Effect on Antenna Structure of High Power RF During Plasma Operation

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INTRODUCTION

High-power, long-pulse operation on the Tore Supra tokamak results in considerable stress on the plasma-facing components. The ICH antennas must deliver high-power rf (up to 4 MW per antenna) in this environment. The antenna structure is therefore subjected to the power flux resulting from the interaction between rf and the edge plasma. The structure's response during operation is described, as is the condition of the antenna after prolonged use.

TORE SUPRA ANTENNAS

ICH power is launched from two side-by-side resonant double loops\(^1\) per antenna. Bumper limiters are located along the sides and at the top and bottom. The Faraday shield has evolved through two versions, as indicated in Fig. 1. In the first version, two tiers of water-cooled tubes pass through an uncooled septum between the two current straps. Carbon tiles are brazed to the outer surfaces of the outer tier of tubes. In the second version, water on one side flows through a single tier of tubes into a plenum on the septum, and out through tubes on the other side. A coating of boron carbide covers the outer surfaces of the water-cooled tubes and the cooled septum.

Each strap of each antenna is independently powered by a separate transmitter. The phase between straps may be specified. There are six transmitters, each of 2-MW capability, so 4 MW per antenna is available. Although 4 MW has by now been reached for one antenna, the operation described here ranged between 2 and 2.5 MW per antenna.

ANTENNA RESPONSE DURING PLASMA OPERATION

IR imaging, using a camera which viewed the antennas through endoscopes, permitted a time history of the temperatures of the front face of the antenna structure. For these experiments, the antenna was 2 cm beyond the shadow of the limiter. For

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that reason, very little temperature increase was seen for the structure, except during and following the rf pulse. Noise pickup during rf prevented a reliable determination of the antenna temperatures, so the bulk of the information applies to the post-pulse period.

Briefly stated, rf leads to localized heating. The hot spots correspond to concentrated power flux and/or lack of cooling. As an example of the latter, the uncooled inconel septum in the first version got hot enough (>600°C) to limit operation. There was a large increase in the nickel concentration when using that antenna and an increase in the radiated power consistent with the observed heavy impurity increase. That antenna was operated only with the straps out of phase (–180°). Conversely, when the antenna with the cooled septum was operated with a –180° phase difference, there was little or no temperature increase for the septum. However, as shown in Fig. 2, even the cooled septum could become hot when using other phase differences.

Often, the hottest spot on the antenna face was on one of the two diagonally opposite corners, those where the magnetic field lines just graze the corner (considering the "q-tilting" of the field lines). In general, the lower of those would be the hottest, but as shown in Fig. 3, phase differences other than 180° could cause the upper corner to be about as hot. The heating in the upper corner was enough to debraze the carbon tile there, with the result that the corner tile fell off during one shot.

**CONDITION OF ANTENNA FACE**

After one of the antennas was removed, damage was observed to the tile on the bottom corner, such that part of the tile was missing. Why the part was missing is not clear, but in the light of experience with the upper corner (on another antenna), thermal shock is a serious contender. After the part had broken off, the area had clearly been eroded by the plasma.

Three of the carbon tiles on one of the side bumpers (on the "electron drift" side) had been broken, but that bumper had suffered a mechanical jolt, so that may have been the cause for the tile breakage seen. The sharp edges still present on the breaks indicated negligible plasma erosion after the fractures.

A band of discoloration extends along this side bumper, about where the maximum heating is expected. That location is at the maximum of the product of the exponentially decaying heat flux times the cosine of the angle between the normal to the tile surface and the magnetic field direction. Very small-scale damage occurred to the tiles along that band. There are sharp edges where one tile overlaps the next, and areas of a few square millimeters were broken at those edges.
Localized pitting, consisting of a large number of small pits in an area of about 4 x 20 mm, was seen at a few random spots on the antenna face. The cause is unknown.

About 20 of the carbon tiles were missing from the water-cooled tubes of the Faraday shield, predominantly in the area where intense heating was seen. Thermal shock is suspected for their departure.

**CORNER HEATING**

Although corner tiles are not cooled as well as the rest of the bumper tiles, the high temperatures on the corners seem to indicate localized heating, as opposed to poor cooling. Enhanced heating at the corners is somewhat surprising because the corners are well below (~6 cm) the ends of the current straps. The maximum current, and therefore the maximum rf B fields, occur at the center of the antenna, about 30 cm from the corners. The corners seem to be remote from the strong field regions; nevertheless, some of the antenna power is being coupled there, with a high power density.

One possible mechanism for concentrating power at the corners is the electromagnetic excitation of the plasma sheath. Electric fields (electromagnetic rather than electrostatic) can heat electrons via Fermi acceleration. As a result, a large positive sheath potential is formed. Ions, accelerated through the sheath potential, will deposit their energy on the material surface—in this case, the carbon tile.

The driving force for this mechanism is an electric field parallel to the static magnetic field. Image currents in the antenna structure give rise to such electric fields, particularly at the bottom and top. The principal image currents flow vertically in the sides of the structure, beside the current strap, but at the top and bottom of the sides, these currents must turn and flow horizontally.

Measurements of the rf magnetic field distributions can be used to estimate the parallel electric field near the corner, for vacuum conditions. The value of the electric field in a plasma is not apparent because of the large dielectric constant and the flux compression expected for a plasma in close proximity. Additional work will be required to determine whether this mechanism, which gives qualitative agreement with the observations, is of the right magnitude to explain the effects.

**SUMMARY**

The ICH antennas in Tore Supra have operated at high power for long pulses. In the first version of the Faraday shield, the septum became very hot and was probably the source for nickel impurity in the plasma. Septum heating was greatly alleviated in the second version.

The bumper limiters had several broken tiles, some of which were known to be due to mechanical causes, some to thermal shock. The tiles subjected to the most thermal stress were at the corners. The reason for the intense heating there is not known with certainty, but electromagnetic excitation of the sheath is a possible cause.

A new Faraday shield is now being designed which will take advantage of the lessons from the first two versions; this shield will have a cooled septum, a single tier of tubes, and boron carbide coating. The bumper limiters will be repaired, but their design will not be altered.
REFERENCES
