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Abstract: Artificially grown diamond has extremely low absorption for microwaves in the millimeter wave range, making this material an attractive candidate for output windows on high power gyrotrons. Several windows have failed in this application due to higher than expected losses. Infrared measurements of the window temperature on a high power gyrotron operating at 110 GHz have been performed. The peak central temperature and time to equilibrium during the rf pulse were consistent with the low loss properties of the material determined from low power cavity measurements.

INTRODUCTION

The importance of gyrotrons as powerful tools in fusion plasma research is growing. Due to the very high localization of rf power in tokamak plasmas and relatively simple rf transport and launch hardware required, gyrotrons can be considered not only a source of electron cyclotron heating but also an instrument to efficiently suppress different kinds of plasma instabilities. These applications require increasing the total power and pulse duration of the gyrotrons and up to about 1 MW generated power is now possible at frequencies up to 170 GHz. One of the main technological problems facing gyrotron producers has been the gyrotron output window. With traditional window materials, for example BN, megawatt rf power level and a few second pulse duration can cause a large temperature increase in the output window due to dielectric loss. Another material with low loss, sapphire, has relatively poor thermal conductivity and must be face cooled with a low loss coolant, such as a chloro-fluorocarbon liquid. A very promising new material for the gyrotron window is synthetic diamond, which has a small value of dielectric loss and very high thermal conductivity. A few research groups are commissioning high power gyrotrons with diamond windows. Unfortunately, some diamond windows have failed, apparently owing to a lossy surface layer which sometimes forms during the braze process. Infrared measurements of the diamond window installed on a 110 GHz gyrotron in the 1 MW class at the DIII–D tokamak have been performed to qualify the gyrotron for full performance operation and validate the code calculations of window performance.

110 GHz GYROTRON WITH DIAMOND WINDOW AT DIII–D

General Atomics (GA) is now operating four gyrotrons in the 1 MW class at 110 GHz. Three of them were produced by Gycom and have boron nitride output windows.

The average power absorbed in these windows is 26–30 kW, or about 4% of the transmitted power. Window temperature reaches a maximum temperature of 450°C after a 2 s pulse at a generated power of 700 kW, which consitutes a practical operational limit for this type of gyrotron. The second type of gyrotron, produced by Communications and Power Industries (CPI), uses a synthetic diamond window. The frequency of this gyrotron is also 110 GHz and the designed output power is 1.0 MW for 10 s pulses. The maximum pulse length obtained to date at GA is 5 s at 700 kW output power, although maximum power of 1.0 MW has been demonstrated in a 1 ms pulse. The performance of the gyrotron has been limited operationally after failures on other gyrotrons using the same window technology. The diamond window on this gyrotron has a 50.8 mm clear aperture and a $2\lambda/2$ thickness of 1.14 mm. The window is edge cooled by water, has an Au/Cu braze and has a loss tangent near 1.0×10^{-4}, which corresponds to 1–2 kW or 0.22% absorption. A photograph of the gyrotron and schematic representation of the test setup for window temperature measurements is shown in Fig.1.

Several factors combine to make the in situ measurement of the window temperature difficult. The 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), which is also fitted with an rf cutoff screen. The contributions to the infrared signal from the sapphire and screen and their filtering effect on the radiation originating in the diamond window must be taken into account. The diamond is also a low loss transmitter of infrared in the region of sensitivity of the camera, from 3–5 μm, therefore emission from the copper body of the gyrotron which passes through the diamond window also will contribute to the infrared signal and must be considered. For the measurements described here, a laboratory calibration was performed on an equivalent configuration shown in Fig. 2 and an effective emissivity was determined for the setup.

Each element in the optical system contributes both its own infrared signature determined by its temperature and emissivity and filters the radiation which passes through it. Characterization of the individual elements and combining their effects mathematically is time consuming, therefore the equivalent optical setup was investigated as a single unit to determine an empirical calibration for the view through the MOU of the gyrotron window. It was assumed that the gyrotron internal components, which are water-cooled copper and the rf screen and sapphire windows do not appreciably change in temperature during the gyrotron pulse. This assumption would be questionable if the center of the last mirror in the gyrotron were in view, but the off-axis sightline does not intersect the directly-heated components.

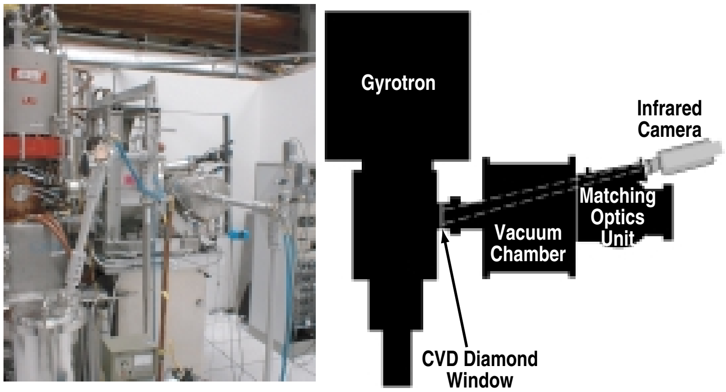

Figure 1. CPI gyrotron with diamond window and a schematic representation of the measurement setup.

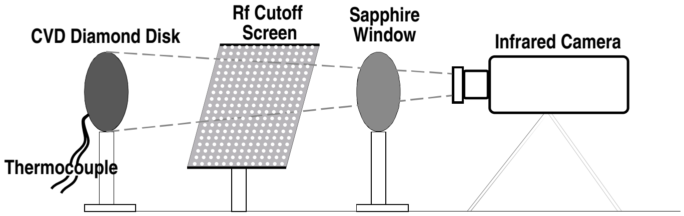

Figure 2. Calibration setup for temperature dependent diamond emissivity using an equivalent optical geometry.

The calibration was performed by heating an unbrazed diamond disk with a heat gun and monitoring its temperature with thermocouples. The apparent temperature was simultaneously measured with the infrared camera and an effective emissivity was derived so that the camera measurement agreed with the thermocouples. This procedure was followed over a range of diamond temperatures between ambient and 100°C.

The camera gave the correct value for the window temperature using an effective emissivity of 1.0 at ambient temperature which decreased to 0.1 at 100°C. A set of window temperature measurements, shown as the lowest trace in Fig 3, was made using this arrangement. But this procedure gave a poor temperature resolution for the camera measurement due to attenuation of the IR emission by the rf screen, therefore a second set of calibrations and measurements was made in which the rf screen was removed. In this case the range of effective emissivities was 1.0 at ambient to 0.28 at 100°C. With the screen removed in the MOU, the rf leakage through the window was measured to be in the mW range, an acceptably low value resulting from the high quality Gaussian beam. The profiles and the time dependence curves have all been corrected for effective emissivity appropriate for the measurement.

EXPERIMENTAL RESULTS

The IR measurements were performed using the gyrotron operating at moderate parameters and for pulse lengths up to 4.0 s with an evacuated MOU, transmission line and dummy load. The temperature increase of the synthetic diamond window stabilized near 90°C after 3 s which is consistent with ANSYS calculations [4]. In Fig. 3, the time dependence of the peak temperature is plotted as a function of time for a 4.0 s pulse having about 570 kW passing through the window and the rf cutoff screen in place and a second 2.0 s pulse at 600 kW generated power for 2.0 s with the screen removed, for which the average temperature in a 15 mm diameter circle at the center of the window is plotted. Once the screen had been removed, the camera data permitted several small hot

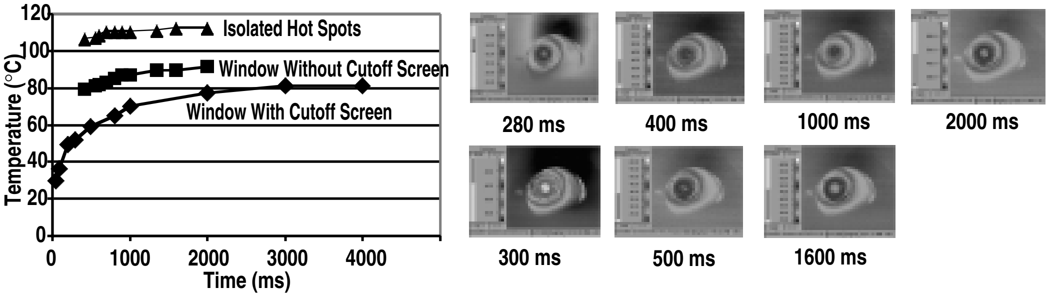

Figure 3. Time dependent peak temperature of the gyrotron diamond window and of an isolated hot spot. The four second data were obtained with the rf screen in place. Infrared camera data are presented for the case with the rf screen removed. A filter change was made for $t > 400$ ms.

spots to be resolved. These were a few pixels in size, corresponding to about 1 mm in diameter. The temperature at the hot spots was about 20°C higher than the surrounding temperatures. The fact that the middle curve in Fig. 3 is about 15°C higher than the lower curve reflects the inclusion of several of these hot spots in the averaged region plus slightly higher generated power. The upper curve in Fig. 3. displays time dependence of one of these spots. The temperature of the hot spot saturates more rapidly than the bulk of the window, but there is no tendency for its temperature to increase with time after saturation. Similar local hot spots were also observed under similar conditions elsewhere [3].

The absorbed power in the diamond window was less than 1.5 kW with total power passing through the window of 670 kW, an absorption of about 0.22%. A temperature profile, corrected at each point for the effective emissivity, is presented in Fig. 4. The profile was taken along an approximately vertical line through the window center. The profile is extremely flat, substantially flatter than ANSYS modeling would indicate for the known Gaussian beam profile. The flatness could be due to measurement problems or higher thermal conductivity than was used in the modeling, or due to a thermal impedance at the edge of the window which was not correctly modeled or a combination of these effects. This is under investigation.

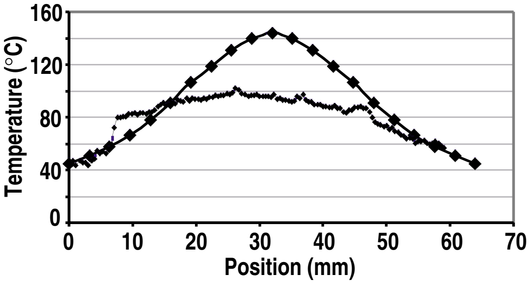

FIGURE 4. Measured temperature profile of gyrotron diamond window compared with ANSYS model for a 1.0 MW Gaussian beam.

SUMMARY

Infrared measurements of an artificial diamond disk window on a high power gyrotron at 110 GHz have been made. An *ad hoc* calibration of the viewing setup was made in the laboratory. The window temperature equilibrates at about 2.5 s and for about 600 kW generated the temperature increase was about 60°C. Isolated hot spots about 20°C hotter than the nearby material were seen, which because of their size and limited temperature increase should not affect the operational limit of the window. The measured temperature profile across the window was much flatter than expected.

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