Numerical Challenges in Modelling Near-Antenna Field Behaviour in Cold Plasmas

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Background

In the cold plasma edge of tokamaks two types of waves can coexist: (i) the fast wave - the mode commonly intended to be excited by poloidal strap antennas - because of its ease to carry wave power across magnetic surfaces and thus reach the plasma core; and (ii) the slow mode often parasitically excited and mainly carrying power along magnetic field lines. Experimental evidence shows that Ion Cyclotron Radio Frequency (ICRF) waves give rise to sputtering. These processes are potentially harmful to the wave launchers and to the magnetically connected objects, especially in metallic environments used on JET and ASDEX-Upgrade and envisaged for ITER. The observed detrimental effects include DC biasing of the peripheral plasma, enhanced heat loads on plasma facing components, local modifications of the plasma density, DC current circulation and enhanced sputtering. In view of the risk of triggering a thermal quench when impurity radiation is excessive, processes responsible for sputtering need to be understood and their impact minimised. This wave-plasma interaction is likely caused by biasing of the plasma edge, via the rectification of RF oscillations by sheaths, non-linear electrical boundary layers at the plasma-wall interface. Since the dimensions of the antennas and the typical scale lengths on which sheaths occur differ by various orders of magnitude, it is numerically

![Figure 1: (a) The ISHTAR geometry, (b) $|E|$ in vacuum, (c) $|E|$ with modest dielectric ($S_{Stix} = P_{Stix} = 80; D_{Stix} = 0$), (d) $|E|$ with realistic dielectric ($S_{Stix} = P_{Stix} = 1000; D_{Stix} = 0$), (e) $|E|$ with plasma ($S_{Stix} \neq 0; D_{Stix} \neq 0; P_{Stix} \neq 0$ and $S, D$), (f) $|J|$ on antenna (with plasma) (using the cold plasma dielectric tensor description [1])](image-url)
difficult to model near-antenna field behaviour accounting for the actual density profiles and for the different types of waves that the plasma supports. Describing wave propagation in plasmas using the cold plasma tensor [1] has proven to be challenging, in particular in the presence of metallic boundaries and in low to very low density plasmas, where both slow and fast waves are present, either as propagative or as evanescent modes [2].

**Numerical modelling results**

In order to complement and advance the theoretical descriptions and numerical simulations of RF sheaths, quantitative experimental verifications are needed to acquire insight in the interaction of waves and plasmas in the antenna-near-field low plasma density region. Aside from requiring specific diagnostics and sufficient experimental time to build up an experimental database, adopting simple geometries allows to match the experimental and modelled antenna and antenna environment. IShTAR (Ion cyclotron Sheath Test ARrange ment) is a novel test facility dedicated to the study of near-antenna field behaviour in plasmas. It is located at the Max Planck Institut für Plasmaphysik in Garching (Germany) and starts its operation. It is intended to develop diagnostic methods for characterising the sheath properties, validate and improve theoretical predictions, and optimise antennas. A dedicated test bed eases the requirement for in-situ measurements, because of the better accessibility. In addition, conditions can be better controlled, there are fewer constraints on experimental time and simpler antenna geometries can be used, which is cheaper, more versatile and easier to compare with theory. Preliminary simulations of a single strap antenna in IShTAR have been performed using CST Microwave Studio [3] and COMSOL [4]. Some of the Microwave Studio results are illustrated in figure 1. It shows the total electric field of the antenna for different conditions: vacuum, dielectric media and cold plasma. For a dielectric medium with large values of relative permittivity, for example $\varepsilon_r = 1000$ (Fig.1d), and for an Argon plasma with density $n_e = 10^{18}$ m$^{-3}$ (Fig.1e) the solver does not reach convergence. The simultaneous presence of various wave types in a metallic antenna box yields a wave structure that contains long as well as short wavelength modes.
Such modes are physically acceptable but it needs to be demonstrated if these modes ultimately survive. The COMSOL RF package does not find a solution neither for the same cases, whereas good agreement between the two codes is found for vacuum and dielectric media with modest values of $\varepsilon_r$. Commercial codes are partly operated as a "black box" and a clear investigation into the convergence issues is not possible. Therefore a new wave code was developed, applying the usual cold plasma description [1]. It has started with a simplified 2D model based on a finite difference scheme [2]. For the modelling of the antenna field interaction in the IShTAR environment (and more general in tokamaks), complex 3D geometries are required, as well as the possibility to zoom in on regions where sheaths form. Therefore the code has been upgraded to a full 3D code and is now using a finite element technique. Base elements are tetrahedrons and local barycentric coordinates are used to describe the variations in each of the base elements (figure 2). The advantage is more flexibility in the description of the boundary conditions and the possibility of using an adaptive meshing, depending on the geometry and scale length of the physical phenomena in the sheath layer. Due to the vastly different densities, both short and long wavelength waves appear, and they can both be either propagative or evanescent. In view of the higher difference in relevant scale lengths, solving the relevant wave equation is a numerical challenge. Three complex wave field components need to be calculated and for capturing the evanescence sufficiently accurately at least cubic base functions are required. In three dimensions this yields to 20 coefficients, i.e. 60 unknowns at each grid point; sparse systems with more than $10^6$ unknowns need to be solved. The large number of unknowns necessitates running the simulation program on a powerful computer. The code has been installed on the HELIOS supercomputer system at IFERC-CSC (Rokkasho, Japan) [5]. It runs typically on a couple of hundred CPU’s (MPI is used for passing info). Figure 3 shows one of the electric field components in the $(y, z)$ plane at $x = 0$ m, as it is calculated in a geometry similar to figure 2, and for increasing number of nodes and elements. Figure 3(c) shows the limit of what can presently be obtained on the HELIOS supercomputer. At around 4 million unknowns a memory limit was encountered. Perhaps some of the libraries used by the MUMPS solver are not working fully parallel, investigation is ongoing. Convergence issues remain at this level of spatial resolution, an increase in number of unknowns by at least an order of magnitude would be helpful.

Conclusions

A better understanding of near-field wave patterns (input for sputtering studies) and of wave-induced density depletion (and its deleterious impact on the wave coupling) is crucial for proper RF operation in future fusion machines. Modelling tools are being developed and can be applied to the IShTAR test facility, which will moreover allow dedicated measurements of near-fields.
Figure 3: Increasing number of nodes and elements in the simulation reduces the short wavelength structures, but convergence is not yet reached on IFERC, limited by the memory requirements of the MUMPS solver. Number of nodes (N) and elements (E) that have been used are respectively (a) $N$: 9028, $E$: 43178; (b) $N$: 35618, $E$: 190355 and (c) $N$: 44488, $E$: 238309.

At present the cold plasma description is used, different existing simulation packages have been explored as well as a newly developed finite element code. Convergence problems appear in all codes especially for regimes where slow and fast wave components co-exist either as propagative or evanescent modes, as it is the case in the neighbourhood of the metallic surfaces of an RF antenna. It might be necessary to omit the dielectric tensor and solve the actual equations of motion, continuity and energy, to allow a sufficiently adequate description of the physics behind, such as modelling of the image currents formed on metallic surfaces and a self-consistent computation of the current densities on the antenna strap(s).

References


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