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ICRH COUPLING IN DIII-D*

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I. INTRODUCTION. A 9-MW ion cyclotron resonant frequency (ICRF) experiment has been proposed to heat the Doublet III-D (DIII-D) plasma. DIII-D is a 2.2-T, 3.5-MA tokamak at GA Technologies with a major radius of 1.67 m and minor radius of 67 cm (elongation ~ 2). The device was recommissioned in early 1986. The initial experimental program includes ohmic plasma and neutral beam studies; high-power rf experiments will follow in later years. Compact loop antennas (which fit completely in a 35- by 50-cm port) have been chosen to convey this power because of their inherent ease of maintenance, high efficiency, and versatility. In order to verify that the antenna will have sufficient loading, a prototype low-power (2-MW) antenna has been designed and installed. Measurements will be made through September 1986. The antenna is a cavity antenna that will operate from approximately 30 to 80 MHz with a 50-Ω match for a load resistance of ~1 Ω. It is surrounded by a fixed graphite-covered frame and can be extended from 3 cm behind this frame to 2 cm in front. This can be used to adjust coupling to the plasma. The electrical, mechanical, and thermal characteristics of this antenna system (and its extrapolation to ignited tokamaks) are discussed. In addition to experimental exploration of coupling, we have investigated wave propagation and absorption in DIII-D by using a cold collisional plasma model in straight tokamak geometry with rotation transform. Loading and power deposition profiles as a function of frequency, density, and species mix are presented.

II. MECHANICAL DESCRIPTION. The antenna for DIII-D is in the cavity configuration (Fig. 1). The main current strap is held by a ground plane at one end and by a vacuum variable capacitor at the other end. The capacitor and strap inductance determine the antenna frequency. At some distance up the current strap, power is fed to the structure. The input impedance is determined by the feed point. The Faraday shield is bolted onto the face of the antenna structure. The antenna is designed to be movable relative to the plasma. Motion of the whole assembly is accomplished by bellows and a remotely controlled drive-motor mechanism shown in Fig. 1. An I-beam frame (not shown in Fig. 1), mounted on the vacuum side of the port, supports the antenna. Both external and vacuum bearings are made of graphalloy—a bronze-impregnated graphite material.

A fundamental problem to the mechanical integrity of the antenna is the thermal/mechanical characteristics of the Faraday shield (Fig. 2). In order to minimize plasma impurities, the Faraday shield, which is composed of 1-cm-diam Inconel rods, is coated with 1.5 mm of graphite on the plasma side; copper plating is used on the antenna side to minimize rf losses. The equivalent disruption pressure at 5 MA is 6 atm (radially inward). At 6 atm, the rods are subject to stresses that are 80% of yield stress (140 ksi) at 1000°F. A finite-element stress analysis of the antenna shows that the rest of the antenna structure has stresses below 11 ksi; consequently, stainless steel is used for the remainder.

DISCLAIMER

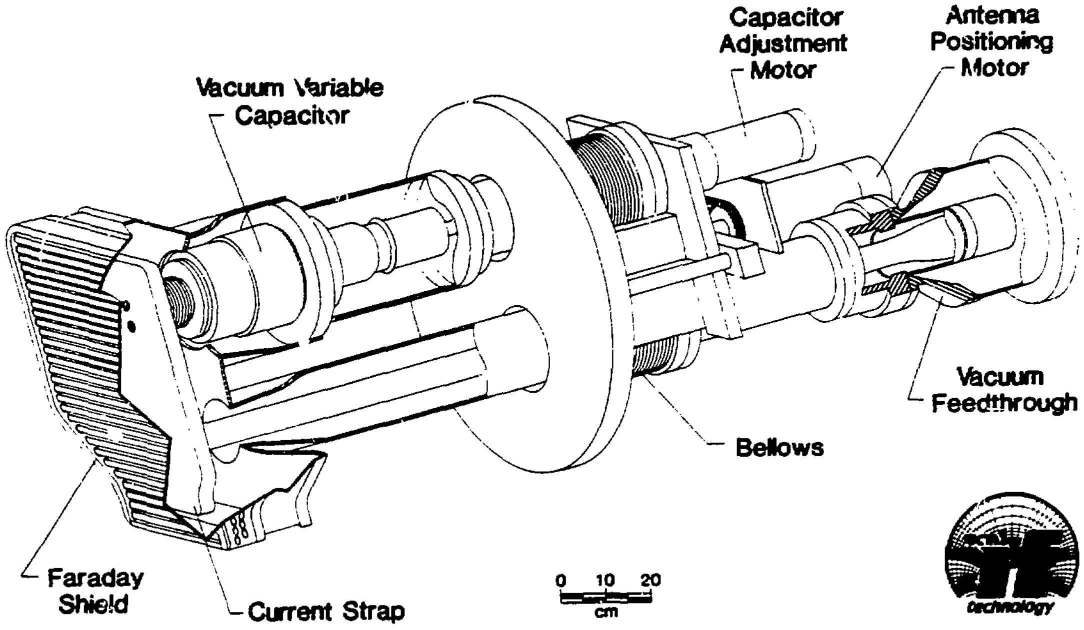

Fig. 1. The cavity antenna designed for DIII-D.

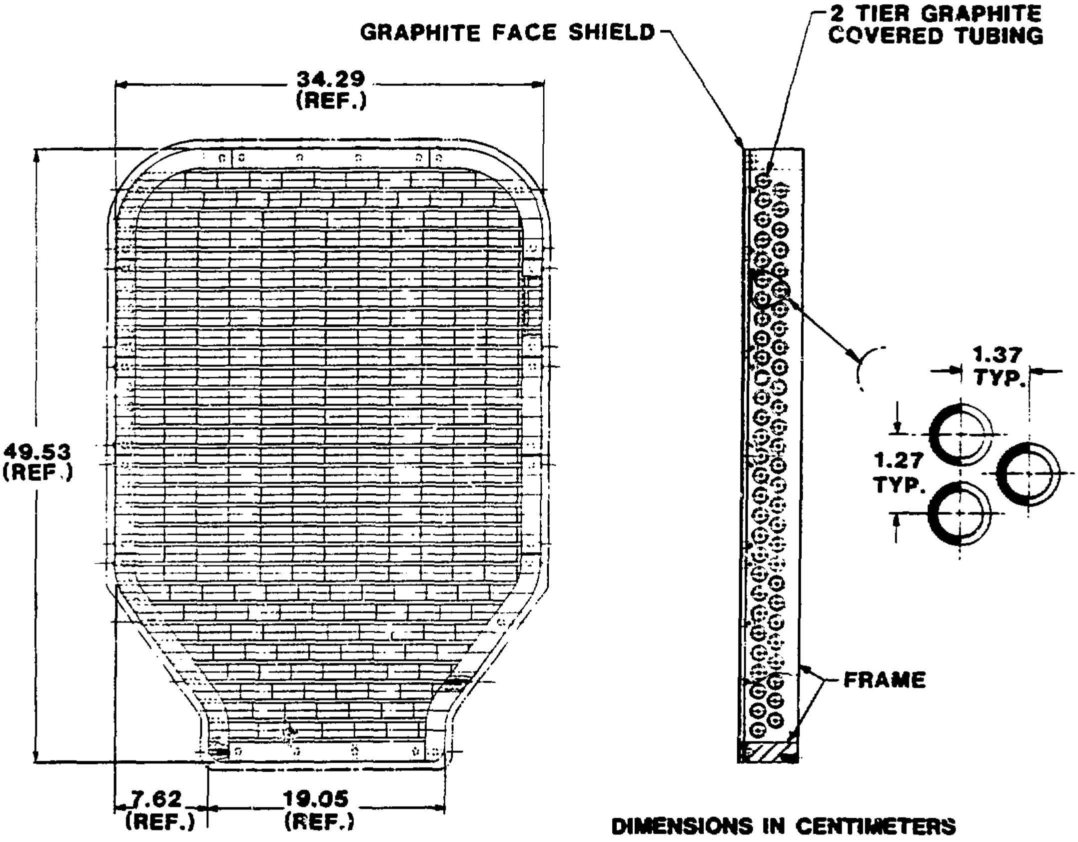

Fig. 2. The Faraday shield configuration for the cavity antenna.

The thermal loads for the exploratory antenna are completely due to the plasma. A total of $\sim 80\ \mathrm{W/cm^2}$ is deposited on the shield for 3 s every 4 min. With radiative cooling only, the graphite heats to 330°C after ten shots, which is 500°C below the braze temperature. When operated at 2 MW, some active cooling is probably required. An actively cooled Faraday shield has been designed and fabricated for use on the Radio-Frequency Test Facility.

The vacuum feedthrough for the cavity antenna is basically the same as the ORNL feedthrough used on TEXTOR. The feedthrough is also illustrated in Fig. 1. The major change is that this feedthrough was designed to bolt to a standard 9 3/16-in. coaxial transmission line. On the vacuum side, the coax has an outer diameter of 4 1/2 in. because there is not enough room for anything larger.

III. ELECTRICAL CHARACTERISTICS. In order to assess power limits, power losses, and plasma coupling, it is necessary to describe the unloaded characteristics of the antenna. The resonant frequency and input impedance are given by

$$f = \frac{1}{2\pi\sqrt{LC}} , \tag{1}$$

$$Z = \frac{\alpha^2 L}{Cr} , \tag{2}$$

where L and C are antenna inductance and capacitance, α is the feed point, and r is the load. The capacitance (including stray) can be varied from 38 to 474 pF. The apparent total inductance ranges from 130 nH at 20 MHz to 115 nH at 74 MHz. This yields a useful frequency range of 20 to 74 MHz.

Measurements, with and without Faraday shields, show that the structure has an equivalent 25 mΩ of load and the shield has 0.1 Ω at 20 MHz. When the apparent decrease of inductance is included, the losses scale as $\sqrt{f}$. Of the 25 mΩ in the structure, approximately 20 mΩ is attributable to the capacitor. While the capacitor clearly needs to be cooled for high-power operation, the body of the antenna does not. If plasma loading is on the order of 1 to 3 Ω, then up to 10% of the rf power will go to the Faraday shield. Therefore, the shield for the high-power version will be cooled.

The power capacity of the antenna depends on the voltage and current limits of the capacitor. An improved, high-current capacitor has been designed and will be tested. However, for 3-s pulses, the power will be limited by the maximum voltage that the capacitor can withstand. Including the decrease of inductance of the current strap and assuming 48-kV peak, the maximum operating power is 1.7 MW/Ω at 30 MHz, 1.0 MW/Ω at 50 MHz, and 0.72 MW/Ω at 70 MHz. Since loading is expected to be 1 to 3 Ω (per 40 cm of current strap), the antenna is nominally a 2-MW antenna.

IV. LOADING CALCULATIONS. As previously discussed, the amount of loading determines power limits and cooling requirements. The antenna design is centered around a 1- to 3-Ω load in the 30- to 50-MHz range. Calculations of coupling in DIII-D were made to support the design point. The method of calculation is as follows.

Global solutions for the ICRF wave fields in a straight tokamak with rotational transform are calculated in the cold plasma limit. The component of the wave field parallel to **B** is assumed zero. Symmetry allows Fourier decomposition in the toroidal coordinate, and the resulting set of two coupled, two-dimensional partial differential equations is solved by the method of finite difference. Energy absorption and antenna impedance are calculated using a simple collisional absorption model. Resonance can be observed. For the small transforms of DIII-D, only heating at the two-ion hybrid resonance is observed.

The calculations were based on the following parameters: $B_0 \sim 2.2$ T, $n_{\text{central}} \sim 3 \times 10^{13}$ cm^{-3}, $n_{\text{edge}} \sim 10^{12}$ cm^{-3}, $f \sim 30$ MHz, $R \sim 2.2$ m, $a_p \sim 0.67$ m, and potential antenna extent of 40 cm. The majority of power absorption is seen between the two-ion hybrid resonance and the fundamental resonance. The electric fields on the plasma peak in this region. For some cases, where the resonance is near the edge of the plasma, coax modes dominate with high edge fields. Antenna loading is weakly dependent on species mix, central density, frequency, and magnetic field. However, a variation in edge density from 1 to 6 $\times 10^{12}$ cm^{-2} showed a threefold increase in loading (Fig. 3). Since the antenna can move relative to the plasma, the role of edge plasma in coupling can be explored without perturbing other plasma parameters.

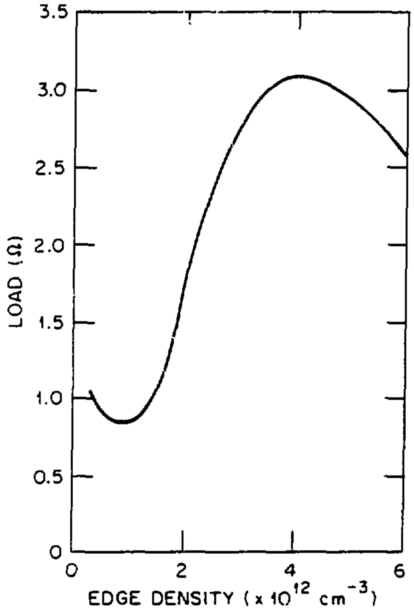

Fig. 3. Coupling for a 40-cm antenna in DIII-D. Central density = 3×10^{13} cm^{-3}, B_ϕ = 2.2 T, $f \sim 30$ MHz.

V. SUMMARY. A cavity antenna has been installed on DIII-D to explore coupling. The antenna was designed to operate at 1 to 3 Ω. Calculations show this to be the expected load. Measurements of the coupling will be made first to verify this and then to determine power limits, antenna dissipation, and the efficiency of the antenna.

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