# Modeling ECRIS Plasma Using 2D GEM

# (Generalized ECRIS Model)

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# Abstract


- The GEM (General ECRIS Model) code is developed by FAR-TECH, Inc. to model plasmas in ECRIS devices using experimental knobs such as magnetic field, rf and the geometry of the device.

- The code models ECRIS plasma electrons by the bounce-averaged Fokker-Planck equation, ions as fluid and neutrals by particle balancing.

- It has been extended to include 2D (axial and radial) spatial features such as 2D ECR heating and ion radial diffusion. The convergence and consistency of the code have been studied. It is parallelized using the MPI technique to boost the calculation speed.

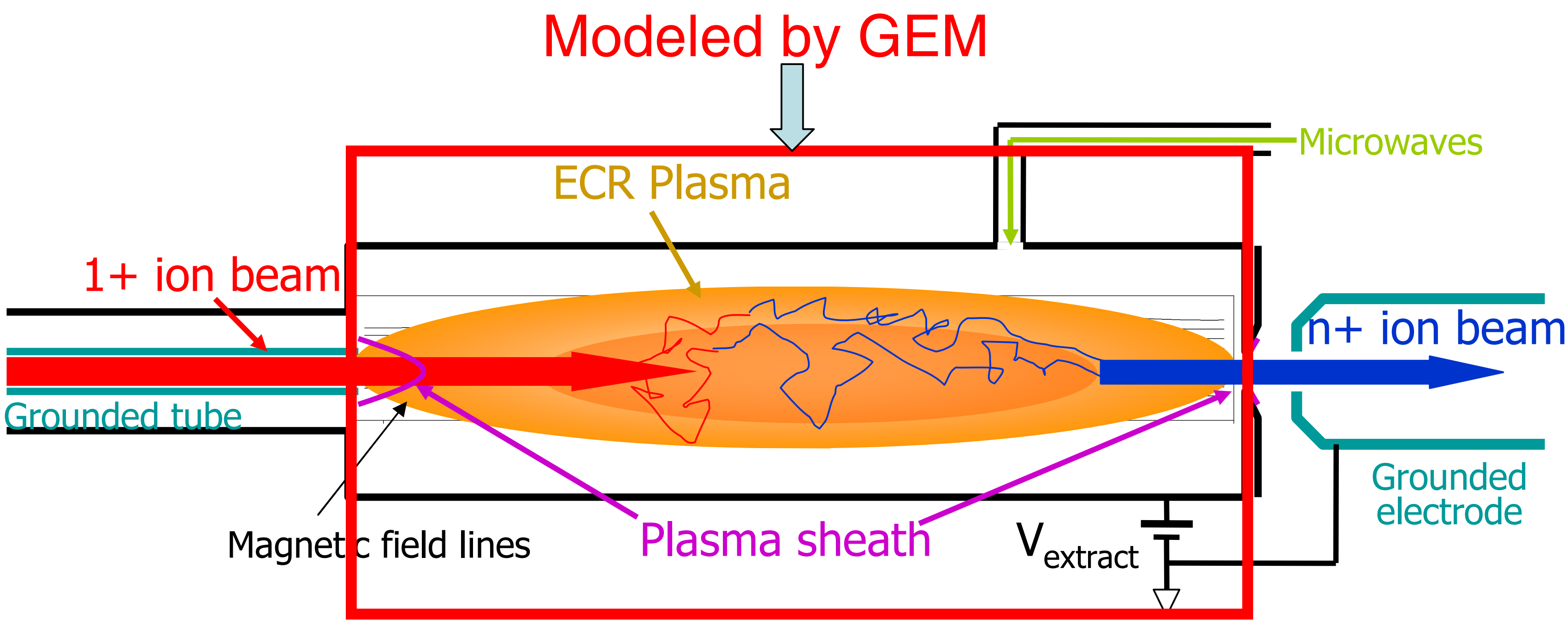
- Example results of simulated 2D profiles of ECRIS plasma and the radial dependence of CSD (charge state distribution) will be presented.

# Extension of GEM 1D(z) to 2D(r,z)

- **GEM 1D simulates ECRIS plasma along the axis.**
  - Use only experimental knobs as inputs.
  - Advance hybrid model: bounce-averaged Fokker-Planck EDF modeling, ion fluid modeling, and neutral particle balancing modeling.
  - Has produced consistent results with the experiments.

- **GEM 2D simulates ECRIS plasma in both radial and axial directions.**
  - The importance of radial dependence of ECR ion sources is recognized experimentally.
  - GEM 2D can model the football shape ECR resonance surface more accurately.

# GEM 2D can simulate ECRIS device



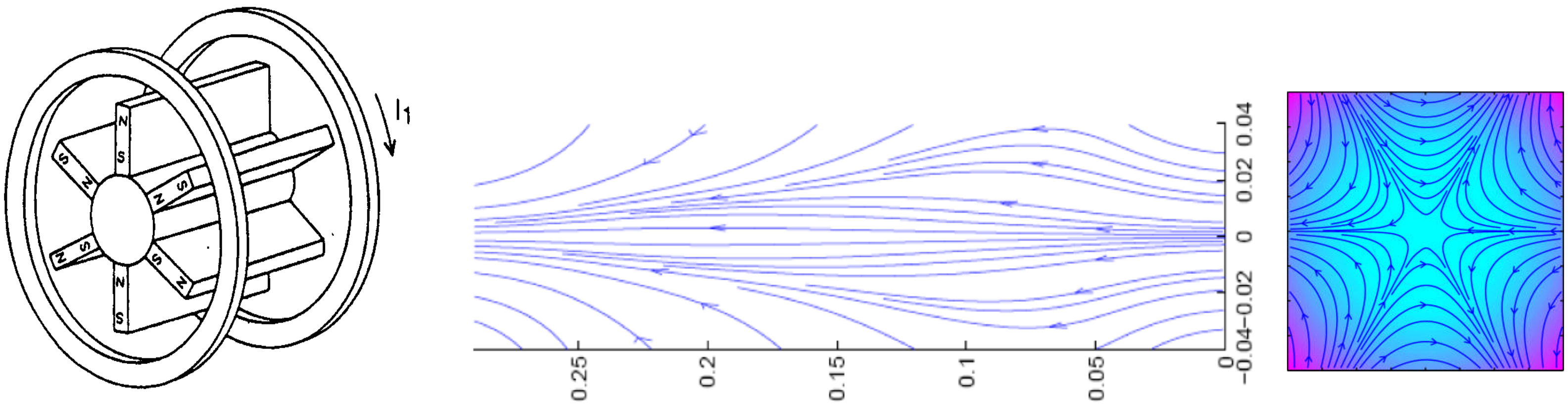

**Simulation parameters for ANL ECR-I device:**
**RF: 323 W @ 10 GHz**

**Vessel: 3.8 cm radius,**
**29 cm length**

**Gas pressure: $10^{-6}$ – $10^{-7}$ Torr, Oxygen**
**$n_e \sim 10^{18}$ m$^{-3}$**
**$T_e \sim$ 10-100eV (edge)**
**1 – 10's keV (core)**
**$T_i \sim$ 1eV**

# ECRIS plasmas are confined in minimum-B magnetic mirror configuration – 3D geometry

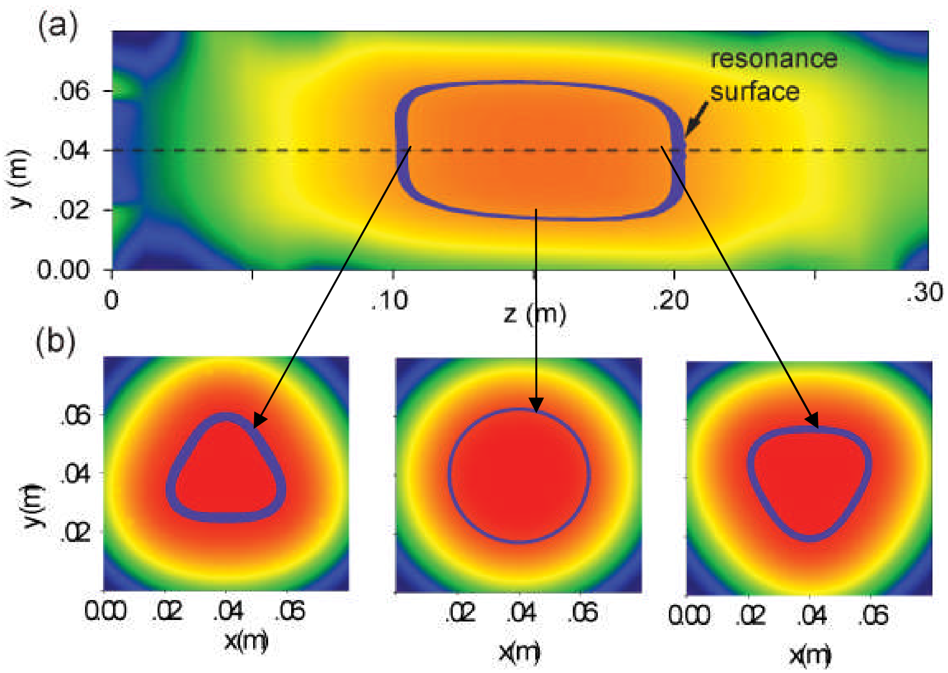
**Magnetic confinement is a simple magnetic mirror with a multicusp hexapole field for min-B stability.**



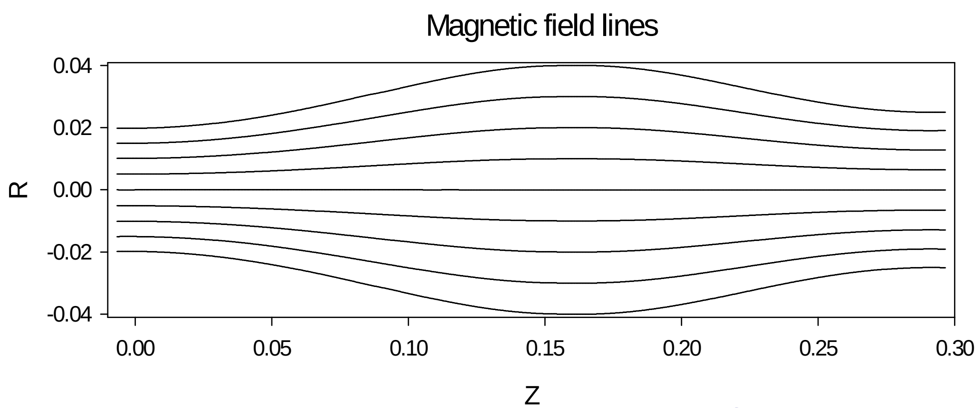

Experimental B magnetic field configuration on ANL ECR-I

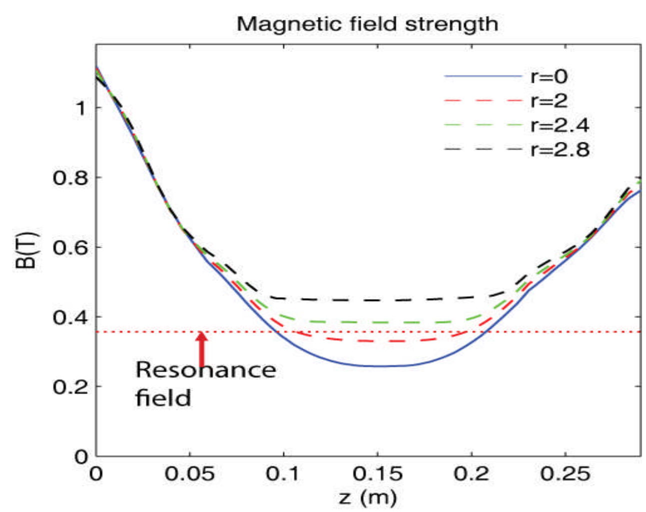
Mirror: 0.3-0.5 T on axis at midplane,
Mirror ratio= 4.5 & 3
Hexapole: 0.8 T at chamber wall

# Radial grids are azimuthally averaged 2D magnetic field flux surfaces. GEM 2D models volume heating.




Contour of 3D field



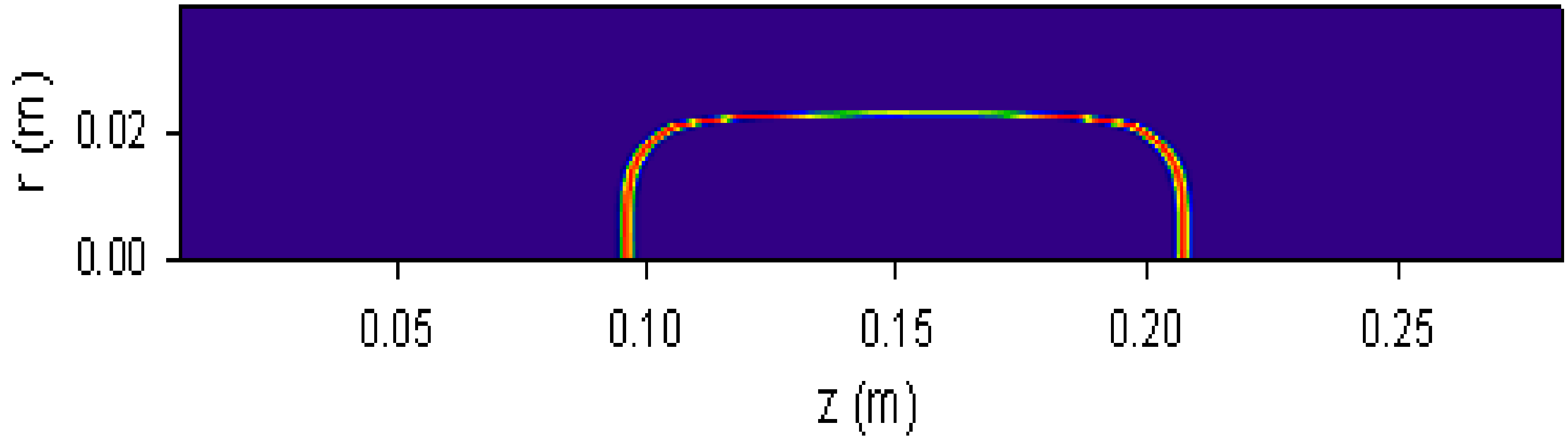




2D filed lines

# 2D ECR resonance surface

2D modeling of rf diffusion term:

$$D^{rf}(z,r) = D_0^{rf}\frac{\gamma B_{res}}{\pi^{1/2}\Delta B_{res}} e^{-\left(\frac{B(z,r)-\gamma B_{res}}{\Delta B_{res}}\right)^2} \qquad \gamma = \frac{1}{\sqrt{1-\frac{\upsilon^2}{c^2}}}$$

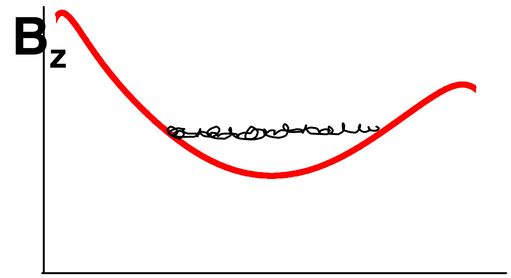


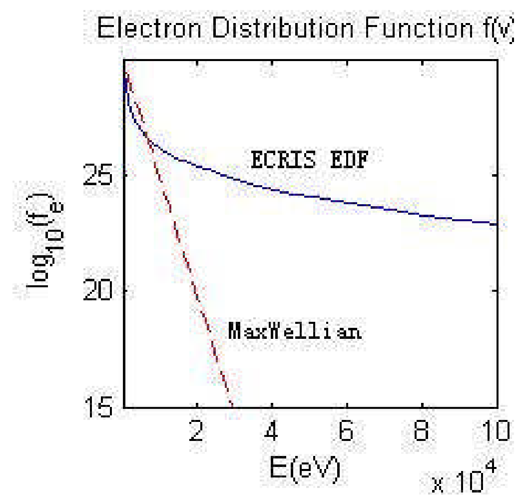
# GEM models ion, electron, and neutral dynamics

**IONS:**
**Cold and highly collisional,**
**Fluid ion model**

**ELECTRONS:**
**bounce time << collision time**
**Non-Maxwellian electron distribution function (EDF)**
**1D bounce-averaged**
**Fokker-Planck electron code $f_e(v,\theta)$**

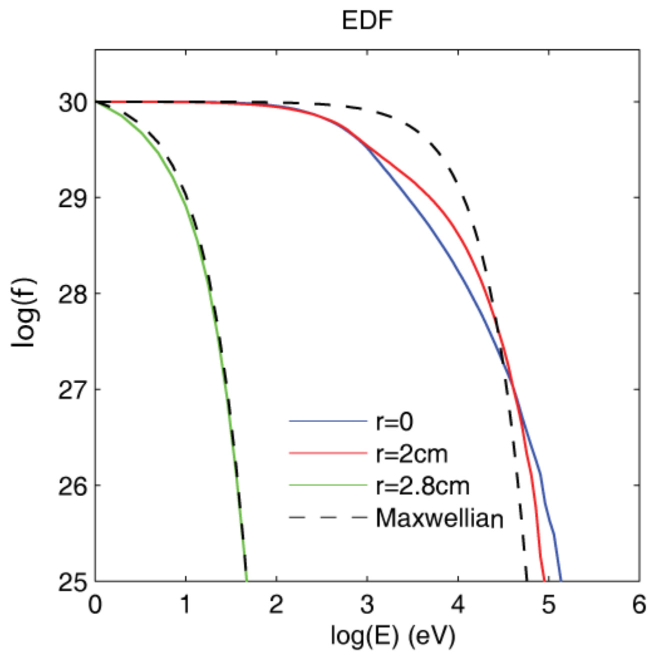
**NEUTRALS:**
**Unimpeded by magnetic fields:**
**Density profile determined by particle balance**



# Bounce-averaged Fokker-Planck code modeling 2D EDF

- Mirror trapped electrons in ECRIS are almost collisionless.
- EDF is non-Maxwellian.
- 0D bounce-averaged Fokker Planck code, FPPAK94 , is used to calculate EDF.
- Bounce averaging greatly reduces run time.
- Model includes
  - ECR heating
  - Velocity space diffusion
  - Loss cones
  - Plasma sheath




GEM 2D calculated EDF

# EDF mapping: EDF *f*(v) at mid-plane to *f*(v,z) in space

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

$$vdv = v_0 dv_0$$

$$\cos\theta d\theta = \sqrt{\psi}\frac{v_0}{v}\cos\theta_0 d\theta_0$$

•In GEM 2D, EDF on each radial cell is calculated independently with the assumption that radial transport of electrons is negligible.

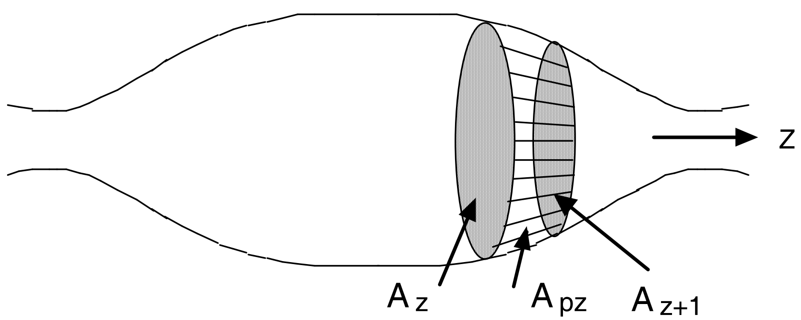
•Sheath potential at both ends defines the lose cone of the electrons in Fokker Planck code.

•Electron temperature is defined as the average electron energy.

# Neutrals: volume averaged modeling

- **Assume neutral density distribution has no radial dependence and neutral temperature is room temperature everywhere in space.**
- **Neutral losses inside the plasma due to ionization and charge-exchange are balanced by neutral gas input from outside of the plasma:**

$$0.5v_0\left[A_{pz}(n_g - n_{0,z}) + A_{z-1}(n_{0,z-1} - n_0) + A_{z+1}(n_{0,z+1} - n_0))\right] =$$
$$n_{0,z}V(R_{ionization} + R_{cx}) - n_{1,z}VR_{cx}$$




$v_0$: neutral flow speed,

A: area of flow surfaces,

$n_{0,z}$: neutral density at z position,

V: plasma volume,

R: collision rates.

# GEM 2D Ion fluid modeling radial and axial transport

- Ions are cold, Ti~1 eV, and highly collisional
  - Mean free path < 1 mm
  - Ions all have same axial speed
  - Radial and azimuthal speed are different for each ion.

- Full 2d2v EDF used to calculate ionization rates:
  - $A^{+n} + e^{-} \rightarrow A^{+n+1} + 2e^{-}$
- Ion loss rate is limited by electron confinement in magnetic mirror.

- The 2D ion continuity equation is solved using upwind method:

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

# Equations of 2D fluid modeling

The ion continuity equation:

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

The radial and azimuthal velocities are calculated from ion momentum equations:

$$\upsilon_{j,q\theta} = -\frac{E_r}{B} - \frac{1}{\omega_{cj,q}}\left[-\frac{k_B T_{j,q}}{n_{j,q} m_j}\frac{\partial n_{j,q}}{\partial r} - \frac{S_{j,q}^{in}}{n_{j,q}}\left(\left\langle \upsilon_{j,qr}\right\rangle^{in} - \upsilon_{j,qr}\right) - \frac{F_r^{jk}}{n_{j,q} m_j}\right]$$

$$F_r^{jk} = n_{j,q}\sum_{k,p}\mu_{jk} n_{k,p} K_{j,q\to k,p}(\upsilon_{j,qr} - \upsilon_{k,pr})$$

$$\upsilon_{j,qr} = \frac{1}{\omega_{cj,q}}\left[-\frac{S_{j,q}^{in}}{n_{j,q}}\left(\left\langle \upsilon_{j,q\theta}\right\rangle^{in} - \upsilon_{j,q\theta}\right) - \frac{F_\theta^{jk}}{n_{j,q} m_j}\right]$$

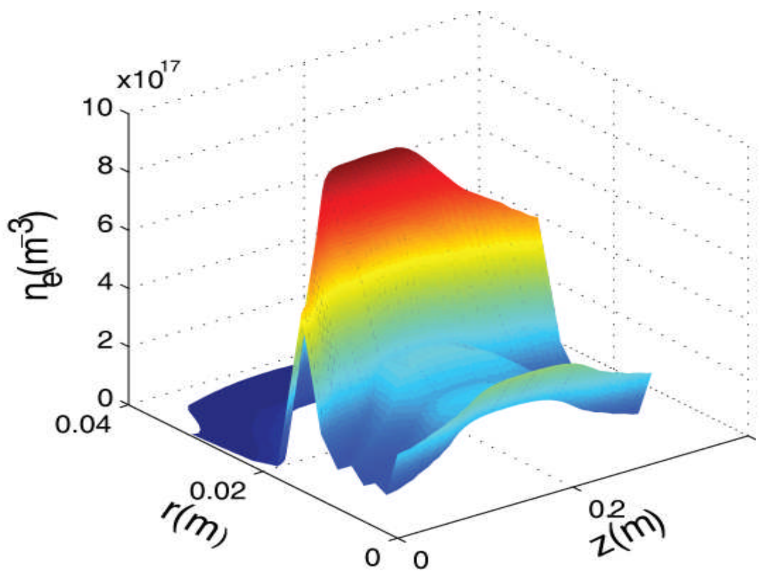
$$F_\theta^{jk} = n_{j,q}\sum_{k,p}\mu_{jk} n_{k,p} K_{j,q\to k,p}(\upsilon_{j,q\theta} - \upsilon_{k,p\theta})$$

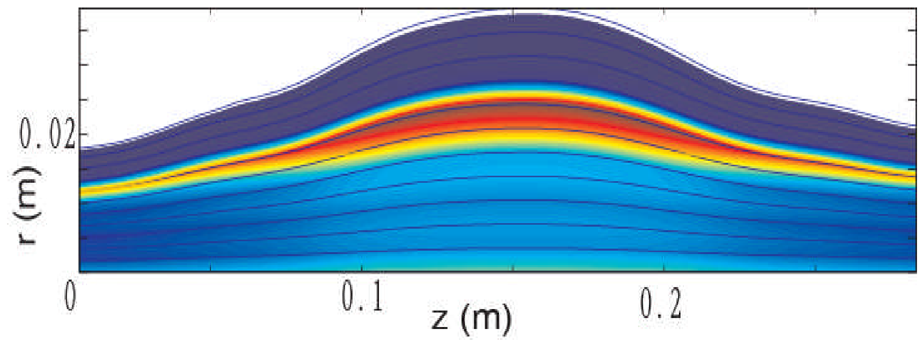
$$\omega_{cj,q} \equiv \frac{qeB}{m_j}$$

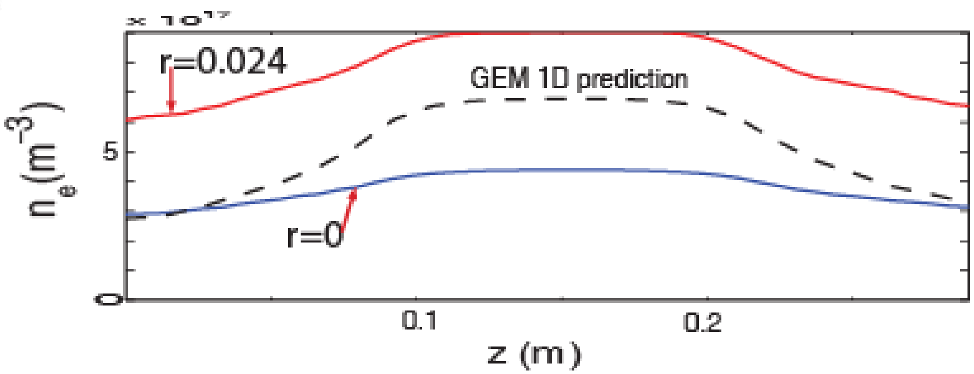
The axial ion momentum equation is

$$\frac{\partial u_{j,q}}{\partial t} = -v_{j,qr}\frac{\partial u_{j,q}}{\partial r} - u_{j,q}\frac{\partial u_{j,q}}{\partial z} - \frac{k_B T_{j,q}}{m_j}\frac{1}{n_{j,q}}\frac{\partial n_{j,q}}{\partial z} + \frac{1}{n_{j,q}} S_{j,q}^{in}\left(\left\langle u\right\rangle^{in} - u_{j,q}\right) + \frac{qe}{m_j}E_z$$

# GEM 2D predicts  hollow electron density profiles in device

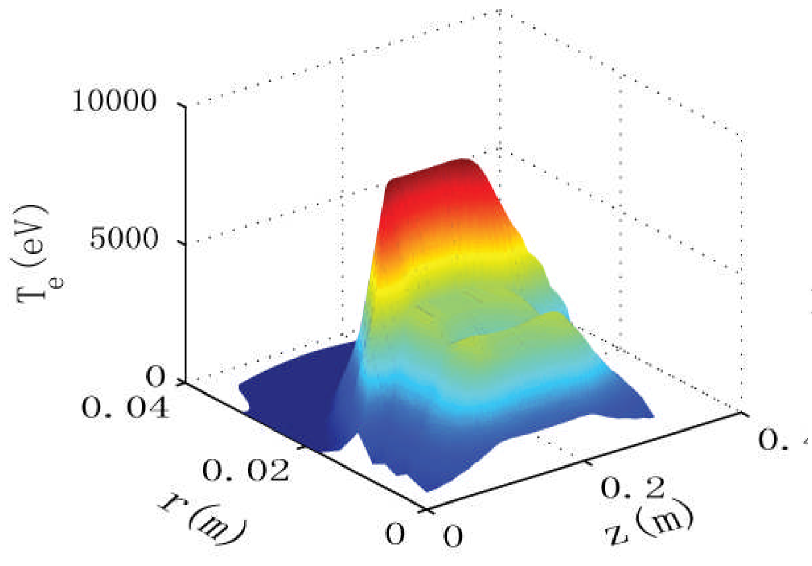


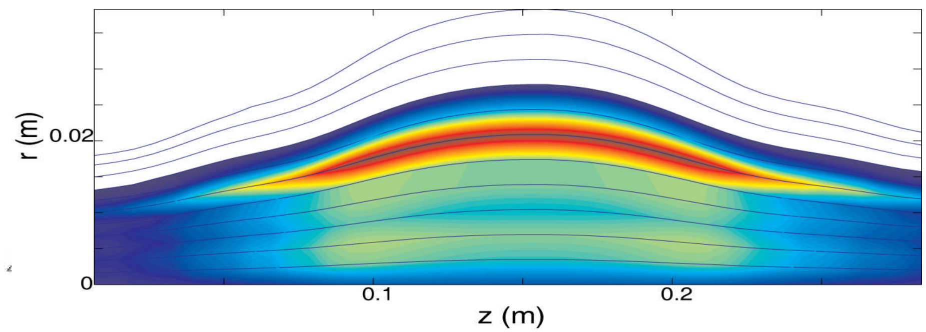



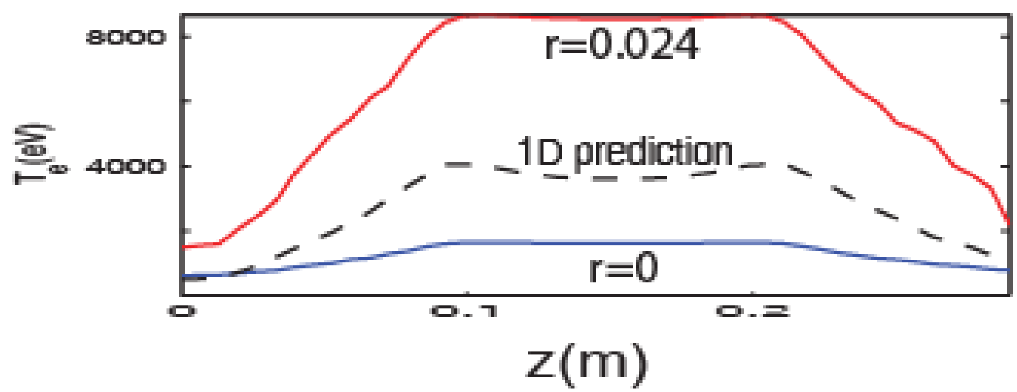

Density peaks where most ECR power is absorbed

# GEM 2D predicts hollow electron temperature profiles of plasma



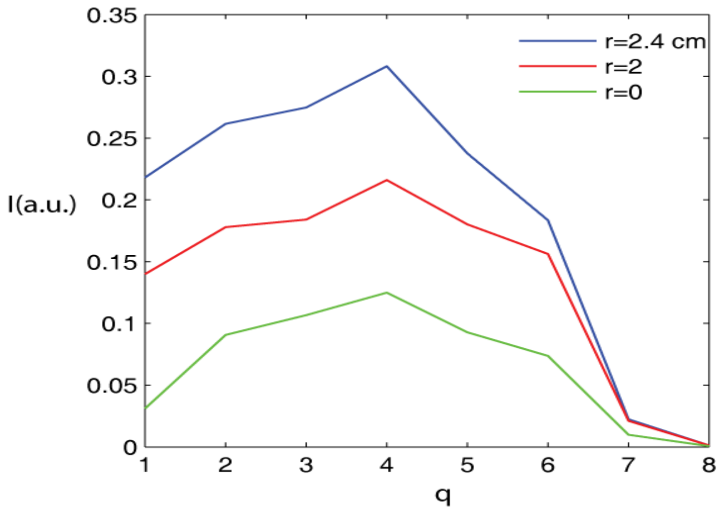




Peak in temperature coincides with resonant surface

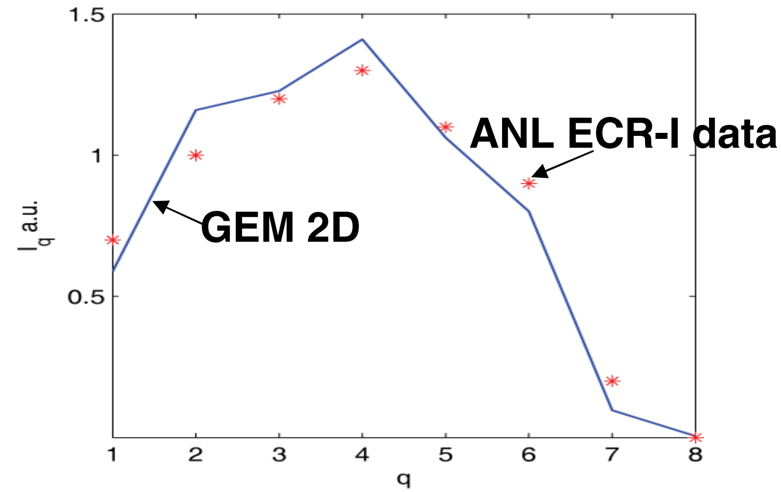


# GEM 2D predicts  hollow CSD of extracted ion sources

## Extracted Charge State Distribution (CSD)

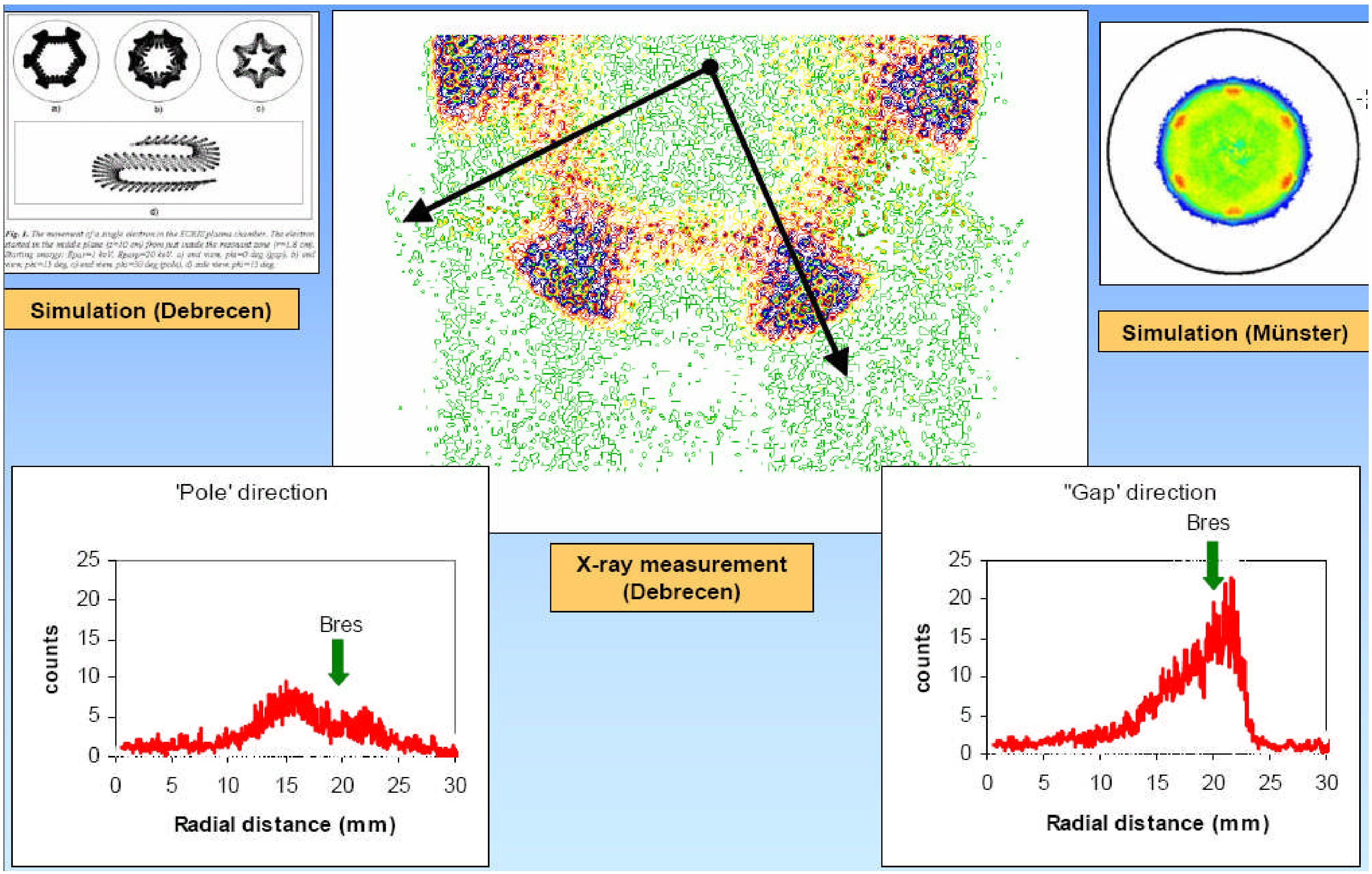



CSD at different radial positions




Radially integrated CSD and experimental data

# Experimental evidence of the hollow profile of ECRIS plasma*




* S. Biri, ICIS03, Dubna, Russia

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# Summary

- GEM 1D is successfully extended to 2D:
  - 3D ECRIS magnetic field modeling and 2D azimuthally averaged field.
  - 2D ion fluid modeling.
  - 2D ECR heating modeling.
  - GEM 2D is parallelized using MPI.
  - Improved stability by using upwind method.
- GEM 2D results are cross-checked with GEM 1D.
- The radial dependence of plasma profiles and CSD are consistent with the experimental observations.