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ICRF COUPLING ON DIII-D AND THE IMPLICATIONS ON ICRF TECHNOLOGY DEVELOPMENT*

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ABSTRACT

Low-power coupling tests have been carried out with a prototype ion cyclotron range of frequencies (ICRF) compact loop antenna on the DIII-D tokamak. Plasma load resistance values higher than originally calculated are measured in ohmic and L-mode, beam-heated plasmas. Load resistance decreases by a factor of ~2 in H-mode operation. When edge localized modes (ELMs) occur, the antenna loading increases transiently to several ohms. Results indicate that fast-wave ICRF antenna coupling characteristics are highly sensitive to changes in the edge plasma profiles associated with the H-mode regime.

INTRODUCTION

The feasibility of using rf waves in the ion cyclotron range of frequencies to heat the proposed Compact Ignition Tokamak (CIT) to ignition depends to a large extent on whether rf power can be coupled efficiently from compact launching structures to shaped, diverted plasmas with good (H-mode) confinement. An attractive concept for this purpose is the compact loop antenna[1] because it can be (1) inserted through a single port, (2) tuned over a wide frequency range, and (3) internally impedance matched, thus reducing standing wave voltages in the vacuum feedthrough and external transmission lines. To determine the compact loop antenna coupling to dee-shaped plasmas with limiter and divertor edge configurations, a prototype compact loop antenna has been installed on DIII-D for low-power tests. This paper emphasizes coupling results obtained during neutral-beam injection (NBI) experiments in which the H-mode regime of improved confinement was obtained with divertor plasmas (I_p = 1 MA, B_T = 21 kG, κ = 1.8, $n_e = 2-7 \times 10^{13}$ cm^{-3}).

ANTENNA DESCRIPTION

Figure 1 is a diagram of the compact loop antenna built by ORNL. The radiating element consists of a vertical current strap ~35 cm long, grounded at the bottom, connected to a vacuum variable capacitor at the top, and fed by a length of 50-Ω coaxial line. The entire antenna structure fits through a single DIII-D midplane port (50 cm high, 35 cm wide) and is movable over a 5-cm range to facilitate impedance matching. The Faraday shield consists of two tiers of horizontal Inconel tubes covered with graphite on the plasma side to reduce metallic impurity influx into the plasma.

An equivalent electrical circuit of the antenna is shown in Fig. 2. The resonant frequency is given by $f = 1/(2\pi\sqrt{LC})$, where L = 120 nH is the inductance of the current strap and C = 38–474 pF is the value of the vacuum variable capacitor. By varying C, the antenna can be tuned over the frequency range f = 20–74 MHz. At resonance, the input impedance of the antenna is approximately given by $Z \approx \alpha^2 L/RC$, where R is the total loading resistance and

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$\alpha = 0.22$ is determined by the position of the tap point on the current strap. The antenna losses are given by $R_{loss} = 0.027 f^{1/2}\ \Omega$, where f is in MHz, and are due mainly to the graphite in the Faraday shield.

RESULTS

Up to 6 MW of NBI heating power has been applied to single-null divertor discharges in deuterium ($H^{\circ} \rightarrow D^{+}$). At sufficient densities ($n_e > 2.0 \times 10^{13}\ cm^{-3}$) and NBI power levels ($P_{NBI} > 2.8$ MW), a transition into the H-mode regime has been achieved in which the plasma energy confinement time becomes comparable to the pre-NBI level.[2] Typical traces from a typical H-mode discharge are shown in Fig. 3. After an initial L-mode phase during the first 70 ms of beam injection, the H-mode transition occurs, signaled by the drop in D_α emission from the divertor region and by the steady rise in line-average density and plasma energy. The antenna loading resistance R exhibits a slight increase during the L-mode phase, followed by a sudden drop by a factor of 2 at the H-mode transition. Despite the subsequent large increase in density and the decrease in the limiter/separatrix gap, the antenna loading remains nearly constant during the quiescent portion of the beam pulse. This is also shown in Fig. 4, where antenna loading is plotted as a function of line-average density for L-mode, H-mode, and ohmic discharges. In contrast to the H-mode results, during L-mode and ohmic discharges, antenna loading increases linearly with line-average density. According to ICRF coupling theory,[3] the weak antenna coupling to H-mode plasmas could be caused by a steepening of the edge density gradient near the separatrix accompanied by a density reduction in front of the antenna. Experimental measurements of the edge density profile at the midplane of DIII-D will be carried out in the near future using a movable Langmuir probe.

As shown in Fig. 3, bursts of D_α emission, accompanied by sudden drops in density and plasma energy, can occur periodically during H-mode discharges. The phenomena appear similar to the edge localized modes (ELMs) observed in ASDEX.[4] When these occur, antenna loading increases suddenly and dramatically to levels that can exceed 3 Ω. The transient increase in loading associated with ELMs is attributed to a rapid expulsion of particles from the main plasma, which temporarily increases the edge plasma density in front of the antenna.

Antenna loading as a function of the antenna-plasma separation distance is plotted in Fig. 5. For all these data, the antenna was positioned flush with the graphite tiles, approximately 2 cm behind the face of the limiter. For both L-mode and H-mode discharges, antenna loading increases as the gap between the separatrix and the limiter is decreased. However, for a given antenna/plasma separation, L-mode loading exceeds H-mode loading by a factor of 2. Under the most favorable conditions for coupling, where the limiter-separatrix gap was less than 1 cm and an H-mode transition was still observed, antenna loading exceeded 1 Ω.

DISCUSSION

The DIII-D (and ASDEX[4]) results indicate that ICRF heating of H-mode plasmas will require several changes from techniques used when heating L-mode or ohmic plasmas. First, the current and voltage capabilities of the antenna must be higher to couple a given amount of power to the plasma because $P_{plasma} = R_{load} I^2$. For future experiments such as CIT, operation with ~2 MW of coupled power will require antenna holdoff voltages in the 50–70-kV range and electric fields of 30–50 kV/cm. These values appear to be within the range of existing technology, but this must be proven in actual tokamak experiments (e.g, TFTR, Tore Supra).[5]

Second, the rf power system must be able to respond to abrupt changes in load resistance while maintaining adequate power coupled to the plasma. This will require either dynamic adjustment of the coupling circuitry to maintain a matched load to the transmitter or relatively robust power transmission systems that can withstand reasonable mismatches in loading. The latter course appears to be relatively easy, provided that a modest decrease in power is acceptable for some portion of the rf pulse.

Finally, improvements to the antenna, such as changing the antenna cavity geometry, the Faraday shield, or the plasma-antenna separation, may improve the coupling. These possibilities are being investigated as part of the U.S. rf development program.

REFERENCES

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COMPACT LOOP ANTENNA
(cavity type for DIII–D)

ORNL-DWG 86-2025 FED

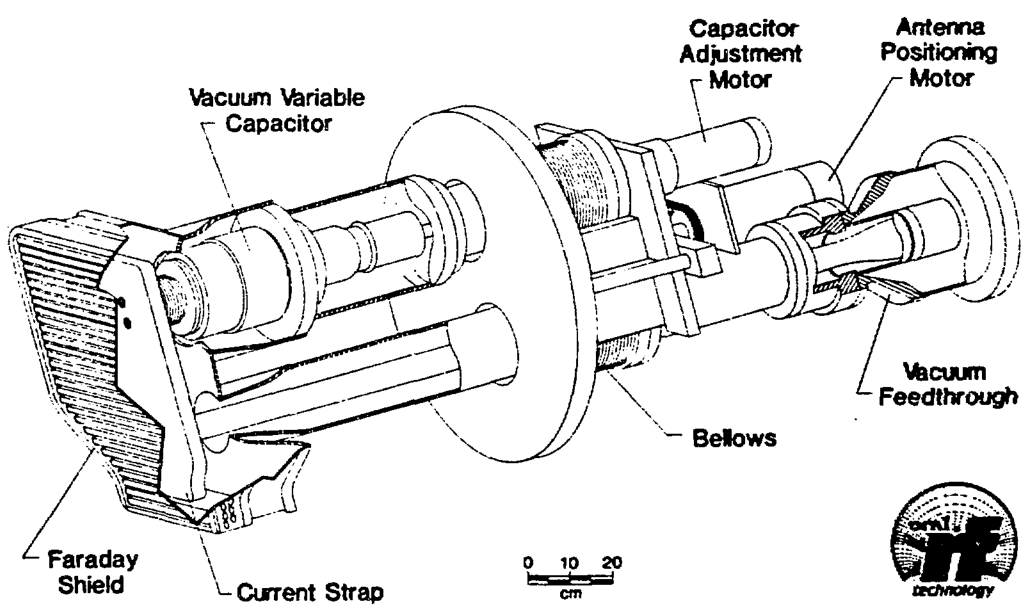

Fig. 1. Diagram of the compact loop antenna.

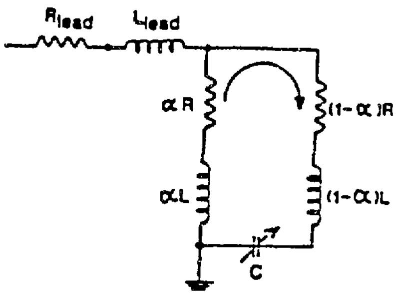

Fig. 2. Equivalent circuit of the compact loop antenna.

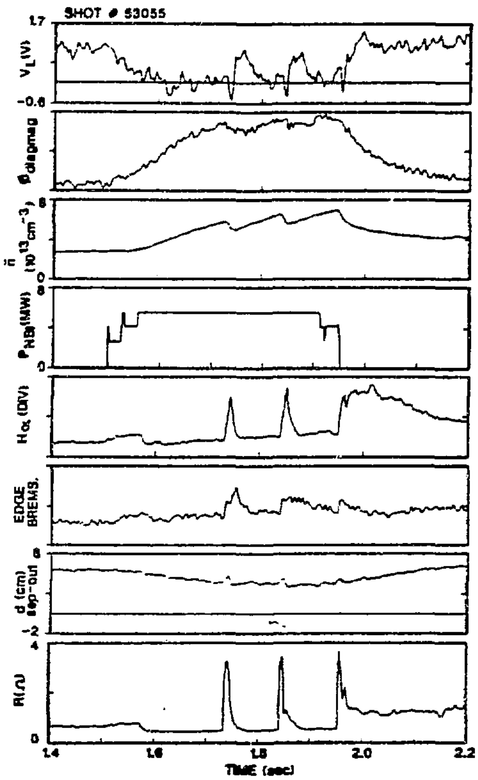

Fig. 3. Traces from a divertor discharge in DIII-D in which an H-mode transition is observed at t = 1575 ms.

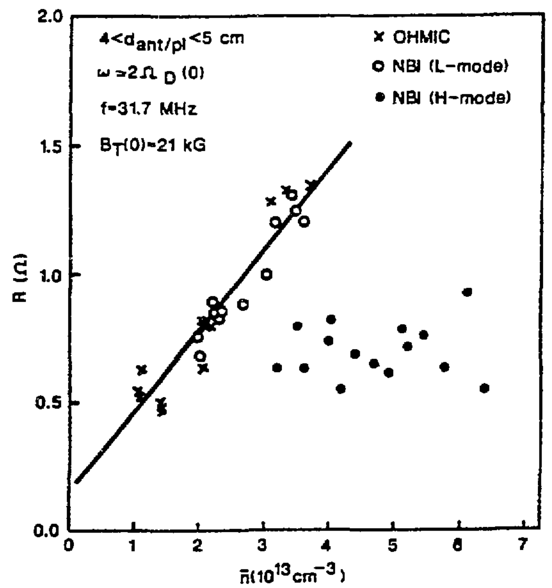

Fig. 4. Antenna loading vs. line-average density.

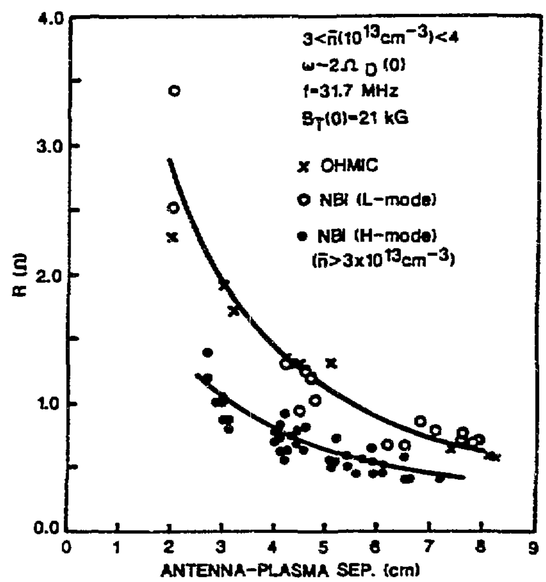

Fig. 5. Antenna loading as a function of the distance between the antenna Faraday shield and the plasma separatrix.

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