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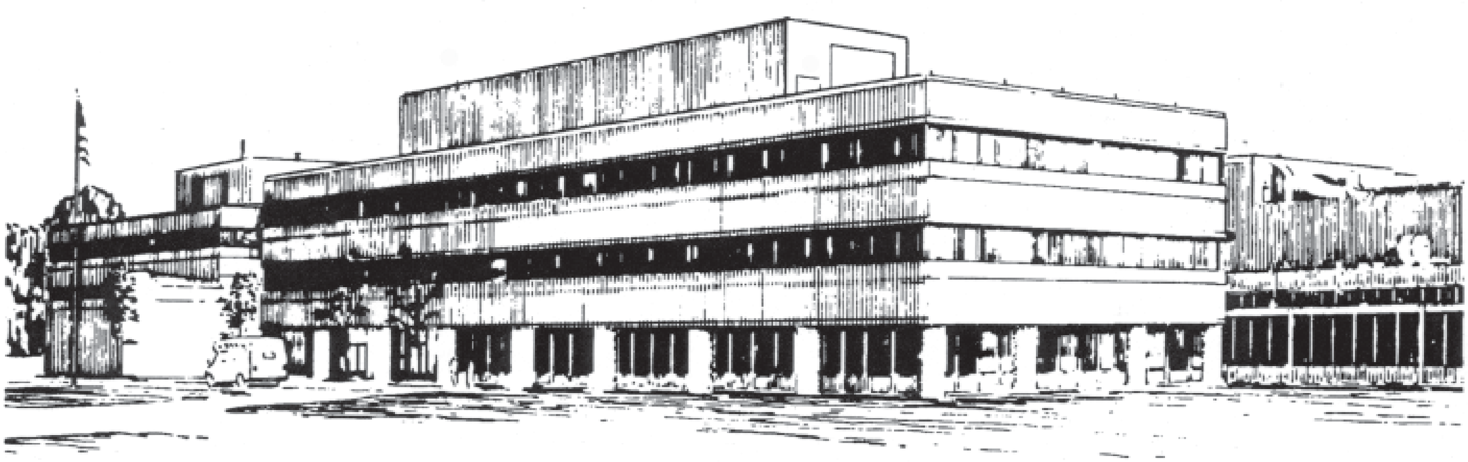

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Analysis of 4-strap ICRF Antenna Performance in Alcator C-Mod

G. Schilling[1], S. J. Wukitch[2], R. L. Boivin[3], J. A. Goetz[4], J. C. Hosea[1], J. H. Irby[2], Y. Lin[2], A. Parisot[2], M. Porkolab[2], J. R. Wilson[1], and the Alcator C-Mod Team

[1]Princeton University Plasma Physics Laboratory, Princeton NJ 08543, [2]MIT Plasma Science and Fusion Center, Cambridge, MA 02139, [3]General Atomics, San Diego CA 92186, [4]University of Wisconsin, Madison WI 53706

Abstract. A 4-strap ICRF antenna was designed and fabricated for plasma heating and current drive in the Alcator C-Mod tokamak. Initial upgrades were carried out in 2000 and 2001, which eliminated surface arcing between the metallic protection tiles and reduced plasma–wall interactions at the antenna front surface. A boron nitride septum was added at the antenna midplane to intersect electric fields resulting from rf sheath rectification, which eliminated antenna corner heating at high power levels. The current feeds to the radiating straps were reoriented from an $\mathbf{E}\|\mathbf{B}$ to $\mathbf{E}\perp\mathbf{B}$ geometry, avoiding the empirically observed ~15 kV/cm field limit and raising antenna voltage holding capability. Further modifications were carried out in 2002 and 2003. These included changes to the antenna current strap, the boron nitride tile mounting geometry, and shielding the BN-metal interface from the plasma. The antenna heating efficiency, power and voltage characteristics under these various configurations will be presented.

INTRODUCTION

The antenna design provides four vertical current straps in a configuration that allows efficient heating as well as providing a directed launched wave spectrum for current drive by changes in current strap phasing.[1] An antenna's ability to deliver useful power to the plasma may be limited by the injection of impurities into the plasma or by arcing at high voltage limits. The 4-strap antenna power capability has increased from an initial value of 5 MW/m^2 to ~11 MW/m^2 by eliminating impurity generation and improving high voltage handling.[2,3,4]

IMPURITY GENERATION BY PLASMA-FACING SURFACE INTERACTIONS

Initial antenna operation in 1999 resulted in high levels of metallic impurity influx at heating power levels above ~1.3 MW. The impurity source was identified from the melt damage found upon inspection after the initial commissioning campaign. The molybdenum tiles on separate ground elements had melt damage, while those on the same ground element did not. This suggests a voltage was being developed across tiles on separate ground elements. Induced RF currents of ~25 A resulted in a tile-tile potential of ~100 V at 78 MHz, sufficient to arc across the gaps under the local edge plasma conditions. The gaps were short-circuited in 2000 with stainless steel straps installed underneath the plasma protection tiles, eliminating this problem.

Operation with the metal plasma-facing components was satisfactory, but the level of Mo impurity at 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. No deleterious effects have been observed on plasma operation resulting from the boron nitride.

A new front surface interaction limit appeared later in 2000 above 2.5 MW. Camera images of ICRF operation revealed antenna side and corner hot spots that were aligned along the edge magnetic field lines and resulted in impurity injection and disruption. An analysis of the hot spot mechanism suggests that the tokamak's field line pitch in front of the antenna results in nonzero rf magnetic flux linkage to tokamak field lines connecting antenna surfaces. The resulting rf electric field expels electrons, and plasma neutrality results in ion acceleration leading to an enhanced sheath potential.[6] All front protection tiles were realigned with side tiles, all remaining exposed metal surfaces were covered with boron nitride or removed, and a central boron nitride septum was installed to reduce the tokamak field line connection length.

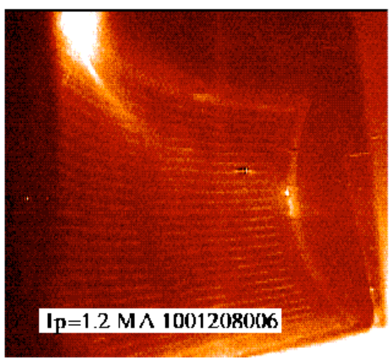

FIGURE 3. Antenna front surface hotspots

Several of the top and bottom tiles fractured during the 2002 run period, with the fragments falling through the plasma into the divertor chamber. The fragments appeared not to have a major impact on the plasma, but the newly exposed metal surfaces reduced the antenna power level before metallic impurity injection set in once more. Disruption forces induced in the metal mounting structure were transmitted to the boron nitride, which yielded under tensile stress. The tiles and their fasteners were redesigned, and no losses have been observed in 2003 so far.

RF-induced arcing was detected in the metal spine supporting the central septum tiles. This was originally designed with slots to reduce induced currents, but sufficient rf voltage developed across the slots in (0,0,0,0) phased operation to arc across the gaps. A new spine without slots was fabricated, and operation in 2003 so far has been successful.

ARCING IN ANTENNA INTERNAL STRUCTURE

During the 1999 operation arcing was observed along the direction of the tokamak magnetic field between the high voltage portion of the antenna current straps and adjacent resistive terminations of the Faraday shields. Grounded stainless steel cups were placed around the base of the Faraday shield rods to protect the resistive terminations in 2000.[7] Subsequent inspections showed no damage.

Extensive arc damage was observed in 2000 between the striplines feeding rf current to the antenna straps, in a direction along the tokamak edge magnetic field. An effective stripline voltage limit of ~15-20 kV in plasma (45 kV in vacuum) limited the antenna heating power to ~2.5 MW. 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 ~0.5 mTorr. The mechanism for this breakdown is not clear. 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 had been designed with **E**||**B** in order to achieve maximum compactness, but a redesign was performed in 2001 to reorient the striplines to an **E**⊥**B** configuration. High voltage gaps were increased to reduce electric fields, and in the case of arcing at the current strap crossover, electrodes were reshaped to reorient the region of highest field.

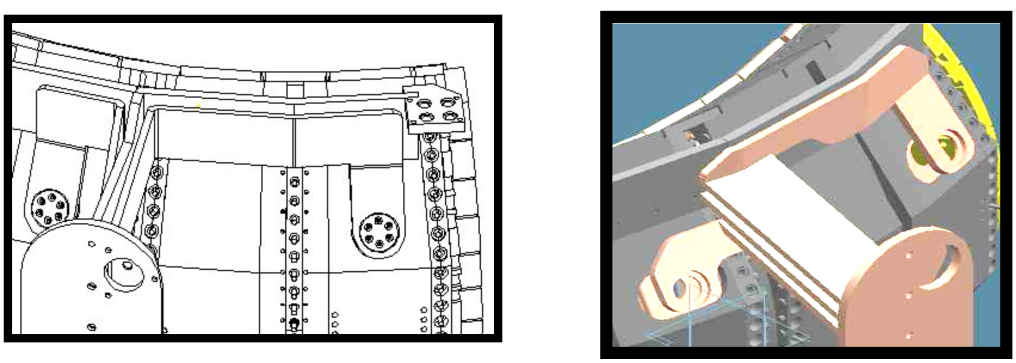

FIGURE 2. Original **E**||**B** current feed design (left) and modified **E**⊥**B** design (right). The tokamak magnetic field is roughly horizontal on left, and rises at ~30° on right.

Series arcing was observed in 2002 in bolted contacts both in the current feeds and the antenna mounting plate. These have been redesigned with more bolts, improved mating surfaces, and copper plating where needed to improve electrical contact.

SUMMARY

C-Mod has presented a challenge to install a high power (~4 MW) 4-strap ICRF antenna in a tight space. Modifications have been made to the antenna plasma-facing surfaces and the internal current-carrying structure. At the present time the antenna has performed up to 3 MW into plasma with heating phasing, with good efficiency and no deleterious effects.

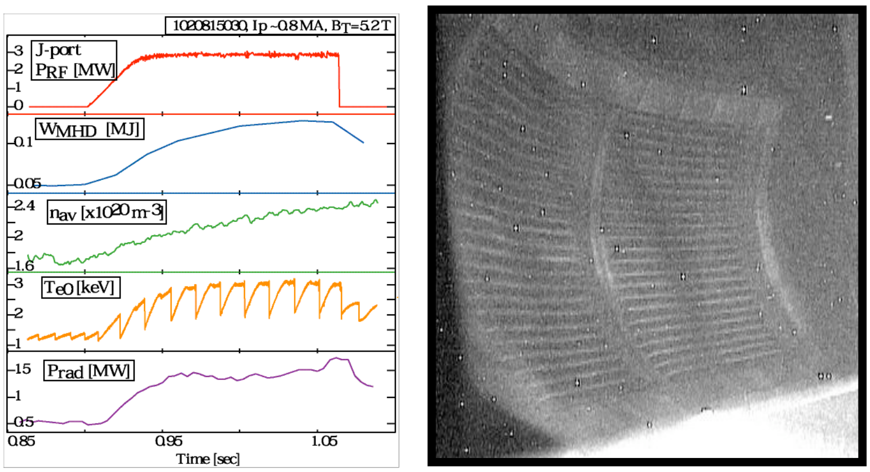

FIGURE 4. 3 MW pulse into C-Mod.

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