FAR-TECH’s ECR Charge Breeder Simulation Toolset – MCBC, GEM, IonEx*

Jin-Soo Kim, Liangji Zhao, Brian Cluggish, I. Nick Bogatu, S. Galkin, L. Grubert
FAR-TECH, Inc. and Richard Pardo, ANL

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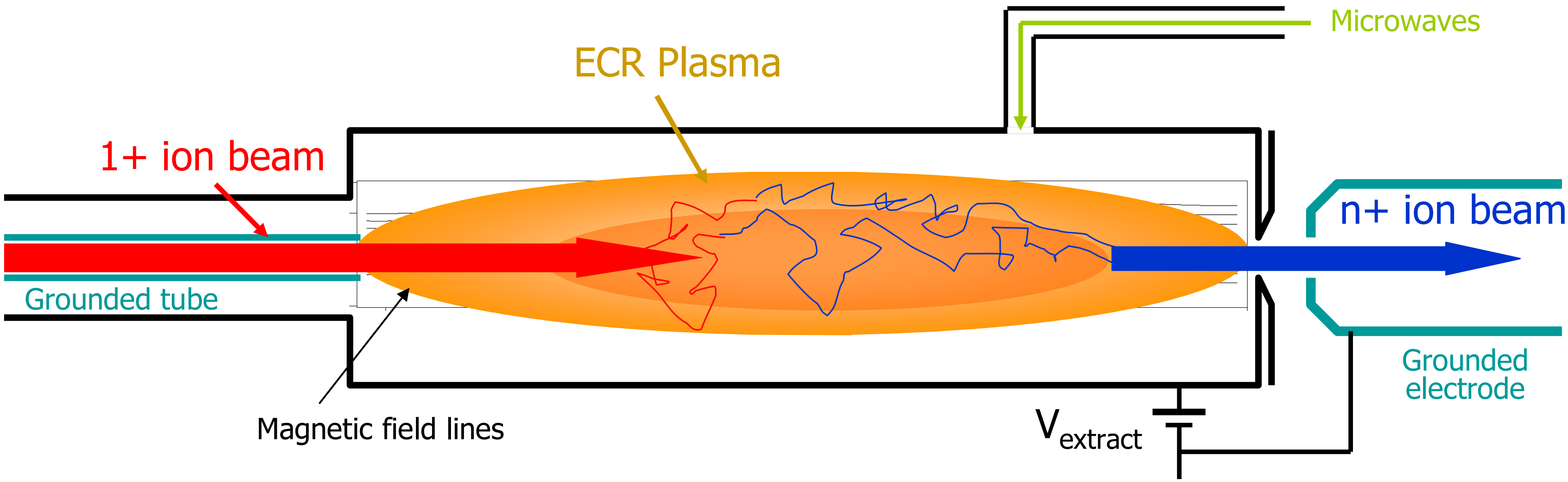
FAR-TECH, Inc., 3550 General Atomics Court, MS 15-155, San Diego, CA 92121
Tel: (858) 455-6655, Fax (858) 450-9741 www.far-tech.com

ECR Charge Breeder produces highly charged ions by injecting low charge state ions into ECR heated plasma.

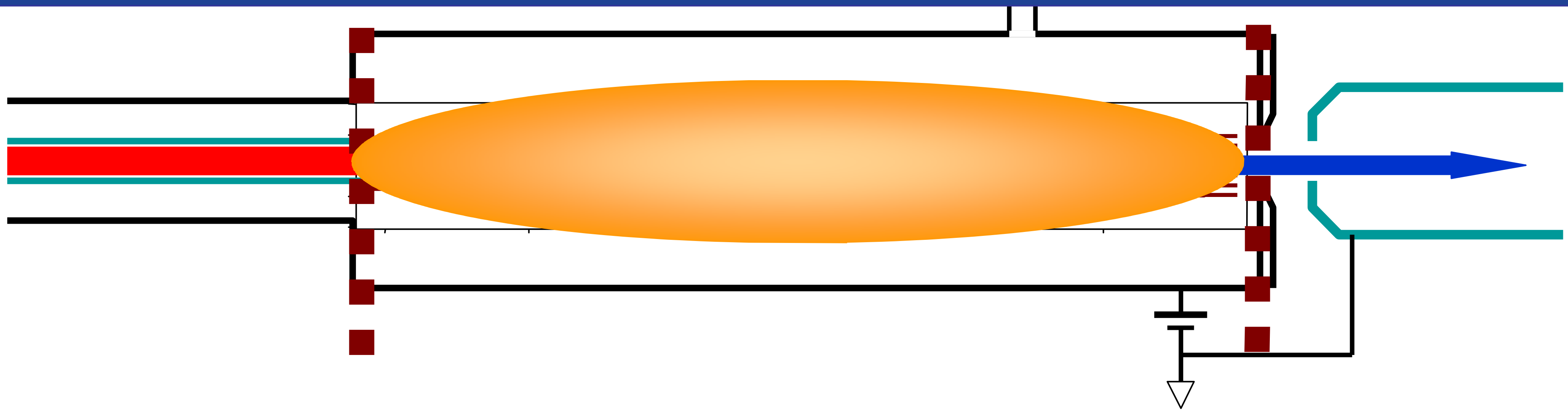


FAR-TECH is developing an integrated suite of codes for ECR CB modeling and optimization.

ECR CB involves three distinctive regions with different processes

FAR-TECH's Suite of Codes for ECR Charge Breeder Modeling

MCBC **GEM** **IonEx**

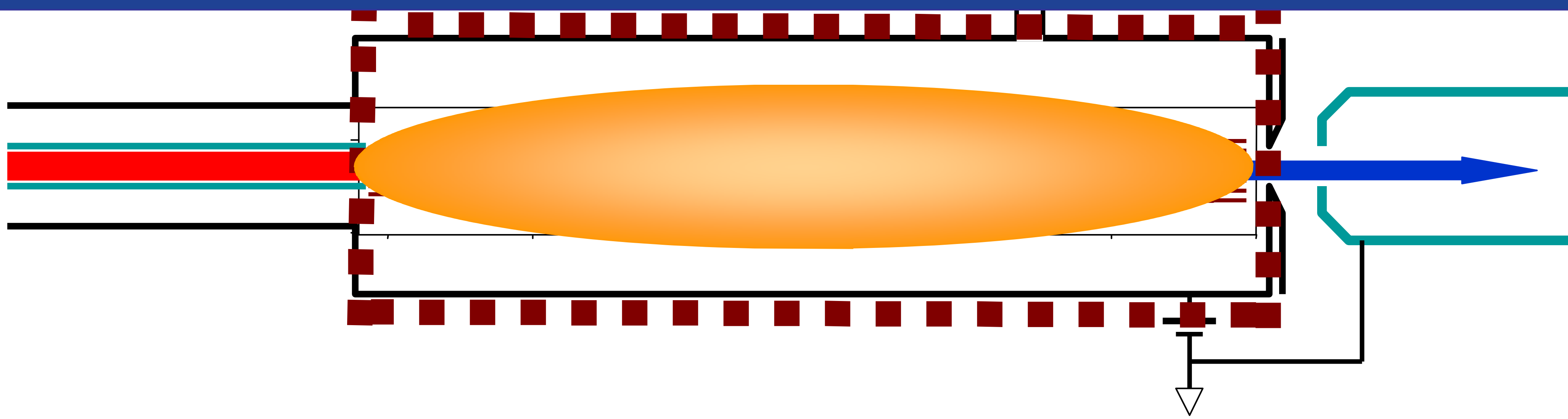


ECR heated plasma region is modeled by Generalized ECRIS Modeling (GEM).

GEM models fluid ions, Fokker-Plank electrons, and particle balance neutrals.

FAR-TECH's Suite of Codes for ECR Charge Breeder Modeling

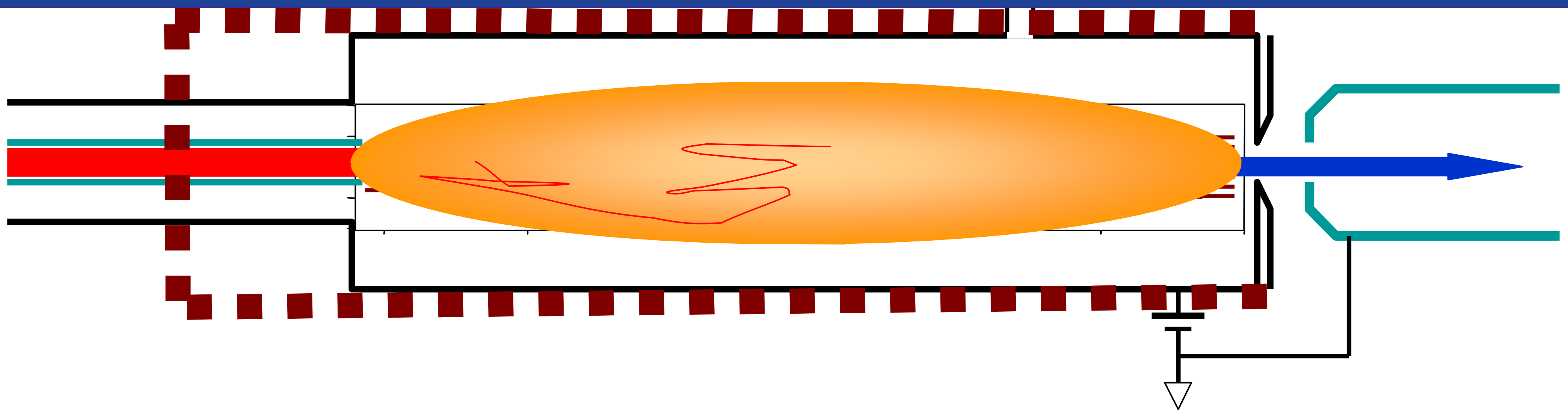
MCBC GEM IonEx



For beam injection region the dynamics of injected ions into plasma is modeled by a particle tracking code, Monte Carlo Beam Capture (MCBC).

FAR-TECH's Suite of Codes for ECR Charge Breeder Modeling

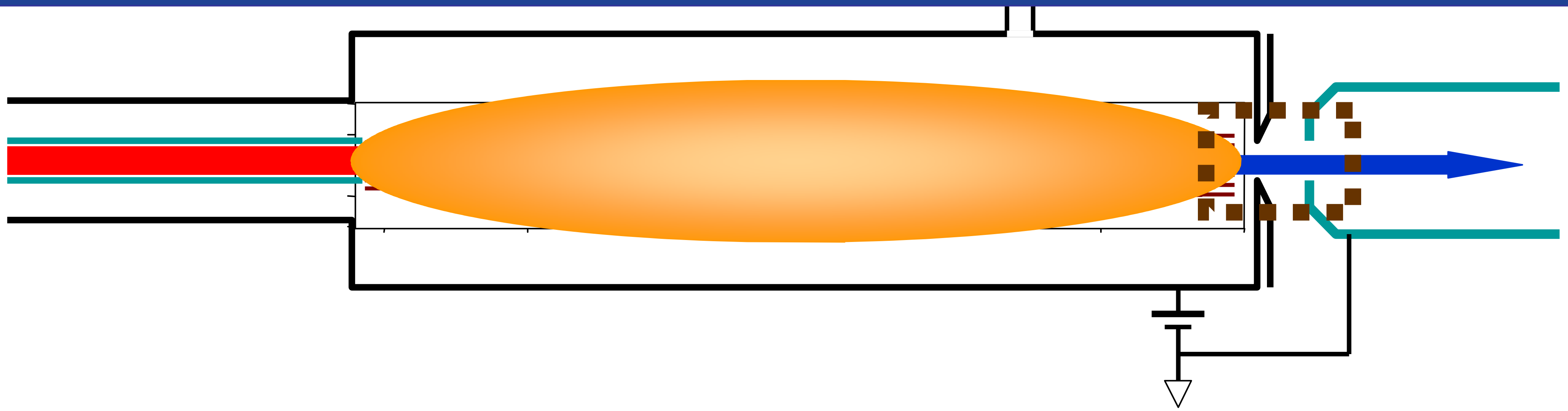
MCBC GEM IonEx



In the beam extraction region, beam optics is modeled by IonEx. IonEx uses an innovative algorithm “particle in cloud-of-points” (PICOP).

FAR-TECH’s Suite of Codes for ECR Charge Breeder Modeling

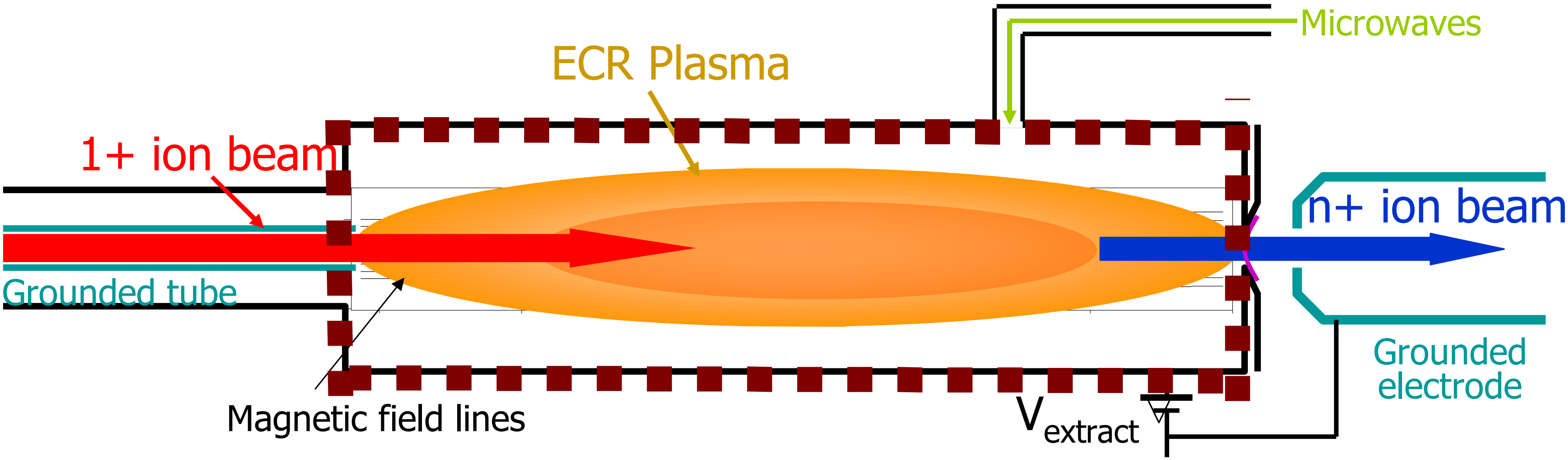
MCBC GEM IonEx

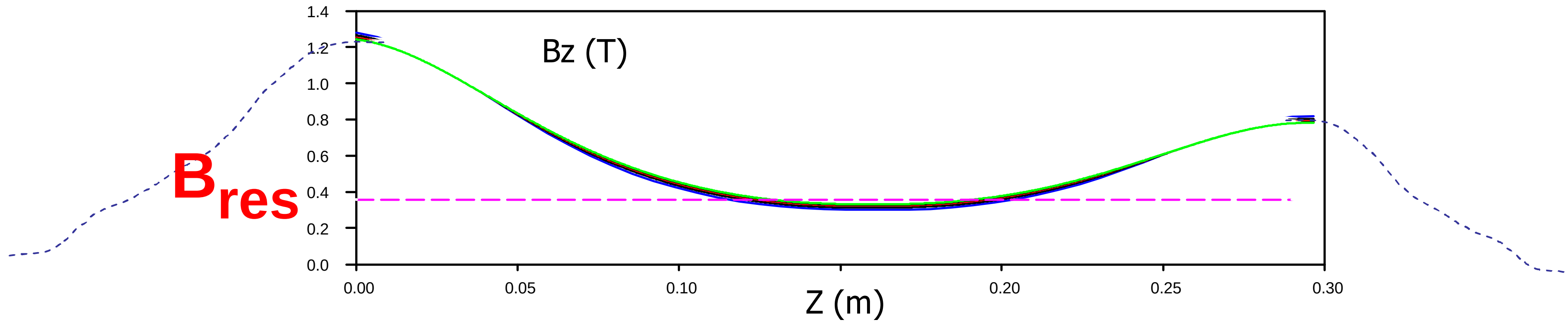


GEM

Generalized ECRIS Modeling Code

GEM models ECR plasmas, where electrons are ECR heated and magnetic-mirror trapped.

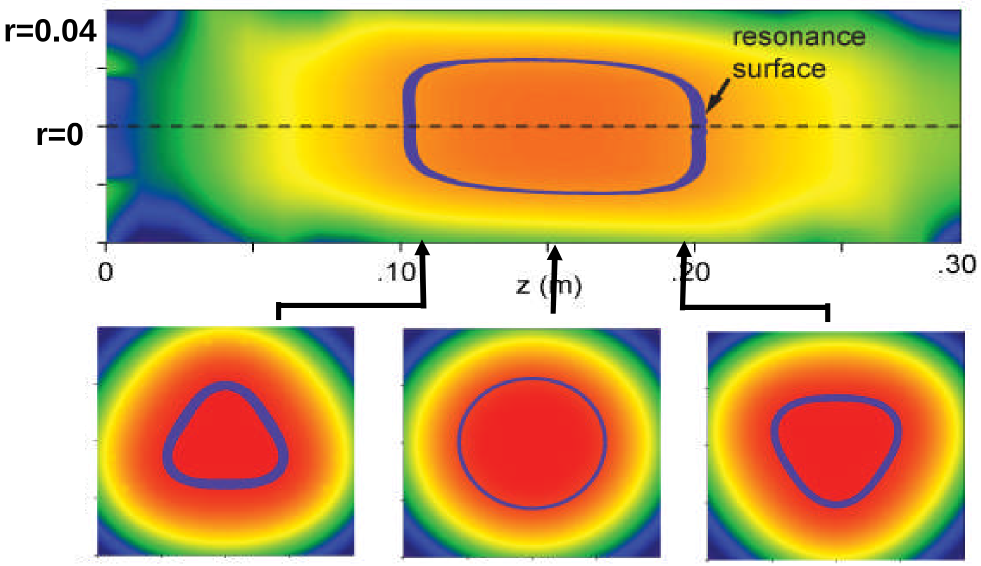




GEM 2D(r,z) includes (r,z) dependance for rf resonance zone.

Resonance condition: ω_{rf}=e|B|/mc

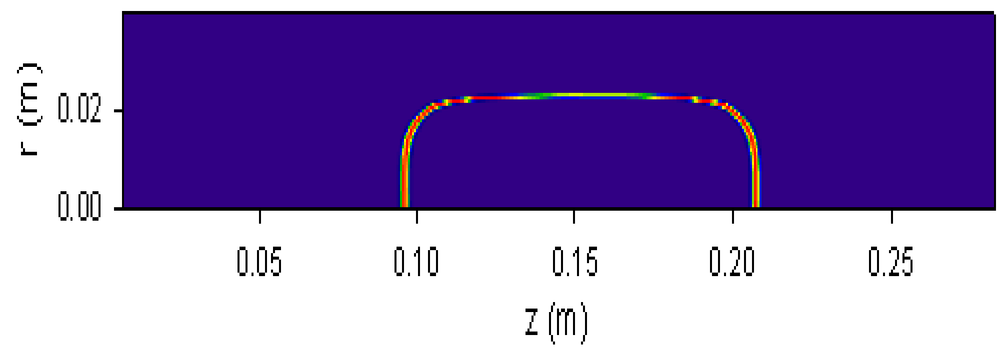
Color contours of |B|
- full 3D
rf resonance surface



Color contours of |B|
- 2D approximated
rf resonance surface

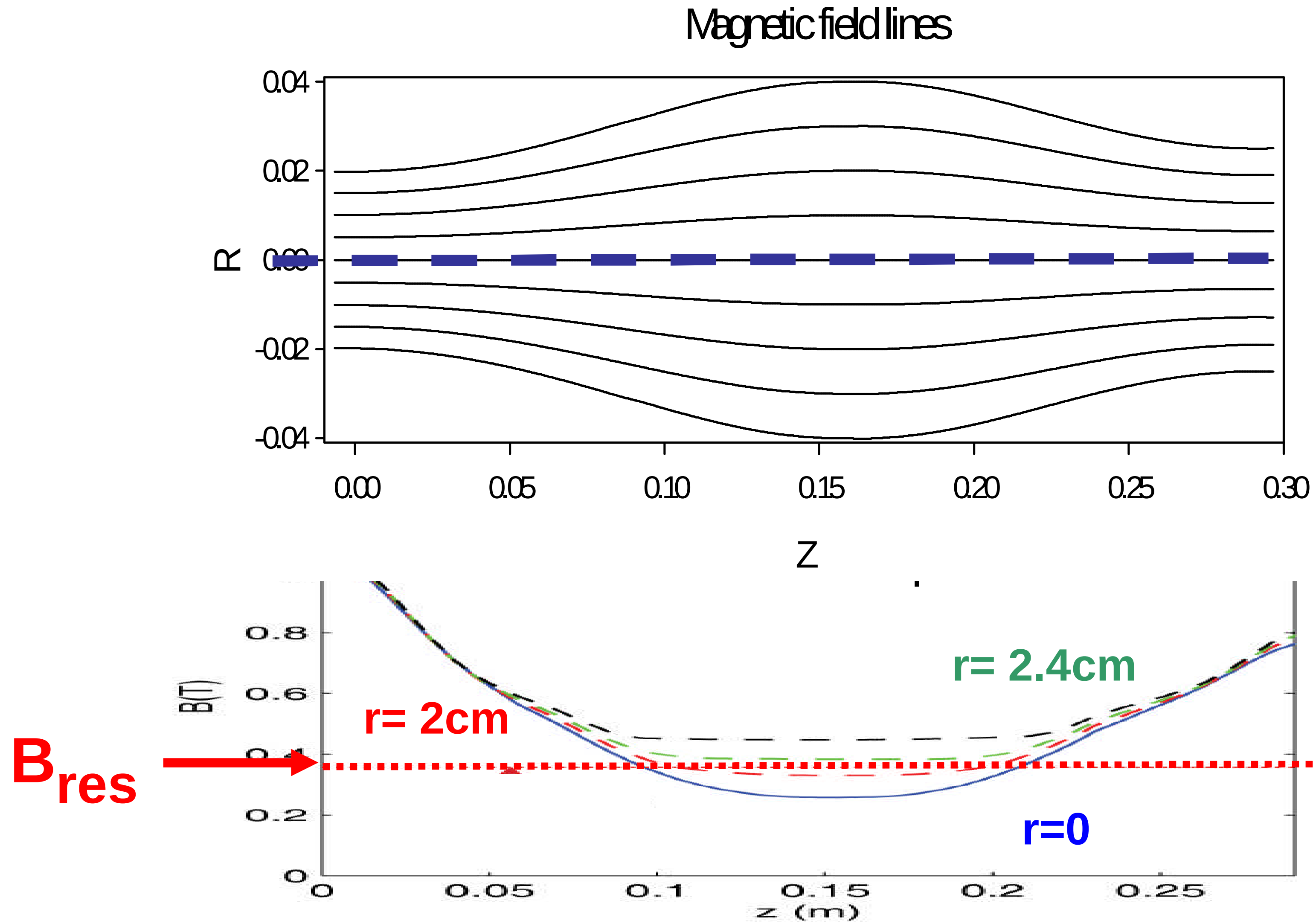
Radial dependence of resonance surface represented!

– IMPORTANT!



GEM 2D(r,z) grids

r: radial position of, azimuthally averaged, B-field flux tubes
z: axial coordinate



GEM models dynamics of

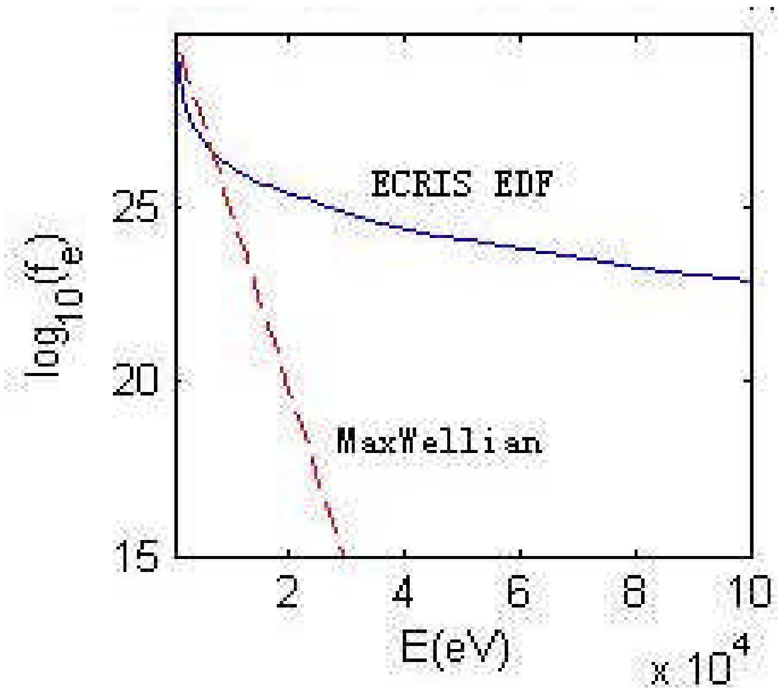
(1) Fokker-Plank electrons,

(2) fluid ions, and

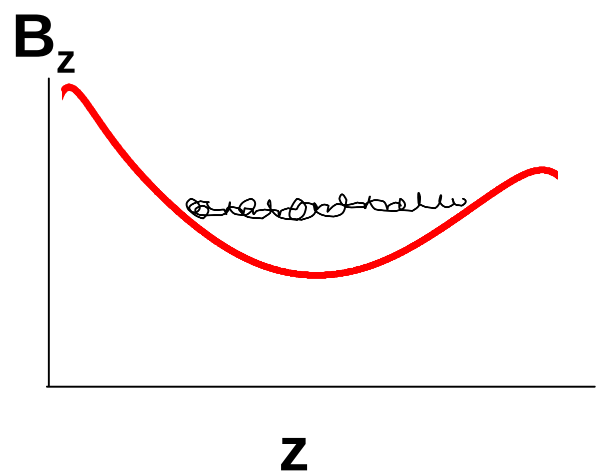
(3) particle balanced neutrals.

Electron Modeling: Non-Maxwellian electrons are modeled by Fokker-Planck, Bounce-averaged in the magnetic mirrors.

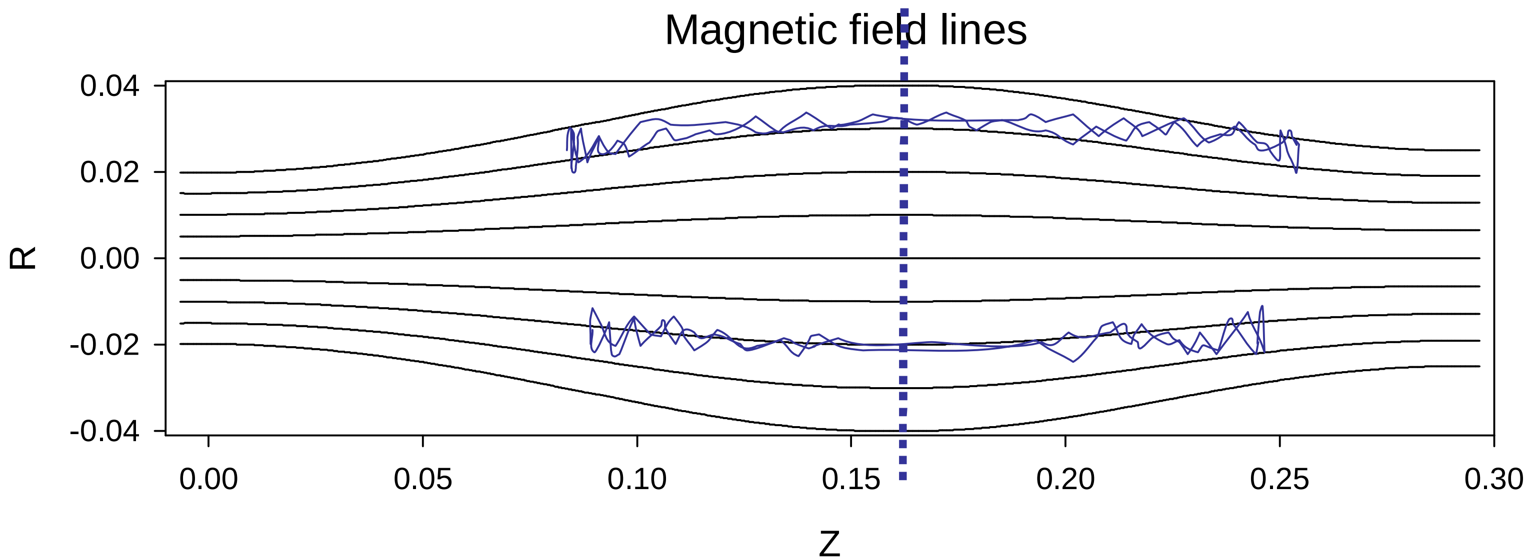
ECR EDF is Non-Maxwellian



Mirror trapped electrons in ECRIS are collisionless.



EDF $f_e(v,\theta;r,z)$ is mapped from $f_e(v_{mid},\theta_{mid};r_{mid}, z_{mid})$



EDF at any axial location $f_e(v,\theta,z)$ **is related with EDF on midplane through energy and magnetic momentum conservation.**

A 0D bounce-averaged FokkerPlanck code , FPPAK94* , is used to calculate EDF on midplane by solving Fokker-Planck equation.

*

Ion Modeling: fluid ions with radial and axial transport

- Ions are cold, Ti~1 eV, and highly collisional
  - **Mean free paths much shorter than device**
  - **Ions all have same axial speed**
  - **Radial and azimuthal speed are different for each ion.**

- 2D (r,z) 2V (v, θ) EDF used to calculate ionization rates:
  - $\mathbf{A^{+n} + e^- \rightarrow A^{+n+1} + 2e^-}$

- Ion loss rate is limited by electron confinement in magnetic mirror.
- The 2D ion continuity equation is solved using upwind method:

$$\frac{\partial n_{j,q}}{\partial t} = S_{j,q}^{in} - S_{j,q}^{out} - \frac{1}{A_z}\frac{\partial}{\partial z}\left[A_z n_{j,q} u_{j,q}\right] - \frac{1}{r}\frac{\partial}{\partial r}\left[r n_{j,q} v_{j,qr}\right]$$

Summary of GEM model

IONS:

Cold and highly collisional:

Fluid ion model

ELECTRONS:

bounce time << collision time:

1D bounce-averaged for each flux surface

Fokker-Planck electron code $f_e(v,\theta; r,z)$

NEUTRALS:

Unimpeded by magnetic fields:

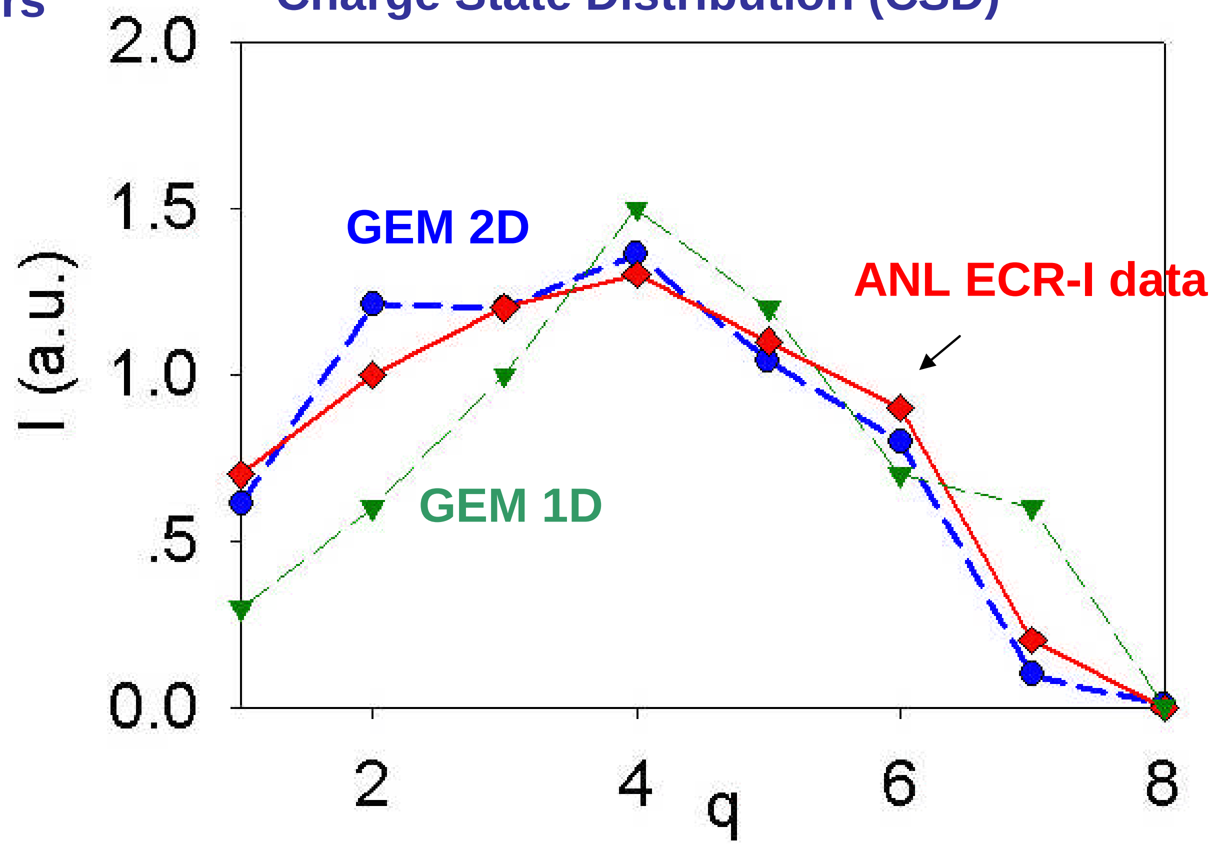
Density profile determined by particle balance

Using experimental "knobs" as input, GEM predicts features observed in ECRIS. Improved agreement with measured CSD by GEM 2D.

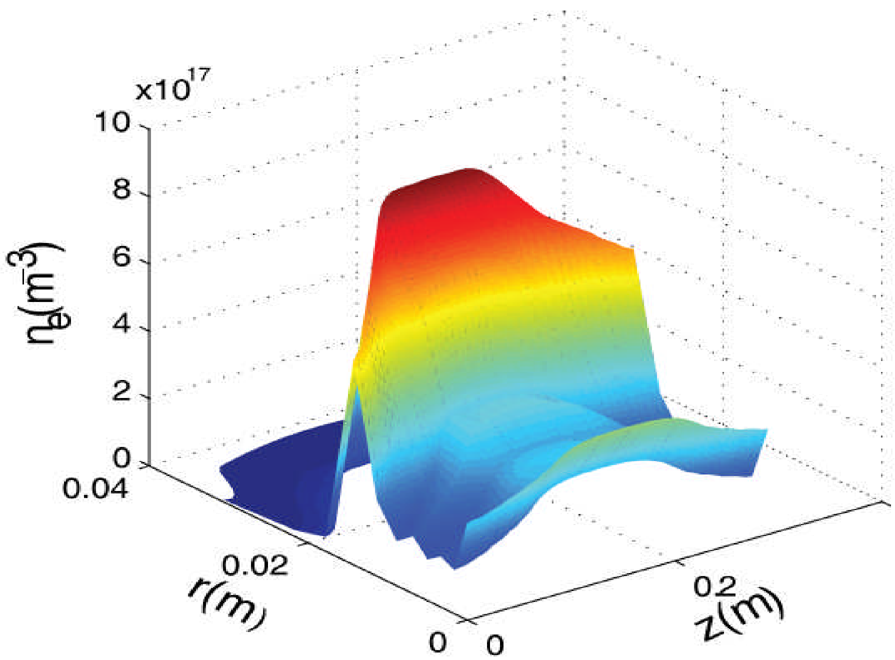
ANL ECR-I Run input parameters

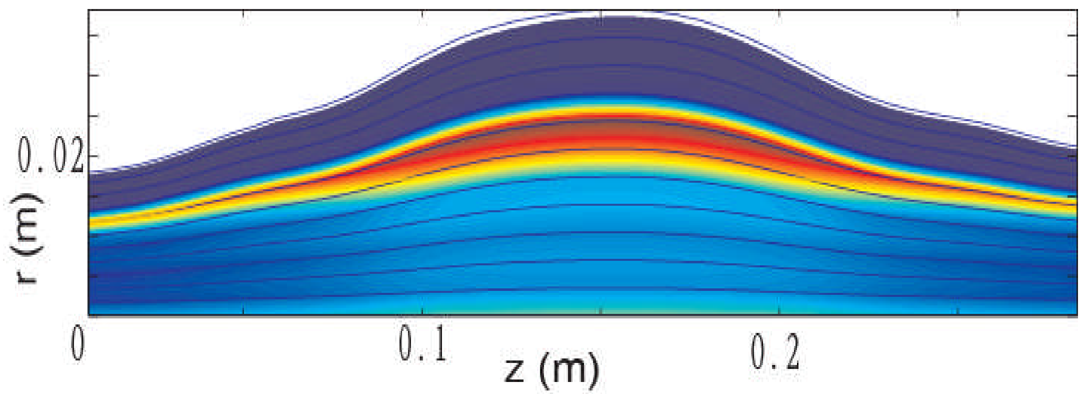
Length	**29 cm**
Radius	**4 cm**
Plasma Radius (mid plane)	**3 cm**
Mirror Ratios	**4.5 & 3**
rf Frequency	**10 GHz**
rf Power	**323 W**
Ion Species	**oxygen**
Gas Pressure	**$1.2 \cdot 10^{-7}$ torr**

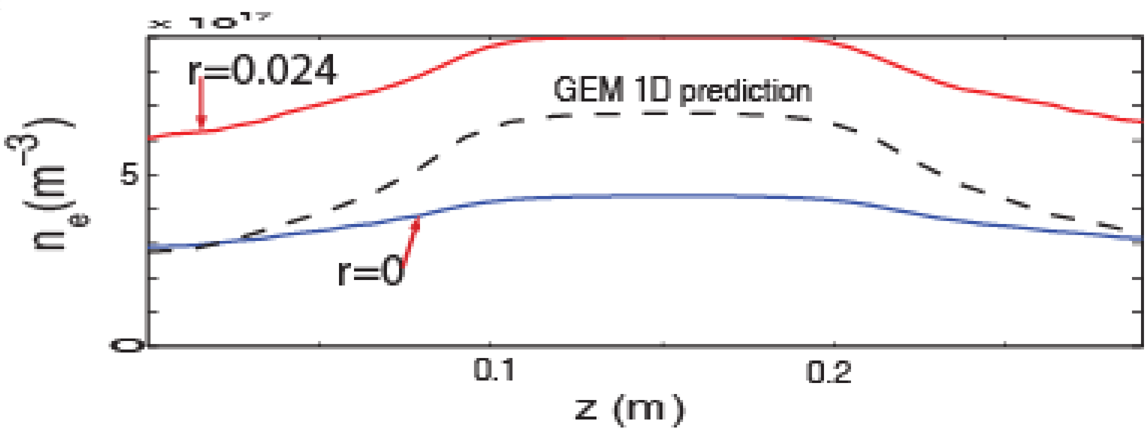
Charge State Distribution (CSD)



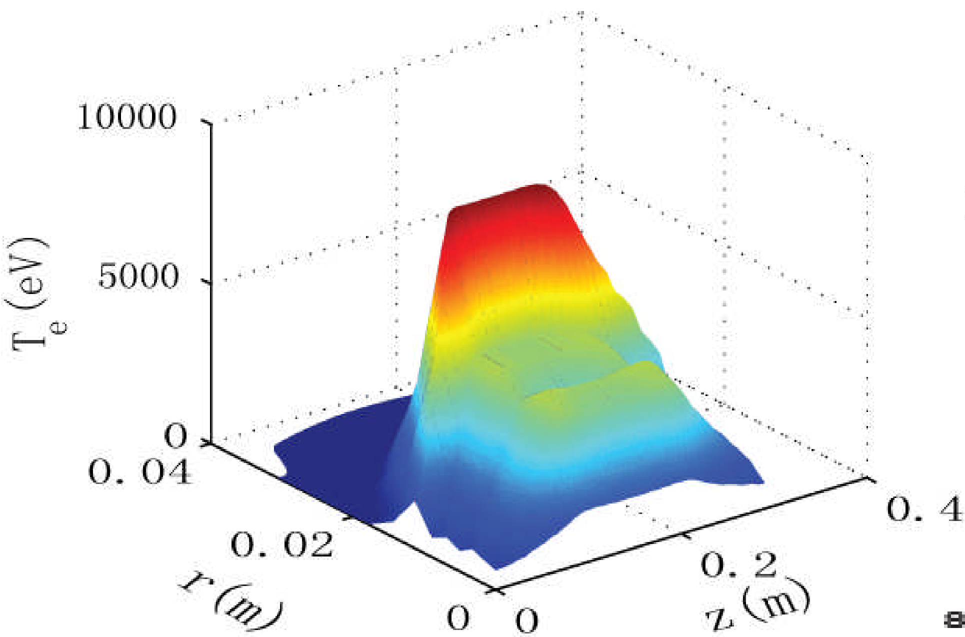
GEM 2D predicts hollow electron density profiles in device, peaking at rf resonance region

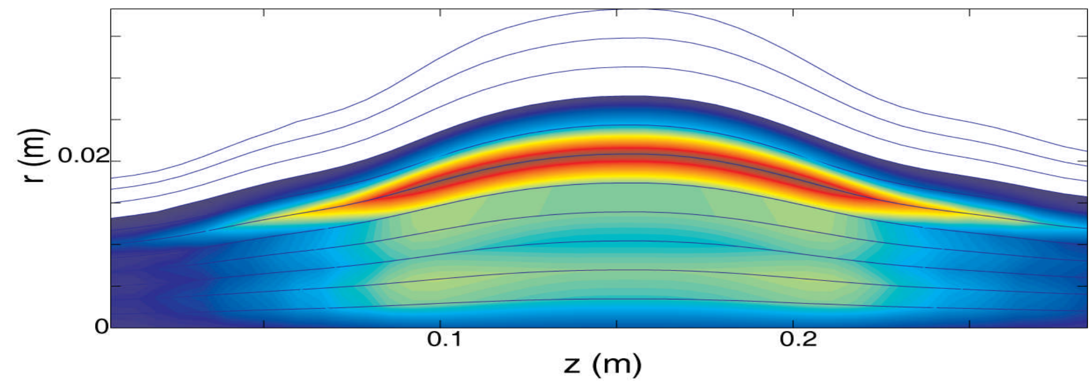


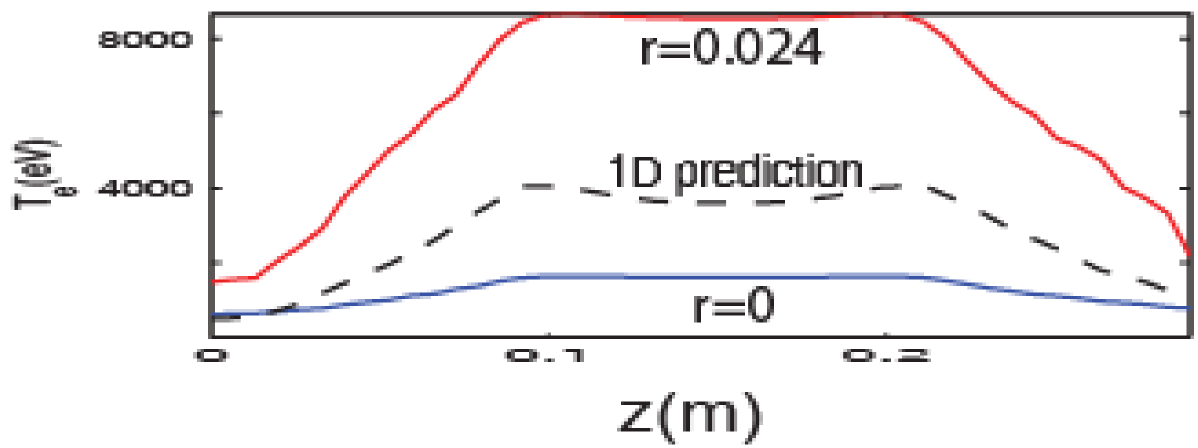




GEM 2D predicts hollow electron temperature profiles of plasma, peaking at rf resonance region

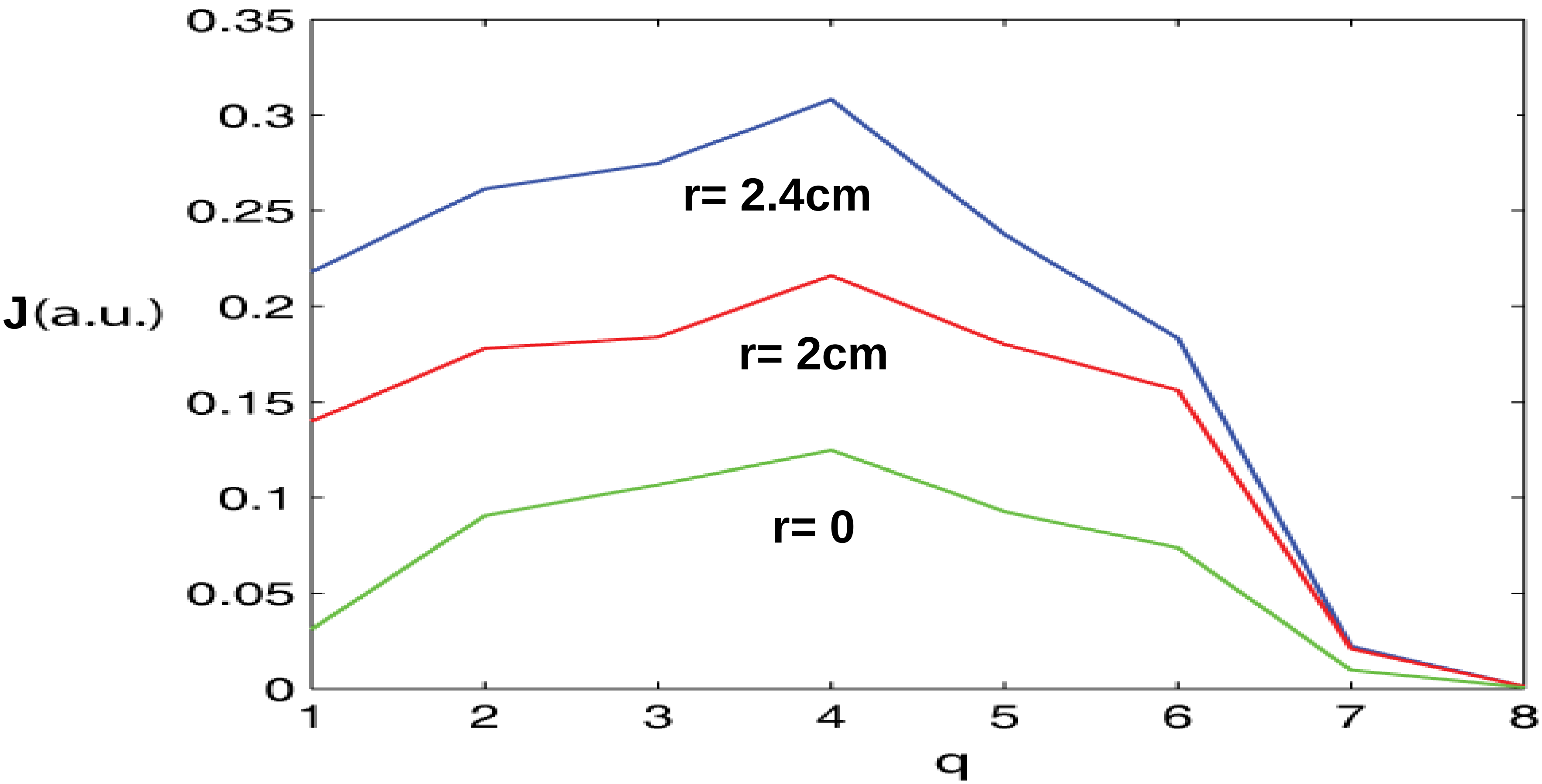




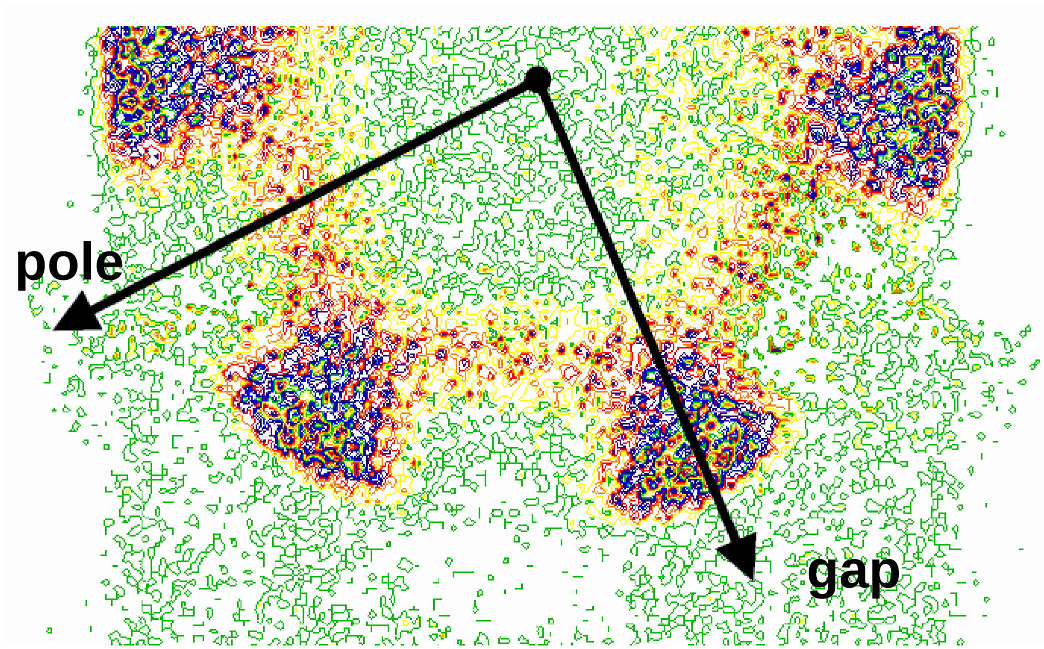


GEM 2D predicts hollow CSD of extracted ion sources, similar to experimental observations.

ANL ECR-I data



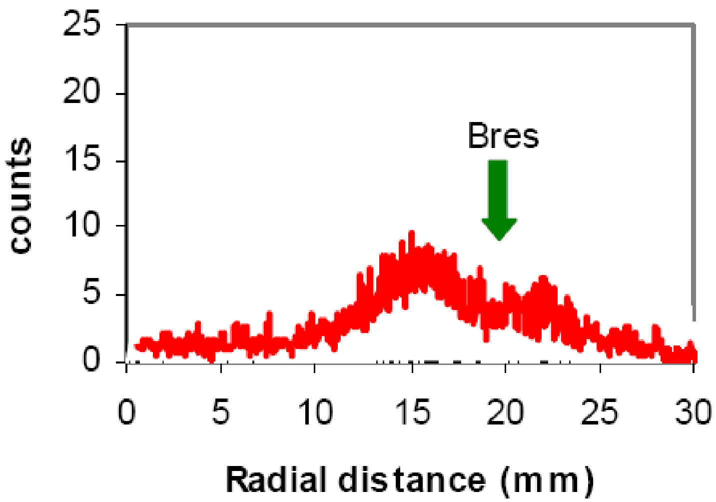
Experimental evidence of hollow profiles; X-ray image of ATOMKI-ECRIS.

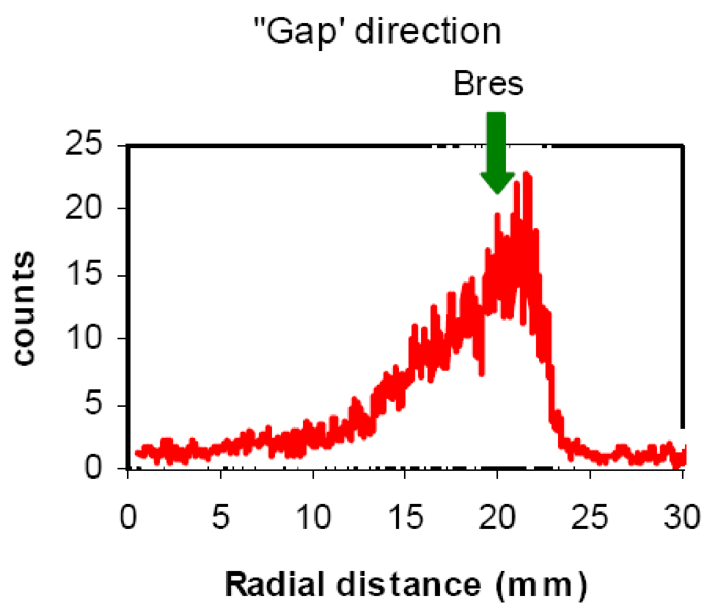


X-ray image and profiles in ‘pole’ and ‘gap’ directions:

ATOMKI-ECRIS, Hungary

X-ray fluence ~ f (q, n_e, T_e)

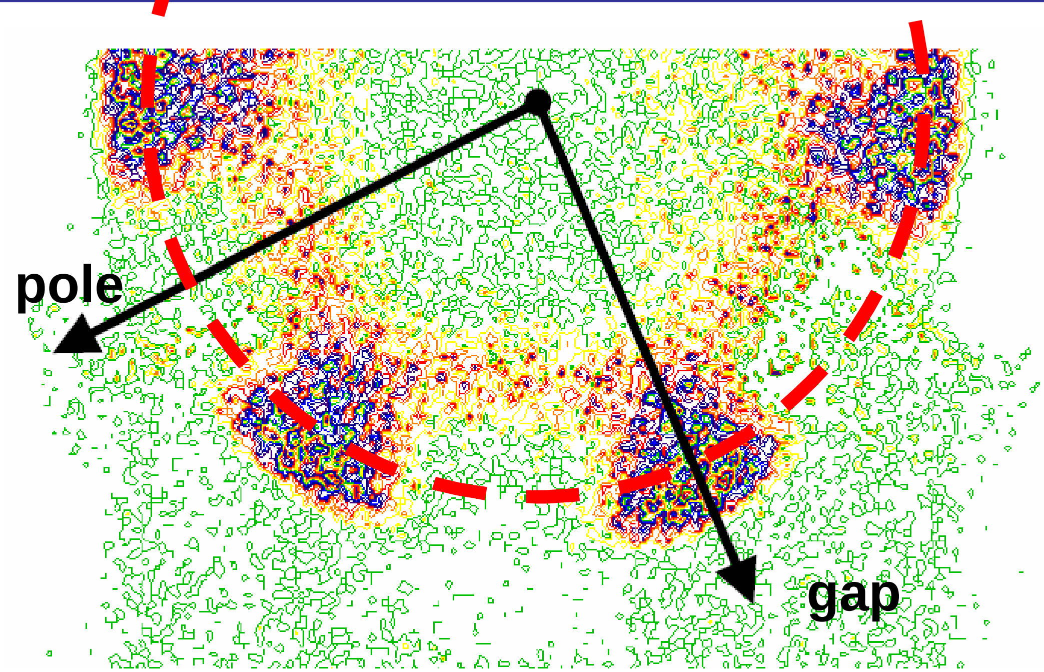




From ICIS03 talk (and RSI 2004) by

S. Biri, A. Valek,T. Suta, E. Takács, J. Pálinkás, B. Radics,J. Imrek, B. Juhász, L.T. Hudson, Cs. Szabó

Experimental evidence of hollow profiles; X-ray image of ATOMKI-ECRIS.



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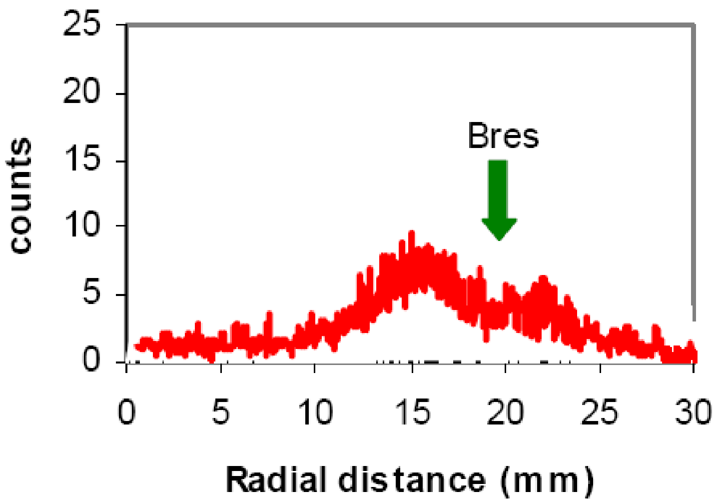

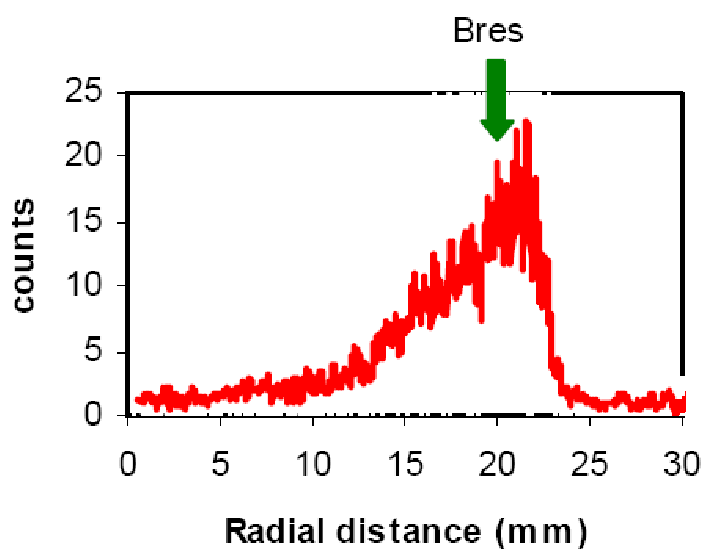

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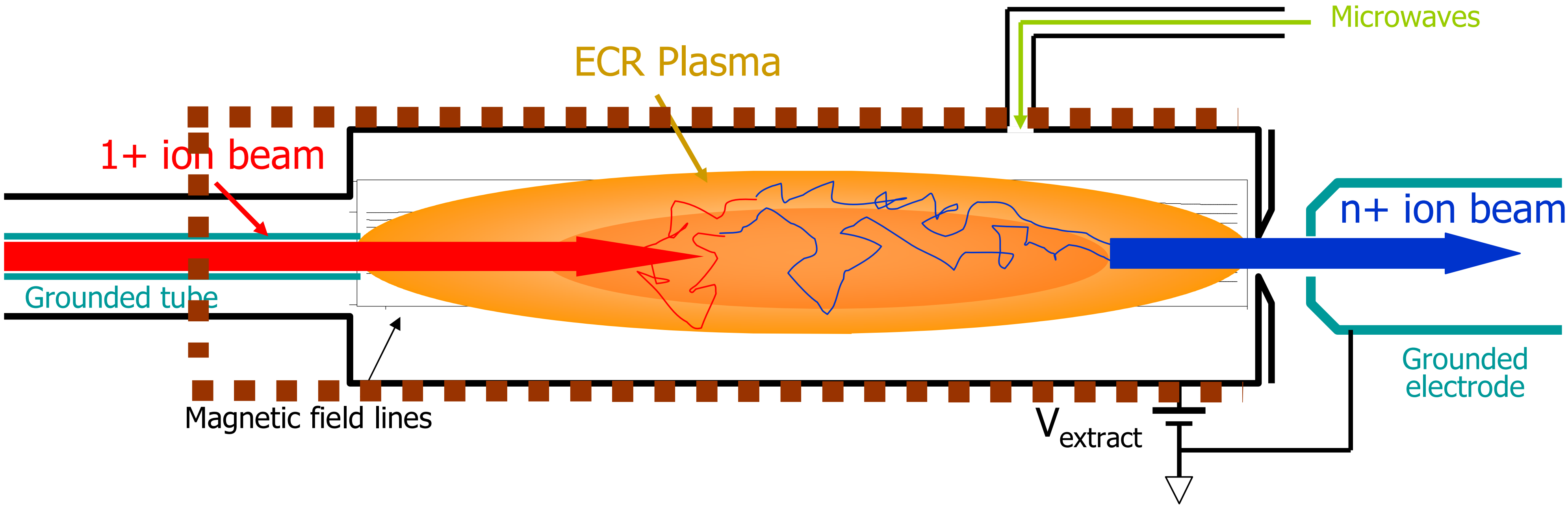
MCBC

Monte Carlo Beam Capture Code

MCBC tracks injected beams until thermalized by plasma.

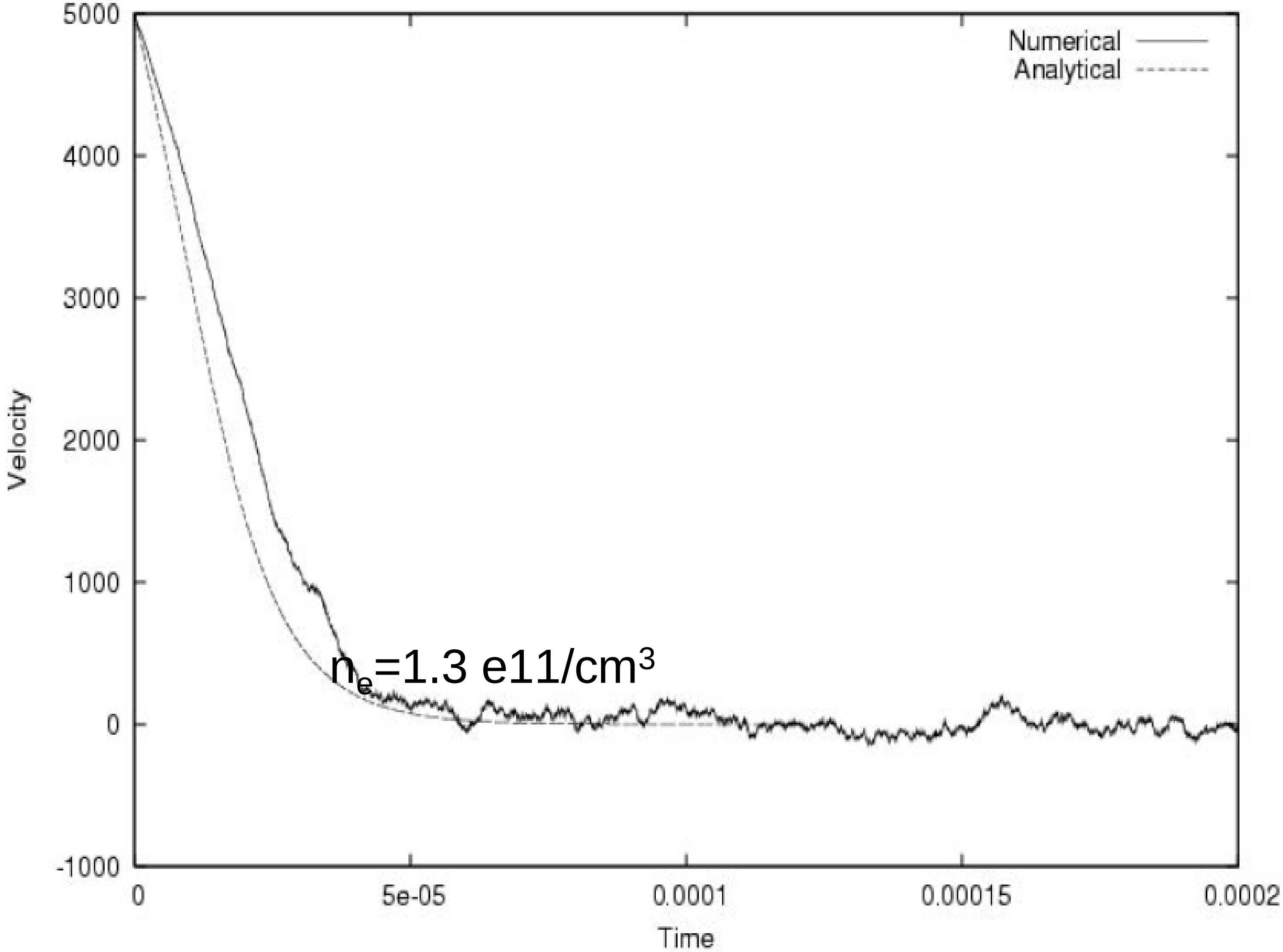


MCBC is a Monte Carlo particle tracking code in plasma

- **Runge-Kutta orbit tracing**
- **Coulomb collisions treated as continuous force**
  - Long range Coulomb force modeled with modified Boozer form*
  - Continuous drag force plus random velocity step
- **Other collisions treated with rejection method**
  - Ionization (key atomic process: DI, AU, Double Ionization, …)
    EDF is far from Maxwellian
    Ionization rates evaluated using Fokker-Plank calculation
  - Charge exchange (small but included)
  - Recombination (small, neglected, easy to include)

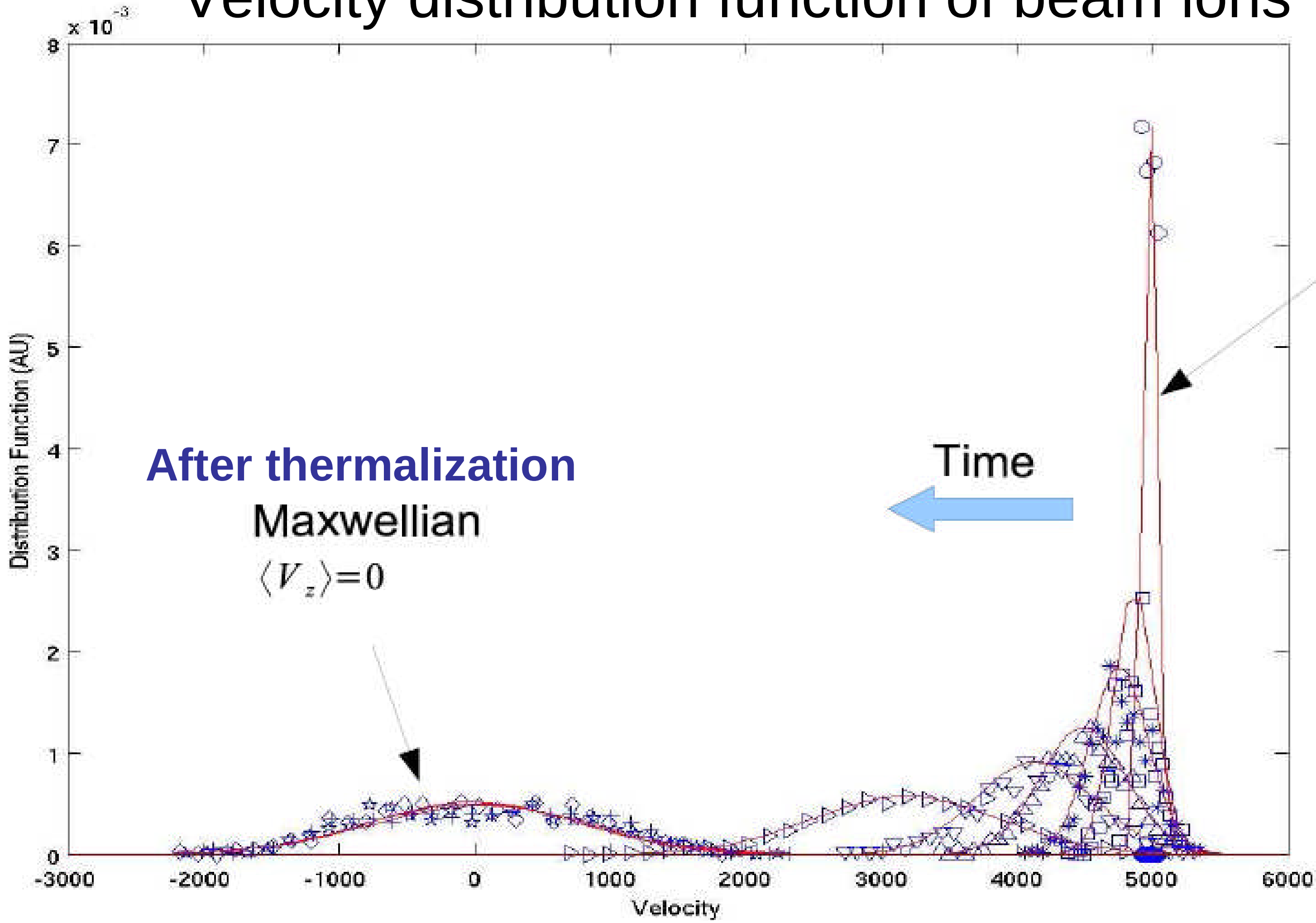
*A. H. Boozer, *Phys. Plasmas* **9**, 4389 (2002)

Slowing down of beam ions by plasma



Beam ions slowed down and are thermalized mainly by Coulomb collisions with plasma ions

Velocity distribution function of beam ions



Initial beam

Delta function broadens in just one time step!

$v = \delta(v - v_o)$

$T_{beam} < V_{beam}$

$V = \langle V \rangle = V_o$

Drag by the background plasma ions is mostly due to ion-ion Coulomb collisions

- For our parameters,

$$\frac{v_{i-i}}{v_{i-e}} \approx Z^4 \left(\frac{\mathrm{T_e}}{\mathrm{T_i}}\right)^{3/2} \left(\frac{\mathrm{m_e}}{\mathrm{m_i}}\right)^{1/2} >> 1$$

Maximum drag due to ion-ion collision occurs when $v_{i,beam} \approx v_{th,i\text{-}plasma}$

ECR CB Optimization Example

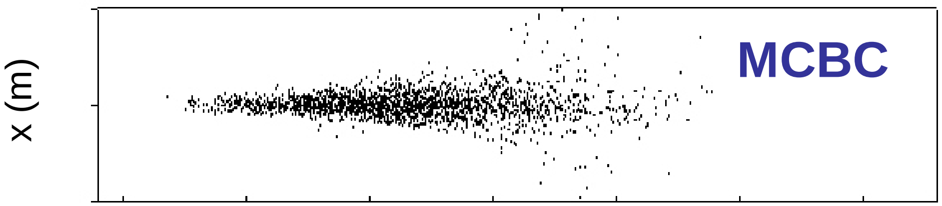
Using MCBC and GEM 1D

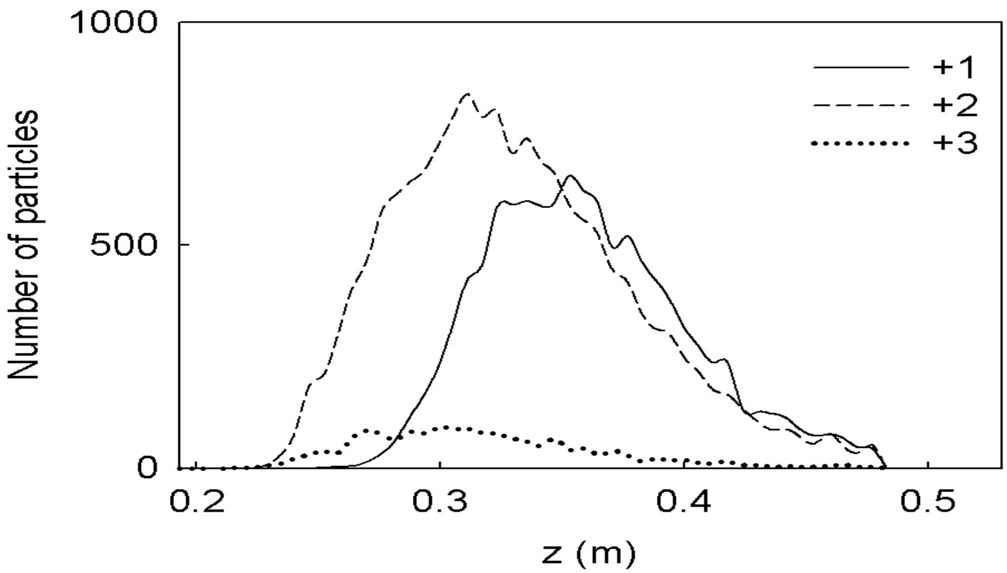
**Ar1+ ion beam injected into
oxygen background plasma
using ANL ECR-I parameters**

**Goal: Optimize beam energy
for maximum Ar8+ production**

Beam ions are either captured, pass through, or lost

Distribution of captured ions





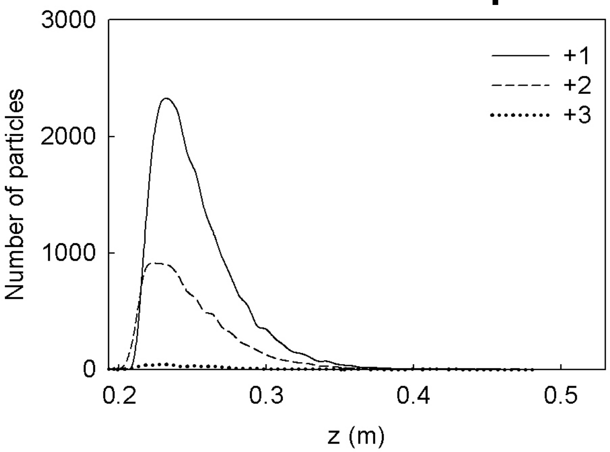
- **When a MCBC beam ion slows to the ion thermal speed in the plasma, it is considered “captured”**
- **Distribution of captured ions used as source profile in GEM**

Input ion sources for GEM

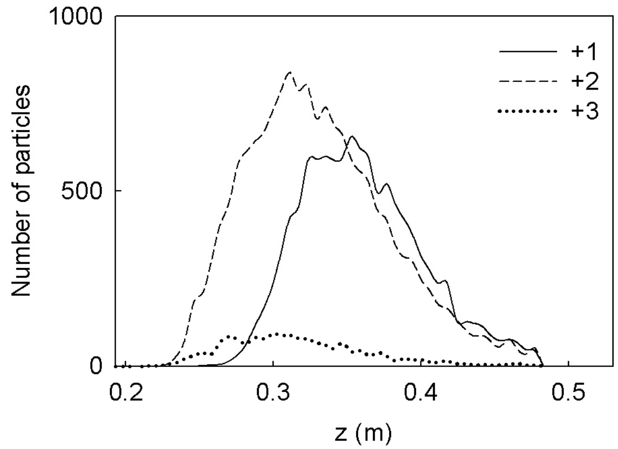
Beam capture near the center of the plasma yields better CB

- Reduces backstreaming
- Reduces pass through
- Increases confinement time

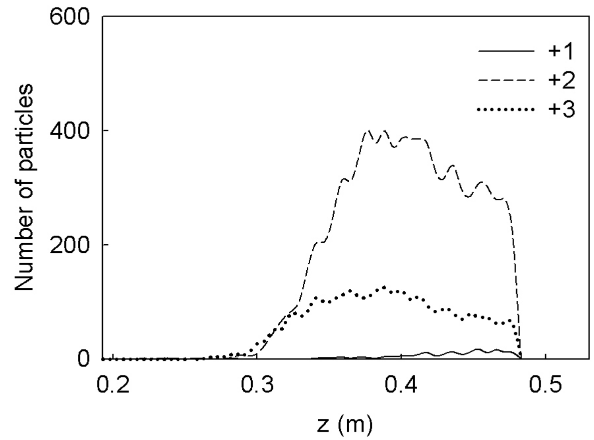
Beam energy 5eV
above sheath potential



15eV

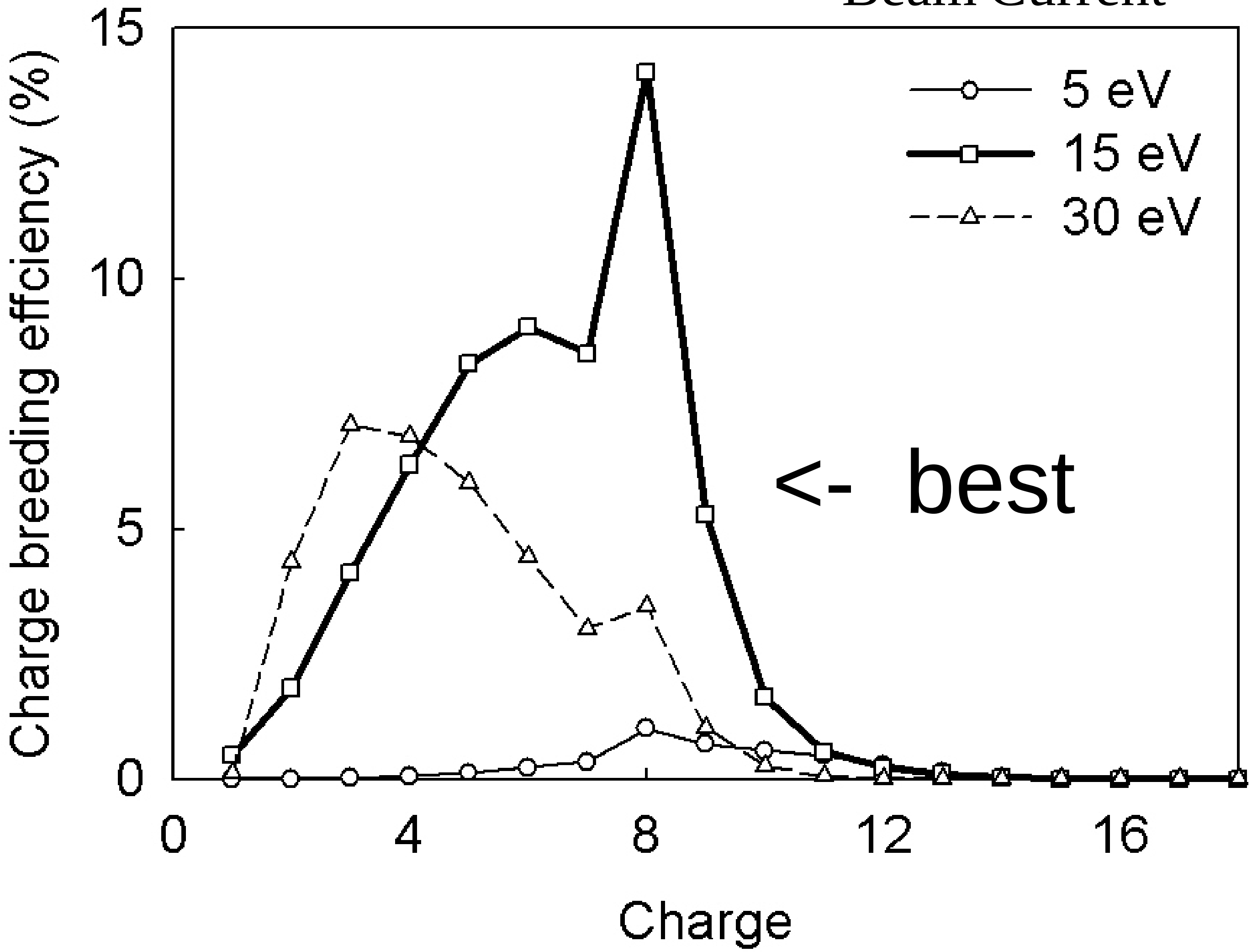


30eV

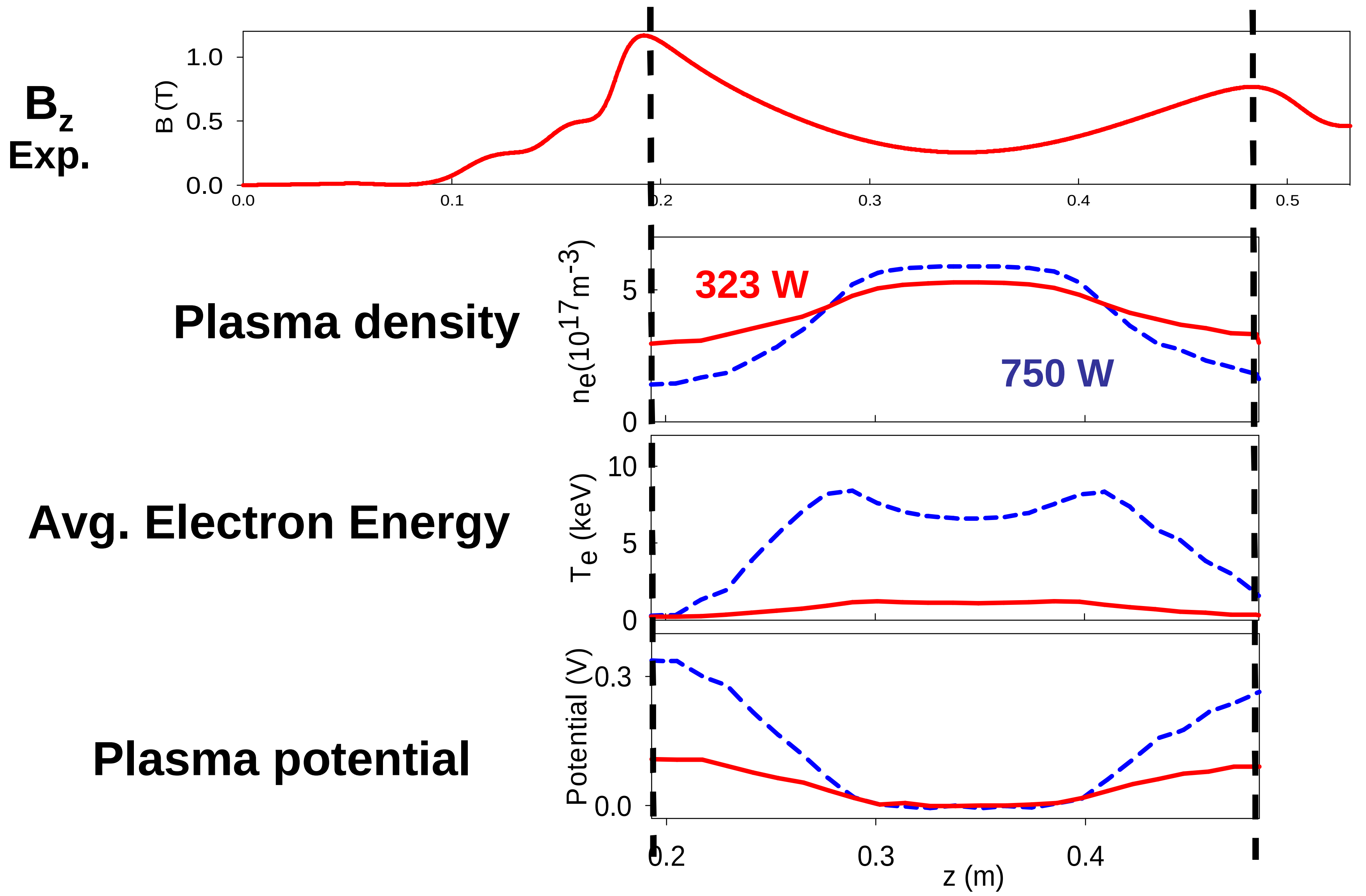


CB efficiency optimization for Ar^{8+} wrt injected beam energy

$$\text{Charge breeding efficiency} = \frac{\text{Extracted Current of Captured Ions}}{\text{Beam Current}}$$



GEM 1D obtained plasma steady states for P_{rf} = 323W and 750W



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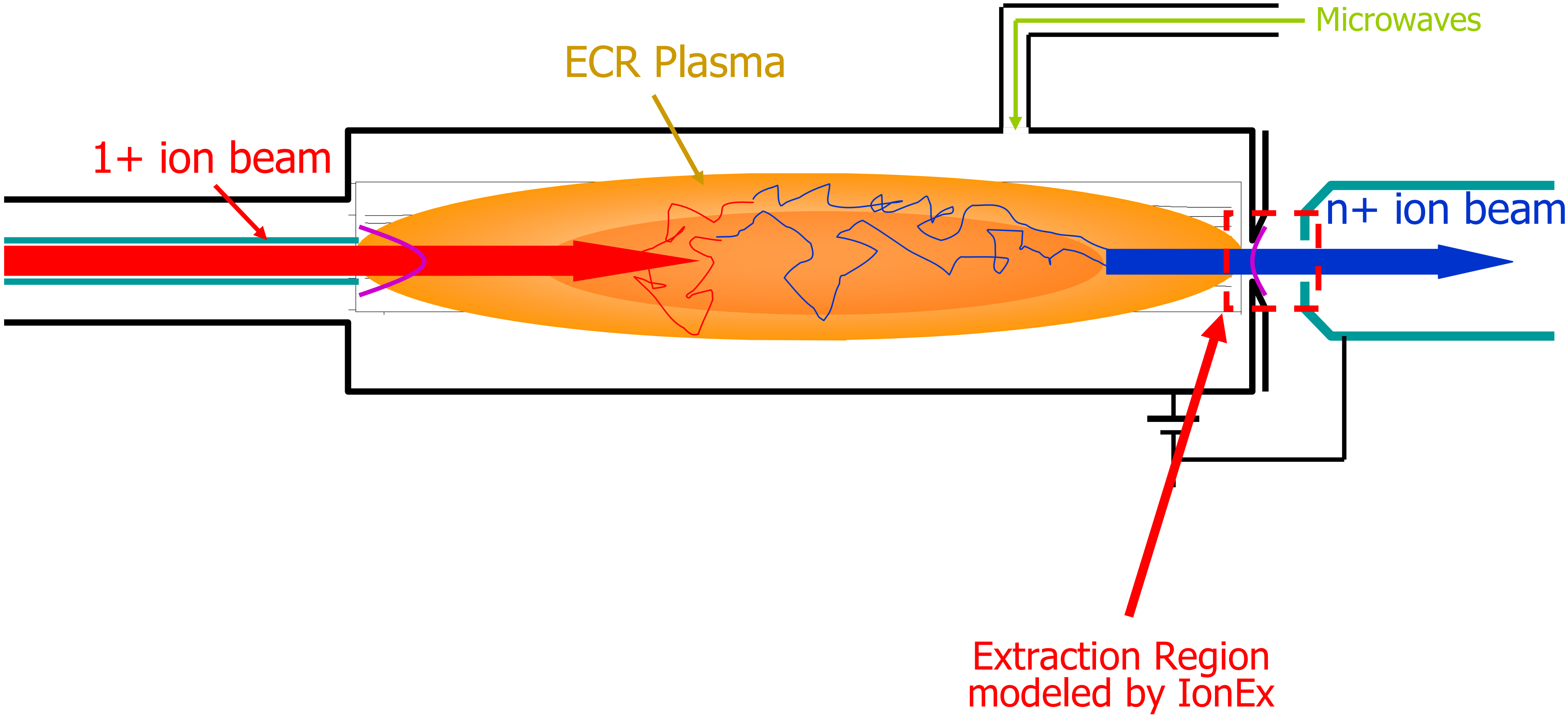
Summary up to this point

- **Beam capture near the center for optimum beam extraction**
- **Higher rf power provide larger central potential dip**
  - Modify beam capture locations (further towards extraction)
  - Tends to increases optimum beam energy required
- **Higher rf power provide larger electron density, more temperature (large) – more peaked profiles – may produce higher flux**
- **Back flow is not small**

IonEx

Ion Extraction Modeling Code

IonEx models beam trajectories in the extraction region



IonEx uses innovative technique to model beam trajectories in ion extraction region

- Ion beam trajectories depends sensitively on the shape of the “plasma meniscus”
- Meniscus is much smaller than extraction optical region
- Adaptive techniques are required for accurate modeling in reasonable run time

- IonEx uses innovative Particle-In-Cloud-Of-Points (PICOP) technique
  - **Only points/nodes used in computation**
  - **No need to define cells**
  - **Easily adapts to complex geometries**
  - **Can handle strong anisotropy**

- Potentially much faster than standard adaptive mesh techniques
  - **3D mesh generation can take days for complicated geometry**
  - **Point generation is simple**
  - **Adaption is easy as no need to redefine cells when points are added or removed**

IonEx models ion particles (kinetic) and Boltzmann electrons (fluid)

- **Ions**
  - Ions are tracked in self-consistent electrostatic fields and static B- fields
  - Charge densities are distributed over “neighborhood” of points
  - Electric fields are calculated from potentials at neighborhood points

- **Electrons**
  - Low mass electrons have the Boltzmann distribution

$$n_e = n_0 \exp\left[\frac{e(\phi - \phi_0)}{T_e}\right]$$

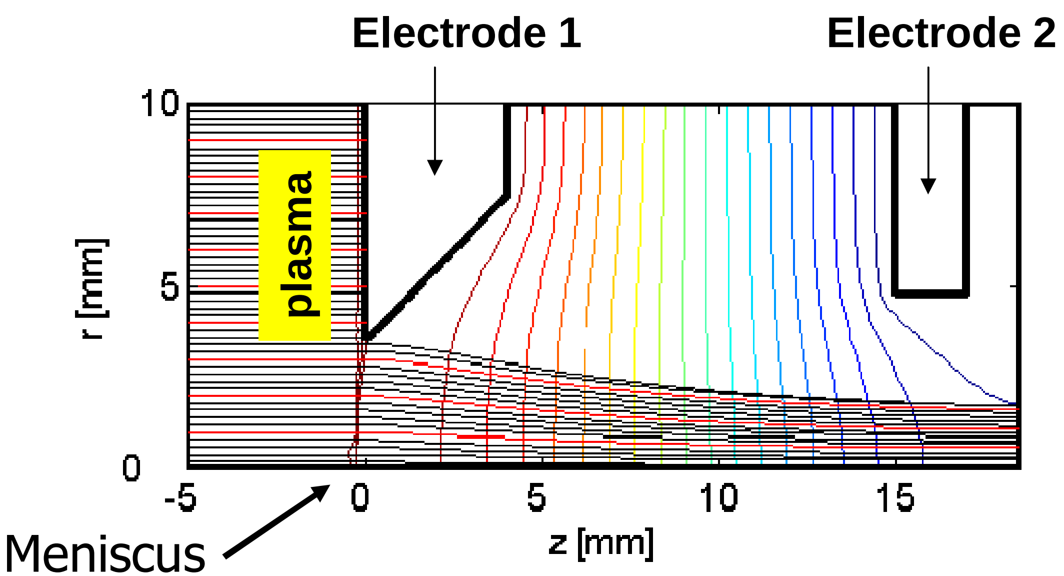
- **Point/node locations adapted based on density and potential gradients to obtain self-consistent, steady state solution, accurately and fast.**

Sample IonEx ECRIS extraction region simulation with resolved plasma sheath

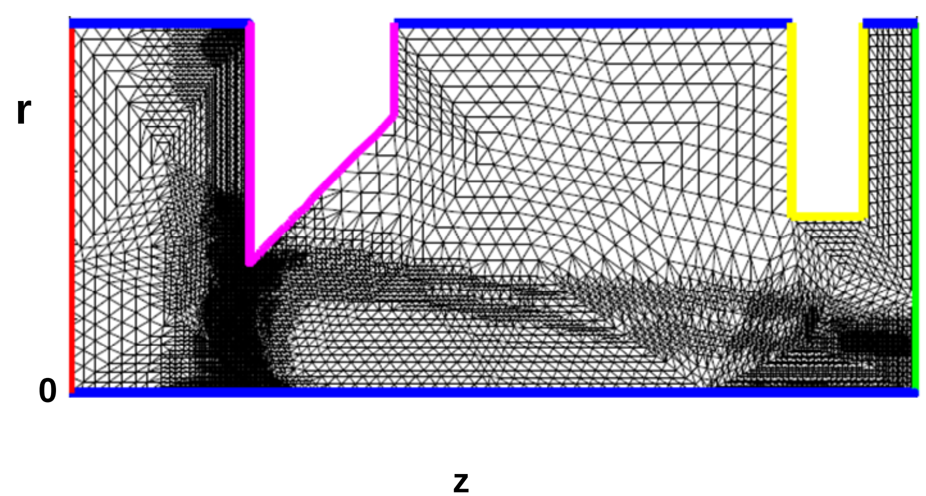
Plasma and electrode parameters:

n_0 (m^{-3})	T_e (eV)	m_i (amu)	Z_i	U_i (eV)	ϕ_0 (V)	Φ_1(V)	Φ_2(V)
2.24 x 10^{17}	20	1	+1	20	65063	65000	0

Short Debye length: $\lambda_D \approx 70\,\mu\text{m} << L \approx 2\,\text{cm}$



Ion trajectories & equipotentials

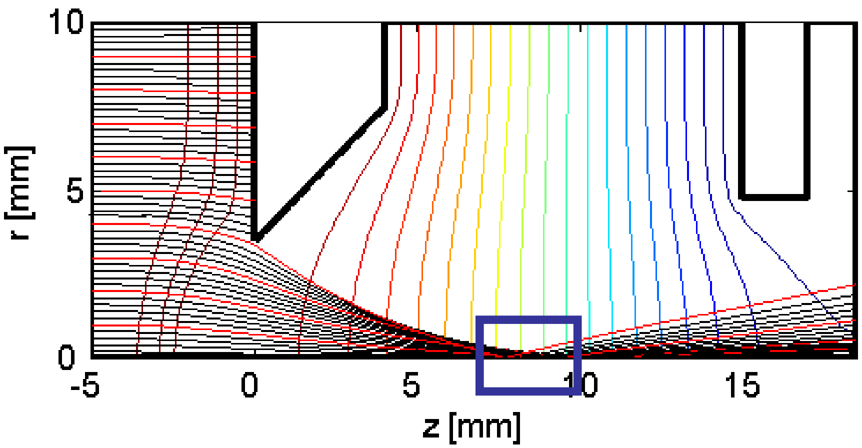


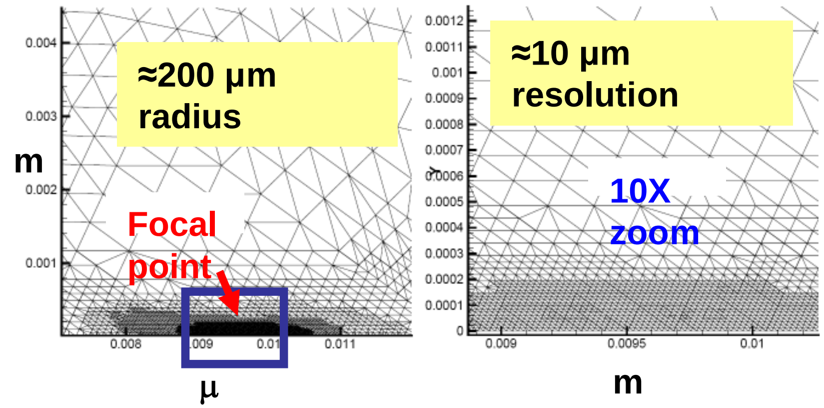
Point Locations

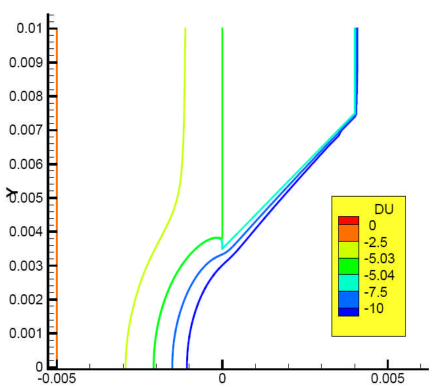
IonEx resolves beam focal region, sharp corner of electrodes as well as plasma sheath

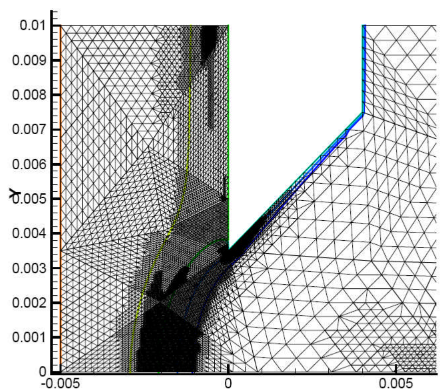
$$\lambda_D \approx 743\mu m < L \approx 2cm$$

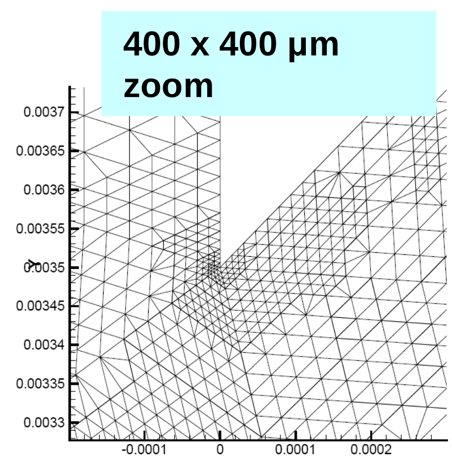
n_0 (m^{-3})	T_e (eV)	m_i (amu)	Z_i	U_i(eV)	f_0 (V)	Φ_1(V)	Φ_2(V)
1.0×10^{16}	100	40	+1	100	60503	60000	0









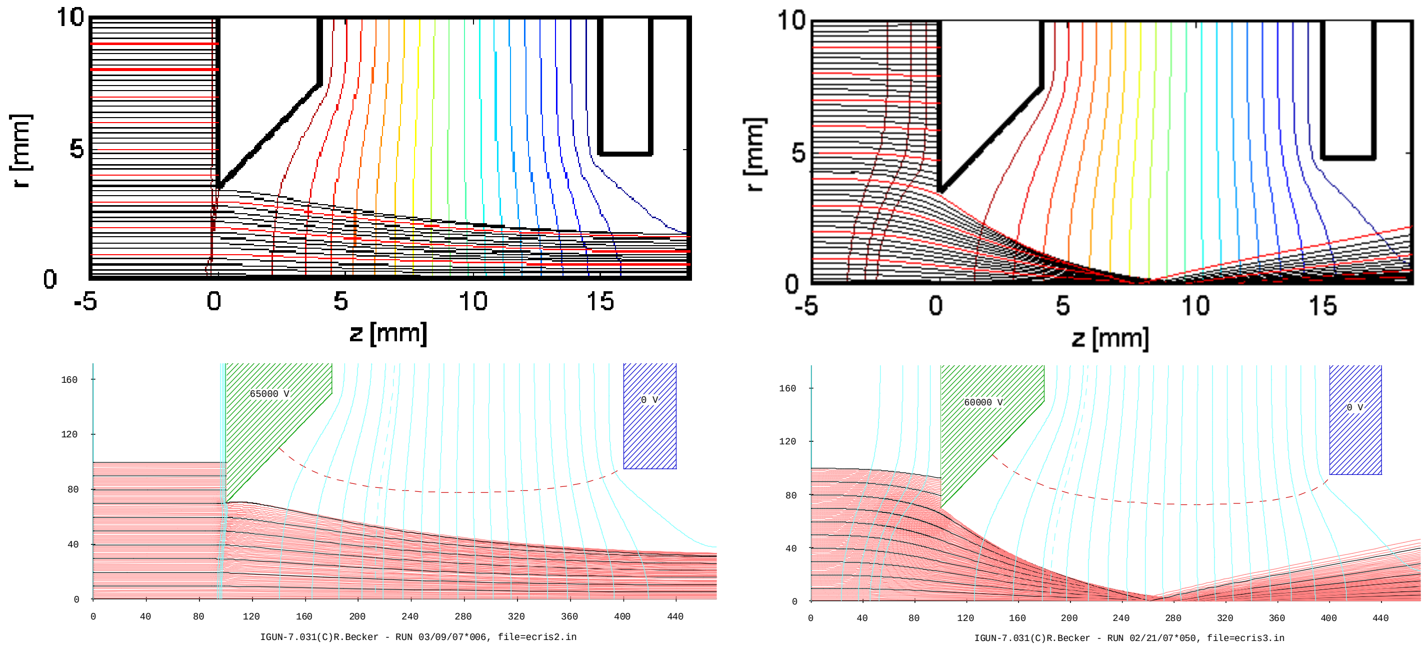


IonEx is benchmarked against IGUN[1]

IonEx spatial resolution near the focal point was ~10 μm.

IonEx used 11,670 nodes. (cf. over 2M modes required in rectangular grid for the same resolution.)

15,000 nodes **11,670 nodes**



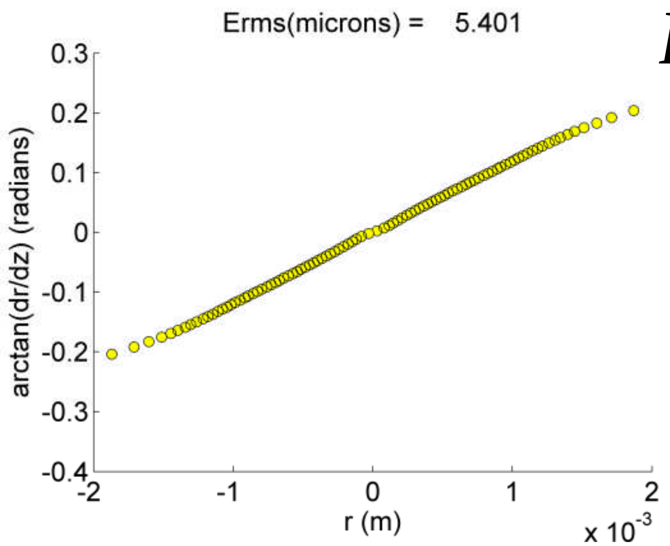
← IonEx

← IGUN

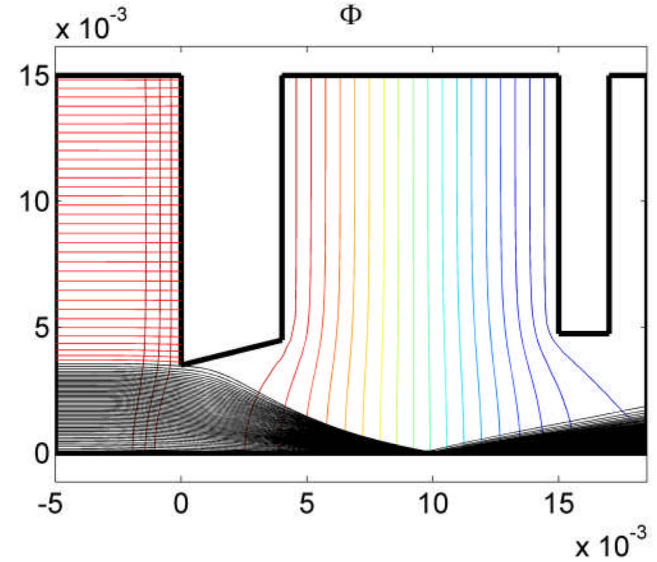
94,000 rectangular grid

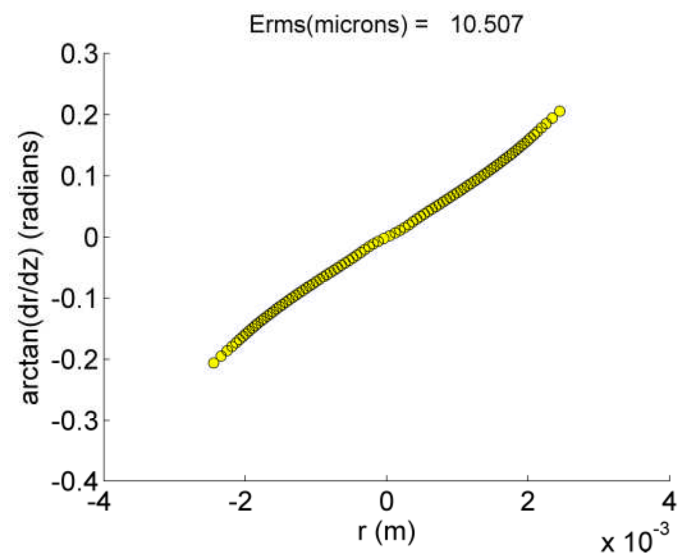
[1]: R. Becker and W.B. Hermannsfeldt, "IGUN-A program for the simulation of positive ion extraction including magnetic fields," *Rev. Sci. Instrum.*, 63 (4), 2756 (1992)

B-field is implemented in IonEx. IonEx conserves total energy and the cannonical momentum.

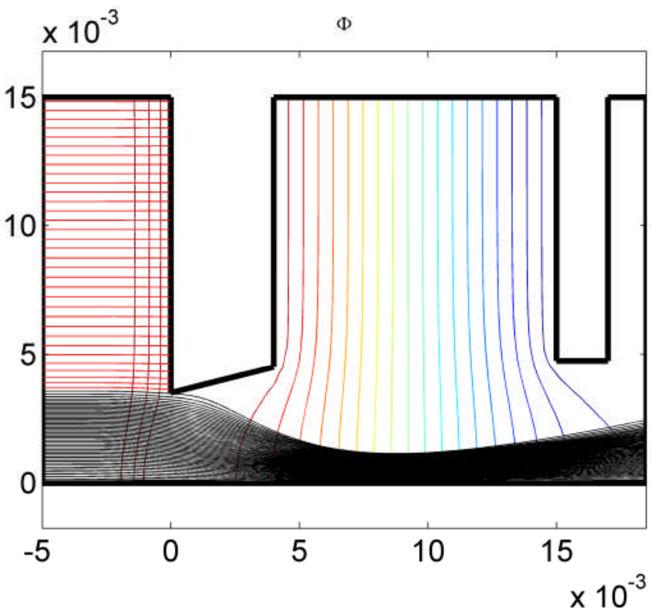


$B = 0$





$B \neq 0$



Towards 3D simulations: 3D shape, points and trajectories

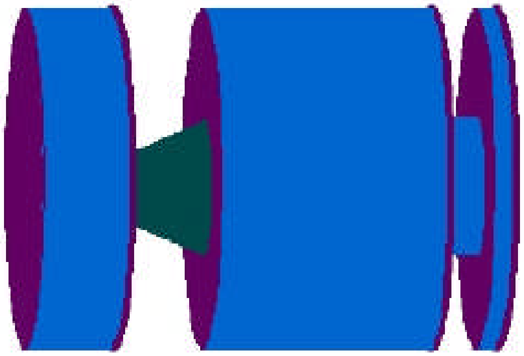
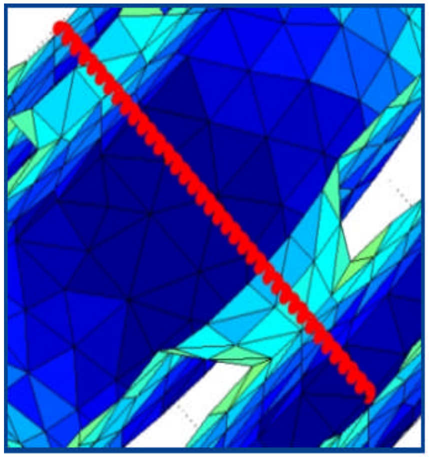
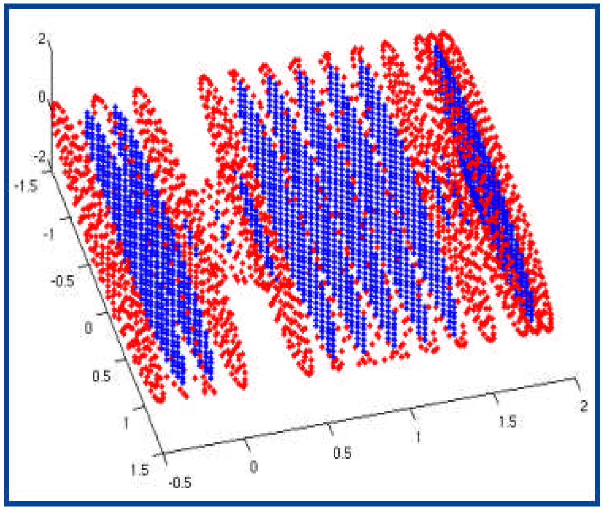


Figure 1: A sketch of 3D ECRIS inner volume and boundaries



3D particle trajectory (test)

Boundary (red) and interior points



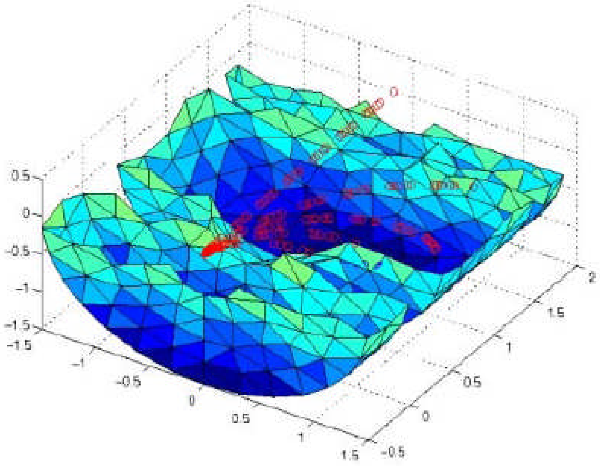
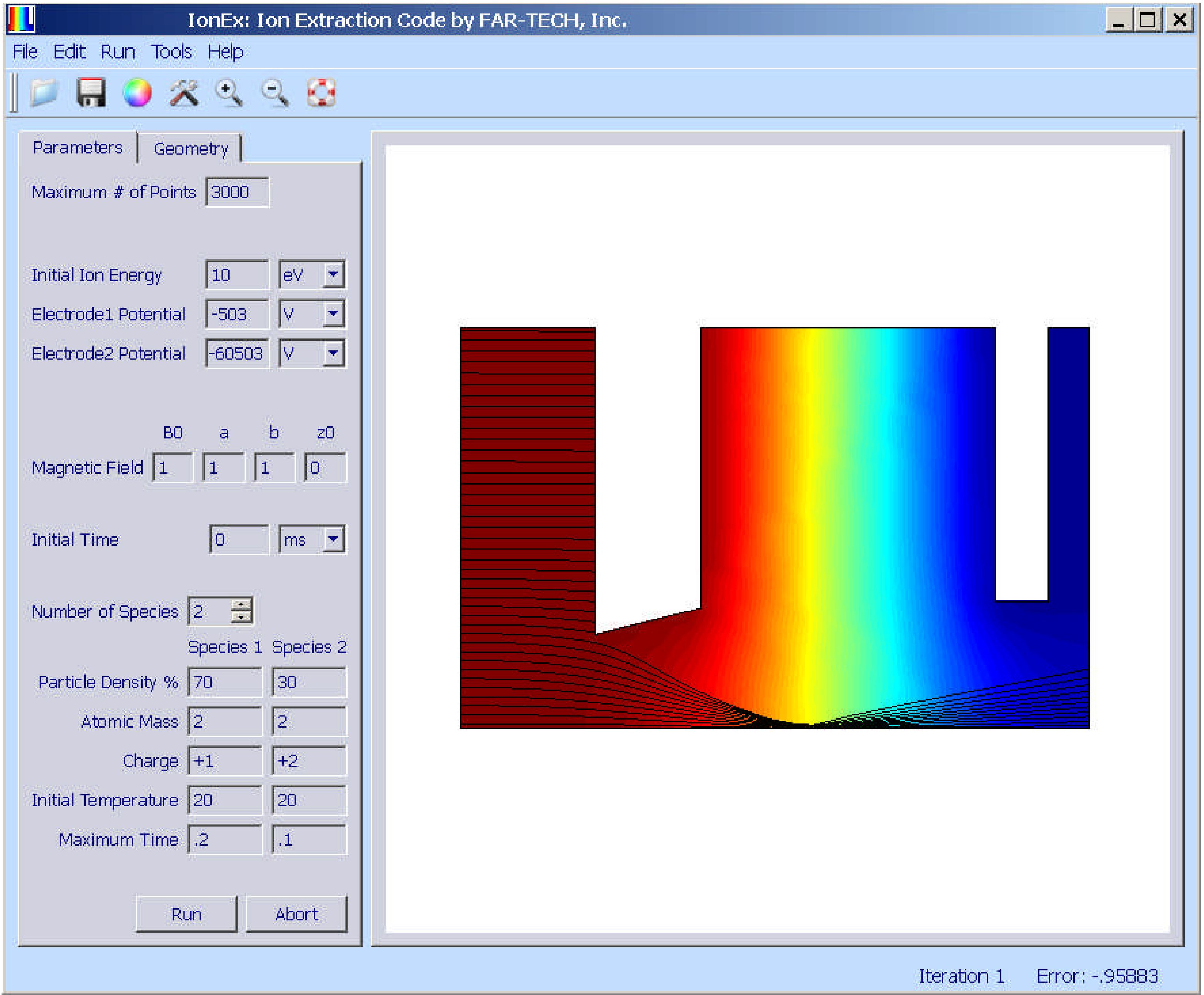


Figure 12: Trajectories (red circles) of Several Particles, a bottom half of the 3D boundary is shown

IonEx GUI implementation started



Summary:
End-to-End Integration of ECR Charge Breeder Modeling underway

FAR-TECH's Suite of Codes for ECR Charge Breeder Modeling is underway.

MCBC – Full 3D3V particle tracking in plasmas

GEM – GEM 1D has improved convergence
- **GEM 2D starts producing results**
- **Hybrid model (fluid ions and bounce averaged FP electrons) allows more realistic simulations with affordable computer time**
- **Many aspects yet to be implemented- eg. plasma-wall interaction**

IonEx – Innovative meshfree technique
- **potentially faster and more accurate modeling, in particular 3D**
- **2D IonEx is benchmarked with IGUN**
- **3D IonEx is underway**
- **B-field is implemented**
- **Memory is optimized**
- **GUI implementation is started**

Future Work

- Complete 2D extension of GEM
- Complete 3D IonEx
- Validate, validate, and validate!