The Lower Hybrid resonance effect in the simulation of Ion-Cyclotron plasma heating

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***Abstract*—The TOPICA (TOrino Polytechnic Ion Cyclotron Antenna) code is an advanced tool for simulating ion-cyclotron (IC) radio frequency antennas. This document presents a study based on simulations of the lower hybrid (LH) resonance effect in the TOPICA code. The document briefly explains the lower hybrid resonance problem, describes the simulation setup, and presents the results in terms of electric field distribution. Additionally, we propose a possible approach to identifying the problem.**

***Index Terms*—Plasma, TOKAMAK, TOPICA, FELICE, Lower Hybrid resonance, Ion Cyclotron, Antenna.**

I. Introduction

TOKAMAK devices require external heating to reach fusion; among the available options, Ion Cyclotron (IC) antennas are quite effective. In essence, the energy associated with a wave generated by an IC antenna travels through the plasma until a proper resonant layer is met. This resonance enables the ions to absorb energy from the waves, increasing their velocity and temperature, which is essential for achieving the conditions necessary for nuclear fusion. Antennas are critical components of RF heating systems, responsible for managing and delivering high power to the plasma while enduring extreme thermal and mechanical stresses. In this demanding environment, accurately predicting antenna performance in coupling electromagnetic energy to the plasma is crucial for designing effective heating systems.

The TOPICA code is a tool for simulating ICRF antennas over frequencies ranging from 10 MHz to several hundred MHz. It considers the entire antenna geometry and solves Maxwell's equations using the method of moments with an integral equation formulation [1]. The code also incorporates the plasma impedance matrix [2], which describes a realistic hot plasma computed by the Finite Elements Ion Cyclotron Evaluation (FELICE) code. FELICE solves the full-wave equation for a plane-stratified geometry using a semi-spectral representation; it assumes a Fourier description in the poloidal and toroidal directions while modeling the plasma as a slab in the radial direction [3], considering temperature effects and collisions.

II. Lower Hybrid resonance

Due to space limitations in this document, we will rely on the description of cold plasma to explain what LH consists of. In the context of wave propagation in magnetized plasmas, the dielectric response of the plasma to electromagnetic waves can be characterized using Stix notation, represented by the cold plasma dielectric tensor ϵ (see equation 1). This dielectric tensor depends on the static magnetic field taken to be in the toroidal direction, the electron plasma frequency (ω_{pe}), the electron cyclotron frequency (ω_{ce}), and the angular frequency of the wave (ω) [4].

$$\boldsymbol{\epsilon} = \begin{pmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{pmatrix} \tag{1}$$

where:

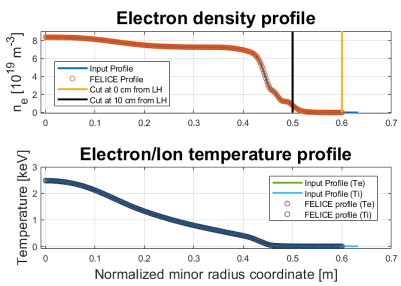
- $S = \frac{R+L}{2}$ is the perpendicular dielectric constant,
- $D = \frac{R-L}{2}$ represents the asymmetry due to the magnetic field,
- $P = 1 - \frac{\omega_{pe}^2}{\omega^2}$ is the parallel dielectric constant,
- $R = 1 - \frac{\omega_{pe}^2}{\omega(\omega-\omega_{ce})}$ is the right-hand circularly polarized wave component,
- $L = 1 - \frac{\omega_{pe}^2}{\omega(\omega+\omega_{ce})}$ is the left-hand circularly polarized wave component.

The equation 1 has two roots that can be considered "spurious" when $S = 0$, where S represents the average of the right-hand and left-hand dielectric responses $0 = (R + L)/2$. This condition typically occurs near the LH resonance, often found in low-density plasmas in front of IC antennas [5]. In such cases, the plasma refractive index tends to approach infinity. When this occurs, the FELICE code cannot provide the TOPICA code with the correct boundary condition at the plasma interface.

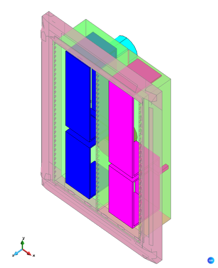
In TOPICA, the effect of the LH can be avoided by removing the low-density portion of the plasma and substituting it with a vacuum layer of equivalent length. This approach produces acceptable results regarding coupled power to plasma, but local phenomena (near fields) are not predicted with enough accuracy.

III. Simulation setup

To investigate the issue caused by the LH effect in TOPICA, we conducted simulations using a low-density profile relevant to the AUG experiment [6] (see Figure 1a). We also gradually shifted the profile in the direction of the LH resonance, starting from an initial position 10 cm away from it. A simplified flat 3D antenna geometry similar to one of the AUG IC antennas (see Figure 1b) was used in the simulations. The Faraday screen was removed to simplify the analysis, and the model was loaded in TOPICA with a mesh of 20451 RWG functions, among which 425 are in charge of taking into account the plasma loading. The antenna is fed assuming infinite coaxial lines connected to the two ports with a maximum voltage of 25 kV. The phasing is set at 0π, and the operating frequency is 30 MHz.



(a) Electron density and temperature profiles as a function of the major radius



(b) Isometric view of the two-strap antenna

Fig. 1: FELICE input and TOPICA input

IV. Simulation results

The impact of the LH resonance on the fields is evident in the calculated electric field on a surface in front of the antenna, as illustrated in Figure 2. The figure compares two results: the left side shows a profile cut 10 cm from the LH resonance, while the right side shows a profile that includes the resonance.

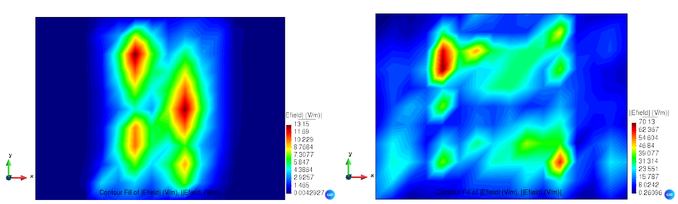


Fig. 2: Electric field in a surface in front of the antenna

To detect the influence of the LH resonance, we calculated the condition number from the TOPICA interaction matrix shown in equation 2 [1]. Here, Gp' represents the plasma contribution through the plasma impedance matrix computed by FELICE. In figure 3, the green values indicate that the LH resonance has minimal effects on electric field distribution compared to the reference case (cut profile at 10 cm). Conversely, the red values correspond to cases with clearly incorrect results. However, multiple computations of the $[G_{22} - (G_P{'} - G_{P,VAC})]$ matrix must be performed to determine a threshold that can be used to discriminate between good and wrong predictions.

$$\mathrm{SYS} = \begin{bmatrix} -G_{11} & G_{12} \\ G_{12}^T & G_{22} - \left(G_P{'} + G_{p,\mathrm{vac}}\right) \end{bmatrix} \tag{2}$$

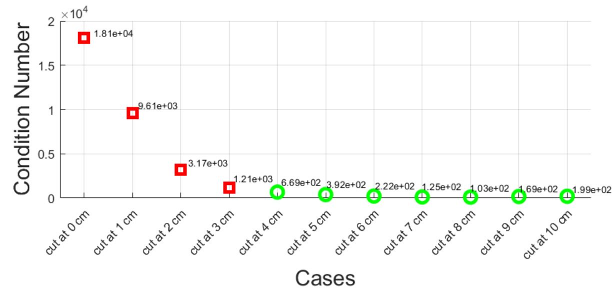


Fig. 3: Condition number of matrix $[G_{22} - (G_P{'} + G_{P,VAC})]$

Finally, the cumulative relative variation of the singular values, as shown in Figure 4, corresponding to $[G_{22} - (G_P{'} + G_{P,VAC})]$, indicates a significant change in the last few values. This change could suggest the influence of the LH effect on the interaction matrix.

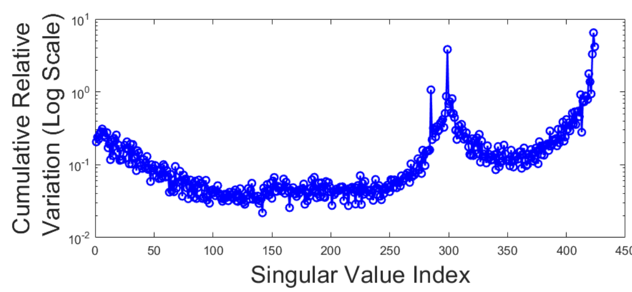


Fig. 4: Inverse Cumulative Relative Variation of Singular Values for 11 cases.

V. Conclusions

The effect of the LH resonance is evident in the computed electric field at the plasma interface. Besides, the increase in the condition number also indicates an issue in the interaction matrix. Finally, based on the analysis of the singular values, a potential solution may be to remove the singular vectors associated with the smallest singular values.

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