A new approach to ICRF antennas modeling based on coupling the surface impedance matrix of the plasma to commercial antenna codes

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Abstract.

Although modern commercial antenna codes can handle the complex 3D geometry of ion cyclotron resonance frequency (ICRF) antennas they still can not correctly describe hot fusion plasmas. In view of the impact the plasma has on the antenna-near fields and hence the need to use a sensible mock-up for the plasma behaviour, ICRF antenna modeling is currently mostly done by substituting the plasma with suitably chosen dielectric [1,2]. One of the limitations of this approach is the incorrect evaluation of the fields on the plasma surface.

In this work a theoretical basis is given and a practical implementation is shown for coupling the spectral plasma surface impedance matrix [3] to modern commercial antenna codes for self-consistent correct calculation of the fields and scattering ('S') parameters of the ICRF antennas, hereby allowing to interface the antenna coupling code with a much more realistic model for capturing the subtleties of magnetized plasmas. The approach uses subsequent application of induction and uniqueness theorems of electromagnetism. In a first step the fields of the antenna in vacuum are computed. Once these incident fields are known one can use the surface impedance of the plasma to calculate the total electric and magnetic fields on the plasma surface and the power flow into the plasma. The evaluation of the S-parameters of the antenna requires a second step. We use the obtained tangential electric field on the plasma surface as a necessary boundary condition to solve the equivalent problem and find the S-parameters of the antenna and all the fields around it.

This new approach is similar in physics potential to the TOPICA code [4] for its application to antenna design. Moreover, in the new approach it is possible to simulate the presence of cold low density plasma in the antenna box, which is needed for the correct evaluation of the fields and for addressing the sheath effect. The here presented, new approach is numerically more efficient and user-friendly than codes that attempt to directly incorporate the plasma response in the antenna computation. The paper also compares results obtained using the new approach with those obtained by other modeling methods. A new approach to the problem of the minimization of the toroidal electric field of the ICRH antennas is also proposed.

Theoretical basis for the approach.

Figure 1 (left) shows the sketch of the problem to be solved. A strap antenna - usually inside a box - radiates toward magnetized tokamak plasma.

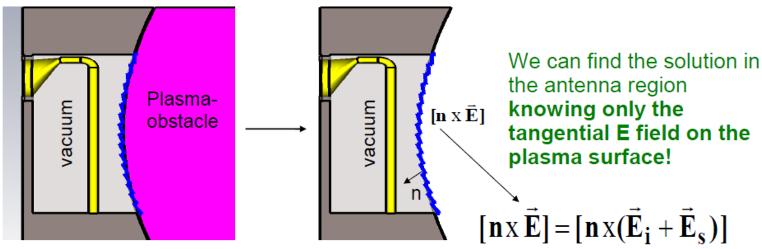

Figure 1. Problem to be solved (left) and the equivalent problem in which plasma is substituted by equivalent tangential electric field on its boundary (right).

In order to solve the problem first we revoke the induction theorem [5]. It states that the total field can be expressed as the sum of the incident and the scattered field. We consider the fields from the antenna radiating in vacuum (without plasma) as incident fields and plasma to be an obstacle. According to induction theorem we can write:

$$\vec{E} = \vec{E}^i + \vec{E}^s \quad (1)$$

where $\vec{E}$ is the electric field around the antenna we are solving for, $\vec{E}^i$ the incident field produced by antenna in vacuum and $\vec{E}^s$ is the scattered field produced by surface currents on the plasma surface. These surface currents $\vec{J}^s$ and $\vec{M}^s$ are expressible via only incident fields:

$\vec{J}^s = [\vec{H}^i \times \vec{n}]$, $\vec{M}^s = [\vec{n} \times \vec{E}^i]$, $\vec{n}$ - the normal to the plasma surface, see fig.1. (2)

Thus the field we are looking for has two parts. Incident field can be easily calculated by any modern antenna code. The calculation of the scattered field in presence of plasma is in principle as complicated as the initial problem. But at this point we invoke the uniqueness theorem [5]. It states that the fields in a lossy region are uniquely specified by the sources within the region plus the tangential component of electric field over the boundary. Thus if we can find the scattered field $\vec{E}^s$ only on the plasma surface (not everywhere in the space) we can use $[\vec{n} \times (\vec{E}^i + \vec{E}^s)]$ as the boundary condition for equivalent problem, fig. 1 (right). This kind of a problem can be again easily solved by any modern commercial antenna code and all the fields, currents and input parameters of the antenna radiating in plasma will be found self consistently. It is known [3] that in the spectral domain the scattered tangential electric field have linear dependence on incident field:

$$[\vec{n} \times \vec{E}^s] = \hat{G}[\vec{n} \times \vec{E}^i] \quad (3)$$

where $\hat{G} = (\hat{Z}_v + \hat{Z}_p)^{-1}(\hat{Z}_v - \hat{Z}_p)$ (4)

is 2 by 2 matrix, $\hat{Z}_v$ and $\hat{Z}_p$ are spectral surface impedance matrices of the vacuum and of the plasma. For plane waves reflecting from the flat plasma surface, $\hat{Z}_v(k_y, k_z)$ is the known function, see for example [3] and $\hat{Z}_p(k_y, k_z)$ can be calculated analytically for cold magnetized slab plasma or numerically with FELICE code for hot magnetized plasmas with 1D density and temperature profiles [3]. One can notice that equation (4) is similar to the one for the reflection coefficient of a wave in a waveguide at the jump of characteristic impedance from $\hat{Z}_v$ to $\hat{Z}_p$. In the spectral domain the following equations for the fields on the plasma surface can be written:

$$\vec{E}_{\tan}(\vec{k}_t) = \vec{E}^i_{\tan}(\vec{k}_t) + \vec{E}^s_{\tan}(\vec{k}_t) = (\hat{I} + \hat{G}(\vec{k}_t))\vec{E}^i_{\tan}(\vec{k}_t) \quad (5)$$

$$[\vec{n} \times \vec{H}_{\tan}(\vec{k}_t)] = \hat{Z}_p(\vec{k}_t)^{-1}\vec{E}_{\tan}(\vec{k}_t) = \hat{Z}_p(\vec{k}_t)^{-1}(\hat{I} + \hat{G}(\vec{k}_t))\vec{E}^i_{\tan}(\vec{k}_t) \quad (6)$$

$$P_{plasma}(\vec{k}_t) = real(0.5[\vec{E}_{\tan}(\vec{k}_t) \times \vec{H}^*_{\tan}(\vec{k}_t)]) \quad (7)$$

where $\vec{k}_t = (k_y, k_z)$ and $\hat{I}$ is the identity matrix.

Thus the tangential fields on the plasma surface and power coupled to the plasma can be calculated directly from the antenna fields in vacuum, provided $\hat{Z}_p$ is known.

Another useful equation is

$$\vec{E}_{\tan}(\vec{k}_t) = (\hat{I} + \hat{G}(\vec{k}_t))\vec{E}^{i}_{\tan}(\vec{k}_t) = (\hat{I} + \hat{G}(\vec{k}_t))\hat{Z}_v(\vec{k}_t)\vec{J}^{i}_{\tan}(\vec{k}_t) = \hat{T}(\vec{k}_t)\vec{J}^{i}_{\tan}(\vec{k}_t) \quad (8)$$

Where $\hat{T}(\vec{k}_t) = (\hat{I} + \hat{G}(\vec{k}_t))\hat{Z}_v(\vec{k}_t)$ and $\vec{J}^{i}_{\tan}(\vec{k}_t) = [\vec{H}^{i}_{\tan}(\vec{k}_t) \times \vec{n}]$ is the surface electric current on the virtual plasma-vacuum boundary. If the virtual plasma surface is close to the antenna conductors (in the most plasma application it is), then $\vec{J}^{i}_{\tan}(\vec{r})$ represents the current distribution on the antenna and antenna geometry itself to some extent. We can invert equation (8):

$$\vec{J}^{i}_{\tan}(\vec{k}_t) = \hat{T}(\vec{k}_t)^{-1}\vec{E}_{\tan}(\vec{k}_t) \quad (9)$$

Now for a wanted electric field distribution on the plasma surface we can find the necessary $\vec{J}^{i}_{\tan}(\vec{r})$ distribution which represents the antenna geometry and may help us in antenna design. For example in ICRH the electric field component parallel to static magnetic field should be as small as possible hence we may solve:

$$\begin{pmatrix} J^{i}_{\perp}(\vec{k}_t) \\ J^{i}_{//}(\vec{k}_t) \end{pmatrix}_{ideal} = \hat{T}(\vec{k}_t)^{-1} \begin{pmatrix} E_{\tan\perp}(\vec{k}_t) \\ 0 \end{pmatrix}_{ideal} \quad (10)$$

The solution for $\vec{J}^{i}_{\tan}(\vec{k}_t)_{\text{ideal}}$ should be back Fourier transformed in to the real space and then it will indicate how to change antenna geometry for $E_{\tan//}$ minimization. This process could be interactive.

Implementation and results.

The work flow for practical implementation is shown on the figure 2.

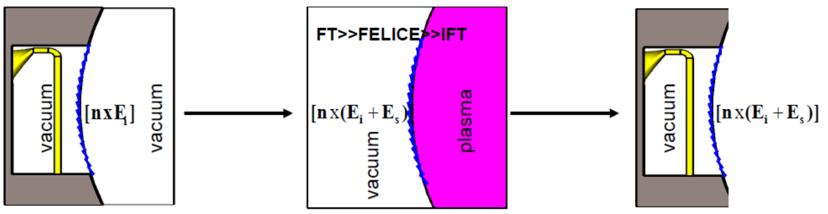

Figure 2. Work flow for working with CST MWS [6] or COMSOL [7].

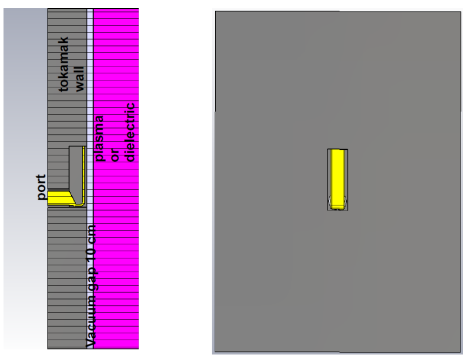

Figure 3. One strap antenna for testing the method, side and front views.

First we calculate the fields produced by antenna in vacuum $\vec{E}^{i}$ with MWS. In a second step we Fourier transform $\vec{E}^{i}$, calculate $\vec{E}_{\tan}(k_y, k_z)$ using eq.5 and back Fourier transform it for applying as boundary condition for the equivalent problem. As a third step we solve equivalent problem with MWS and find the antenna port impedance, fields and currents everywhere on the antenna.

In order to test the method and practical applicability with CST MWS we simulated simple one strap antenna (fig. 3) radiating toward a dielectric (ε =10) and cold uniform magnetized plasma.

Comparison of the electric fields on the dielectric surface gives satisfactory result (fig.4).

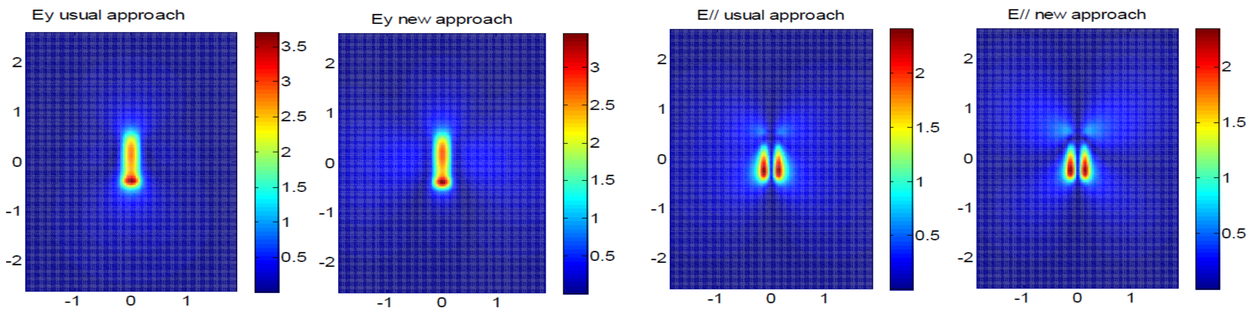

Figure 4. Comparison of the electric fields amplitudes on the dielectric surface in front of antenna obtained by usual and new approach. Antenna fed with 1W at the port.

The electric field distribution on the plasma is shown on fig. 5. One can observe $E_{//}$ screening by the plasma. For plasma case comparisons with TOPICA[4] and COMSOL[7] are foreseen in the nearest future as well as extensive benchmarking, debugging and optimization of the method.

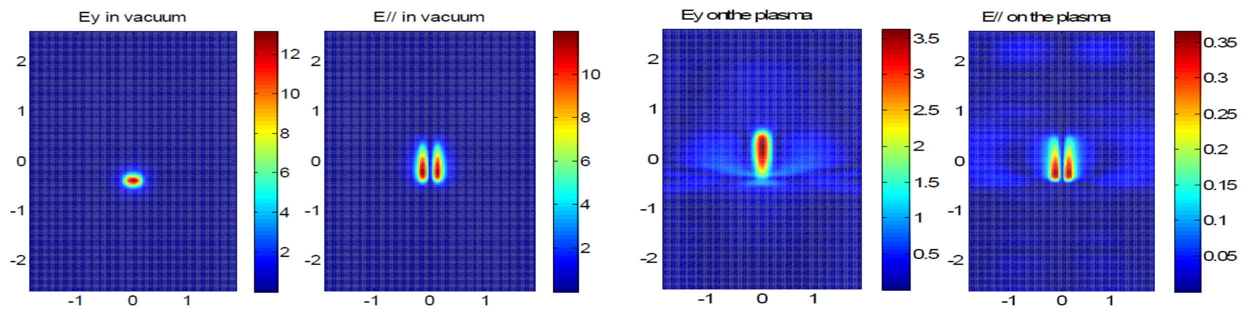

Figure 5. Electric fields in vacuum (V/m) at 10 cm from the wall (incident electric field) and on the plasma surface. $N_e=10^{17}$ m^{-3}, 50%D, 50%T B_0=3.2T, slab, cold model. Antenna fed with 1W at the port.

Conclusions.

A new approach to simulations of the antennas facing plasmas is proposed. It combines finite Larmor radius (FLR) description of the plasma of tokamak by its impedance matrix and the versatility of commercial antenna codes. First results obtained by the new method compares well to usual MWS simulation results. More simulations with plasma and comparisons with TOPICA [4] and COMSOL [7] are foreseen as well as benchmarking and optimization of the method. A new approach to the problem of reduction the toroidal electric field of the ICRH antennas is also proposed.

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