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Recent Improvements to the ICRF Antenna Coupling Code "RAPLICASOL"

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Abstract. In this paper we discuss recent improvements to the ICRF antenna coupling code "RAdiofrequency wave couPLing for Ion Cyclotron Antenna in Scrape-Off-Layer" or RAPLICASOL for short, including its ability to handle curved antenna geometries, to simulate ICRF wave propagation through plasmas with arbitrary 3D density and magnetic field profiles, and its validation against other ICRF codes such as TOPICA and ERMES.

INTRODUCTION

Ion cyclotron range of frequencies (ICRF) heating is a commonly used heating method in tokamaks. The design of ICRF antennas, which must couple as much power as possible while minimizing impurity production via RF sheath excitation, relies heavily on numerical modelling and simulations. Thus, the ability to quickly calculate the coupled power as well as the electromagnetic fields near an ICRF antenna, even in highly non-trivial plasma conditions, is of great value. The tool we discuss in this paper, an ICRF coupling code called "RAPLICASOL", does just that.

It is a Finite Element code [1, 2, 3] implemented using the GUI of the commercial software COMSOL. It solves Maxwell's equations in cold plasma and in the frequency domain near the ICRF antenna, which is assumed to be a perfect conductor. The solution is the RF electric field near the antenna. From this, the scattering matrix is calculated, from which other quantities of direct experimental interest, such as the coupling resistance and coupled power, can be obtained.

In what follows, we discuss, in order:

1. The validation of RAPLICASOL against other ICRF codes.
2. The recently added ability to handle both arbitrary 3D density profiles and arbitrary 3D magnetic field profiles
3. The newly added ability to handle curved antenna geometries.

VALIDATION EFFORTS: TOPICA

In [4], we compared RAPLICASOL with a thoroughly validated ICRF code, TOPICA [5, 6]. For the ASDEX Upgrade (AUG) 2-Strap (2S) antenna, we found that the voltage reflection coefficients at the antenna ports as calculated by RAPLICASOL and TOPICA agreed to within 2% (using a flat AUG 2S antenna geometry in both cases). This remains true for a wide range of plasma density profiles. Related quantities such as the scattering and impedance matrix entries, coupling resistance, coupled power, optimal matching settings, and even the near RF fields, were also found to be in good agreement. A similar comparison, this time using the curved antenna geometries that will be discussed later, is

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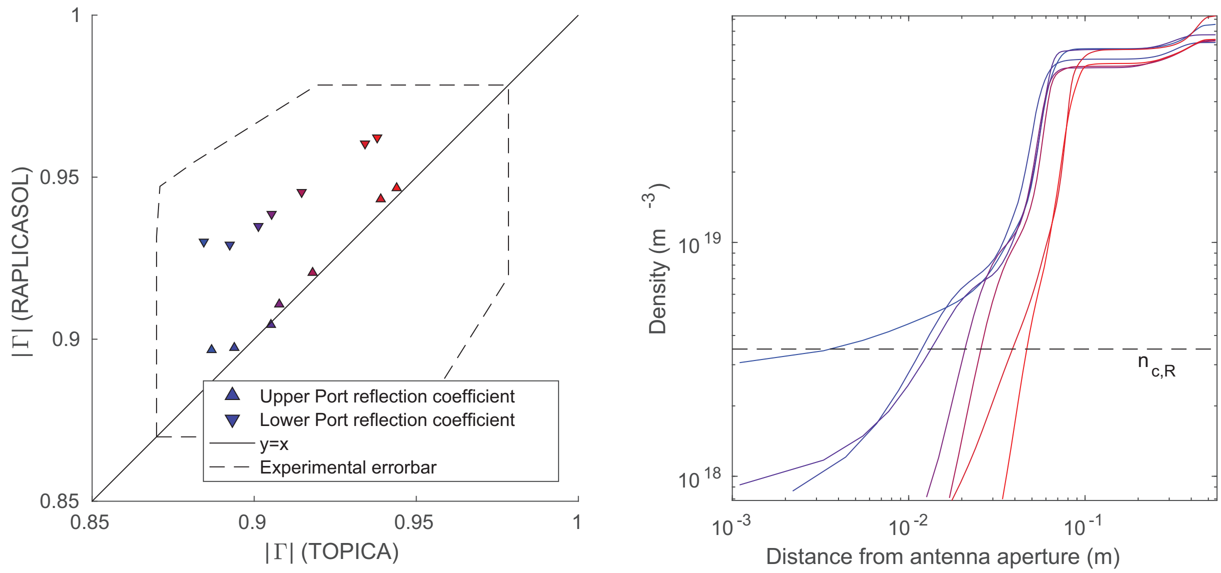

FIGURE 1. Comparison of port voltage reflection coefficients as calculated by RAPLICASOL and TOPICA for 7 different density profiles. The horizontal dashed line in the right figure is the R-cutoff density of about $3.5 \cdot 10^{18} \mathrm{m}^{-3}$. Unlike in [4], this comparison was done with curved geometry in both RAPLICASOL and TOPICA. Although the agreement is generally good, there is a systematic difference on the lower port, but not on the upper port. We believe that within the RAPLICASOL geometry, one of the straps is less accurately aligned than the other, which would explain this deviation.

shown in figure 1. Both the RAPLICASOL and the TOPICA calculations predict reflection coefficients that lie within the error bars of the corresponding experimental measurements.

This agreement is achieved despite the fact that RAPLICASOL requires vastly fewer computational resources than TOPICA: the required number of CPU-hours for the AUG 2S antenna is reduced, from about 3000 (5 hours on 600 CPUs) to about 100 (3 hours on 32 CPUs).

VALIDATION EFFORTS: ERMES AND THE LH RESONANCE

The standard Finite Element formulation of Maxwell's equations, using the Nédélec "edge" vectorial basis-functions [7] which are commony used in commercial Finite Element solvers, has several limitations especially when applied to cold plasma: it is unable to handle the LH resonance, where $S = 0$ in the cold plasma dielectric tensor, and its convergence, when using iterative solvers, is unreliable (the latter is believed to be caused by the former). For this reason, it has become standard practice to resort to poorly-justified resonance-avoidance techniques in most ICRF codes. Both including RAPLICASOL and TOPICA, for example, use a discontinuous density jump which keeps the antenna in vacuum and avoids the LH resonance. This has the added benefit of not having to resolve the short wavelength of the slow wave in the antenna [8, 9]. Luckily, this trick does not appear to significantly influence the calculated coupling resistance, as shown by numerical studies [8], and by comparison with experiment [4, 6].

The recently developped fully open-source ERMES code [10, 11] provides a less ad-hoc solution to this problem. By imposing $\nabla \cdot \vec{D} = 0$ (microscopic current continuity) everywhere, spurious numerical oscillations are avoided even in the presence of the LH resonance. The physical validity of this approach remains to be ascertained, especially in light of [12] (is $\nabla \cdot \vec{D} = 0$ the correct condition to enforce at the resonance?). Thus, in this paper we make no strong claims regarding the correctness of the ERMES approach for the collisionless LH resonance, but we do see in figure 2 that it avoids a typical failure mode of other Finite Element approaches near this resonance [8].

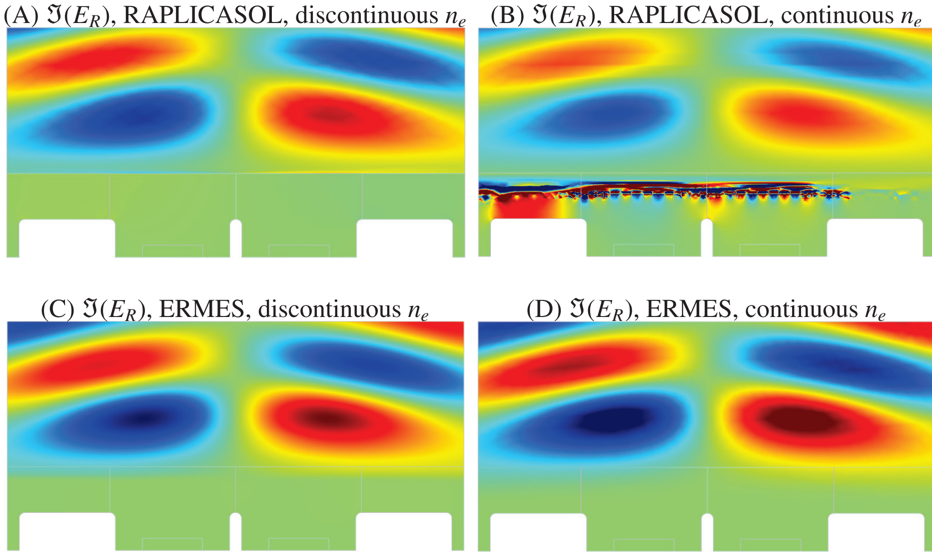

FIGURE 2. Imaginary part of the radial electric field component on a 2D antenna like in [8], as calculated by RAPLICASOL and ERMES, with and without artificial vacuum layer and discontinuous vacuum-plasma transition. A typical failure mode of the standard FE approach at the LH resonance can be seen in (B). ERMES in (D) avoids this issue. The difference between (A) and (C) is due to the stronger continuity enforced by ERMES, which assumes a continuous density profile even if it changes steeply and abruptly. Creating a real discontinuity is possible [13], but beyond the scope of this paper.

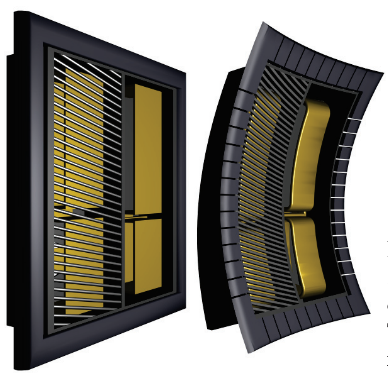

FIGURE 3. Left: flat geometry for the AUG 2-strap antenna. Right: the new curved geometry for the same antenna. The Faraday screen bars in front of the right strap are removed for clarity.

3D DENSITY AND MAGNETIC FIELD

EMC3-Eirene [14] and VMEC [15] are codes which can calculate 3D density and magnetic field distributions throughout the tokamak. In previous work [16] we showed that RAPLICASOL can simulate ICRF wave propagation through plasmas with such 3D density distributions, a capability we successfully used to predict the influence of local gas puffing on ICRF power coupling [14]. Now, RAPLICASOL can also import arbitrary 3D vector fields for the confining magnetic field $\vec{B}_0$. We also adapted the perfectly matched layers used to artificially damp the wave [17] to work in 3D conditions (although further validation, especially in the case of a 3D magnetic field, is still required). We intend to use this capability to model ICRF power coupling in plasmas which are non-axisymmetric, either because of MHD perturbations (e.g. RMPs[18, 19], ELMs [20]), or by design, as in stellarators.

CURVED PROCEDURAL GEOMETRY

The geometry in RAPLICASOL is generated programmatically from a number of numerical parameters that specify the antenna, such as the width, height and depth, details of the folded straps, and number and angle of faraday screen bars. Until now, only flat antenna geometries were available. Now, we have also constructed a procedural geometry for the curved AUG 2-strap antenna (figure 3). It is constructed to resemble the corresponding TOPICA model as closely as practically possible, within the limitations of COMSOL's geometry generation capabilities.

The advantages of the curved geometry are twofold: first, it is a better approximation to the true shape of the antenna. This is not just due to the curvature: it was noted in [4] that several existing flat models of the AUG 2S antenna have inaccuracies beyond the absence of curvature. Having the correct geometry is especially important when we are interested in the detailed behaviour of the electric field near the antenna. Second, having a curved geometry frees us from having to deform/flatten density or magnetic field distributions to make them match the flat antenna model.

CONCLUSION

In this paper we have discussed several recent improvements to the ICRF code RAPLICASOL, including validation, improvements to the geometry, and ability to handle 3D density and magnetic field profiles. In future work, we will further validate ERMES against RAPLICASOL, and attempt to add sheath boundary conditions on the antenna surfaces in RAPLICASOL.

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