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HIGH POWER MILLIMETER WAVE TRANSMISSION THROUGH CVD DIAMOND

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In order to check the usability of large-sized CVD (Chemical Vapor Deposition) diamond disks for high power millimeter wave vacuum barrier windows at room temperature (T∼293K) a first series of experiments, using a 170GHz, 300kW, 200ms JAERI/Toshiba gyrotron$^{1)}$, have been performed. The dielectric loss tangent at a frequency of 170GHz has been determined to be $\tan(\delta)=1.3\times10^{-4}$. By comparing the experimental results to numerical simulations the thermal conductivity was estimated to be about $k\approx1800$W/mK. This preliminary result indicate that a single-disk CVD diamond window assembly using a water-edge cooling could fulfill the requirements for a continuous wave(CW) transmission of millimeter wave power in the megawatt range. This is needed for the Electron Cyclotron Heating (ECH) on the International Thermonuclear Experimental Reactor (ITER).

Keywords: CVD Diamond, Gyrotron, ECH, High Power Window, ITER, Loss Tangent, Thermal Conductivity

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ＣＶＤダイヤモンドを用いた大電力ミリ波伝送

日本原子力研究所那珂研究所核融合工学部
春日井　敦・坂本　慶司・高橋　幸司・恒岡まさき
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（1997年２月５日受理）

高周波伝送窓として化学気相成長法（ＣＶＤ）によって製作された大口径ダイヤモンドディスク（直径96mm，厚さ2.23mm）の有効性を調査するための初めての実験が，ＩＴＥＲ協力のもとにドイツのカールスルーエ研究所と共同で原研のジャイロトロン（周波数170GHz，出力 200kW，パルス幅 200ms）を用いて行われた。実験の結果，周波数170GHzにおいて誘電損失係数が 1.3×10^{-4} と評価でき，また実験結果と数値シミュレーション結果の比較から，熱伝導率が約1800W/mKであると評価できた。この初期実験の結果は，水を用いた周辺冷却方式のＣＶＤダイヤモンド窓は，ＩＴＥＲ（国際熱核融合実験炉）などの電子サイクロトロン加熱システムで要求されているＭＷクラスの大電力高周波の連続動作に十分対応できることを示している。

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1. Introduction

ECH (Electron Cyclotron Heating) is one of the major candidates for plasma heating, non-inductive current drive, start-up and profile control of the plasma current in fusion reactors such as ITER (International Thermonuclear Experimental Reactor)[2]. Gyrotron oscillators operating at a frequency of 170 GHz are foreseen as highly efficient ECH power sources for ITER. An output power of at least 1 MW per unit is needed for economical use of such heating systems. The requirement of CW operation results in extremely high demands on the material properties of the vacuum barrier windows at gyrotrons and plasma torus. One answer to this problem is to use a single-disk edge-cooled sapphire window at cryogenic temperatures (liquid Nitrogen at 77 K or liquid Neon at 30 K). To avoid the necessity of a cryogenic coolant, research interests currently concentrate on materials which allow operation at room temperature with simple water cooling.

A very promising material is synthetic diamond which nowadays can be manufactured in samples of up to 110 mm diameter (thickness, approx. 2mm)[3-5]. Diamond is an attractive material due to its low loss tangent, high thermal conductivity, outstanding mechanical properties and modest permittivity. It is specially worth noticing that the thermal conductivity of diamond at room temperature is about 5 times higher than that of copper[6]. Finite element calculations show that such a diamond window assembly using a water edge-cooling would be capable to withstand a CW power transmission of 2 MW at 170 GHz[7].

In a first collaborative experiment between JAERI and the FZK (as part of the ECH window collaboration between Japan and EU within an ITER-Task) the excellent material properties of diamond have been demonstrated.

This paper reports on the result of the first high power RF experiment using a large-sized CVD diamond disk. Section 2 shows the experimental setup employing a 170 GHz, high power gyrotron. In section 3 the experimental results will be presented and compared to numerical simulations. The dielectric loss tangent and thermal conductivity of the CVD diamond disk will be estimated.

2. Experimental Setup

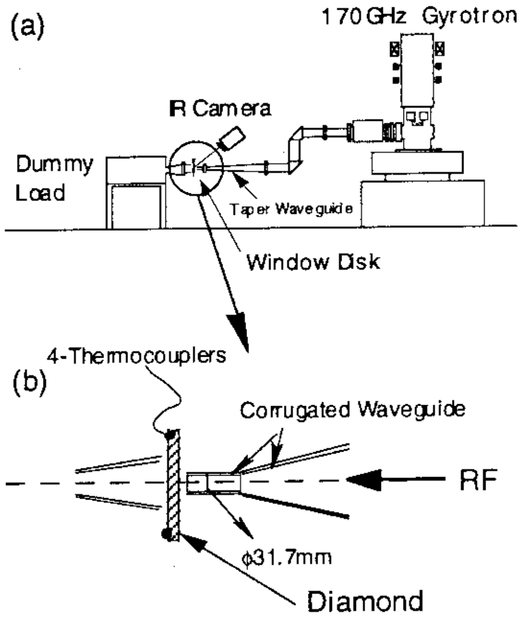

Fig. 1: (a) Schematic drawing of the experimental setup,
(b) Detailed drawing of the window configuration.

Figure 1(a) shows a schematic drawing of the high power experimental setup. The unbrazed window disk has been placed in the output beam of a 170 GHz JAERI/Toshiba gyrotron. For transportation of the RF power from the gyrotron to the test facility a non-evacuated corrugated HE_{11} waveguide with a diameter of 88.9 mm was used. In order to increase the power density and to reduce the spot size on the target disk the waveguide was tapered down to a diameter of 31.75 mm. Finally the RF power was radiated as a Gaussian beam through the window disk. To determine the loss tangent at different locations the disk could be moved to several positions. The transmitted RF power was measured using a calorimetric load. In Fig. 1(b) a detailed drawing of the diamond disk setup is given. Figure 2 shows a photograph of the 96 mm diameter, 2.23 mm ($6\times\lambda_{diamond}/2$) thick diamond disk manufactured by DeBeers (UK) which has been used for this experiment.

The average surface roughness on both sides of the CVD diamond disk has been determined to be 0.25 μm and 0.28 μm, respectively. This roughness, caused by the growing process of the chemical vapor deposition, is still acceptable for a 170 GHz millimeter wave transmission.

Fig. 2: Photograph of the 96mm diameter, 2.23mm thick diamond disk.

To monitor the increase and the rise time of the disk's edge temperature, caused by the passing through of the

RF power, four sheath of non-grounded type thermocouples with and a diameter of 0.6 mm have been used. The 63.2 % and 90 % response time for heat up from 65 °C to 100 °C in hot water are about 40 msec. and 70 msec., respectively. In order to minimize the heat diffusion through the mounting support the disk was held only by the four coupler's wires. Since the time constants for the heat removal due to the four wires as well as that for convection is much longer than the heat diffusion in the diamond disk cooling effects can be neglected in the numerical simulation for several seconds.

Figure 3 shows the thermal beam image measured at the position of the window disk. Since diamond is completely transparent for infrared (IR) wavelength a sapphire disk was placed as a reference target. The thermal image which is directly linked to the passing through RF power distribution was recorded by an IR camera. Due to the oblique view angle the measured beam profile has an elliptical shape. The full width at half maximum (FWHM) of the beam is about 23 mm which is small enough to illuminate different sections of the CVD diamond disk.

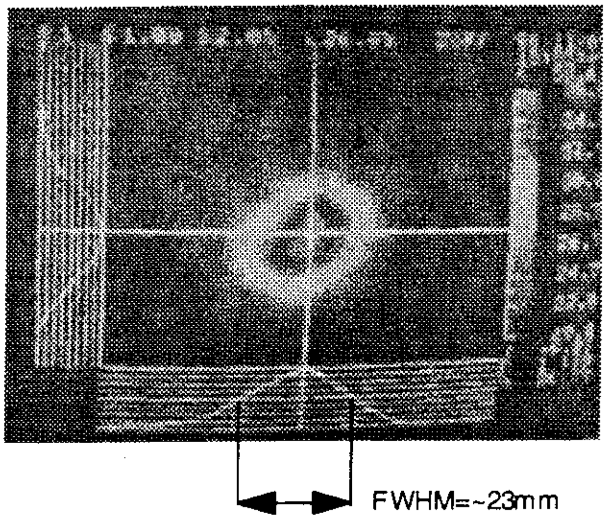

Fig.3: Thermal beam image at the position of the CVD diamond disk.

3. Experimental Results and Discussion

Millimeter waves at a frequency of 170 GHz, a power level of 160 - 170 kW and 50 - 105 ms pulse duration have been injected to a large-sized CVD diamond disk. The Pulse duration and RF power were limited by break down in the non-evacuated transmission line used here. The linear dependence of the disk's temperature increase on the pulse duration, shown in Fig. 4, indicate that cooling effects are negligible in the observed time period. The loss tangent of the CVD diamond has been determined by the following formula:

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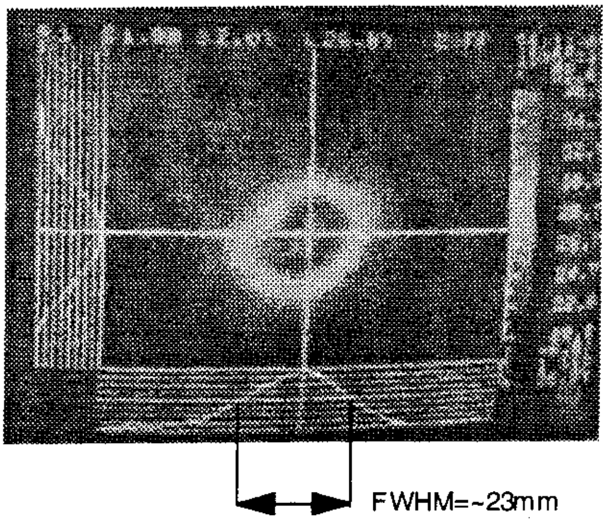

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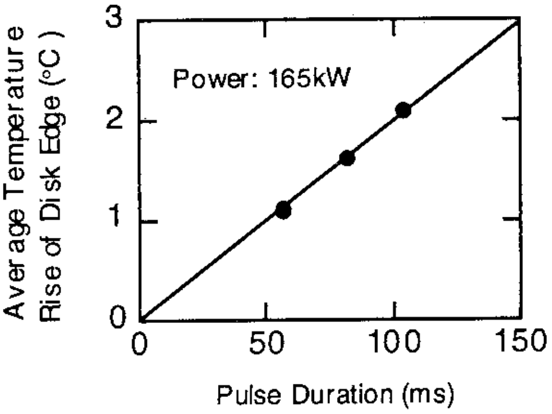

Fig. 4: Disk's edge temperature increase vs. pulse duration of incident RF power.

$$\tan\delta = \frac{c_0 \rho D^2 C_p}{4f(1+\varepsilon')} \bullet \frac{\Delta T}{P_{RF}\Delta t} \qquad \text{------------- (1)}$$

where c_0 is the velocity of light, ρ is the mass density, D is the disk diameter, C_p is the specific heat, f is the frequency, ε' is the permittivity, ΔT is the disk's temperature increase, P_{RF} is the incident RF power level and Δt is the pulse duration. Transmitting the RF beam through several positions of the disk gave slightly different temperature increases. This indicates an inhomogeneous distribution of the loss tangent across the CVD diamond disk. These results which are shown in Fig. 5 are in fairly good agreement with low power measurements performed at FZK. At the disk's center, which is mostly relevant for the use as a vacuum window, a value of $\tan(\delta) = 1.3\times10^{-4}$ has been determined.

The thermal conductivity of the CVD diamond has been estimated by comparing numerical simulations with the measured increase of the disk's edge temperature. To simulate this time behavior the following equation has been used:

$$\rho C\frac{\partial T}{\partial t} = \frac{K}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + Q \qquad \text{-------- (2)}$$

where T is the window temperature expressed as $T(r,t)$ (r: radius, t: time), ρ (3.54×10^3 kg/m^3) is the mass density, C ($7.42\times10^{-2}\ T^{1.556}$ J/(kg K) in the range of 300 K $< T <$ 500 K) is the specific heat [2)] and K (1800 W/(mK)) is the thermal conductivity. Q is a rate of heat generation represented as

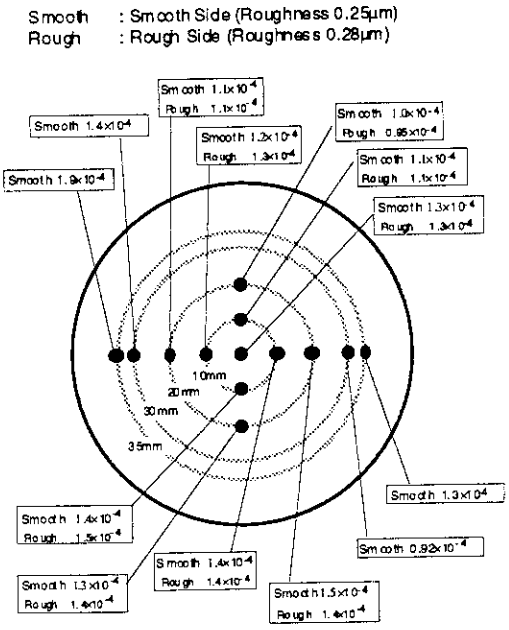

Fig. 5: Distribution of loss tangent across the CVD diamond disk.

$$Q = \pi f \varepsilon_0 \left(\frac{1+\varepsilon'}{2\sqrt{\varepsilon'}}\right)\varepsilon' \tan\delta \left|E(r,t)\right|^2 \qquad \text{------------ (3)}$$

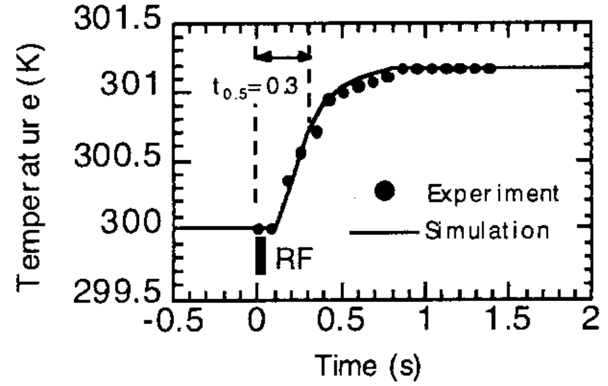

Fig. 6: Time behavior of the disk's edge temperature increase.

where, f is the frequency of the incident RF, ε_0 is the dielectric constant in vacuum, ε' is the permittivity, tanδ is the dielectric loss tangent and $E(r,t)$ is the electric field strength of the incident RF. Assuming an azimuthally symmetric distribution of the heat deposition Equation (2) is solved using a one dimensional (radial direction) finite element method. For the simulated temperature increase shown in Fig. 6 a loss tangent of $\tan(\delta) = 1.3\times10^{-4}$, an RF power of 165 kW and a pulse duration of 57 ms have been used. The other required CVD diamond material parameters have been taken from literature. They are summarized in Table I. The best agreement between measurement and simulation has been found by taking a thermal conductivity of 1800 W/mK into account. A value which also has been measured at a smaller sample by applying a photoacoustic method at FZK.

Table I : Properties of CVD diamond

Property	Unit	Value
Diameter	mm	96.1
Thickness	mm	2.23
Roughness	µm	0.25 - 0.28
Loss tangent (center)		$0.92 - 1.9\times10^{-4}$: high power measurement (1.3×10^{-4}) : high power measurement $0.55 - 2.0\times10^{-4}$: low power measurement at FZK
Permittivity		5.67 : low power measurement at FZK
Thermal conductivity	W/mK	~1800 : high/low power measurement

4. Conclusions

In a first collaborative experiment between JAERI and FZK the excellent material properties of CVD diamond have been demonstrated. An unbrazed window disk therefore was placed in the output beam of a 170 GHz JAERI/Toshiba gyrotron.

The determined loss tangent of $\tan(\delta) = 1.3\times10^{-4}$ is 6.5 times higher than values which already have been measured in smaller size samples. However due to the phenomenal thermal conductivity measured to be k = 1800 W/mK this CVD diamond disk is still very promising for a single-disk water edge-cooled vacuum window at room temperature.

In order to reduce the measurement's uncertainty and to expose the window disk to more CW relevant thermal stress conditions a second series of experiments with longer pulses duration and higher power levels is foreseen in 1997. For this experiment the CVD diamond disk will be fixed by O-rings in a water cooled housing.

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References

1) K. Sakamoto, A.Kasugai, M.Tsuneoka, K.Takahashi, T.Imai, T.Kariya, Y.Okazaki, K.Hayashi, Y.Mitsunaka and Y.Hirata, 20th Int. Conf. Infrared and Millimeter Waves, Orlando, USA (1996) 269-270.

2) M. Makowski, IEEE Transaction on Plasma Science, Vol. 24, No 3, (1996) 1023.

3) R. Heidinger, Proc. 19th Int. Conf. Infrared and Millimeter Waves, Sendai, Japan (1994) 277.

4) R. S. Sussmann, Industrial Diamond Review 239, De Beers Industrial Diamond Division, UK.

5) R. S. Sussmann, J. R. Brandon, C. G. Sweeney, T. J. Valentine, A. J. Whitehead and C. J. H. Wort, Diamond and Related Materials, 3,(1994) 303.

6) Y. S. Touloukian, R. W. Powell, C. Y. Ho and P. G. Klemens: Thermophysical Properties of Matter, (IFI/Plenum , New York, 1970) Vol. 3, 5.

7) M. Thumm, O. Braz, H. E. Häfner, R. Heidinger, A. Möbius, P. Norajitra and G. Soudee, ITER final report, ID No. T25, FZKA-Report No. 5808, (1996).