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Electromagnetic Wave Propagation in Magnetized Plasmas: Numerical Model and Experimental Validation

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Abstract

This paper describes three-dimensional numerical simulations and Radio Frequency (RF) measurements of wave propagation in the microwave-heated magnetized plasmas of ion sources. Our 3D Full-wave numerical model considers the inhomogeneous and anisotropic magnetized plasma medium in the "cold" plasma approximation. Maxwell's equations have been solved through the Finite Element Method (FEM). For the first time, by means of a two-pin RF probe, it has been possible to measure the electromagnetic field in a compact plasma trap where the experiment conditions resemble very closely the features of a common ion source for a direct comparison with the simulations. The numerical model has been supported by direct measurements of the plasma density profiles performed for different magnetic field configurations.

1 Introduction and Motivation

Electromagnetic wave propagation in microwave-heated plasma confined in a magnetic field, is modelled in this paper through numerical simulations and verified by experiments; the proposed study is devoted to understand how the RF wave propagation depends on the electron density profile and external magnetic configuration. 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) and Microwave Discharge Ion Sources (MDIS) [1]–[3]. Studies about the electromagnetic wave propagation in plasmas and RF power deposition are crucial in order to provide a cost-effective upgrade of ion-sources: in fact alternative plasma heating methods can avoid the use of extremely high magnetic fields for plasma confinement, excessive RF power level and high pumping wave frequency [4]. Simplified model on wave propagation at frequencies in the range 3-40 GHz in ECRIS compact plasma fails since this scenario (with non-uniform magnetic field of few Tesla and electron density of $\approx 10^{18}$ m^{-3}) cannot be accurately described by means of the standard plane wave model or by "ray-tracing". The proposed full wave approach can address minimum-B configuration scenarios where the plasma nonuniformity, $L_n = |n_e/\nabla n_e|$, and the magnetostatic field nonuniformity, $L_{B_0} = |B_0/\nabla B_0|$, are comparable or even smaller than the free space, λ_0, and guided, λ_g, wavelengths.

Hereinafter we present numerical results of 3D simulations of RF wave propagation in the magnetized plasma of the "Flexible Plasma Trap" (FPT) [5], a versatile test-bench developed for research purposes at INFN-LNS, for testing innovative RF systems for plasma heating and launching condition [6] as well as diagnostic schemes. We used COMSOL Multiphysics [7] 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. The main goal of the paper is to directly compare, for the first time in ECR ion sources, the numerical models results with RF measurements of the wave amplitude inside the FPT plasma chamber, performed through a two-pin RF probe antenna.

2 Modeling and Results of RF Wave in anisotropic plasma

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 $\bar{\bar{\varepsilon}} \cdot \vec{E}$. Tipically $\bar{\bar{\varepsilon}}$ 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, $\bar{\bar{\varepsilon}}$ depends in a complex way from the 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 in [2]. The relative permettivity $\bar{\bar{\varepsilon}}_r$, depends on the angular frequency ω of the microwave, the plasma oscillation angular frequency $\omega_p = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}}$, and the collision frequency ω_{eff} ; the latter accounts for the collision friction (thus modeling wave damping) and avoids any singularity in the tensor elements. Combining Maxwell's equations and using the constitutive relations for an anisotropic medium, the wave equation reads as:

$$\nabla \times \nabla \times \vec{E} - \frac{\omega^2}{c^2} \bar{\bar{\varepsilon}}_r \cdot \vec{E} = 0 \tag{1}$$

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. In the simulations the computational domain consists of the cylindrical plasma chamber cavity and microwave double ridged injection waveguide operating in the fundamental TE_{10} mode. The inner cavity volume is filled by lossy plasma characterized by dielectric tensor. The cavity walls are modeled via the appropriate "Perfect Electric conductor" boundary condition.

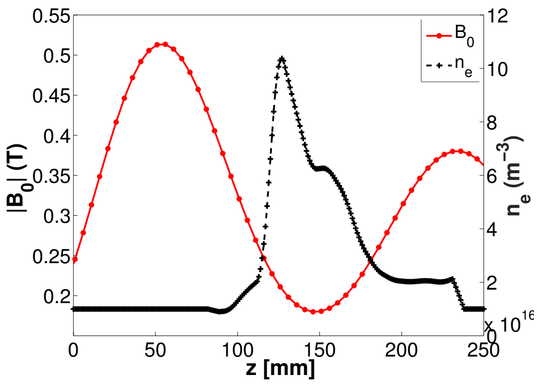

Figure 1. Electron density profile, n_e, and static magnetic field, B_0, measured along longitudinal z-axis. This data are used as input parameters to calibrate $n_e(x,y,z)$ and $\mathbf{B_0}(x,y,z)$ in numerical simulations.

Our three-dimensional 3D RF field solver uses the experimentally measured plasma density, $n_e(x,y,z)$ and magnetostatic, $B_0(x,y,z)$ profiles as input functions (see Fig. 1). In particular, the electron density n_e is measured through a Langmuir probe (determined by means of a multimodel approach developed at INFN-LNS [4]) for a magnetic ratio $B_{min}/B_{ECR} = 0.73$ where $B_{ECR} = \frac{m_e \omega}{e}$ is the magnetic file value at the ECR layers. The simulated Electric field $|E|$ is shown in Fig. 2 in proper colors scales range that emphasize the strong gradient near the resonance layers.

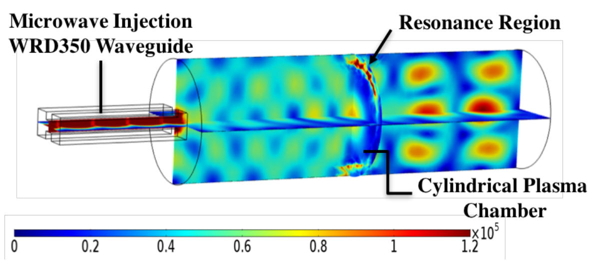

Figure 2. Simulated Electric field |E| [V/m] The simplified simulated geometry consists in the cylindrical plasma chamber cavity and the microwave double ridged waveguide injection.

3 Experimental Setup

The Flexible Plasma Trap (FPT) installed at INFN-LNS and described in [5] consists of a copper cylindrical plasma chamber 250 mm long and 65 mm in radius. Figure 3 shows a schematic diagram of the FPT machine [5], including the RF power injection system, the three magnetic coils, and RF probe for electric field detection. The FPT plasma has been fed by continuous mode microwaves at the operating frequency of 6.827 GHz generated by a TWT Microwave Amplifier. The experiments are performed at wave input power P_{in}=100 W in an Argon plasma at the pressure of $1.5{\cdot}10^{-4}$ mbar. We used two different configuration for the external magnetic field leading to two "simple mirror"-like profiles:

1. Simple mirror configuration $B_{min}/B_{ECR} = 0.56$ with a z-distance between ECR layers w_{ECR} (where $B_0 = B_{ECR}$) of 80 mm.
2. Simple Mirror configuration$B_{min}/B_{ECR} = 0.73$ with $w_{ECR} = 65$ mm.

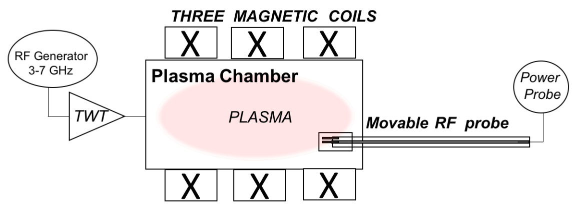

Figure 3. Schematic of the FPT experimental setup at the INFN-LNS.

A ceramic-coated RF two-pins probe small antenna (see Fig. 4), with one pin grounded and another connected to the inner wire of a coaxial transmission line, has been developed and used to measure the wave electric field inside FPT plasma chamber.

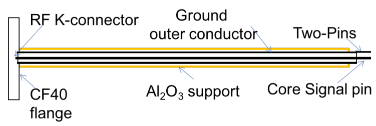

Figure 4. Sketch of the "Customized" Microwave coaxial Cable "Sucoflex 102" DC/40 GHz enclosed in Alumina tube.

The miniaturized antenna allowed a position resolved measurement of the E-field component perpendicular to the pins thus allowing a polarization selective measurement as demonstrated in [8].

The pins length and distance have been designed to be sensitive to the short wavelengths and small enough to achieve the desired spatial resolution. The probe exposes two linear tips having length of 3.5 mm and a distance of 2 mm, and it is shielded by a high-purity alumina tube allocated parallel to the longitudinal axis of the plasma chamber. The probe is connected to vacuum by a RF feed-through K-connector that was mounted on a standard CF-40 flange. A bellow allows movements via computer controlled step motor which provides a 0.1 mm precision. In the current setup (see Fig. 3), the probe can penetrate into the plasma chamber along a line parallel to the chamber axis. The RF probe pins are protected from direct contact with the plasma by a cup of MACOR. The RF probe collected signal is read by power probes and stored via PC acquisition system.

4 Experimental Results and Discussion

Figure 5 shows the simulated and measured field intensity for the case 1, which presents a simple mirror configuration at $B_{min}/B_{ECR} = 0.56$, with a z-distance between ECR layers w_{ECR} of 80 mm. This is the case with the largest plasma volume enclosed by the ECR layers. The amplitude peaks near the ECR layers confirm that the presence and position of the ECR layers can be predicted by the FEM calculations.

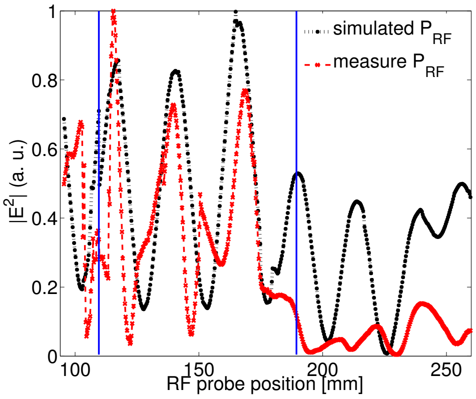

Figure 5. Simulated and Measured RF field distribution for Simple mirror configuration $B_{min}/B_{ECR} = 0.56$ with a z-distance between ECR layers w_{ECR} (where $B_0 = B_{ECR}$) of 80 mm. The positions of the ECR layers are indicated with vertical blu lines

We can observe in Fig. 6 that, if we reduce the resonance volume by increasing the magnetic ratio at $B_{min}/B_{ECR} = 0.73$, the electromagnetic field propagates more and more outside the ECR layers.

It is relevant to note that for the configurations at larger w_{ECR}, the electromagnetic field seems to self-confines in the plasma volume enclosed by the resonance layers. This "plasma-cavity" effect was already predicted in [2], [9] occurring under specific conditions of plasma density and sizes. It is now confirmed also by the direct RF measurements. In a more practical fashion, we define an useful and operative parameter as ratio R between the integral of the detected field outside the resonance layers L_{out} over the integral of the detected field in the line L_{in} between the two ECR layers:

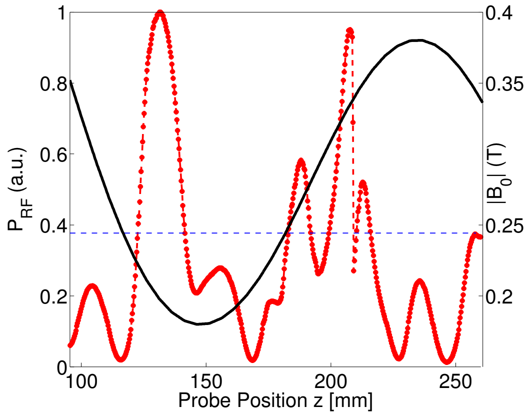

Figure 6. Measured RF Electric field intensity $|E|^2$. Simple Mirror configuration $B_{min}/B_{ECR} = 0.73$ with $w_{ECR} = 60$ mm.

$$R = \frac{\int_{L_{out}} P_{RF}}{\int_{L_{in}} P_{RF}} \tag{2}$$

Therefore, the R value is a metric to evaluate how much the electromagnetic filed is outside from the inner resonance volume. From Fig. 7, it is clear that R increases for larger w_{ECR} by confirming the FEM predictions. In particular, measurements show that the electromagnetic energy starts to "escape" from the inner resonance volume as w_{ECR} becomes smaller and smaller.

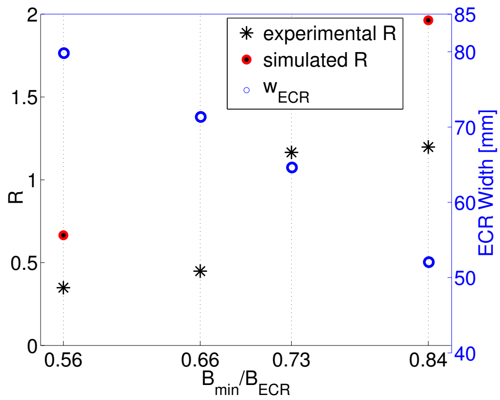

Figure 7. Measured and simulated R versus magnetic field (B_{min}/B_{ECR}). The calculated ECR width, that is the z-distance between ECR layers and the ratio is also shown.

5 Conclusion

The wave propagation in plasmas has been modeled with a full wave numerical numerical approach under "cold" plasma appproximation. The numerical results have been successfully validated by measurements. For the first time, the electric field amplitude has been measured (by mean of a two-pins RF probe) in complex scenario such as a compact plasma trap in conditions resembling very closely the features of a common simple-mirror-configuration ECR ion source. The excellent agreement between model predictions and experimental data are very promising for the study and design of future launchers or "exotic" shapes of the plasma chambers in compact machines, such as ECR Ion Sources and other similar devices. Further steps forward are going to be done as concerning the improvement of the model, including the "hot" plasma tensor: this will perspectively allow to master additional mechanisms such as modal conversion at the hybrid resonance.

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