Measurement of the Effects of Faraday Shields on ICRH Antenna Coupling

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Abstract—**Compact loop antennas are being applied to several fusion experiments, including DIII-D, the Advanced Toroidal Facility, Tore Supra, and the Tokamak Fusion Test Reactor. Although individual configurations vary, all of these antennas generally comprise a current strap in a recessed box and a Faraday shield. The effect of the cross-sectional shape of the current strap on voltage and current levels was measured previously. In this work the coupling characteristics of cavity antennas that have current straps with the previously evaluated cross-sectional shapes are tested with several Faraday shields. The coupling is purely a measure of the magnetic flux linkage at relevant ICRH frequencies and does not include plasma spectral effects. Impedances and relative fields are measured for various combinations of the current strap and Faraday shield. The experiments show that the fractional reduction in the magnetic flux linkage to the plasma resulting from the addition of any particular Faraday shield is virtually independent of the shape of the current strap. This is true in spite of the fact that the same mechanism which is responsible for the reduction in flux is also responsible for a significant redistribution of the antenna current on the current strap. Thus the process of optimizing antennas is reduced to that of separately optimizing the current strap and Faraday shield.**

I. Introduction

ION-CYCLOTRON resonance heating (ICRH) is one of the preferred supplemental heating methods for present and future fusion experiments. The object of this method is to launch the fast wave and heat the plasma without any deterioration in plasma confinement. Recent experimental results are encouraging. The *H*-mode, a regime of improved energy confinement, has been realized for the first time with ICRH alone [1]. Excitation of the fast wave could be accomplished by several types of launching systems. The prototypical antenna is a simple loop matched to the plasma shape. Cavity antennas, resonant double-loop antennas, and U-slot antennas are other, more advanced types of launching structures [2]. Waveguide launchers are also being developed [3]–[5]. Except for the last, every launcher has two primary parts: A current strap and a Faraday shield. The current strap launches the wave, and the Faraday shield controls the wave polarization and prevents plasma arcing around the current strap. This combination should be chosen to minimize the voltage and current requirements and to maximize the power coupling to the plasma. Plasma loading is a very important parameter in power-handling calculations. At a given power, larger plasma loading leads to relatively smaller voltage and current requirements. We measure how the power loading changes when a Faraday shield is added to a current strap configuration.

A cavity antenna consisting of a current strap in a recessed box and a Faraday shield at the front panel of the box is used in the present experiment. This kind of antenna was first used on DIII-D [6], and is now used on several large fusion experiments (e.g., the Tokamak Fusion Test Reactor, Tore Supra, and the Advanced Toroidal Facility). The coupling characteristics of this antenna have been studied theoretically and experimentally [2], [7], [8], and the effect of changing the current strap cross section was measured without a Faraday shield [9]. Faulconer [10] calculated the magnetic shielding effect and ohmic losses of the Faraday shield with a loop antenna model. The basic result can be applied to any antenna model.

Our experimental results show that a Faraday shield changes the current profile on the current strap, as shown in Fig. 1. The magnetic profile signal measured on the front side of the antenna strap also changed significantly when a Faraday shield was added, as shown in Fig. 2, in accordance with the numerical modeling of Chen *et al.* [11]. The shield redistributes currents in the interior of the antenna and attenuates fields outside the antenna. These experimental results indicate that the Faraday shield can create a significant redistribution of current on the current strap. To understand how this redistribution of current affects the optimization of the antenna, we added Faraday shields to the various current straps evaluated in [9] and compared the relative antenna coupling of the plasma surface.

II. Theoretical Considerations

Theoretical calculations for ICRH antennas have been performed by several authors [8], [12], [13]. We review some important results for the purpose of this experiment.

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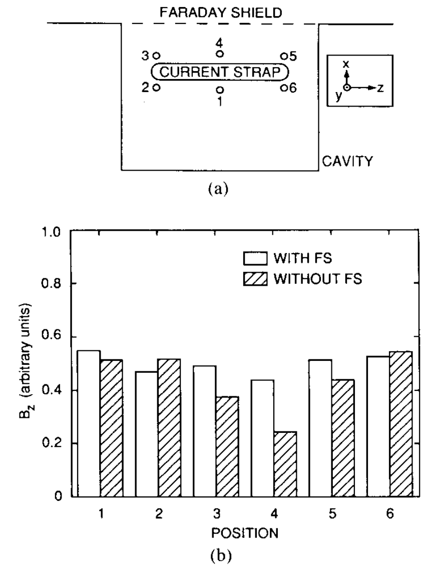

Fig. 1. (a) Sketch of the experiment with six measurement positions. (b) Changes of the magnetic flux at six locations around the current strap when a Faraday shield was added.

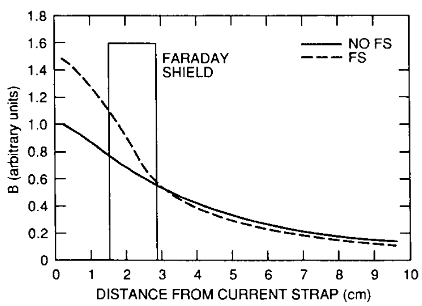

Fig. 2. Changes of the magnetic flux along the radial position on the front side of the current strap as the Faraday shield is added.

From Maxwell's equations, the plasma surface impedance seen by the antenna is calculated as

$$Z_p(k_z) = \left.\frac{E_y(k_z)}{H_z(k_z)}\right|_{\text{surface}}. \quad (1)$$

Here E_y and H_z are the values of the field at the plasma surface, and k_z is wave number in the z direction. We assume that $E_z \simeq 0$, which is true with a Faraday shield. The antenna impedance can be represented by

$$Z_a = R + i\omega L \quad (2)$$

where R is the antenna resistance, ω is the frequency of the launched wave, and L is the antenna inductance. This power out of the antenna is given by

$$P = P_{\text{plasma}} + P_{\text{loss}} \quad (3)$$

where

$$P_{\text{plasma}} = \frac{1}{2}\,\text{Re} \int \left|H_z(k_z)\right|^2 Z_p(k_z)\,\frac{dk_z}{2\pi}\,dy \quad (4)$$

$$= \frac{1}{2}\left|I\right|^2 \text{Re} \int \frac{Z_p(k_z)}{\mu_0^2}\left|\frac{B_z(k_z)}{I}\right|^2 \frac{dk_z}{2\pi}\,dy \quad (5)$$

$$\equiv \frac{1}{2}\left|I\right|^2 R_R \quad (6)$$

and

$$P_{\text{loss}} = \frac{1}{2}\left|I\right|^2 (R_{\text{FS}} + R_{\text{loss}}) \quad (7)$$

$$= \frac{1}{2}\left|I\right|^2 R_D. \quad (8)$$

Therefore

$$P = \frac{1}{2}\left|I\right|^2 (R_R + R_D). \quad (9)$$

Here R_{FS} is the loss in the Faraday shield, R_{loss} is the loss in the antenna structures, R_R is the radiation loading resistance, R_D is the dissipative resistance from the structures and shield, and I is the peak antenna current.

The voltage at the input of an electrically short antenna is given by

$$\left|\Delta V\right| = \left|(R + i\omega L)I\right| = \left[R^2 + (\omega L)^2\right]^{1/2}\left|I\right| \quad (10)$$

where

$$R = R_R + R_D.$$

Therefore

$$P = \frac{1}{2}\,\frac{R}{R^2 + \omega^2 L^2}\left|\Delta V\right|^2. \quad (11)$$

Usually for an inductive antenna $R << \omega L$, so

$$P \simeq \frac{R}{\omega^2 L^2}\left|\Delta V\right|^2. \quad (12)$$

For a given power, $\left|\Delta V\right|^2$ has a minimum when R/L^2 has a maximum. From these considerations, the required voltage and current are given by

$$\left|\Delta V\right| = \left[R^2 + (\omega L)^2\right]^{1/2}\left(\frac{2P}{R}\right)^{1/2} \simeq \omega L\left|I\right| \quad (13)$$

and

$$\left|I\right| = \left(\frac{2P}{R}\right)^{1/2}. \quad (14)$$

All quantities (voltage, current, power, and fields) are MKS.

III. Experimental Setup

A general diagram and equivalent circuit of the experiment are shown in Fig. 3. In this experiment the resistance R and inductance L of the antenna and the voltage ratio between the antenna and a probe are measured. A Hewlett Packard HP4191A impedance analyzer was used to measure the precise load resistances and inductances, and a Hewlett Packard HP8505 network analyzer was

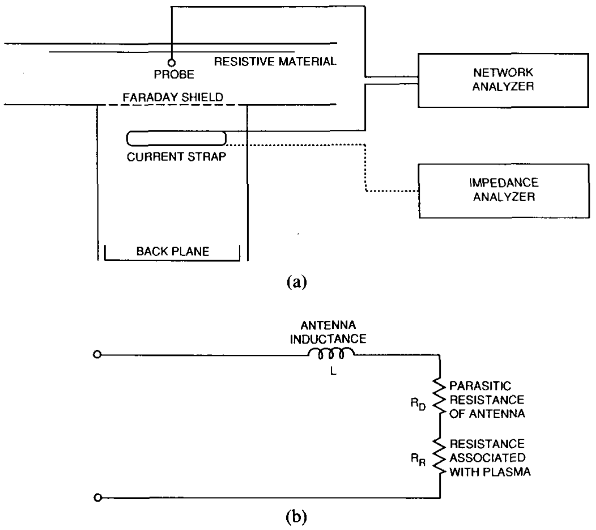

Fig. 3. (a) Schematic outline of the experimental setup, and (b) equivalent circuit diagram. Lead inductance, lead resistance, and probe impedance were also measured but for simplicity are omitted from the figure.

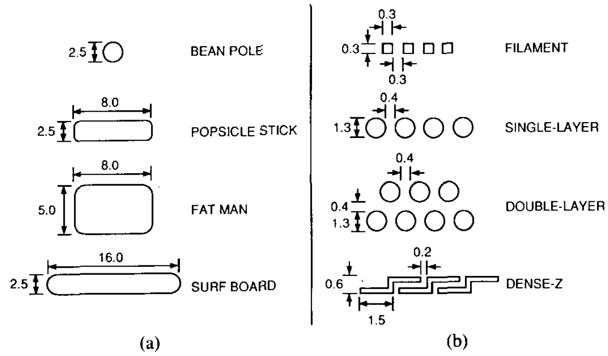

Fig. 4. The shapes and dimensions of the current straps (a) and Faraday shields (b) used in this experiment. All straps and Faraday shields were made of copper. All dimensions are in centimeters. Shapes are not to scale.

used to measure the probe voltage relative to an input voltage. The plasma was simulated by a stack of 13 sheets of resistive material (Eccosorb V060). The antenna was spaced 6-cm away from these sheets and run at 55 MHz, and a magnetic loop probe was placed close to the resistive material to measure the simulated plasma loading and magnetic field at the plasma surface. To obtain the antenna resistance, the input impedance was measured first with and then without a load. The resistance of the second measurement was subtracted from the first to eliminate losses due to the antenna structure. The magnetic flux was measured indirectly as a voltage ratio between the antenna and a probe,

$$\left|\frac{B_z}{I}\right| \simeq \left|\frac{v_p}{v_a}\right| \left|\frac{Z_a}{\omega A_p}\right| \tag{15}$$

where v_p is the induced voltage at the plasma, v_a is the voltage at the antenna, Z_a is the antenna impedance, and A_p is the probe area. Finally, since we have measured R_R,

$$R_R = \frac{1}{|I|^2} \text{Re} \int |H_z(k_z)|^2 Z_p(k_z) \frac{dk_z}{2\pi}\, dy \tag{16}$$

$$\simeq \frac{1}{\mu_0^2} (\text{Re } Z_p) \int \left|\frac{B_z}{I}\right|^2_{\text{surface}} dA \tag{17}$$

where we have assumed that Z_p is independent of k (valid for the current experimental setup, but not for a real plasma) and have made use of Parseval's theorem. For our purposes, this result can be written as

$$R_R \simeq \frac{A}{\mu_0^2} (\text{Re } Z_p) \left|\frac{B_z}{I}\right|^2_{\text{surface}} \tag{18}$$

where A is an "effective area" which accounts for the shape of the field pattern in a plane in front of the antenna, and B_z is measured at just one point. This means that R_R is proportional to $|B_z/I|^2$ at the plasma surface. In the experiment, 4 current straps and 4 Faraday shields were used to provide 16 possible combinations. Cross sections and dimensions of the current straps and Faraday shields are shown in Fig. 4.

IV. Results and Discussions

The Faraday shields change the antenna coupling characteristics, as shown in Fig. 5. The antenna resistance and magnetic field decreased and the required voltage and current increased when the Faraday shield was added. Coupling to the plasma is better with an open-type of Faraday shield (filament and single-layer) than with a closed-type (double-layer and dense Z).

Flux linkage was reduced only ~1% with filament shields and ~10–12% with single-layer shields, while it was reduced ~21–24% with double-layer shields and ~53–57% with dense Z shields. This reduction was described by Faulconer as "magnetic shielding." The shielding effect of a Faraday shield can be represented as a transmission coefficient, which is a function of both the current distribution in the current strap and the physical dimensions of the Faraday shield. In our experiment, it can be expressed as

$$\left(\frac{B_{\text{FS}}}{I_{\text{FS}}}\right) = T\left(\frac{B_{\text{NF}}}{I_{\text{NF}}}\right)$$

where T is the transmission coefficient summed for all wave modes, and the subscripts FS and NF denote measurements with and without Faraday shields, respectively. The value of T is 0.99 for the filament shield, 0.9 for the single-layer shield, 0.77 for the double-layer shield, and 0.45 for the dense Z shield according to our result.

A key experimental result is that the transmission coefficients are nearly independent of the current distributions, as shown in Figs. 6 and 7. Given that the Faraday shield significantly affects the distribution of current on the current strap, it is not immediately obvious why this should be true. However, as we shall explain below, this

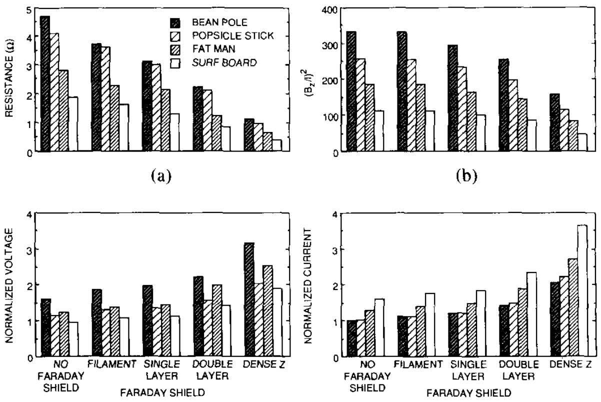

Fig. 5. Effects of the Faraday shield on the (a) antenna load resistance, (b) magnetic field, (c) required voltage, and (d) required current for the given power for the four current straps studied. The current and voltage curves are determined from the inductance measurements with an arbitrary load.

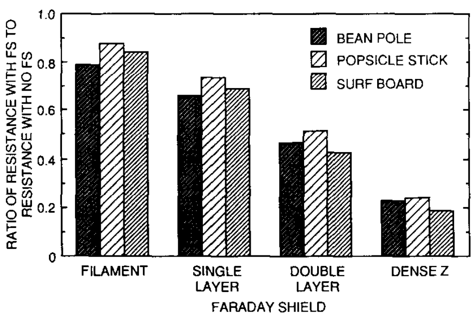

Fig. 6. Ratio of the resistance with a given Faraday shield to the resistance with no Faraday shield as a function of the current strap width. The current strap widths are 2.5 cm for the "bean pole," 8 cm for the "popsicle stick," and 16 cm for the "surf board." These show that the flux linkages of the various current straps are reduced by approximately the same amounts with an individual Faraday shield configuration.

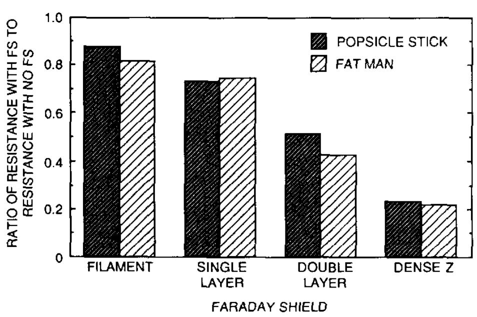

Fig. 7. Ratio of the resistance with a given Faraday shield to the resistance with no Faraday shield as a function of the current strap thickness. The current strap thicknesses are 2.5 cm for the "popsicle stick" and 5 cm for the "fat man."

result can be understood intuitively. This implies that, when designing an ICRF antenna, the optimization of the current strap and Faraday shield may be done separately. Figs. 6 and 7 show that the reduction in RF coupling which results from the addition of a Faraday shield is almost independent of the current strap configuration.

This result should be useful for choosing an optimal combination of Faraday shield and current strap. Since for a given power R/L^2 determines the required voltage, the information presented in Fig. 8 can be used to determine the voltage limitation with each combination, and the data in Fig. 5 can be used to determine current limitations with each combination. Fig. 9 shows the optimal regions for various combinations of current strap and Faraday shield. An optimum design would have as large a value as possible for R/L^2 to minimize voltage requirements, coupled with as large a radiation resistance as possible to minimize current requirements. Very thin current straps yield high values of radiation resistance at the expense of also producing large inductances. Widening the current strap allows the antenna current to disperse over a wider area, hence reducing the inductance, but also reduces the loading resistance. Varying the thickness of the current strap has less of an effect. Thinner straps are to be preferred. The result that the current strap and Faraday shield can be separately optimized is exhibited in Fig. 9 by the fact that none of the lines cross and that the symbols for the various Faraday shield configurations appear in the same order in each line.

Faulconer's shielding effect arises from the shield surface current in which the effect of the conductivity in the axis direction (y axis) is included. More specifically, in locations where the field due to the antenna current strap alone is tangent to the surface of the Faraday shield, the shield behaves almost like an ideal Faraday shield. However, in locations where the field due to the antenna current strap have components normal to the surface of the Faraday shield, diamagnetic eddy currents are included in the Faraday shield. These currents reduce the magnetic flux that links the antenna current loop and also modify the distribution of the current on the strap, as can be understood intuitively by referring to Fig. 10. For simplicity, only a single-layer Faraday shield is shown in Fig. 10, and the shield is modeled as an infinitesimally thin strap, but of finite width in the y direction. When one adds a Faraday shield to an antenna, one expects the field lines to be compressed to some extent between the shield and current strap. The mechanism for this can be understood by considering how the field generated by the diamagnetic eddy currents in the shield adds to the field generated by the current strap alone to produce the net field, as shown in Fig. 10. In the region between the Faraday shield and current strap, the parallel (z) components of these two fields add, while the perpendicular (x) components oppose one another, resulting in reduced field line curvature. However, at the edges of the current strap the field line curvature increases in order to bend around to the back of the strap. That increase in curvature cannot result directly from the diamagnetic eddy currents because they produce a B_x component of the wrong sign. The only possible source of this curvature would be an increase in the

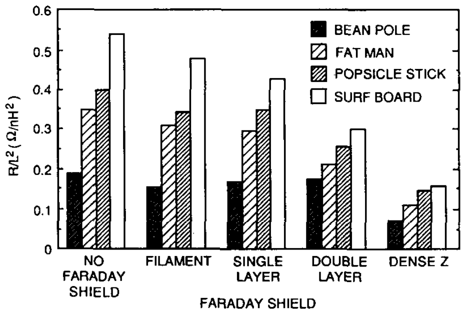

Fig. 8. Figures of merit R/L^2 for the 16 combinations of Faraday shield and current strap.

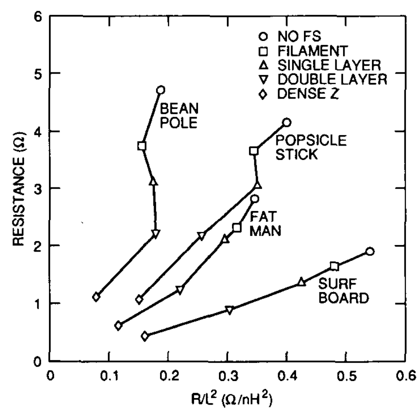

Fig. 9. Antenna load resistance versus R/L^2 for all 20 cases. The upper right corner is the optimum region.

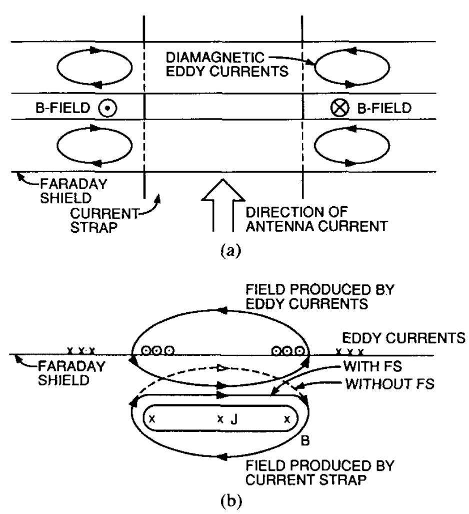

Fig. 10. Effects of eddy currents induced in the Faraday shield. The current strap and a single layer of Faraday shield strips are diagrammed. A view in a plane parallel to the "plasma" surface is shown in (a), and a section through the current strap is shown in (b). The directions of the applied and induced currents and fields are indicated.

current flowing in the edges of the strap, by redistributing it from the center of the strap, in agreement with the measurement in Fig. 1. (There would also be a corresponding increase in the image current flowing in the sidewall of the antenna cavity.) Note also that the image current which would flow in the antenna current strap in response to the Faraday shield eddy currents would increase the current in the antenna edges.

It is also not difficult to understand intuitively why this current redistribution effect has no significant effect on the Faraday shield transmission. The dispersion relation for launching waves into "free space" is given simply by

$$k_x^2 = \omega^2/c^2 - k_z^2. \tag{19}$$

Thus only wave components with very low values of k_z propagate away from the antenna, the higher k_z components being evanescent. But the redistribution of current on the antenna affects only these higher k_z values. More specifically, the evanescence length for these components is on the order of the width of the current strap. Since the distance between the current strap and resistive load was larger than the width of the current strap, it is not surprising that the current redistribution had a negligible effect on the coupling. We should note cautiously that a real plasma allows significantly higher values of k_z to couple, in which case this current redistribution effect might be more significant.

Other factors affecting the current redistribution and magnetic shielding are the effect of the reflected wave from the plasma surface and ohmic losses. In an intuitive treatment of eddy currents in the Alcator C antenna [14] similar to the preceding, it was shown that the effect of ohmic losses in the Faraday shield is to reduce these effects. This was also pointed out by Faulconer [10].

Analysis of the net effect of the Faraday shield on the transmission characteristics in the plasma region requires a self-consistent method which includes the plasma response. The physics of the plasma scrape-off layer (SOL), and the interaction of the SOL with the antenna involve both coupling and spectral contents. While the shape of the current strap and its interaction with the Faraday shield can be optimized to the lowest order, further refinement to incorporate plasma selectivity is needed. Therefore, the next step in the process of antenna optimization should include plasma effects.

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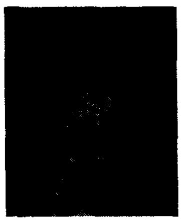

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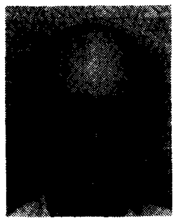

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