

PFC/JA-89-57

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December 1989

To be published in Fusion Engineering and Design

This work was supported by the U. S. Department of Energy Contract No. DE-AC02-78ET51013. Reproduction, translation, publication, use and disposal, in whole or in part by or for the United States government is permitted.

ICRF-EDGE PLASMA INTERACTION STUDIES AT MIT

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ABSTRACT

The Alcator C-Mod experiment will study high power ICRF heating of elongated, diverted plasmas at high density in a compact, high field tokamak. ICRF heating will be carried out in the minority heating regime by fast wave excitation in a deuterium plasma with a ^3He or H minority. Because of compact size of the tokamak, high loading will be required to couple the power at acceptable voltages and there will be high power density at the antenna surface. High edge densities and steep edge gradients are expected, making the ICRF-edge plasma interactions a key issue. Several studies have been undertaken to better understand these effects. Measurements have been made of the short wavelength perturbations to the rf fields caused by various Faraday shield geometries. Magnetic field probes show a perturbation which is largest near the ends and between the shield elements where the rf magnetic field is mostly radial. Electric field probes show a perturbation which is larger in the center of the elements and close to each element. A test antenna is being installed in the Versator II tokamak to study ICRF-edge plasma effects. The rf will be excited in the IBW polarization with k_{\parallel} chosen for interaction with edge electrons. The properties of different Faraday shield coatings, including titanium carbide and boron nitride, will be explored. It will also be possible to bias the protection limiters of this antenna in order to study the effect of biasing on the plasma density in the vicinity of the Faraday shield and resultant impurity generation.

I. INTRODUCTION

The Alcator C-Mod tokamak currently under construction at MIT will have an experimental program to study high power ICRF fast wave heating. In preparation for these experiments, several studies have been undertaken to better understand some of the issues concerning ICRF interaction with the edge plasma. Before discussing these studies, the Alcator C-Mod tokamak and the proposed ICRF experiments will be described.

Alcator C-Mod will add the benefits of plasma elongation and divertor operation to the features of the previous Alcator experiments, namely, high field, high density, and compactness. The magnetic field will be up to 9 T, the density $n_e=1-10 \times 10^{20} \text{ m}^{-3}$, the major radius $R=0.665 \text{ m}$, and the minor radius $a=0.21 \text{ m}$, with an elongation of up to $\kappa=1.8$. Expected plasma temperatures for ohmic heating with up to 3 MA of current will be in the range of 2-4 keV. Single-null and double-null divertor configurations with a variety of plasma shapes will be available, as well as pellet fueling.

ICRF heating will be carried out by fast wave excitation in the minority heating regime. The rf frequency of 80 MHz permits experiments in deuterium majority plasmas with either a ^3He minority at $B=7.9 \text{ T}$ or a hydrogen minority at $B=5.3 \text{ T}$. Up to 4 MW of rf power will be available with a 1 second pulse duration, and plans call for up to 2 MW to be applied by a single antenna. In order to limit the peak voltages to the range of 40-50 kV, load resistances of 10-20 Ohms/m will be necessary. The antenna will have to be as close to the plasma as possible and conform to the plasma shape to attain such loading. The first antenna [1,2] will be movable radially in order to accommodate a variety of plasma shapes and antenna-separatrix distances. The optimum plasma shape and the antenna-separatrix distance that will not affect divertor operation will be established during initial experimental operation. The desired range of radial movement requires that the antenna retract into the side port opening. This constraint on the antenna size makes the rf power density $P/A \gtrsim 1.7 \text{ kw/cm}^2$.

The antenna will have a single current strap, also because of the size limitation. An antenna with two current straps driven out-of-phase, which has proven so successful in other experiments [3,4] has an n_{\parallel} spectrum which is too high for effective coupling when forced to fit into the port opening. Once the plasma shape and antenna radial position have been established experimentally, an optimally spaced two-strap antenna will be mounted inside the vacuum vessel.

Alcator C-Mod will be the first experiment to study diverted plasmas at high density. The edge plasma conditions may be quite different from other ICRF heating experiments. The density in front of the antenna is likely to be much higher. The density scrape-off length for limiter plasmas in Alcator C was short (~ 4 mm) [5] and the effect of a divertor is not known for these conditions. The expected high edge density and short scrape-off length combined with the desired high power density and high loading will make the ICRF-edge plasma interaction a key issue for these experiments.

II. THE ALCATOR C-MOD ANTENNA FARADAY SHIELD DESIGN

The Faraday shield for the first antenna in Alcator C-Mod will have a double layer of elements tilted along the magnetic field. The coating will most likely be titanium carbide, although boron nitride is also being considered. The elements will have a triangular cross-section with a flat side of the outer layer facing the plasma and a flat side of the inner layer facing the current strap. Figure 1 shows the antenna configuration. The sides of the antenna box are slotted halfway to the backplane. The Faraday shield elements are mounted in pairs made up of an inner and outer element, with a slot for each pair. This paired configuration of the elements is shown in Fig. 2.

The features of the Faraday shield were chosen with particular attention paid to interactions with the edge plasma. The elements were tilted along the magnetic field because the angle of the field lines can be large for elongated plasmas, up to 20° in Alcator C-Mod. Experiments on JET [6] have shown the

importance of aligning the elements with the field for reducing impurities. Other experiments have observed parasitic edge coupling from rf fields not in the fast wave polarization [7].

A two layer shield was chosen to better isolate the resonant circuit of the antenna from plasma reactive effects. The triangular cross-section of the elements allow the radial width of the two layers to be short, making the gap between the current strap and the plasma as small as possible. A second reason for using a triangular cross-section was the suggestion by Perkins [8] that impurity influx by sputtering of the Faraday shield can be reduced if the material is sputtered primarily away from the plasma.

The use of slots on the sides of the antenna box improves the coupling to the plasma, which is very important since high loading will be required to couple 2 MW from one antenna. The slots also reduce the rf power density by increasing the effective surface area of the antenna.

III. FARADAY SHIELD FRINGING FIELD MEASUREMENTS

Near the elements of the Faraday shield, the rf fields will have a perturbation with the periodicity of the element spacing and therefore a large poloidal wave number. This may result in undesirable interactions with the edge plasma such as local heating or excitation of edge wave modes. A test antenna was constructed to study these perturbations in the absence of plasma. The antenna has a single, centertapped current strap in a box with closed sides. A single layer Faraday shield of the flat strips covers the top and bottom thirds of the box. Several different shields geometries were tested in the middle third of the front of the box. All shields tested have 12.5 mm wide elements with 6 mm gaps between them, but differ in the element cross-section. Single layer shields of circular and triangular cross-section, as well as single and double layer shields of flat strips have been studied. A 6 mm diameter, single turn, shielded magnetic loop was used to measure the rf magnetic fields and a 2 mm diameter disk probe similar to

that used by Fortgang and Hwang [9] was used to measure the rf electric fields. Measurements were made at the center of the Faraday shield elements and near the ends where they connect to the box. Two dimensional scans were carried out along the length of the current strap and radially out from the antenna.

The rf magnetic fields are most strongly perturbed at the ends of the elements where the field from the antenna is mostly radial (perpendicular to the elements). There is almost no perturbation at the center of the elements where the rf magnetic field is parallel to the elements. Figure 3 shows contour plots constructed from the magnetic probe data for each of the four geometries studied. The circular cross-section elements show the weakest perturbation since the fields are not measured where the gap is narrowest. The perturbations caused by the other geometries are similar.

The electric field probe measured the largest perturbation at center rather than the ends of the elements and directly in front rather than between the elements. Figure 4 shows the electric field probe measurements at 1-2 mm and 4-5 mm from the surface of each of the four element geometries. The perturbation caused by the elements is only seen close to the elements and virtually disappears when the probe is moved away by 4-5 mm. The magnetic perturbation is still visible in the data 14 mm from the element surface. The gradual rise in the electric field probe data, seen at both radial positions, occurs because the probe is being moved away from the grounded centertap toward the high voltage end of the current strap. The single layer strip data is higher because it is taken closer to the current strap.

There does not appear to be any substantial difference between the geometries studied from either the electric or magnetic probe measurements. Circular cross-section elements produce somewhat less ripple relative to the other shapes since the gap between them increases gradually toward the plasma. This feature also makes the elements radially thicker, increasing the distance between the current strap and the plasma. The presence of plasma would alter the field

distributions in front of the Faraday shield. If the density were high enough to produce sheaths, the electric fields could be quite different. The magnetic fields would likely be somewhat distorted by plasma. The plasma affects the magnetic flux as if it were a perfect conductor at some distance in front of the antenna.

IV. EDGE PLASMA-FARADAY SHIELD INTERACTION STUDIES

Impurity generation has often been observed to accompany high power ICRF heating. These impurities have been identified to come from the Faraday shield directly [4,10] or from limiters [10]. Several mechanisms have been proposed that could lead to sputtering of Faraday shield material [8,11] and enhanced sputtering from limiters could be the result of rf heating of the edge plasma. A novel technique has been proposed by LaBombard to reduce impurity generation at the Faraday shield [12]. The sputtering of Faraday shield material can be decreased by reducing the density scrape-off length in front of the shield, thereby reducing the plasma density at the surface and between the shield elements. The technique, termed an electrostatic barrier scrape-off layer (or EBSOL), uses limiter biasing to produce the desired effect. This mechanism has been verified in limiter biasing experiments on TEXTOR [13].

For this application, only the antenna protection limiters are biased. The basic idea is to control the potential of the plasma located between the antenna protection limiters directly in front of the Faraday shield. A potential difference between this plasma and the main scrape-off plasma is maintained, resulting in a radial electric field that impedes transport from the main scrape-off plasma and reduces the density in front of the Faraday shield. The mechanism can be modelled as competition between the particle mobility in the radial electric field and radial diffusion [12]. The model predicts that biasing the antenna limiters positive relative to the scrape-off plasma floating potential would impede ion transport and result in a reduced scrape-off length and lower plasma density at the shield surface. Reducing the density directly in front of the antenna can reduce antenna loading so there may be some trade-off involved in applying this

technique.

When biasing the antenna protection limiters, it is only necessary to bias the inner sides of the limiters (that is, the sides which are linked by the magnetic field lines directly in front of the Faraday shield). This configuration is shown schematically in Fig. 5. Biasing only the inner sides has two beneficial effects [12]. Since only as small percentage of the scrape-off plasma is lost to this area, the potential of the scrape-off plasma as a whole remains virtually unaffected. Also, by affecting only a small volume of plasma, the amount of current, and therefore power, necessary to produce a given bias is kept as small as possible. Calculations show this technique to be feasible in Alcator C-Mod [12].

An experiment is planned in the Versator II tokamak to study several issues related to ICRF interaction with the edge plasma and, in particular, interaction with the Faraday shield. An antenna has been designed specifically for interaction with the edge plasma, not heating of the main plasma. The current strap will be oriented along the magnetic field (the polarization used for ion Bernstein wave heating). It would be interesting to vary the orientation of the current strap relative to the magnetic field but space restrictions in the Versator II vacuum vessel make this unfeasible. The axial length of the antenna was chosen to produce the appropriate k_{\parallel} to interact with the edge electrons. A single layer Faraday shield will be used. Up to 100 kW of power will be available at 3-10 MHz. Various Faraday shield coatings will be compared using the spectroscopic diagnostics of the tokamak to look for impurity generation. Boron nitride, being an insulator with low Z , might be a very good coating material but has not yet been used in high power ICRF experiments. Issues for boron nitride include effects on antenna losses, impurity generation, and adhesion of the coating to the Faraday shield. Direct comparisons will be made between boron nitride and titanium carbide. It will also be possible to insert various material samples into the scrape-off plasma to look for enhanced impurity generation due to edge heating by the rf. The antenna will also have protection limiters which can be biased as shown in Fig.

5. Studies to test for EBSOL effects on impurity generation and antenna loading will be carried out.

ACKNOWLEDGEMENTS

This work was supported by United States Department of Energy Contract DE-AC02-78ET51013.

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Figure Captions

Figure 1. A front and side view of the Alcator C-Mod antenna mounted in a side port.

Figure 2. A set of two Faraday shield elements and box side clips

Figure 3. Contour plots of the radial rf magnetic fields near ends the Faraday shield elements for the four geometries studied. Contours with no Faraday shield are shown as dotted lines. The radial position is defined as zero at the front face of the current strap and the relation of the front face of each element to the data is indicated.

Figure 4. The electric field probe measurements for each of the four Faraday shield geometries studied. The squares are for 1-2 mm from the surface and the diamonds for 4-5 mm from the surface of the elements. The relation of the element surface to the measurements is indicated on the bottom graph.

Figure 5. The proposed geometry for biasing of the antenna limiter to produce an EBSOL. This closely resembles the layout of the antenna being installed in Versator II to test this effect.

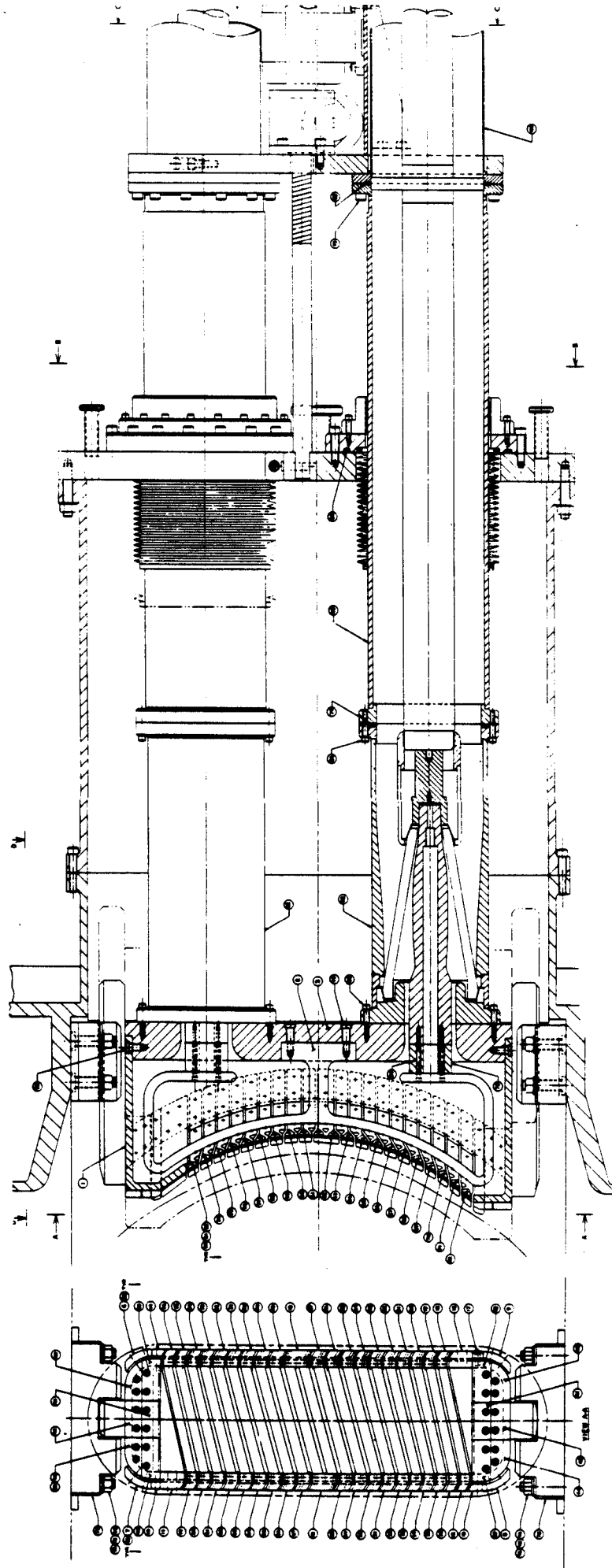
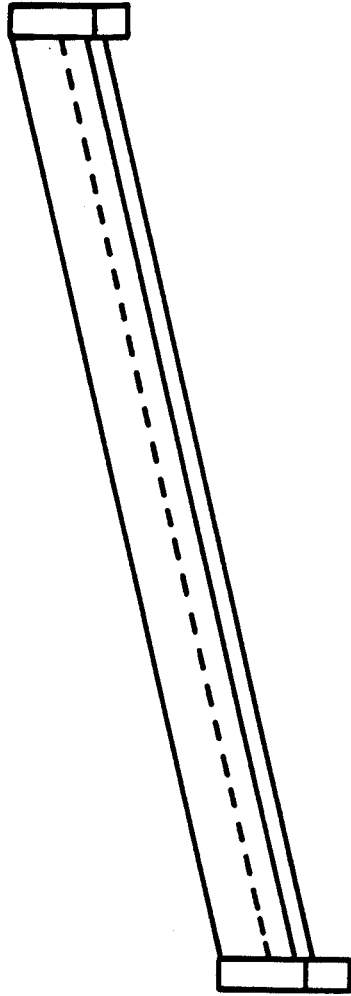
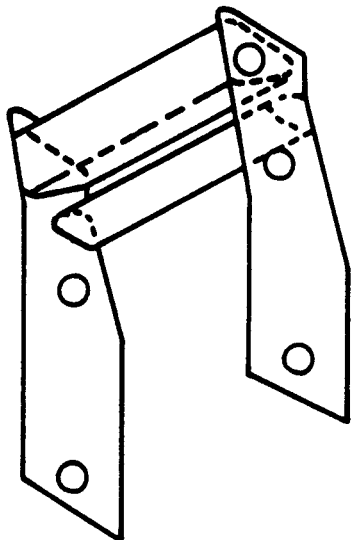


Figure 1



FRONT



SIDE

Figure 2

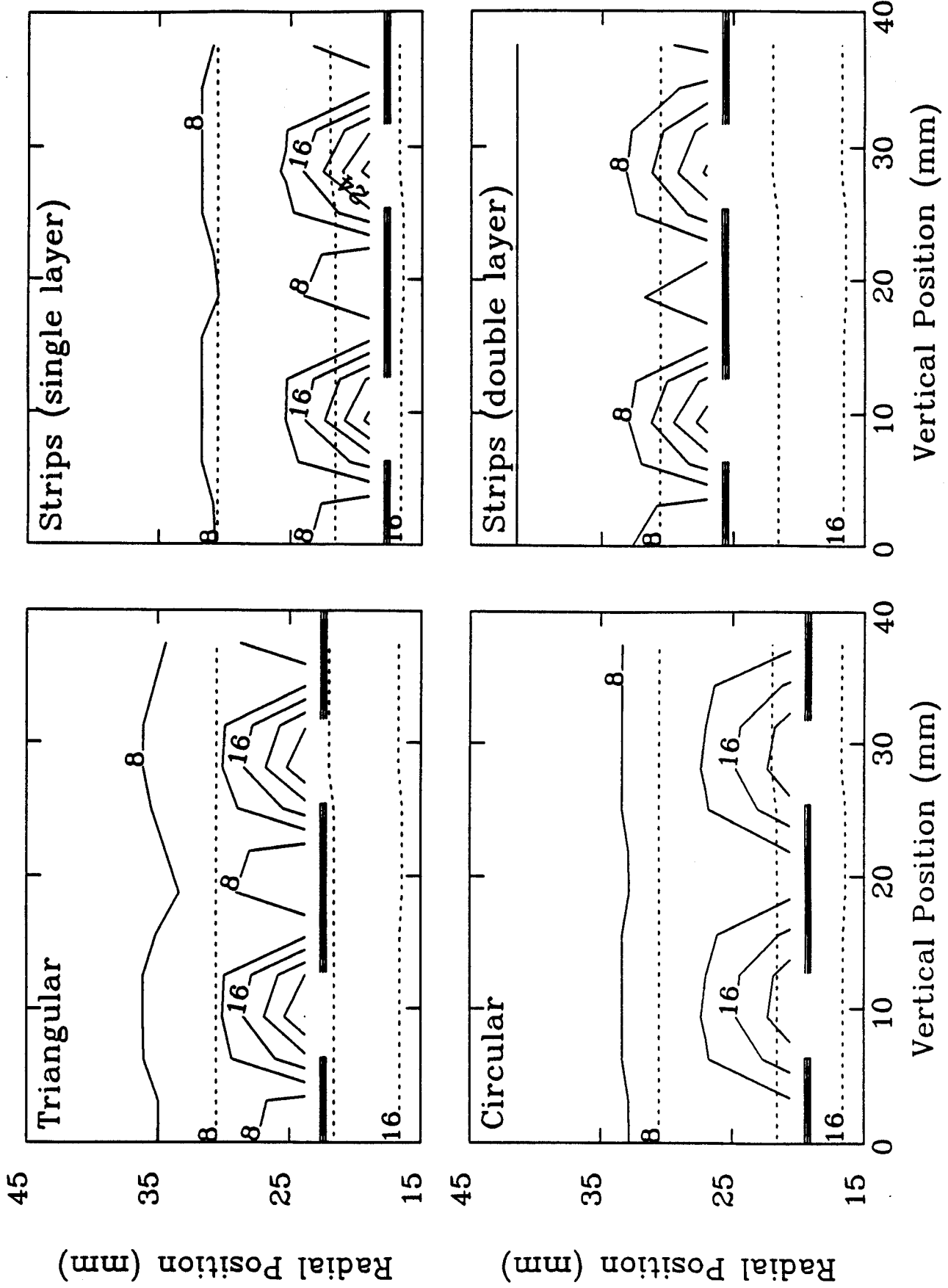


Figure 3

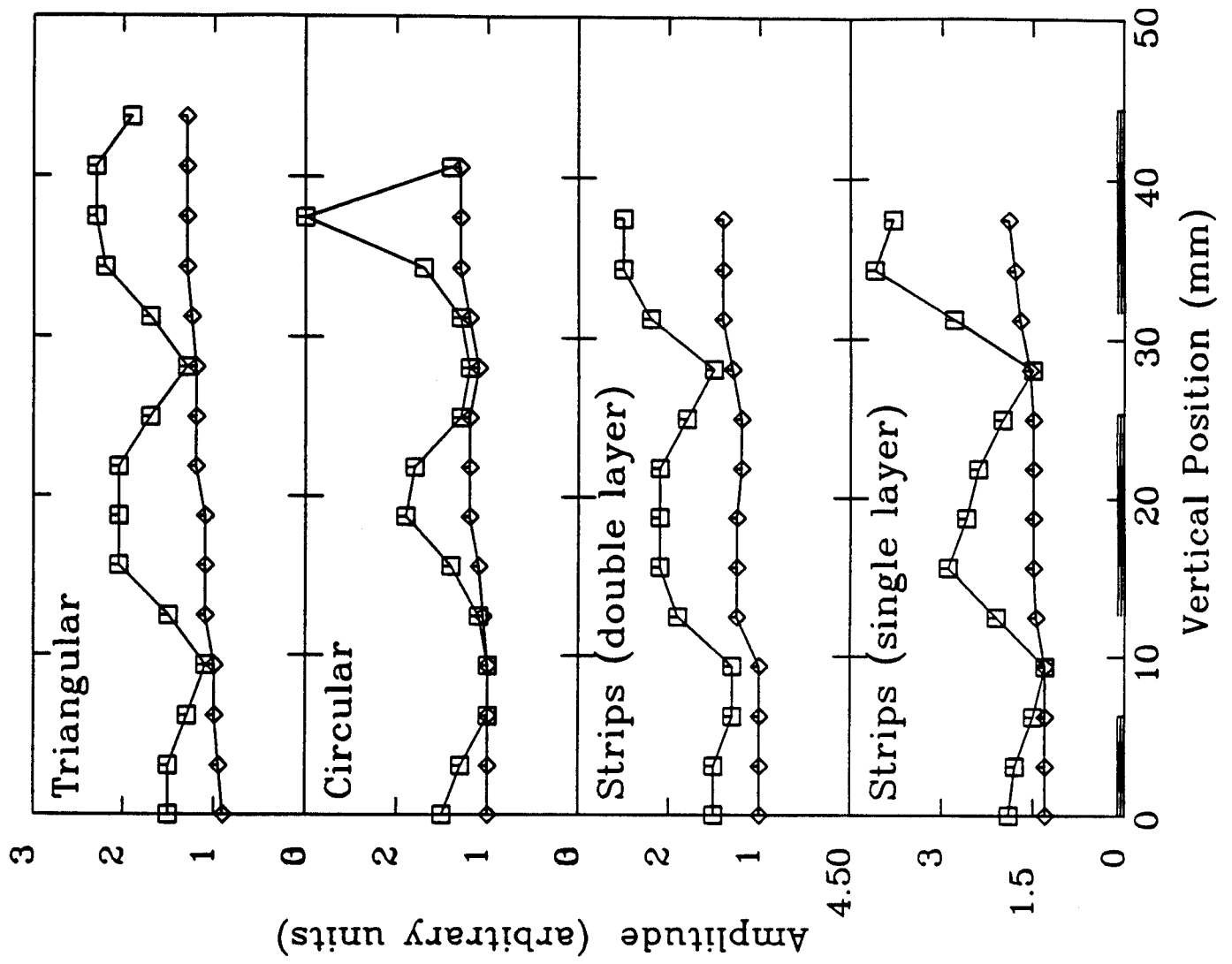


Figure 4

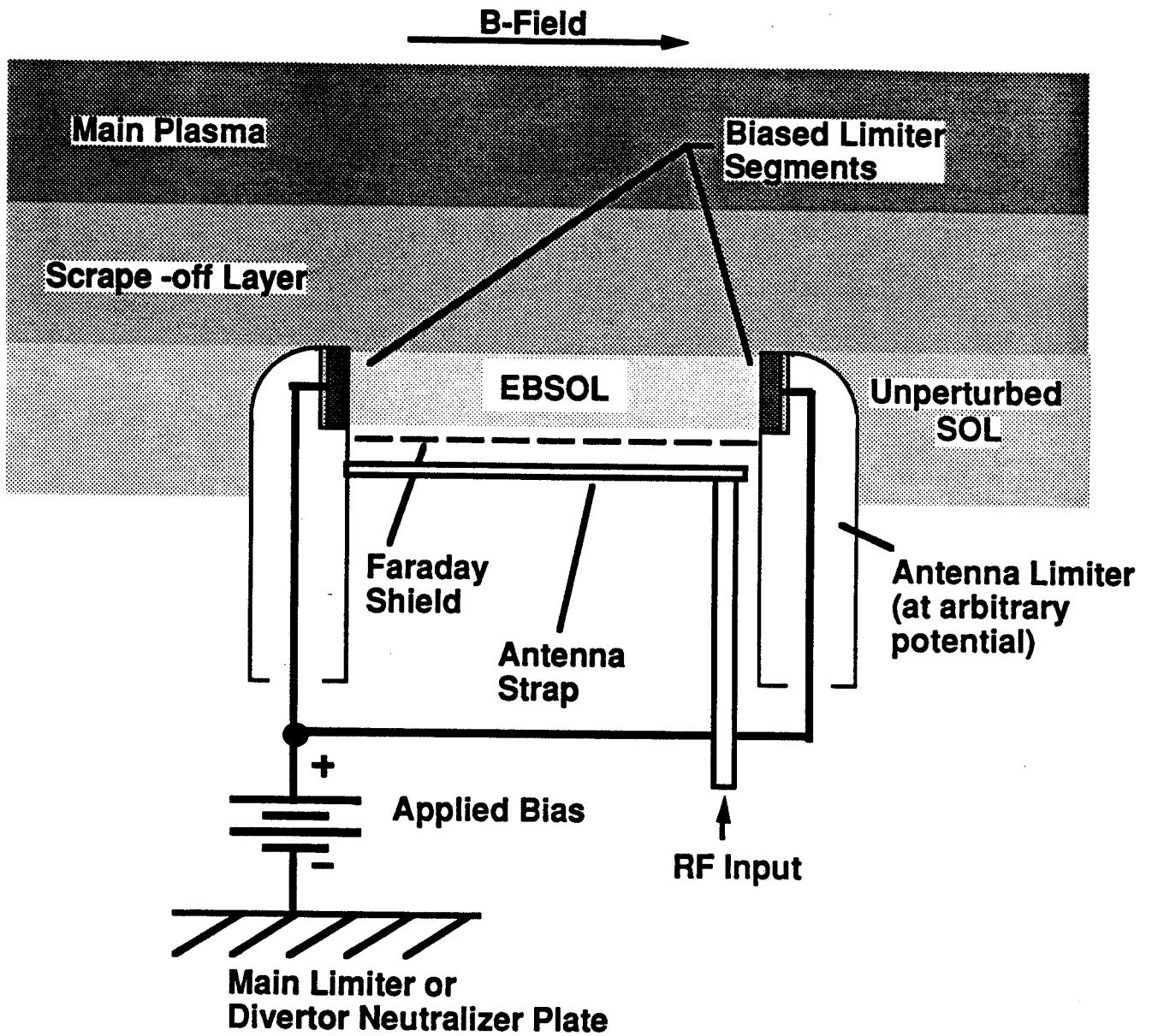


Figure 5