial conditions within the solid ellipse have 100% overlap of the ion trajectories with the electron beam, and more than 50% if inside the dashed ellipse.

In the trap region, the ions were tracked by time-dependent PIC Monte Carlo method, utilizing the electron current density obtained by the PBGUNS simulations (Figures 2 and 3). The electric fields are solved self-consistently with the ion and electron space charge evolving as ions being ionized to higher charge states. The ionization of the ions by electron impact, charge exchange of the ions with the background neutral gas, and heating of the ions by Coulomb collisions with the electrons are included in the Monte-Carlo model. The ion density was calculated on the grid based on the ion locations and the charge states. Detailed description of the setup and physical model can also be found in [4]. EBIS-PIC is able to predict the evolution of ion charge states, the distribution of ions and the CSD of trapped ions.

EBIS-PIC SIMULATION RESULTS

We have performed a full EBIS-PIC simulation for an EBIS experiment [2] of the Test EBTS at BNL using the experimental parameters listed in Table 1. The primary ions were Cs 1+ and injected for 0.2 ms, after which the trap voltage was ramped down to 6 kV in 10 microseconds. The ions were then confined for an additional 2 ms before being extracted.

The details of the EBIS-PIC simulation results are shown in Figure 7. Time evolution of ion charge states in the trap is shown in Figure 7a, and the charge breeding times for different charge states are shown in Figure 7c. The charge breeding time is defined as the time that an ion charge state reaches its peak. The charge state distribution (CSD) of trapped ions is shown in Figure 7d. Figure7b shows the radial distribution of captured ions in the trap in the fast trapping test. The profiles are all peaked near the center of the electron beam. The radial distribution of each ion charge state keeps rising until the number of the ions with that charge state reaches its peak and starts to drop. In general, the higher the charge states, the ion distribution are more concentrated at the center if the number of that charge state has reached its peak.

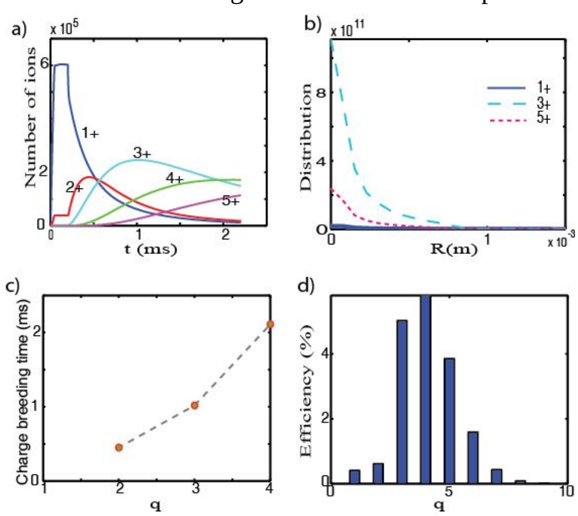

Figure 7: EBIS-PIC simulation results: a) time evolution of ion charge states in the trap; b) Radial distribution of different ion charge states; c) Charge breeding time for different charge states; and d) CSD of trapped ion charge states.

The result was compared with experiments and summarized in Table 2. Here, the trapping efficiency for a charge state is defined as the ratio between the number of ions in that charge state and the total injected ions. Including ion space charge and background gas ionization, our simulations show both agreement and disagreement. Our simulations gave the trapping efficiency 17.4%, lower than experimental value of 19%, while Cs ions was 95% of the trapped charge, the same as the experimental value. The average cesium charge state in the simulations was about +4, while +6 was observed in the experiments.

Table 2: Comparison of simulation and experimental results

Results	Simulation	Experiment
Primary ion trap efficiency	17.4%	19%
Gas ion trap efficiency	83.8%	
Total primary ion charge(pC)	2178	3400
Total gas ion charge(pC)	119	170
Average primary ion charge	4.1	6.0
Average gas ion charge	2.0	

CONCLUSIONS

EBIS-PIC has been developed and tested for ion capture and breeding simulations in EBIS. The energetic background electron beam is modelled by PBGUNS by dividing the long beam path into several segments to resolve the big length-to-radius spatial scaling problem. The ion dynamics has been studied using time-dependent PIC Monte Carlo method. The simulation results of EBIS-PIC show qualitative agreement with the experiment. Future improvements of the code will be focused on improving the physical model by adding ion-ion collision and recombination and speeding the code by using non-uniform grid.

REFERENCES

[1] PBGUNS code page: http://www.far-tech.com/pbguns/

[2] A. Pikin, J. Alessi, E. Beebe, A. Kponou, K. Prelec, G. Kuznetsov, and M. Tiunov, AIP Conf. Proc . Vo. 572, pp. 3-19.

[3] S. Kondrashev, J.G. Alessi, E.N.Beebe, C. Dickerson, P.N.Ostroumov, A. Pikin, G. Savard, Meausrement of Charge State Breeding Efficiency at BNL Test EBIS, Nuclear Instruments and Methods in Physics Research A, 642 (2011), 18-24.

[4] L. Zhao, B. Cluggish, J. S. Kim, and E. G. Evstatiev, "A particle-in-cell Monte Carlo code for electron beam ion source simulation ", Rev. Sci. Instrum. **83**, 02A508 (2012).