3D-full wave and kinetics numerical modelling of Electron Cyclotron Resonance Ion Sources plasma

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Abstract - We present a numerical approach to solve the 3D Maxwell-Lorentz system with the aim of investigating the interaction of the electromagnetic waves with the magnetized non-homogeneous plasma produced inside Electron Cyclotron Resonance Ion Sources. The FEM COMSOL Multiphysics® software was used to compute the electromagnetic field in a cavity filled by the anisotropic-inhomogeneous plasma, described by a full non-uniform dielectric tensor in "cold plasma" approximation. The full-wave solution is then coupled to an “in-Matlab” developed kinetic code based on a PIC – Particle-In-Cell strategy, solving the Newton-Lorentz equation of motion for plasma electrons. Our model explains the experimentally observed frequency sensitivity and gives a relevant contribution to the challenging goal of predicting the electron/ion dynamics in ECR plasmas.

INTRODUCTION

Wave propagation modelling in magnetized plasma – including the coupling with the Newton-Lorentz equations of motion – represents a powerful tool for a better understanding of the physical phenomena occurring in the ECRIS plasma-filled resonant cavity, and a necessary step towards future developments and further optimization of advanced ECRIS.

COUPLED ELECTROMAGNETIC AND PARTICLE MOTION MODEL

Considering the plasma as a dispersive medium modelled as a cold magneto-fluid with collisions, in the Maxwell's equations appears a tensorial relation $\vec{\varepsilon}(r) \cdot \vec{E}(r)$ that describes the field-plasma interaction.

According to the the "cold plasma" approximation, considering the actual magneto-static structure of an ECRIS (minimum-B configuration, see [1] for $B_{x,y,z}$ components) that is not uniform nor axis-symmetric, $\vec{\varepsilon}(r)$ depends in a complex way from the magnetostatic field and the local electron density $n_e(x,y,z)$ (details in [1]). Full wave simulations are carried out, through the COMSOL Multiphysics FEM solver, considering the geometry shown in Fig. 1 (a) with an initial electron density $n_e(x,y,z)$ and the above described "cold plasma" model. Since nearby the resonance surface, individuated from the iso-surface $|B_0| = B_{ecr} = \frac{m_e}{e} \omega$, the permittivity $\vec{\varepsilon}(r)$ varies widely, in such narrow region the mesh needs to be finer and to achieve this, the ECR iso-surface has been used also to start the mesh construction and growth (Fig 1).

Figure 1: on the left, the simulated geometry: Cavity and waveguide; on the right, the non-uniform mesh density: it is finer nearby the ECR layer.
FULL-WAVE AND PARTICLES MOTION
3D SIMULATION SETUP

The electromagnetic field \( \{E(r), H(r)\} \) solution is coupled to a 3D kinetic Matlab® code that is based on a numerical particles-in-cell method that simulates a plasma as a collection of N macro-particles, (being N much smaller than real plasma particles), with corresponding spatial coordinates and momenta described by the functions \( r_i(t) \) and \( p_i(t) \) for \( i^{th} \) particle. We considered a plasma consisting of a single species only (electrons), whose trajectories obey the Lorentz single particle equation of motion, considering electro-static (Spitzer) collisions at 90°:

\[
\frac{dp_i(t)}{dt} = q[E(r_i(t)) + v_i(t) \times B(r_i(t), t)] \tag{1}
\]

The kinetic code, following the relativistic Boris scheme, solves the equation of motion (1) of each single macroparticle for its entire life (i.e. until they impinge on the chamber walls), accumulating the electron density in a 3D grid; the output of the kinetic code is a new map for the chamber walls), accumulating the electron density in a macroparticle for \( i \). The electromagnetic field \( \{(E(r), H(r)) \} \) is used for computing the electron motion.

In Figure 2, we show the dissipated power density by multislise, representation (3D): it is evident that the most part of the power is absorbed at the ECR layer, forming a high density plasma core that can be named as “plasmoid”, surrounded by a rarefied halo; iii) a density depletion region appears in the quasi-axial region, and it may be the responsible of hollow shapes in the transversal ion beam intensity plots, often observed in ion transport beam lines; iv) although the modal field distribution is perturbed by the medium, a standing wave pattern still persists in the plasma filled cavity as we can see in Fig. 2, and this may explain the sensitivity to the frequency tuning [3] manifested by many ECRIS.

This results highlight very interesting effects: i) the overall structure of the plasma assumes an hexagonal shape in agreement with the few available imaging results [2]; ii) the electrons (see fig. 3) accumulate mostly inside the volume limited by the ECR surface, forming a high density plasma core that can be named as “plasmoid”, surrounded by a rarefied halo; iii) a density depletion region appears in the quasi-axial region, and it may be the responsible of hollow shapes in the transversal ion beam intensity plots, often observed in ion transport beam lines; iv) although the modal field distribution is perturbed by the medium, a standing wave pattern still persists in the plasma filled cavity as we can see in Fig. 2, and this may explain the sensitivity to the frequency tuning [3] manifested by many ECRIS.

ACKNOWLEDGEMENTS

The authors are warmly grateful to the INFN V Nat. Sci. commision funding the RDH-UTOPIA and ARES project.

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