RESONANT LOOP ANTENNA DESIGN WITH A 2-D STEADY STATE ANALYSIS*

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Evaluation of resonant loop antenna designs for ICRF heating of plasmas requires information concerning the electrical characteristics of the structure. Our 2-D steady state model described herein provides us with current strap inductance and capacitance, surface current distributions, and flux linkage to the plasma. These are used to determine the current and voltage requirements, ohmic dissipation, frequency limits and matching requirements, maximum electric fields, and plasma loading in order to compare antenna designs.

THE MAGNETOSTATIC MODEL

The resonant loop structure which we consider consists of a current strap, surrounding conducting cavity, and plasma surface; it is similar to that treated by Mau¹ and is shown in Fig. 1. The antenna and plasma are considered uniform in the ignorable y-direction (poloidal direction in tokamak geometry). The plasma and cavity walls are considered perfectly conducting surfaces, enabling the system to be described by the Laplace equation for Λ_y :

$$\nabla^2 \Lambda_y = \frac{\partial^2 \Lambda_y}{\partial x^2} + \frac{\partial^2 \Lambda_y}{\partial z^2} = 0, \quad (1)$$

with the boundary conditions $\Lambda_y = \Lambda_{yo}$ on the current strap surface and $\Lambda_y = 0$ on the cavity walls and the plasma surface.

The magnetic field can be expressed as

$$\mathbf{B} = \nabla \times \mathbf{A} \rightarrow B_x = \frac{-\partial \Lambda_y}{\partial z}, \quad B_z = \frac{\partial \Lambda_y}{\partial x}. \quad (2)$$

Knowledge of Λ_y and $\mathbf{B}$ enable us to solve for the inductance per unit length of the current strap

$$L' = \frac{\Lambda_{yo}}{I_o} = \frac{\Lambda_{yo}}{\mu_o} \left| \oint \mathbf{B} \cdot d\mathbf{l} \right|^{-1}, \quad (3)$$

where the line integral of $\mathbf{B}$ is taken around the perimeter of the current strap to yield the antenna current I_o .

The calculated inductance per unit length was 2.23 nH/cm for the DIII-D geometry and 3.08 nH/cm for the TFTR geometry; the measured values were 2.0 nH/cm and 3.1 nH/cm, respectively. We also verified that the inductance changes only slightly when the antenna is moved closer to the plasma in both machines.

The surface current distribution $\mathbf{J}_s$ on the conducting surfaces is found by invoking the boundary conditions on $\mathbf{B}$ at a perfect conductor.

$$\mathbf{J}_s = \frac{\mathbf{n} \times \mathbf{B}}{\mu_o} = \frac{\mathbf{n} \times \nabla \times \Lambda_y}{\mu_o}. \quad (4)$$

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A typical plot of J_s for TFTR on the wall and the strap is shown in Figs. 2 and 3. It is apparent that the current is concentrated on the ends of the strap and is returned in the wall sections that are in closest proximity to them.

This current distribution can then be used to determine the average resistance per unit length in the current strap and the overall ohmic power dissipation in the structure.

$$R' = \frac{\eta \delta}{2} \frac{\oint J_s^2 dl}{(\oint J_s dl)^2}, \quad (5)$$

$$P'_{diss} = R' I^2, \quad (6)$$

where R' is the effective resistance per unit length, η is the resistivity and δ the skin depth of Cu, and I is the rms current in the strap.

The cooling requirements of an antenna become critical as rf pulses extend to multisecond duration and as current densities increase to provide the high power densities required by tokamaks. The ohmic resistance per unit length of the current strap was calculated to be 0.028 Ω/m at 47 MHz and 150°C; the power dissipation using this value was found to be in good agreement with the cw calorimetric measurements made on the TFTR prototype.

For given plasma conditions, the power loading of an ICRH antenna is related to the amount of toroidally directed magnetic flux that is linked to the plasma. If one neglects the k_z dependence and takes the plasma surface impedance $Z_p = E_y/H_z$ to be a constant, the power delivered to the plasma per unit length of antenna is approximated by

$$P'_{plasma} = \frac{Z_p}{\mu_0^2} \int_{-\infty}^{\infty} |B_z|^2 dz. \quad (7)$$

This may be rewritten in terms of the rms strap current by use of (3), normalized to $\Lambda_{y0} = 1$ amp-henry/meter:

$$P'_{plasma} = \frac{Z_p}{\mu_0^2} I^2 \left[I_s'^2 \int_{-\infty}^{\infty} |B_z|^2 dz \right]. \quad (8)$$

For a given antenna current, maximizing the term in brackets maximizes the coupling efficiency of the antenna. Figure 4 shows this coupling factor vs. distance to the plasma for the TFTR single loop and the DIII antenna geometries.

ELECTROSTATIC MODEL

The current distribution along the strap and the frequency range of operation are determined by the wavelength of the antenna, $\lambda = v_p/f$, where the phase velocity is determined by the inductance and capacitance per unit length, $v_p = (L'C')^{-1/2}$. In the absence of the Faraday shield the phase velocity is the speed of light and $C' = (c^2 L')^{-1}$, the capacitance being primarily determined by the current strap ends and the proximity of the side walls in an analogous fashion to the inductance L' . However, the addition of a perfect Faraday shield ($\sigma_z = \infty$, $\sigma_y = 0$) will influence C' while L' will not be affected.

We may estimate the total capacitance in two ways. The first, method I, models a section of a two-tier periodic Faraday shield (Fig. 5) to obtain the strap-to-shield

capacitance. The equation to be solved is $\partial^2\Phi/\partial x^2 + \partial^2\Phi/\partial y^2 = 0$, subject to the boundary conditions in Fig. 5. The capacitance per unit length is then

$$C_s' = \frac{Q'}{\Phi_1 - \Phi_2} = \frac{W}{a} \int_0^a E_x dy = \frac{W}{a} \int_0^a \frac{\partial\Phi}{\partial x} dy, \quad (9)$$

where W is the effective width of the current strap. The phase velocity is then $v_p = [(C_s' + C_w')L']^{-1/2}$ where $C_w' = (c^2L')^{-1}$, the capacitance due to the side walls.

An alternative method, method II, replaces the Faraday shield with a conducting plane and solves the 2-D Laplace problem in (x, z) space, $C'' = \oint \nabla\Phi \cdot d\mathbf{l}$, with the integration taken around the current strap. The phase velocity is $v_p = (L'C'')^{-1/2}$ with the L' calculated with no Faraday shield present. Method II is more accurate for large gaps. The phase velocity from both methods is plotted in Fig. 6 as a function of distance between the strap and shield for TFTR geometry.

1. T. K. Mau, S. C. Chiu, and D. R. Baker, "Coupling Analysis for the ICRF Resonant Cavity Launcher on DIII-D," to be published in IEEE Trans. on Plasma Science (1987).

Fig. 2. The surface current distribution on the antenna strap for the TFTR geometry.

	D-III-D (cm)	TFTR (cm)
ANTENNA/PLASMA DISTANCE (d)	0-10	0-10
CAVITY DEPTH (a)	17	22
CAVITY WIDTH (b)	32	23
CURRENT STRAP WIDTH (w)	15.24	11
CURRENT STRAP THICKNESS (t)	2.5	1
CURRENT STRAP REAR WALL (f)	7.5	16
CURRENT STRAP TO FARADAY SHIELD (s)		1.5

Fig. 1. The geometry and boundary conditions for the steady state analyses.

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Fig. 3. The surface current distribution on the cavity walls for the TFTR geometry.

Fig. 4. The power coupling factor as defined in the text vs. the strap to plasma distance.

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Fig. 5. The geometry for calculating the capacitance per unit periodic area (method I in text).

Fig. 6. Phase velocity vs. the strap to Faraday shield gap. The dotted line and solid line are methods I and II as mentioned in the text. The data point was measured on the TFTR development antenna.