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CHARACTERISTICS OF DIAMOND WINDOWS ON THE 1 MW, 110 GHz GYROTRON SYSTEMS ON THE DIII–D TOKAMAK

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Characteristics of Diamond Windows on the 1 MW, 110 GHz Gyrotron Systems on the DIII-D Tokamak

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Abstract. Diamond disks made using the chemical vapor deposition (CVD) technique are now in common use as gyrotron output windows. The low millimeter wave losses and excellent thermal conductivity of diamond have made it possible to use such windows in gyrotrons with ~1 MW output power and pulse length up to and greater than 10 s. A ubiquitous characteristic of diamond gyrotron windows is the presence of apparent hot spots in the infrared images registered during rf pulses. Many of these spots are co-located with bright points seen in visible video images. The spots do not seem to compromise the integrity of the windows. Analysis of the infrared observations on several different gyrotrons operating at the DIII-D tokamak are reported.

I. INTRODUCTION

The DIII-D electron cyclotron heating (ECH) system is comprised of five operational gyrotrons operating at a frequency of 110 GHz. The total rf power injected into the tokamak vessel exceeds 2.5 MW. Modification of current density profile stabilization of instabilities can require long rf pulses. With nearly 1 MW output power from each gyrotron, diamond windows have made possible rf pulse lengths greater than 2 s to be used. Successful application of CVD diamond technology has required diagnostic measurements of the properties of diamond gyrotron output window assemblies and, in particular, of their thermal response to transmission of microwave beams at high power density. The fundamental diagnostic measurement is infrared imaging of the window during operation.

II. WINDOW CONTAMINATION

The low absorption characteristic of diamond, which makes it ideal for use as a window, also makes this a difficult measurement because the low emissivity of the diamond requires empirical calibration of the setup. In the DIII-D installation, the waveguide transmission line and coupling system are evacuated, so the window must be viewed off-axis through a sapphire viewport in the matching optics unit (MOU). The diamond windows are partly transparent for infrared (IR) radiation from inside the gyrotron. Radiation from this source also will contribute to the observed IR image and will bias the temperature determination. The contribution to the image from this source must be estimated. Three diamond windows with two different thicknesses were measured. The main parameters of the three windows are summarized in Table 1.

Table 1. Main Parameters of Three Diamond Windows

	Gyrotron		
	CPI-P1	CPI-P2	CPI-P3
Window clear aperture (mm)	50.8	50.8	50.8
Window disk diameter (mm)	73.5	57.0	73.5
Window thickness (mm)	1.71	1.14	1.71
Thermal conductivity (kW/m^2K) (estimate)	6.5	6.5	6.5
tan(δ)	$<1\times10^{-4}$	$<1\times10^{-4}$	$<1\times10^{-4}$
P_{abs} at 800 kW (kW)	2.8	1.8	2.0

All the diamond windows observed to date share the common property that isolated regions of high infrared emission are clearly evident. These are distributed across each of the disks. The spots could arise from points with higher than the local emissivity or of higher than the local temperature or both. Either of these possibilities provides cause for concern. If these hot spots resulted from non-diamond phase inclusions in the bulk material, they might indicate a material degradation at the sites of highly absorbing graphitic phases. If the hot spots were due to impurities on the surfaces of the windows, they might be able to be eliminated by cleaning.

One of the windows mounted on a gyrotron was examined for graphite or other impurities with Raman scattering. It was found that contamination by graphite was present both on the surface and deeper in the lattice. This window was subjected to cleaning by air driven alumina grit. Following this procedure, some, but not all, of the contaminants, presumably those on the surface, had been removed. Raman scattering verified the removal of most of the surface contamination. Blowing on the window surface with dry nitrogen gas resulted in no additional change in the number of hot spots.

III. TEMPERATURE PROFILES

Profiles of the window temperatures taken on diameters across the windows permit quantitative comparisons among the three windows and with ANSYS modeling to be performed. As is clear from Figs 1(a-c), there are

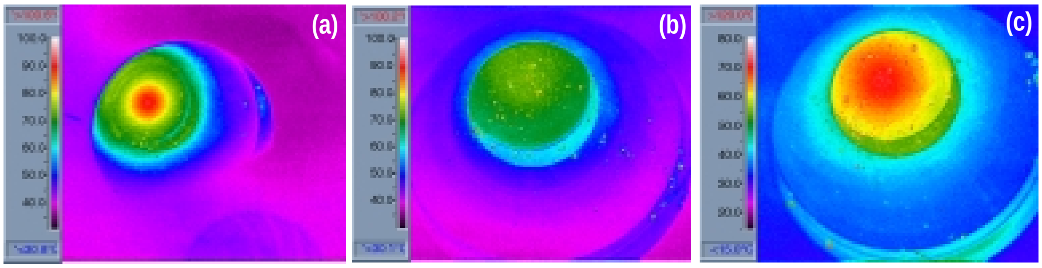

Fig. 1. The infrared images of the gyrotrons windows differ qualitatively. In (a) the CPI-P2 window infrared image is seen to have a Gaussian character with several pinpoint hot spots. (b) The CPI-P3 window has a much broader temperature, which is nearly flat across the central part of the image. (c) The infrared image has a distinctive hot area in the middle of the window similar to CPI-P2, although the parameters of the diamond disk are similar to the CPI-P3 window.

qualitative differences among the three images. In Fig. 1(a), the CPI-P2 window, which is unique in that it is $2\lambda/2$ in thickness, is seen to have a qualitatively Gaussian character with several pinpoint hot spots. The images in Fig. 1(b) and Fig. 1(c) are of the CPI-P3 and CPI-P1 windows and have much broader temperature profiles, which are nearly flat across the central part of the image. The images in Fig. 1(a) and Fig 1(b) were obtained under similar conditions at the end of 5.0 s long pulses at ~800 kW transmitted power. The image in Fig. 1(c) was obtained at the end of a 1.0 s long pulse at 500 kW. At the time of this writing, longer pulse data for this gyrotron were not available. However, previous measurements on all the windows showed after about one second that the central temperature reacges ~80% of the maximum at equilibrium, so the qualitative character of the profile is not expected to change appreciably for longer pulses. The empirically derived corrections for the viewing optics, the change in diamond emissivity with temperature and infrared radiation from inside the gyrotron did not change the qualitative differences among the images. In Fig. 2, the ANSYS calculation for the window installed on CPI-P2 is presented for comparison with the measurements. For the thicker windows and the same Gaussian beam profile, ANSYS predicts

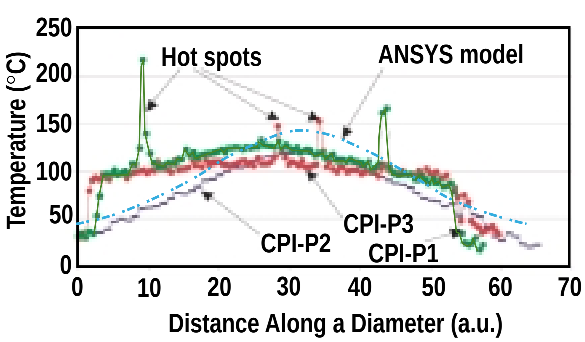

Fig. 2. Temperature profiles for the three CVD diamond windows measured with an infrared camera are compared with the ANSYS calculation for one of them. The measurmeents are broader and lower than the model.

the same radial profile shape and about 30°C higher peak temperature than for the thinner window. The model overestimates the peak temperatures for all three windows. The measured profiles for the two thicker windows are considerably flatter than either the ANSYS model or the measurement of the thinner window.

The reason for the extremely flat profiles for the thicker windows compared with the thinner one is not understood, however there is a design difference between the thinner and the thicker window assemblies. The thinner disk is only in contact with the cooling water at its outer circumference. The two thicker windows, however, were cut from larger diameter disks and, although the clear aperture is the same, they are supported so that their edges extend into the cooling water flow, greatly increasing the heat transfer efficiency. Although intuition and ANSYS both suggest that the improved heat transfer at the edge should peak, rather than flatten the profile, in other respects the window mount and cooling geometries are identical for the two types of windows.

IV. CONCLUSIONS

Three different diamond disks in service as output windows for high power gyrotrons were analyzed using an IR camera. Maximum temperatures of the windows for 800 kW transmitted rf power are in rough agreement with theoretical modeling, but temperature profiles differ significantly in details. The window temperatures equilibrate after ~2.5 s at low peak values, which indicates that diamond windows should be able to transmit up to 1 MW rf beams even up to cw operation. Apparent hot spots in the windows apparently do not lead to thermal runaway or other difficulties.

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