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3D/1D Prediction of ICRF Antennas Parameters during Operation

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Abstract

An innovative tool has been realized for the 3D/1D simulation of Ion Cyclotron Radio Frequency (ICRF), i.e. accounting for antennas in a realistic 3D geometry and with an accurate 1D plasma model. The approach to the problem is based on an integral-equation formulation for the self-consistent evaluation of the current distribution on the conductors. The environment has been subdivided in two coupled region: the plasma region and the vacuum region. The two problems are linked by means of electromagnetic current distribution on the aperture between the two regions. In the vacuum region all the calculations are executed in the spatial domain while in the plasma region an extraction in the spectral domain of some integrals is employed that permits to significantly reduce the integration support and to obtain a high numerical efficiency leading to the practical possibility of using a large number of sub-domain (rectangular or triangular) basis functions on each solid conductor of the system. The plasma enters the formalism via a surface impedance matrix; for this reason any plasma model can be used; at present the FELICE code has been adopted, that affords density and temperature profiles, and FLR effects. The source term directly models the TEM mode of the coax feeding the antenna and the current in the coax is determined self-consistently, giving the input impedance/admittance of the antenna itself. Calculation of field distributions (both magnetic and electric), useful for sheath considerations, is included. This tool has been implemented in a suite, called TOPICA, that is modular and applicable to ICRF antenna structures of arbitrary shape. This new simulation tool can assist during the detailed design phase and for this reason can be considered a "Virtual Prototyping Laboratory" (VPL). The TOPICA suite has been tested against assessed codes and against measurements and data of mock-ups and existing antennas. The VPL has been used in the design of various ICRF antennas and also for the performance prediction of the ALCATOR C-MOD D and E antenna. An extensive set of comparisons between measured and simulated antenna parameters during ALCATOR C-MOD operation will be presented.

TOPICA Theory

The strategy followed in this work fulfills certain requirements which are worth mentioning at this point: 1) the procedure is full-wave and self-consistent in that it starts from the Maxwell's equations without any *ad hoc* simplification and it assumes no known distribution of electric current on the antenna conductors; 2) it permits an easy coupling with available assessed codes, like FELICE or TORIC, to include the description of a real plasma (i.e. with finite Larmor radius effects, inhomogeneous profile of density and temperature and so on); 3) it is numerically efficient, since it allows a high degree of accuracy and simultaneously affordable CPU times even when analyzing large complicated structures with relatively small details as compared to the wavelength; 4) it is intrinsically prone to the optimization phase, in that it allows to improve the antenna performances by trimming its shape and size in successive iterations independently of the plasma parameters, which are usually fixed by the nature of the fusion experiment.

A key point in achieving all the outlined features is to conceptually separate the antenna region from the plasma one by means of the equivalence theorem (also known as Huygens' principle) applied in two different and successive steps. This approach leads to the introduction of two unknown (magnetic and electric) surface current densities and consequently to a formulation by two coupled integral equations.
Firstly, the equivalence theorem is applied to the torus region as it is actually; namely, a curved surface S_T coinciding with the torus wall, and the magnetic and electric current densities are placed on S_T, as shown in Fig. 1. To accomplish separation from the antenna, the aperture is closed by a perfect electric conductor (PEC) patch. Invoking the boundary condition at a PEC interface, it is seen that J_T does not radiate any field, while the magnetic current exists just on S_A.

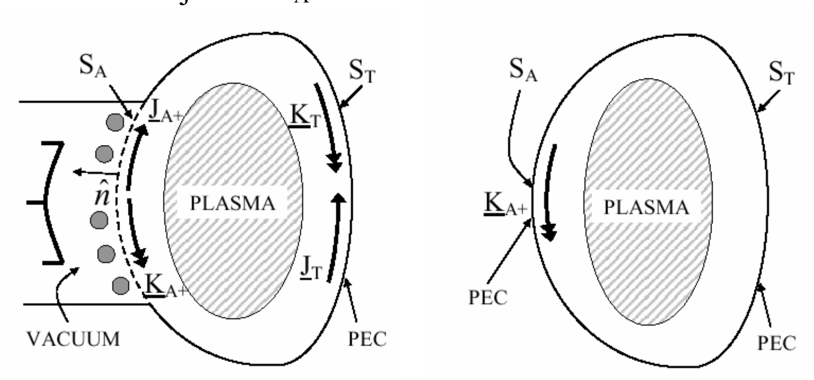

Fig. 1 First application of the equivalence theorem

To proceed further, in the recess the equivalence theorem is applied on a surface S_C that wraps all conducting parts, but, unlike before, the unbounded volume outside V_C is now entirely substituted with free space. Replacing *all* the conductors and the plasma itself by *free space* reveal to be a successful choice. In fact, the problem greatly simplifies in that all the relevant current densities radiate in vacuum (see Fig. 2), and solving the Maxwell's equations in vacuum is a classical problem in electromagnetism that does not pose particular difficulties. As a result, the unknown current J_C extends over the whole S_C, while the magnetic current is not-null only on the aperture.

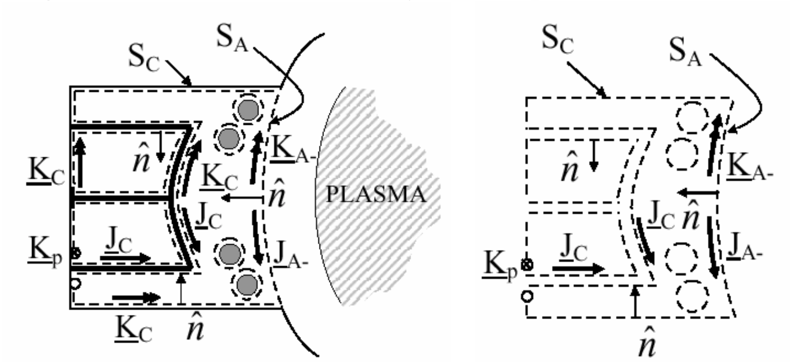

Fig. 2 Second application of the equivalence theorem

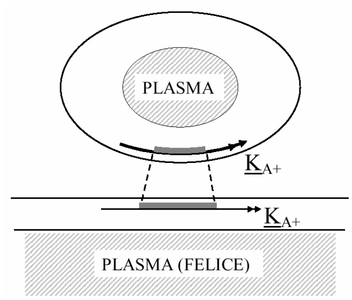

Fig. 3 Stretching procedure

The boundary condition that E satisfies in the recess region is now that the tangential electric field is either zero on the conductors or equal to the magnetic current density on the aperture. These considerations plus the need for taking into account both a curved aperture (and hence an actual ICRH antenna geometry) and a real plasma had leaded to the definition of the 1.5D plasma approximation, which relies on two basic hypotheses: 1) in the torus region side the slab plasma approximation is assumed, thus the recess aperture is considered flat; 2) in the recess region an arbitrary curved aperture is allowed. The latter two conflicting assumptions are realized formally *flattening* the current K_{A-}, whereas no modifications are applied to K_{A+}. More precisely, the stretching of $K_{A-}(\underline{r})$ is accomplished by mapping the points $\underline{r}$ on S_A to a plane by means of a suitable non-linear transformation. This procedure, schematically depicted in Fig. 3, is indeed an approximation.

The first step involved in the numerical solution of the problem is the reduction into a finite-dimensional space, obtained applying to them the method of moment technique. The problem is reduced to an algebraic system in a two-step procedure. As a first step the unknown vector functions J_C and K_{A-} are approximated as a linear combination of known vector triangular functions with unknown coefficients. In the second step, the coefficients are determined so as to minimize the residual, in particular enforcing it to be zero when tested (averaged) over a set of weighting functions. In the scheme to be used (sometime called *Galerkin testin*g) the set of test functions is identical to the sets of basis functions.

It is to be remarked that once the basis functions are chosen, and the residual integrals evaluated, the problem of self-consistently determining the currents J_C and K_A reduces to that of a linear system solution, which does not pose special problems until the number of unknowns exceeds some thousands.

In Fig. 2 a magnetic current surface density K_P was introduced and regarded as a forcing term. The actual source consists of (usually more than one) coaxial line, reaching the bottom wall of the recess cavity and therein truncated. The inner conductor of the coaxial is directly connected to the antenna *feede*r, while the outer one is grounded to the wall. Then, the equivalence theorem can be applied to the surface S_C: the coaxial aperture can be closed by means of a PEC patch, while all the other parts of the structure are left unchanged.

The requirement of shorting the coaxial ports that derives from the equivalence theorem application points at the admittance matrix as the natural circuit representation (impedance would require an open, and S-parameter would call for termination on a matched load).

Results of comparison (TOPICA simulations vs. measurements)

The present TOPICA code capabilities are:

- fully 3D solid antenna structure model (including FS, box,…);
- CAD input GUI interface; import/export standard file formats (IGES, DXF,...);
- realistic plasma, non-homogeneous, FLR, absorption (FELICE plasma model); fitted to curved boundary (1.5D);
- Multi-port circuit parameters (Z, Y, S matrices) calculation; full interfacing capability to external commercial RF simulators for circuit parts;
- Coax, voltage and current excitation of strap ports;
- Port loading (capacitors) available;
- Computes currents, fields, and voltages everywhere around antenna and housing;
- Computes power density spectra;

In this section we compare the results of a simulated actual antenna with TOPICA versus the measurements of the same antenna both in vacuum and during real operation with plasma. The antenna under analysis is the Alcator C-mod 'E' Antenna. A picture, a CAD drawing and a TOPICA model of this antenna are shown in Fig. 4.

The first set or results refer to the analysis in vacuo. In Fig. 5 the S_{11} ($\approx S_{33}$), S_{12} ($\approx S_{34}$), S_{22} ($\approx S_{44}$), and S_{23} ($\approx S_{14}$) parameter (absolute value and phase) of the antenna are shown versus frequency. In this examples the green line refers to measurements and the blue circles refer to simulations.

The measurements during operation are taken as reflection coefficient by means of direction coupler in particular position along the main transmission line feeding the antenna. In Fig. 6

the comparison between measured and computed results in two different positions are shown. The results refer to three particular plasma shots named 1157, 1430, and 1153.

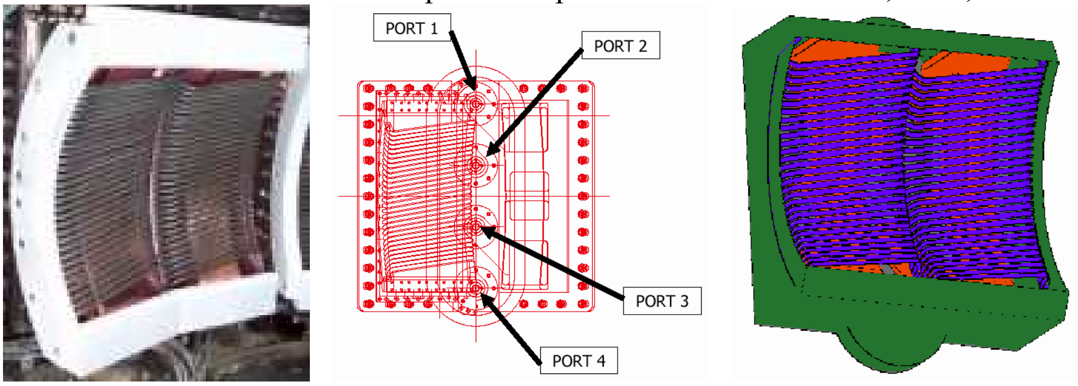

Fig. 4 Antenna under analysis (picture, CAD, and model)

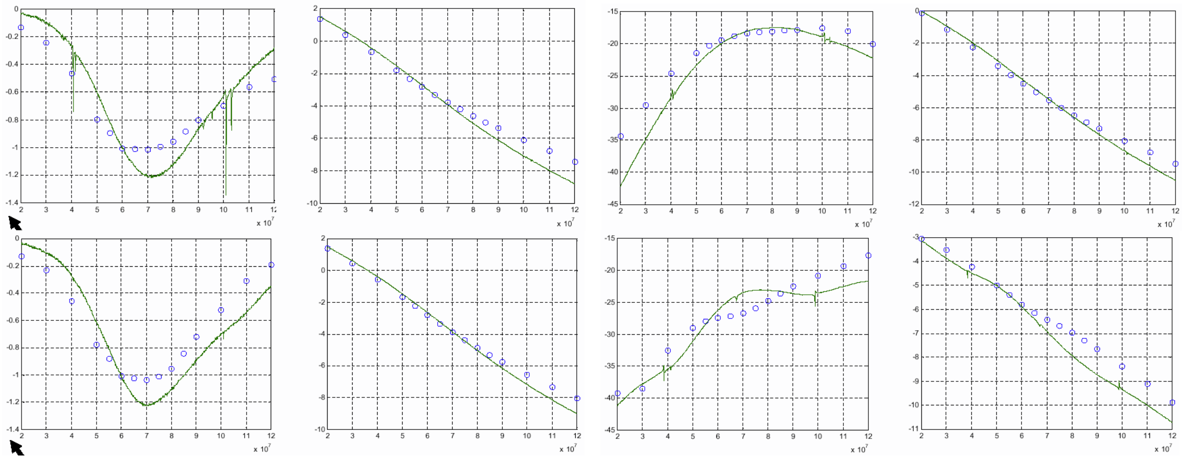

Fig. 5 Results in vacuum (green line: measured, blue circles: computed)

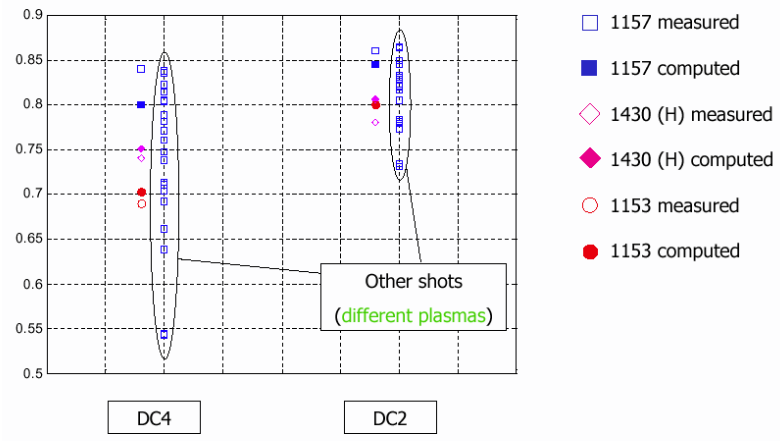

Fig. 6 Results during operation with plasma

Conclusions

The TOPICA code demonstrated a good efficiency and a controllable convergence with affordable CPU (the simulations presented here had 9000 unknowns and took about 10 hours on a LINUX-PC with a 2.66 GHz CPU and 2Gbyte RAM).

Analyzing the comparisons, we obtained a good agreement both in vacuum and with real plasma. This demonstrated that a 1.5D plasma model is suitable for antenna analysis.

A major next step will be the coupling of the TOPICA code with a 3D plasma model to be able to exactly predict the power deposition profiles inside the plasma column.