Quasi-3D Modeling of Electron Cyclotron Resonance Ion Source (ECRIS) Plasmas*

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FAR-TECH, Inc. Management and Facility

- Located in San Diego, CA
- Founded in 1994, formerly known as Fusion and Accelerator Research (FAR), to pursue fusion and accelerator related research, technology and development.
- Core staff of 16 (14 PhDs)
- Facility:
  - Linux cluster (88 processors) with 96GB of memory via Infiniband connection; 15 TB redundant storage
  - RF laboratory

Motivation

Highly charged ions are needed for Nuclear Physics studies, medical and industrial applications.

Primary means for high charge (rare) ions are
Electron Cyclotron Resonance Ion Sources (ECRIS) /
Electron Cyclotron Resonance Charge Breeders (ECRCB).

Modeling of ECRIS/ECRCB plasmas is needed to guide, interpret and optimize current experiments and to design expensive next generation devices.

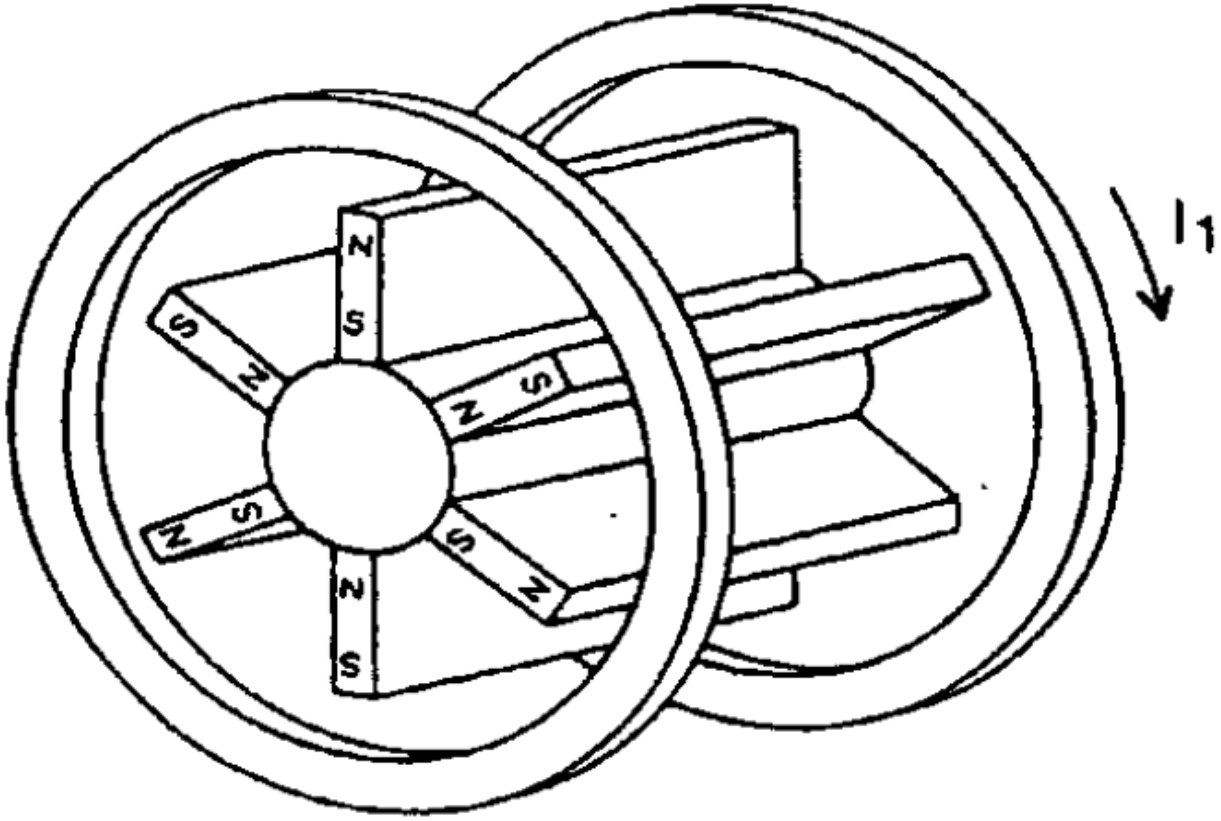
Project Goal

Develop a (Quasi3D) numerical tool for optimizing the design and operation of an ECRIS/ECRCB.

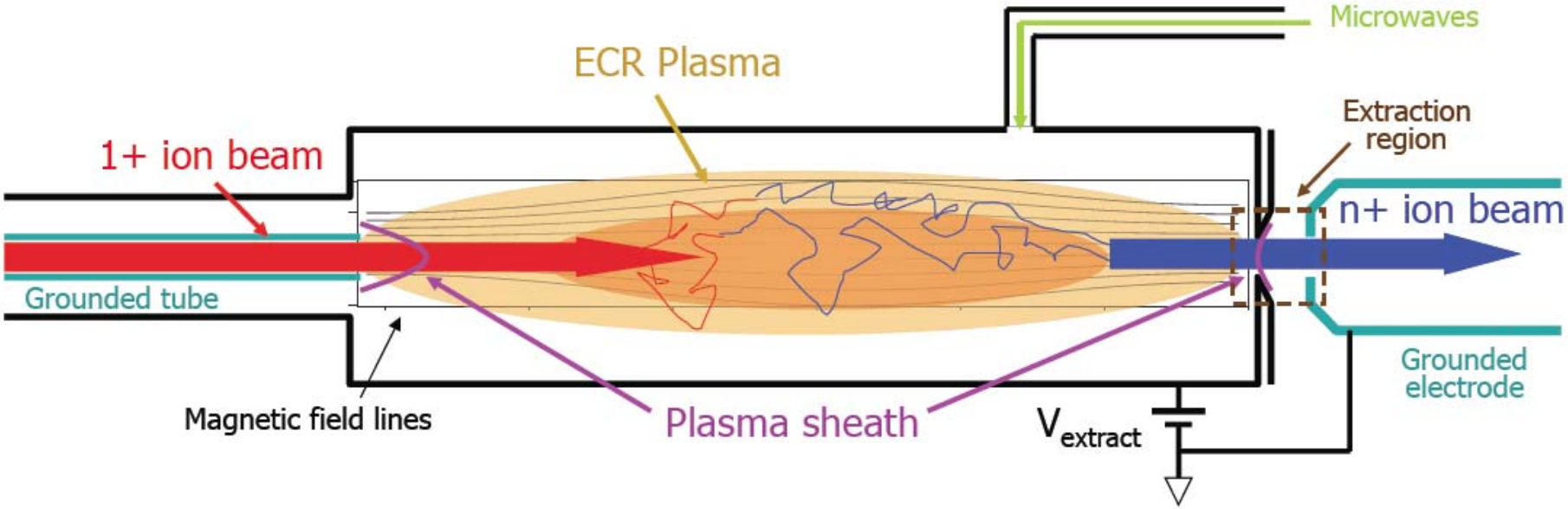
- ***Simulation should be performed within reasonable time***
- ***Model should be justifiable and capture important physics***
- ***Data-Visualization to be used to help comprehension***

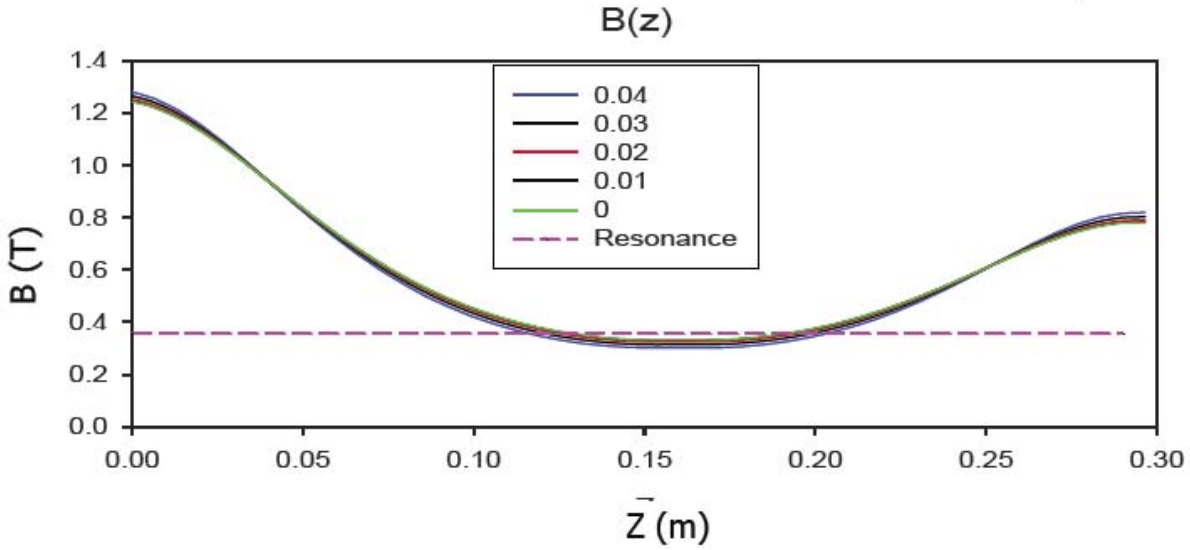
Brief description of ECRIS/ECRCB:

They use plasmas confined in a magnetic mirror device for ions to become multiply charged by impact ionization with ECR heated electrons.
The longer the ions are confined, the higher the charge states are.
Plasma confinement is by magnetic mirrors (axially) and hexapole fields (radially)



Schematics of ECRIS/ECRCB





Many Challenging Questions to be answered

How to maximize extracted highly charged ion current?

- Scaling of extracted current wrt RF frequency
- Sensitivity wrt RF frequency
- Multiple frequency heating
- Volume heating effect

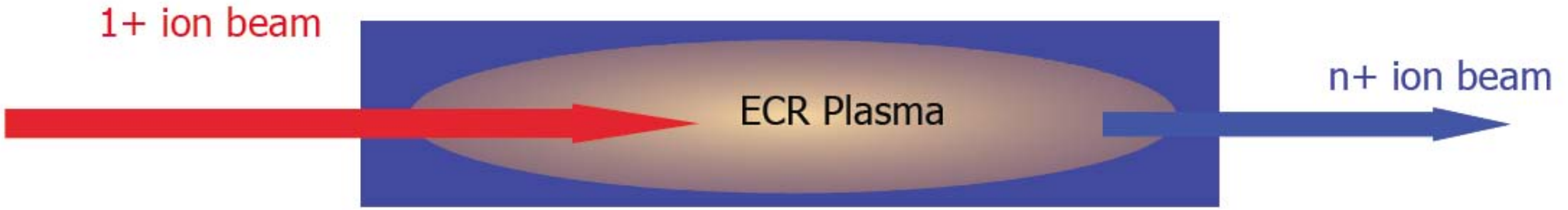
3D profile of extracted ion beams

- charge density
- current density

Minimize extracted ion beam emittance

Parameter study/control knobs for optimization

FAR-TECH's ECRIS/ECRCB Modeling Status: Have developed a few modules, each representing distinctive physical process.



MCBC

Monte Carlo Beam Code

Full 3d3v

GEM

Generalized ECRIS Modeling

Fluid

1d2v

2d2v

IonEx/PBGUNS

Ion/beam extraction

2d3v

3D effect of plasma is needed

“Modeling consideration”

FAR-TECH's two stage plan for 3D simulations

- **Emphasis on 3D aspect of Plasma (while using a simple ECRH model)**

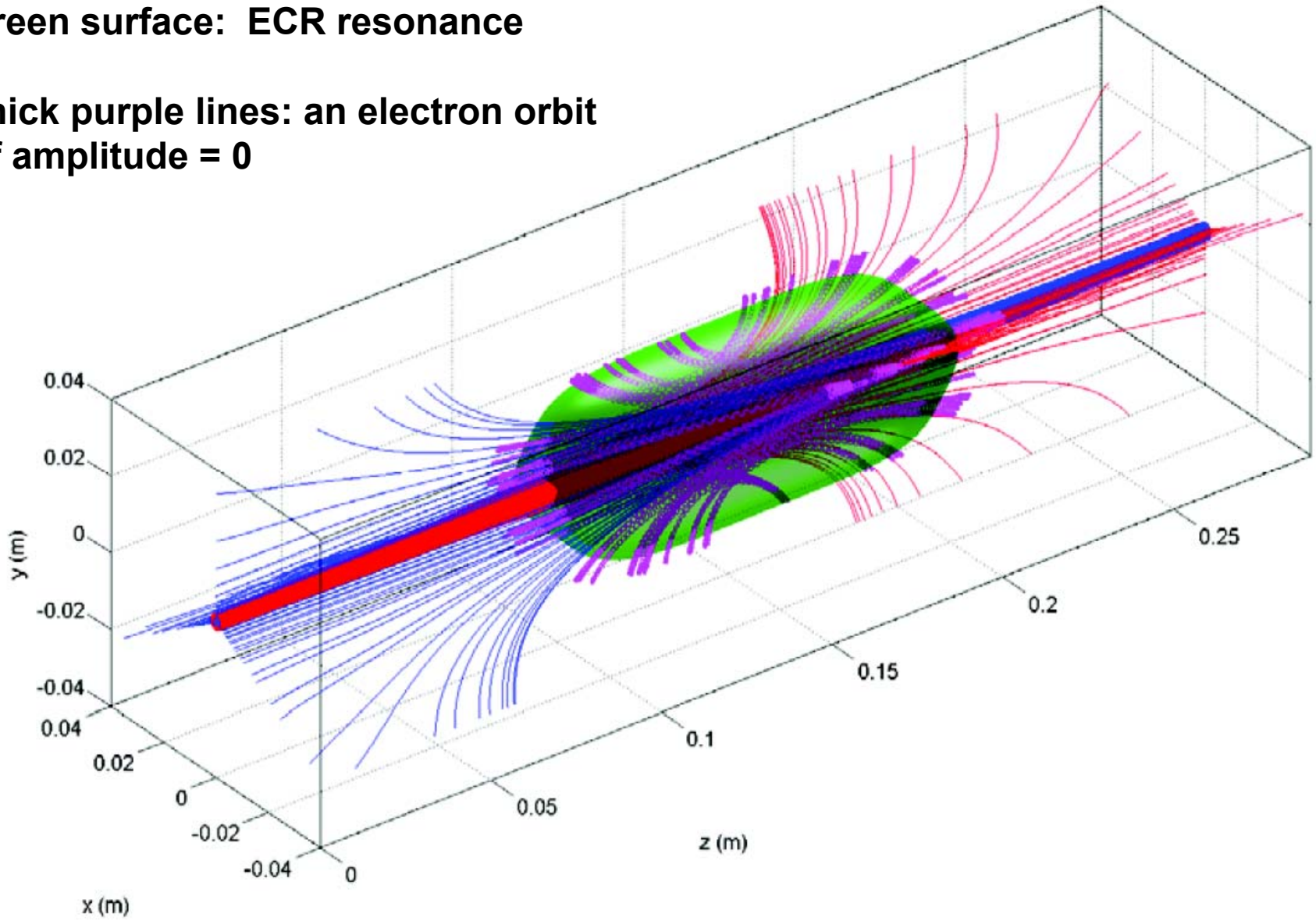
- **Emphasis on realistic modeling of ECRH by through study of rf coupling to plasma (a separate project)**

- **Combine the two to perform a comprehensive realistic simulation of ECRIS/ECRCB plasmas.**

An Electron Orbit in ECRIS/ECRCB

Thin red and blue lines: B-field
Green surface: ECR resonance

Thick purple lines: an electron orbit
Rf amplitude = 0

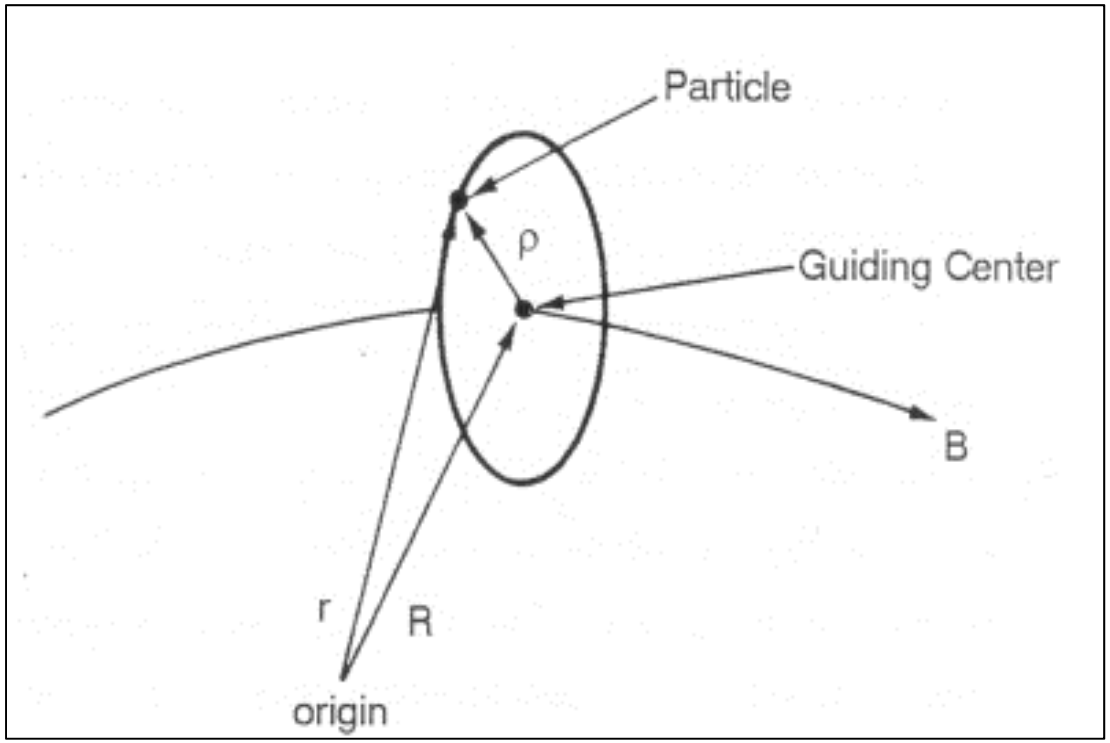


Drift-kinetic model for electrons

Treat electrons by guiding center motion

Change coordinates:

$$\begin{pmatrix} x \\ y \\ z \\ v_x \\ v_y \\ v_z \end{pmatrix} \xrightarrow{\rho \to 0} \begin{pmatrix} x_g \\ y_g \\ z_g \\ v_{||} \\ \mu \\ \Theta \end{pmatrix}$$



$\mu = mv_\perp^2/2B$; Θ is a fast oscillating phase.

Compared to fully kinetic, computational speedup is ~100.

RF coupling to electrons modeled by a "kick" [L&L]

[L&L: Lieberman & Lichtenberg, IEEE Trans. Plasma. Sci., vol. 15, pp. 125-150 (1973)]

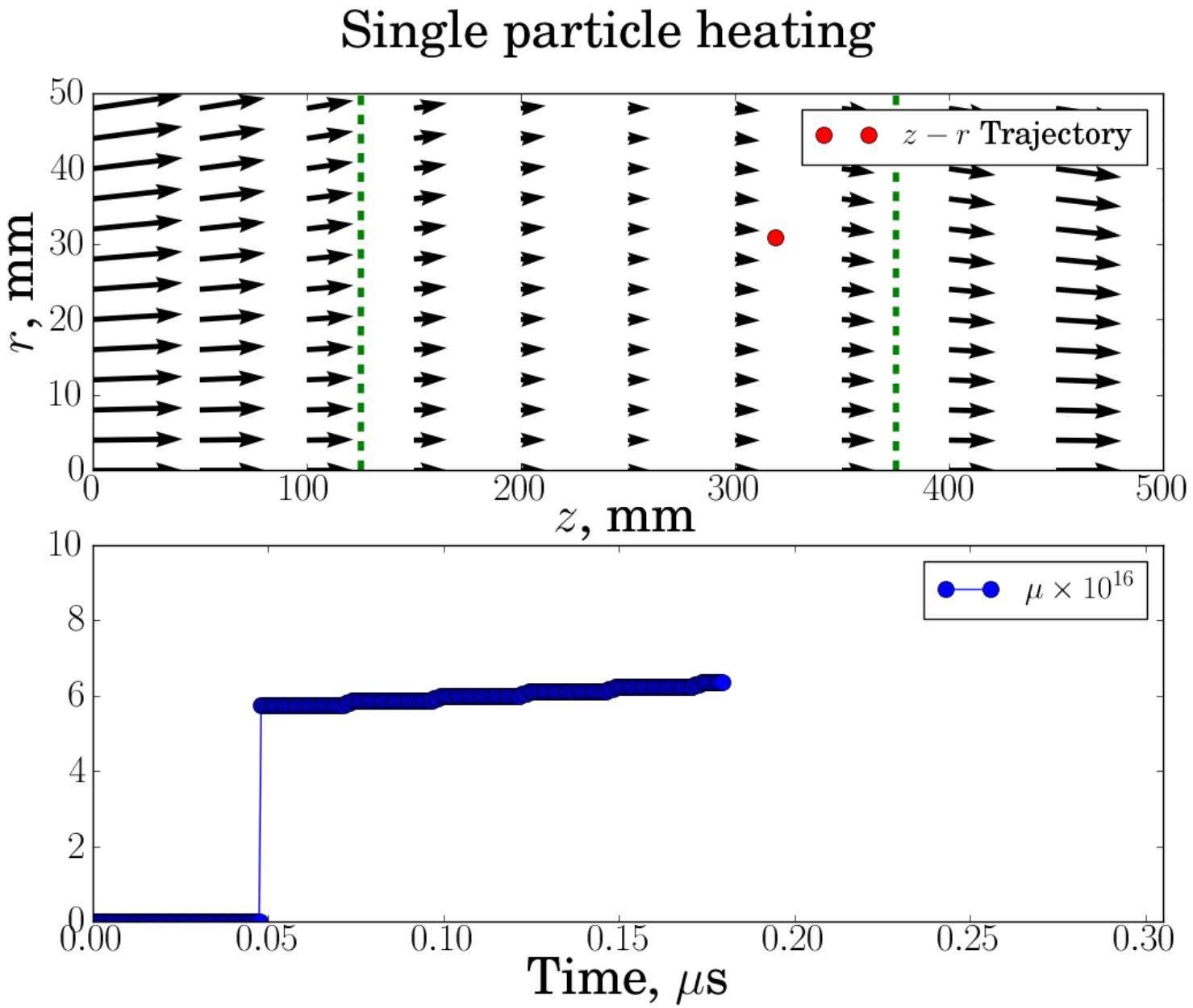
When an electron crosses a resonance surface, it obtains an increase of the perpendicular velocity, with $\Delta v_\perp = \frac{q}{m} E\, t_e$

$$t_e \simeq 1.13\omega_{\mathrm{rf}}^{-1}\left(\frac{2\omega_{\mathrm{rf}}}{|\alpha v_{||}|}\right)^{1/2}$$ **, when turning point is away from the resonant surface**

$$t_e \simeq 0.71\omega_{\mathrm{rf}}^{-1}\left(\frac{2\omega_{\mathrm{rf}}}{|\alpha v_{\perp}|}\right)^{2/3}$$ **, when turning point is near the resonant surface**

where $\alpha = B_z^{-1}/(\mathrm{d}B_z/\mathrm{d}z)$ **and *E* is the electric field magnitude.**

Numerical simulation of single electron heating



ECRIS/ECRCB plasmas modeled by the SIMPL (SIMulation of PLasmas) code

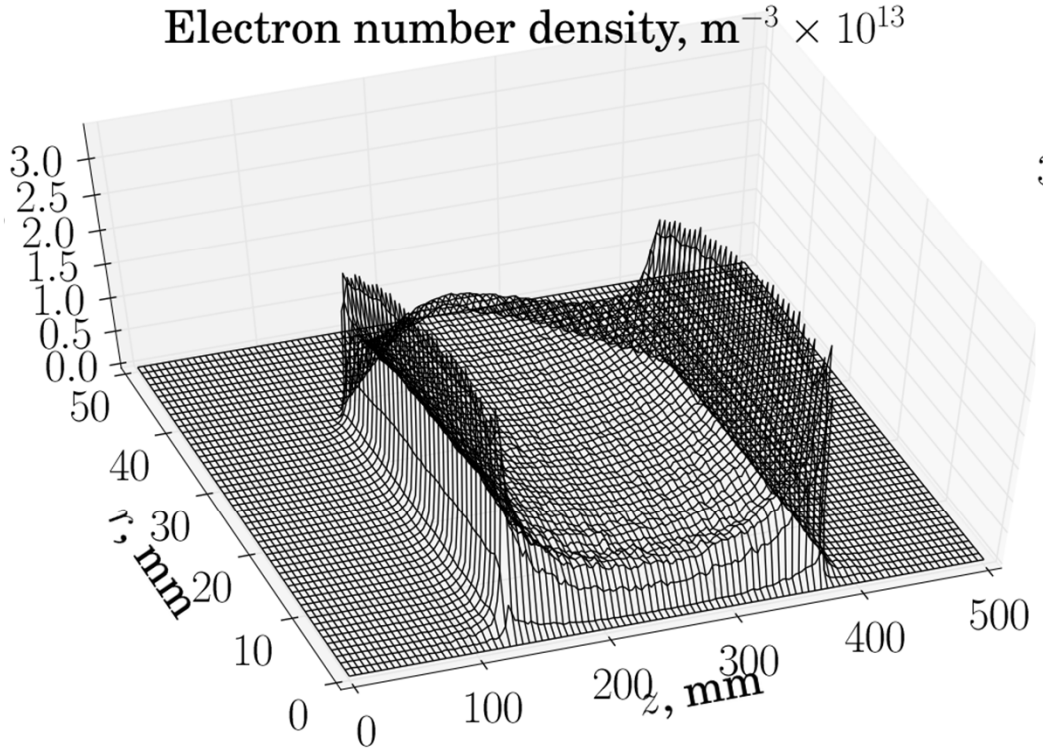
- Electrons have guiding center motions with the Lieberman &Lichtenberg 'kick' RF-heating model.

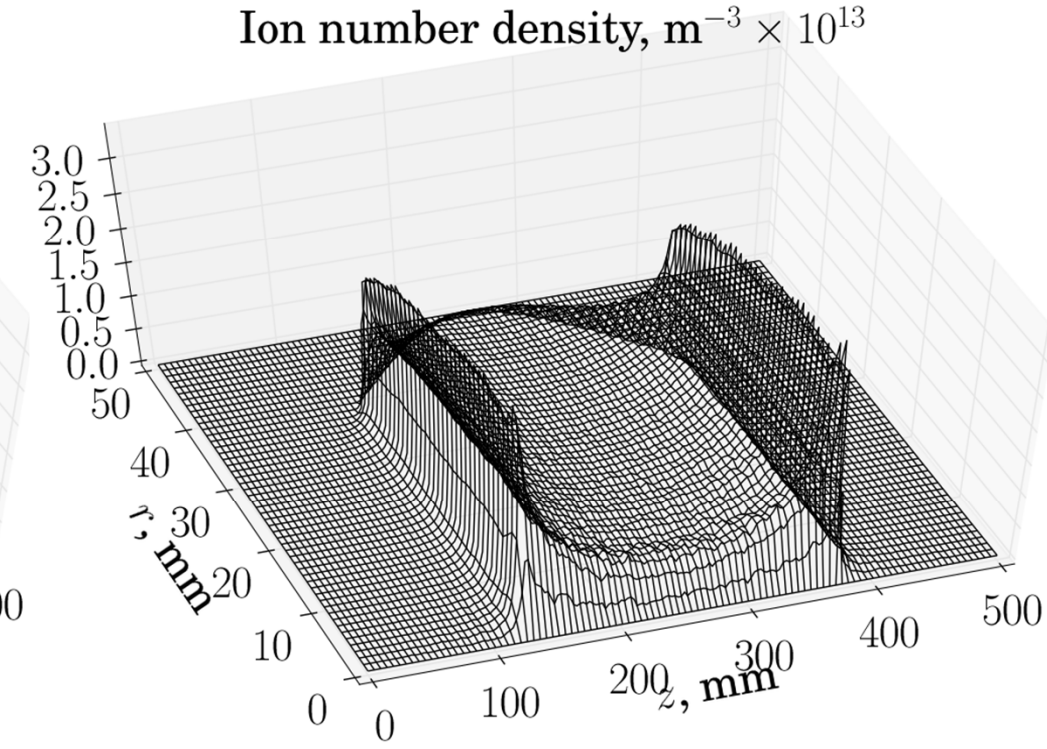
- Ions are fully kinetic.

- Atomic collisions included.

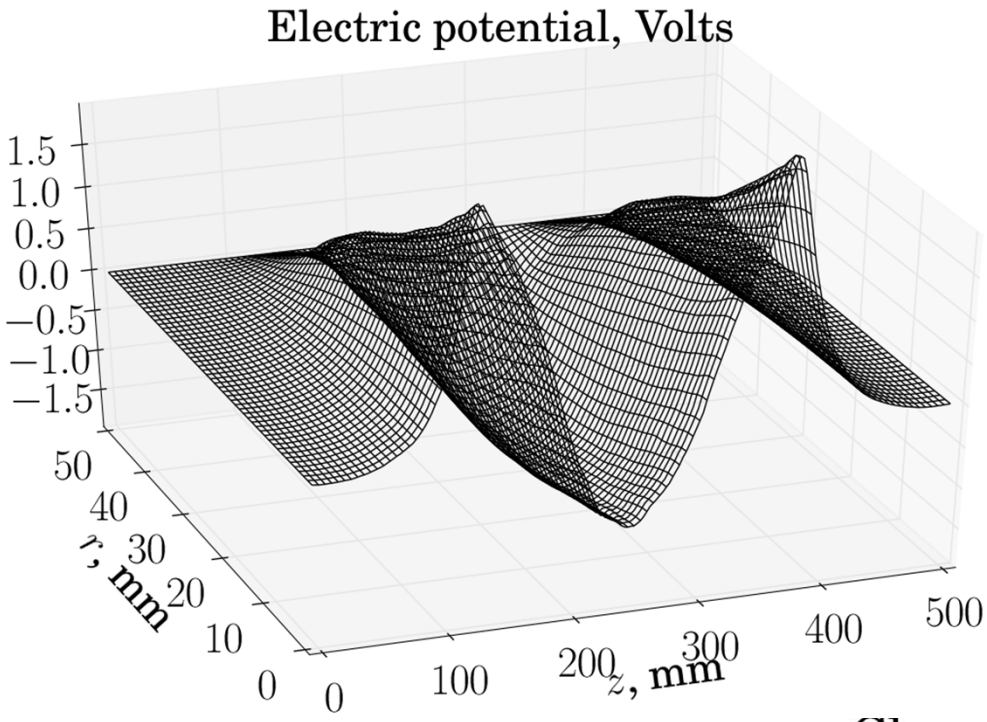
Next we show SIMPL simulation results showing a trend of quasi-neutrality and ambipolarity of the plasma.

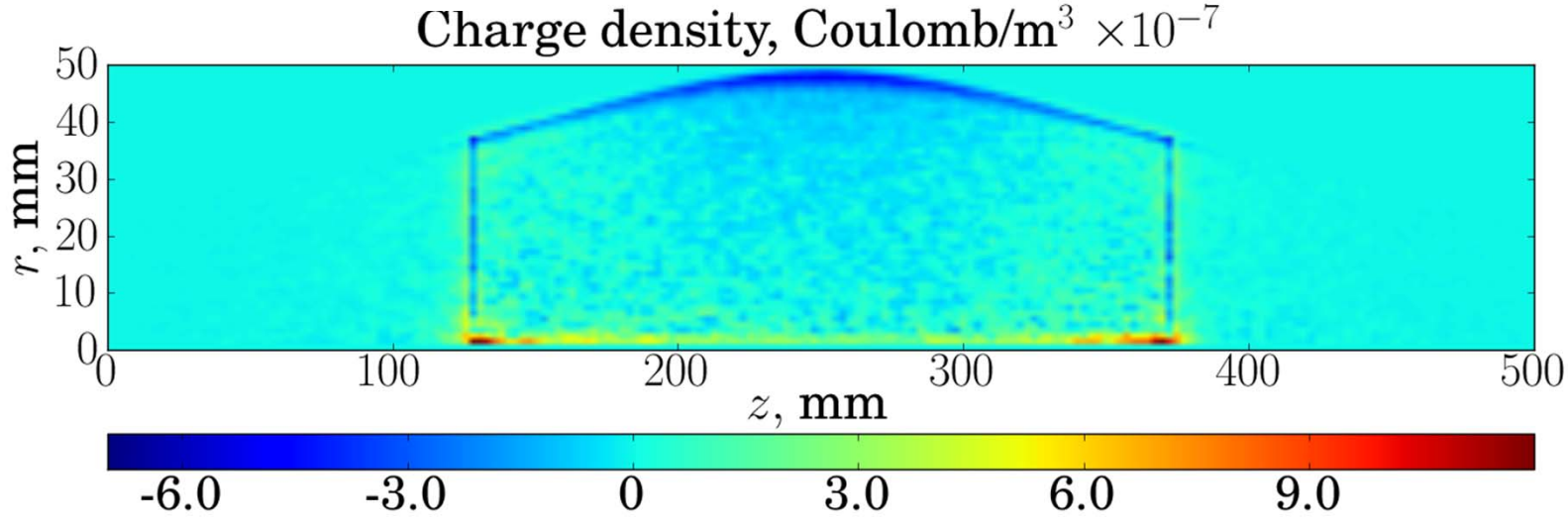
Ambipolarity (at 20 μs)





Quasi-neutrality (at 20 μs)

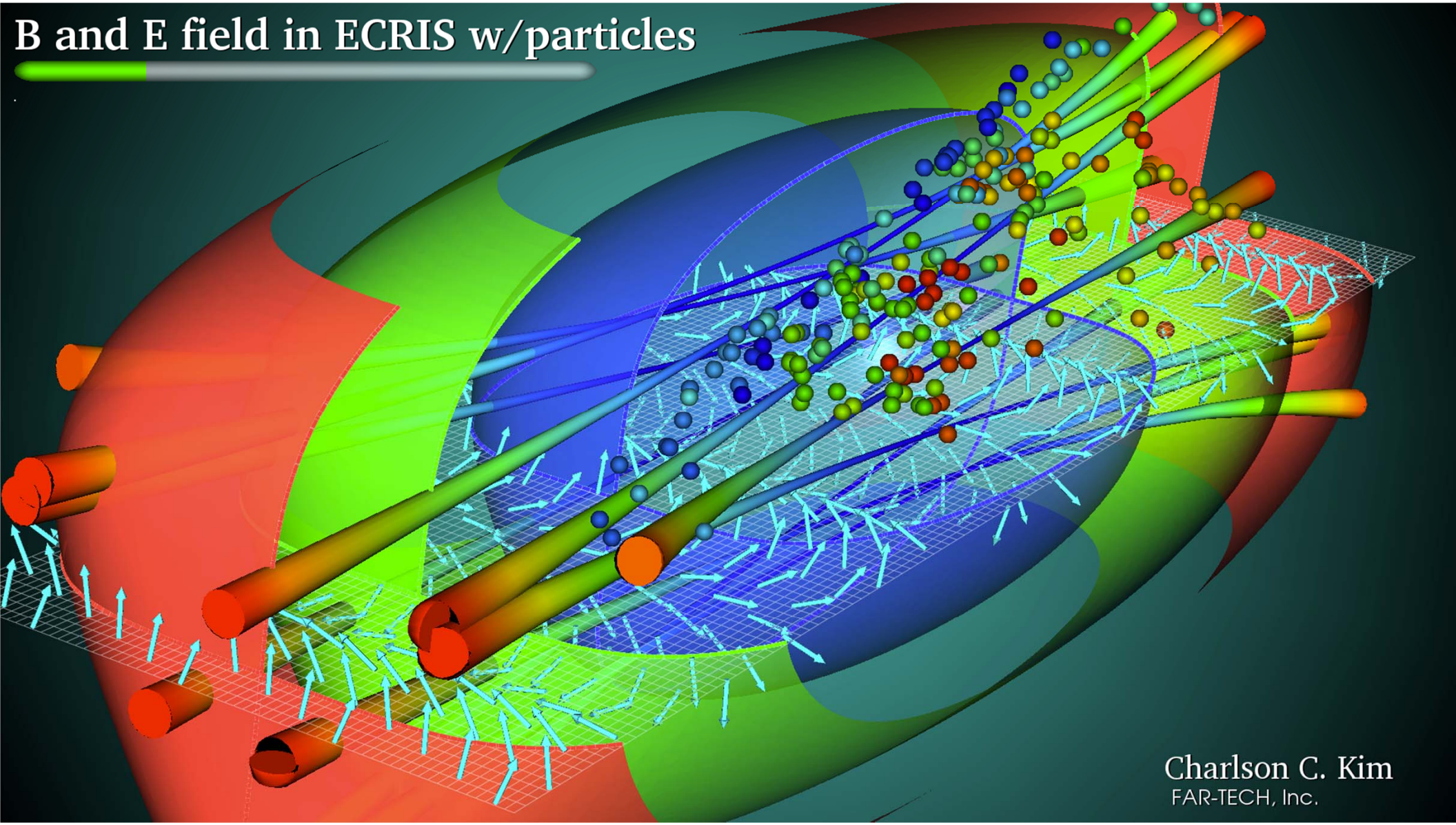




CPU estimation

- Currently drift-kinetic calculation takes 2-3 weeks for a 2D ECRIS/ECRCB simulation to ~ ms with ~48 processors.
- Recently obtained an improved algorithm - this allows x10 speedup.
- We believe a 3D ECRIS/ECRCB simulation, to ~ ms evolution, may be achieved in 2 ~ 3 weeks with 48 processors.

Visualization of ECRIS electron orbits and fields



Project Status

A drft-kinetic 3D ECRIS/ECRCB modeling code (SIMPL) is being developed:

Electrons are modeled by center motion with a 'kick' rf-heating model

Ions are treated fully kinetically.

Basic features are successfully tested.

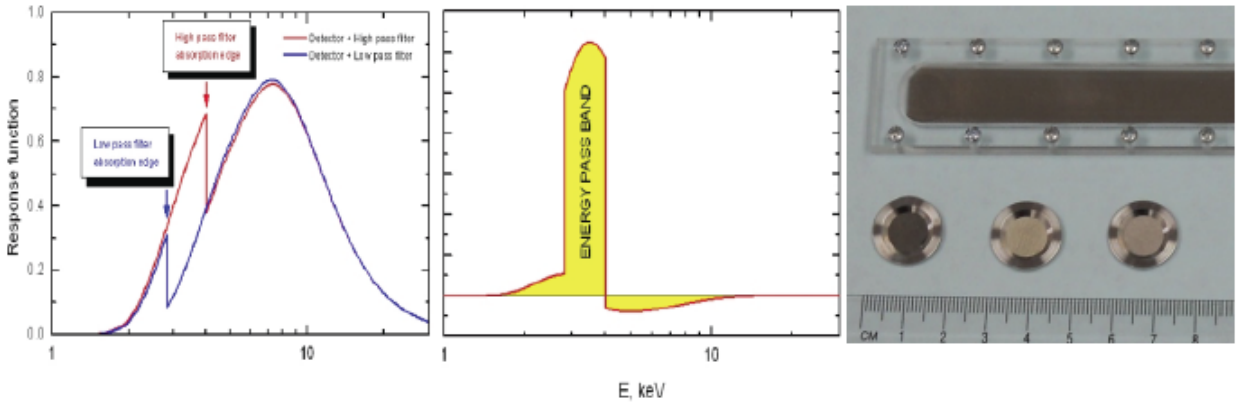
More realistic modeling of RF-heating is on-going under a seperate project

Future work:

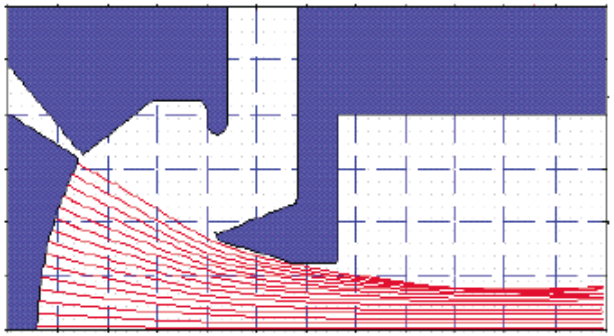
- Will implement more complete and realistic atomic and collision model
- Improve computational efficiency by further MPI parallelization and domain decomposition
- Validate code with experiments for charge breeding efficiency, emittance of extracted beams, and charge states.
- Develop user-friendly GUI
- Visualize data for enhanced comprehension
- Support ECRIS/ECRCB facilities

Commercialization

X-ray Ross Filter sets are installed (at KSTAR)



PBGUNS (particle source code)



Pre-buncher to Industry (Custom order)