3D calculations of RF inductive coupling in the drivers of SPIDER: comparison with experimental data

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Introduction

SPIDER is the 1:1 scale prototype negative ion source for the main NBI heating system in ITER [1]. Before reaching the acceleration grids, negative ions are produced in the plasmas produced and sustained in cylindrical chambers commonly called drivers. In SPIDER, the power is transmitted from strong RF currents to the source plasma via electromagnetic induction. The process of inductive coupling between the radio-frequency (RF) current drive and the plasma, namely ICP, can be solved numerically if the appropriate geometry and material properties (e.g. plasma conductivity) are given. When three-dimensional (3D) structures are present, like the Faraday shield lateral wall (FSLW) that separates the RF coil and the plasma chamber, the calculations are involved and difficult to verify. A comparison with experimental data is mandatory.

2D [2, 3, 4] and 3D [5] calculation tools of the ICP have been already developed for SPIDER. Several cross-checks among them give confidence to the mathematical solutions obtained. However, direct comparison with experimental data is still due. Part of the problem is that, in a large machine like SPIDER, only a few outcomes of the calculations are amenable to comparison with experimental measurements. One possibility of direct comparison is the ohmic power dissipated in different parts of the driver. Calorimetry measurements, despite their lack of accuracy in the present stage of SPIDER operation, provide such information for some metallic parts, like the FSLW. In the present work we make several parameter scans with the 3D ICP model for SPIDER sources to find the equivalent impedance of different parts of the model driver. This information is then used to obtain the power dissipated in the FSLW, which can then be compared with calorimetry data.

Driver 3D model

A wireframe of the meshing of the metallic parts in the FEM calculation can be appreciated in Figure 1. Due to the high electrical conductivity of metals, the mesh is finer in these regions while it becomes coarser in the rest of the calculation domain, which includes insulator, vacuum and plasma regions. In all the calculation domain we use the typical combination of Maxwell equations to give the steady-state solution of the vector potential, **A**, for a purely harmonic drive of angular frequency ω,

$$\nabla \times \nabla \times \mathbf{A}(\mathbf{x}) + (\imath\omega\mu\sigma - \omega^2\mu\varepsilon)\mathbf{A}(\mathbf{x}) = \mu\mathbf{J}_\mathrm{b} = 0. \qquad (1)$$

The notation is standard in Eq. 1. The current drive in the RF coil, $\mathbf{J}_\mathrm{b}$, is null because the coil is excluded from the calculation domain. Appropriate boundary conditions are based on the amplitude of the current in the RF coil, I_b, assuming a set of perfectly circular filamentary coils instead of the real helical coil.

The calculations yield the **A**-field in the integration domain, and hence all magnitudes that can be derived from it, like the ohmic dissipation $\sim A^2$. For example, Figure 1 shows a selection of cells of the calculation mesh where the power density is above 0.1 W/cm^3. These concentrate in the inner side of an annulus near the FSLW center, particularly in the facing sides of the apertures that permit the penetration of the inductive field inside the plasma region (slits); and also in the extremity of such slits in contact with the copper back disk. The latter points can be appreciated as “hot-spots” in the figure.

Figure 1: Selection of cells of the calculation mesh (note the semi-transparent wireframe) where the power density is above 0.1 W/cm^3.