HEATING PROFILES ON ICRF ANTENNA FARADAY SHIELDS*

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ABSTRACT

Poor definition of the heating profiles that occur during normal operation of Faraday shields for ion cyclotron resonant frequency (ICRF) antennas has complicated the mechanical design of ICRF system components. Inadequate understanding of shield heating has led to damage of experimental equipment and to overconservative design. With the increased heat loads, disruption currents, and pulse lengths predicted for future experiments, a more accurate assessment of shield heating is needed.

At Oak Ridge National Laboratory (ORNL), Faraday shield analysis is being used in defining rf heating profiles. In recent numerical analyses of proposed hardware for the Burning Plasma Experiment (BPX) and DIII-D, rf magnetic fields at Faraday shield surfaces were calculated, providing realistic predictions of the induced skin currents flowing on the shield elements and the resulting dissipated power profile. Detailed measurements on mock-ups of the Faraday shields for DIII-D and the Tokamak Fusion Test Reactor (TFTR) confirmed the predicted magnetic field distributions. Calculated rf loads presented by Faraday shields have also been confirmed by measurements on a variety of shield materials and geometries. The heat deposition profiles are input to heat transfer and stress analysis codes, which then predict temperatures and stresses for various hardware configurations. These analyses are iterated until acceptable temperatures and stresses are found. This process also helps to place limits on the power, pulse length, and/or duty cycle for a design.

A conceptual design for an uncooled Faraday shield for the BPX ion cyclotron resonance heating (ICRH) antenna, which should withstand the proposed long-pulse operation, has been completed. A high-heat-flux, uncooled Faraday shield has also been designed for the fast-wave current drive (FWCD) antenna on DIII-D. For both components, the improved understanding of the heating profiles made it possible to design for heat fluxes that would otherwise have been too close to mechanically established limits.

The analytical effort is described in detail, with emphasis on the design work for the BPX ICRH antenna conceptual design and for the replacement Faraday shield for the DIII-D FWCD antenna. Results of analyses are shown, and configuration issues involved in component modeling are discussed.

INTRODUCTION

The designs of the BPX Faraday shield and the upgrade Faraday shield for the FWCD antenna for DIII-D have required an accurate understanding of the rf heating profiles

and resulting temperatures and stresses to prevent hardware failure or overconservative design. At ORNL, Faraday shield design has consisted of (1) using three-dimensional (3-D) magnetostatic analysis to determine the magnetic field strength and distribution, (2) using the magnetic field information to predict rf heating profiles, and (3) applying the predicted rf loads along with plasma and disruption loads to describe the temperatures and stresses induced in the Faraday shield.

DESIGN

BPX

The optimized conceptual design for the BPX Faraday shield is an array of copper-plated Inconel rods (0.625 in. OD) tilted 15° in a single tier. Tiles made of a high-electrical-conductivity graphite composite are attached to the plasma side of the rods by snapping the carbon-carbon composite tiles onto the Inconel rod. The shield is cooled primarily by radiation to the cooled current straps and back plate and by conduction through the Faraday shield tubes and support frame to the vacuum vessel, which is cooled by gas at 350°C.¹ Figure 1 shows a front elevation view of the BPX ICRH launcher.

DIII-D

The FWCD antenna for DIII-D is being upgraded to increase antenna coupling by moving the current straps closer and by increasing the optical transparency of the Faraday shield. The replacement Faraday shield consists of Inconel 625 rods (0.5 in. OD) plasma-sprayed with copper followed by boron carbide (B₄C). They are arranged in a single tier and welded on both ends into a frame bolted to the antenna box. The rods are tilted 12° clockwise when viewed from machine center and are spaced 0.92 in. apart between centers. The shield is cooled primarily by radiation to the box at 200°C. Figure 2 shows a front assembly of the DIII-D FWCD antenna.

RF HEATING PROFILE

The rf power losses in the Faraday shield depend on the magnetic field strength and distribution, the shield design, and the plasma loading.

MAGNETIC FIELD

A complete magnetic field distribution is obtained with a 3-D magnetostatic analysis that uses the long-wavelength approximation to find a 3-D Laplace solution for the magnetic scalar potential over one poloidal period of the Faraday shield.

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Fig. 1. Front elevation view of the 3PX antenna with part of the Faraday shield cut away.

SHIELD DESIGN

The two most important shield design variables influencing rf power losses are the shield geometry and the shield material.

Shield geometry, such as optical transparency, determines magnetic field compression. Optical transparency is defined as the percentage of the total area of the Faraday shield footprint facing the plasma that consists of gaps between the rods. Increasing the optical transparency by widening the gaps between rods decreases magnetic field compression and therefore decreases rf losses. Figure 3 demonstrates the enhancement of surface fields and surface currents in regions of the shield cross section where the normal component of the magnetic field is compressed.

The shield material determines the surface resistance, which depends on the rf frequency f and the resistivity η of the material:

$$R_s = \sqrt{\pi f \mu_0 \eta}$$

The rf power absorbed in the Faraday shield can be the dominant heating source for the Faraday shield tubes during normal ICRH operation if a substance with relatively high electrical resistivity (e.g., graphite) is used to cover the Faraday shield tubes. The resistivity of low-loss graphite composite is 300 mW·cm at 0°C, and a similar temperature dependence has been assumed for POCO graphite, yielding resistivities of 250 mW·cm at 500°C, 300 mW·cm at 1375°C, and 330 mW·cm at 1700°C. This insignificant temperature dependence has been neglected in these heating calculations. The lower electrical resistivity of the B₄C coating of the DIII-D Faraday shield has reduced the importance of the rf power loading, and the plasma heating makes up the larger

Fig. 2. Front elevation view of the Faraday shield upgrade for the FWCD antenna for DIII-D.

Fig. 3. Compression of magnetic flux through Faraday shield gaps and the power distribution.

share of the total power on the shield (163-W average rf loss vs 1451 W of plasma heating per 9-in. length of rod). Figure 4 shows the distribution of the power on the B₄C-coated rods.

Calculation of the Faraday shield loading, R_{FS}' , is based on the surface resistance, the rms strap current at that location, the optical transparency, and magnetic field parameters.²

Fig. 4. Power distribution on boron carbide-coated Faraday shield rods.

PLASMA LOADING

The plasma loading, P_{plasma} , is a factor in P_{diss} , the amount of rf power dissipated on the Faraday shield:

$$P_{\text{diss}} = \frac{R_{FS}'}{R_L'} P_{\text{plasma}} = \frac{R_{FS}'}{R_{FS}' + R_L'} P_{\text{max}},$$

where R_L' is the plasma loading per unit poloidal length and P_{max} is the maximum power distribution along the tube with the greatest power dissipation. The distribution of dissipated power along the Faraday shield tube is shown in Fig. 5, where the maxima occur near the ends of the current strap. The compressed normal component of the field is responsible for most

of the power dissipation. Table 1 lists the major parameters that enter into the calculation of the Faraday shield losses.

Fig. 5. RF power distribution along the Faraday shield.

The power distribution around the circumference of the tube is a maximum in the shield gap, as in Fig. 3. This azimuthal peak power (Q_{rf}) determines the temperature of the hottest point on the shield. In the subsequent two-dimensional (2-D) thermal calculations, Q_{rf} is related to the maximum power defined by the assumption of a $\cos^2\theta$ distribution around the front half of the circumference where the power is dissipated in the graphite tile:

$$Q_{rf} = \frac{4P_{\text{max}}}{\pi d}.$$

This assumed power distribution approximates the distribution in Fig. 3 when the optical transparency of the shield is high.

THERMAL ANALYSIS

Configurations for the BPX and DIII-D antenna Faraday shields were optimized by using thermal analysis codes to apply the rf heating profiles and disruption and plasma loading for a range of load cases; the output allows consideration of design issues such as the rod diameter, rod material, and joint design.

BPX

Two-dimensional transient thermal analyses were performed on the BPX antenna Faraday shield rod and tile cross section to estimate peak temperatures during a single pulse. The initial temperature of the shield was assumed to be 350°C; this assumption is justified by the between-shot thermal analysis of the Faraday shield. Normal operating loads included radiation from the plasma, neutron heating, and heating from direct rf losses. Disruption heat loads were included as well. The specific conditions are a 350-MW fusion power 8-s pulse with a 3-s flattop and constant 30-MW rf heating. The disruption energy flux is 3.34 MW/m², most of which is deposited in 4 ms beginning at the end of the pulse flattop. Neutron heating was scaled from the values specified for a 500-MW fusion power pulse.

Table 1. Parameters and results of Faraday shield heating calculations for the BPX antenna

Shield geometry	
Tube effective radius, cm (0.0125-in. tiles on 0.625-in. tubes)	0.953
Tube length, cm	29.3
Tube-tube gap, cm	0.953
Optical transparency, %	33
Strap-shield gap, cm	1.5
Electrical characteristics	
Frequency, MHz	90
Phasing	0/ π
Graphite tile resistivity η , $\mu\Omega\cdot\text{cm}$	300
Tube substrate resistivity η	Negligible
Shield calculations (plasma independent)	
Flux compression factor β	5.85
Toroidal peaking factor PF	2.45
Resistance per tube R_{FS} , Ω	3.49×10^{-3}
Shield loading, R_{FS}' , Ω/m	0.122
Plasma assumptions	
Plasma loading R_L' , Ω/m	8.5
Power to plasma, MW per strap	1.25
Maximum rms strap current, A	655.7
Power dissipation (plasma dependent)	
Maximum tube power P_{tube} , kW	1.50
Maximum power along tube P_{max} , W/cm	130
Azimuthal power peak Q_{rf} , W/cm ²	84

The thermal model is shown in Fig. 6. The carbon-carbon composite tile is loosely attached by mechanical means to the 0.625-in.-diam Inconel 625 rod. The tile varies in thickness from 0.125 in. (position closest to plasma) to 0.0625 in. (position closest to adjacent rods). In the thermal model, the only means of heat transfer between the tile and the rod is via radiation, since the loose contact in vacuum will result in very low thermal conductance. The attachment design must ensure this low conductance. It must also ensure that any attaching metal is not directly exposed to disruption or plasma heat loads.

Disruption, alpha, and reradiated rf heat loads were modeled including only a component normal to the tile surface from the plasma center or X-direction in Fig. 6. Direct rf loss heating impinges only on the tile, and it varies as the square of the cosine of the angle that the surface tangent makes with X between the rods.¹

Many variations of this analysis were performed to find the best design option. For the results presented here, the side of the rod facing the current strap is radiating to a 350°C sink; the tile surface radiates to a 600°C sink. Material properties were temperature dependent. The tile properties were based on a carbon-carbon composite material designed to have high thermal conductance, from 500 W/(cm²·°C) at 100°C down to 200 W/(cm²·°C) at 1750°C.

The peak temperature prior to disruption is 1040°C, well below the 1700°C limit for carbon imposed for nondisruption

pulses. There is no limit for carbon under disruption conditions, but the analysis indicates a peak temperature of 2529°C at 4 ms into disruption. This estimate is low because of the coarseness of the mesh in the model where there is a high gradient at the temperature surface. Sublimation of the carbon-carbon tile becomes the important issue during a disruption. A specialized analysis code can be used to estimate the amount of material sublimated per disruption. A preliminary estimate based on past analyses of carbon-carbon tiles elsewhere inside the vacuum vessel indicates that approximately 6.5 μm of tile would be sublimated per disruption.

Fig. 6. Two-dimensional thermal model of Faraday shield cross section.

The results show that the temperature of carbon-carbon composite tile on a solid Inconel rod is well below the 1700°C limit at the end of the flattop, indicating a feasible design under nondisruption conditions. Even with a disruption, the maximum temperature of the Inconel is below 440°C at the end of the pulse, where 600°C is the limit. Sublimation of the tile from the disruption heat loads is the more critical issue, and further quantitative analyses will be done to estimate how much material will be lost.

DIII-D

The thermal and stress analysis of the DIII-D antenna Faraday shield was simplified by the increased transparency and by the selection of B₄C as the coating. This reduced the rf losses drastically. A finite element model was constructed of plate and beam elements to represent the box and Faraday shield rods. Under combined thermal and disruption loading, the worst-case scenario, the maximum stress in the rod is 22 000 psi compression, well below the allowable stress 40 000 psi. The box endures a stress of 70 000 psi, which is

above the yield strength and as a thermal stress will be self-relieving. A bulk temperature rise of 65°C increases the rod temperature to 395°C during the first 10 s of a pulse, but no thermal ratcheting occurs.

CONFIRMATION

The accuracy of the magnetic and rf heating analytical methods has been verified by measurements on mock-ups of Faraday shields and rods.

MAGNETIC MEASUREMENTS

Detailed measurements on mock-ups of the Faraday shields for DIII-D and TFTR confirmed the accuracy of the magnetic field distributions predicted by 3-D magnetostatic analysis. These measurements were performed on the Radio Frequency Test Facility at ORNL.³

THERMAL MEASUREMENTS

High-heat-flux tests of shield elements by exposure to energetic particle beams were performed at ORNL. The purpose was (1) to determine the adequacy of brazed graphite tiles on uncooled Inconel rods and (2) to demonstrate the performance of brazed graphite tiles and TiC,N coatings on Inconel rods during a singularity event such as a short-term burst of high-energy particles. This testing was conducted during the conceptual design phase of the DIII-D Faraday shield upgrade, when the design consisted of copper-plated Inconel rods with graphite tiles brazed on.

The test apparatus consisted of coupons cut from Faraday shield elements from the Tore Supra and FWCD antennas. These were equipped with embedded thermocouples and mounted on a water-cooled, cantilevered structure. A high-energy particle beam of hydrogen ions was calibrated to simulate various power levels. The test sample was installed in the beam line vacuum vessel directly in the path of the beam.

Two test cases were analyzed. The first heat load was based on the 2-MW power output capability of the current transmitter installed at DIII-D. The second heat load was based on the full 4-MW output case. Hand calculations were used initially to estimate the required heat parameters. A 2-D, transient thermal model was created to evaluate and accurately assess the gradient across the tube cross section. Finally, a 3-D model was created to evaluate the effects of conduction and nonuniform heating (Gaussian distribution) along the length of the tube. Predicted end-of-pulse temperatures generated by the model are compared with the actual measurements in Table 2.

Table 2. Actual and calculated temperatures of copper-plated Inconel rod with brazed graphite tiles

	Temperature of graphite after 30 s (°C)	
	Actual	Predicted
Beam power, W/cm ²		
100	538	545
175	575	580
185	590	590
200	600	605
220	625	625

Although the thermocouples in the rods were unable to accurately track the temperature maxima during transients, there was good agreement between the thermocouples and the analysis results for the condition at the end of 30 s (prior to the next pulse). Due to the high-vacuum operating conditions, it is believed that the thermocouple surface area in intimate contact with the Inconel tubing was insufficient to allow conductive heat transfer into the thermocouple. With radiative heat transfer as the primary mechanism for heating the thermocouple, it is assumed that 15- to 30-s time scales are reasonable periods of time for the thermocouple to come into equilibrium with the surrounding surface.

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