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MEASUREMENTS OF THE ELECTROSTATIC AND ELECTROMAGNETIC FIELDS
OF FARADAY SHIELDED HALF-TURN LOOP TYPE
ICRF ANTENNAE

By

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ABSTRACT

Detailed measurements of both the electrostatic and electromagnetic fields are performed for various types of Faraday shields mounted on PLT ICRF antennae. The data show that the shields have little effect on the electromagnetic fields when the antenna is driven such that it is generating a constant total flux for the various cases. A new type of shield (Type II) is investigated that has no effect on the antenna inductance and performs equally as well as the conventional shields (Type I) in shielding out the electrostatic fields. Measurements indicate, for the shields investigated, that each layer of shield strips degrade the Q by approximately a factor of two.

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Introduction

The effects of Faraday shields on the wave characteristics excited by loop antennae have been demonstrated by experiments conducted on the C-stellarator at Princeton.¹ In these experiments, when a Faraday shield was not used, the coupling of power to the plasma did not exhibit resonant behavior. The 'non-resonant' coupling was accompanied by a large influx of impurities which raised the electron density by as much as a factor of two. When an electrostatic Faraday shield was employed, the impurity influx was measured to be negligible and both the ion heating rate and maximum temperature increased. More recently, the need to use Faraday shields on loop antennae in the Ion Cyclotron Range of Frequencies (ICRF) has been illustrated in the heating experiments on TFR² where various shaped shields are found to have a significant effect on the heating and antenna loading results.

A Faraday shield serves several purposes. From a structural point of view a shield can provide protection for the antenna from plasma, neutral, and photon bombardment. A Faraday shield should be opaque to the electrostatic fields but transparent to the electromagnetic fields. From the coupling efficiency standpoint, it is desirable to minimize the image currents on the shield so energy is not wasted in joule heating of the shield strips. A single design cannot fully optimize all these aspects at once and so involves trade-offs of these various requirements. For example, the perfect electrostatic, particle, and photon shield would entail complete enclosure of the antenna within a grounded case. On the other hand, the least lossy and most transparent shield (to the electromagnetic fields) is no shield at all.

Experimental results from PLT,³ TFR,⁴ and JFT-2M⁵ have motivated a series of recent theoretical investigations of the effects of Faraday shields on the fields produced by ICRF antennae.⁶⁻⁸ These theoretical studies have

emphasized the calculation of a transmission coefficient for the electromagnetic fields and little attention has been given to the attenuation of the electrostatic fields. This paper presents the results of experimental studies where the emphasis has been on observing the effects of various Faraday shields on both the electrostatic and electromagnetic fields produced by ICRF loop antennae. The measurements were performed with the antennae radiating into free space rather than a plasma. The antennae used are PLT half-turn loop type. Measurements were performed with two different types of Faraday shields and with no shields at all. The remainder of the paper begins with a short discussion on how Faraday shields work in principle. Then a description of the shield design and field measurement techniques is presented. The experimental results and discussion are given together followed by a summary.

Heuristic Discussion

In the ICRF experiments a coaxial line is used to transmit the energy from the rf source to the ICRF antenna. Assuming there are no wall losses, the electric and magnetic fields in the transmission line are in the directions shown in Fig. 1a giving rise to a Poynting flux down the coaxial line and towards the antenna. The net rf electric field is purely radial. The $\oint$ and $|\vec{A}|$ contours for a particular integration constant are schematically shown in Fig. 1b. The $-\vec{\nabla}\phi$ electric field has both radial and axial components. The $-\vec{A}$ electric field is antiparallel to the current and therefore in the axial direction. The purpose of a Faraday shield is to screen out the $(-\vec{\nabla}\phi)_r$ and $(-\vec{\nabla}\phi)_z$ components leaving only the $(-\vec{A})_z$ electric

field, which along with the azimuthal (around the center conductor) magnetic field generates a Poynting flux radially away from the antenna instead of a Poynting flux along the conductors, as in the case of the coaxial transmission line. The scrape-off plasma region where the antenna resides is in the near field of the antenna and therefore, an electrostatic shield is necessary if it is desirable to keep the $-\nabla\phi$ fields from the plasma. A Faraday shield accomplishes this by slotting the outer conductor of the coaxial line. The slots allow the azimuthal magnetic flux from the transmission line to "leak" out. An electric field is induced between the shield strips (a gap voltage), which is in a direction such that it supports $\vec{E} \times \vec{B}$ movement of flux from the gap and away from the antenna. The electrostatic field lines, which without a shield terminate either on the antenna or on the nearby ground plane, with a shield terminate on the shield strips, a relatively shorter scale length, and thus are not present outside the shield.

Apparatus

As mentioned above, the antenna used in this study is a PLT half-turn type loop antenna. The antenna and some of the Faraday shields that were investigated are illustrated in Fig. 2. The large metal backplate simulates the vacuum vessel wall. Mounted on the antenna in Fig. 2 are the various types of shields used in the study. On the left are some Type II shields. They are oriented so the strips lie in the plane of the magnetic flux generated by the antenna strap and are therefore nearly 100% transparent to a line of sight. Moving to the right is a section of bare antenna and then some Type I bottom layer shields. On the far right are the Type I shields with both top and bottom layers mounted, which is the usual way in which the PLT

antennae are shielded. For further reference it should be noted that individual Type I and Type II shield strips are nearly identical in their dimensions and that the only important difference is their orientation with respect to the antenna surface. PLT has a minor radius of 50 cm and the antenna subtends $\sim 180^\circ$ of poloidal angle with the center of the antenna at the midplane. The antenna is driven at a frequency of nearly 30 MHz ($\pm 0.5\%$). As is done in the PLT experiments, open ended transmission line is added to one of the antenna feeds so that the electrical length from the open to the midplane is equal to a quarter wavelength. Under these conditions, the current maximum (a virtual ground) is on the midplane. An equal amount of transmission line is added to the other feed making the entire structure half-wave resonant at 30 MHz. When driven in this configuration, the antenna has an impedance $\gg 50 \Omega$ and so stubs are used for impedance matching. A vector impedance bridge was used for the Q measurements and measuring the effects of the Faraday shields on the antenna capacitance and inductance.

The probes used to measure the electrostatic and magnetic fields are shown in Fig. 3. The electrostatic probe⁹ is triaxial with the inner shield driven at the center conductor potential in order to negate the probe capacitance. The probe was tested by looking for a flat frequency response and measuring the potential between parallel plates driven at 30 MHz. The magnetic pickup probe was designed to shield out electrostatic pickup, a Faraday shielded loop in essence. The slot in the shield was placed at the center of the loop so any electrostatic pickup would drive both leads at the same potential and therefore could be more easily removed with a differential amplifier or rf transformers if desired. An rf choke is used for further attenuation of any common mode pickup. The electrostatic pickup on the probe was found to be negligible. A second magnetic pickup loop (normalization

probe) similar to the one just described was placed between the antenna and the backplate, on the midplane. Since all the flux generated by the antenna must return through this region, this probe provided a signal proportional to the total flux generated. In order to compare various shields, the driving power was adjusted to keep the signal from the normalization probe constant. The normalization probe also provided a phase reference for the magnetic and electrostatic probes. A vector voltmeter was used to measure the amplitude and phase of the various signals.

Some of the paths on which the probes were moved are schematically shown in Fig. 4, with the Faraday shields not shown for clarity. Paths E1 and E2 were measured at a poloidal angle of about 70° from the midplane. Paths M1 and M2 were measured at the midplane where the electromagnetic fields are largest. Since the electrostatic probe measures potential, the data along a given path were fitted with a cubic spline and the derivative of the curve was used to calculate the electrostatic field.

Experimental Results and Discussion

Impedance Measurements

Useful information about a Faraday shield can be obtained by measuring the complex impedance of the antenna and how it changes as shield strips are added to it. The results of this measurement for the Type II shield are shown in Fig. 5. Before any shields are added, the antenna, feedthroughs, and equal lengths of coaxial cable at each feedthrough are driven at the half-wave resonant frequency (≈ 30 MHz). Under these conditions the impedance is purely real and has a value of $R_0 \approx 7$ k Ω . As shields are added, while the frequency is kept constant, the real part of the impedance gets smaller and the reactive

part first begins to get larger, and then once it equals the real part, becomes smaller. After all the shields are added, the structure is well off resonance and has nearly a purely reactive impedance with a magnitude that is 600 Ω . Once all the shields are added, the driving frequency is adjusted to the new resonant frequency to compensate for the impedance change. In this case the frequency changed such that $\Delta\omega/\omega = -0.004$. Though $\Delta\omega$ is relatively small, the Q is high enough such that the impedance undergoes the dramatic change that is illustrated in Fig. 5. The reason for this behavior can be understood by modelling the antenna structure as a parallel LRC circuit. Such a circuit has an impedance given by

$$Z = \frac{R_0 L - j R^2 (\omega^2 LC - 1)}{\omega L + R^2 / \omega L (\omega^2 LC - 1)^2} .$$

At $\omega^2 LC = 1$, $Z = R + j(0)$, which in the case of the unshielded antenna is 7 k Ω . Since the resonant frequency is downshifted, this indicates that the shields either increased the capacitance or inductance of the antenna structure. In addition, the above equation demonstrates that by increasing either L or C the imaginary part will go negative and thus look capacitive. However, a physical argument can be made (discussed later) that the Type II shields add capacitance. With this assumption the above equation explains the behavior exhibited in Fig. 5. As capacitance is added such that $\omega^2 LC > 1$, the imaginary part starts becoming more negative and the real part decreases as the denominator becomes larger. The real and imaginary parts are equal in magnitude when

$$\omega L = R (\omega^2 LC - 1) ,$$

which in the case of Fig. 5 is 3.5 k Ω . It can easily be shown that a peak in the magnitude of the reactance is also given by the above condition. As the capacitance continues to increase, the structure begins to look mostly capacitive and, as expected, the eventual limit is a short circuit.

A more interesting behavior is exhibited by the Type I shields shown in Fig. 6. Again the structure is driven at its half-wave resonant frequency without any shields resulting in a purely real impedance of 7 k Ω . As the first layer of shields is added (starting at the midplane or current maximum), the antenna structure starts looking inductive. As more shields are added (moving towards the high voltage ends), the effect is to make the structure look more and more capacitive. As the last few inner shields are added, the behavior looks similar to the Type II shields. After the first layer of shields is installed, the new resonant frequency has a value such that $\Delta\omega/\omega = -0.003$. As with the Type II shields, the net effect is added capacitance but clearly there is an additional effect when the first few shields are added and the antenna looks inductive. The impedance equation indicates that the imaginary part is positive (inductive) when $\omega^2 LC < 1$. Therefore, the shields are either decreasing the antenna capacitance or inductance. Since by bringing a grounded conductor closer to the antenna should increase the capacitance, the first few shields must be decreasing the inductance. There is a simple explanation for this effect. Since the field strips do not lie in the plane of the field lines, everywhere except where the strip is tangent to the field there is a component of $\vec{B}$ normal to the shield. This component induces current in the shield which in turn generates flux to make $\hat{n} \cdot \vec{B} = 0$ at the conductor. These particular currents, arising from the antenna $\vec{B}$ field having a component normal to the conductor, are diamagnetic. That is, they decrease the antenna inductance, and thus for the same antenna current,

decrease the net flux generated by the antenna. A schematic of this effect is illustrated in Fig. 7. The field lines generated by the antenna and the sides of the shield strips are shown separately. The net flux through the side strips is zero. Note that the field lines generated by the currents in the shield have a y-component, whereas the antenna field lines lie in the x-z plane. It is this y-component that "pushes" the flux away from the shield and to a gap through which the flux escapes. The Type II shields lie in the plane of the flux surface and thus no diamagnetic currents are generated. This explains why the Type II shields only increase the antenna capacitance and do not affect the antenna inductance.

Referring back to Fig. 6, after the first layer was installed and the frequency changed to the new half-wave resonance, the second layer was added. The effect of the outer shields is the same as the effect of the first few inner shields. That is, they tend to decrease the antenna inductance and any effect on the capacitance is not observed. This suggests that only the first layer is necessary to shield the electrostatic field. The second layer essentially sees a ground plane established by the first layer and not the charge distribution on the antenna. This claim is supported by the field measurements presented below. The diamagnetic effect is still present with the second layer tending to increase the resonant frequency as the inductance is lowered. Comparing the first and second layer half-wave resonant frequencies show $\Delta\omega/\omega = +0.017$. Before proceeding with the field measurements, a word should be mentioned about shield currents generated by the component of $\vec{B}$ that is tangential to a shield surface. The tangential component of $\vec{B}$ generates shield currents that exclude the flux from inside the shield, but unlike the diamagnetic currents, they increase slightly (by compression) the flux just above and below the shield surface. Ideally there

is no net change in flux, and when the shield thickness is much less than all other scale lengths (which is the case on PLT), this slight rearrangement of flux is negligible. This claim is also substantiated by the field measurements.

Electrostatic Fields

As described earlier, all cases were run with the same signal on the probe that measured flux passing between the antenna and backplate. Figure 8 shows the electrostatic potential for an unshielded antenna measured 1 cm above the antenna (radial direction) as a function of poloidal angle. Near 0° (midplane) the data indicate a virtual ground as expected. A sharp 180° phase shift is detected when the probe is moved poloidally past the virtual ground and little phase shift is measured between all the data on one side or the other of the virtual ground indicating the presence of a standing wave. The fitted curve is the spline fit from which the poloidal electrostatic field is calculated. The poloidal electrostatic field for this case is shown in Fig. 9. Note that it points in one direction as expected but falls off in magnitude as the feeds are approached. It is incorrect to explain the effect by claiming that the feeds are voltage maxima and thus the field (the slope of the potential curve) should go to zero there. The electrical length from feed to feed is a good deal less than a half-wavelength. The feeds and added transmission line on each end are added to make the entire structure have a half-wave resonance near 30 MHz. Therefore, it is probably a fringing effect that causes the poloidal electrostatic field to fall off rapidly near the feeds. This same sort of behavior is observed with the magnetic field and is discussed below.

In the opinion of many investigators of ICRF heated plasmas an important role of a Faraday shield is to shield out the electrostatic field component parallel to the dc magnetic field. Since the confining field is mostly toroidal, $(-\vec{\nabla}\phi)_\parallel$ lies in a plane parallel to the antenna surface $(\hat{z})$. Figure 10 shows the electrostatic potential for three different cases as the probe is moved between two shields in the direction indicated by path E1 in Fig. 4. The effect of the shields on the electrostatic potential is such that outside the shield the potential is nearly zero. The fitted curves are used to calculate $(-\vec{\nabla}\phi)_z$ which is plotted in Fig. 11. Note that near the antenna the electrostatic fields are stronger for the shielded cases than the nonshielded case. However, at 4 cm from the antenna both shields show > 90% attenuation of the $(-\vec{\nabla}\phi)_z$ field or > 20 dB attenuation of the electrostatic field energy. It is interesting to note that although the physical orientation of the Type II shields keeps the antenna almost 100% transparent to visible light (see Fig. 2), they appear to work equally well in attenuating the electrostatic field as one layer of the Type I shields. The measurements with both layers of the Type I shields showed no measurable change in the electrostatic field outside the shields, in agreement with the conclusion made earlier in regard to the impedance measurements.

Electrostatic potential and field data for probe path E2 (Fig. 4) are shown in Figs. 12 and 13. The electrostatic field measured here is normal to the antenna surface and thus tends to accelerate charged particles into the antenna. Ion bombardment of the antenna can result in high impurity influx and antenna damage. Therefore, attenuation of the radial electrostatic field should be considered an important task of a Faraday shield. The data in Figs. 12 and 13 are similar to the $(-\vec{\nabla}\phi)_z$ data. The Type I and II shields enhance the radial electrostatic field below the shield but show a factor of 2

10 of attenuation of the field outside the shield. The physical explanation for the enhancement of the electrostatic fields between the antenna and shields is a simple one. A Faraday shield is a grounded conductor whose surface area is smaller and closer than the total surface area on which the field lines would terminate if the shields were not present. With a smaller and closer surface area, the field lines are compressed, and therefore the field intensity increases.

Electromagnetic Fields

Figure 14 shows $\dot{B}_z$ as the probe is moved radially away from antenna at the midplane (path M1 from Fig. 4). Since the total flux is constant for each of the four cases, it is not surprising that the total area under each of the curves is approximately equal. The important result here is that there appears to be very little rearrangement of the flux due to the shields as shown by the nearly identical curves for the four cases. There are no inflections in the data as the probe moves past the shields, and the scale lengths for the four different cases are nearly equal. The data show that the addition of a second layer to the Type I shield had no measurable effect on the field pattern at the midplane.

Figure 15 shows $\dot{B}_z$ when the probe is moved along path M2 of Fig. 4. At the surface of the antenna, $B_z(z) \propto J_y(z)$, which is the current distribution on the antenna. Figure 15 shows nearly a doubling of J_y at the edges of the antenna as compared to the center value. This behavior will affect the k_z spectrum launched by the antenna and could influence theoretical predictions where it is often assumed that the current distribution is constant across the antenna. As with Fig. 14 it appears that the Faraday shields have little effect on the electromagnetic measurements.

Figure 16 shows the dependence of $\dot{B}_z$ on the poloidal angle for a constant distance above the antenna. For this data the probe was kept 1 cm above the antenna, which placed it between the shields and the antenna surface. Once again the various shields had little effect on the data. Changes in antenna electrical length due to slightly different driving frequencies, antenna inductance, or antenna capacitance are too small to be seen in this case. The data from Fig. 16 seem to suggest that the antenna is only slightly less than a half-wavelength long from feed to feed. As discussed with Fig. 9, this conclusion is erroneous. The flux must collapse around the feeds and the effect manifests itself by a sudden drop of $\dot{B}_z$ due to fringing effects near each of the feeds. This effect should probably be included in any model that predicts a spectra of poloidal modes excited by this type of antenna. A similar set of data taken 3 cm above the antenna and therefore above the shields, showed results similar in shape to the curves of Fig. 16 but reduced in amplitude.

Because of their periodicity, it is possible that Faraday shields excite modes with a short wavelength in the poloidal direction. It is hypothesized that these modes propagate on the plasma surface where they can collisionally damp and ultimately enhance impurity influx. In order to provide some information to answer this question, the electromagnetic probe was moved in the poloidal direction at a distance from the antenna such that it was just grazing across the tops of the shields. The data for the Type I shields, both layers, are shown in Fig. 17. The probe was moved over a few shields near the midplane where the amplitude is constant. The data indicate about a 3% peak-to-peak ripple in the $\dot{B}_z$ field. A top view of the strips as the probe moves in the poloidal direction is shown below the data. Minima in the signal are measured when the probe is above a top shield and maxima when it is above a

bottom shield. Though a few percent variation seems small, in a high power experiment it can represent several kilowatts of power which, if deposited in a thin layer at the surface, can result in a relatively high power density. Similar measurements for the Type II and Type I (bottom layer only) shields showed no detectable ripple in the data.

Antenna Q measurements with the various types of Faraday shields are shown in Table I. The data indicate about equal degradation of the Q for the Type II and Type I (bottom layer only) shields. The total shield surface area for the two cases is about equal and so the image currents generated by the field lines tangential to the shields will produce about equal losses. As discussed previously, there are also diamagnetic currents which further spoil the Q for the Type I shields. All the Q measurements show a substantial degradation from the no shield case. However, even the double-layered Type I case has a relatively high Q as compared with the plasma loaded Q in the PLT experiments. This means that only a small fraction of the power gets dissipated in the shields. On the other hand, a few percent of the large coupled powers planned for the future (PLT now couples > 1 MW per antenna) can still present formidable problems for shield integrity, especially as the pulse lengths are increased.

Summary

The most important result of this investigation can be stated as follows: When the measurements are performed so the total flux generated by the antenna is kept constant, the data indicate that there is little difference in the rf magnetic field profile for the various types of shields investigated. The concept of a decrease in transmission of magnetic flux due to a Faraday shield is not that a smaller fraction of the flux gets coupled to

free space or a plasma when a shield is present, but rather that there is a net decrease in the total flux generated by the antenna, for constant current, and is due to a decrease in antenna inductance.

Except for the small rippling effect seen with the Type II shields (both layers), the measurements with the Type I and Type II shields did not indicate any gross perturbations to the no shield magnetic field pattern (Figs. 14, 15, 16). The magnetic measurements show that the antenna current peaks on the edges of the center conductor. The poloidal variation of B_z indicates a drop in magnitude near the feeds that is greater than the $\cos \theta$ dependence (θ is the electrical length from the midplane to the feed) that might be expected from a simple transmission line type of analysis. The electrostatic measurements show about equal shielding for the various cases considered. The Type II and Type I (bottom layer only) shields spoiled the antenna Q by about a factor of two. Adding a second layer of Type I shield strips produced another factor of two degradation of the antenna Q.

TABLE I

<u>Shield Type</u>	<u>Q</u>
No Shields	1246 $\pm$ 8%
Type II	694 $\pm$ 1%
Type I - bottom layer	614 $\pm$ 0.5%
Type I - top and bottom layers	328 $\pm$ 0.5%

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References

1. Rothman, M.A., Sinclair, R.M., and Yoshikawa, S., "Non-Resonant' Coupling of R.F. Power to a Plasma," J. Nucl. Energy 8 (1966) 241.
2. Jacquinet, J. and TFR Group, "ICRF Antennae and Heating Studies in High Density TFR Plasmas," Proceedings of International Conference on Plasma Physics, Nagoya (1980), 226.
3. Hosea, J. Bell, R., Budny, R. et al., "PLT Ion Cyclotron Range of Frequencies Heating Program," Heating in Toroidal Plasmas, (Proc. of the 4th Internat. Symp., Vol. 1) Rome (1984) 261.
4. Adam, J., TFR Group, "ICRF Heating in TFR in Conditions of Low Impurity Radiation," Heating in Toroidal Plasmas, (Proc. of the 4th Internat. Symp., Vol. 1) Rome (1984) 277.
5. Odajima, K., Matsumoto, H., Kimura, H., et al. "Second Harmonic ICRF Heating Experiment in the JFT-2M Tokamak," Heating in Toroidal Plasmas, (Proc. of the 4th Internat. Symp., Vol. 1) Rome (1984) 243.
6. Faulconer, D.W., "Adverse Shielding of the Heating Field and High Ohmic Loss Introduced by Electrostatic Shields Employed in Radio-Frequency Heating of a Plasma," Nucl. Fusion 54 (1983) 3810.
7. Perkins, F.W., "Magnetic Shielding by a Faraday Shield," Heating in Toroidal Plasmas, (Proc. of the 4th Internat. Symp., Vol. 1), Rome (1984) 1148.
8. Bhatnagar, V.P., Koch, R., Messiaen, A.M., Weynants, R.R., "A 3-D Analysis of the Coupling Characteristics on Ion Cyclotron Resonance Heating Antennae," Nucl. Fusion 22 (1982) 280.
9. Patrick Colestock, private communication

Figure Captions

- Fig. 1. a) Traveling wave fields inside a coaxial transmission line.
 b) Contours of constant $|\vec{A}|$ and ϕ for a particular integration constant in a coaxial transmission line.
- Fig. 2. Photograph of bench set-up of antenna with various shields mounted for illustration. From left to right are the Type II shields, bare antenna, bottom layer Type I shields, and bottom and top layer Type I shields.
- Fig. 3. a) Bootstrap circuit used for electrostatic probe to reduce the effect of probe capacitance.
 b) Magnetic probe with electrostatic shielding and an rf choke to reduce common mode pickup.
- Fig. 4. Probe paths for measuring (a) $\phi(z)$, (b) $\phi(r)$, (c) $\dot{B}_z(r)$, and (d) $\dot{B}_z(z)$.
- Fig. 5. Effect on antenna impedance as Type II Faraday shield strips are added one at a time to bare antenna driven at the half-wave resonant frequency.
- Fig. 6. Solid points illustrate the effect on antenna impedance as bottom layer Type I shields are added one at a time to bare antenna driven at the half-wave resonant frequency. Open points illustrate the effect on antenna impedance as the top layer Type I shields are added one at a time to antenna with Type I bottom layer shields already mounted and driven at the half-wave resonant frequency.
- Fig. 7. Diamagnetic currents are induced in shield strips when antenna field lines are normal to the surface of the shield so as to make $\hat{n} \cdot \vec{B} = 0$. These currents lower the antenna inductance.

- Fig. 8. Electrostatic potential as a function of poloidal angle measured 1 cm above the antenna. A virtual ground exists at $\theta \approx 0^\circ$.
- Fig. 9. Poloidal electrostatic field obtained by differentiating the spline fit to the data of Fig. 8.
- Fig. 10. Electrostatic potential measurements along path E1 of Fig. 4 for various shield configurations.
- Fig. 11. $(-\nabla\phi)_z$ obtained by differentiating the spline fit to the data of Fig. 10.
- Fig. 12. Electrostatic potential measurements along path E2 of Fig. 4 for various shield configurations.
- Fig. 13. $(-\nabla\phi)_r$ obtained by differentiating the spline fit to the data of Fig. 12.
- Fig. 14. B_z data as a function of radial distance from the antenna show little difference for the various shield configurations when all cases are driven with the same output signal on the normalization probe.
- Fig. 15. $B_z(z)$ measured on surface of antenna gives $J_y(z)$. Antenna current peaks on the edges of the center conductor.
- Fig. 16. $B_z(\theta)$ for various shield configurations. The data fall off more rapidly near the feeds than would be expected from a simple transmission line analysis.
- Fig. 17. A ripple in $B_z(\theta)$ is observed when the probe is moved such that it grazes along the top of the Type I shields (both layers). This effect is not seen with the Type II shields or Type I shields, bottom layer only.

Fig. 2

84X1835

Fig. 3

84X1834

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

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