THREE DIMENSIONAL SIMULATION OF ION BEAM EXTRACTION FROM AN ECR ION SOURCE

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Abstract

Accurate prediction of ECR ion extraction behavior is important for high current density operation and subsequent beam transport calculations. In this paper we review the combined electric and magnetic space charge beam simulation of ion beam formation from an ECR ion source with a multi-electrode extraction system. Included in the simulation is the influence of secondary charged particles generated by ion collisions in the residual gas on the space charge in the beam. The self-consistent space charge simulation uses a finite element method with mixed linear and quadratic elements, magnetic fields incorporating non-linear magnetic materials, a plasma free surface emission model, and the generation of secondary charged particles by sampling of the primary beam trajectories. This method is useful for predicting the ion beam behavior from the ECR ion source under conditions of varying current density, electrode potential, and background gas pressure, including the behavior of suppressed electron flow and the influence of magnetic fields.

INTRODUCTION

This simulation represents an electron cyclotron resonance (ECR) ion source for producing a proton beam. The source is similar to a CEA-Saclay ECR source [1], though with a much higher magnetic field. New Vector Fields SCALA software [2] simulation capabilities permit fast prediction of ion beam formation with automatically generated secondary charged particles from background gas. The model is used for a space charge simulation of ECR extraction system with an accel-decel extraction system from a plasma free surface in combined electric and magnetic fields. The simulation includes beam neutralization from gas secondary electrons.

MODEL

The finite element model is composed of a three-electrode accel-decel extraction system and two solenoid magnets with non-linear magnetic materials (Fig. 1). The ion source dimensions are as follows:

Extraction aperture diameter	3.0 mm
Accel and decel aperture diameters	4.0 mm
Extractor-accel gap	12.5 mm
Accel-decel gap	1.5 mm
Ion beam drift space length	84.0 mm
Solenoid coil center spacing	100.0 mm
Magnet pole inside diameter	150.0 mm

The magnetic field model is analyzed first and the magnetic field information added to the electrostatic space charge database before solving.

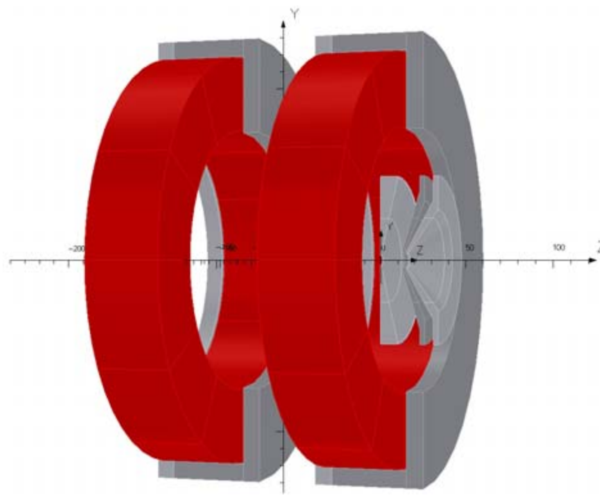

Figure 1: Source geometry with non-linear magnetic materials.

The model incorporates mixed linear and quadratic tetrahedral elements of varying size (Fig. 2).

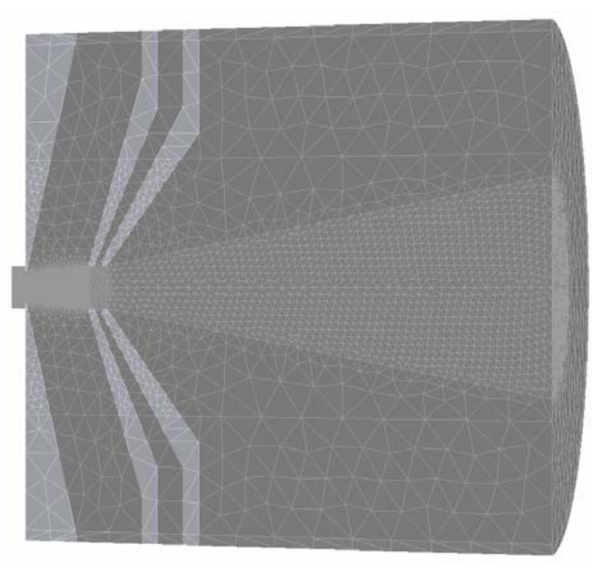

Figure 2: Tetrahedral mesh.

The source electrode (magenta) is held at 0 V, the extractor or accel electrode (blue) is biased at -12 kV, and the electron suppressor or decel electrode (aqua) is operated at -10 kV (Fig. 3).

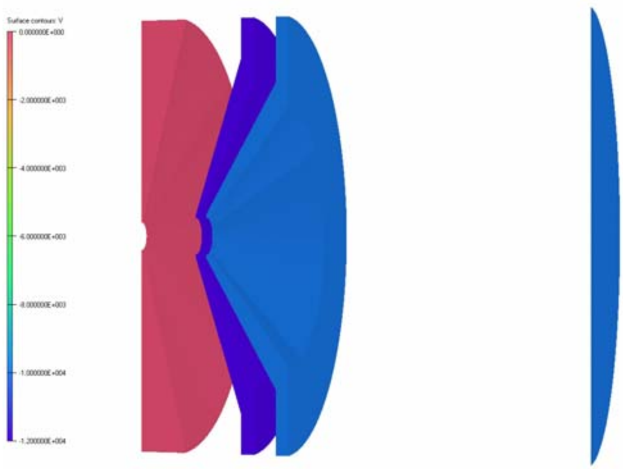

Figure 3: Boundary conditions, 0 V, -12 kV, -10 kV.

PRIMARY CHARGED PARTICLE EMISSION

The primary ion emitter is self consistently simulated, over a range of concave to convex meniscus, by Bohm current density ion emission from a free plasma surface. Concave to convex meniscus.

The primary emission model assumes an ion temperature much lower than the electron temperature. The user specifies the Bohm current density, particle mass and charge, electron temperature, and meniscus voltage. Parameters for the primary emitter are:

Ion species	Proton
$J_{Extraction}$	0.040 $A{\cdot}cm^{-2}$
$T_{Electron}$	23209 K
$E_{Meniscus}$	-1.6022×10^{-12} V

BEAM INTERACTIONS

Secondary emission from background gas, with user specified energy and angular distributions, is automatically simulated.

Secondary particles can be generated from a volume representing the background gas, conductive surfaces, and lossy dielectric surfaces including the influence of beam induced insulator charging. Other behavior can include scattering, recombination, beam energy loss, and beam current loss. Beam current (Eq. 1) and energy loss (Eq. 2) (negative for losses) can be simulated by sampling the primary beam trajectories and generating yields along the primary trajectory paths.

$$\frac{dI}{ds} = \Gamma_I(x, y, z, \vec{E})\,I \quad (1)$$

$$\frac{dE}{ds} = \Gamma_E(x, y, z, \vec{E})\,E \quad (2)$$

where: I is primary beam current

E is primary beam energy

s is distance along trajectory

Ion beam neutralization from background gas volume secondaries (Eq. 3) can be simulated by sampling the primary beam trajectories and generating an emission fraction of electrons along the primary trajectory paths.

$$\frac{dn}{ds} = \Gamma_n(x, y, z, E)\,N \quad (3)$$

where: N is primary beam linear density

n is secondary particle linear density

A simple Gaussian energy distribution (Fig. 4) and a spherical angular distribution were used for the emission fraction in this model.

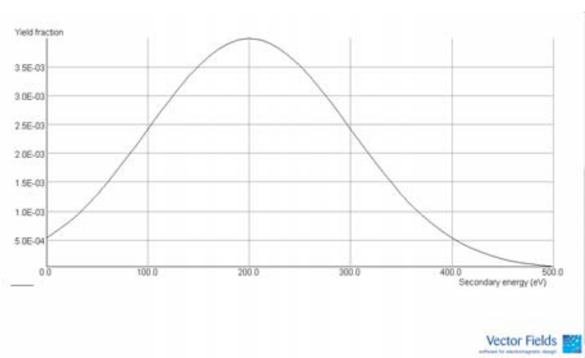

Figure 4: Gaussian secondary emission fraction used for simulations.

All volume secondaries are generated at a randomized, user-defined characteristic length along the primary beam trajectories.

RESULTS

Simulation of emission from a free plasma surface agrees well with Child's law space charge limited emission, both analytically and by simulation. In other work, we have seen good agreement to extraction from a glow discharge ion source. Magnetic field simulations, with non-linear materials, agree well with physical measurement. The magnetic flux density along the ion source axis is shown in Fig. 5 with the extraction aperture located at Z = 0 mm.

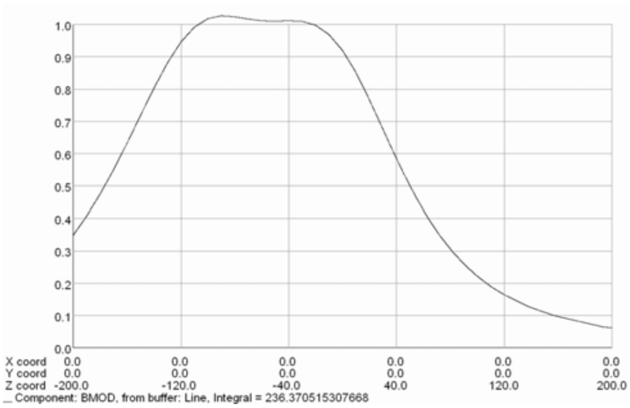

Figure 5: On-axis magnetic flux density.

The gas secondary electrons are highly magnetized and are confined near the ion beam by both the magnetic field and the ion beam space charge. The secondary electrons can be seen to orbit as expected around the magnetic flux lines in Fig. 6.

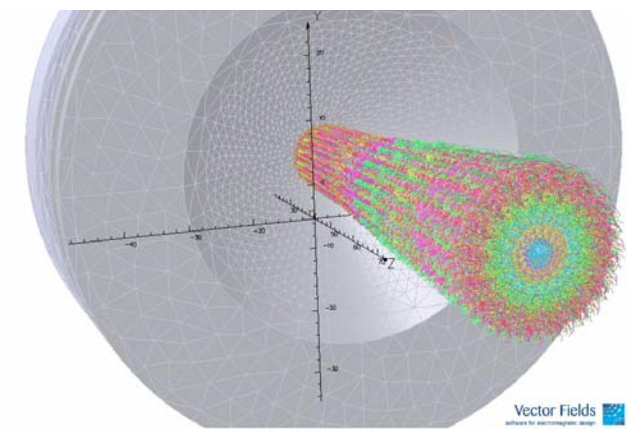

Figure 6: Magnetized secondary electrons.

The ion beam envelope divergence is reduced with neutralization (Figs. 7 and 8).

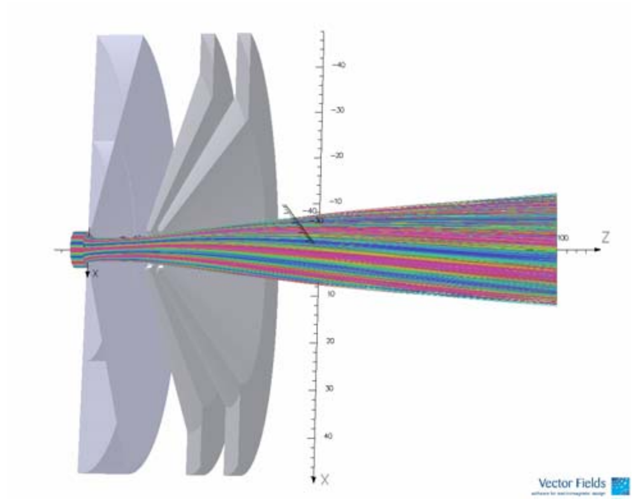

Figure 7: Ion beam without neutralization.

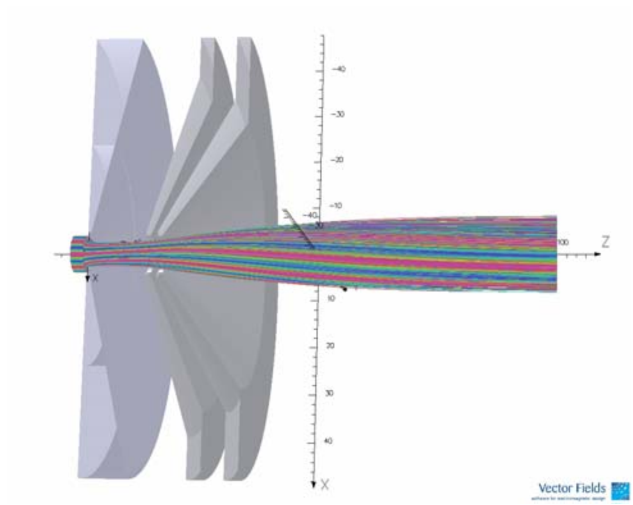

Figure 8: Ion beam with neutralization.

Figs. 9 and 10 further illustrate the beam envelope divergence with and without neutralization.

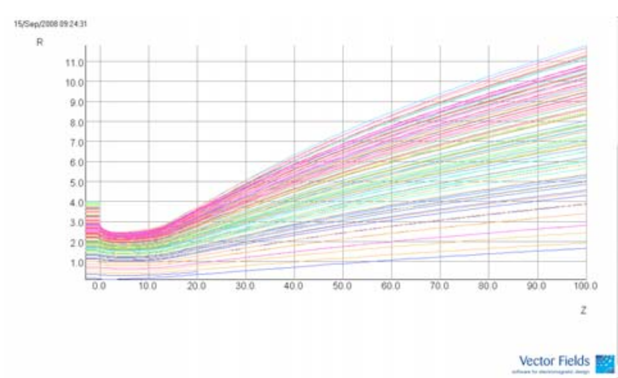

Figure 9: Ion beam without neutralization, note vertical scale.

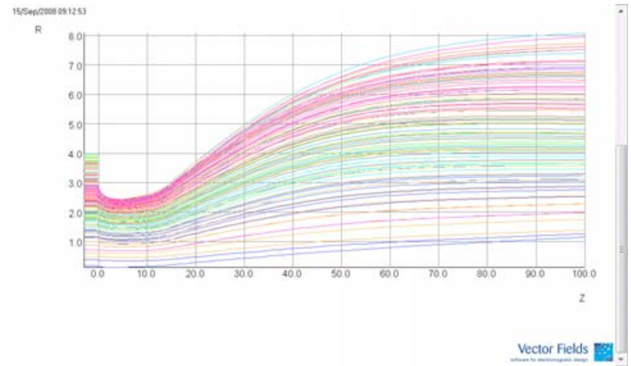

Figure 10: Ion beam with neutralization, note vertical scale.

The space charge, in Coulombs·mm^{-3}, is generally seen to be smaller with gas secondary electron neutralization, but varies spatially (Figs. 11 and 12).

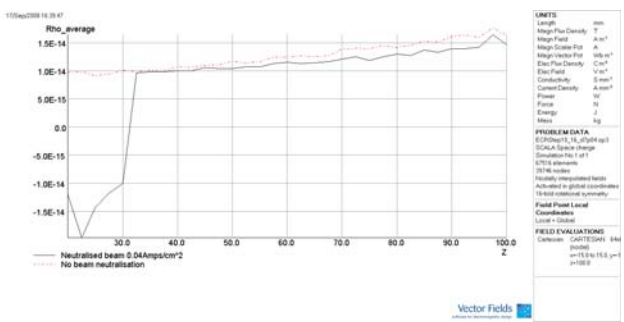

Figure 11: Average space charge across beam diameter.

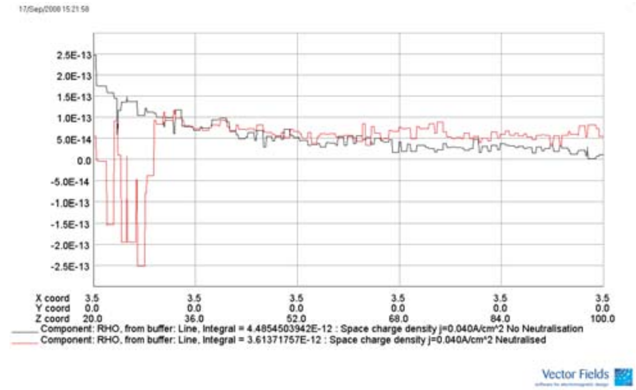

Figure 12: Space charge along a line, radius = 3.5 mm.

CONCLUSIONS

The extracted ion beam conditions are consistent with glow discharge ion source conditions, though this may not be a good approximation to low pressure ECR source operation [3] [4]. Simulation of ion beam neutralization by gas secondary electrons is demonstrated. Gas secondaries are simulated by automatic sampling of primary ion beam trajectories within a finite element environment without the need of particle-in-cell methods.

REFERENCES

[1] P-Y. Beauvais, P. Ausset, D. Bogard, O. Delferrière, J. Faure, R. Ferdinand, A. France, R. Gobin, P. Gros, J-M. Lagniel, P-A. Leroy, “First Beam of the CEA-Saclay CW-High Intensity Microwave Source”, PAC’07, Albuquerque, June 2007, p. 2720 (2007); http://www.JACoW.org.

[2] OPERA 3d, Vector Fields Ltd., Oxford, UK

[3] P. Spädtke, R. Lang, J. Mäder, J. Roßbach, K. Tinschert, J. Stetson, “Ion Beam Extracted from a 14 GHz ECRIS of CAPRICE Type”, ECRIS’06, Lanzhou, September 2006, (2006).

[4] J.W. Stetson and P. Spädtke, “Inhomogeneities in Beams Extracted from ECR Ion Sources”, PAC’07, Albuquerque, June 2007, FROBAB02, p. 3789 (2007).