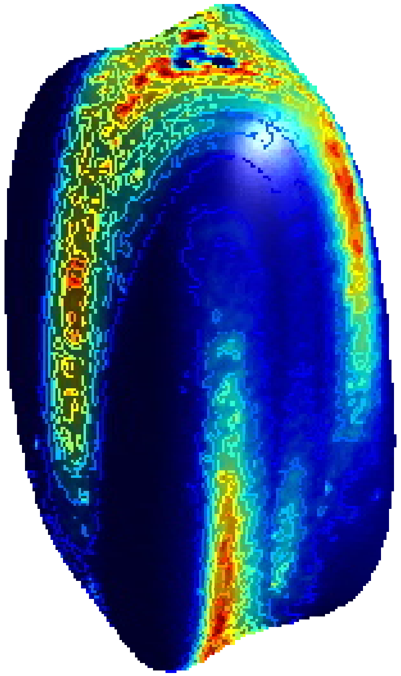
Some Considerations on Frequency Tuning Effect



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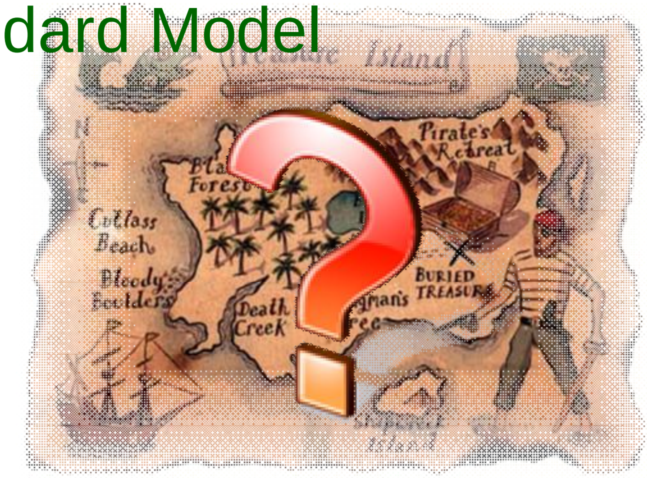
ECRIS Workshop 2010, Grenoble, August 2010

Overcoming the current limits of ECRIS

Roadmap indicated by the ECR Standard Model (Scaling Laws + High-B Mode):

- High Frequency Generators;
- High Magnetic Fields;



$$\langle q \rangle \sim n_e \tau_i$$

$$I \sim n_e / \tau_i$$

Investigations about RF energy transfer to the electrons may allow to overcome the limits

⇩

By quickly replacing the loss hot electrons we can increase the Electron Density and the heating rapidity

The optimization of the wave-electron energy transfer allow to slightly relax the confinement conditions

The “prophecy” of Richard Geller

Already in 1990 Geller, who was the “father” of ECRIS, underlined the importance of plasma physics for future improvements of the source performances:

We want to show that without a minimum of plasma science no progress is possible in ECRIS and probably also in other source development.

R. Geller

Alternative mechanisms of plasma heating

1. Two Frequency Heating

2. "Flat B Field" heating

3. "Broadband" heating

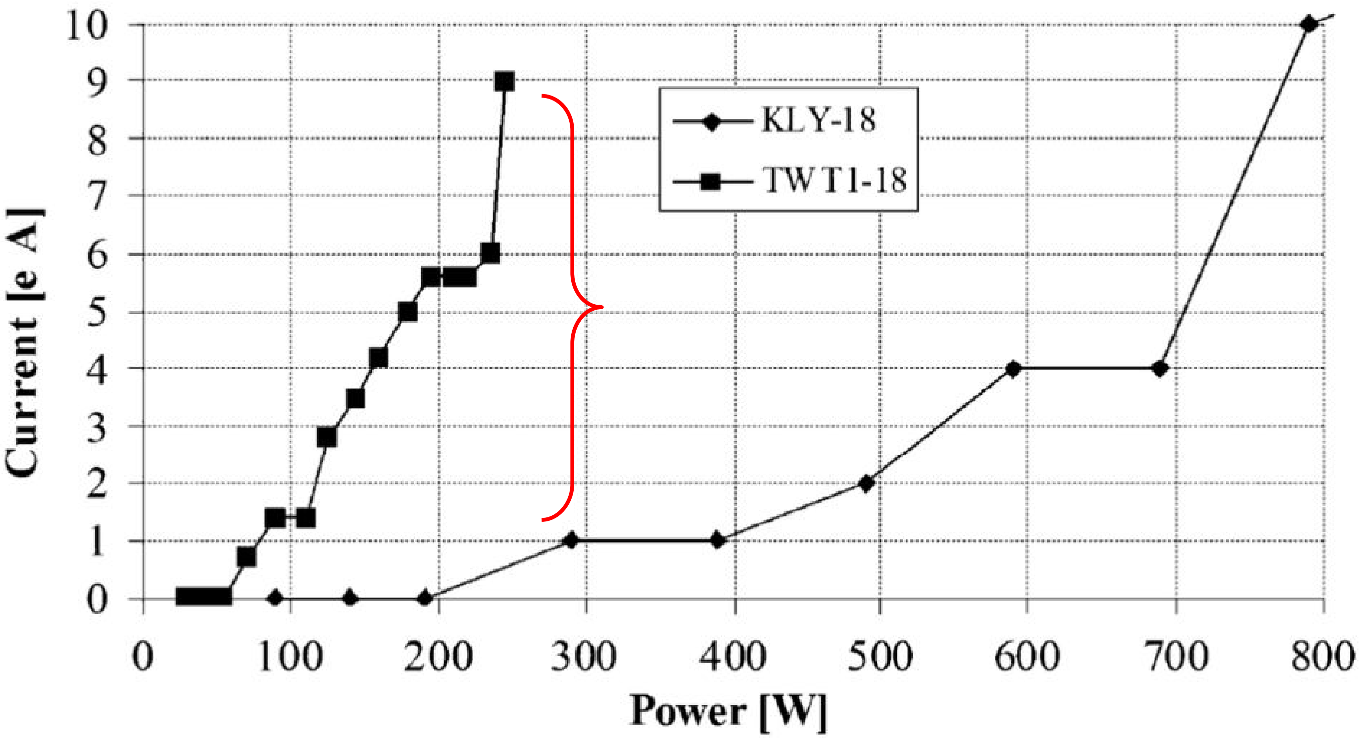
INCREASE OF THE HEATING RAPIDITY

Production of high energy electrons

4. Frequency tuning

5. Two Close Frequency Heating **to be tested**

Signs about the importance of the frequency tuning effect came already in 2001-2004 from an experiment carried out on SERSE [L. Celona et al., ECRIS04]



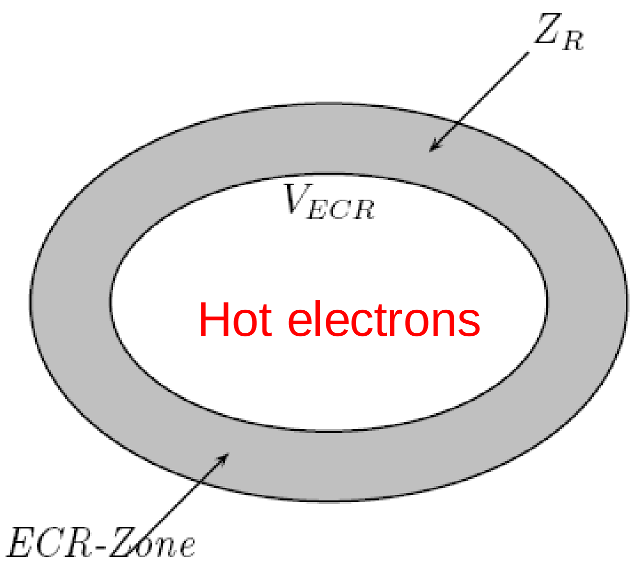
Comparison between trends of O^{8+} at 18 *GHz* for klystron (up to 800 W) and TWT1 operating in the same range of frequency.

TWT worked better than klystron: why?

Why do TWT and Kly give so different results?

HYPOTHESIS 1:

The TWT emission bandwidth is larger than the Klystron one



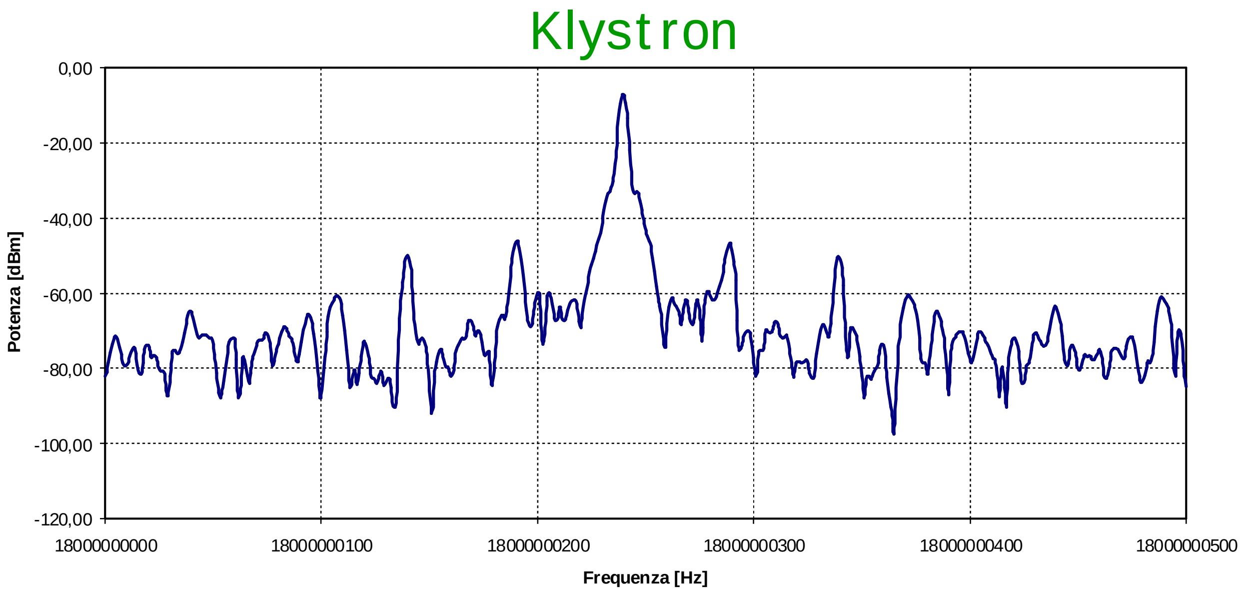
Increase of hot electrons number because of the bigger resonance volume

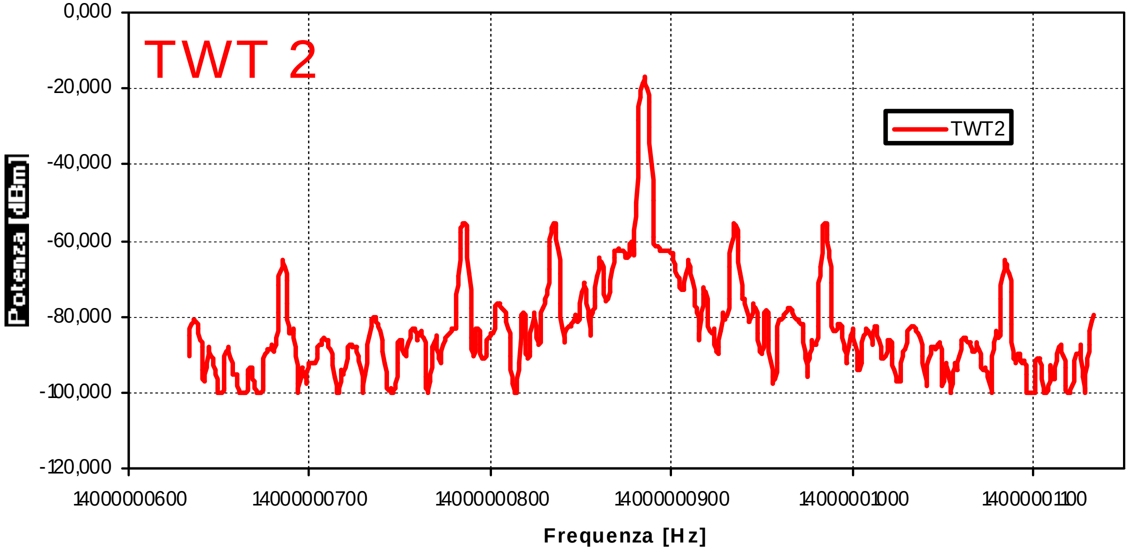
The larger number of heated electrons per time unit makes longer τ_i

Why do TWT and Kly give so different results?

Hyp. 1 is not correct !

Spectrum Analyzer was used for emission band characterization for TWT and Klystron





Why do TWT and Kly give so different results?

Hyp. 1 is not correct !

The spectral structure of the two generators is quite similar → Looking to experimental data it was found that the frequency of the two generators differed of some MHz.

THEREFORE…

Our investigations were focused on the different behavior of source when using fine tuning of frequency

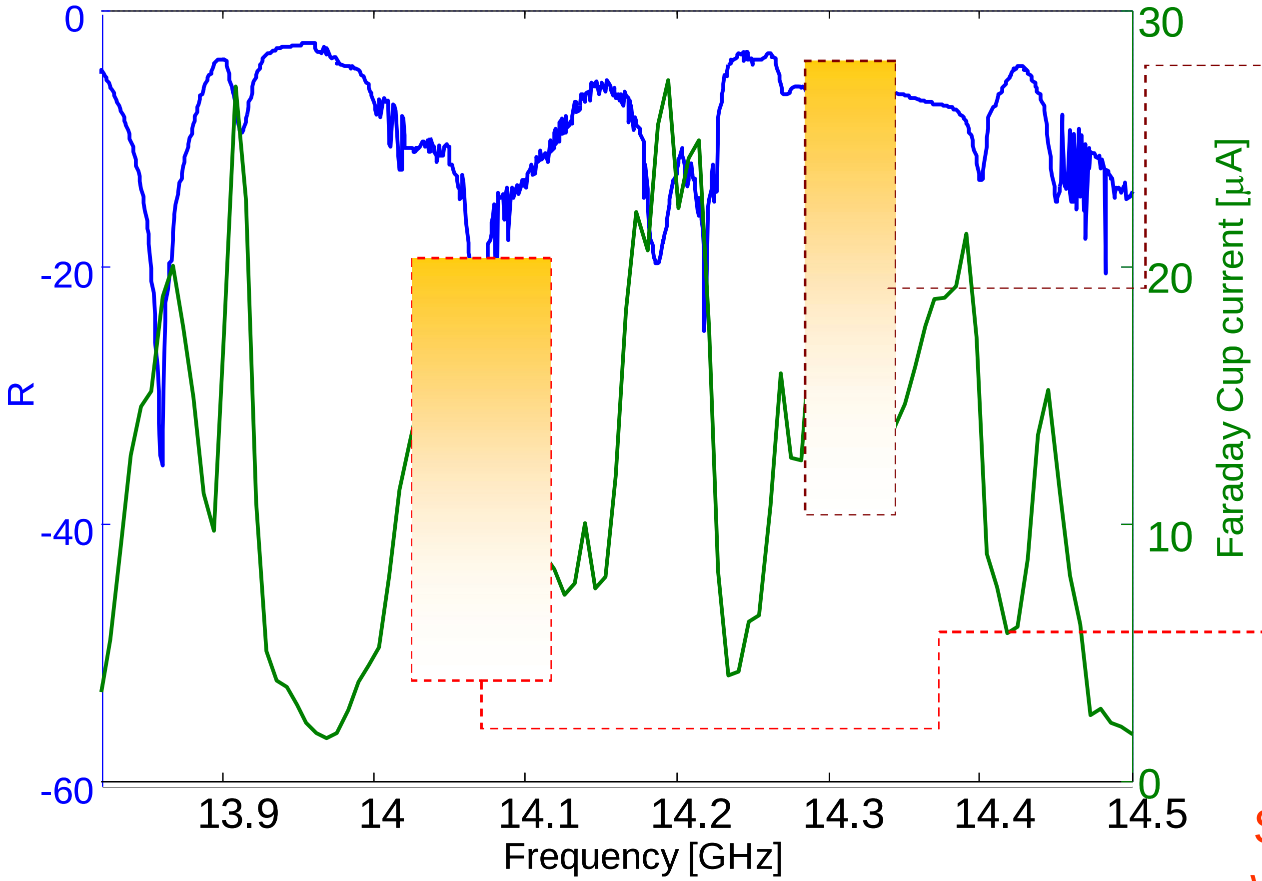
Why does Frequency tuning work so well?

Hypothesis 2:

The strong variation of performances may be due to changes in MW generator-to-waveguide-to-chamber coupling properties.

When resonant modes are excited peaks of current appear.

Relationship between modes and current's peaks: the experiment at CNAO



comparison between extracted current and reflection coefficient at different but close frequencies (test on the CNAO ECRIS)

Minima of reflection coefficient are cavity modes.

Often to resonant modes correspond current's peaks

But…

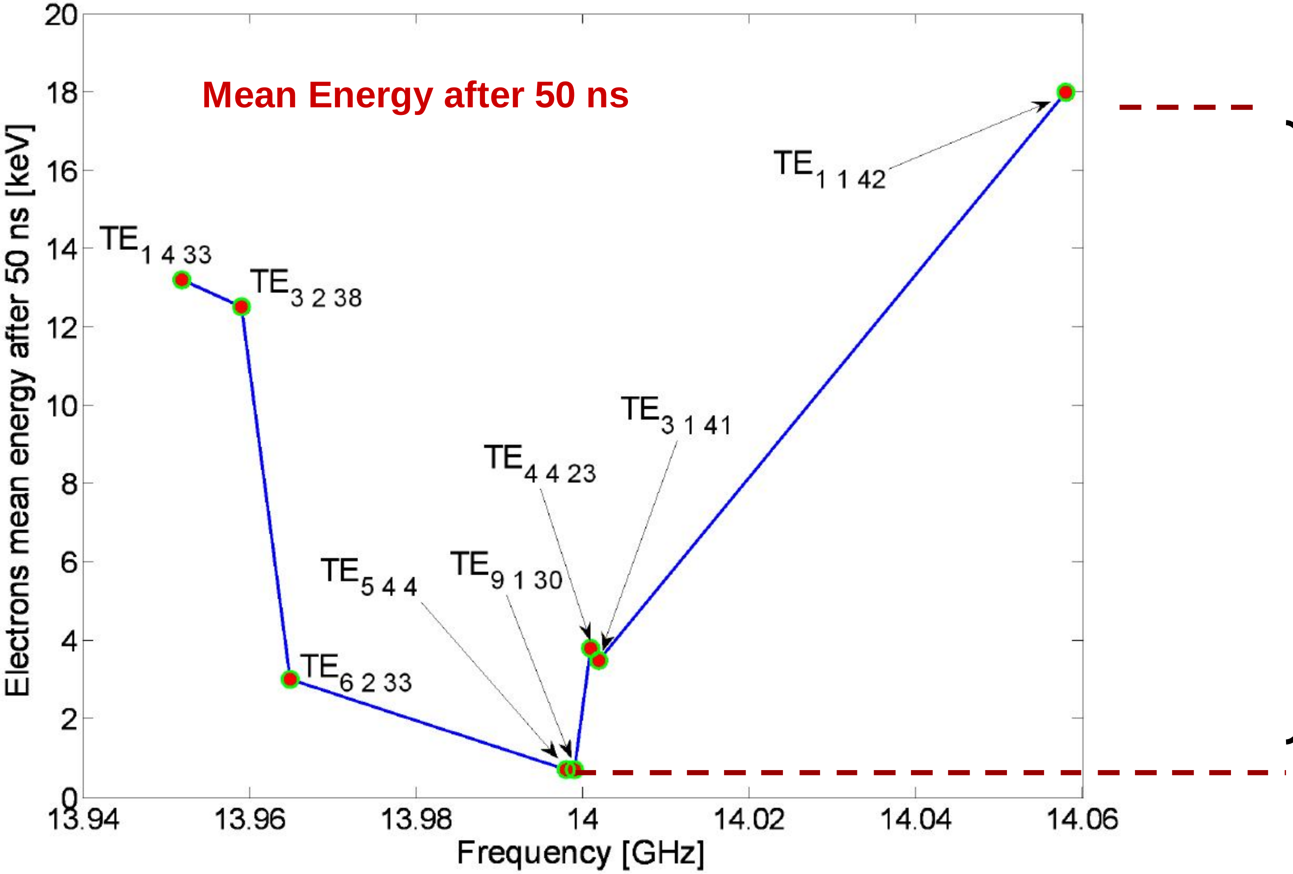
… it is not a rule!

Some modes are coupled with cavity but they do not match properly with plasma!!!

Overcoming Hypothesis 2: it does not explain fluctuation of performances for different excited modes

[S. Gammino et al, IEEE Trans. Plasma Sci., 2008]

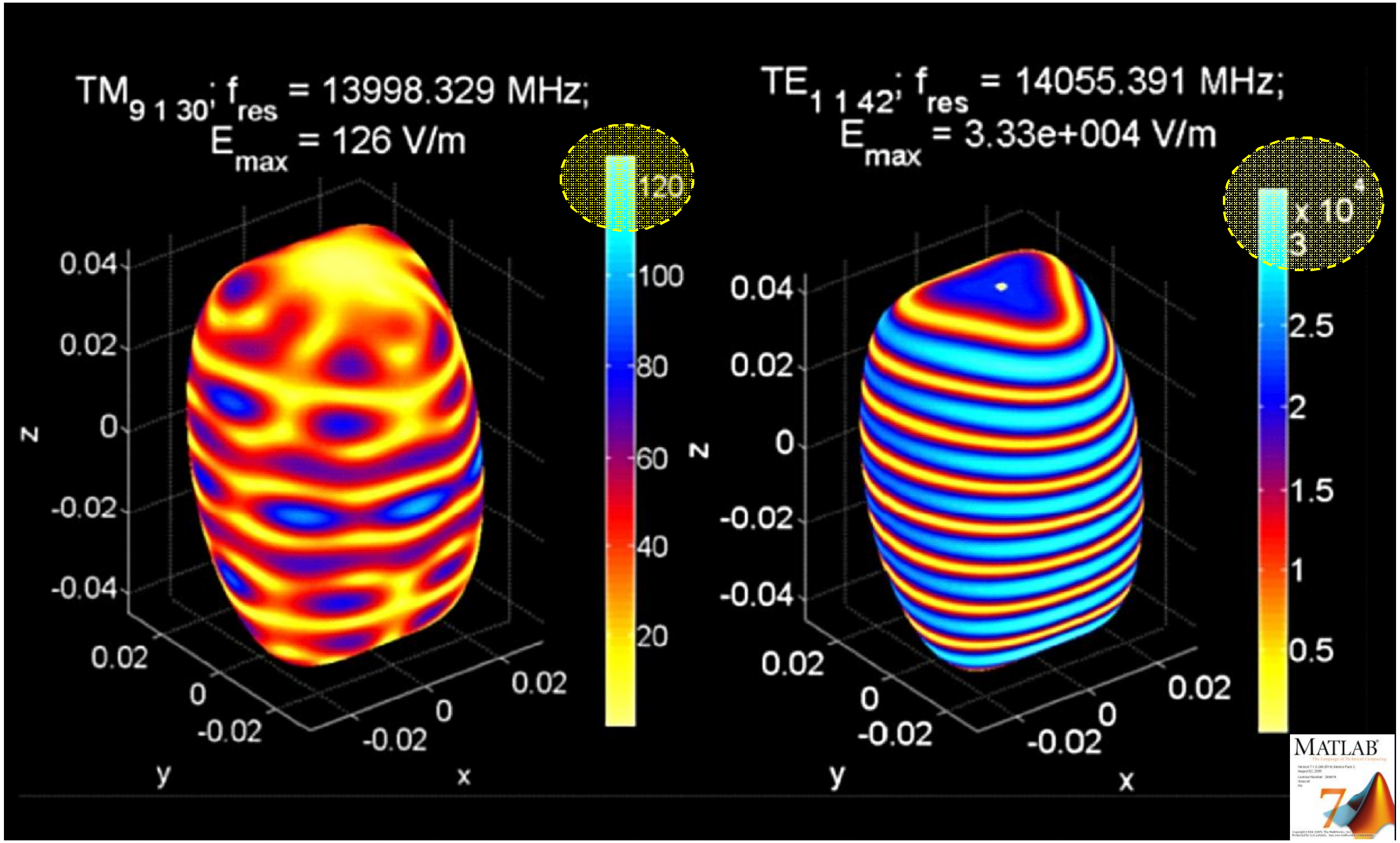
3D collisionless Monte Carlo simulations about ECR-heating of electrons crossing many times the resonance zone in a min-B configuration.



Strong fluctuations of heating rapidity for different excited modes inside the plasma chamber

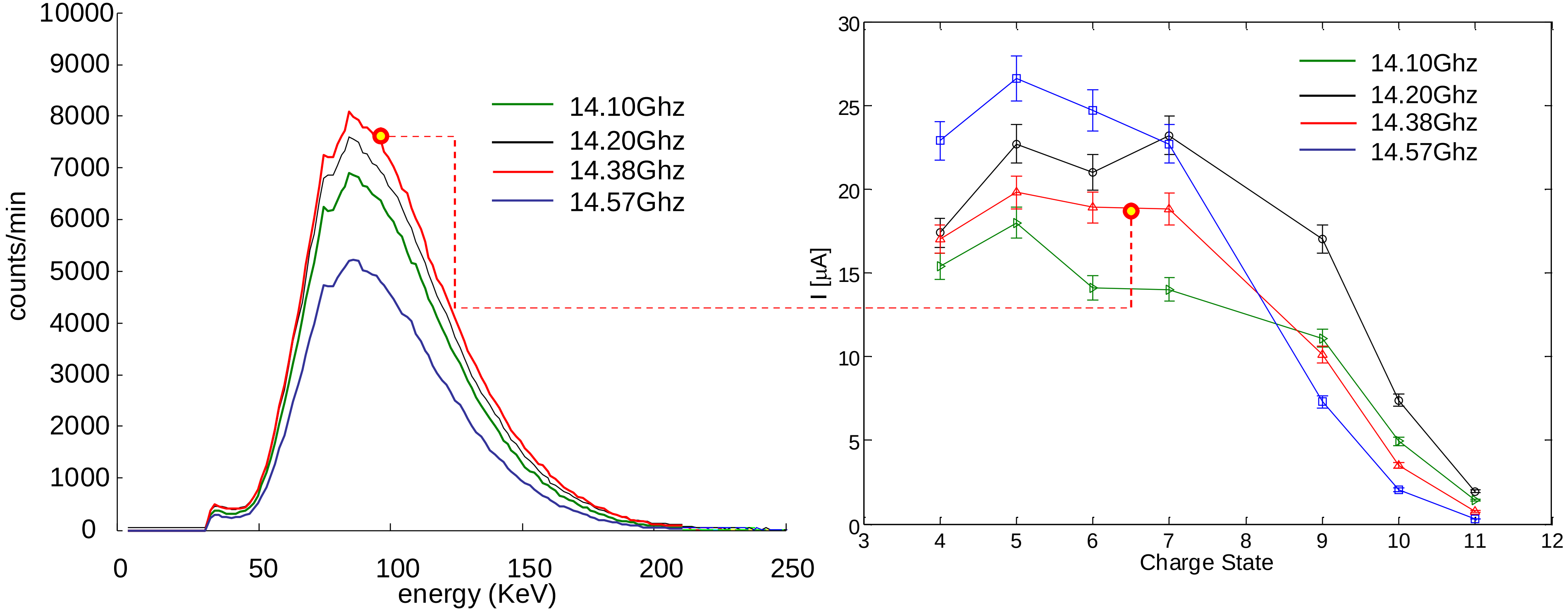
Exciting a mode is not enough: standing wave structure is dominant!

Hypothesis 2 is only partially true: Mode excitation is not enough



Even slight variation of the exciting frequency produce strong changes in the electric field distribution over the resonance surface. The heating depends mainly on the mode pattern!

Relationship between X-ray spectra and CSD: the experiment at LNS



Measurements with CAESAR at LNS reveal that X-ray spectra are not strictly related to frequency tuning.

→

Frequencies producing large numbers of counts do not necessarily produce optimal CSD

Relationship between X-ray spectra and CSD: the experiment at LNS

Assuming that the number of counts is somehow related to electron density, then the FTE must regulate also the ion lifetime

$$< q > \sim n_e \tau_i$$

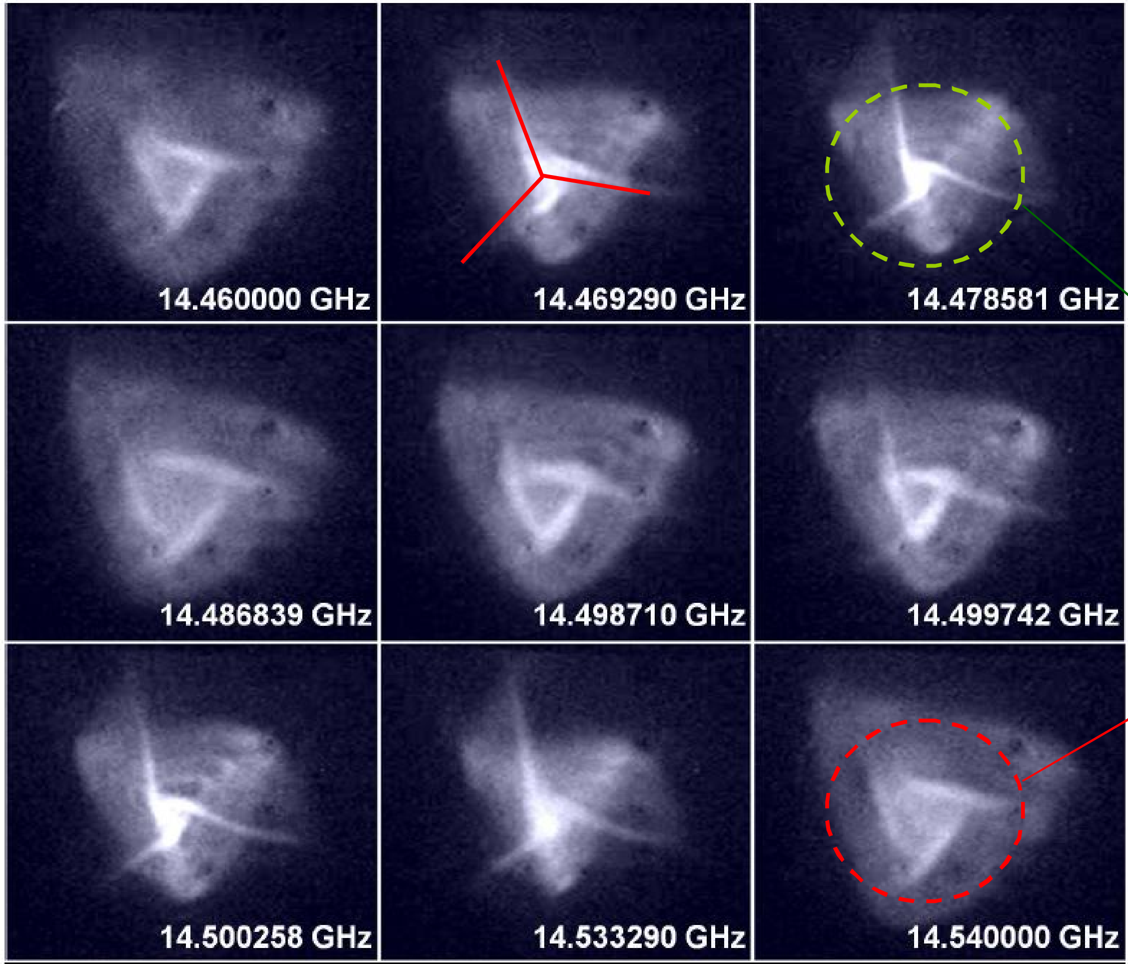
$$I \sim n_e / \tau_i$$

Hypothesis 3:

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

First experimental confirmation of hypothesis 3

[L. Celona, et al. Observations of the frequency tuning effect in the 14 GHz CAPRICE ion source. *Rev. Sci. Instrum.*, Feb. 2008. vol. 79, no. 2, p. 023 305.]



Frames of the extracted beam for different frequencies

“three cusp” shape of the extracted beam according to the magnetic structure

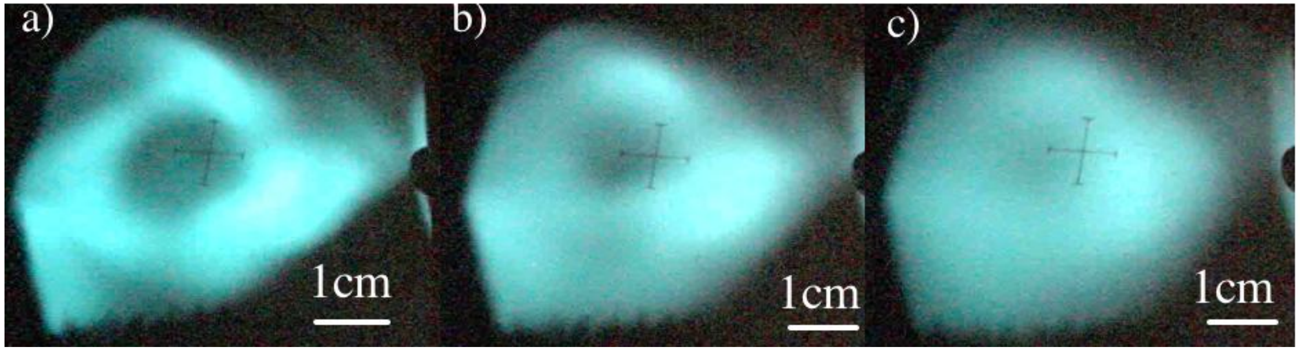
Well focused and high brightness beam

Broadened, low brightness beam

The Frequency Tuning strongly affects also the beam shape and brightness

Additional Experimental confirmations of hypothesis 3

Ar^{9+}



14.050 GHz **14.090 GHz** **14.108 GHz**

[V- Toivanen et al. Rev. Sci. Instrum. 81, 02A319 2010]

For some frequencies the hollow beam shape partially disappears.
Experiments suggest that variation in beam shape are due to inner plasma dynamics

Relative variation of emittance with frequency was more pronounced than output current.

Trasmission through the cyclotron is influenced more by mismatches in phase space than by the output current.

[V. **Toivanen et al., this workshop TUPOT10]**

Hypothesis 3.1

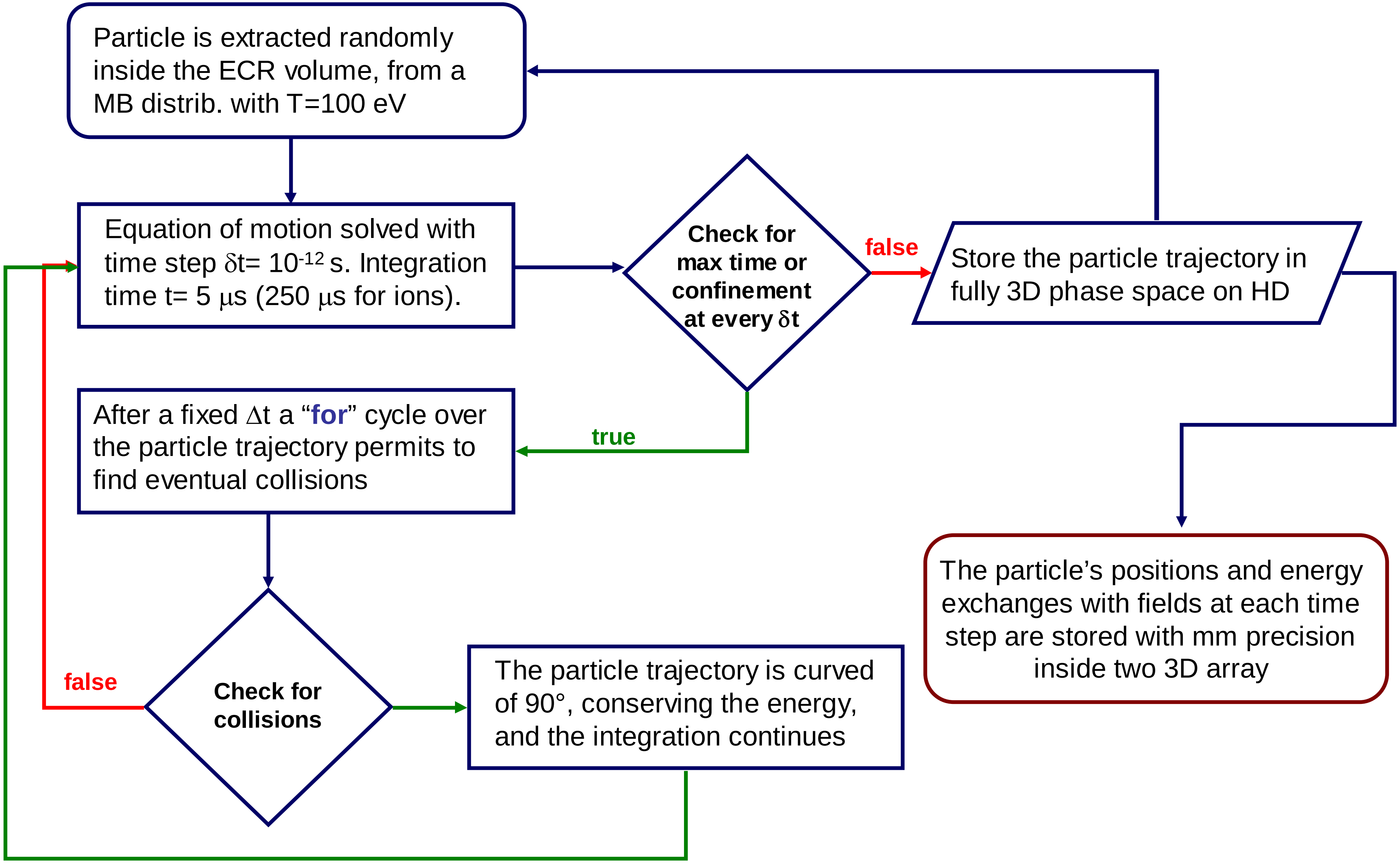
Influence of FTE on plasma separates in:

-Effects on the electrons heating rapidity;

-Effects on ion lifetime;

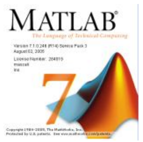
-Effects on beam properties (EMITTANCE).

Modeling of electron and ion dynamics with Monte-Carlo calculations



Modeling of electron and ion dynamics with Monte-Carlo calculations: ELECTRONS

A MATLAB code solves the equation of motion of a single particle:



$$\frac{d\vec{v}}{dt} = \begin{cases} \dfrac{q}{M}\left[\vec{v}\times\vec{B}+\vec{E}_s\right] & (i) \\ \dfrac{q}{m}\left(1-\dfrac{v^2}{c^2}\right)^{3/2}\left[\vec{v}\times\vec{B}_S+\vec{v}\times\vec{B}_{em}+\vec{E}_{em}-\dfrac{1}{c^2}\left(\vec{E}_{em}\cdot\vec{v}\right)\vec{v}\right] & (e) \end{cases}$$

$$\begin{aligned}
\dot{x} &= v_x \\
\dot{y} &= v_y \\
\dot{z} &= v_z \\
\dot{v}_x &= F(v)[(v_y B_z - v_z B_y) + (v_y B_{em_z} - v_z B_{em_y}) + E_{em_x} - \\
&- \frac{1}{c^2}\left(E_{em_x} v_x + E_{em_y} v_y\right) v_x] \\
\dot{v}_x &= F(v)[(v_z B_x - v_x B_z) + (v_z B_{em_x} - v_x B_{em_z}) + E_{em_y} - \\
&- \frac{1}{c^2}\left(E_{em_x} v_x + E_{em_y} v_y\right) v_y] \\
\dot{v}_z &= F(v)[-B_x v_y + v_x B_y - B_{em_x} v_y + v_x B_{em_y} - \\
&- \frac{1}{c^2}\left(E_{em_x} v_x + E_{em_y} v_y\right) v_z]
\end{aligned}$$

Magnetostatic field for the plasma confinement

Magnetic and electric fields associated with the pumping wave

MATLAB solves the six first order ODEs by means of the "*ode45*" Runge-Kutta routine.

- 3000 electrons/week, 8 CPU

- $\delta t = 10^{-12}$ s ~ 10 points of integration per Larmor radius

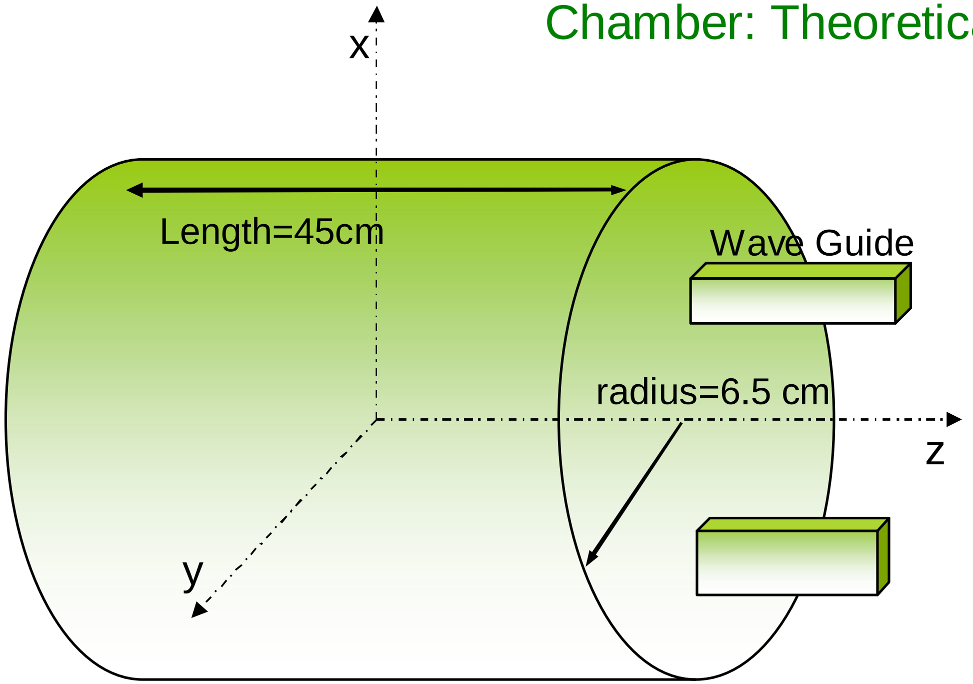
- **Collisions are taken into account**

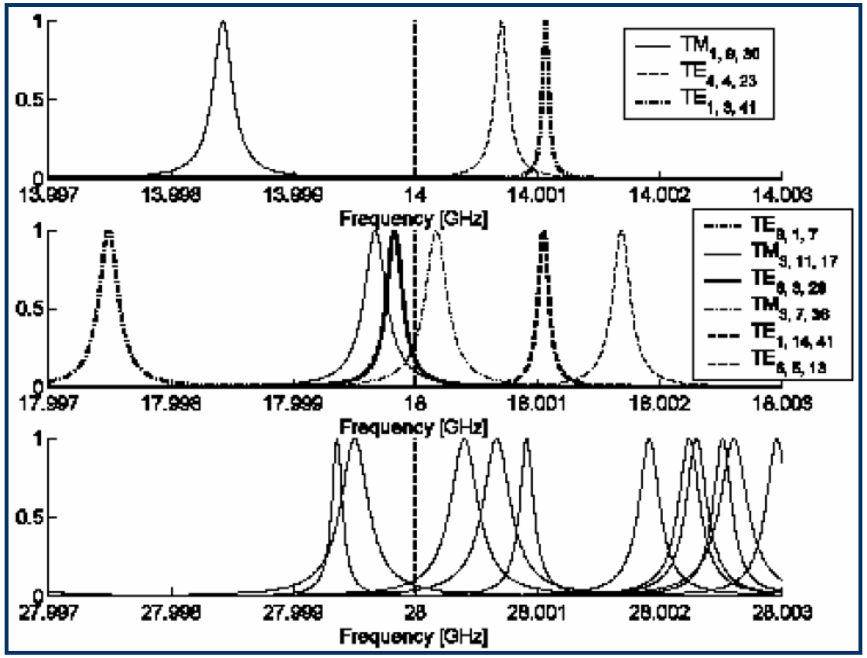
- Fully 3D calculations with B-min structure

Modeling of electron and ion dynamics with Monte-Carlo calculations: SERSE Plasma Chamber: Theoretical Properties

OUR CRUCIAL ASSUMPTION IS THAT THE INTRINSIC ELECTROMAGNETIC STRUCTURE OF THE PLASMA CHAMBER IS PRESERVED EVEN WHEN THE CHAMBER IS FILLED BY DENSE PLASMAS GENERATED THROUGH ECR.

Modeling of electron and ion dynamics with Monte-Carlo calculations: SERSE Plasma Chamber: Theoretical Properties





$$
\begin{aligned}
E_x &= A_n \frac{\mu\omega}{h} \sin\left(\frac{r\pi z}{l}\right) J_n' \sin[(n-1)\phi] + J_{n+1} \sin n\phi \cos n\phi \cos(\omega t + \varphi) \\
E_y &= A_n \frac{\mu\omega}{h} \cos\left(\frac{r\pi z}{l}\right) J_n' \sin[(n-1)\phi] + J_{n+1} \sin n\phi \sin n\phi \cos(\omega t + \varphi) \\
H_x &= -A_n \frac{\pi r}{hl} \cos\left(\frac{r\pi z}{l}\right) J_n' \cos[(n-1)\phi] + J_{n+1} \sin n\phi \sin n\phi \sin(\omega t + \varphi) \\
H_y &= A_n \frac{\pi r}{hl} \cos\left(\frac{r\pi z}{l}\right) J_n' \sin[(n-1)\phi] + J_{n+1} \sin n\phi \cos n\phi \sin(\omega t + \varphi) \\
H_z &= -A_n \sin\left(\frac{r\pi z}{l}\right) J_n' \cos n\phi \sin(\omega t + \varphi)
\end{aligned}
$$

Resonant Frequencies

$$
\omega = c\sqrt{\frac{r^2\pi^2}{l^2} + h^2}
$$

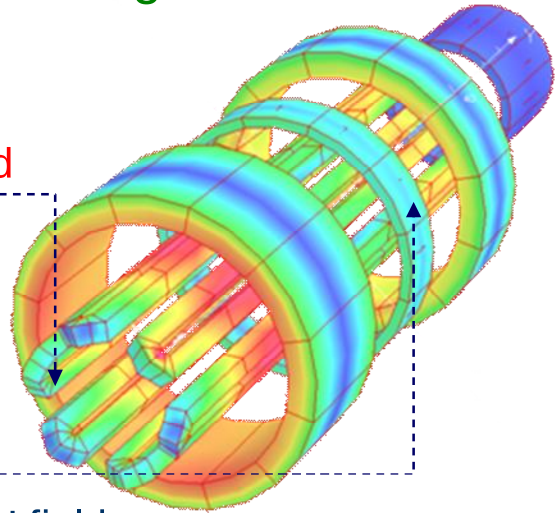
Modeling of electron and ion dynamics with Monte-Carlo calculations: The SERSE magnetic field

$$B_x = -B_1 xz + 2Sxy$$

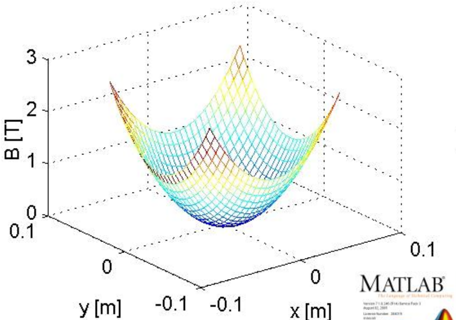
$$B_y = -B_1 yz + 2S(x^2 - y^2)$$

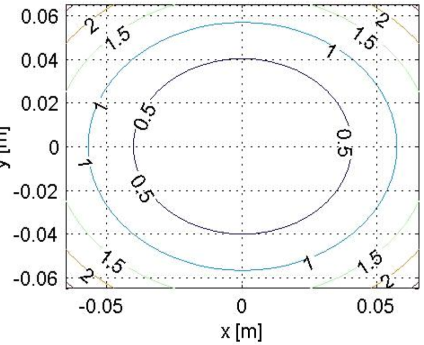
$$B_z = \begin{cases} -B_0 + B_{inj} z^2 & \forall z < 0 \\ -B_0 + B_{ext} z^2 & \forall z > 0 \end{cases}$$

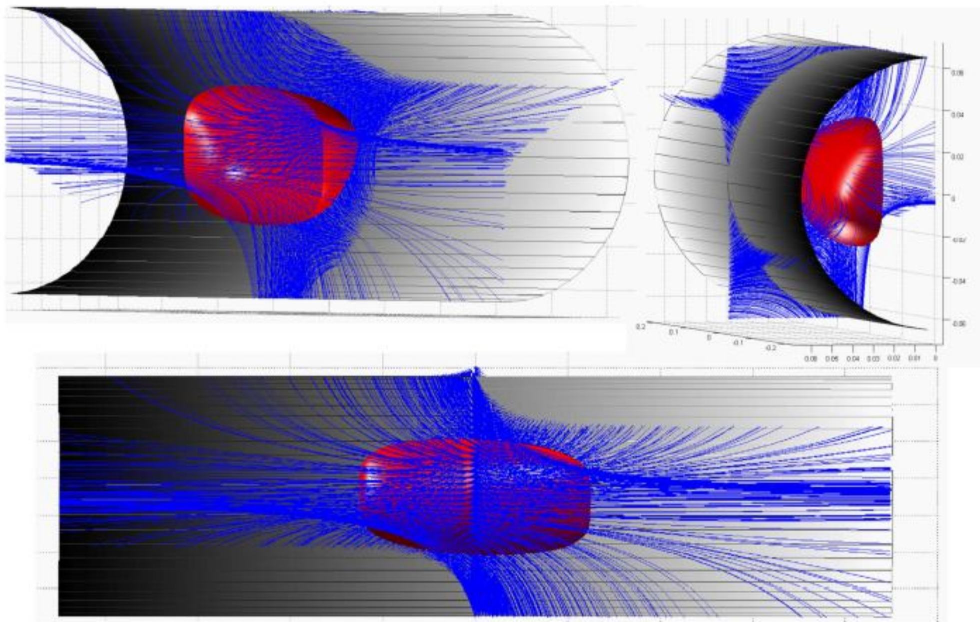
Hexapolar field

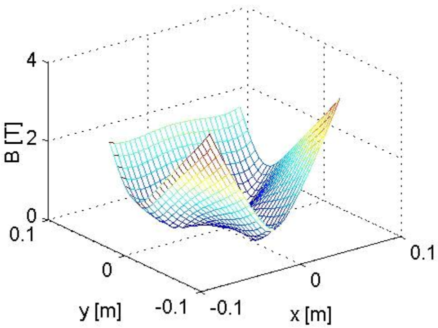


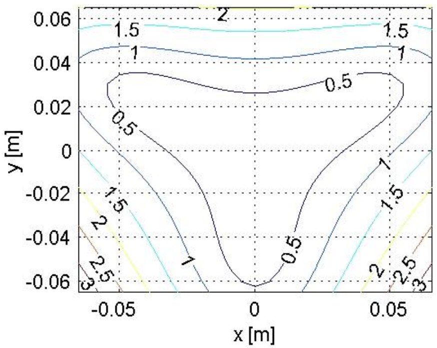
Solenoids' field











COLLISIONS

1. The most probable collision type are the electrostatic i-i and e-e multiple collisions with velocity rotation of 90°
2. Collision position is determined by comparing a randomly extracted number in the range 0-1 with the collision probability

$$(0 < rnd < 1) < P(t) = 1 - \exp\left(-\frac{t}{\tau_{coll}}\right)$$

The collision time is given by:

$$\tau_{coll} = \frac{M_{i,e}^2 2\pi\varepsilon_0^2 v_{i,e}^3}{n_e z^4 e^4 \ln\Lambda}$$

Where the plasma density is an input parameter

$$n_{ECRIS}(x,y,z) = 0.3 n_{cutoff} + \Sigma_i h n_{cutoff} \exp\left\{-\frac{[B_{tot}(x,y,z) - (B_{ECR} - ki)]^2}{k^2}\right\}$$

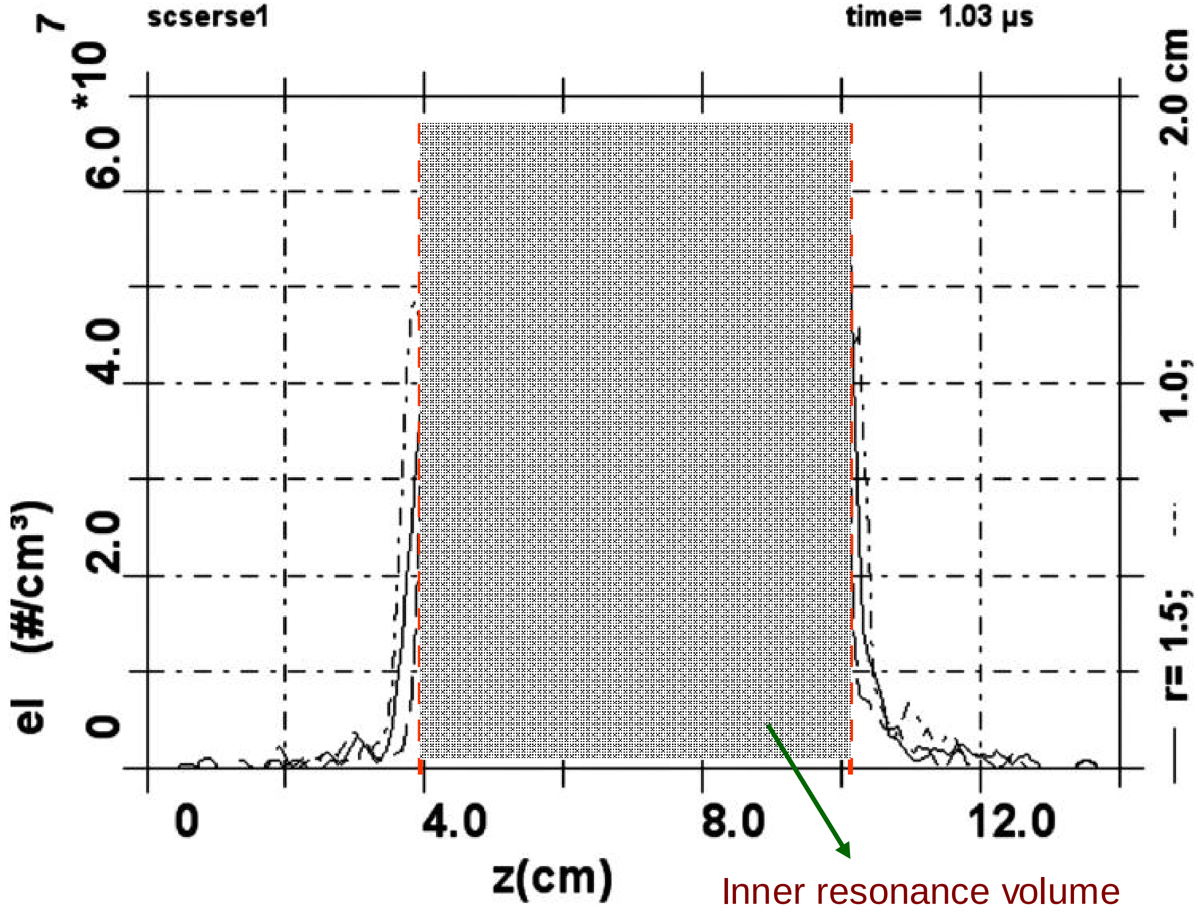
This formula is a parameterization of plasma distribution coming out from PIC simulations

A different theoretical approach:
PIC simulations

[in collaboration with S. Chikin and V. Serebrennikov of Kurtchatov Institute of Moscow, Russia.]

1. 2D simulations of electrons and ions in Simple Mirror;
2. No ionizing or Spitzer collisions ($p \sim 10^{-7}$ mbar);
3. E.M. field self-consistently determined by Maxwell equation resolutions in cells;
4. The boundary conditions take into account that the plasma is generated in a resonant cavity;
5. RF power producing electric field amplitudes of 1 – 5 kV/cm;
6. Mirror ratios: 1.4 – 4.

PIC Simulations: evidences of a “rigid” structure of electron density distribution



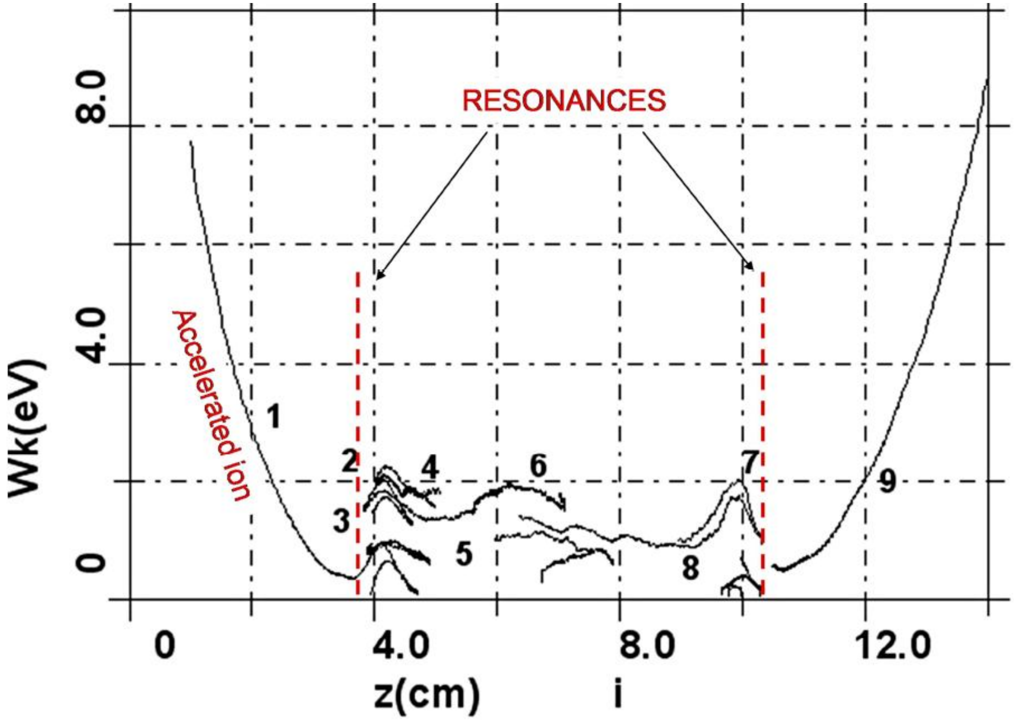
The electrons are mainly confined inside the resonance volume

electrons provided by ionization are “captured” in the inner resonance zone.

“resonantly sloshing electrons” trapped in the inner ECR volume. “non resonant sloshing electrons” cross the ECR

This density structure is an “attractor” for other initial plasma distributions

PIC Simulations: the inner resonance plasma accelerates ions outward because of positive potential



Ions are strongly accelerated by the plasma potential acting over the ECR layer

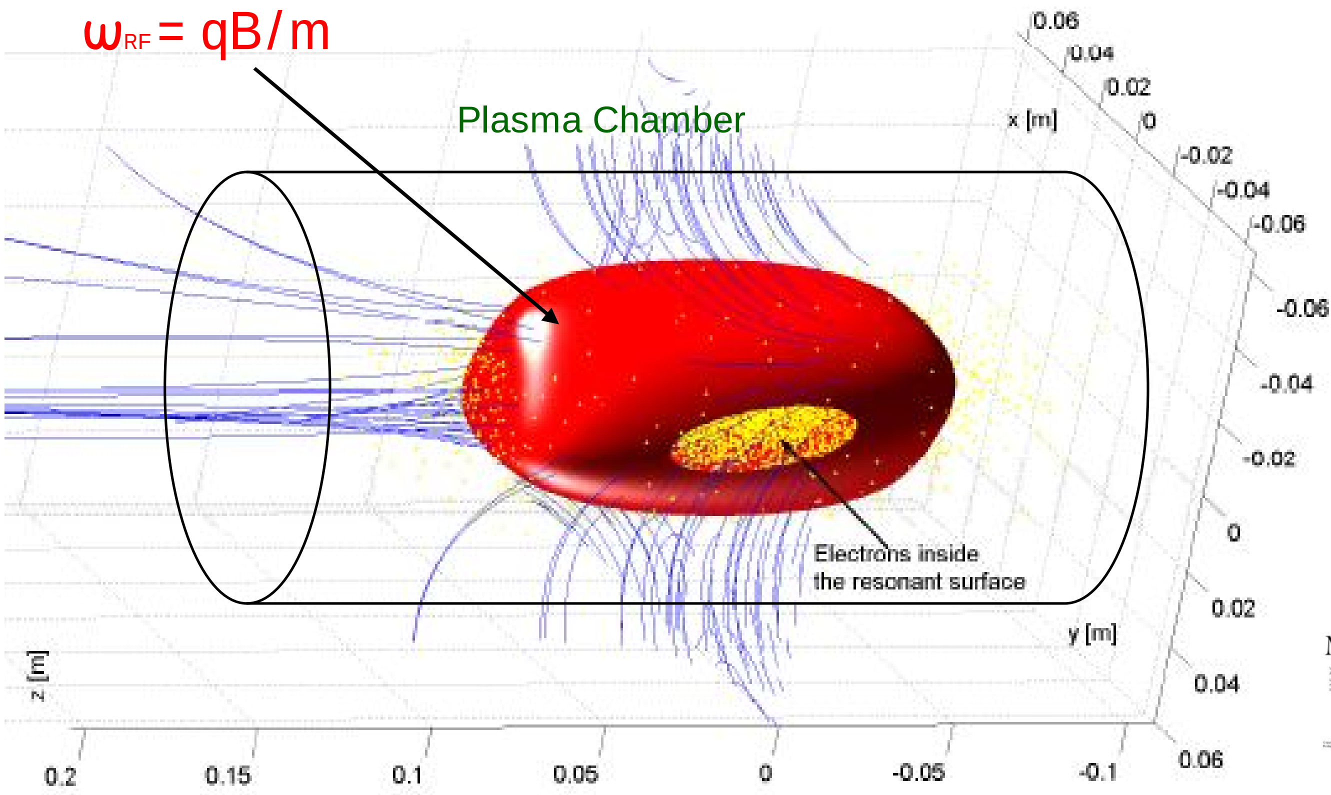
Electric field over the resonance surface must be included in ion equation of motion

The Plasma can be divided into two regions: inner resonance high density plasma & outer resonance low density plasma

$$\frac{d\vec{v}}{dt} = \begin{cases} \frac{q}{M}\left[\vec{v}\times\vec{B} + \vec{E}_s\right] & (i) \\ \frac{q}{m}\left(1-\frac{v^2}{c^2}\right)^{3/2}\left[\vec{v}\times\vec{B}_S + \vec{v}\times\vec{B}_{em} + \vec{E}_{em} - \frac{1}{c^2}\left(\vec{E}_{em}\cdot\vec{v}\right)\vec{v}\right] & (e) \end{cases}$$

Modeling of electron and ion dynamics with Monte-Carlo calculations

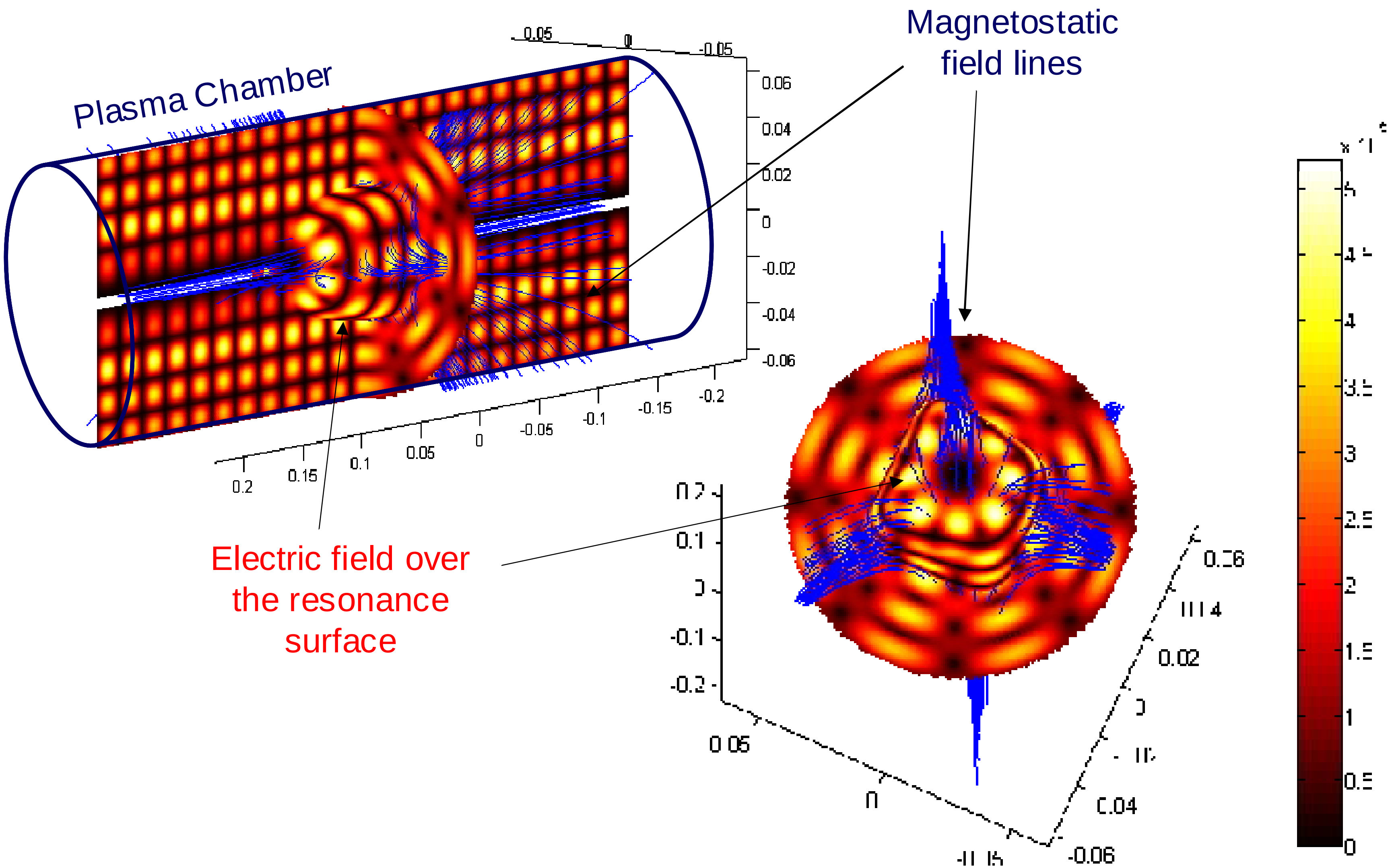
Simulation of electron and ion distribution at t=0



RED	Resonant Surface
BLUE	Magnetic Field lines
YELLOW	Plasma Electrons

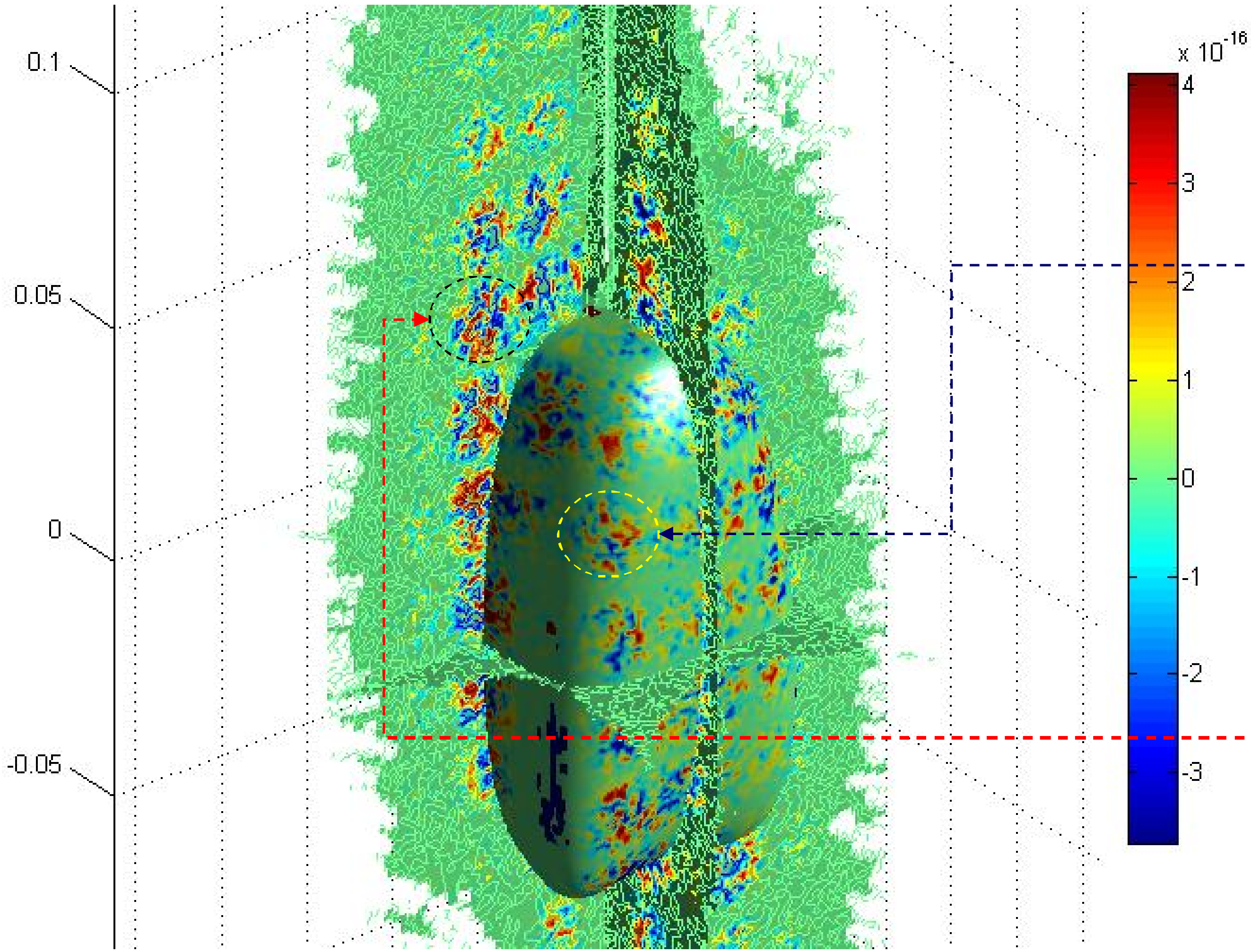
Modeling of electron and ion dynamics with Monte-Carlo calculations

Inner cavity electric field distribution for the $TE_{4\,4\,23}$ mode close to 14 GHz



Modeling of electron and ion dynamics with Monte-Carlo calculations

Localization of electrons energy absorption during 5 μs



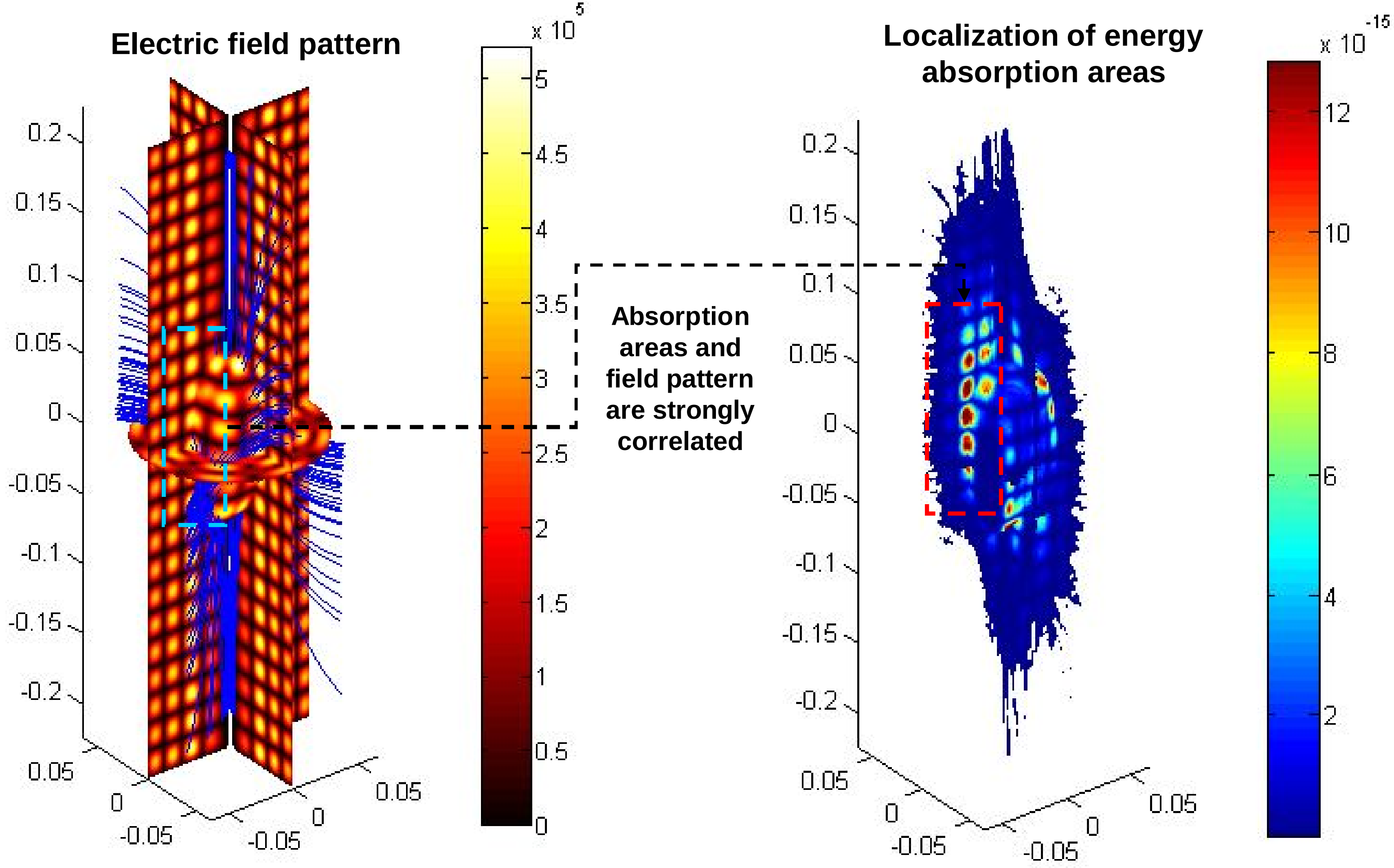
Interaction of the wave with the plasma takes place in some localized areas over the resonance surface. Particles gain or loss energy locally, being positive for electrons the net balance.

Energy exchange takes place also in off-resonance regions.

Off resonance interaction between wave and electrons must be more deeply investigated: relativistic effects (Doppler, mass)? It may be linked to ultra-hot electrons…

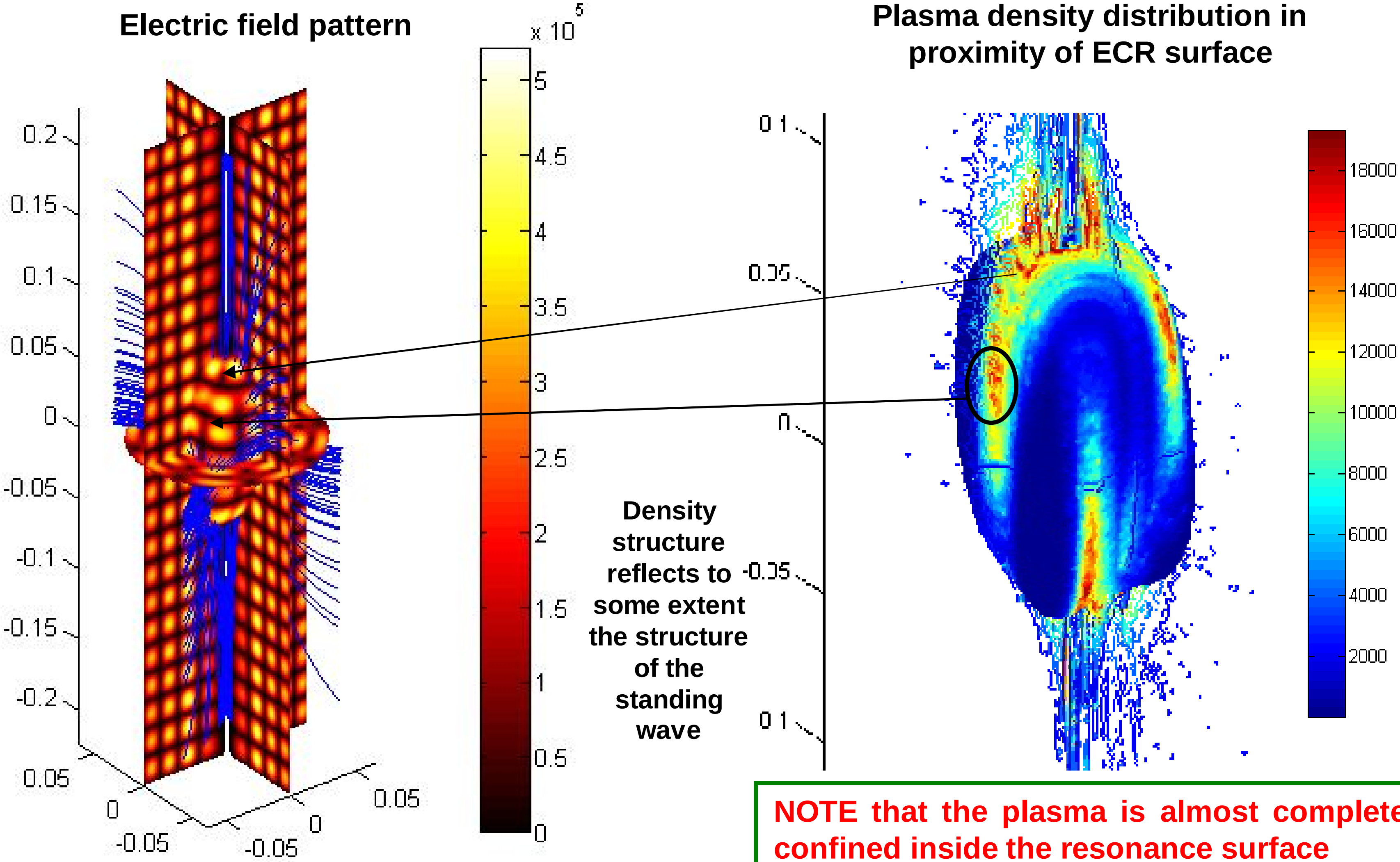
Modeling of electron and ion dynamics with Monte-Carlo calculations

The pattern of the electromagnetic field influences strongly the localization of absorption areas



Modeling of electron and ion dynamics with Monte-Carlo calculations

The pattern of the electromagnetic field influences also the plasma density distribution

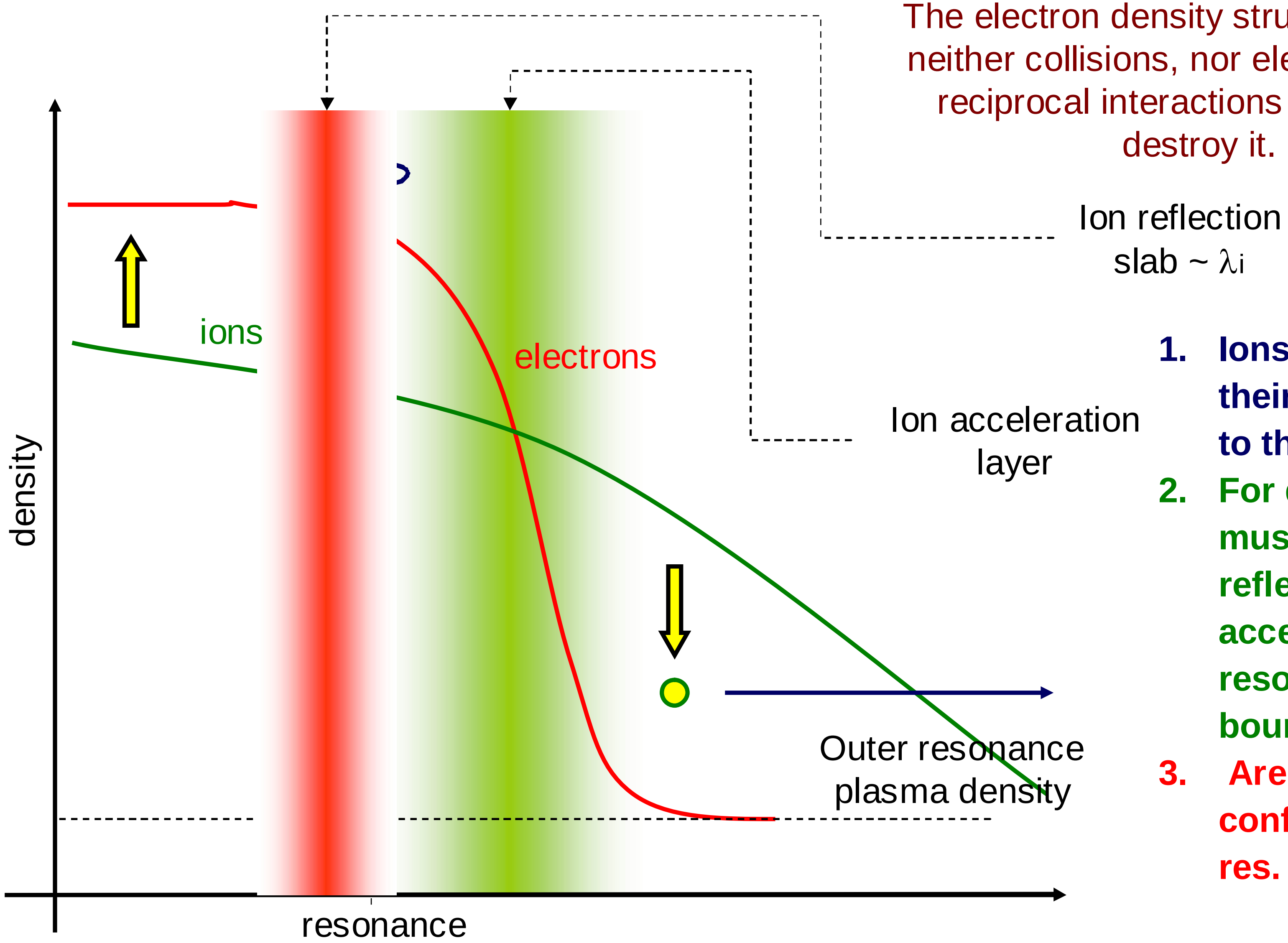


NOTE that the plasma is almost completely confined inside the resonance surface

Modeling of electron and ion dynamics with Monte-Carlo calculations

The dynamical model of ion confinement

The electron density structure is rigid: neither collisions, nor electrostatic e-i reciprocal interactions are able to destroy it.

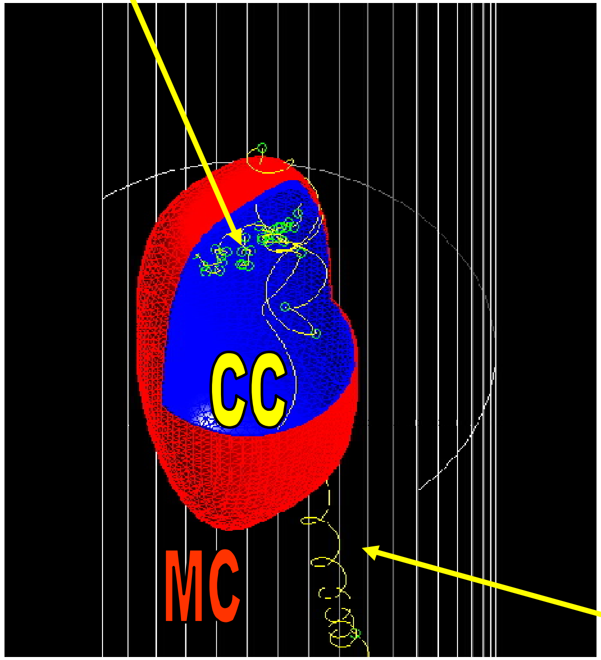


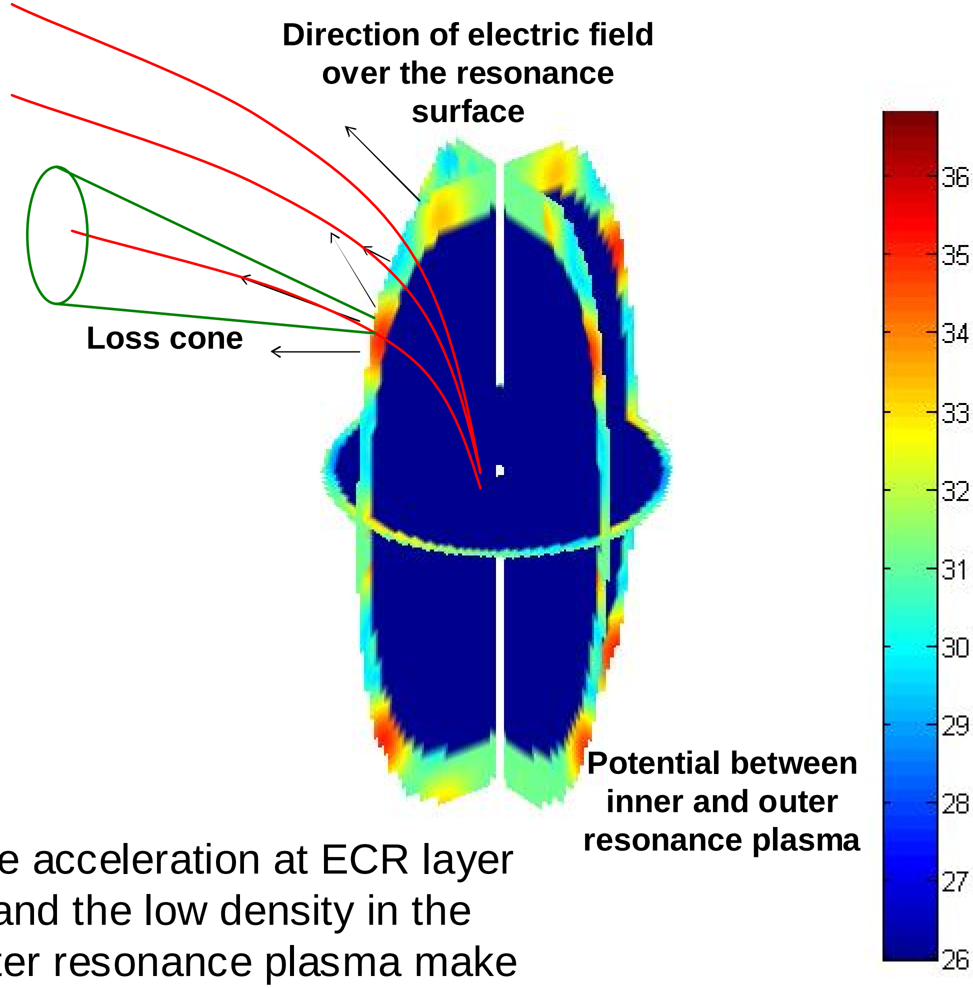
1. **Ions must adapt their density shape to the electrons one**
2. **For doing this they must be partially reflected, partially accelerated at resonance boundary.**
3. **Are magnetically confined in the outer res. region**

Modeling of electron and ion dynamics with Monte-Carlo calculations

The injection of ions inside the loss cone depends strongly on the mutual orientation of electric field and magnetic lines over the resonance surface

Inner resonance motion is governed by collisions.





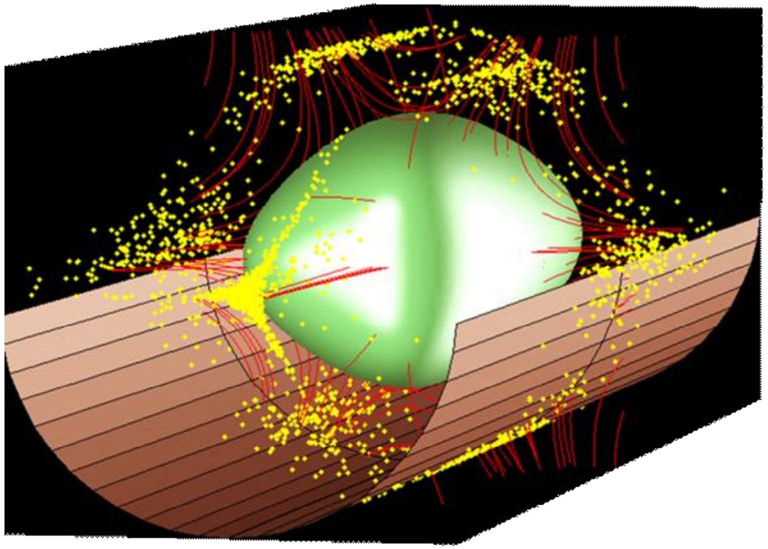
The acceleration at ECR layer and the low density in the outer resonance plasma make the ions magnetically confined

Preliminary results on Ion Dynamics and Beam Formation presented at ICIS 2009

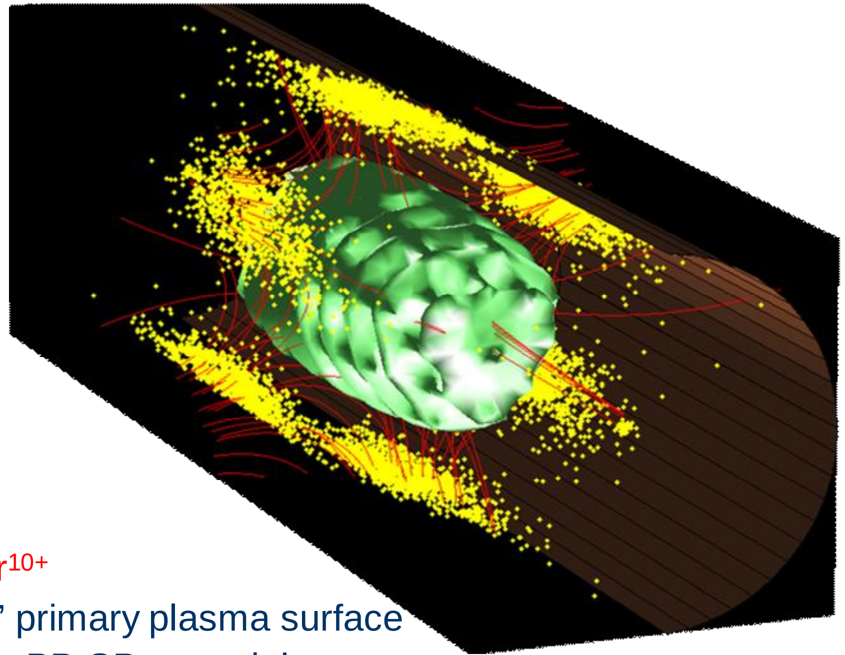
Corrugation of the primary plasma surface:

At first approximation it was assumed to be the same of the electromagnetic field pattern

[D. Mascali et al. *Plasma ion dynamics and beam formation in Electron Cyclotron Resonance Ion Sources*, Rev. Sci. Instrum.]



Simulated Ar^{10+}
Smooth primary plasma surface
30 V of PP-SP electrostatic potential



Simulated Ar^{10+}
"Corrugated" primary plasma surface
30 V of mean PP-SP potential

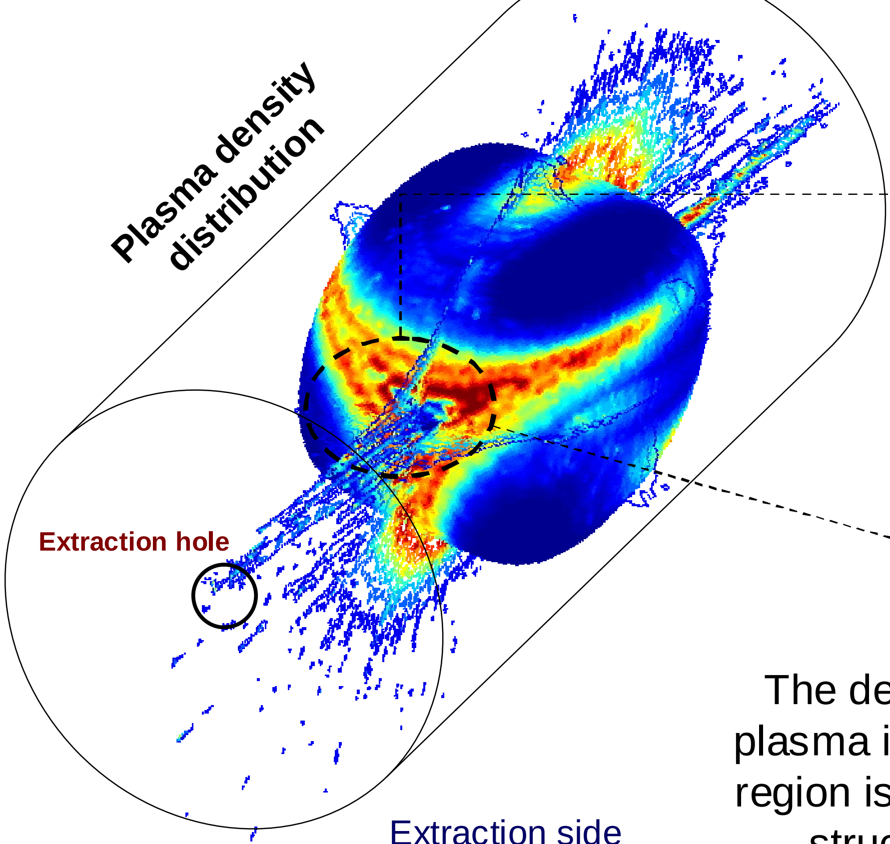
Ion lifetime depends strongly on corrugation, mean value of accelerating potential and inner resonance plasma density. Recent simulations estimate τ_i~0.5-3 ms, according to density fluctuations.

Also the beam formation and handling may take advantage from Frequency Tuning

Modeling of electron and ion dynamics with Monte-Carlo calculations

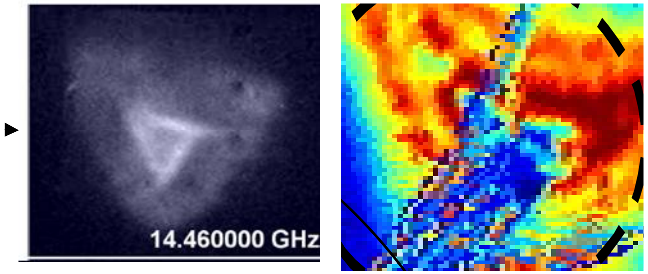
Hollow beams are probably a consequence of plasma depletion in the near axis region

Injection side

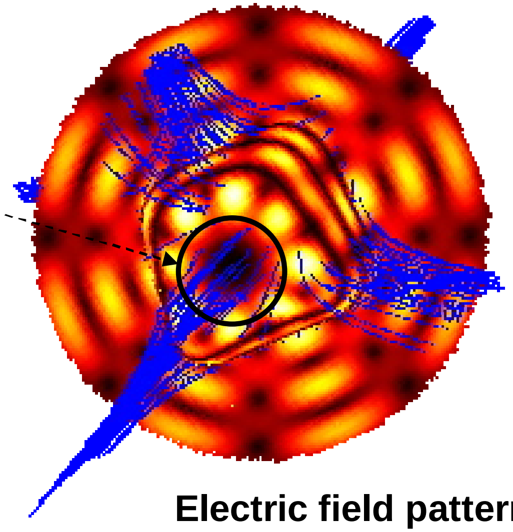


Extraction side

The density distribution explains why for some frequencies the beams appear hollow



The depletion of plasma in near axis region is due to the structure of electromagnetic field.



Electric field pattern

CONCLUSIONS

Hypothesis 3.1 is confirmed by calculations:

1. different modes affect differently the **heating rate**;
2. Density non-uniformity can make shorter the **ion lifetime** τ_i. Although the density n_e remains about unchanged: Q decreases.
3. tuning of frequency may restore conditions of good axial confinement, removing the hollow shape of extracted beam, and positively affecting the **emittance**.

Perspectives and next steps

Computer simulations must be optimized in order to give more reliable results:

we are trying to migrate the code on GRID:

180 CPU available, 10000 e/day

1. The initial assumed distribution of ion positions must be chosen self-consistently with electron distribution after 5μs
2. Ionization must be taken into account, in order to visualize where ions are preferably generated
3. Matching of plasma simulation with extraction simulations is one of the most important goals
4. The code can be used also to check for electron and ion dynamics on long timescales when the magnetic field profile is changed.

Therefore for additional results and news….

See you in Giardini-Naxos –TAORMINA!!!

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