Recent improvements to the ICRF antenna coupling code "RAPLICASOL"

W. Tierens[1], G. Suárez López[1,6], R. Otin[2], G. Urbanczyk[3,4], L. Colas[4], R. Bilato[1], W. Zhang[1], V. Bobkov[1], and J.-M. Noterdaeme[1,5]

[1]Max-Planck-Institut für Plasmaphysik, Garching, Germany
[2]CCFE, Culham Science Centre, United Kingdom
[3]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China
[4]CEA, IRFM, F-13108 Saint-Paul-Lez-Durance, France
[5]Applied Physics Department, Ghent University, Gent, Belgium
[6]Ludwig Maximilians University of Munich, München, Germany

February 27, 2019

Abstract

In this paper we discuss recent improvements to the ICRF antenna coupling code "RAPLICASOL", 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.

1 Introduction

Ion cyclotron range of frequencies (ICRF) 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 and 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.

RAPLICASOL is a Finite Element code, originally developed by J. Jacquot [1]. It is based on the commercial software COMSOL. It solves Maxwell's equations, in cold plasma and in the frequency domain, near the ICRF antenna, and calculates the S-matrix, from which quantities of direct experimental interest such as the coupling resistance and coupled power can be calculated.

In section 2, we discuss the validation of RAPLICASOL against other ICRF codes. In section 3, we show RAPLICASOL's recently added ability to handle both arbitrary 3D density profiles and arbitrary 3D magnetic field profiles, and in section 4 the newly added ability to handle curved antenna geometries.

2 Validation efforts

2.1 TOPICA

In [2], we compared RAPLICASOL with a thoroughly validated ICRF code, TOPICA [3, 4]. For the ASDEX Upgrade (AUG) 2-Strap (2S) antenna, we found that the voltage reflection coefficients at the antenna ports as calculated by RAPLICASOL

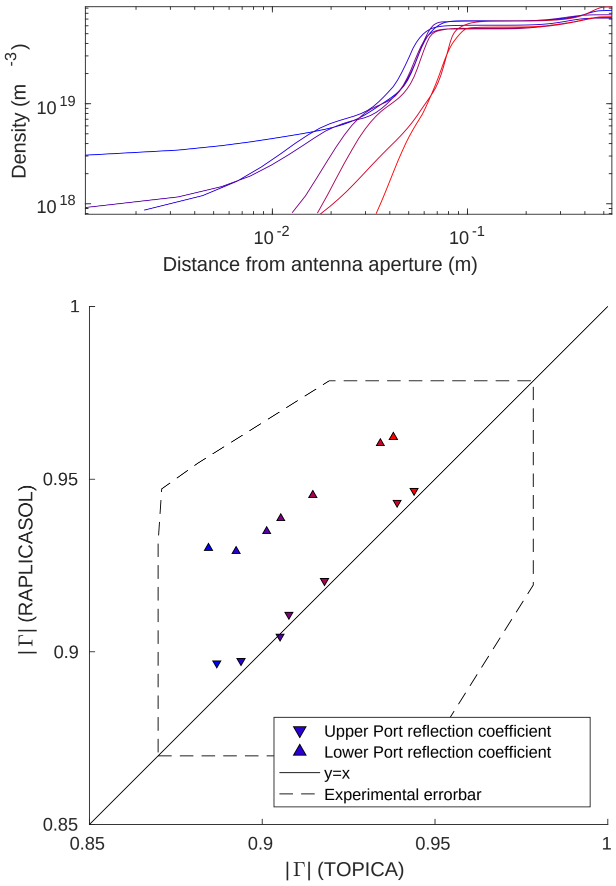

Figure 1: Comparison of port voltage reflection coefficients as calculated by RAPLICASOL and TOPICA for 7 different density profiles. Unlike in [2], this comparison was done with curved geometry in both RAPLICASOL and TOPICA.

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 S- and Z-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 in section 4, is 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).

2.2 ERMES & the LH resonance

The standard Finite Element formulation of Maxwell's equations, using Nédélec "edge" vectorial basis-functions [5], has several flaws when applied to cold plasma: it is unable to handle resonances (notably the LH resonance, where $S = 0$ in the 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, including RAPLICASOL and TOPICA. For example, a discontinuous density jump may be used to avoid the LH resonance [6], or a non-physical loss mechanism may be introduced.

The recently developped fully open-source ERMES code [7, 8] provides a less ad-hoc solution to this problem. By imposing $\nabla \cdot \vec{D} = 0$ (microscopic current continuity) everywhere, ERMES converges even in the presence of the LH resonance. The physical validity of this approach remains to be ascertained, especially in light of [9], but numerical results in figure 2 confirm that the numerical issues around the resonance (previously described in [6]) are avoided.

3 3D density & magnetic field

EMC3-Eirene [10] and VMEC [11] are codes which can calculate 3D density and magnetic field distributions throughout the tokamak. In previous work [12] 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

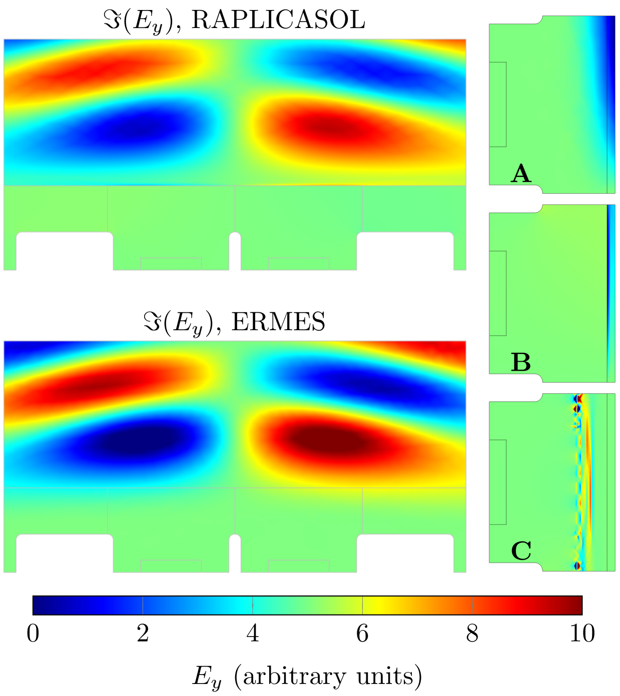

Figure 2: Left: $\Im(E_y)$ on a 2D antenna like in [6], as calculated by ERMES and RAPLICASOL. Right: detail view of $\Im(E_y)$ in (A) ERMES with continuous density, (B) RAPLICASOL with discontinuous vacuum-plasma transition, (C) RAPLICASOL with continuous density, where the solution is numerically ill-behaved near the LH resonance.

power coupling [10]. 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 [13] to work in 3D conditions (although further validation is still required). We intend to use this capability to model ICRF power coupling in tokamak plasmas that are perturbed in various ways [14, 15].

4 Curved procedural geometry

The geometry in RAPLICASOL is procedural: it is not usually imported from external CAD models[1], but rather generated programmatically from a large 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.

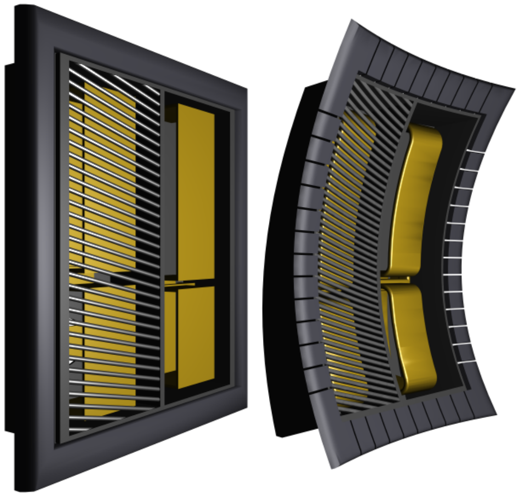

Figure 3: Old flat and new curved model of the AUG 2-strap antenna, with some of the Faraday Screen bars removed for clarity.

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 [2] that several existing flat models of the AUG 2S antenna have inaccuracies be-

---

[1] One reason for this is that TOPICA CAD models specify and mesh surfaces, while RAPLICASOL meshes volumes, and it is not generally possible to automatically convert from one to the other. In practice, only the simplest TOPICA geometries can be reliably imported into RAPLICASOL.

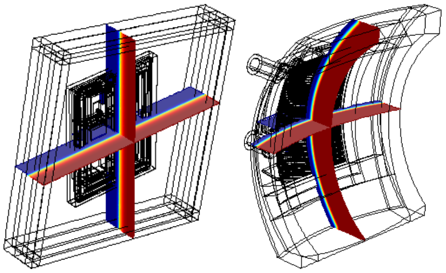

Figure 4: The curved geometry removes the need to flatten density and magnetic field distributions.

yond 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 (figure 4).

5 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.

Acknowledgement

I. Stepanov provided experimental data for figure 1. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] J. Jacquot et al. Full wave propagation modelling in view to integrated ICRH wave coupling/RF sheaths modelling. *AIP Conference Proceedings*, 1689(1):050008, 2015.

[2] W. Tierens et al. Validation of the ICRF antenna coupling code RAPLICASOL against TOPICA and experiments. *Nuclear Fusion*, 59(4):046001, 2019.

[3] D. Milanesio et al. A multi-cavity approach for enhanced efficiency in TOPICA RF antenna code. *Nuclear Fusion*, 49(11):115019, 2009.

[4] I. Stepanov et al. A detailed comparison of antenna impedance measurements on ASDEX Upgrade with the ion cyclotron range of frequencies antenna code TOPICA. *Nuclear Fusion*, 55(11):113003, 2015.

[5] J.-C. Nédélec. Mixed finite elements in $\mathbb{R}^3$. *Numerische Mathematik*, 35(3):315–341, 1980.

[6] L. Lu et al. Ion cyclotron wave coupling in the magnetized plasma edge of tokamaks: impact of a finite, inhomogeneous density inside the antenna box. *Plasma Physics and Controlled Fusion*, 58(5):055001, 2016.

[7] R. Otin. ERMES: A nodal-based finite element code for electromagnetic simulations in frequency domain. *Computer Physics Communications*, 184(11):2588–2595, 2013.

[8] R. Otin et al. Full wave simulation of RF waves in cold plasma with the stabilized open-source finite element tool ERMES. This conference, 2019.

[9] A. Nicolopoulos et al. A Stable Formulation of Resonant Maxwell's Equations in Cold Plasma. <hal-01743546v2>, 2018.

[10] W. Zhang et al. Effects of outer top gas injection on ICRF coupling in ASDEX Upgrade: towards modelling of ITER gas injection. *Plasma Physics and Controlled Fusion*, 59(7):075004, 2017.

[11] SP Hirshman, P Merkel, et al. Three-dimensional free boundary calculations using a spectral green's function method. *Computer Physics Communications*, 43(1):143–155, 1986.

[12] W. Tierens et al. 3-Dimensional density profiles in edge plasma simulations for ICRF heating. In *EPJ Web of Conferences*, volume 157, page 03053. EDP Sciences, 2017.

[13] L. Colas et al. Perfectly matched layers for time-harmonic transverse electric wave propagation in cylindrical and toroidal gyrotropic media. *Journal of Computational Physics*, 2019.

[14] G. Suarez et al. ICRF coupling in ASDEX Upgrade magnetically perturbed 3D plasmas. *Submitted to Plasma Physics and Controlled Fusion*, 2019.

[15] W. Zhang et al. Influence of ELMs on ICRF. This conference, 2019.