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WAVES FOR PLASMA

PLASMAS FOR WAVES

ANSYS HFSS to study wave propagation inside anisotropic magnetized plasmas in the Ion Cyclotron Range of Frequencies

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Abstract/Résumé

The paper summarizes the use of ANSYS HFSS as a tool to simulate wave propagation in an inhomogeneous anisotropic magnetized plasma. The methodology used throughout the paper is first illustrated with a uniform plasma case. We then narrow our study to antennas used to heat the plasmas in magnetically confined fusion devices in the Ion Cyclotron Range of Frequencies (ICRF), i.e. typically a few tens of megahertz. We implement a 1D inhomogeneous plasma density profile in front of a simplified WEST tokamak ICRF antenna where we perform a first benchmark against the ANTITER II code. We finally present a 3D case for the WEST tokamak and compare the radiation resistance calculated by the code to the experimental data.

The main result of this paper -- the implementation of a cold plasma medium in HFSS -- is general and we hope it will also benefit research fields besides controlled fusion.

1 Introduction

Resonance Heating (ICRH) is a primary heating technique in current fusion devices and should be a first-choice method in upcoming fusion reactors like DEMO, ARC, or CEFTR [1,2,3]. ICRH utility extends beyond heating, encompassing various applications like wall conditioning, plasma start-up, control, and landings. The potential of ICRH antennas in future fusion reactors underscores the critical importance of precise modeling and design to ensure their optimal performance. Although achieving a comprehensive simulation of all physical aspects of an ICRH antenna remains challenging, ongoing advancements in numerical models are progressing and any new simulation tool development represents an opportunity to further characterize those complex phenomena.

Given this context, the possibility to use ANSYS HFSS, a widely used 3D high frequency simulation software, to study waves propagation in a plasma is of interest given the fact that the tool has a versatile python interface, an automatic adaptative meshing feature and can easily be distributed on clusters for high-performance computing. In addition, the results obtained in ANSYS HFSS can be easily transferred as input loads into other ANSYS softwares, such as Mechanical which is widely used for mechanical engineering and accelerate the design cycle. While the capability of incorporating a plasma tensor into HFSS has been previously demonstrated in the lower hybrid frequency range for diagonal yet anisotropic and inhomogeneous cold plasma dielectric tensors and validated [4], this study aims to extend the methodology to the Ion Cyclotron Range of Frequencies (ICRF), that is a few tens of megahertz in present magnetized fusion experiments. For this frequency range, ICRF is characterized by the presence of non-negligible off-diagonal terms in the cold plasma dielectric tensor. The primary objective of the paper is to investigate the potential and limitations of this approach in the context of ICRF simulations.

2 Uniform Plasma Case

The possibility of including off-diagonal terms in the dielectric tensor in HFSS is first explored using a simple uniform cold plasma case in the ICRF.

The cold plasma dielectric tensor is conventionally expressed in a coordinate system $\left(e_{\perp,1}, e_{\perp,2}, e_{\parallel}\right) \equiv \left(e_1, e_2, e_3\right)$ where $e_{\parallel}$ is aligned to the total magnetic field direction:

$$\epsilon \equiv \begin{pmatrix} \epsilon_1 & i\epsilon_2 & 0 \\ -i\epsilon_2 & \epsilon_1 & 0 \\ 0 & 0 & \epsilon_3 \end{pmatrix} \equiv \begin{pmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{pmatrix} \quad (1)$$

with

$$\begin{aligned} \epsilon_1 &\equiv S &&\equiv 1 - \textstyle\sum_s \frac{\omega_{ps}^2}{\omega^2 - \omega_{cs}^2}, \\ -\epsilon_2 &\equiv D &&\equiv \textstyle\sum_s \frac{\omega_{cs}}{\omega} \frac{\omega_{ps}^2}{\omega^2 - \omega_{cs}^2}, \\ \epsilon_3 &\equiv P &&\equiv 1 - \textstyle\sum_s \frac{\omega_{ps}^2}{\omega^2}, \end{aligned} \quad (2)$$

where S, P and D are the so-called Stix parameters [5, 6]. S and D terms stand for the half-sum and the half-difference of left (L) and right (R) terms.

In the ICRF, two distinct sets of waves can propagate inside the plasma: the fast and the slow magnetosonic waves. In the cold plasma limit, the dispersion relation of each wave can be approximated by:

$$k_{\perp,\mathrm{FW}}^2 \approx \frac{(k_0^2 R - k_\parallel^2)(k_0^2 L - k_\parallel^2)}{k_0^2 \epsilon_1 - k_\parallel^2}, \quad (3)$$

$$k_{\perp,\mathrm{SW}}^2 \approx \frac{\epsilon_3}{\epsilon_1}(k_0^2 \epsilon_1 - k_\parallel^2). \quad (4)$$

The propagation of an incident plane wave at 55 MHz inside a uniform plasma was used to test the validity of the approach described in the previous paragraph. For the rest of the manuscript, the background magnetic field direction is chosen to be aligned with the toroidal direction such that $e_\parallel \equiv \mathrm{e}_z$, unless specified otherwise. Uniform cold plasma Stix components S, D and P are chosen such that the slow wave is evanescent and the fast wave is propagative. Those values are close to values expected near the core of a fusion plasma. With these parameters, using (3), the wavelength of the fast wave is $\lambda = 0.14$ m. The outcome of the simulation is presented in Figure 1, showing the E_y fields of the fast wave propagating radially inside the plasma. Measuring the distance between two field maxima, we find a wavelength $\lambda \approx 0.14$ m as expected from equation (3).

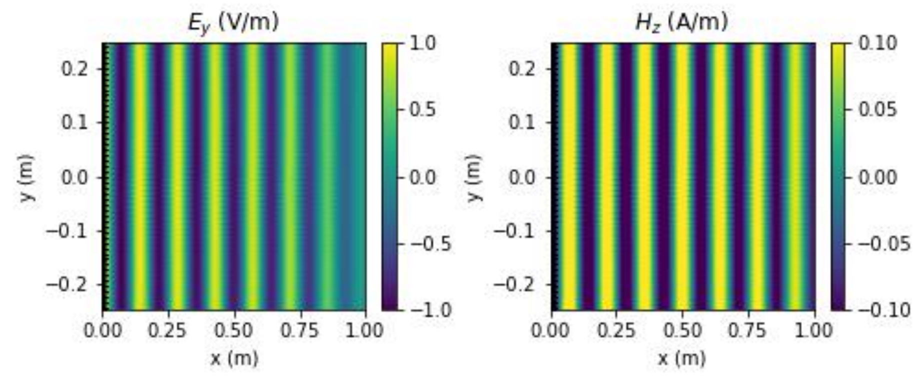

Figure 1. E_y and H_z waves characteristic of the FW propagation in the medium.

3 Plasma Profile Case

The results shown in section 2 were performed with an absorbing boundary layer (ABL)[1] which relies on the introduction of losses analytically inside the HFSS diagonal conductivity terms of our cold plasma dielectric tensor formulation. This method introduces nonphysical reflections in the simulations. After an optimization of these ABL to avoid large reflection at the end of the domain, an inhomogeneous 1D density profile was implemented in HFSS in front of a simplified flat ICRF WEST antenna and benchmarked with the semi-analytical code

[1] Also known as adiabatic absorber.

ANTITER[7]. The 1D density profile parameters considered come from the WEST pulse #56898. In the experiment, the plasma composition is D-(H) with a minority concentration around 4%. The electron density profile is reconstructed from reflectometry data and shown in Figure 2 for t=6 s. The reflectometer is toroidally located between the Q1 and Q4 WEST ICRF antennas, on the equatorial plane of the machine.

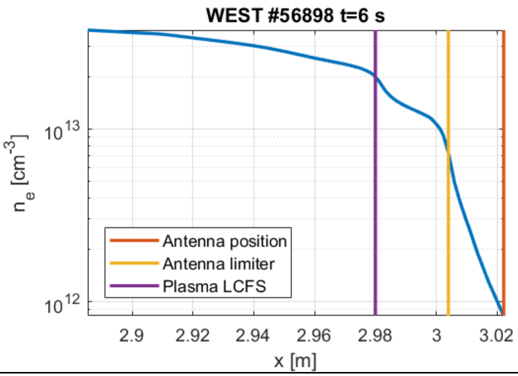

Figure 2. Electron density profile WEST shot #56898 at 6 s along with the antenna front face, the antenna limiter and the LCFS positions.

Good to excellent agreement was found for the fields and the power spectrum of the simplified antenna for an excitation of 1 A at the straps. As shown in Figures 3 and 4. The small discrepancy in the poloidal spectrum can be explained by the fact that ANTITER assumes a constant current on the strap while HFSS does calculate the current self-consistently.

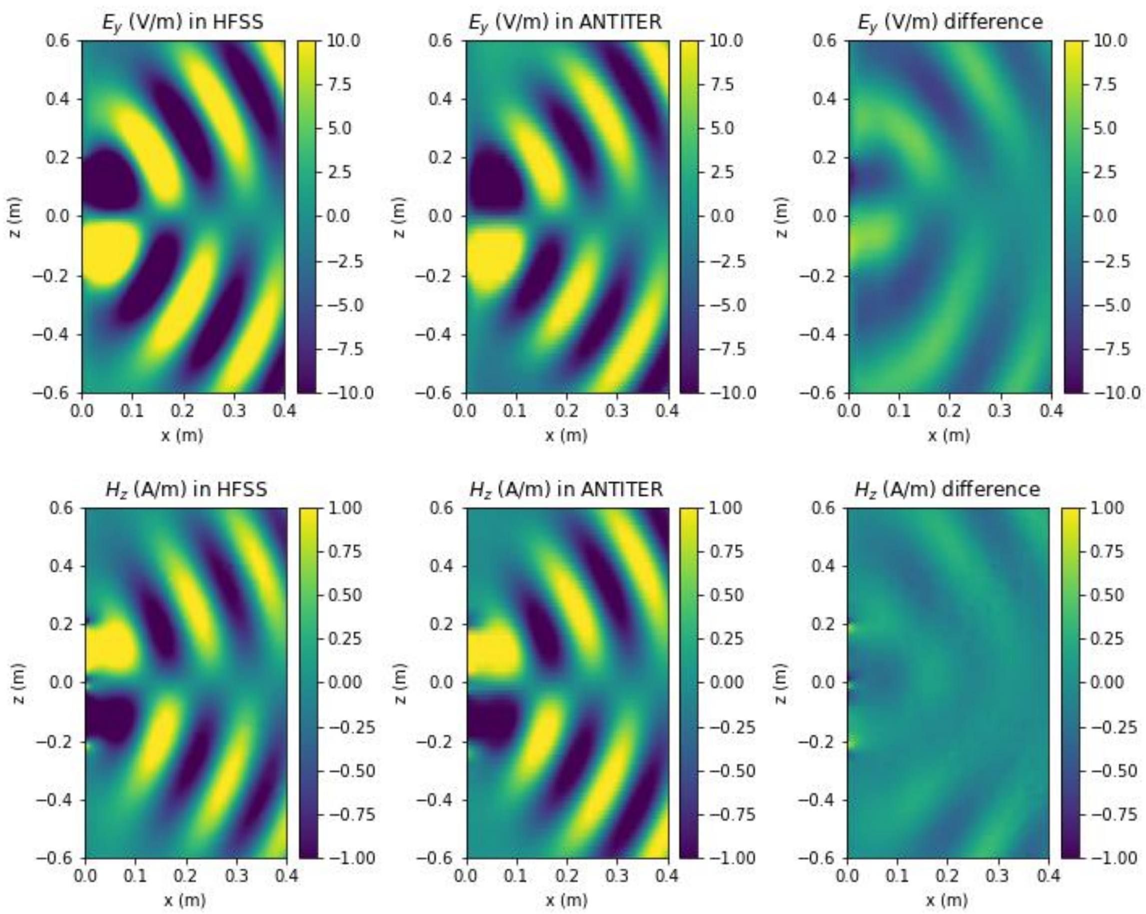

Figure 3. Comparison of the (top) E_y and (bottom) H_z field found in HFSS and in ANTITER as well as their difference.

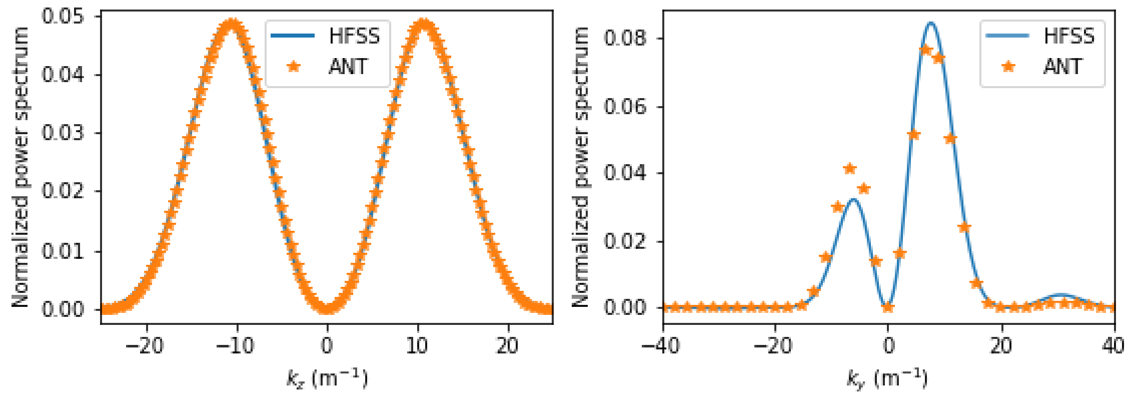

Figure 4. Comparison of the (left) toroidal and (right) poloidal power spectra calculated from HFSS and ANTITER.

4 Plasma 3D Case

Now that the possibility of implementing a 1D plasma profile in HFSS has been demonstrated, the possibility of implementing a 3D plasma is explored. The model used roughly represents one-third of the WEST tokamak vessel (simplified geometry) and is presented in Figure 5. This simulation considers toroidal and poloidal rotations of the cold plasma conductivity tensor necessary to account for the toroidal and poloidal field component of the total magnetic field of the device. The whole workflow uses the open source possibilities of python. First, the magnetic equilibrium of the WEST shot #56898 is recreated with the open source Free boundary Grad-Shafranov package (FreeGS) [8]. The 1D density profile presented in Figure 2 is then mapped over magnetic flux surfaces of the equilibrium to create 2D maps as presented in Figure 6. Simulations in 3D are typically heavy and long, spanning more than 3 days, involving more than 300,000 2nd order elements and performed on a 300 GB RAM station.

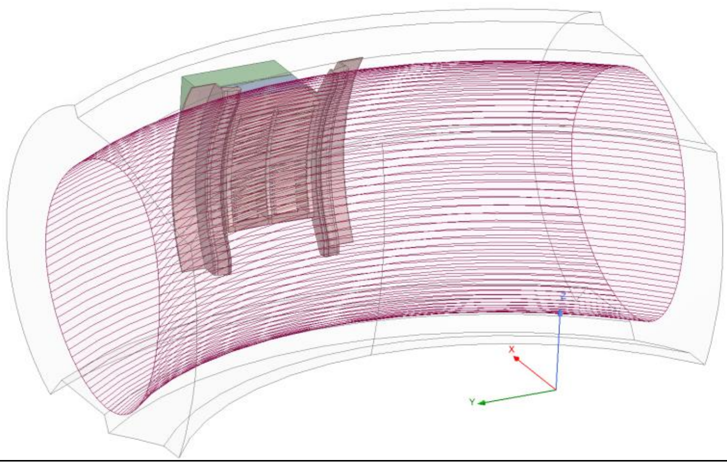

Figure 5. 3D model of the antenna and a third of the WEST vessel used in HFSS for the 3D plasma simulation case.

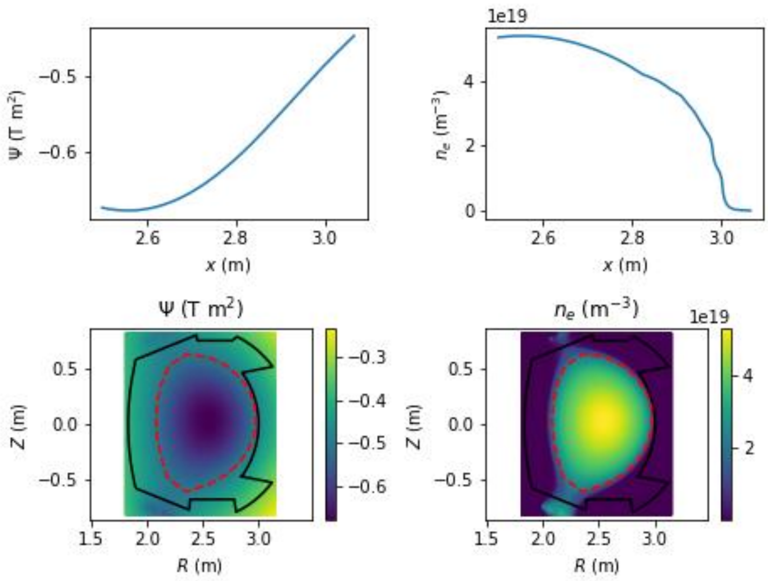

Figure 6. Map of the 1D density profile over the magnetic flux surface to create 2D maps.

Thus one can compare the antenna coupling resistance and the antenna voltages on each strap measured in the WEST shot #56898 at 6s with the HFSS-modeled antenna ones. This is presented in Figure 7.

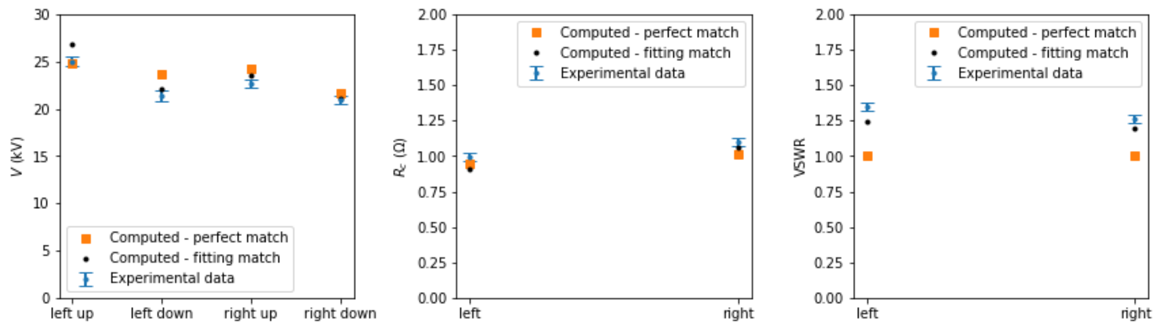

Figure 7. (a) Voltage on straps, (b) coupling resistance and (c) VSWR antenna characteristics obtained experimentally along with the ones computed with the HFSS S-matrix for a perfect match and for a match fitting as much as possible the antenna experimental characteristics provided a maximum error of 0.5 pF imposed to the capacitor layout of the perfectly matched case.

5 Conclusion

In this paper, the possibility of using HFSS as a versatile tool for ICRF simulations was demonstrated. The code was first tested for fast wave propagation inside a uniform cold plasma case. Subsequently, the code was benchmarked with ANTITER for a WEST 1D density profile. Finally, the code was tested for a 3D WEST plasma taking a third of the WEST tokamak into account. The code reproduces well the results obtained experimentally, further validating it.

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