Some Considerations on Frequency Tuning Effect

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Overcoming the current limits of ECRIS

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

- High Frequency Generators;
- High Magnetic Fields;

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

\[ \langle q \rangle \sim n_e T_i \]

\[ I \sim n_e / T_i \]

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
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

4. Frequency tuning

5. Two Close Frequency Heating to be tested
Comparison between trends of $O^{8+}$ at $18 \text{ GHz}$ 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

The larger number of heated electrons per time unit makes longer $T_i$
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.
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.

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

**Hyp. 1 is not correct!**

**Why do TWT and Kly give so different results?**

**THEREFORE...**
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.
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


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!
Measurements with CAESAR at LNS reveal that X-ray spectra are not strictly related to frequency tuning.
Assuming that the number of counts is somehow related to electron density, then the FTE must regulate also the ion lifetime

\[ \langle q \rangle \sim n_e T_i \]

\[ I \sim n_e / T_i \]

**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


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

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

[For citation.]

[For citation.]

[V. Toivanen et al., this workshop TUPOTIO]
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).
Particle is extracted randomly inside the ECR volume, from a MB distrib. with $T=100$ eV

Equation of motion solved with time step $\delta t = 10^{-12}$ s. Integration time $t = 5 \mu$s (250 $\mu$s for ions).

After a fixed $\Delta t$ a “for” cycle over the particle trajectory permits to find eventual collisions.

Check for collisions

Check for max time or confinement at every $\delta t$

false

Store the particle trajectory in fully 3D phase space on HD

false

The particle’s positions and energy exchanges with fields at each time step are stored with mm precision inside two 3D array

true

The particle trajectory is curved of 90°, conserving the energy, and the integration continues
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 $\sim$ 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

\[ E_x = A_n \frac{\mu \omega}{h} \sin \left( \frac{\pi r z}{l} \right) J_n' \sin((n-1)\phi) + J_{n+1} \sin(n\phi \cos(n\phi) \cos(\omega t + \varphi)) \]

\[ E_y = A_n \frac{\mu \omega}{h} \cos \left( \frac{\pi r z}{l} \right) J_n' \sin((n-1)\phi) + J_{n+1} \sin(n\phi \sin(n\phi) \cos(\omega t + \varphi)) \]

\[ H_x = -A_n \frac{\pi r}{hl} \cos \left( \frac{\pi r z}{l} \right) J_n' \cos((n-1)\phi) + J_{n+1} \sin(n\phi \sin(n\phi) \sin(\omega t + \varphi)) \]

\[ H_y = A_n \frac{\pi r}{hl} \cos \left( \frac{\pi r z}{l} \right) J_n' \sin((n-1)\phi) + J_{n+1} \sin(n\phi \cos(n\phi) \sin(\omega t + \varphi)) \]

\[ H_z = -A_n \sin \left( \frac{\pi r z}{l} \right) J_n' \cos(n\phi \sin(\omega t + \varphi)) \]

Resonant Frequencies

\[ \omega = c \sqrt{\frac{r^2 \pi^2}{l^2} + \hbar^2} \]
Modeling of electron and ion dynamics with Monte-Carlo calculations: The SERSE magnetic field

\[
B_x = -B_1 x z + 2 S x y \\
B_y = -B_1 y z + 2 S (x^2 - y^2) \\
B_z = \begin{cases} 
-B_0 + B_{inj} z^2 & \forall z < 0 \\
-B_0 + B_{ext} z^2 & \forall z > 0 
\end{cases}
\]
Modeling of electron and ion dynamics with Monte-Carlo calculations

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

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

The collision time is given by:

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

Where the plasma density is an input parameter

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

This formula is a parameterization of plasma distribution coming out from simulations
Modeling of electron and ion dynamics with Monte-Carlo calculations

Simulation of electron and ion distribution at t=0

\[ \omega_{RF} = \frac{qB}{m} \]

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 $\text{TE}_{4423}$ mode close to 14 GHz

Electric field over the resonance surface

Plasma Chamber

Magnetostatic field lines

In the diagram, the electric field distribution and magnetostatic field lines are illustrated within the Plasma Chamber, demonstrating the behavior of the electric field over the resonance surface for the specified mode.
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 lose 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

Electric field pattern

Localization of energy absorption areas

Absorption areas and field pattern are strongly correlated
The pattern of the electromagnetic field influences also the plasma density distribution.

Modeling of electron and ion dynamics with Monte-Carlo calculations.

Electric field pattern

Plasma density distribution in proximity of ECR surface

Density structure reflects to some extent the structure of the standing wave.

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

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 resonance region

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

Modeling of electron and ion dynamics with Monte-Carlo calculations.
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 $\text{Ar}^{10+}$
Smooth primary plasma surface
30 V of PP-SP electrostatic potential

Simulated $\text{Ar}^{10+}$
“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 $\tau_i \sim 0.5\text{-}3 \text{ ms}$, according to density fluctuations.

Also the beam formation and handling may take advantage from Frequency Tuning
Hollow beams are probably a consequence of plasma depletion in the near axis region.

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.
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** $\tau_i$. 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!!!