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PLASMA HEATING AND INNOVATIVE MICROWAVE LAUNCHING IN ECRIS: MODELS AND EXPERIMENTS

G. Torrisi*, D. Mascali, G. Castro, L. Celona, G. Mauro, M. Mazzaglia, E. Naselli[1], S. Gammino, INFN-LNS, Catania, Italy, [1]also at University of Catania, DFA, Catania, Italy
A. Galatà, INFN-LNL, Legnaro, Padua, Italy
G. Sorbello[2], University of Catania, DIIEI, Catania, Italy; [2]also at INFN-LNS, Catania, Italy

Abstract

Microwave-to-plasma coupling in ECRIS has been based on the classic scheme of waveguide-to-cylindrical plasma cavity matching. Optimization has been often obtained by empirical adjustments leading to an oversimplified model, obtaining however satisfying performances. In order to overcome the ECR-heating paradigm, on-purpose design of launchers' setup and adequate diagnostics have to be developed. This paper describes three-dimensional numerical simulations and Radio Frequency (RF) measurements of wave propagation in the microwave-heated magnetized plasmas of ion sources. Moreover, driven by an increasing demand of high frequency ECR ion sources, innovative ideas for the geometry for both the plasma chamber and the related RF launching system - in a plasma microwave absorption-oriented scenario – are presented. Finally, the design of optimized launchers enabling "single-pass" power deposition, not affected by cavity walls effects, are described.

INTRODUCTION AND MOTIVATION

In this paper, the electromagnetic wave propagation in microwave-heated plasma confined in a magnetic field, is addressed through numerical simulations and experiments, devoted to understand how the RF wave propagation depends on the electron density profile and external magnetic configuration [1–3]. In particular, we focus on the mechanism of RF propagation into the non-homogeneous magnetized anisotropic lossy plasma of Electron Cyclotron Resonance Ion Sources (ECRIs) [4], ECR-based charge breeder [5] and simple mirror linear plasma trap [6]. A better comprehension of electromagnetic wave propagation and RF power to plasma coupling mechanisms in ion-sources magnetoplasmas is crucial in order to provide a cost-effective upgrade of these machines alternative to the use of higher confinement magnetic fields, higher RF power level and higher pumping wave frequency [7]. Several full-wave numerical simulation codes have been developed [8–12] also exploiting ray-tracing technique [13].

The wave propagation at frequencies in the range 3-40 GHz in ECRIS compact plasma chamber (having magnetic field of the order of few Tesla, electron density in the order of 10^{18} m^{-3}) cannot be predicted by the plane wave model nor addressed by "ray-tracing"often adopted to describe waves in fusion toroidal devices [13–15]. These models, in fact, fail in minimum-B configuration scenarios where the scale length of plasma nonuniformity, $L_n = |n_e/\nabla n_e|$, and the magnetostatic field nonuniformity, $L_{B_0} = |B_0/\nabla B_0|$, are smaller than the free space, λ_0, and guided, λ_g, wavelengths.

We used COMSOL Multiphysics [16] software to model a "cold", anisotropic magnetized plasma, described by full-3D non uniform dielectric tensor, enclosed by the metallic cylindrical cavity where the plasma is generated. A proper mesh generation, exploiting FEM-based COMSOL versatility, allowed us to optimally modelize the cavity and microwave waveguide launching structure, with a good computational efficiency and high resolution especially around the resonance regions. The validity of the code was demonstrated by reproducing experimental results obtained with:

- X-ray imaging experiment on ATOMKI ECRIS ion source [4];
- PHOENIX Charge Breeder acceptance test at the Laboratoire de Physique et de Cosmologie [5];
- "Flexible Plasma Trap" (FPT) at INFN-LNS, where the numerical electric field profile has been compared with RF measurements of the wave amplitude inside the FPT plasma chamber [6]

The article is arranged as follows. In the first section wave field solution of the Maxwell's equations taking into account the magnetic field which makes plasma anisotropic, non-uniformity of plasma density, and the metallic plasma chamber is presented. Then, the above listed experimental benchmarks are described. Finally, some perspective is given as short term, mid-term and long term proposals for next generation ECRIS development based on: reshaping plasma chambers with non-conventional features, innovative RF launcher [17] and futuristic all-dielectric mm-waves launching structures.

RF WAVE-PLASMA INTERACTION MODELING

A magnetized plasma in the GHz range frequencies can be modeled as a cold magneto-fluid with collisions where the field-plasma interaction is described by the tensorial constitutive relation $\bar{\bar{\epsilon}} \cdot \vec{E}$. Tipically $\bar{\bar{\epsilon}}$ is derived assuming a magnetostatic field $\vec{B}_0$ directed along just one axis. This assumption is valid in most of cases but not in ECRIS where $\vec{B}_0$ is not strictly axis-symmetric. Considering the actual magneto-static structure of an ECRIS, that is not uniform nor axis-symmetric, $\bar{\bar{\epsilon}}$ depends in a complex way from the

* giuseppe.torrisi@lns.infn.it

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magnetostatic field $\vec{B}_0(x, y, z)$ and the local electron density $n_e(x, y, z)$. Under the "cold plasma" approximation, (i.e. $v_\phi \gg v_{th}$, being v_ϕ the wave's phase speed and v_{th} the electron thermal speed), the tensor components have been derived as it follows [3]:

$$\bar{\bar{\epsilon}}_r = \left(\bar{\bar{\epsilon'}} - i\bar{\bar{\epsilon''}}\right) = \left(\bar{\bar{I}} - \frac{i\bar{\bar{\sigma}}}{\omega\epsilon_0}\right) =$$
$$= \begin{bmatrix} 1 + i\frac{\omega_p^2}{\omega}\frac{a_x}{\Delta} & i\frac{\omega_p^2}{\omega}\frac{c_z + d_{xy}}{\Delta} & i\frac{\omega_p^2}{\omega}\frac{-c_y + d_{xz}}{\Delta} \\ i\frac{\omega_p^2}{\omega}\frac{-c_z + d_{xy}}{\Delta} & 1 + \frac{i\omega_p^2}{\omega}\frac{a_y}{\Delta} & i\frac{\omega_p^2}{\omega}\frac{c_x + d_{yz}}{\Delta} \\ i\frac{\omega_p^2}{\omega}\frac{c_y + d_{xz}}{\Delta} & i\frac{\omega_p^2}{\omega}\frac{-c_x + d_{zy}}{\Delta} & 1 + i\frac{\omega_p^2}{\omega}\frac{a_z}{\Delta} \end{bmatrix} \tag{1}$$

where

$$\begin{aligned} a_m &= (-i\omega + \omega_{\text{eff}})^2 + B_{0_m}^2 \left(\frac{e}{m_e}\right)^2, \\ c_m &= B_{0_m}\left(\frac{e}{m_e}\right)(-i\omega + \omega_{\text{eff}}), \\ d_{mn} &= B_{0_m} B_{0_n}\left(\frac{e}{m_e}\right)^2 \end{aligned}$$

with $m = x, y, z$, $n = x, y, z$ and

$$\Delta = (-i\omega + \omega_{\text{eff}})a_x + B_{0_z}\left(\frac{e}{m_e}\right)(c_z - d_{xy}) + \\ + B_{0_y}\left(\frac{e}{m_e}\right)(c_y + d_{xz}).$$

$\bar{\bar{\epsilon'}}$ is the real part of relative permettivity $\bar{\bar{\epsilon}}_r$, $\bar{\bar{\epsilon''}}$ is the imaginary part, ω the angular frequency of the microwave, $\omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$ the plasma oscillation angular frequency, n_e the electron density, m_e the electron mass, e the electron charge, i the imaginary unit and ω_{eff} the collision frequency; the latter accounts for the collision friction (thus modeling wave damping) and avoids any singularity in the elements of (1). Eliminating the magnetic field between Maxwell's equations and using the constitutive relations for an anisotropic medium, the wave equation reads as:

$$\nabla \times \nabla \times \vec{E} - \frac{\omega^2}{c^2}\bar{\bar{\epsilon}}_r \cdot \vec{E} = 0 \tag{2}$$

The above wave equation can be solved as a driven problem by a FEM solver that supports a non homogeneous tensorial constitutive relation; in the present work we used COMSOL and an external MATLAB routine allowing the definition of the full 3D dielectric tensor (1). In COMSOL we were able to model the exact shape of the FPT plasma chamber and the waveguide launching structure. The magnetic field and the plasma density were directly imported from experimental measurements. Since in proximity of the resonance surface (individuated by the iso-surface $B_0 = B_{ECR} = \frac{m_e}{e\omega}$ the permittivity varies strongly, the discretization of such a narrow region needed a very fine mesh: to achieve this, we adopted an adaptive mesh procedure (that was allowed by a specific feature of the solver). An extremely fine mesh has been obtained, thanks to "functional evaluation" based on the electric field gradient.

IMPLEMENTATION AND EXPERIMENTAL BENCHMARKS

Plasma Characterization By Energy Dispersive X-Ray Imaging At the Atomki ECR Ion Source

A Pinhole and CCD based quasi-optical x-ray imaging technique was applied to investigate the plasma of an electron cyclotron resonance ion source (ECRIS). Spectrally integrated and energy resolved images were taken from an axial perspective. We compared the X-ray plasma images recorded by the CCD pinhole camera with the simulated electron density map for two different microwave frequencies. In particular the transversal distribution of the electrons in the energy range 2-30 keV is compared with the filtered X-ray images corresponding to the K-alpha lines of the Argon. The simulations are consistent with the experimental evidence since also the number of warm particles is larger at 12.84 GHz rather than at 12.92 GHz, and the area populated from these particles is broader at 12.84 GHz, [18].

Electromagnetic Analysis of the Plasma Chamber Of PHOENIX ECR-based Charge Breeder At LPSC

During the experiments, by feeding microwaves at 14.324 GHz with a TravellingWave Tube Amplifier (TWTA), in-stead of the commonly used Klystron at 14.521 GHz, it was observed an increase of the efficiency of Cs^{26+} and a decrease in its charge breeding time, both of 15%, while the global capture stayed almost constant. This results revealed a huge difference in the electromagnetic behaviour between the two frequencies. The numerical simulations gave us the possibility to evaluate the power absorptions by the plasma. Results show that the 14.324 GHz frequency is three times more efficiently absorbed by the plasma than 14.521 GHz. These results are in very good agreement with the experimentally observed frequency tuning at exactly the simulated frequencies, confirming the model was sufficiently refined to almost reproduce the real-world conditions [19].

Wave Electric Feld Profile Measurement Inside FPT Plasma Chamber at INFN-LNS

The section reports about the direct comparison of the numerical results (from our full-wave approach) with the inner-plasma measurements of the electric field amplitude performed by means of a two-pins RF probe. Both simulations and measurements have been done considering the compact plasma trap FPT in a simple mirror configuration. The direct comparison between simulations and measurements demonstrate that the COMSOL simulated RF field profile clearly resembles the experimentally measured ones for three magnetic fields configurations. The RFP influence

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is not considered in the FEM simulations, so prediction capability is low. When density increases, the modal behaviour becomes more and more sensitive to the plasma presence within the chamber, whose influence is predicted by the FEM simulations. Therefore, the agreement between FEM predictions and experimental measurements increases [20].

CONCLUSION AND PERSPECTIVES

The excellent agreement between model predictions and experimental data are very promising for the design of future launchers or "exotic" shapes of the plasma chambers in compact machines, such as ECR Ion Sources and other similar devices. We propose hereinafter three different

- Short term (2 years): **Reshaping plasma chambers with non-conventional features for ECRISs**. A novel cavity resonator shape, with a non-uniform cross section matched to the twisting magnetic structure and a new RF launching scheme based on properly matched fundamental mode operating elliptical waveguide and tapered elliptical waveguide is proposed. Preliminary results show that a better geometrical and a dramatically improved RF matching to the new "plasma-shaped" plasma chamber can be obtained.

- Short/mid-term (3 years): **Innovative RF launcher**. A microwave launcher for the FPT, based on a two-waveguide array has been proposed. The experimental characterization is in good agreement with the numerical simulations and it has shown that, setting up a suitable phase difference, it is possible to tilt the angle of maximum radiation up to 40 degree to direct the microwaves towards the peripheral areas of the plasma chamber.

- Long Term (5 years): **futuristic all-dielectric mm-waves launching structures**. The technical challenges at 50 GHz make it attractive to look for new approaches: by taking inspiration from Dielectric accelerator structures we propose the investigation of the emerging electromagnetic concepts about all-dielectric Photonic Crystal (PhC) and Metamaterials structures. They are scalable, potentially low cost, and allow high frequency operation anb mature fabrication technologies. Proof-of-concept experiments are taking place at LNS, such as woodpile EBG Waveguide as a DC-break and dielectric Photonic Crystal Waveguide.

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