Laboratori Nazionali del Sud-LNS

Modeling the Electromagnetic Field in Anisotropic Inhomogeneous Magnetized Plasma of ECR Ion Sources

G. Torrisi[1], D. Mascali[1], A. Galatà[2], G. Castro[1], L. Celona[1], L. Neri[1], G. Sorbello[1,3], S. Gammino[1]

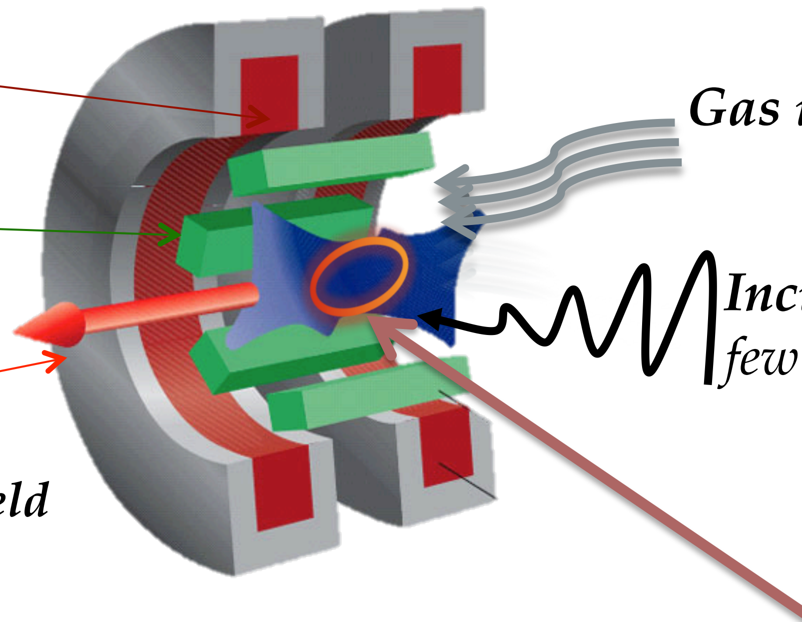
INFN - Laboratori Nazionali del Sud, Via S. Sofia 62, 95125 Catania, Italy
INFN – LNL Viale dell'Università, 2 35020 Legnaro (Padova) Italy
Università degli Studi di Catania, DIIEI, Viale Andrea Doria 6, 95125 Catania, Italy

Basics on Electron Cyclotron Resonance Ion Source (ECRIS)

***Solenoids** for Axial confinement*

***Hexapole** for radial confinement*

Extraction system

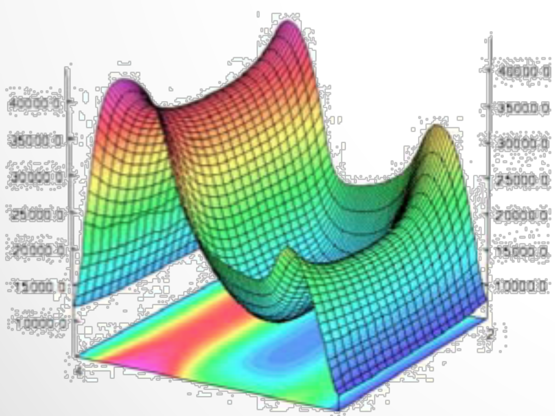


Gas injection system

Incident microwaves
*few **kW** at **tens GHz***

ECR Surface
$B_{ECR} = \omega_{RF} m_e / e$

"B_minimum" Magnetic Field
structure



ECR Plasma
$n_e \sim 10^{12}$ cm^{-3}
$T_e \sim$ tens keV
$\tau_{ion} \sim$ ms

Overcoming the actual limit of ECRIS

$\boxed{\omega_p^2 < \omega^2}$ → $\boxed{n_e < \frac{\epsilon_0 m_e}{e^2}\omega^2 = n_{cutoff}}$ → ***INTRINSIC Density limitation***

ECRIS STD MODEL

$\boxed{I \propto n_e}$ $\boxed{\langle \boldsymbol{q} \rangle \propto \boldsymbol{n_e}}$ $\boxed{n_e \propto \omega_{RF}^2}$ →

1. High Frequency Generators to increase the plasma density;
2. High Magnetic Fields to make longer the ions confining time;

Brute force cannot be anymore used because of technological reasons (magnets, hot electrons generations, plasma overheating, cooling, …)

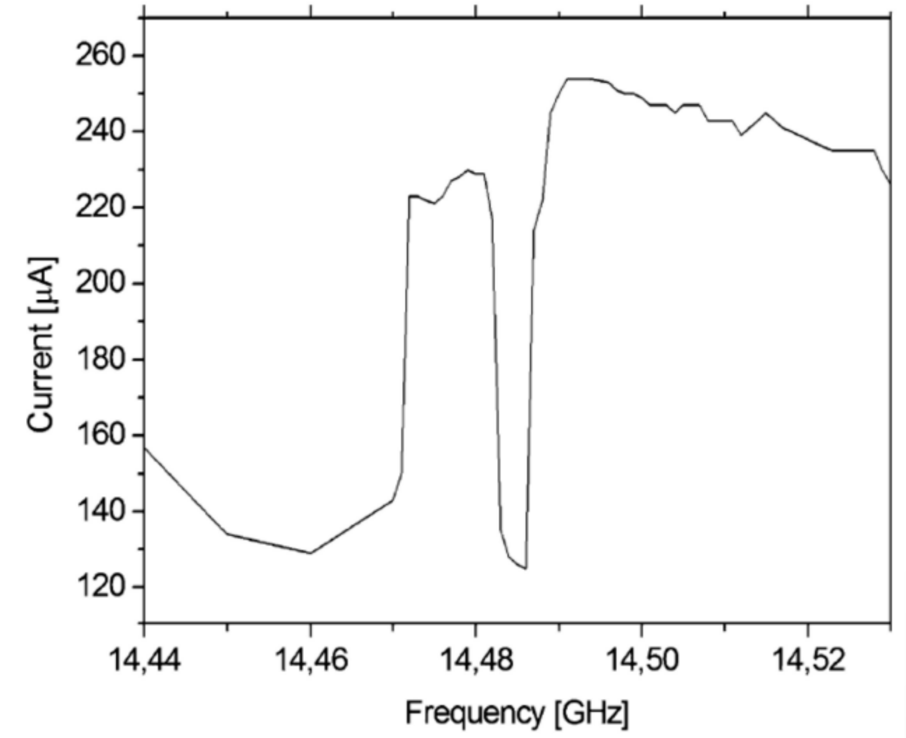
Overcoming the "brute force" empirical approach based on **Geller's scaling laws** $I \propto f_{RF}^2$ $q \propto \log B^{3/2}$

towards a "**Microwave Absorption Optimization-oriented**" design in order to Developing **the next generation Ion Sources**

Experimental results show that…

The extracted **current is doubled** after a **frequency shift of 5 MHz**

Evidence of **Frequency Tuning Effect (FTE)** on
the SUPERNANOGAN source source of Heidelberg HIT (2005)

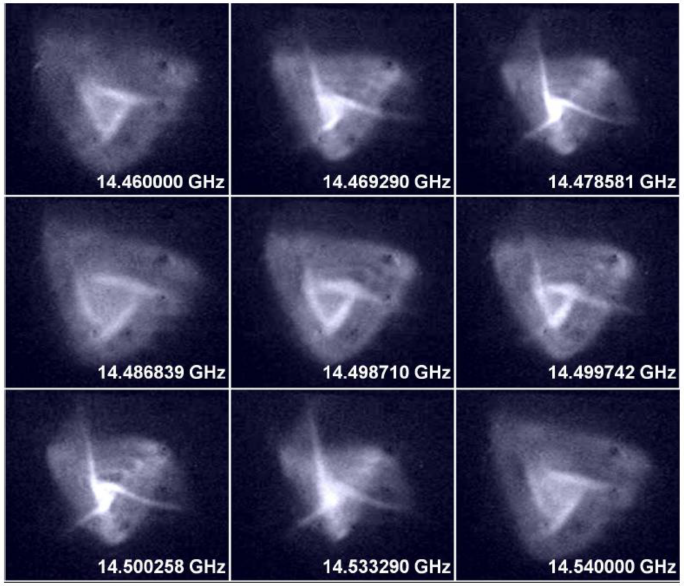


Frequency Tuning effect

The frequency tuning affects globally electrons and ions dynamics, changing not only the heating rapidity but also the **plasma spatial structure**

[L. Celona,et al. Observations of the frequency tuning effect in the 14 GHz CAPRICE ion source. Rev. Sci. Instrum.,Feb. 2008]

Frames of the extracted beam for different frequencies



Evolution of the beam shape with the frequency.

Integrated RF modeling and particle dynamic

3D Maxwell equation	Vlasov equation
Wave propagation absorption	Plasma response

Wave equation solver

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \varepsilon_0 \nabla \cdot \vec{E} = \rho$$

$$\frac{1}{\mu_0} \nabla \times \vec{B} = \vec{J} + \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \qquad \nabla \cdot \vec{B} = 0$$

$$\rho = q \int f d^3 v$$

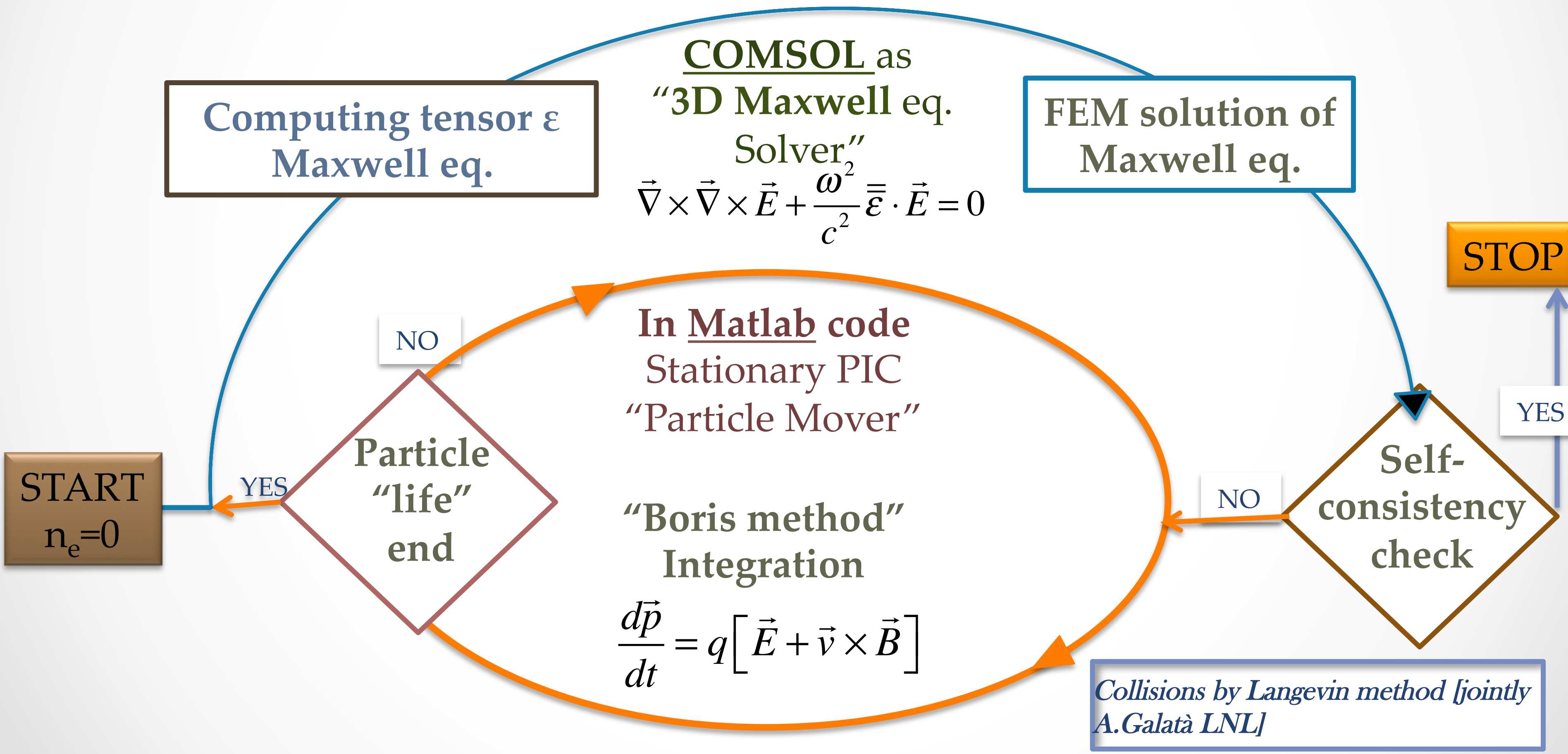
$$J = q \int \vec{v} f d^3 v$$

Plasma dynamics ionization, recombination, diffusion losses, collisions

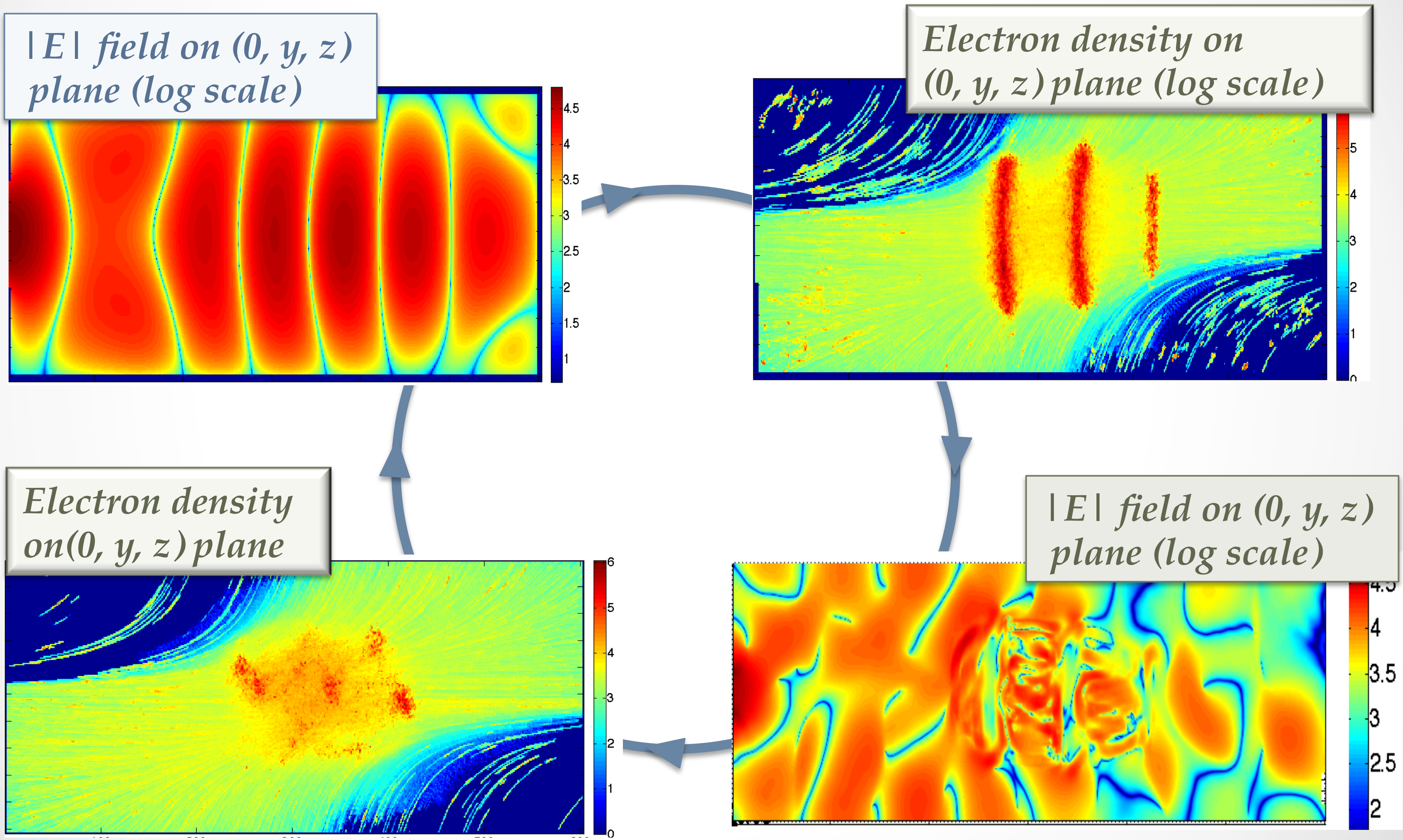
$$\frac{\partial f}{\partial t} + \vec{v} \cdot \frac{\partial f}{\partial \vec{r}} + \frac{q}{m} \left[\vec{E} + \frac{\vec{v} \times \vec{B}}{c} \right] \frac{\partial f}{\partial \vec{v}} = \frac{\partial f}{\partial t}_{coll}$$

Our goal is to obtain quantitatively accurate, predictive understanding of wave processes important for heating plasma

"Stationary" PIC strategy Diagram



Iterative self consistent approach



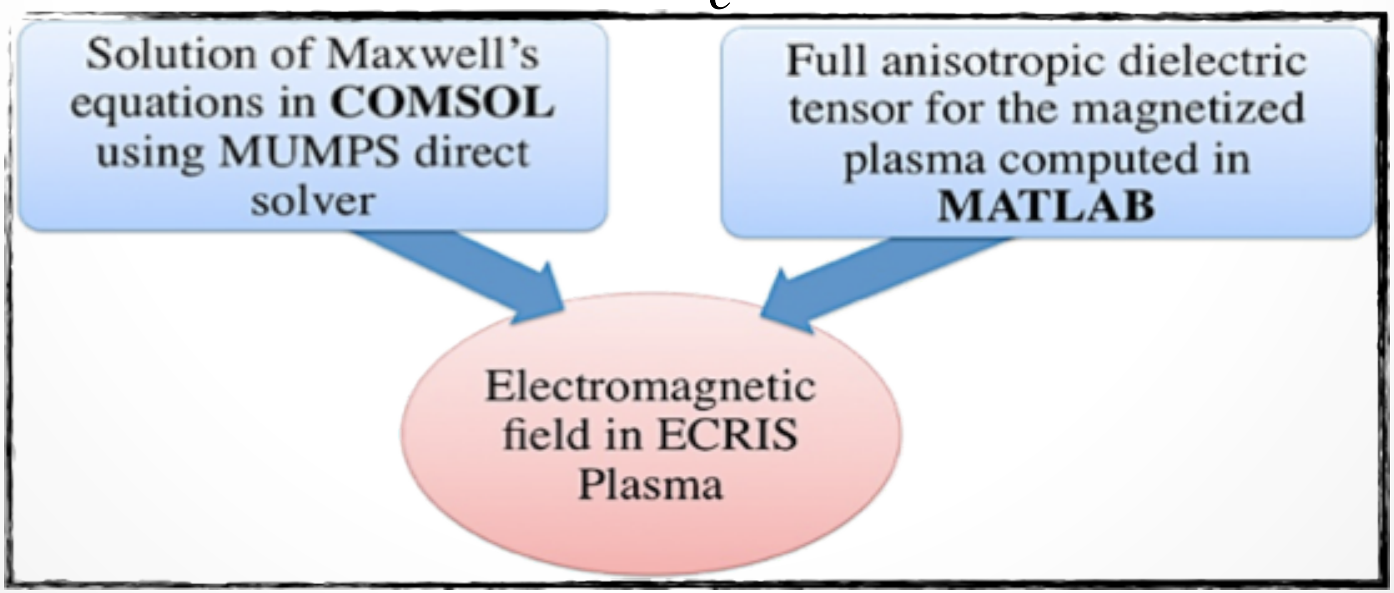
"Stationary" PIC strategy Diagram

COMSOL as "3D Maxwell eq. Solver"

Computing tensor ε Maxwell eq.

FEM solution of Maxwell eq.

$$\vec{\nabla} \times \vec{\nabla} \times \vec{E} + \frac{\omega^2}{c^2} \overline{\overline{\varepsilon}} \cdot \vec{E} = 0$$



Basic equations of wave propagation in "cold" plasma

Maxwell'equations

$$\vec{\nabla} \times \vec{E}(\vec{r}) = -i\omega \vec{B}(\vec{r})$$

$$\vec{\nabla} \times \vec{H}(\vec{r}) = i\omega\varepsilon_0 \vec{E}(\vec{r}) + \vec{J}(\vec{r}) = i\omega\overline{\overline{\varepsilon}} \cdot \vec{E}(\vec{r}) = i\omega \cdot \vec{D}(\vec{r})$$

$$\vec{\nabla} \cdot \vec{D}(\vec{r}) = \rho(\vec{r})$$

$$\vec{\nabla} \cdot \vec{B}(\vec{r}) = 0$$

Constitutive relations

$$\vec{J} = \overline{\overline{\sigma}} \cdot \vec{E}$$

$$\vec{D} = \frac{\vec{J}}{i\omega} + \varepsilon_0 \vec{E} = \left(\frac{\overline{\overline{\sigma}}}{i\omega} + \varepsilon_0 \right) \vec{E} = \overline{\overline{\varepsilon}} \cdot \vec{E}$$

$$\overline{\overline{\varepsilon}} = \varepsilon_0 \left(\overline{\overline{I}} - i \frac{\overline{\overline{\sigma}}}{\omega\varepsilon_0} \right)$$

DERIVATION OF CONDUCTIVITY TENSOR $\overline{\overline{\sigma}}$

__3D cold plasma modeling:__ plasma as a dispersive medium with collisions

- **Random thermal motion neglected** ($v_\varphi \gg v_{th}$)

$$m\frac{\partial \vec{v}}{\partial t} = \left(q\vec{E} + \vec{v} \times \vec{B}_0 \right) - \omega_{eff} m\vec{v}$$

collision frequency ω_{eff} accounts for the **collision friction**, models the **wave damping** and resolves the **singularity** of some elements of tensor

Non-uniform "local" dielectric tensor

Non-symmetric 3D magnetostatic field

$$\begin{cases} B_x = B_1 xz + 2S_{ex} xy \\ B_y = -B_1 yz + S_{ex}(x^2 - y^2) \\ B_z = B_0 + B_1 z^2 \end{cases}$$

Assuming a non uniform magnetostatic field the ***dielectric tensor*** *is:*

$$\frac{\bar{\bar{\varepsilon}}}{\varepsilon_0} = \begin{bmatrix} 1 + j\frac{\omega_p^2}{\omega}\frac{A_x}{\Delta} & j\frac{\omega_p^2}{\omega}\frac{C_z + D_{xy}}{\Delta} & j\frac{\omega_p^2}{\omega}\frac{-C_y + D_{xz}}{\Delta} \\ j\frac{\omega_p^2}{\omega}\frac{-C_z + D_{xy}}{\Delta} & 1 + j\frac{\omega_p^2}{\omega}\frac{A_y}{\Delta} & j\frac{\omega_p^2}{\omega}\frac{C_x + D_{yz}}{\Delta} \\ j\frac{\omega_p^2}{\omega}\frac{C_y + D_{xz}}{\Delta} & j\frac{\omega_p^2}{\omega}\frac{-C_x + D_{zy}}{\Delta} & 1 + j\frac{\omega_p^2}{\omega}\frac{A_z}{\Delta} \end{bmatrix}$$

$$\omega_p^2 = \frac{n_e e^2}{m\varepsilon_0}$$

$$A_i(x,y,z,B_0,n_e,\omega_{eff}) = C_i(x,y,z,B_0,n_e,\omega_{eff}) = D_i(x,y,z,B_0,n_e,\omega_{eff}) = \Delta(x,y,z,B_0,n_e,\omega_{eff})$$

Off-diagonal Elements due to 3D Magnetic field

Real Ion Source Setup

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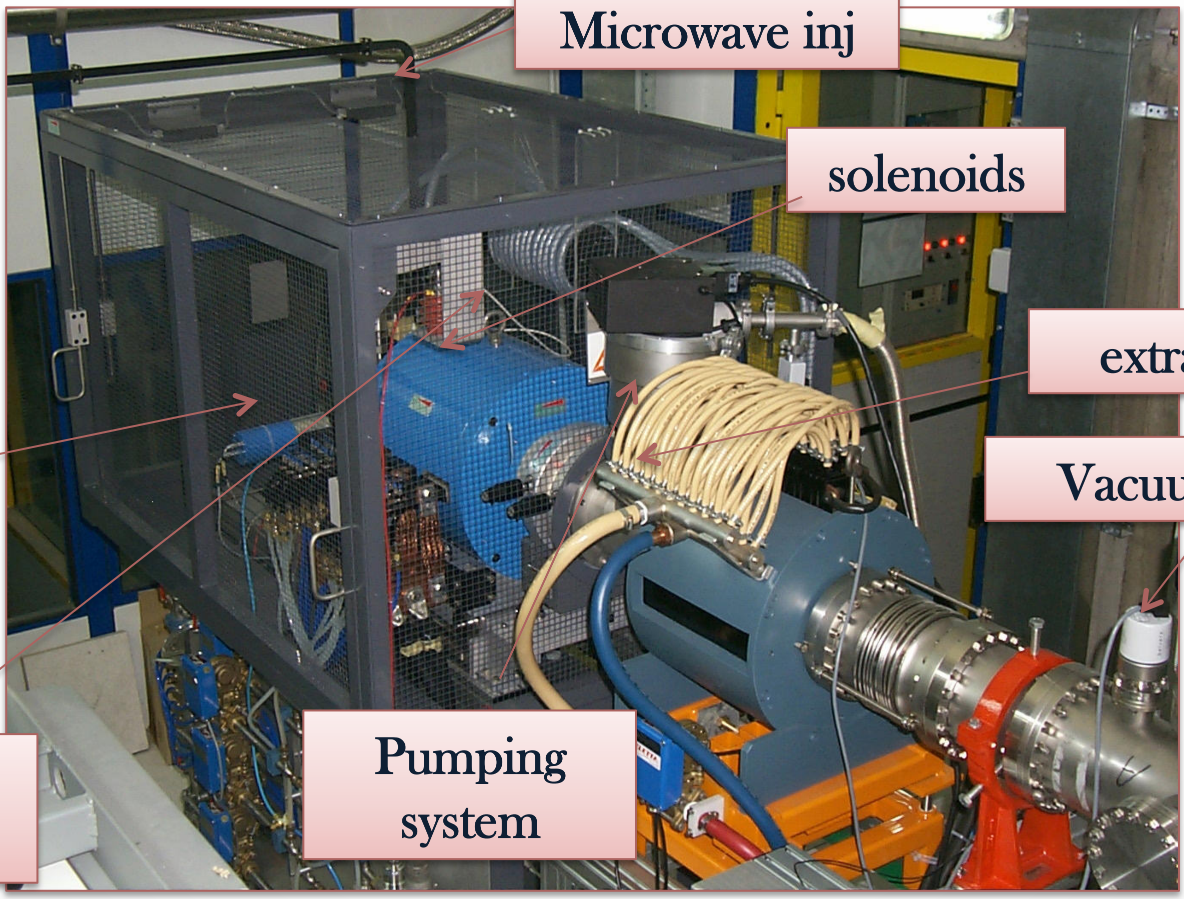
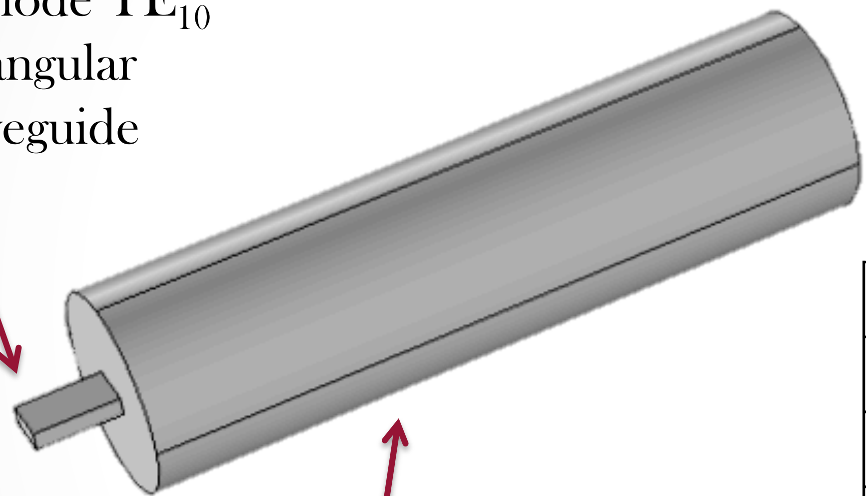


Simulation Setup in COMSOL

Single mode TE_{10}
rectangular
Waveguide

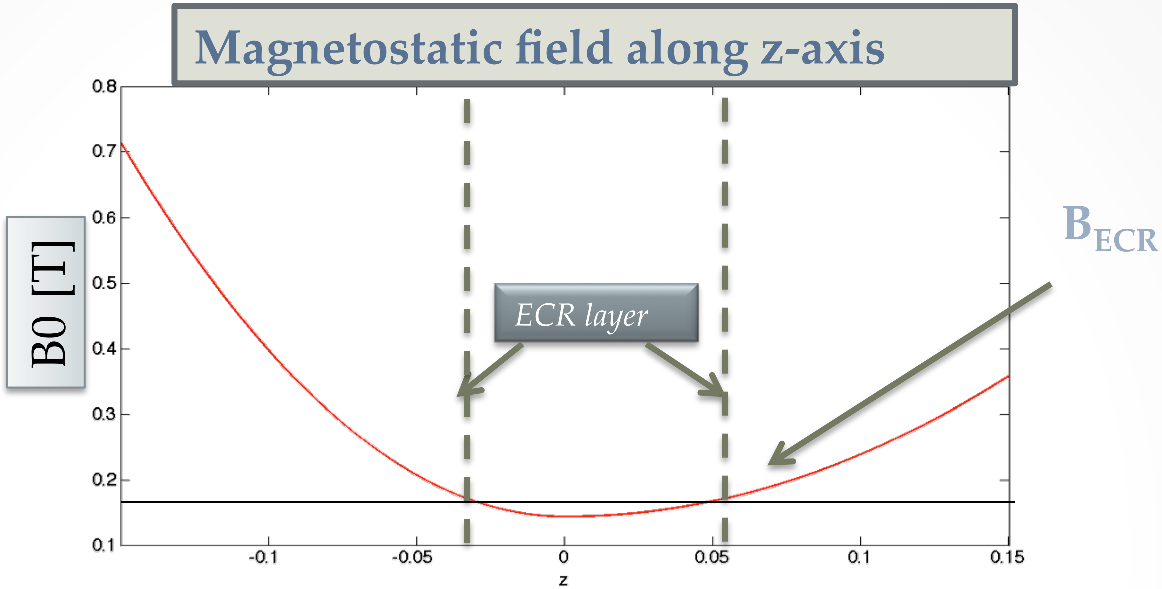


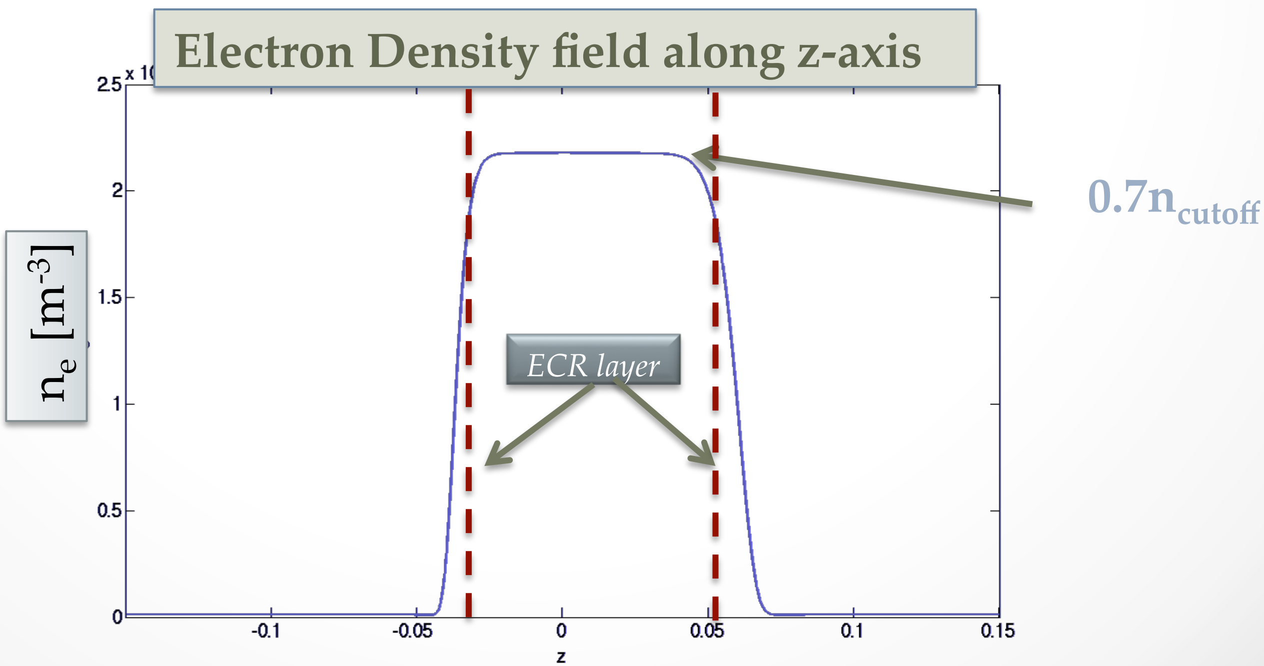
3D cylindrical cavity filled by plasma
described by the dielectric tensor

Simulation parameter

PARAMETER	VALUE
Cavity length	450 mm
Cavity radius	65 mm
Frequency	8 GHz
Waveguide width	28.5 mm
Waveguide height	12.6 mm
RF Power	100 W

Inputs for tensor



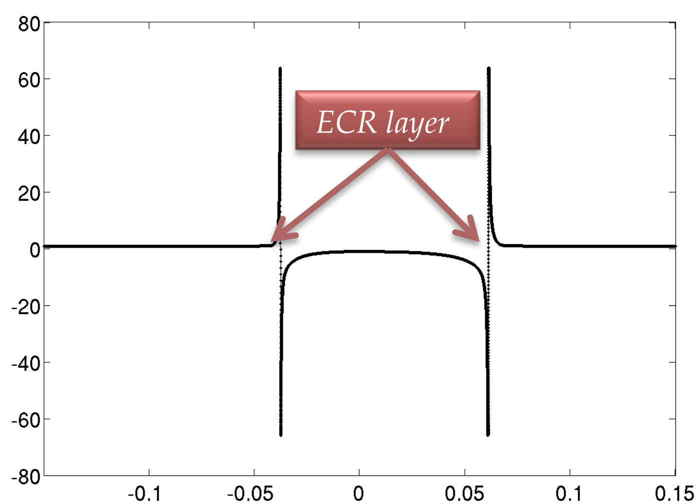


FEM "Full Wave" solution approach

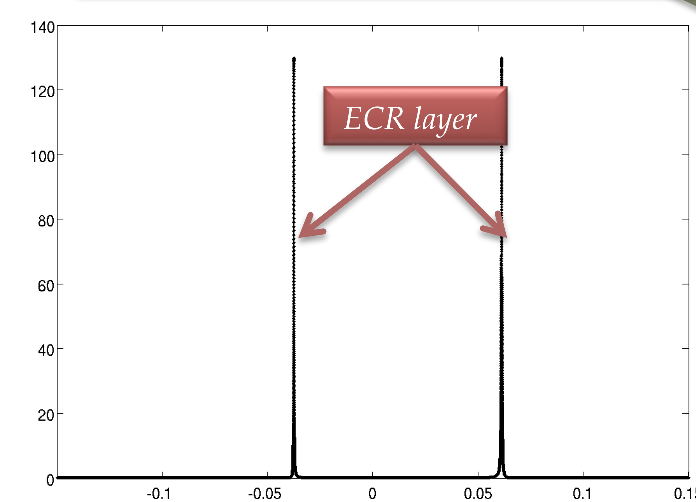
$$\omega_{eff} = \omega_{RF}/10^3$$

$$\frac{\bar{\bar{\varepsilon}}}{\varepsilon_0} = \begin{bmatrix} 1 + j\dfrac{\omega_p^2}{\omega}\dfrac{A_x}{\Delta} & j\dfrac{\omega_p^2}{\omega}\dfrac{C_z + D_{xy}}{\Delta} & j\dfrac{\omega_p^2}{\omega}\dfrac{-C_y + D_{xz}}{\Delta} \\ j\dfrac{\omega_p^2}{\omega}\dfrac{-C_z + D_{xy}}{\Delta} & 1 + j\dfrac{\omega_p^2}{\omega}\dfrac{A_y}{\Delta} & j\dfrac{\omega_p^2}{\omega}\dfrac{C_x + D_{yz}}{\Delta} \\ j\dfrac{\omega_p^2}{\omega}\dfrac{C_y + D_{xz}}{\Delta} & j\dfrac{\omega_p^2}{\omega}\dfrac{-C_x + D_{zy}}{\Delta} & 1 + j\dfrac{\omega_p^2}{\omega}\dfrac{A_z}{\Delta} \end{bmatrix}$$

Real part of ε_{r11}

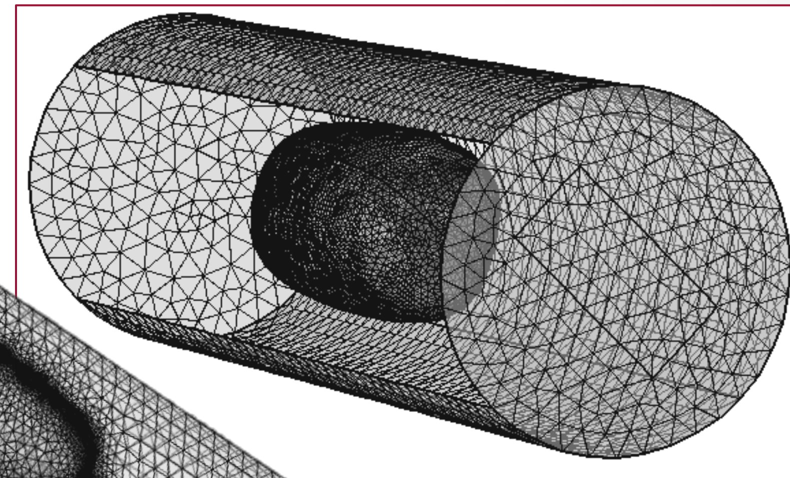


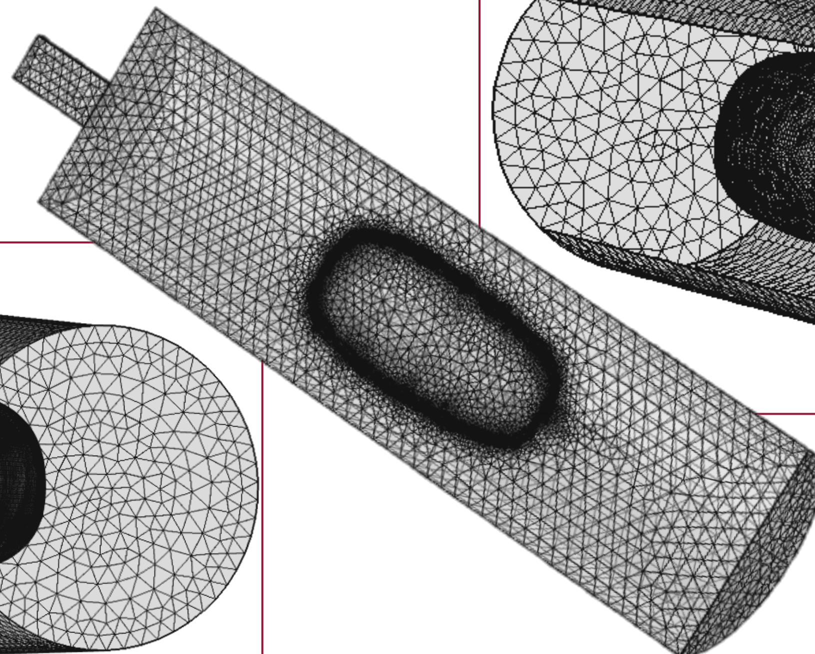
Imaginary part of ε_{r11}

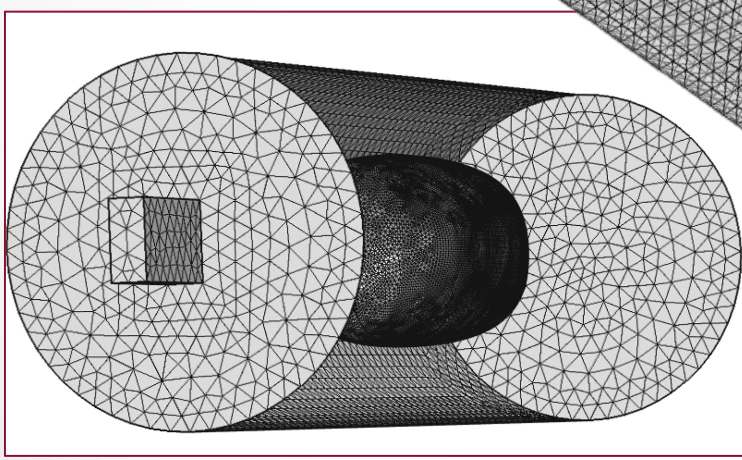


Mesh procedure

ECR-surface-based mesh to create a fine mesh on the ECR surface



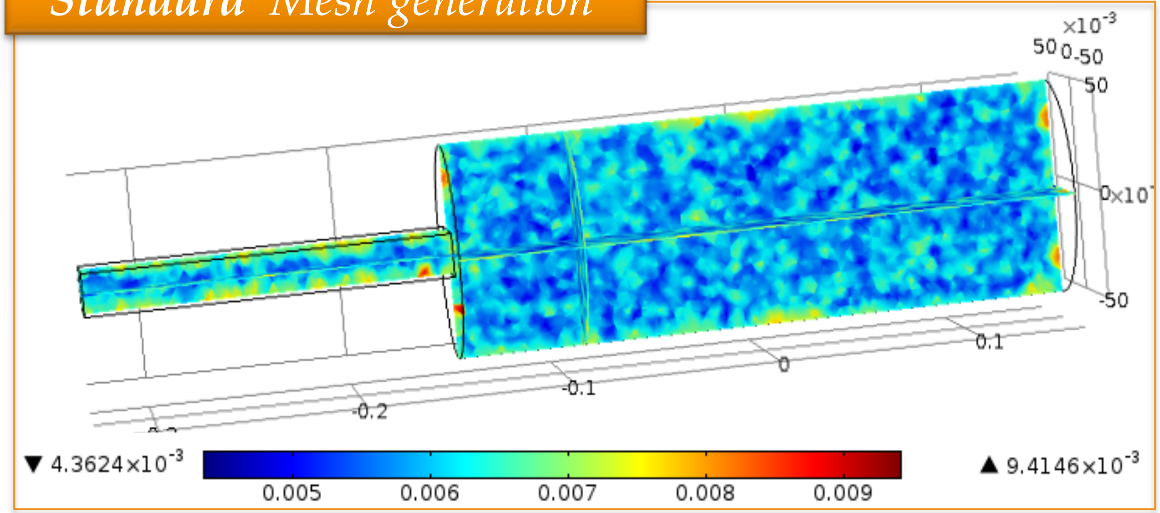




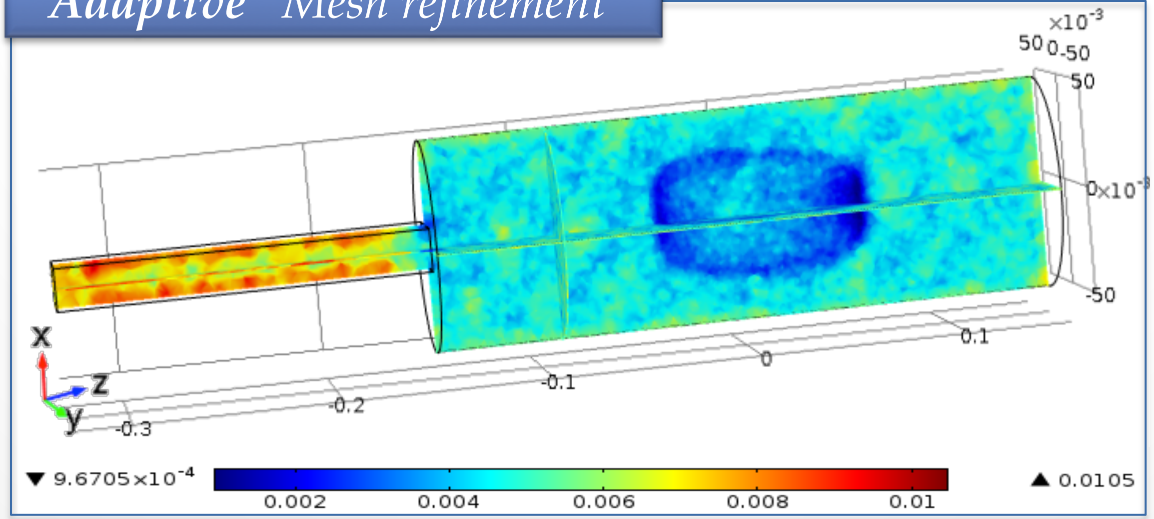
The mesh is very fine on the ECR surface and relatively coarser away from the resonance zone.

“Standard” vs “Adaptive” MESH

“Standard” Mesh generation

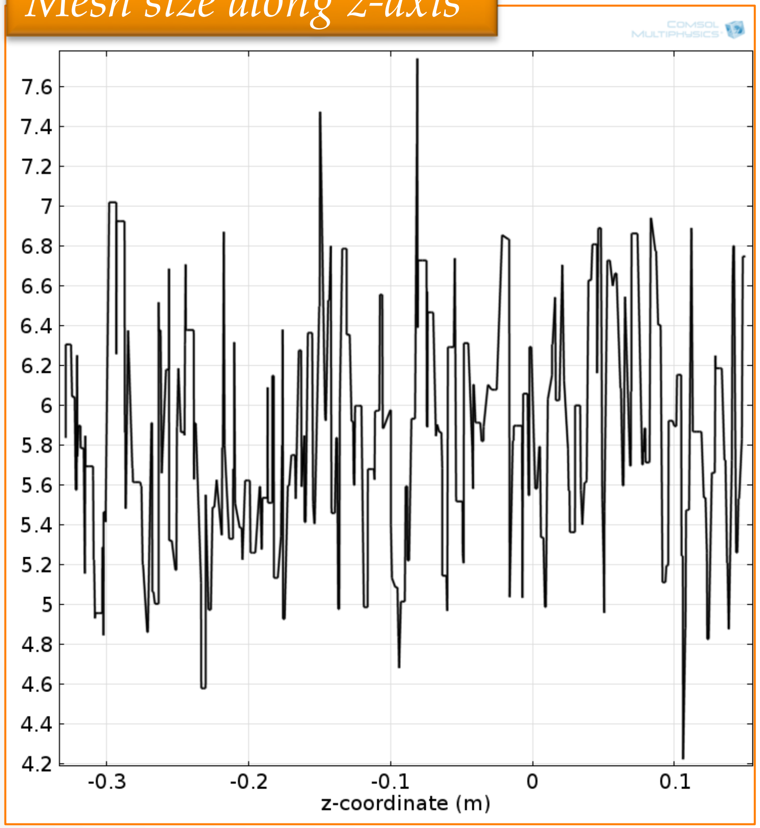


“Adaptive” Mesh refinement



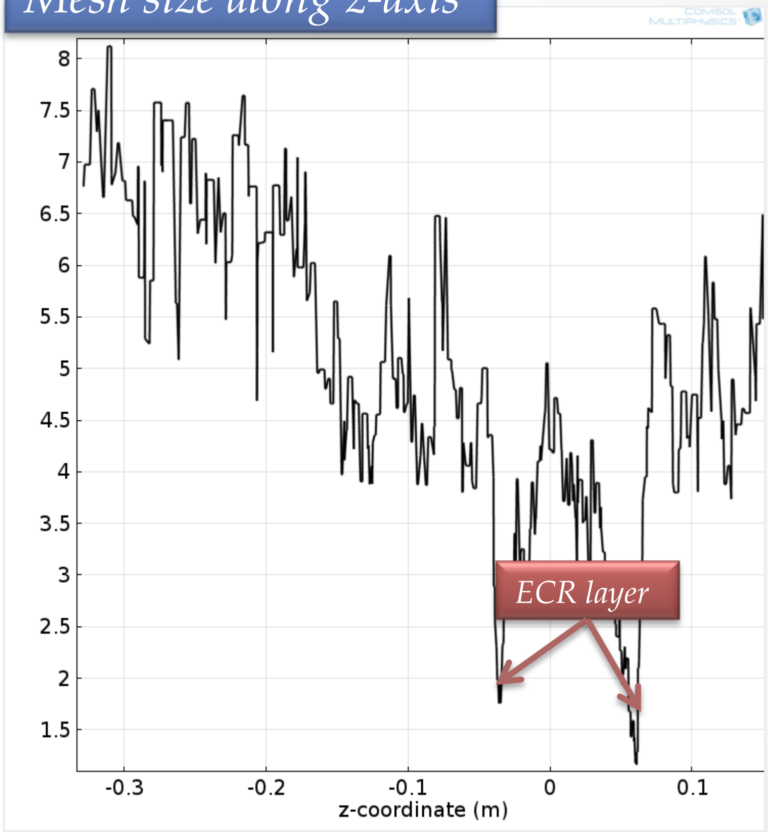
"Standard" vs "Adaptive" MESH

Mesh size along z-axis



$$h \approx \frac{\lambda_0}{10}$$

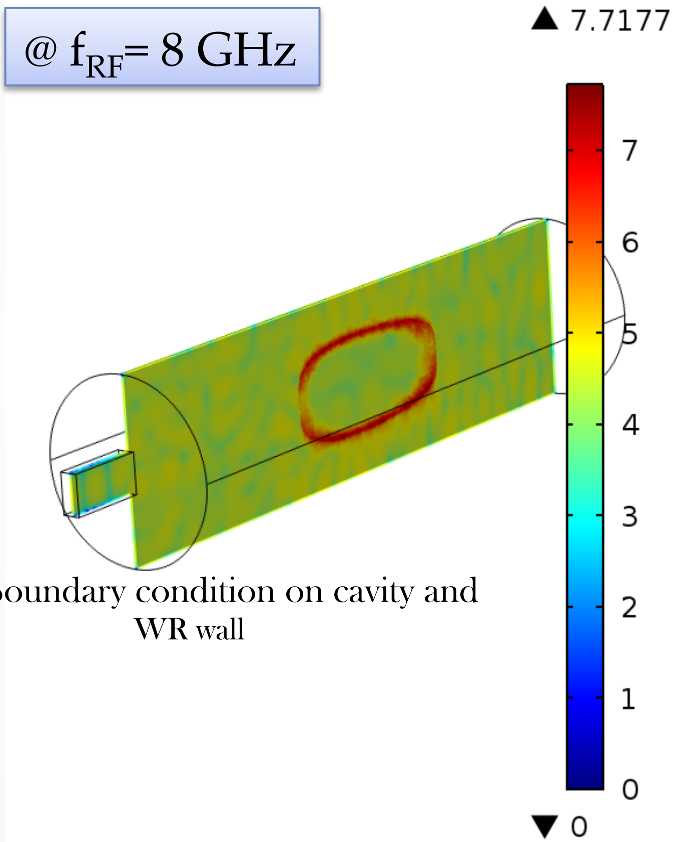
Mesh size along z-axis



$$h \approx \frac{\lambda_0}{40}$$

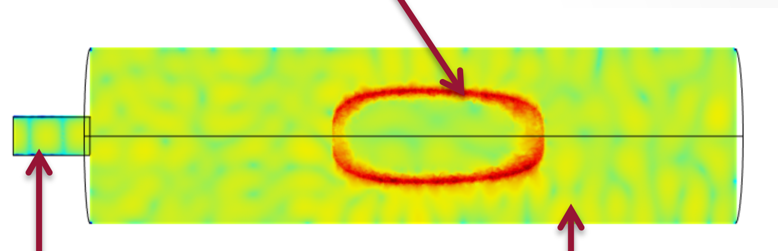
Numerical results: Snapshots of the Electric field on a slice

@ f_{RF}= 8 GHz



PEC Boundary condition on cavity and WR wall

Intensification of the e.m. field in the near resonance zone

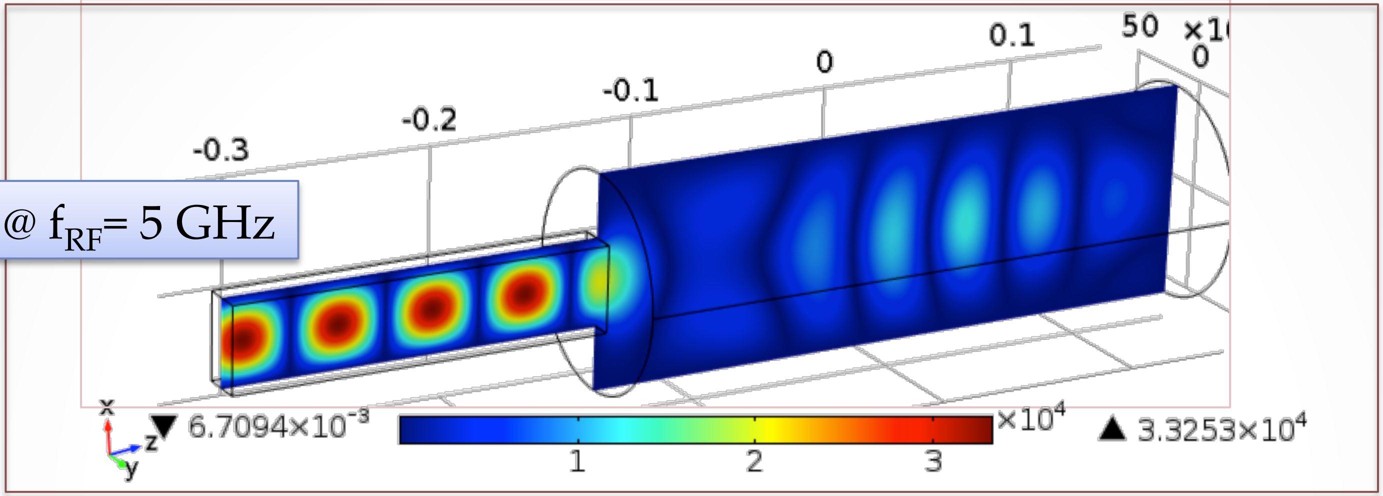


TE_{10} mode in vacuum WR

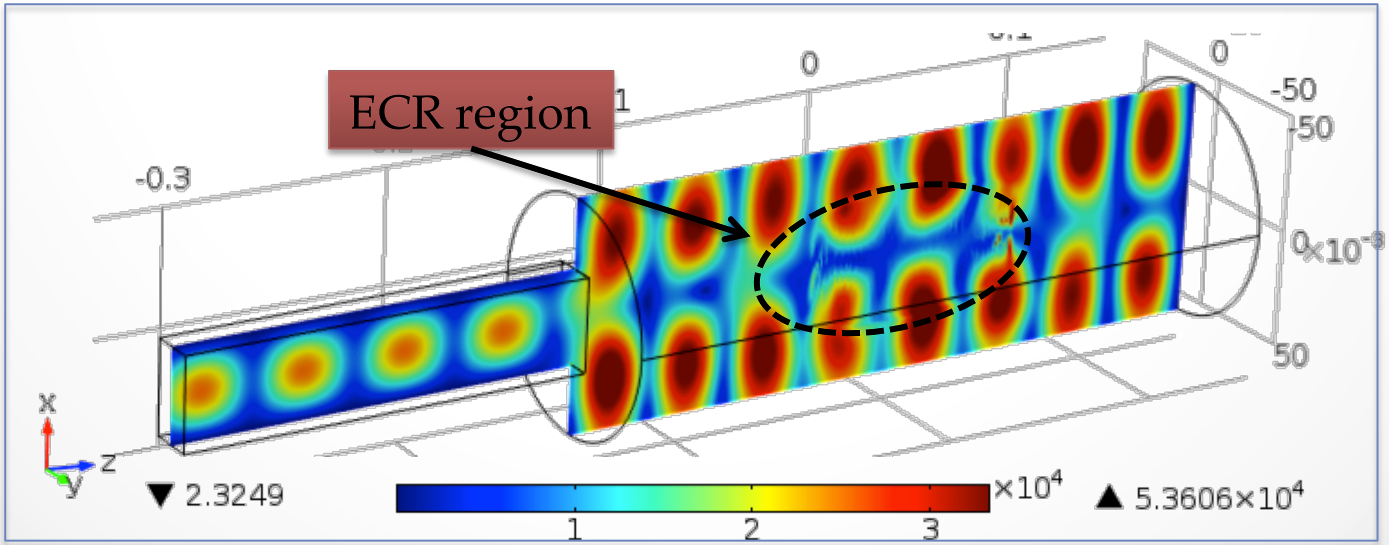
Cold Plasma

2÷3 orders of magnitude Difference between Electric field of ECR zone and outer ones

3-D wave fields in the xz: VACUUM chamber and launching structure RF field



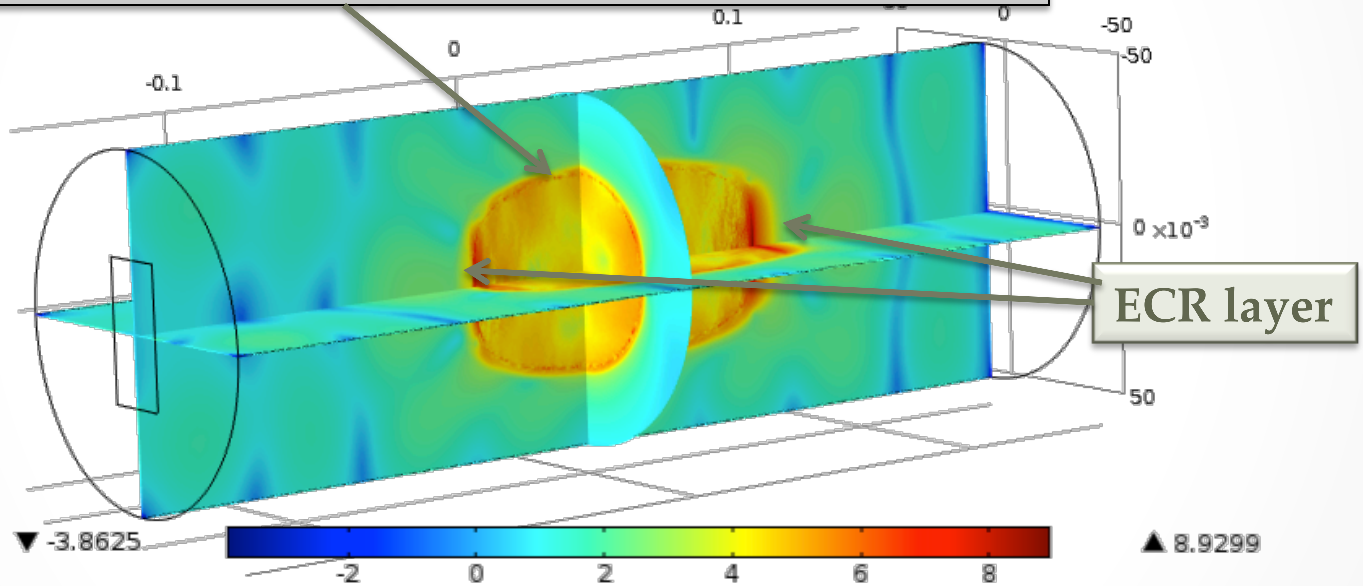
3-D wave fields in the xz : PLASMA FILLED chamber and RF launching structure



Electromagnetic power loss density [W/m3]

$$P_{diss} = \vec{J}\cdot\vec{E} = \left(\bar{\bar{\sigma}}\cdot\vec{E}\right)\cdot\vec{E}$$

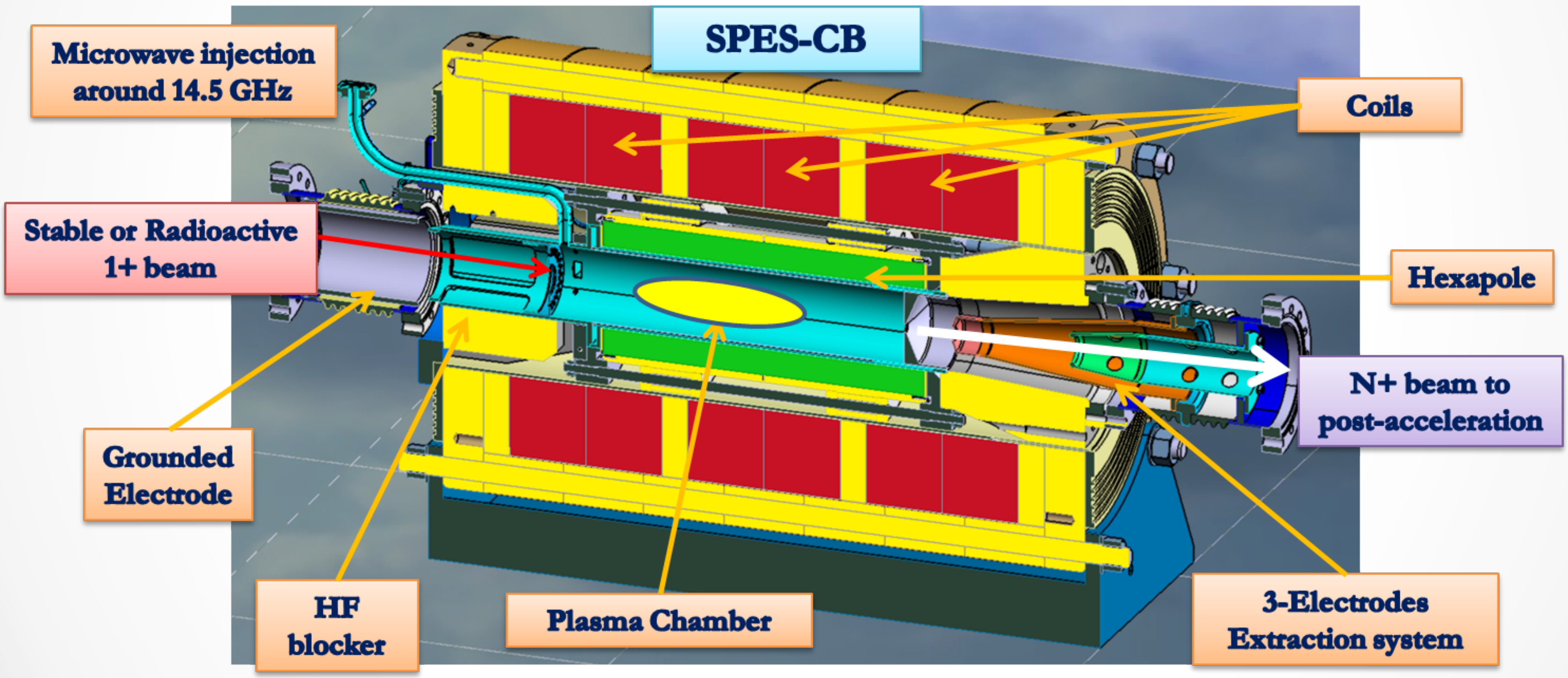
The largest fraction of energy is absorbed at the ECR



Power deposition : the 55 % of the total input Power is absorbed by the plasma

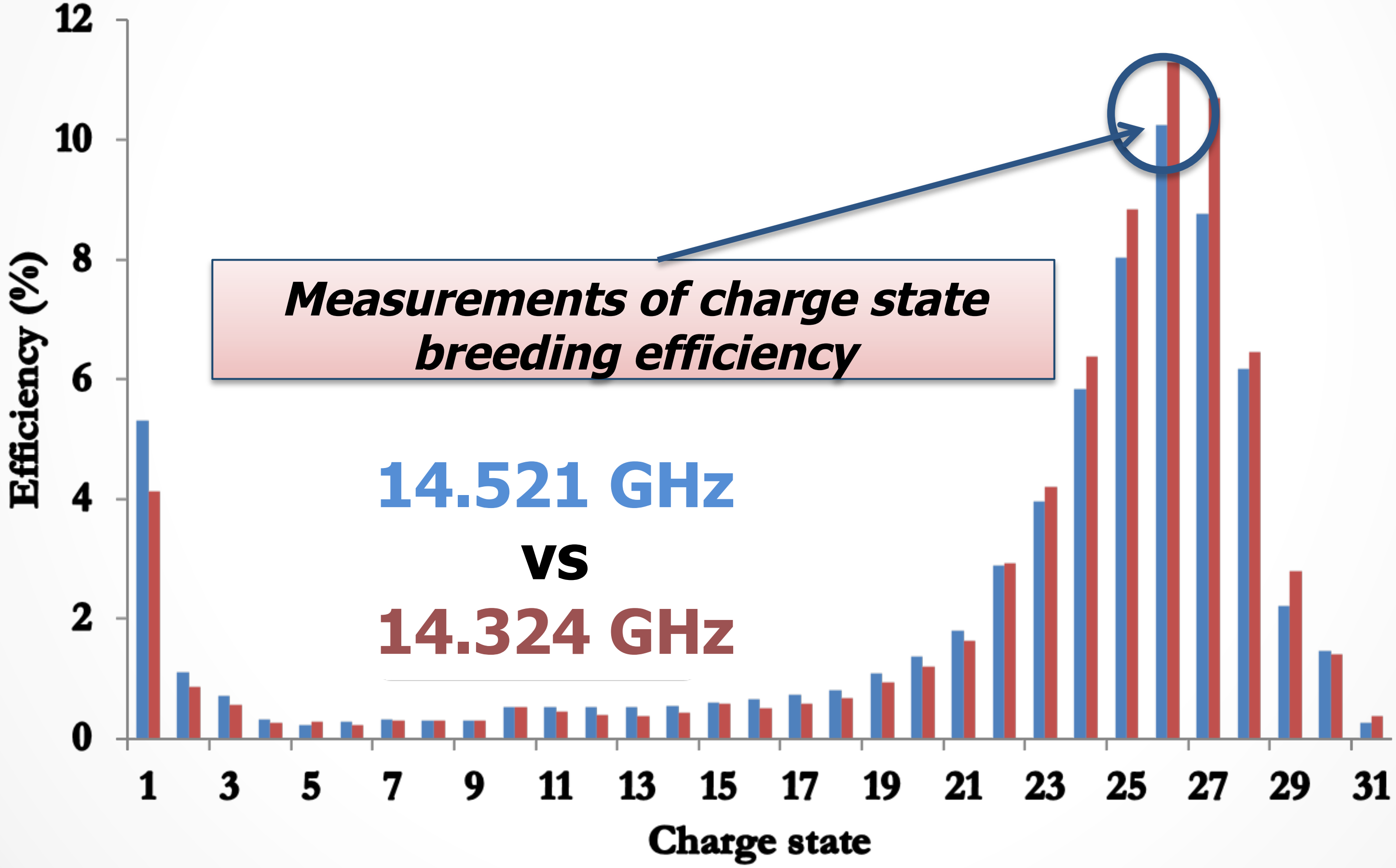
[G. Torrisi, D. Mascali, G. Sorbello, L. Neri, L. Celona, G. Castro, T. Isernia, and S. Gammino, "**Full-wave FEM simulations of electromagnetic waves in strongly magnetized non-homogeneous plasma**", *Journal of Electromagnetic Waves and Application* 28(9), 1085-1099 (2014)]

Electromagnetic Analysis of the Plasma Chamber of an ECR-based Charge Breeder



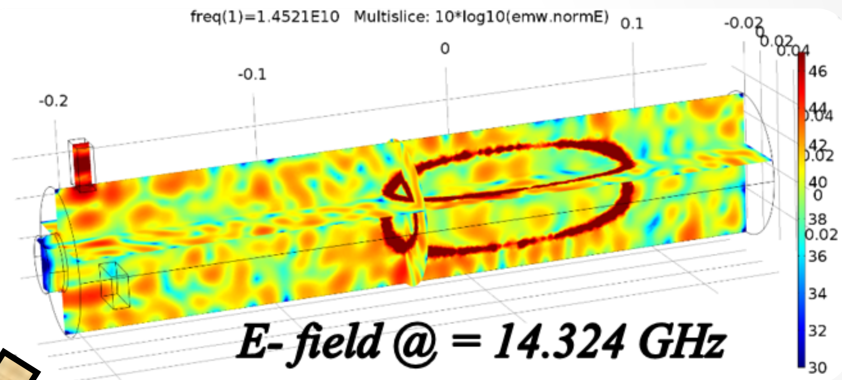
Cut view of the SPES-CB

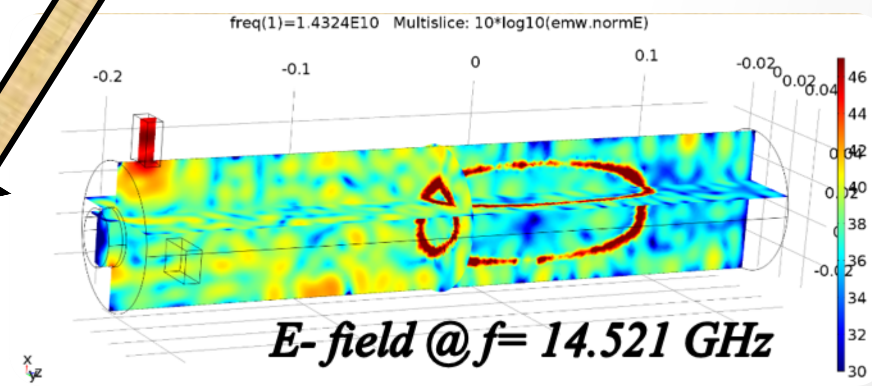
SPES charge breeder Acceptance test



Experimental validation of numerical modeling of EM wave propagation in the anisotropic magnetized plasma of ion sources

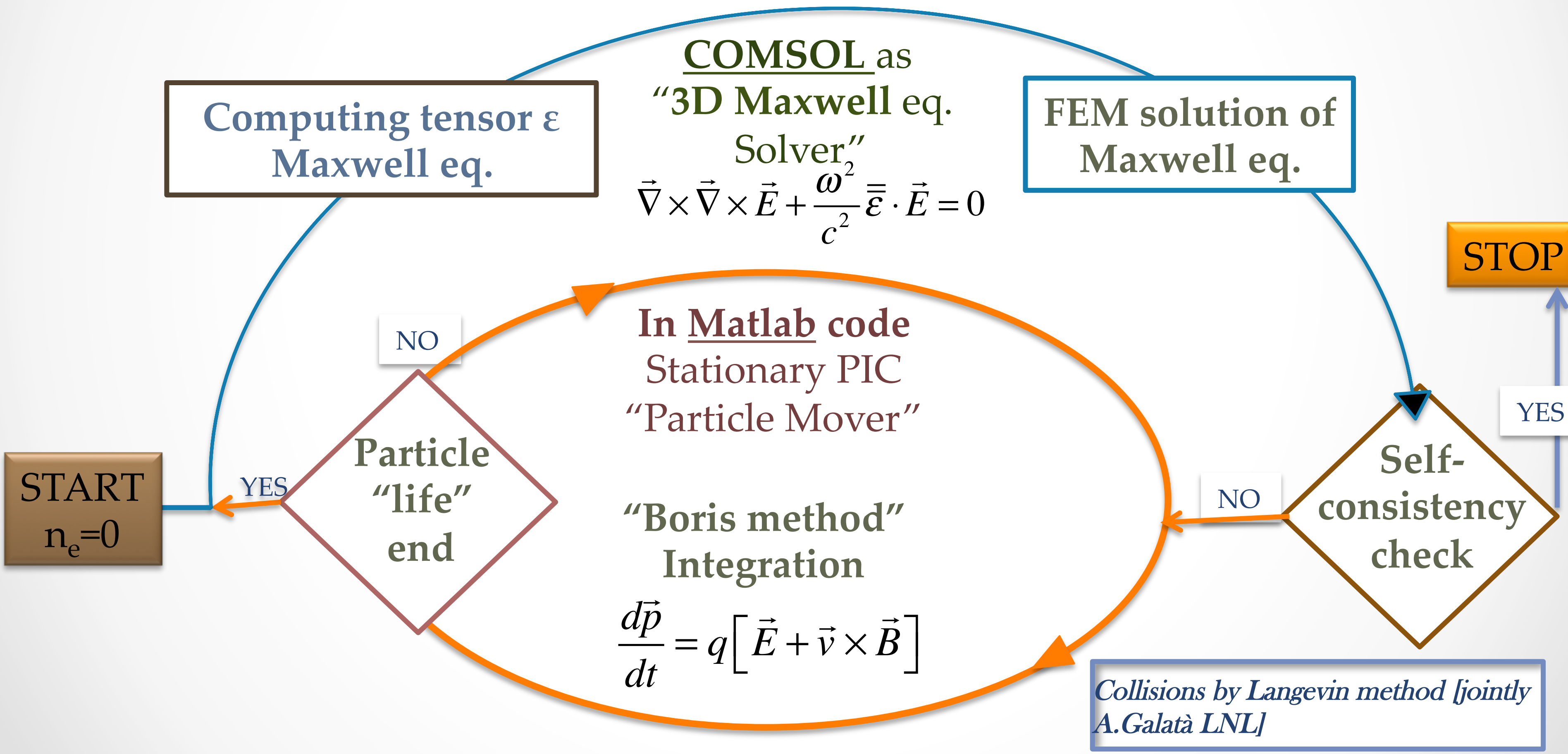
	14.324 GHz	14.521 GHz
P_{input} [W]	100	100
P_f [W]	92.6	68.4
P_{hole} [W]	14.5	41.3
P_{w2} [W]	0.8	3.0
P_{plasma} [W/%]	74.5/80.4	16.6/24.4



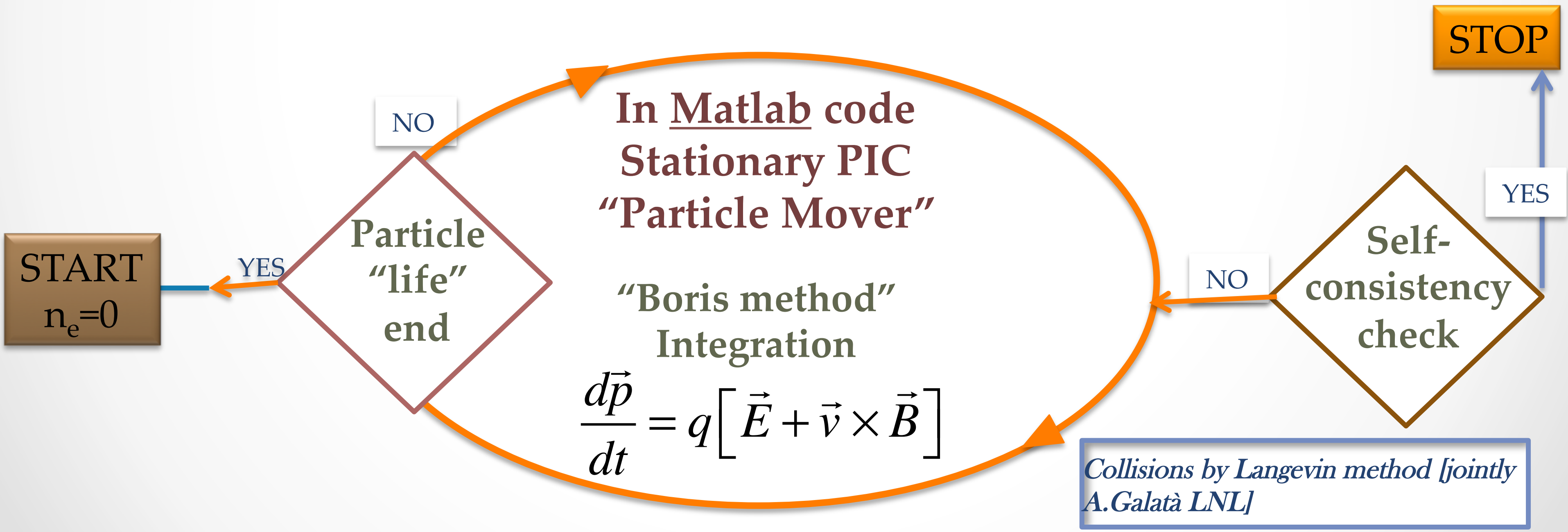


NUMERICAL EVIDENCE OF THE FREQUENCY TUNING EFFECT !

"Stationary" PIC strategy Diagram

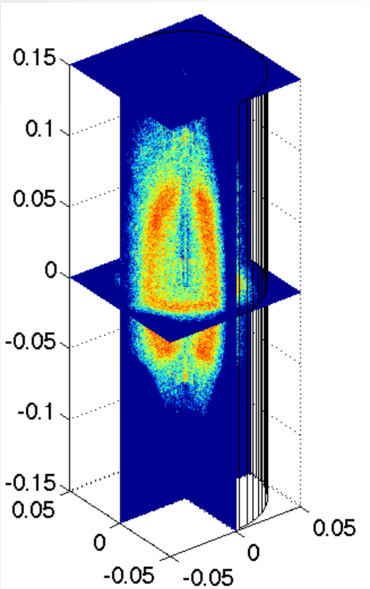


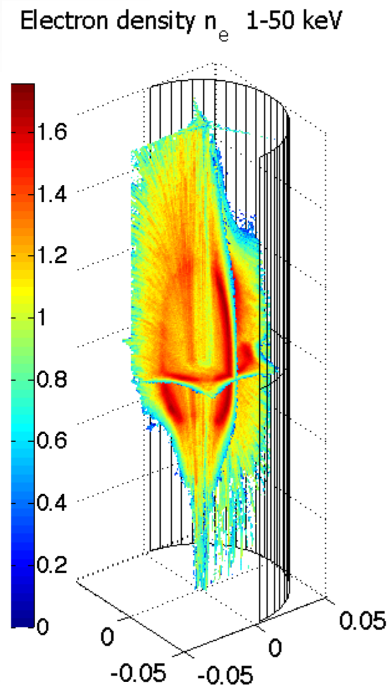
“Stationary” PIC strategy Diagram

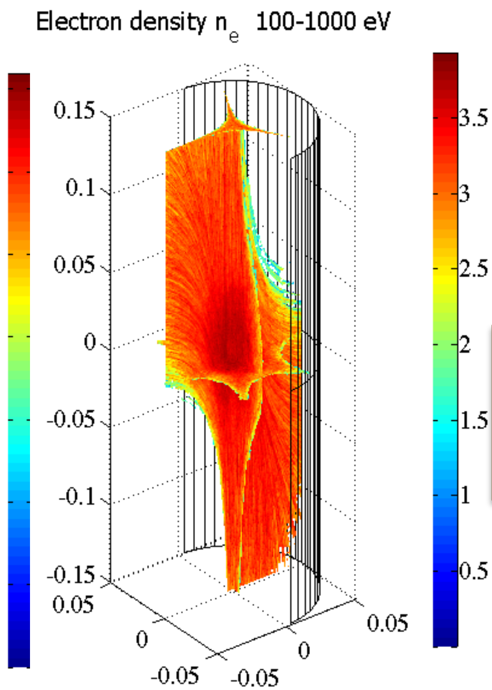


Self-consistent simulations

Electron density >50 keV

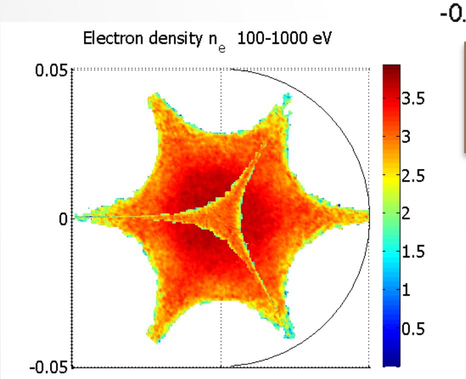




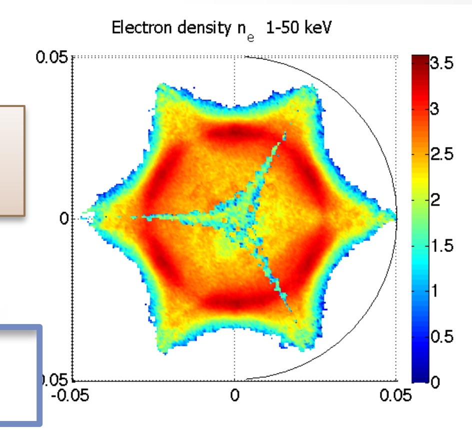


Simulated electron density distribution at different Energy ranges

Different space distribution*: cold electrons in the core, hot ones in near ECR regions*

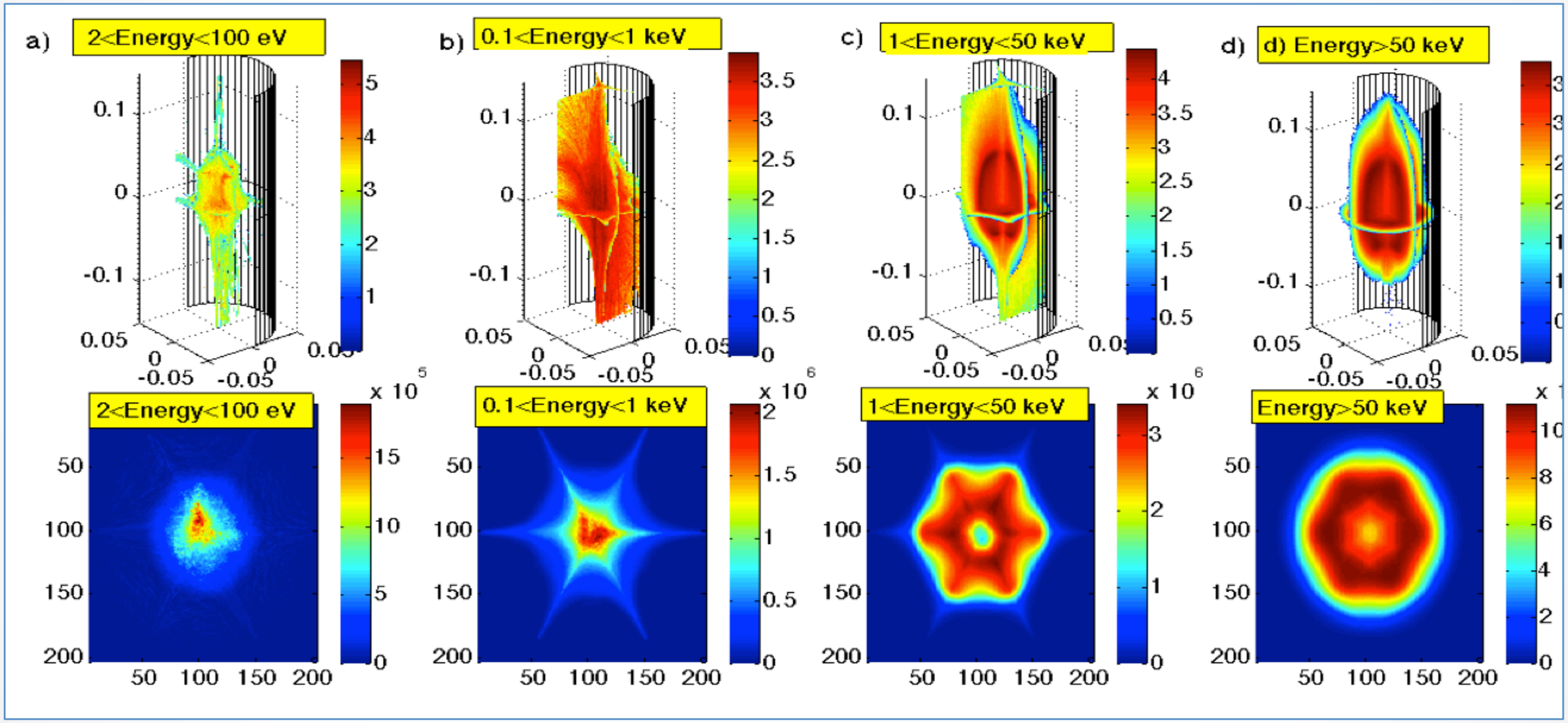


the plasma concentrate mostly **in near resonance region:** a ***dense plasmoid*** is surrounded by a ***rarefied halo***



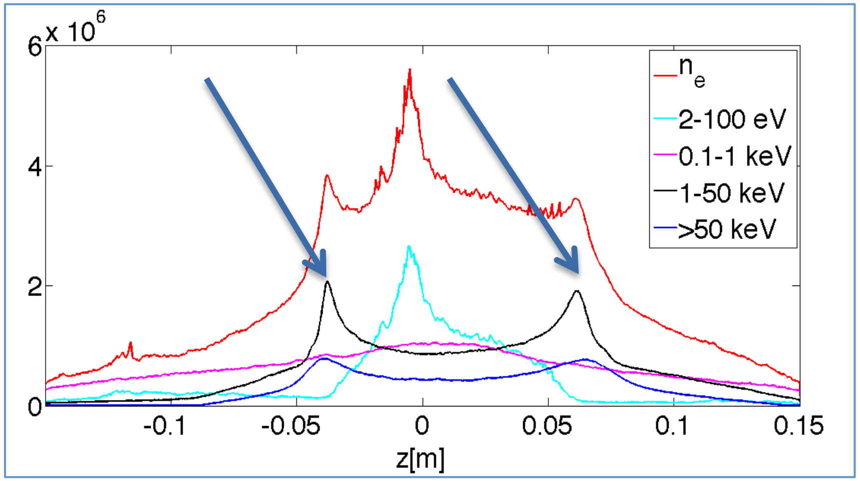
[D. Mascali, G. Torrisi, L. Neri , G. Sorbello, G. Castro, L. Celona, and S. Gammino. *European Physical Journal – D*]

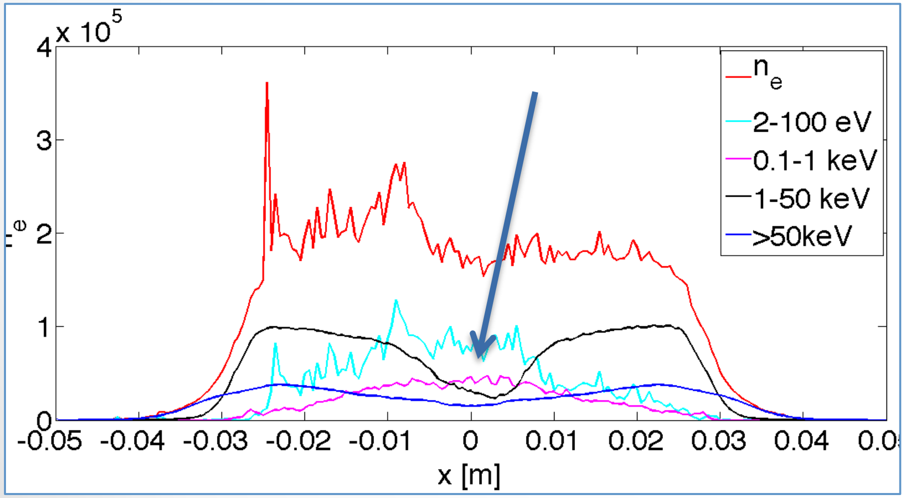
3D density distribution [a.u] at different energy ranges (a.u. in log scale) resulting by the "PARTICLE MOVER" first step

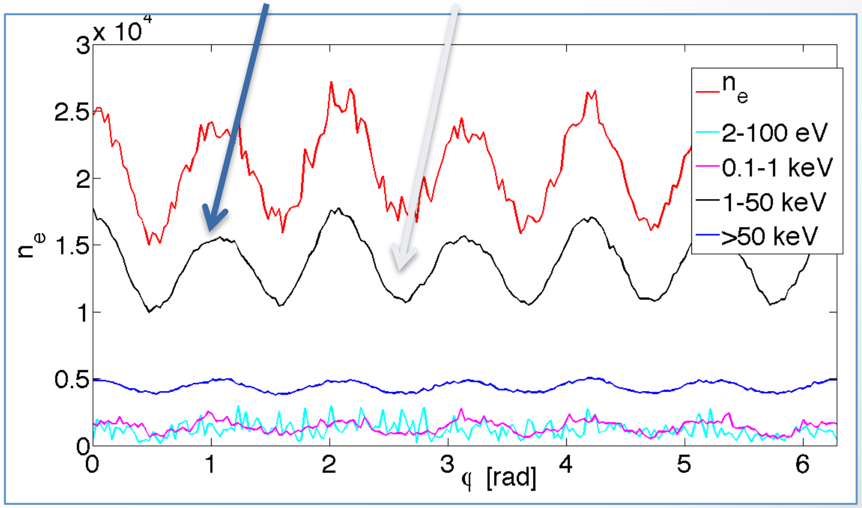


Integrated density: distribution in a 2D transversal view (a.u. in linear scale)

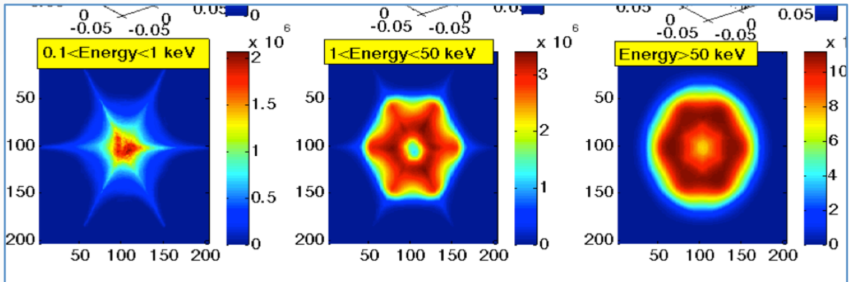
1D profiles of the electron density [a.u] according to the different energetic domains

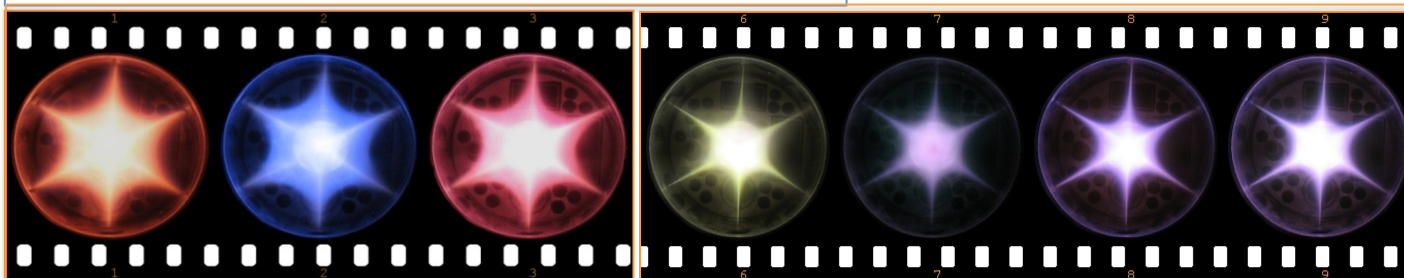






Exploring plasma structure in Atomki-Debrecen





[S. Biri , R. Rácz, J. Pálinkás "Studies of the ECR plasma in the visible light range" talk @ECRIS '08"]

"Visible light (VL) photos transform information mainly on the cold electron component of the plasma. ***Cold electrons are confined in the central plasma part.*** *X-ray (XR) photos show the spatial distribution of ions. These ions and* ***the warm electrons are well confined by the magnetic field lines structure*** *showing strong asymuthal and radial inhomogenity"*

PERSPECTIVES

ION DYNAMICS
WITH COLLISIONS
AND IONIZATIONS

ECR HEATING
WITH COULOMB
COLLISIONS

SELF-CONSISTENCY:
TOOL FOR THE DESIGN
OF FUTURE CHARGE
BREEDERS or ECRIS

ELECTROMAGNETIC
CALCULATIONS
"Hot" plasma
approximation

THE NUMERICAL CODE

IMPLEMENTATION OF COULOMB COLLISIONS

- Forward Difference method

$v(t+1)=v(t) + a*T_{step} \rightarrow x(t+1)=x(t)+ v(t+1)*T_{step}$

- Langevin Equation* (Brownian motion)

$$\Delta v_{Lang}= v(t+1)-v(t)= -\nu_s v(t)*T_{step}+v^{rand}$$

DIFFUSION

$$\phi(\mathbf{v}^{rand}) = \frac{1}{(2\pi T_{step})^{3/2} D_\perp D_\parallel^{1/2}} \exp\left(-\frac{v_3^2}{2D_\parallel T_{step}} - \frac{v_1^2+v_2^2}{D_\perp T_{step}}\right)$$

SLOWING DOWN

Friction: $a=-\nu_s v$

3 // v while 1,2 ⊥ v change at each iteration

Calculated for each particle from the F-P eq.

“Hot” plasma approximation

The nonlocal interaction between spatially separated parts of the materials, leading to what is called

SPATIAL DISPERSION

$$D_i(\omega,\vec{k}) = \varepsilon_{ij}(\omega,\vec{k})E_j(\omega,\vec{k})$$

$$D_i(\vec{r},t) = \int_{-\infty}^{t}\int d\vec{r}^{\,'}\varepsilon_{ij}(t-t^{'},\vec{r}-\vec{r}^{\,'})E_j(\vec{r}^{\,'},t^{'})$$

‘Spatial dispersion’ or ‘nonlocality’ manifests itself in the functional dependence of the medium parameter on the wave vector **k,**

ε (ω, k)

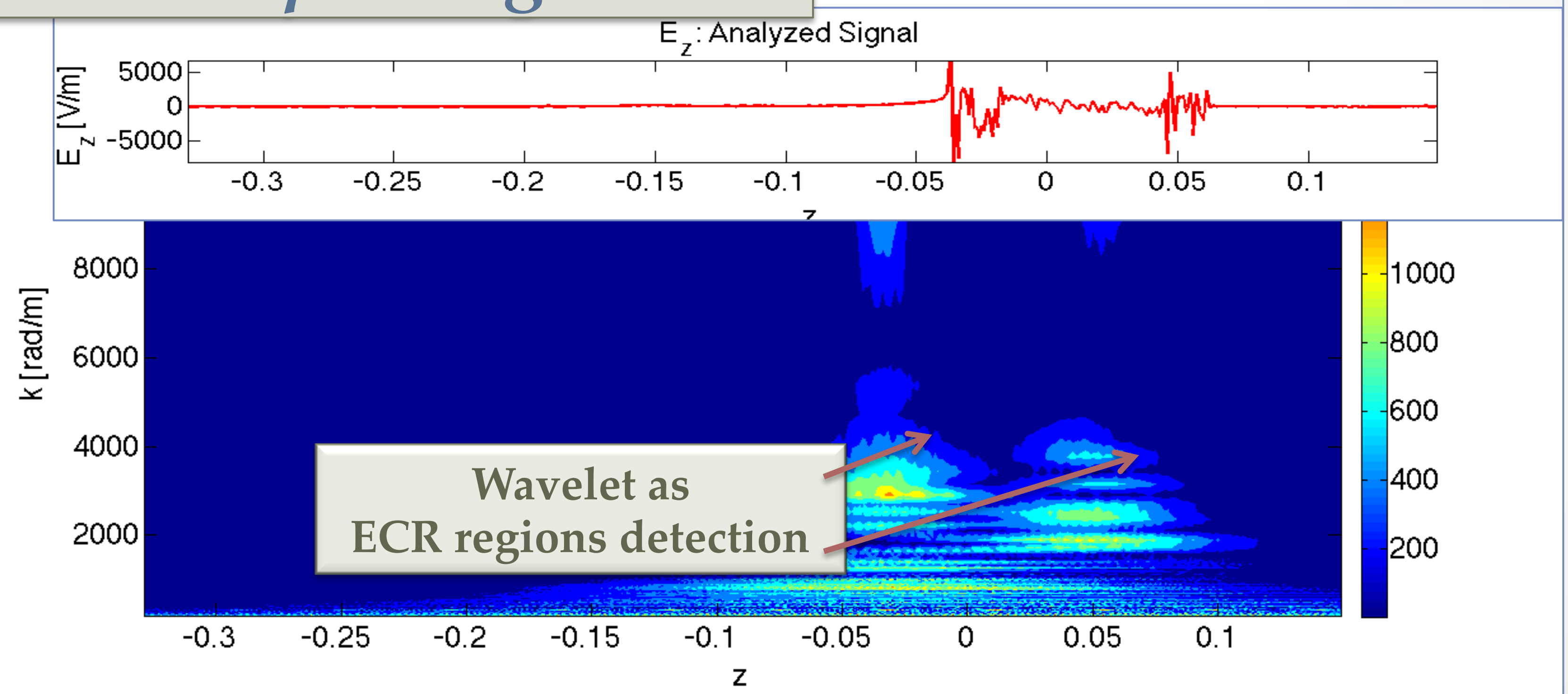
Ongoing development:
Wavelet analysis

Continuous Wavelet Transform (CWT)

for analysing **Full wave wavefield** data in the **spatial domain** to determine the **wavenumber spectrum**

Wavelet of E_z: W{E_z} in cavity with plasma along the z-axis

Wavelet Spectrogram



Thank you!

G. Torrisi[1], D. Mascali[1], A. Galatà[2], G. Castro[1], L. Celona[1], L. Neri[1], G. Sorbello[1,3], S. Gammino[1]

INFN - Laboratori Nazionali del Sud, Via S. Sofia 62, 95125 Catania, Italy
INFN – LNL Viale dell'Università, 2 35020 Legnaro (Padova) Italy
Università degli Studi di Catania, DIIEI, Viale Andrea Doria 6, 95125 Catania, Italy