THE EFFECT OF REALISTIC ANTENNA GEOMETRIES ON PLASMA LOADING PREDICTIONS*

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Introduction

Plasma loading resistances for Ion Cyclotron Resonance Heating (ICRH) antennas are often calculated with sophisticated plasma models and only rudimentary antenna geometries. This paper presents techniques for modifying loading calculations for cavity antennas to account for such realities as return currents in the antenna sidewalls and backplane, the transmission and reflection properties of the Faraday shield, the end effects due to a finite length antenna, the reduction in phase velocity due to strap interaction with the Faraday shield, and the effect of slots in the cavity sidewalls and dividing septa.

Loading Calculations

Plasma loading calculations are made with RANT[1], a two-dimensional (2D) code with provisions for arrays of arbitrarily-phased current straps in recessed cavities. The source current's toroidal distribution on the antenna strap (infinitely thin in the radial or x-direction) can be specified arbitrarily, either from measurements or from a self-consistent 2D magnetostatic calculation, while the return current distribution along the recessed, perfectly conducting cavity walls is determined self-consistently. A diffuse-boundary magnetized plasma, uniform in z, extends to infinity in the radial direction, with its density profile an arbitrary input. The system is assumed uniform in the poloidal direction and the plasma loading for these TE modes is expressed in ohms per meter of strap length. Figure 1 shows a typical plasma profile and regions in which the wave fields are represented.

The plasma loading is greatly affected by the sidewalls of the cavity recess and the septa that separate the current straps. Loading for an early BPX antenna design was reduced by a factor of two when sidewalls were added to the conducting backplane, which constrains the flux to the vicinity of the strap. This code does not model the Faraday shield, which has the effect of redistributing the strap current, decreasing the flux transmission to the plasma, decreasing the strap inductance by flux reflection, and decreasing the phase velocity along the strap. Methods of compensation for these effects are presented in this paper:

Effect of the Faraday Shield

The Faraday shield affects the plasma coupling properties of ICRH antennas in many ways. It necessarily reflects some of the magnetic flux produced by the current strap, thus lowering the strap inductance as well as the flux transmission to the plasma. It also terminates the electrostatic component of the electric field by presenting a ground plane in close proximity to the current strap, greatly increasing the strap capacitance and hence lowering the phase velocity along the current strap. The transmission/reflection coefficients of the Faraday shield and the strap inductance per unit length are calculated with a 3D magnetostatic code that has been described in detail elsewhere[2]. Figure 2 shows the geometry and the boundary conditions for the calculation. Laplace's equation for the magnetic scalar potential is solved over one poloidal period of the shield, with Dirichlet boundary conditions on the midstrap symmetry planes corresponding to the total strap current, and Neumann conditions on all other boundaries.

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surfaces corresponding to a vanishing normal component of the magnetic field. This code is used to calculate the flux and power transmission coefficients (\( T_{\psi} \) and \( T_p \)) and the strap inductance per unit length (\( L' \)), while the strap capacitance per unit length (\( C' \)) is obtained from a complementary 3D electrostatic calculation using the same geometry. The phase velocity along the strap is obtained by representing the current strap as a lossy two-conductor transmission line with \( v_p = (L'C')^{-1/2} \).

While the reflection coefficient of the Faraday shield is essentially independent of the strap-to-shield gap, \( L' \) is dependent on the magnitude of the reflected field and hence decreases as the gap decreases. A \( T_{\psi} \) of 85\% can decrease \( L' \) by 10\% for a 1.5 cm gap and by 20\% for a 0.7 cm gap. However, the increase in \( C' \) is greater than the decrease in \( L' \), and \( v_p \) decreases to values around 0.67\( c \) for a 1.5 cm gap and 0.5\( c \) for a 0.7 cm gap. The increase in \( C' \) with strap width is roughly proportional to the decrease in \( L' \), so that \( v_p \) is nearly independent of strap width, although the characteristic impedance decreases with increasing width.

**Effective Length of Antenna**

Most two-dimensional plasma coupling codes such as RANT calculate antenna loading in terms of ohms per unit poloidal length; the net loading is determined by the length of the antenna. However, the effective length of the current strap is dependent both on the finite wavelength along the antenna and its poloidal geometry. The 3D magnetostatic analysis[3] is used to calculate the decrease in the toroidal field component due to poloidal end effects and return currents in the antenna cavity. The loading from fast wave coupling is proportional to the toroidally-integrated square of the toroidal component of the antenna’s magnetic field. The length attenuation factor due to geometric effects is \( \alpha \), calculated at the Faraday shield,

\[
\alpha = \frac{\int_0^L dy \int_0^{2\pi R} dz B_2^2(y,z)}{\int_0^{2\pi R} dz \max B_2^2}
\]

where \( \max B_2 \) is the maximum value of the toroidal component and corresponds to the value encountered in 2D calculations. Figure 3 shows an example of this falloff in the toroidal component for the DIII-D FWCD end-grounded antenna[4](\( \alpha = 0.87 \)). Typical antennas have \( \alpha \) in the range of 0.87 to 0.93; the shorter the antenna, the greater the end effect influence, and the smaller \( \alpha \). The length reduction factor \( k \) due to finite wavelength effects is

\[
k = \frac{1}{h} \int_0^h dy \cos^2(\beta y),
\]

where \( h = L \) for end-grounded straps, \( h = L/2 \) for center-grounded straps, and \( \beta = \omega/v_p \) uses the previously calculated phase velocity (for \( v_p = 0.55c, k = 0.71 \) at 60 MHz).

**Effects of Slots in the Cavity Sidewalls and Septa**

Providing slots in the side walls of ICRH antennas is a method of allowing expansion of the current strap’s magnetic field pattern, thus downshifting the toroidal wave spectral peaks and increasing the plasma loading. Placing slots in the septa that separate current straps in multiple strap arrays also changes the wave spectrum by redistributing the return currents, at the expense of increasing the interstrap coupling. The effectiveness of such slots is determined by their transparency to magnetic flux, which is a function of slot shape, area, position, thickness, and poloidal periodicity. More care must be taken when slotting septa for arbitrarily phased arrays for current drive than for arrays which are driven with adjacent strap phase shifts of either 0 or \( \pi \). While slotting septa generally increases the array directivity, which is desirable for current drive applications, the increase in mutual coupling can exacerbate the phase stability of the matching system and make phase control more difficult[4].
If the cavity side wall in Figure 2 were extended to meet the "plasma" surface to form a septum, this would be equivalent to a symmetric pair of current straps being driven out of phase. Symmetry demands a Neumann boundary for the potential, that is, the normal component of the magnetic field should vanish along the plane that includes the septum. However, if the straps are driven in phase, then symmetry demands that the tangential component of the magnetic field vanish along the plane of the septum; that is, the nonmetallic part of the symmetry plane, including the slots, becomes an equipotential (Dirichlet) surface, while the conducting walls of the septum remain Neumann surfaces. The magnitude of the scalar potential applied to this symmetry surface is determined by the constraint of global flux conservation: there can be no net flux crossing any constant z surface. In practice, the potential applied to the septum midplane is iterated in a converging fashion until the total magnetic flux passing behind the current strap equals the flux passing in front of the strap.

Once the in-phase and the out-of-phase inductances are known, the mutual inductance or the mutual coupling coefficient can be calculated. The comparison of this coupling coefficient to values obtained from a fully open septum (i.e., slot height extends to full poloidal period) and a fully closed septum (slot height vanishes) gives a indication of the transparency of the slotted septum to magnetic flux. The interstrap coupling coefficient for the DIII-D fast wave current drive array was calculated to be 6.3% and measured to be 6.8%; these slots in the 2 cm thick septum are 5.3 cm deep and 0.32 cm high, spaced every 5 cm. When these slots are extended to the rear of the cavity (i.e., 15 cm deep), the calculated interstrap coupling coefficient increases to 20.1%. The coupling coefficient with no septum at all is 32.6%, indicating that narrow slots can be quite transparent to flux (-4.2 dB) provided they extend far enough behind the current strap to pass the flux generated between the strap and the rear wall.

The mutual coupling coefficient can be calculated in 2D geometry by the same (0,0), (0,π) phasing techniques outlined above. We have obtained good agreement between the measured fields and the calculated fields, both 2D and 3D, when the length of the solid septa in the 2D calculations is adjusted until the coupling coefficients agree with measurements and 3D calculations. This is shown in Fig. 4, where B_z of a test antenna is plotted vs z at 2 cm from the shield, both with and without slots in the septum and sidewalls (mutual coupling is 1.8% or -35 dB for the solid septum, and 4.9% or -26 dB for the slotted septum).

Conclusions

The RANT code calculates plasma loading per poloidal length for recessed cavity geometry, arbitrary strap phasing, and quite flexible plasma profiles; the toroidal distribution and radial location of the strap sheet current may be specified by calculations from a 2D magnetostatic code. Combining results of 2D and 3D magnetostatic codes can give effective septa lengths to be used in RANT. For example, the 18.8 cm long septa of the DIII-D array with the 5.3 cm deep, 6.3% transparent slots can be represented by a solid septum 16.5 cm long. To continue with this particular example (Fig. 3), the length attenuation factor α due to end effects is 0.88, the phase velocity due to the Faraday screen is 0.55c, giving a length reduction factor k of 0.71 at 60 MHz, and the power transmission coefficient is 0.72. The actual length of the current strap is 45 cm, but the overall effective length for obtaining the loading in ohms from the output of RANT is the product of the above factors

$$R_L = \alpha k L T_p R'_L = L_{eff} R'_L,$$

or 20.2 cm, which is only 45% of the actual strap length.

References
