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Assessment of ICRF Antenna Performance in Alcator C-Mod

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ICRF ANTENNA DESCRIPTION

The Alcator C-Mod ICRF system consists of three antennas: two 2-strap antennas, each connected to a 2-MW transmitter, and one 4-strap antenna, whose current straps are connected in pairs to two 2-MW transmitters. The 4-strap antenna design adds the capability of a directed launched wave spectrum for current drive by changes in current strap phasing.[1] The antennas exhibit several design differences.[2] The Faraday shields of the 2-strap antennas are ~27% transparent and aligned with the net (toroidal plus poloidal) magnetic field, while those of the 4-strap antenna are ~50% transparent and aligned with the toroidal magnetic field (Figure 1). Differences exist in the current straps as well. The current straps of the 2-strap antennas are end-fed center-grounded, while those of the 4-strap antenna are folded, end-grounded with a central current feed (Figure 2). The straps exhibit spectral differences as well, $n_\varphi = \pm 10$ vs. $n_\varphi = \pm 13$ for heating phasing.

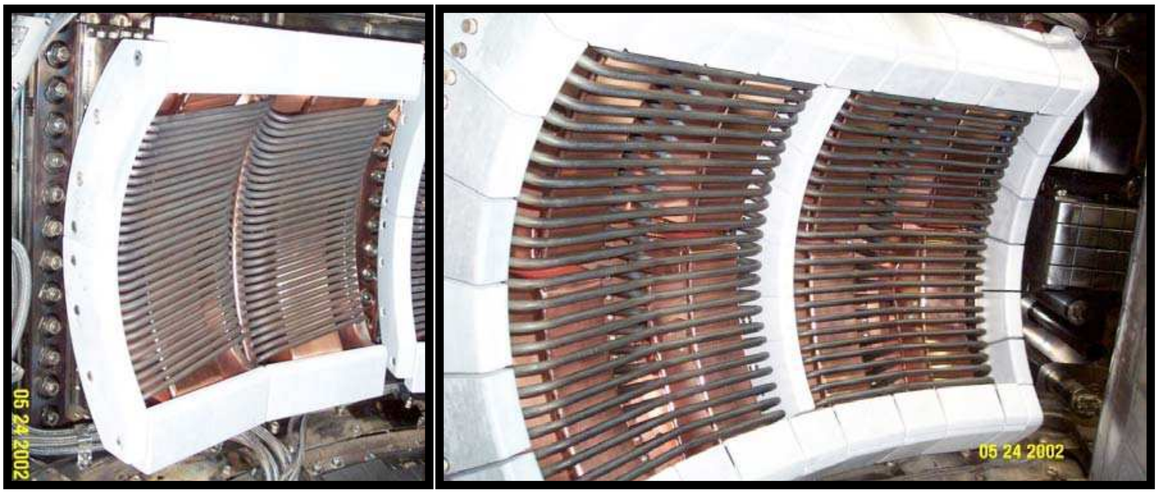


FIGURE 1. One of the two 2-strap antennas (left), and the 4-strap antenna (right).

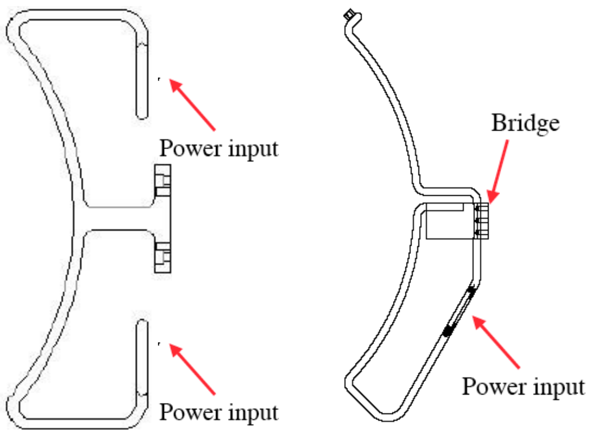


FIGURE 2. Current strap of the 2-strap antenna (left), and the 4-strap antenna (right).

ANTENNA PERFORMANCE LIMITATIONS

The antennas' ability to deliver useful power to the plasma was found to be limited by the injection of impurities into the plasma or by internal arcing at high voltage limits. Both these limits have been pushed upwards through systematic antenna improvements that eliminated impurity generation and improved high voltage handling.[3,4]

Operation with the initial metal plasma-facing components was satisfactory, but the level of Mo impurity in the plasma core was found to scale with the rf power. Although the source rate was low, plasma screening was poor.[5] The antenna's plasma protection tiles were therefore changed from the original molybdenum to boron nitride to completely shield all metal surfaces, BN-metal interfaces, and eliminate sheath rectification effects.[6]

Extensive arc damage has been observed in the 4-strap antenna between the striplines feeding rf current to the antenna straps, in a direction along the tokamak edge magnetic field. This corresponded to an empirical electric field limit of ~15 kV/cm under the local conditions, i.e. **E**||**B,** and plasma edge neutral gas pressure up to ~1 mTorr. The mechanism for this breakdown is not clear.[2] Field emission initiation requires local field strengths considerably higher than those present. For gas breakdown, the Paschen curve minimum is ~Torr-cm, while at the antenna we have ~mTorr-cm, with mean free paths much greater than the electrode spacing. Multipactoring initiation would require lower electric fields or greater path lengths.

The striplines of the 4-strap antenna were redesigned to reorient them to an **E⊥B** configuration (Figure 4)[7]. In order to reduce the electric field below 10 kV/cm in regions with **E**||**B**, high voltage gaps were increased, and in the case of arcing at the current strap crossover, electrodes were reshaped to reorient the region of highest field.

FIGURE 4. Modified **E⊥B** current feed design.
The tokamak magnetic field rises at ~30° to the right.

ANTENNA PERFORMANCE COMPARISON

The 2-strap and 4-strap antenna performance was compared in two different ways. First, the plasma response to the two different antenna types was compared (Figure 5). In an L-mode discharge 2.7 MW were coupled through the 4-strap antenna at J-port in co-current phasing, followed by the same power through the two 2-strap antennas at D and E-port.

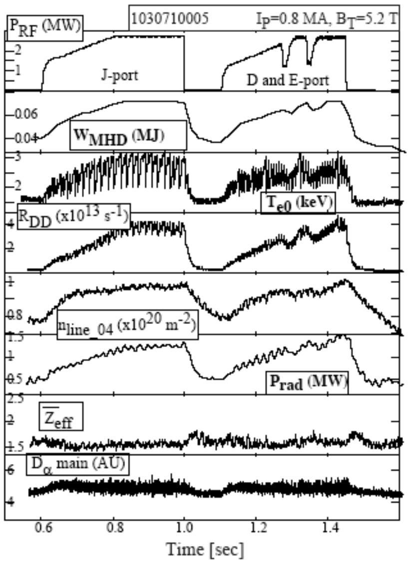


FIGURE 5. Antenna comparison

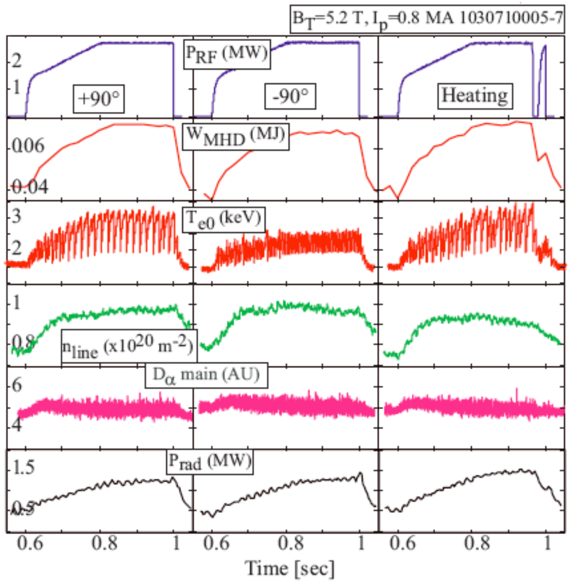
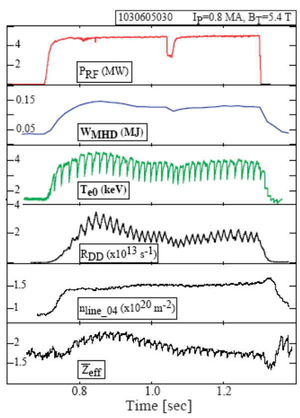


FIGURE 6. 4-strap antenna phasing comparison

The plasma response to the same antenna at different phasings was then compared. A series of limited L-mode discharges was run, and the phasing of the 4-strap antenna was systematically varied while keeping the power constant (Figure 6). In both comparisons all the observed diagnostics, stored energy, electron temperature, neutron rate, density rise, radiated power, Z_{eff}, and D_α are the same within ~10%. These comparisons indicate that the differences in antenna construction, Faraday screen transparency and orientation, and current strap design do not result in observable differences in the plasma response.

TECHNICAL ACHIEVEMENTS

All antennas now are able to be brought up to a peak rf voltage of 35 kV when operating into plasma. The two 2-strap antennas achieve power levels of 1.5 MW each, and the 4-strap antenna has achieved 3 MW. Total power into plasma has reached 5 MW for 0.6 second (**FIGURE 7**, right) and 6 MW for ~0.1 second. On-axis plasma heating power density can exceed 10 MWm^{-3}.



EXPERIMENTAL FLEXIBILITY

The C-Mod ICRF system now allows an extremely useful and flexible combination of ICRF frequencies, toroidal field setting, and phasing for a variety of physics experiments.

$B_{toroidal}$ Tesla	D+E frequ. MHz	J frequ. MHz	D+E location	J location	J phasing	Goal
5.4	80, 80.5	78	r/a ~ 0	r/a ~ 0	heating (0,π,0,π)	maximum on-axis heating
5.4	80, 80.5	70	r/a ~ 0	r/a ~ +0.5	heating (0,π,0,π)	off and on-axis heating for LFS ITB
4.5	80, 80.5	70	r/a ~ -0.5	r/a ~ 0	heating (0,π,0,π)	off and on-axis heating for HFS ITB
5.2	80, 80.5	78	r/a ~ 0	r/a ~ 0	CD (±90°)	on-axis heating and current drive
8.0	80, 80.5	78	r/a ~ 0-0.2	r/a ~ 0-0.2	CD (±90°)	on/off-axis D(^{3}He) heating and MCCD

SUMMARY

C-Mod has presented a challenge to install high power ICRF antennas in a tight space. Modifications have been made to the antenna plasma-facing surfaces and the internal current-carrying structure in order to overcome performance limitations. At the present time the antennas have exceeded 5 MW into plasma with heating phasing, up to 2.7 MW with current drive phasing, with good efficiency and no deleterious effects.

ACKNOWLEDGEMENTS

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REFERENCES

[1]G. Schilling et al., "Extension of Alcator C-Mod's ICRF Experimental Capability," Proceedings of the 13th Topical Conference on Radio Frequency Power in Plasmas, Annapolis MD, April 1999, 429-432.
[2]S. J. Wukitch et al., "Investigation of Performance Limiting Phenomena in a Variable Phase ICRF Antenna in Alcator C-Mod," submitted to Plasma Physics and Controlled Fusion.
[3]G. Schilling et al., "Upgrades to the 4-strap ICRF Antenna in Alcator C-Mod," Proceedings of the 14th Topical Conference on Radio Frequency Power in Plasmas, Oxnard CA, May 2001, 186-189.
[4]S. J. Wukitch et al., "Performance of a Compact Four-Strap Fast Wave ICRF Antenna," presented at the19th IAEA Fusion Energy Conference, Lyon, France, 14 - 19 October 2002, FT/P1-14.
[5]B. Lipschultz et al., "A Study of Molybdenum Influxes and Transport in Alcator C-Mod," Nuclear Fusion **41**, (2001) 585.
[6]J. W. Myra and D. A. D'Ippolito, "Far Field ICRF Sheath Formation on Walls and Limiters," Proceedings of the Tenth Topical Conference on Radio Frequency Power in Plasmas, Boston MA, April 1993, 421-424.
[7]G. Schilling et al., "Analysis of 4-strap ICRF Antenna Performance in Alcator C-Mod," Proceedings of the 15th Topical Conference on Radio Frequency Power in Plasmas, Moran WY, May 2003, 166.