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DETERMINATION OF WALL REFLECTIVITY FOR ECE FREQUENCIES IN DIII–D

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The significance of cyclotron radiation losses in next-generation tokamaks depends on the reflectivity of first wall materials. An experimental study of the effective reflectivity for electron cyclotron frequencies in the graphite-walled DIII–D tokamak is reported. Measurements of optically-thin harmonics ($\omega = n\omega_{\text{ce}}$, $n > 4$) are made for two polarizations from thermal plasma discharges using an absolutely calibrated Michelson interferometer. The reflectivity r and polarization transfer fraction p are obtained by matching measured spectra to simulations from an ECE radiation transport code with adjustable wall parameters. For the frequency range 150–400 GHz average values of $r = 0.76$ and $p = 0.19$ are found.

1 Introduction

The issue of cyclotron emission as a limiting mechanism in a fusion reactor has been studied since the early days of fusion research. For a device with metallic walls the high reflectivity can be shown to prevent excessive energy loss by cyclotron emission.[1] However, present day fusion system designs, *e.g.*, the ITER tokamak, walls of graphite or ceramic are envisioned and these may have low enough reflectivity to create a problem. Since the exact nature of graphite walls is difficult to predict,[2] an experimental measurement of the reflectivity of a graphite-walled machine is desired. The DIII–D tokamak, with its nearly complete interior coverage with graphite, is a good candidate for such an investigation. Here we present results of a study of the reflectivity of the DIII–D vessel for the frequency range covering the third through sixth harmonics of the electron cyclotron frequency from measurements of the plasma emission using a fast scanning Michelson interferometer.

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2 Technique

The simplest reflection model involves two quantities: a reflection coefficient r and a polarization transfer fraction p. This is the plane-parallel wall model used by many investigators.[3] By measuring two orthogonal polarizations of optically thin electron cyclotron emission from a DIII–D plasma we can determine unique values for r and p. The natural polarizations to measure are those perpendicular and parallel to the tokamak total B-field vector, *i.e.*, the extraordinary and ordinary modes. If we know the temperature, density, and magnetic field of the plasma, we can calculate the direct emission from the plasma and use radiation transport and the reflection model to predict what the emission should be. By adjusting the reflection parameters, the best match to the data can be obtained and thus values for r and p. This is the technique employed by several authors previously.[4,5]

The direct electron cyclotron emission from the plasma is calculated from the expressions given by Bornatici.[6] The absorption formula used is that for quasi-perpendicular propagation with respect to the magnetic field. The emissivity is determined assuming Kirchhoff's law and this is integrated across the plasma cross section to obtain the intensity. The intensity is thus obtained this way for a set of frequencies and harmonics appropriate to the plasma conditions.

The electron temperatures in DIII–D for the plasma investigated were less than 6 keV. Under these conditions the emission layers for different harmonics at a given frequency do not overlap in space and thus the total emitted intensity is a simple sum over harmonics. Now employing the reflection model used in Ref. 3 we have for the intensity I' after a single reflection the following:

$$I'_X = r(1-p)I_X + rpI_O \quad ,$$

$$I'_O = r(1-p)I_O + rpI_X \quad .$$

The computer code for the model, which is written in IDL, allows the specification of the number of reflections to calculate. In practice it was found that after 7–11 reflections the calculated emission intensity for the optically thin frequencies reaches a steady-state. The code was originally developed to study optically-gray third harmonic emission[7] does a good job matching the measured intensity at these frequencies for which wall reflection does not play a role.

3 Measurements

The measurements were made using a fast scanning Michelson interferometer. The instrument's frequency range is 60–1800 GHz, its resolution is 4 GHz and the repetition rate is 40 Hz. It is absolutely calibrated with a liquid nitrogen black-body source and has a calibration uncertainty of 5% over the frequency range of 90–300 GHz.

The viewing chord of the Michelson's collection optics is along a major radius of the tokamak as shown in the cross section of Fig. 1. The optics is designed to produce a Gaussian beam across the plasma and has a measured spot size of 6 cm for 110 GHz at the vessel center. There is a wire grid polarizer just after the ellipsoidal mirror which can be oriented to pass either the vertically or horizontally polarized emission from the outboard edge of the plasma. The vertical and horizontal polarization corresponds approximately to the X– and O–mode, respectively, from the plasma.

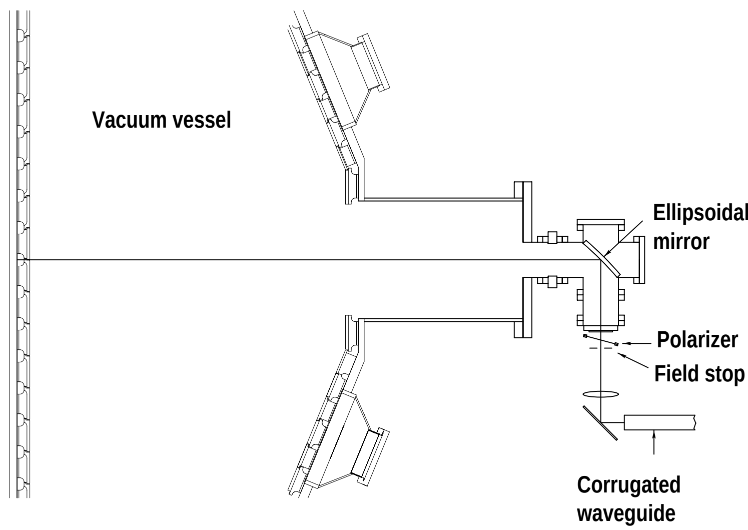

Figure 1: Cross section of the DIII–D tokamak showing the viewing optics and sightline for the Michelson interferometer.

For these experiments, the X–mode and O–mode spectra were measured for pairs of identical discharges. The electron temperature was obtained from second harmonic ECE and Thomson scattering data and the electron density from interferometry and Thomson scattering. Runs of the equilibrium code EFIT gave the total magnetic field and flux coordinate mapping. These data were input to the ECE radiation transport code and simulation spectra were produced.

The simulation code is run for a range of r and p values and the χ^2 difference is calculated between the resulting simulation spectrum and the experimental spectrum. This is done for each polarization and the chosen best values of r and p are those that minimize the χ^2 for X– and O–mode simultaneously.

Figure 2 shows a typical pair of X and O–mode spectra for a neutral beam heated discharge at 2 T. Also plotted is the simulated spectra using the best values

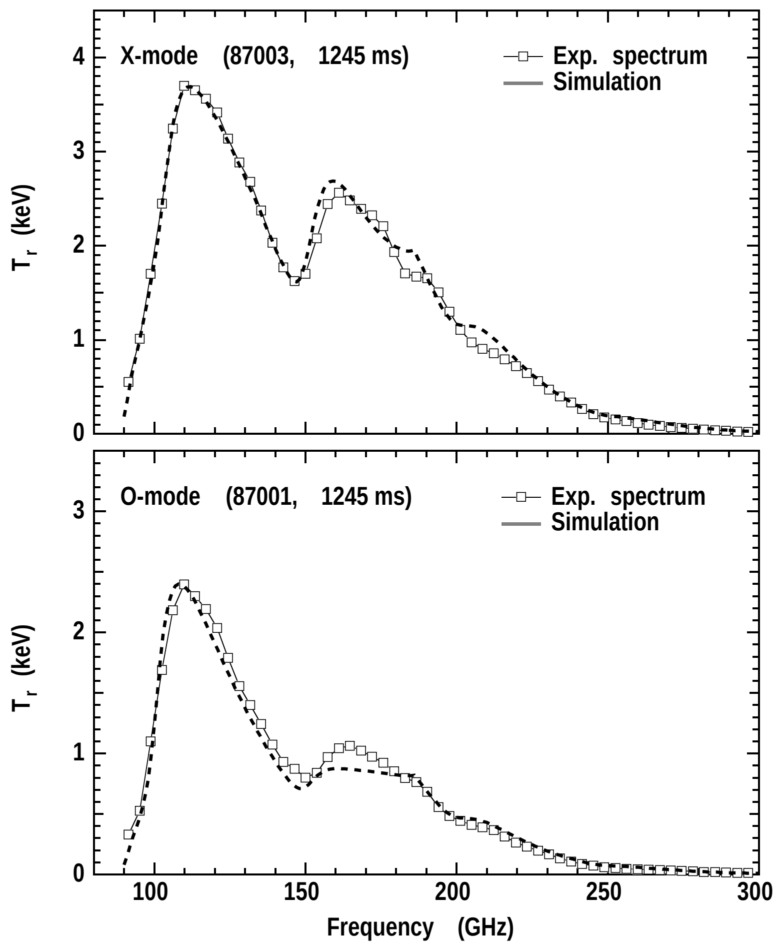

Figure 2: Experimental ECE spectra for X and O-mode polarizations along with the results from the simulation code for best values of r and p.

of r and p, which for this case are $r = 0.77$ and $p = 0.22$. The agreement is good for the optically thin frequencies from 180–300 GHz. Note that the reflection quantities cannot be calculated for second harmonic frequencies that are optically thick since the wall reflection does not enter into the problem. In Fig. 3 are shown contours of combined X and O χ^2 for shot pair 87003/87001. The narrow spread in r shows that this quantity is well determined while the broader spread in p indicates this value has more uncertainty.

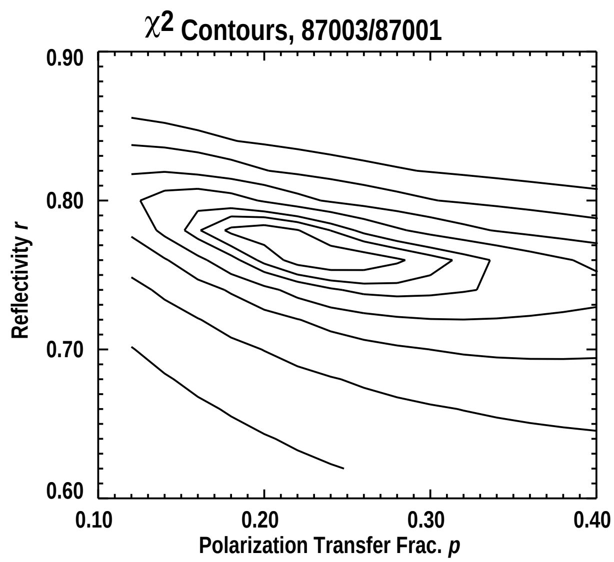

Figure 3: Contours of χ^2 for the data of Fig. 2.

Table I summarizes the results for three shot pairs, shots that are of moderately different parameters. In one shot pair, 86631/86630, the discharge is only ohmically heated and the neutral beam ducts, a set of 4 large area (600 cm^2) ‘‘holes’’ in the vessel, are closed. The results are nearly the same for all three, giving an average reflection coefficient of 0.76 and a polarization scrambling coefficient of 0.19.

Table I: Values of r and p from best matches to simulation code.

shot pairs (X/O)	r	p
86631/86630	0.76	0.16
86793/86792	0.74	0.20
87003/87001	0.77	0.22

4 Conclusions

An electron cyclotron emission simulation code with a simple reflection model had been employed to study the wall reflectivity at electron cyclotron frequencies for the graphite-tiled DIII–D vacuum vessel. Using measured ECE spectra in two polarizations and a multiple reflection model, values for the wall reflection coefficient r and polarization transfer fraction p as a function of frequency have been determined. Average values of $r = 0.76$ and $p = 0.19$ are found for the range of frequencies 150–300 GHz. The value for reflectivity is in the range expected for graphite, as calculated in Ref. 2, and does not lead to excessive cyclotron loss in the case of a high temperature reactor plasma. For the future, these experiments should be repeated for higher temperature plasmas, *i.e.*, more reactor relevant ones, which will also give information over a wider frequency range due to the increased emission at higher harmonics. The analysis could also benefit from a more sophisticated simulation code, one that did radiation transport in more than one dimension and included effects of polarization rotation in the plasma.

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