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ITER ECRF Coaxial Gyrotron and Window Development

Part II: Window Development

– Final Report –

M. Thumm, O. Braz, R. Heidinger, R. Spörl, P. Severloh

Institut für Technische Physik
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ITER ECRF COAXIAL GYROTRON AND WINDOW DEVELOPMENT

Part II: Window Development

- Final Report -

Task No.: G 52 TT 10 FE
ID-No.: GB6-EU-T245/6

Executive Summary:

Development of high performance gyrotron windows for ITER electron cyclotron heating (ECH) systems is sustained by a thorough dielectric materials data study at the relevant millimeter wave frequency range. Together with the completion of the post neutron irradiation studies on sapphire, resulting in a recommended maximum fluence level of 0.3 - $1 \cdot 10^{21}$ n/m^2, first data on the neutron irradiation effects on advanced alternative materials were established, which are specific, high resistivity (H.R.) silicon and CVD diamond grades. No critical degradation was observed after neutron irradiation with a fluence up to 10^{20} n/m^2. Progress in CVD diamond growth has lead to the availability of disks with dielectric loss reproducibly below a tan δ-level of 10^{-4}.

These grades were shown to be suited for up-scaling to actual window sizes and to be compatible with brazing requirements. The elastic properties of a ductile Al-based braze joined by solid-phase diffusion bonding to the CVD-diamond disk are used to reduce the thermal stressing as much as possible. The disadvantage of this technique is the relatively low allowed bakeout temperature of the window unit of 450°C (guaranteed by DeBeers). The test windows were thermally cycled as if they would be installed as a window on a gyrotron. The temperature cycling tests with a series of windows with up to 100 mm diameter and 1 mm thickness were very successful. The leackage rate before and after bakeout was determined to be approximately 10^{-9} mbar · l/s which is the measuring limit of our He-leak tester. No diffusion degrading of the brazing has been observed.

The window development was consolidated by dielectric property measurements for specimens special to concepts studied by the Japanese ITER partners (sapphire and silicon nitride from Kyocera). Guidelines for extrapolating the experimental data obtained at 145 GHz to the neighbouring frequency ranges, especially to the ITER frequency (170 GHz) are given for all materials reported, either on theoretical or on empirical grounds.

KOAXIALGYROTRON- UND FENSTER-ENTWICKLUNG FÜR ITER ECRF

Teil II: Fenster-Entwicklung

- Schlußbericht -

Task No.: G 52 TT 10 FE
ID-No.: GB6 – EU - T245/6

Kurzfassung:

Die Entwicklung zuverlässiger Gyrotronausgangsfenster, wie sie für das ITER Elektronzyklotronheizsystem (ECH) benötigt werden, ist eng an die gründliche Erforschung geeigneter dielektrischer Materialien für den entsprechenden Millimeterwellenfrequenzbereich gebunden. Zusammen mit den erfolgreich abgeschlossenen Untersuchungen zur Änderung der Materialeigenschaften von Saphir nach Bestrahlung mit Neutronen, welche eine maximal tolerable Fluenz von 0,3 – 1 · 10^{21} n/m^3 ergaben, konnten erste Ergebnisse zum Bestrahlungsverhalten von weiterentwickelten Materialien wie hochreines (H. R.) Silizium und CVD-Diamant durchgeführt werden. Selbst nach einer Bestrahlung mit einer Neutronenfluenz von 10^{20} n/m^3 konnten keine bleibenden Veränderungen festgestellt werden. Durch deutliche Fortschritte beim Wachstumsprozeß von CVD-Diamant konnten Scheiben mit dielektrischen Verlustwerten von kleiner als 10^{-4} reproduzierbar bereitgestellt werden.

Es konnte gezeigt werden, daß sich Scheiben mit solcher Qualität auch mit Abmessungen, wie sie für reale Fenstergeometrien benötigt werden, herstellen lassen und daß diese Scheiben zum Hartlöten geeignet sind. Die elastischen Eigenschaften von dehnbaren aluminiumbasierenden Lötverbindungen zusammen mit einer „solid-phase diffusion"-Verbindung führen zu einer deutlichen Reduktion der thermischen Spannungen bei CVD-Diamant-Scheiben. Der Nachteil dieser Verbindung stellt die relativ niedrige Ausheiztemperatur von lediglich 450 °C (garantiert von DeBeers) dar. Das Testfenster wurde demselben Ausheizverfahren, wie es bei Gyrotrons üblich ist unterzogen. Die an Scheiben mit einem Durchmesser von 100 mm und einer Dicke von 1 mm durchgeführten Untersuchungen, bei welchen die Temperatur in einem bestimmten Zyklus verändert wurde, verliefen sehr erfolgreich. Die Leckrate konnte dabei vor und nach dem Ausheizprozeß zu 10^{-9} mbar·l/s, was die untere Nachweisgrenze des verwendeten He-Lecktesters darstellte, bestimmt werden. Hierbei konnten keine diffusionsbedingten Änderungen der Lötverbindung festgestellt werden.

Diese Fensterentwicklung wurde durch dielektrische Verlustmessungen an Scheiben aus anderen Materialien der japanischen ITER-Partner (Saphir und Silizium-Nitrid von Kyocera) vervollständigt. Richtlinien zur Extrapolation der experimentell bei einer Frequenz von 145 GHz bestimmten Materialeigenschaften auf benachbarte Frequenzbereiche, speziell für die ITER relevante Frequenz (170 GHz), werden für alle Materialien angegeben. Diese basieren zum einen auf theoretischen und zum anderen auf experimentellen Überlegungen.

Contents

1. Introduction

Dielectric materials for radiofrequency (rf) heating systems had been identified already at an early stage in the fusion materials development to pose a key material problem which will affect the reactor design [1]. The anticipated importance of their material properties, including their dependence on design temperature and frequency as well as on radiation damage levels, has ever since become most crucial in Electron Cyclotron (EC) wave systems. The emerging data base for potential high power EC transmission windows showed that the required combination of low dielectric loss and excellent resistance against thermal crack formation [2] could only be realized by new and highly demanding concepts. Since then strategy has been to establish window concepts relying on sophisticated operating conditions (e.g. cryogenic cooling, distributed window) or on specially developed alternative materials (e.g. toughened ceramics, covalent/homopolar dielectrics) [3]. The originally assessed scenario defined a cryogenically cooled sapphire window to serve as the reference concept and a conventionally cooled CVD diamond window to ensure a potential alternative. Since the initial demonstration of the potentials for growing low loss CVD diamond grades on a commercial scale [4], the most urgent step to take was the demonstration of the potentials for ensuring reproducibility and up-scaled geometries for these grades. In parallel, high resistivity grades of silicon were being made available as a promising back-up solution [5].

In all EC wave transmission systems, a so-called torus window serves as a tritium barrier. This window will be exposed to a radiation field of both neutrons and gamma radiation. It has been shown that both types of radiation can change the dielectric properties [2,6,7]. As EC waves can be quasi-optically launched into the plasma, the torus window can be placed at a screened position. For a proper design of these systems, maximum tolerable neutron fluence levels and ionising dose rates have to be fixed. Especially for high power EC windows, performance margins are so restricted that any increase of dielectric loss caused by radiation damage sets the tolerable radiation limits. For undoped high resistivity silicon it was known that the low dielectric losses exhibit a very strong increase in the loss tangent under X-ray irradiation even at small dose rates [8]. Such sensitivity to ionizing radiation, associated to the generation of electron-hole pairs and to the very long lifetime of these carriers, was a severe handicap for the use of silicon at high power gyrotrons since at the output of the tube the microwave beam is often accompanied by the presence of ionizing radiation from the electrons stopped in the beam dump. Subsequent work showed that this very high sensitivity to ionizing radiation could be drastically reduced by a previous irradiation with high energy electrons, which induce displacement of the ions in the lattice [6]. Furthermore, this effect was accompanied by a permanent reduction of the losses, attaining loss tangents at room temperature as low as $3x10^{-5}$ at 15 GHz and $(1 \pm 1)x10^{-5}$ at 145 GHz. Both effects have been associated to the creation of permanent defects by displacement damage.

For the cryogenically cooled sapphire window, neutron irradiation tests resulted in recommended neutron fluence limits near to 10^{21} n/m^2 (E > 0.1 MeV), corresponding to 10^{-4} dpa. Irradiation tests were performed mainly at pool temperature (T ≈ 320 K), with a cross-check test performed at cryogenic temperatures ($\approx$ 85 K) [9]. For the validation of the advanced diamond and silicon grades, the data base for the effect of neutron irradiation on the dielectric properties was completely missing. Therefore a first experiment was laid out to reach a damage dose of about 10^{-5} dpa, which would then form the platform for extending the doses in forthcoming tests.

In parallel to establishing this fundamental data base for the development of advanced high power window materials, the measurement facilities were used to provide the window design at the Japanese ITER partners with dielectric data for their specific requirements. With the measurement equipment operating at 145 GHz, the resulting data sets were complemented with indicative frequency scaling laws for extrapolation to 170 GHz.

2. Measurement of low-power loss tangents in specially developed CVD-diamond grades (Subtask A.1.1)

For the millimeter-wave dielectric measurements on CVD diamond, material grades were made available that were specially developed for low EC wave absorption. These grades were grown at De Beers (Charters, UK) by MPACVD (microwave plasma assisted chemical vapour deposition) [10] in continuation of the preceding promising materials screening task on commercial CVD diamond grades [4]. For the present work, six specimens could be purchased (named here: DB1 - DB6) which can be classified as follows:

a) DB1, DB2: Evaluation set (30 mm dia x 0.9 mm)

b) DB3, DB4, DB5: Refinement set (30 mm dia x 0.9 mm)

c) DB 6: Up-scale set (40 mm x 1.1 mm)

The sequence of the above listed sets is according to their production history. The development strategy was to ensure primarily at EC wavelengths a level for the dielectric loss tangent (tan δ) not higher than $1 \cdot 10^{-4}$ at room temperature and subsequently demonstrating the potential for reproducibility and up-scaled geometries.

The dielectric measurements on CVD-diamond, which were performed at 145 GHz with an accuracy limit of $\tan\delta \approx 10^{-4}$ for specimens DB1-5, showed this target level could not be realized coherently in the evaluation set (cf. Table 1). The uncertainty in the measured losses in DB6 are smaller because of the larger material volume.

Table 1: Results of pre- irradiation studies of specially developed CVD diamond grades for high power EC windows (Frequency: 145 GHz)

Internal specimen code	Pre-irradiation studies dielectric loss tanδ [10^{-4}]
D B 1 (evaluation set)	1.2 (± 0.5)
D B 2 (evaluation set)	2.1 (± 0.5)
D B 3 (refinement set)	0.8 (± 0.5)
D B 4 (refinement set)	0.9 (± 0.5)
D B 5 (refinement set)	0.9 (± 0.5)
D B 6 (scale-up set)	0.2 (± 0.1)

3. Development of brazing/bonding techniques for a diamond window (Subtask A 1.2)

In order to integrate CVD-diamond disks in ultra-high vacuum tight window assemblies for gyrotrons and plasma torus, the problems of metallization and brazing to cylindrical metal sleeves for welding to the window mounting have to be solved. The bakeout temperature of gyrotrons at the factory site is between 450°C and nearly 550°C, depending on the company. The brazing has to withstand these temperatures. Recent data on relative thermal expansion of common microwave window and ferrule materials are shown in Fig. 1. The temperature dependence of the thermal expansion coefficient α of CVD diamond is plotted in Fig. 2.

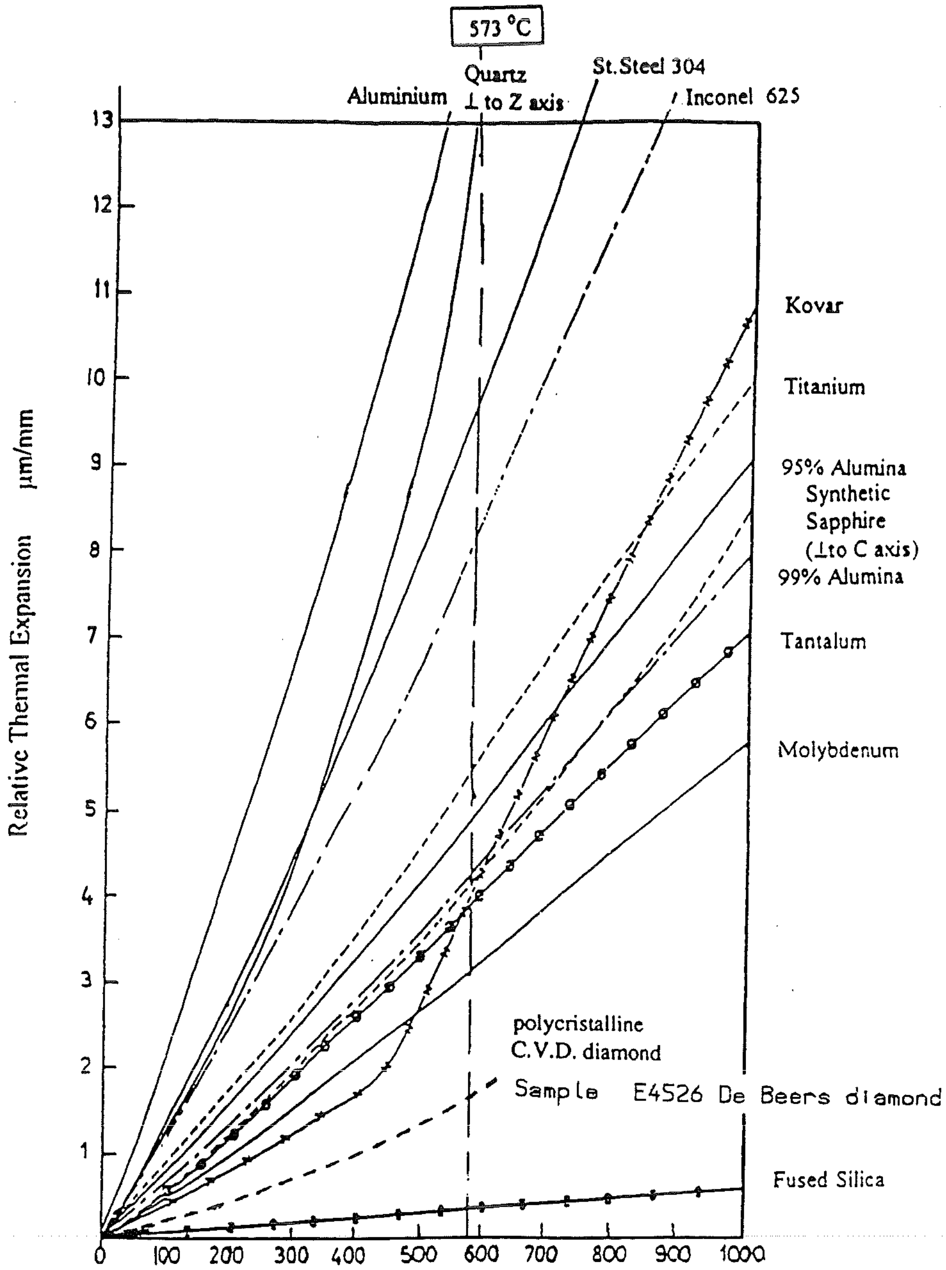

Fig. 1: Relative thermal expansion of common window and ferrule materials.

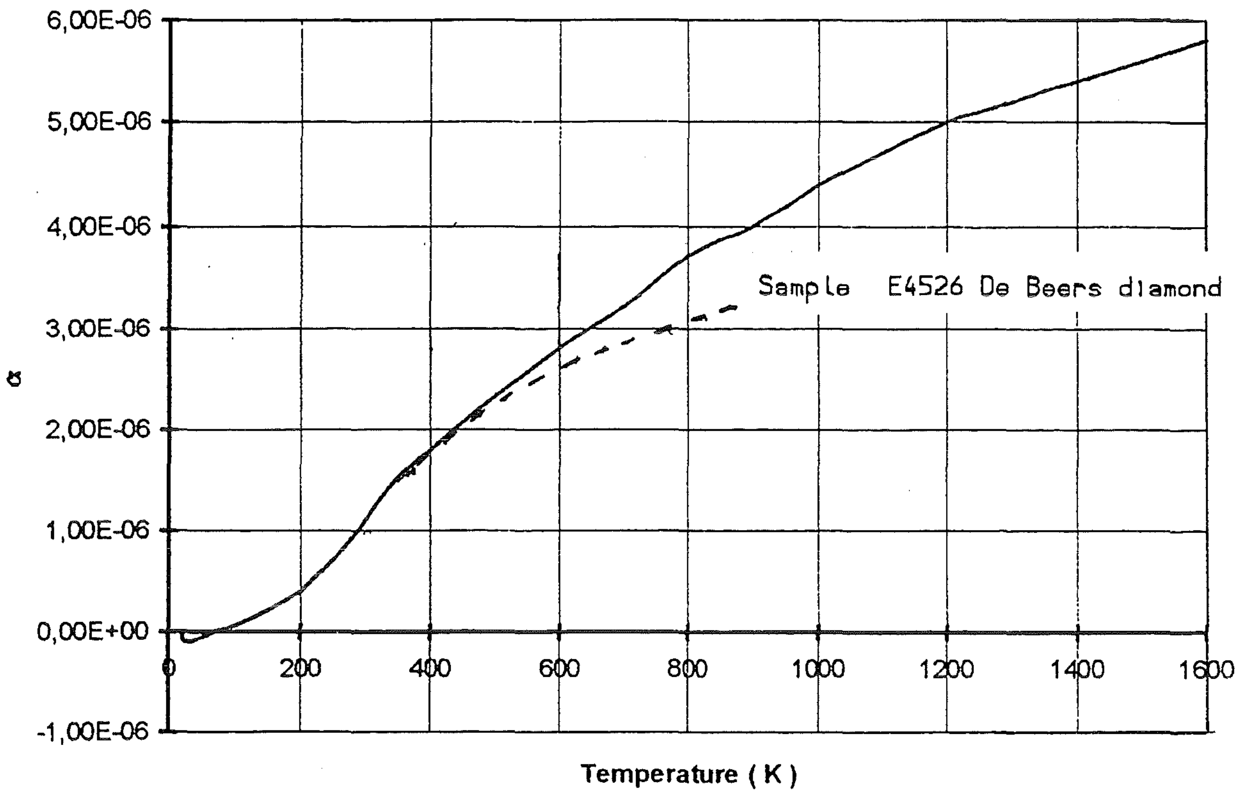

Fig. 2: Temperature dependence of thermal expansion coefficient α of diamond.

Only Kovar, an Iron-Nickel-Cobalt alloy, Molybdenum and Tantalum are ferrule materials with a thermal expansion nearly as low as that of CVD diamond but these materials are difficult to machine.

The metallization and brazing tests described in the following section have been performed in collaboration of EU Industry (DeBeers) and FZK.

We decided to use the following strategy to develop adequate bonding and brazing techniques.

Step 1: Usage of Inconel 600 as ferrule material which is even easier to machine compared to the usual Inconel 625 and very easy to weld to stainless steel. Electron-beam or Laser-beam welding is also no problem. The elastic properties of a ductile Al-based braze joined by solid-phase diffusion bonding to the CVD-diamond disk are used to reduce the thermal stressing as much as possible. The disadvantage of this technique is the relatively low allowed bakeout temperature of the window unit of 450°C (guaranteed by DeBeers) and the brazing joint is prone to corrosion when exposed to cooling water. On the other hand, in a closed circuit cooling system the corrosion resistance can be improved by using the CC.15 Cooling Water Treatment (Sodium Nitride, Sodium Metasilicate, Sodium Borate and Sodium Mercapto-benzothiazole) as corrosion inhibitor. This treatment should be used with deionized or demineralized water to be fully effective. Dosage is calculated at 1 liter of CC.15 to 130 liters of water. The treatment should be checked every three months using a testing kit which the suppliers can provide. Costs are currently in the region of 100 US $ per 25 liter container.

Step 2: Application of intermediate molybdenum rings together with a brazing material that allows higher bakeout temperatures and which may be less prone to corrosion when exposed to cooling water.

The present report describes the result of Step 1, whereas the experiences on Step 2 will be summarized in the final report on ITER Task T360.

Since grey (cheap) diamond shows the same thermal expansion and thermal shock behaviour like white (expensive) diamond, for the first bonding and brazing experiments grey diamond disks, with step by step increasing diameter and thickness, were brazed to a circular Inconel 600 sleeve welded to a CONFLAT (CF) flange for vacuum tests. The dimensions of the CVD-diamond disks were:

25 mm diameter/ 0.5 mm thickness,
48 mm diameter/ 0.5 mm thickness and
100 mm diamater/ 1 mm thickness.

Fig. 3 shows a photograph of the 100 mm diameter test window assembly.

FZK has performed the following thermocycles in a UHV vacuum oven (pressure at 470°C: $5 \cdot 10^{-7}$ mbar) which are typical for bakeout of gyrotrons (see Fig. 4):

heating to 240°C in 7 hours, holding at 240°C for 15 hours,
heating to 390°C in 5 hours, holding at 390°C for 7 hours,
heating to 470°C in 3 hours, holding at 480°C for 20 hours,
cooling to 370°C in 4 hours, holding at 370°C for 8 hours,
cooling to 20°C in 24 hours.

The test windows were thermally cycled as if they would be installed as a window on a gyrotron. According to the supplier, the assembly should be uniformly heated to a maximum of 450°C at a rate of maximal 2°C per minute (we had 470°C and 0.5°C per minute) to reduce any thermal stressing across to whole mounting as much as possible. Fig. 5 shows a top view into the UHV oven with 3 different test windows.

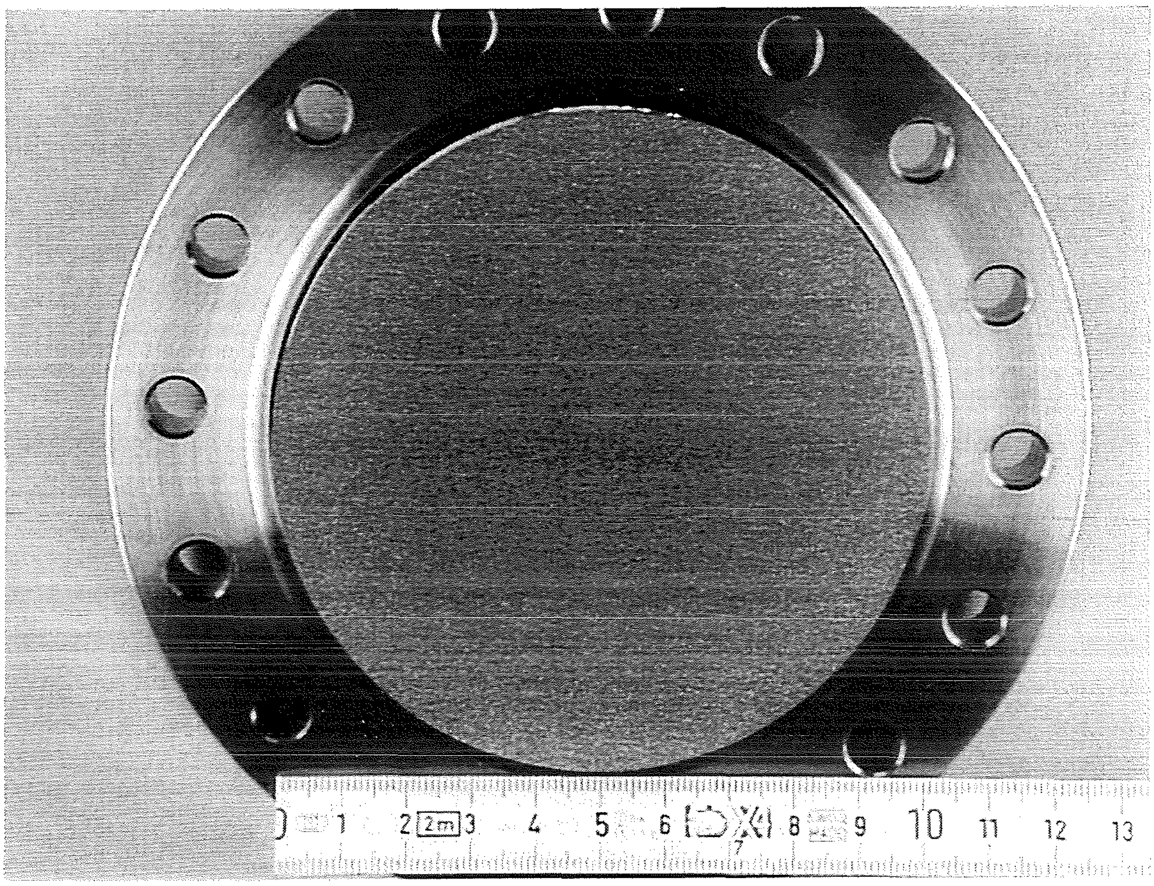

Fig. 3: Photograph of the 100 mm diameter CVD-diamond window assembly with CONFLAT flange.

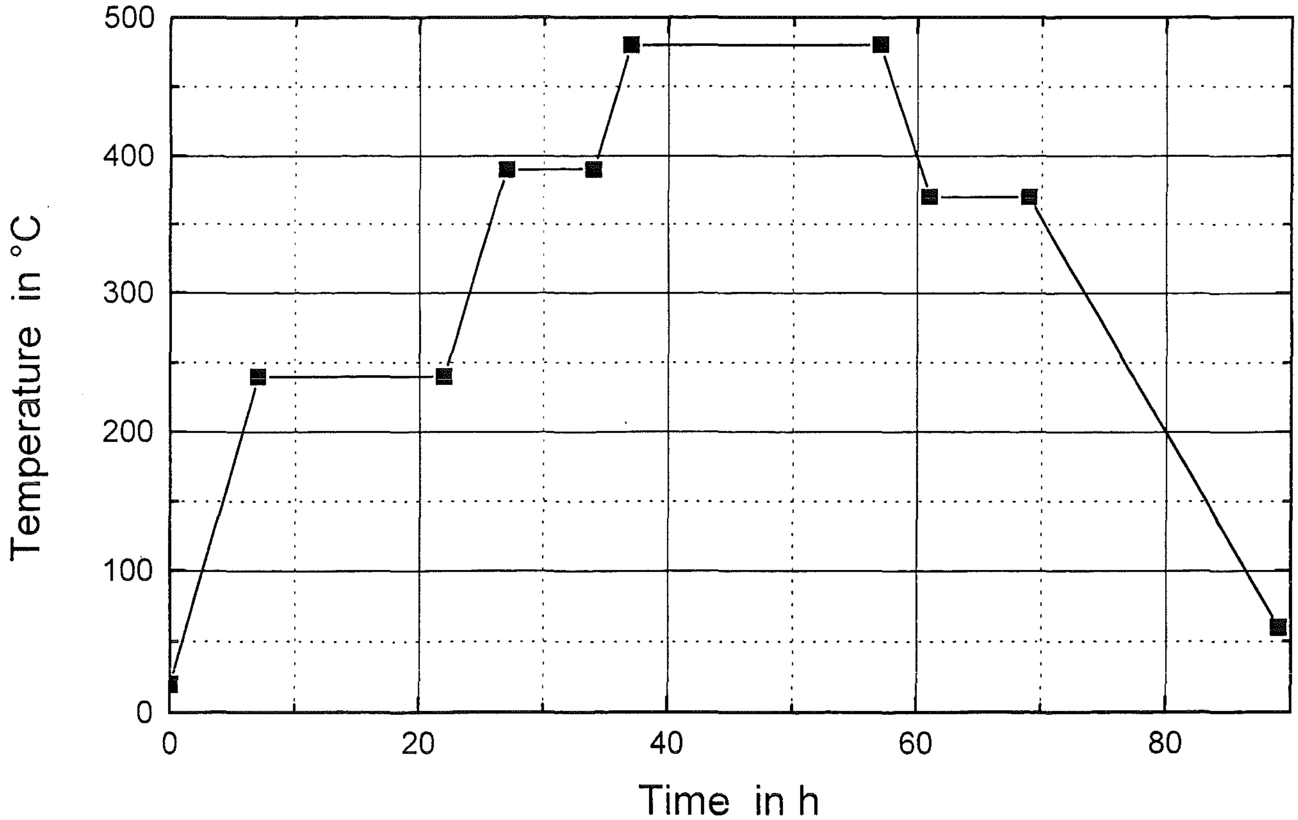

Fig. 4: Thermocycle applied to test diamond windows in a UHV vacuum oven.

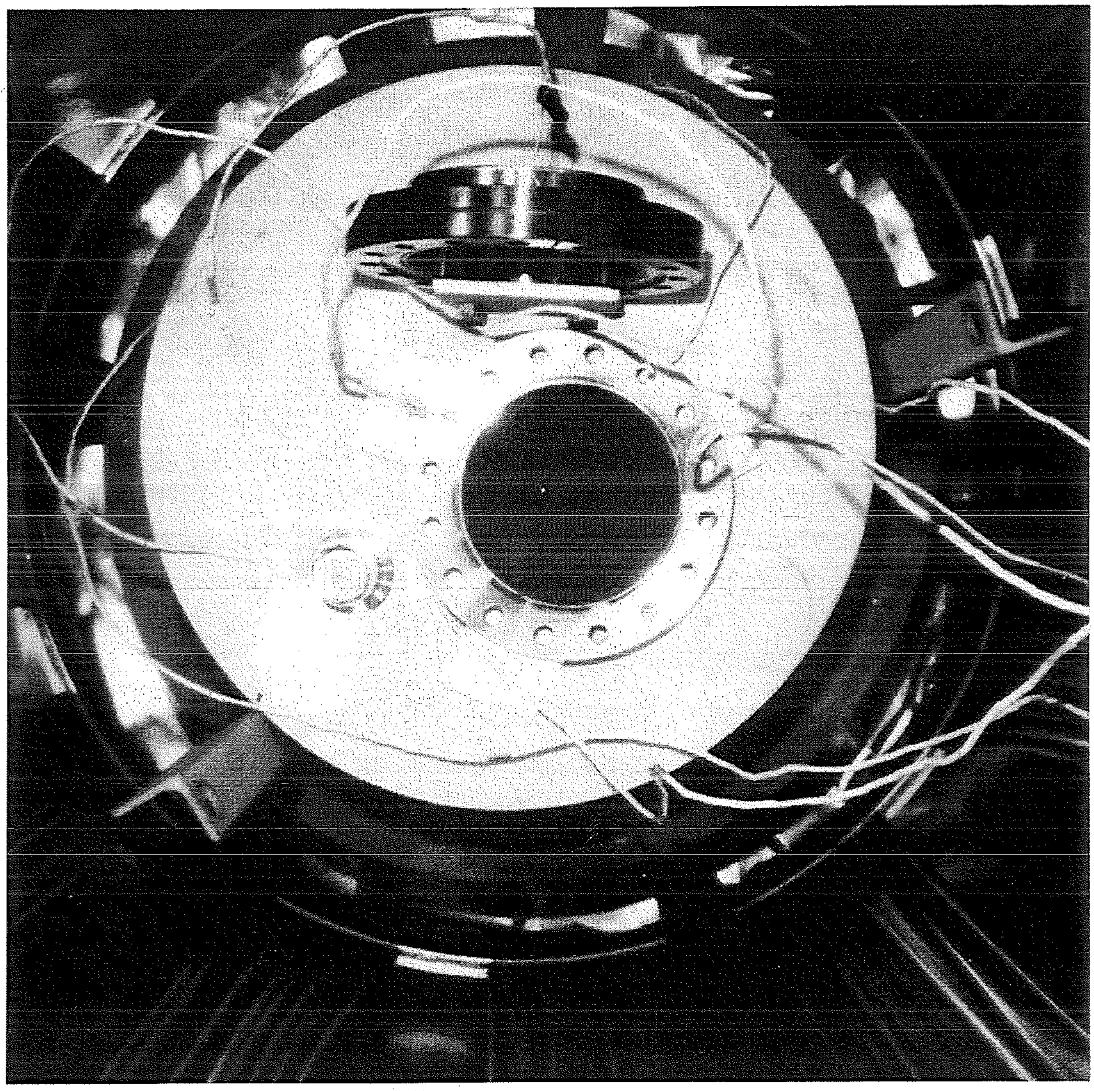

Fig. 5: Top view into the UHV oven with 3 different test diamond windows.

The temperature cycling tests with the different test windows mounted to CF flanges were very successful. The leackage rate before and after bakeout was determined to be approximately 10^{-9} mbar · l/s which is the measuring limit of our He-leak tester. No diffusion degrading of the brazing has been observed.

In the following bonding and brazing experiments Inconel 600 waveguide cylinders were brazed to both sides of a grey-diamond disk with 100 mm diameter and 1 mm thickness to from part of a full window assembly (window aperture = 70 mm, see Figures 6 and 7). The Inconel cylinders are strengthened by Molybdenum rings in order to reduce thermal expansion during bakeout. This assembly was also subjected to the bakeout cycle of a gyrotron up to 470°C without any degradation and measurable leakage.

Currently we are performing bonding experiments with Au-based brazing materials in order to allow the bakeout cycle of a gyrotron up to 550°C.

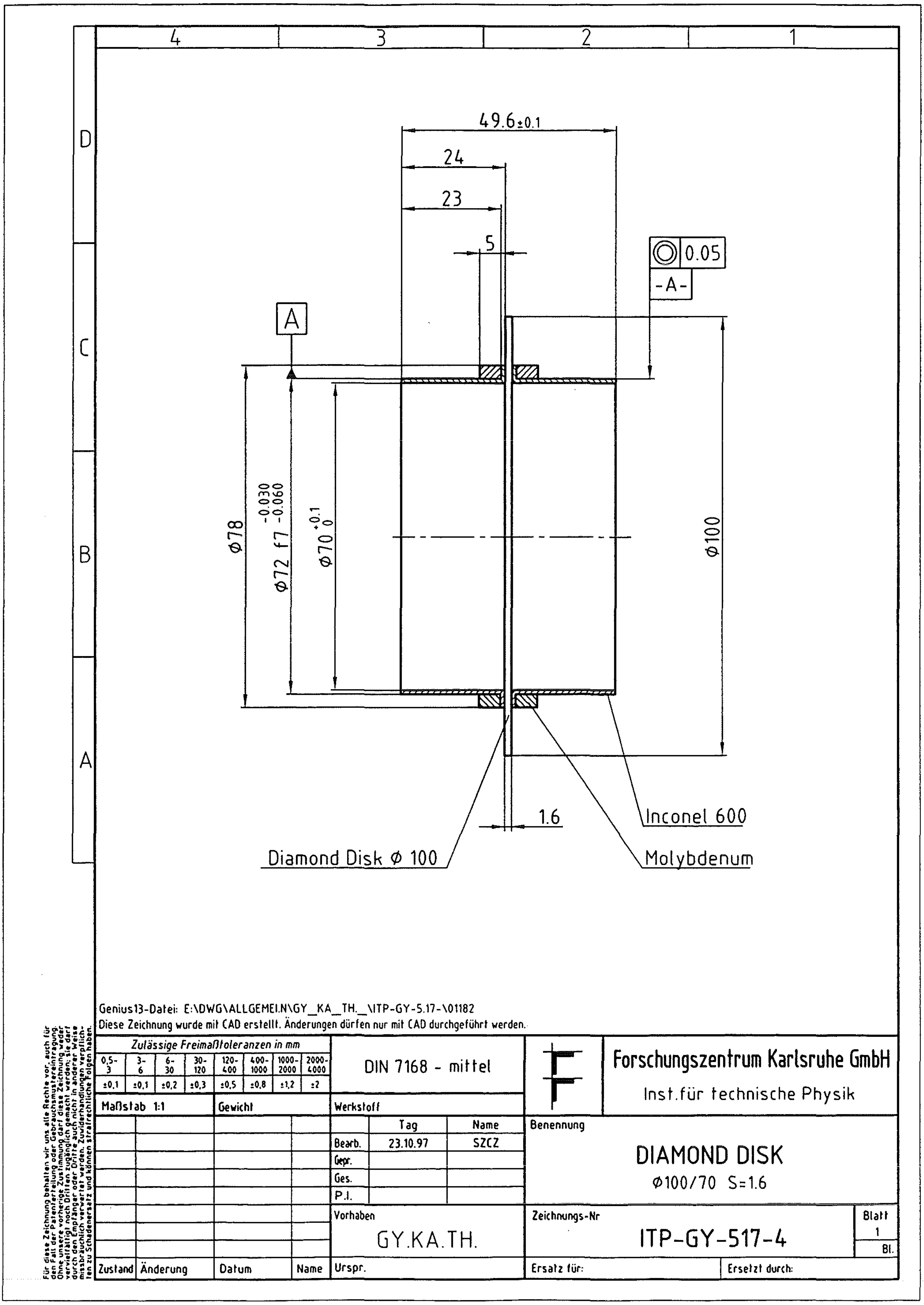

Fig. 6: Geometry of CVD-diamond test window unit.

Fig. 7: Photograph of CVD-diamond test window unit.

4. Characterization of Japanese window materials for 170 GHz (Subtask A.1.3)

Two individual test disks of window materials special to the Japanese ITER partner development were received.

a) A monocrystalline Sapphire disk (∅ 50 mm x 4.8 mm) produced by Kyocera was representative for the window material used for the 170 GHz ITER gyrotron developed by JAERI [11].

b) A polycrystalline Si_3N_4 disk (∅ 50 mm x 1.9 mm) produced by Kyocera was representative for the potential advanced window material for the gyrotron development pursued at NIFS [12].

The dielectric data sets in terms of permittivity (ε) and loss tangent (tan δ) were determined as a function of frequency at 145 GHz. These curves, reproduced in Figures 8 - 11 were given directly to the JAERI and NIFS groups involved.

The guidelines for extrapolating the data to the neighboring frequency ranges of interest (such as 170 GHz) were fixed as follows.

The observed loss levels are low enough to follow the procedure of taking the permittivity as constant over the range, which is also theoretically justified by the Kramers-Kronig relationships. For the loss tangent itself, the situation has to be differentiated:

a) The Kyocera sapphire grade follows well the loss behaviour of the well established HEMEX and CZ sapphire grades (without even showing the apparent low temperature trailing-off of HEMEX), and therefore the theoretical description using the 2-phonon interaction process [13] can be applied (Fig. 12). This means that tan δ may be extrapolated by a f^1 law.

b) For nitride ceramics in general, and for Si_3N_4 grades in particular, no satisfactory model for the dielectric loss mechansims has been established so far. Therefore additional loss measurements were performed at 30 - 40 GHz. The increase of the tan δ data from 1.1 ($\pm$ 0.1)$\cdot 10^{-4}$ at 30 - 40 GHz to 2.4 ($\pm$ 0.2)$\cdot 10^{-4}$ at 145 GHz scales rather like $f^{0.5}$. This may indicate interactions with bound charge carriers which are not moving fully correlated (as in Sapphire). Certainly this issue deserves further systematic inspection. For the present day, the assumption of an empirical $f^{0.5}$ is the best gues for frequency extrapolated data.

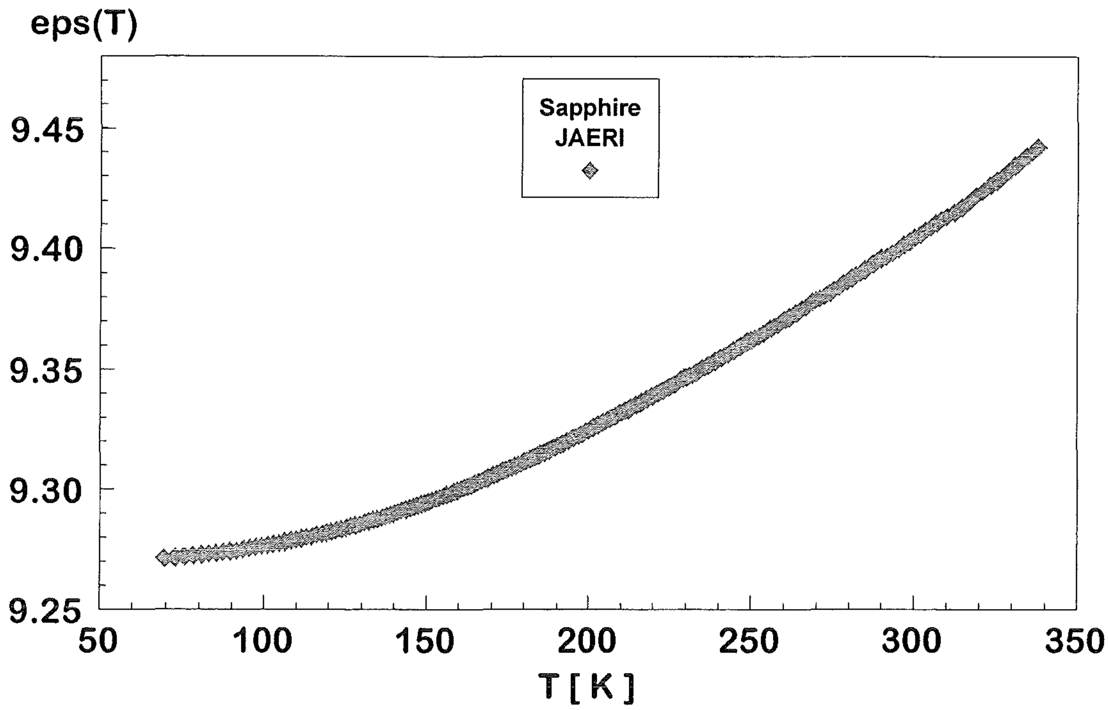

Fig. 8: The temperature dependence of the permittivity of Kyocera sapphire supplied by JAERI (ordinary ray).

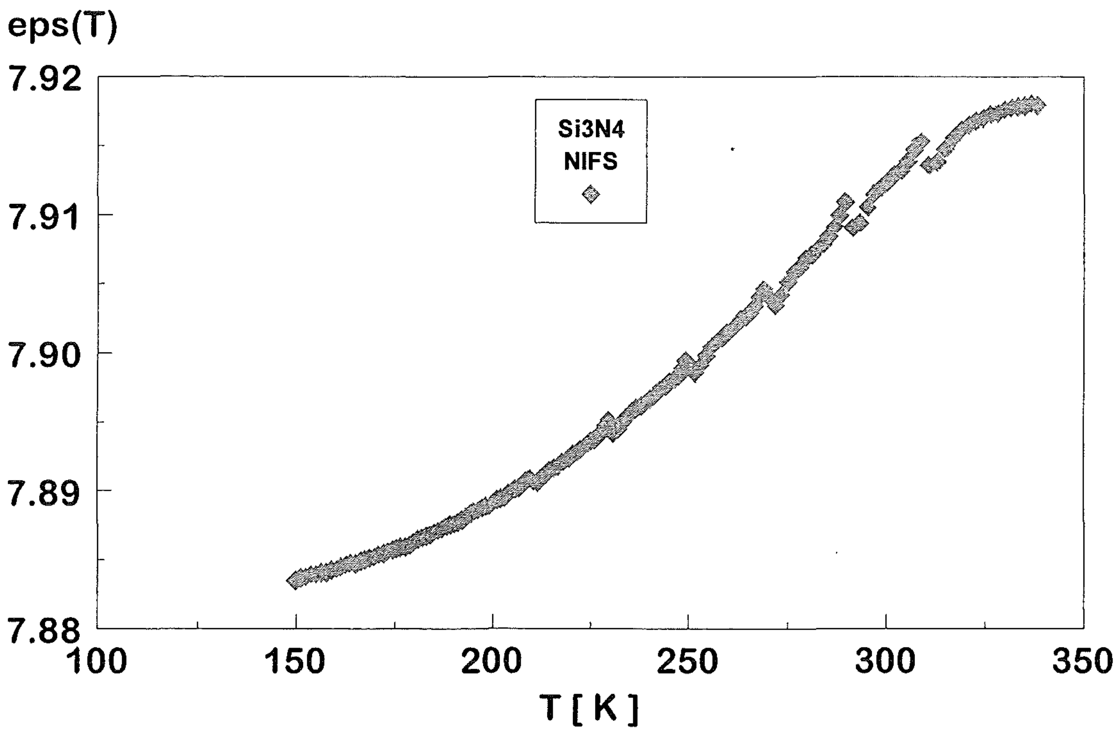

Fig. 9: The temperature dependence of the permittivity of Kyocera Si_3N_4 grade supplied by NIFS.

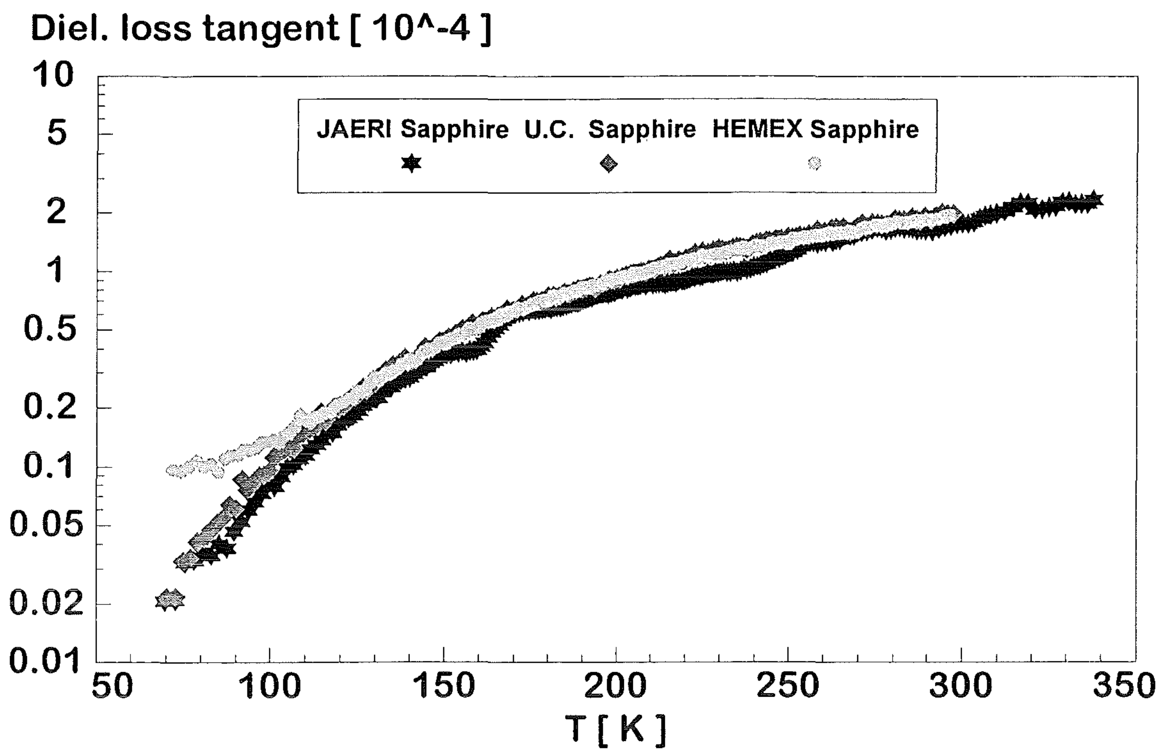

Fig. 10: The dielectric loss (at 145 GHz) of the Kyocera sapphire supplied by JAERI compared to reference sapphire grades (ordinary ray).

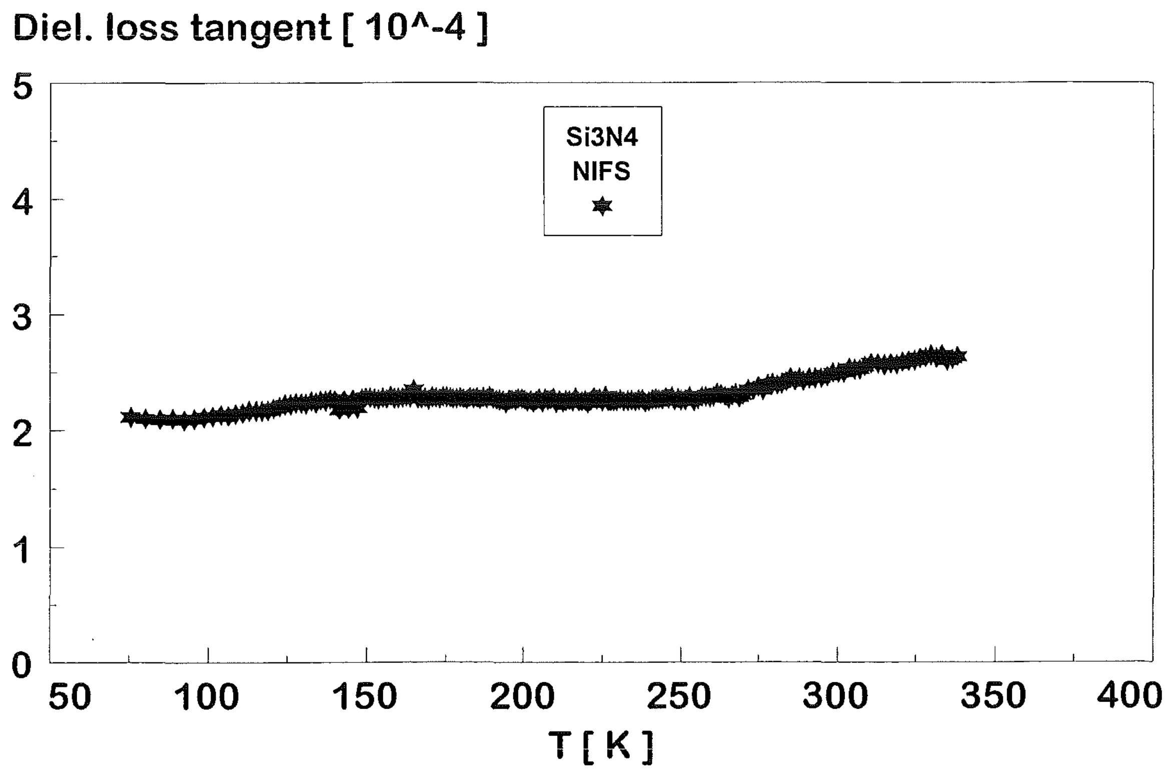

Fig. 11: The dielectric loss (at 145 GHz) of the Kyocera Si_3N_4 grade supplied by NIFS.

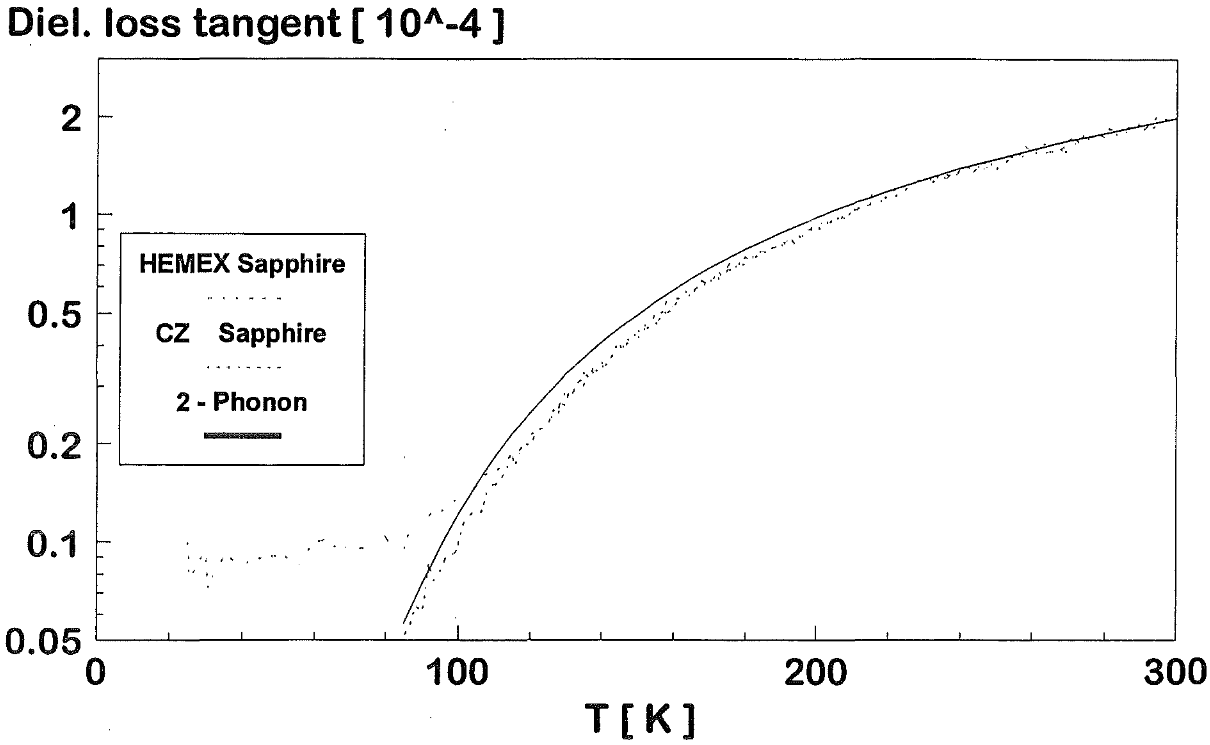

Fig. 12: The comparison of the intrinsic loss (at 145 GHz) in Sapphire modelled by the 2-phonon-interaction with experimental data for reference sapphire grades.

5. Characterization of selected window materials for 170 GHz before and after irradiation (Subtask A.1.4)

As the situation for sapphire can be well understood by an intrinsic absorption process [13] and the data base can be found in related papers [7,9], the report concentrates on the radiation effects on CVD-diamond and silicon. The measurements were performed at 145 GHz; extrapolation to neighbouring frequency ranges should use a $f^{-0.5}$ law for CVD diamond and a f^{-1} law for silicon according to experimental evidence from the presently available specimen grades.

The neutron irradiation to a fluence of 10^{20} n/m^2 (E > 0.1 MeV) - corresponding to 10^{-5} dpa damage level - was performed at GKSS (Geesthacht, D) under conditions following the previous irradiations for sapphire. Thus the irradiation, noted here D20-GKSS, was performed in a Cd-screened capsule immerged into the reactor pool ($T \approx 320$ K).

In parallel to neutron irradiation, the effects of electron irradiation was were studied using a Van-De-Graaff accelerator (D20-CIEMAT). The total electron dose attained was $3.8 \cdot 10^8$ Gy (E_{el} = 1.8 MeV) corresponding to a damage level of $5 \cdot 10^{-6}$ dpa. Irradiation temperature was close to the ambient (300 - 310 K).

There is no dramatic influence of the irradiations seen at 145 GHz. Loss in all three specimens of the refinement set still falls below the 10^{-4} level in tan δ. The low level could be better quantified at the time of the post-irradiation studies. Even higher effective contributions from the nucleation side could be demonstrated in analogy to results achieved for actual window sized material [14]. The difference in dielectric loss observed in the neutron irradiated specimen DB5 falls within the scatter of losses observed for the unirradiated control specimens within the refinement set (cf. Table 2). The well-resolved measurements on the up-scaled specimen DB6 show even in temperature variable measurements loss curves which fall within the band of experiment scatter for the specimen before and after neutron irradiation (Fig. 13).

Table 2: Results of pre- and post irradiation studies of specially developed CVD diamond grades for high power EC windows (Frequency: 145 GHz)

Internal specimen code	Post-irradiation studies		
	specimen status	"growth face in" tanδ [10^{-4}]	"nucl. face in" tanδ [10^{-4}]
D B 1 (evaluation set)	e-irrad. (D20-CIEMAT)	0.85 (± 0.15)	0.85 (± 0.15)
D B 2 (evaluation set)	unirrad. (control)	2.00 (± 0.15)	2.00 (± 0.15)
D B 3 (refinement set)	unirrad. (control)	0.20 (± 0.15)	0.20 (± 0.15)
D B 4 (refinement set)	unirrad. (control)	0.35 (± 0.15)	0.45 (± 0.15)
D B 5 (refinement set)	n-irrad. (D20-GKSS)	0.60 (± 0.15)	0.65 (± 0.15)
D B 6 (scale-up set)	n-irrad. (D20-GKSS)	0.20 (± 0.05)	0.45 (± 0.05)

In the case of silicon the temperature dependence of dielectric properties at 145 GHz is plotted in Fig. 14 for the different specimens. For the pure silicon these curves show a local minimum above room temperature (around 330 K). At higher temperature, losses increase exponentially due to the thermal excitation of electron hole pairs. At lower temperature, the loss curve follows the temperature dependence of the mobility of the extrinsic charge carriers. The effect of Au doping as well as of electron or neutron irradiation results in a strong decrease of the losses due to the decrease of the low temperature contribution, lowering the temperature in which the thermal generation of electron-hole pairs is dominant.

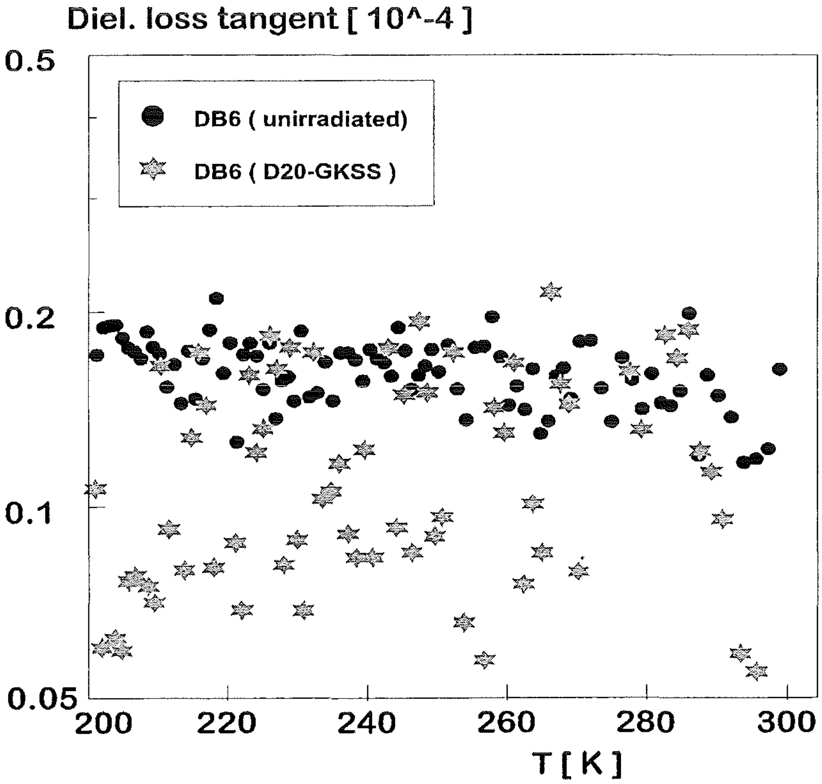

Fig. 13: The dielectric loss (at 145 GHz) in the up-scale CVD-diamond specimen (DB6) before and after irradiation.

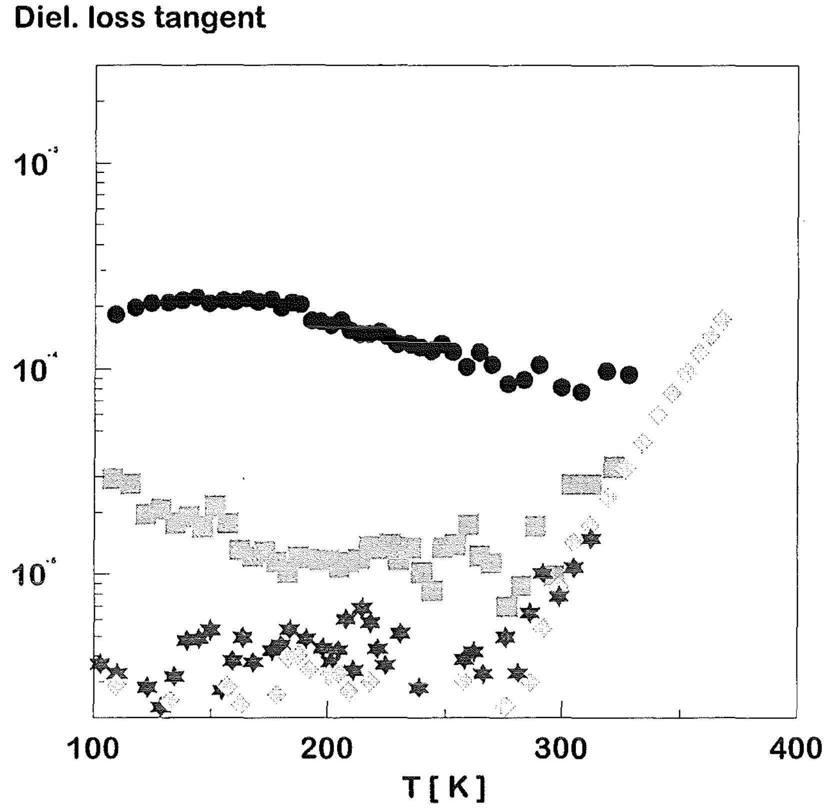

Fig. 14: The dielectric loss (at 145 GHz) in pure HR silicon (•), in e-irr HR silicon, D20-CIEMAT (■), in Au-doped silicon (◆) and in n-irr Au-doped silicon, D20-GKSS (✱).

6. Characterization of materials from high power window prototypes (Subtask A.1.5)

The demonstration of the potential to produce reproducibility test disks of CVD diamond with low dielectric absorption (tan $\delta \leq 10^{-4}$ at 145 GHz) allowed the acquisition of two 4" dia disks (thickness near 2 mm) for first window prototype studies. One disk was provided by the JAERI, one by FZK gyrotron developers. Distinct inhomogeneities over the disk area and from growth and nucleation face could be put to evidence, the overall conclusions were promising as the principal target of loss below 10^{-4} appear to be realistic and within reach. Indeed, the continued activities in this field have experimentally confirmed this hypothesis. The experimental work to be covered within the actual work packages was documented by a conference paper and a journal publication (Appendix 1 and 2).

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8. Appendix 1

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Dielectric loss measurements in CVD diamond windows for gyrotrons

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Abstract

Large sized CVD diamond discs (close to 4" diameter and 2 mm thickness) were studied in open resonator systems for dielectric parameter measurements at 15-20 GHz, 32-42 GHz and 145 GHz. Distinct differences in the dielectric loss tangent were found depending on the contribution of the growth and nucleation face as well as on the disc area seen by the mm-wave beam. On average, tanδ reaches the 10^{-4} level at 145 GHz.

The role of CVD diamond for high power gyrotron windows

Plasma heating and current drive in the next generation fusion devices (ITER, Wendelstein-X) by electron cyclotron wave (ECW) systems call for gyrotrons which provide mm-waves (90-180 GHz) in continuous wave operation at a Megawatt level. As a critical issue, it became evident that the gyrotron output windows were the limiting components unless cryogenic cooling schemes provided for the existing window materials the required combination of low dielectric losses and of high resistance against thermal crack formation [1]. In parallel with the development of cryogenically-cooled sapphire windows, alternative concepts which conceived specially developed materials in conventional cooling scenarios were pointed out and persuaded from a materials point of view [2]. Outstanding potentials are found in high resistivity silicon and CVD diamond because of their homopolar structure [3]. While the loss mechanisms in silicon are related to intrinsic and extrinsic free charge carriers, no dominating mechanism is *per se* evident in diamond. The advent of large diamond discs through the CVD processes [4,5] and the identification of low loss grades [6-8] have stimulated the high power window development opening the path to first actual size test windows.

Experimental set-up

The established open resonator method is used to determine the dielectric properties at mm-wave frequencies covering three different frequency ranges by three individual (quasi-) hemispherical Fabry-Perot resonator installations. The dielectric loss tangent (tanδ) is obtained by Q-factor measurements using Gaussian TEM_{ooq} modes. For spatially varying losses, the apparent value arises from an integration of the loss over the disc plane weighted by the lateral beam profile and over the disc axis weighted by the field distribution in the material (contribution of the faces). The effective lateral beam diameter was determined to be 6 mm for a specially optimised 145 GHz set-up [9] and about 25 mm for a 35 GHz resonator.

Characteristics of 4" test windows

Two discs - 'JAERI' (lapped, uniform white) and 'FZK' (lapped, grey with dark shadows) - were studied in different production states (extension (a), (b)). State (b) was achieved from state (a) by subsequently removing material mainly from the nucleation faces. In contrast to the 'FZK' disc the loss tangent values for the 'JAERI' disc were in general lowered by the thickness reduction (Tab.1). The orientation effect in the 'FZK' disc was strongly superimposed by bulk losses. But in every disc and state, tanδ at 35 GHz and 145 GHz values for 'growth face oriented into the resonator' are lower than for the other orientation. Different loss mechanisms seem to be relevant at 15 GHz. In a third disc - 'EVALUATION' (0.6 mm thick, polished to optical grade), a low tanδ at 145 GHz was determined: $0.5 \cdot 10^{-4}$.

		tanδ [10^{-4}]		
		15 GHz	35 GHz	145 GHz
JAERI(a)	growth	14	4	1.8
t = 2.41 mm	nucleation	3	4.5	1.8
JAERI(b)	growth	12	2	1.3
t = 2.24 mm	nucleation	0.9	2.8	1.7
FZK(a)	growth	-	13	5
t = 2.74 mm	nucleation	-	16	7
FZK(b)	growth	-	12	5
t = 2.15 mm	nucleation	-	16	7

Tab. 1 Results from tanδ measurements at the centre of the discs. ('nucleation' and 'growth' indicate the face that was oriented into the resonator during the test).

Mapping of dielectric loss

To analyse the radial homogeneity of the dielectric loss in large discs spatially resolved measurements were performed at 35 and 145 GHz. As an example the results from the inhomogeneous 'FZK' disc are shown in Fig.1. The level of the losses goes along with the colour of the disc. With an additional line scan along the y-direction in 1 mm steps the results from the mapping were reproduced (Fig.2a). With two succeeding TEM-modes the inhomogeneity of loss tangent along the x-direction was verified (Fig.2b). Also an inhomogeneous tanδ distribution (0.6 - $1.6 \cdot 10^{-4}$) was found in the uniform white 'JAERI' disc and verified with infrared mapping of the temperature rise in the disc exposed to high power mm-waves (170 GHz, 170 kW, 100 ms) [10]. The tanδ values in 'EVALUATION' disc did not go beyond the $0.8 \cdot 10^{-4}$ level.

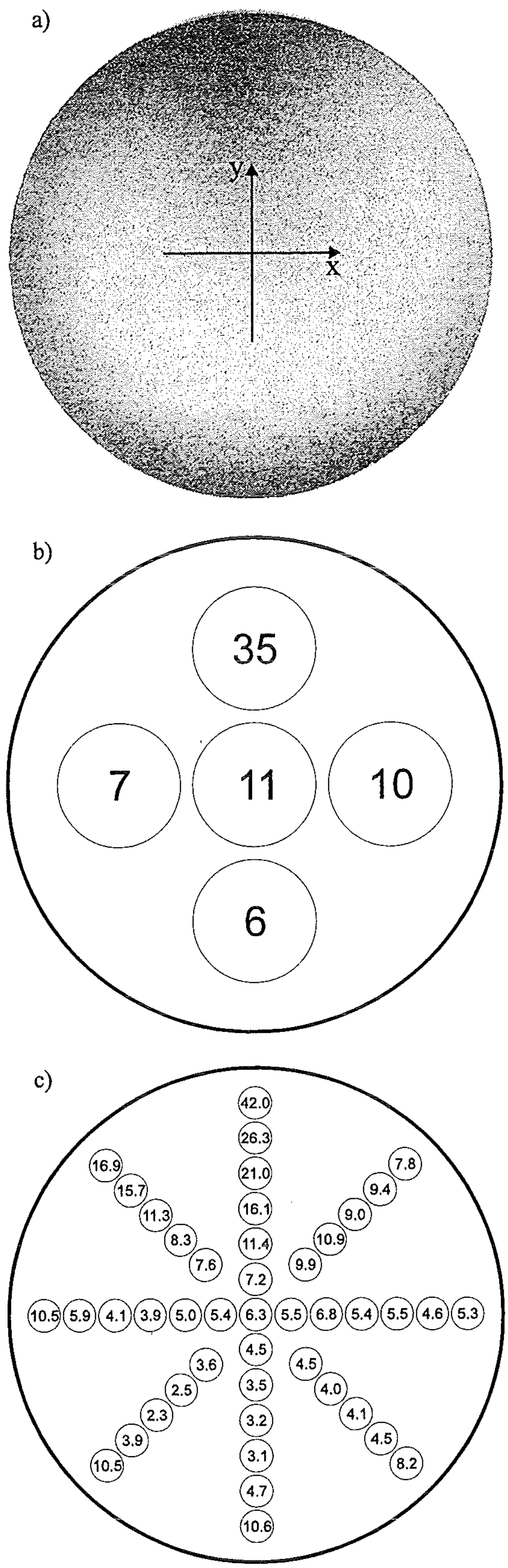

Fig. 1 Picture of 'FZK' disc a) and results of spatially resolved measurement of tanδ [10^{-4}] at 15 GHz b) and 145 GHz c). The circles indicate the area seen by the mm-wave beam.

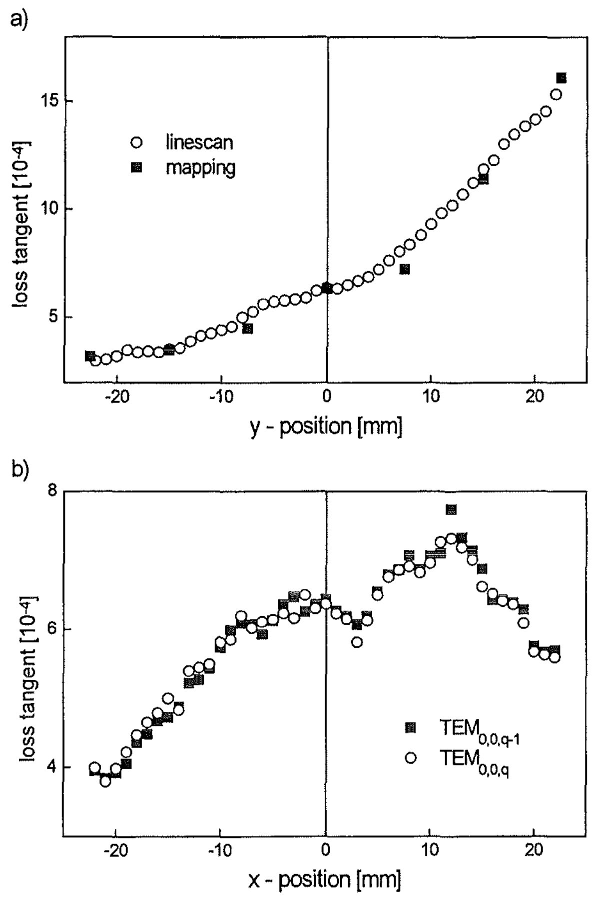

Fig. 2 Line scan of tanδ along the a) x-direction and b) y-direction in 'FZK' disc at 145 GHz.

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HIGH POWER 170 GHz TEST OF CVD DIAMOND FOR ECH WINDOW

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Abstract--- In order to check the usability of large-size CVD (Chemical Vapor Deposition) diamond disks for high power millimeter wave vacuum barrier windows at room temperature (T = 293 K) a first series of experiments, using a 170 GHz, 0.4 MW, 0.2 s JAERI/Toshiba gyrotron [1], have been performed. The dielectric loss tangent at a frequency of 170 GHz has been determined to be $\tan \delta = 1.3 \cdot 10^{-4}$. By comparing the experimental results to numerical simulations the thermal conductivity was estimated to be about $k \approx 1800$ W/mK. This preliminary results 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: Gyrotron, Electron Cyclotron Heating, CVD Diamond Window

I. INTRODUTION

Electron Cyclotron Heating (ECH) 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 [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 continuous wave (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.

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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.

II. EXPERIMENTAL SETUP

Figure 1(a) shows a schematic drawing of the high power experimental setup. The non-metallized, unbrazed window disk has been placed in the output beam of a 170 GHz JAERI/Toshiba gyrotron. For transportation of the radio frequency (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 Figure 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 ($6\lambda_{diamond}/2$) thick diamond disk manufactured by DeBeers (UK) which has been used for this experiment.

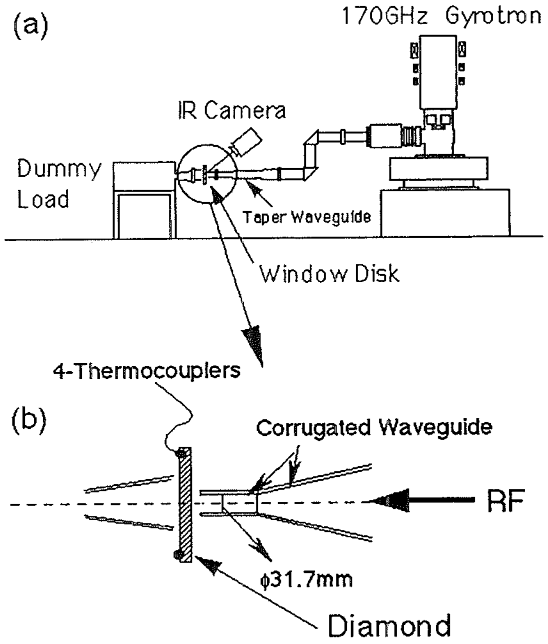

Fig. 1: (a) Schematic drawing of the experimental setup, (b) detailed drawing of the window configuration.

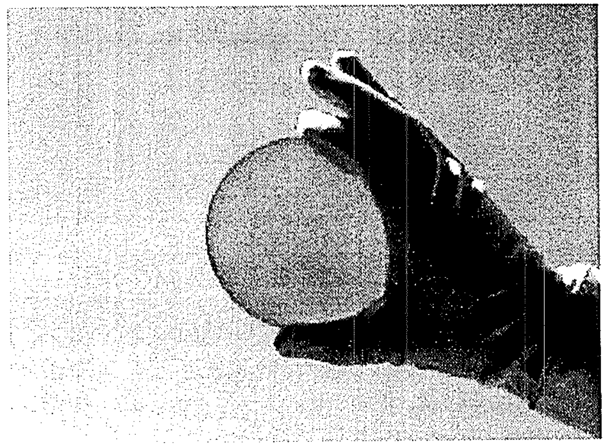

Fig. 2. Photograph of the 96mm diameter, 2.23mm thick diamond disk.

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.

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 ms and 70 ms, 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.

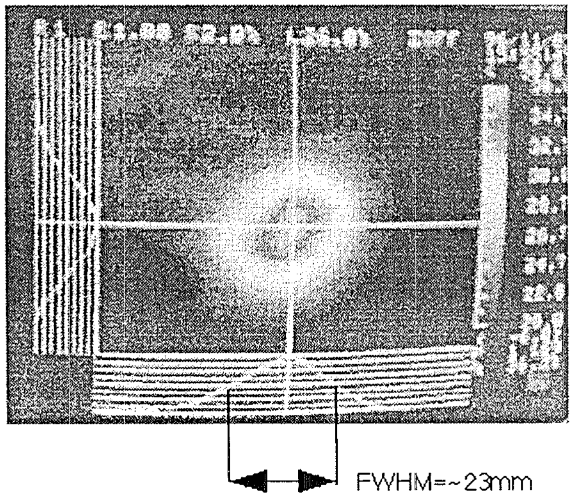

Fig. 3: Thermal beam image at the position of the CVD diamond disk.

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.

III. 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-size 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 Figure 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:

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

where c_0 is the velocity of light, ρ ($3.54 \cdot 10^3$ kg/m^3) is the mass density, C_p ($7.42 \cdot 10^{-2}\, T^{1.556}$ J/(kg K) in the range of 300 K < T < 500 K) is the specific heat[2], D is the disk diameter, 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.

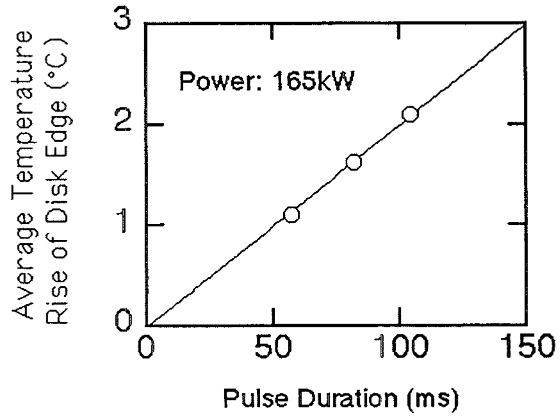

Fig. 4: Disk's edge temperature increase vs. pulse duration of incident RF power.

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 Figure 5 are in 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 $\tan\delta = 1.3 \cdot 10^{-4}$ has been determined.

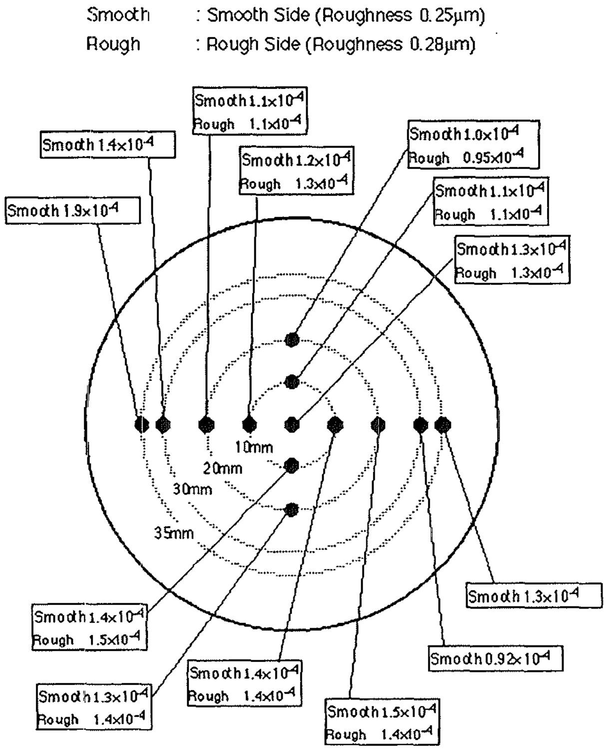

Fig. 5: Distribution of loss tangent across the CVD diamond disk.

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:

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

where T is the window temperature expressed as $T(r,t)$ (r: radius, t: time) and K (W/(mK)) is the thermal conductivity.

Q is the rate of heat generation represented as

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

where ε_0 is the dielectric constant in vacuum 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 Figure 6 a loss tangent of tan δ = $1.3 \cdot 10^{-4}$, 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 FZK for a smaller sample by applying the photoacoustical method.

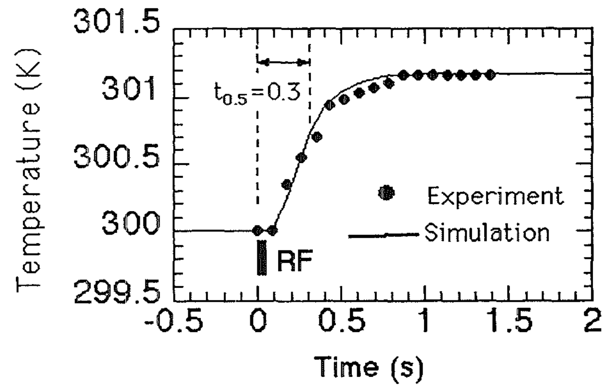

Fig. 6: Time behavior of the disk's edge temperature increase.

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		$0.55 - 2.0\times10^{-4}$
Permittivity		5,67
Mass density	kg/m^3	$3.52 - 3.56\times10^3$
Specific heat	J/(kgK)	514 - 542
Thermal conductivity	W/(mK)	1300 - 2100
Young's modulus	GPa	800
Coefficient of liner expansion	K^{-1}	$1.2 - 2.1\times10^{-6}$ (100-250°C)

Table I: Material properties of CVD diamond.

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IV. CONCLUSIONS

In a first collaborative experiment between JAERI and FZK the excellent material properties of CVD diamond have been demonstrated by placing a non-metallized, unbrazed window disk in the output beam of a 170 GHz JAERI/Toshiba gyrotron.

The determined loss tangent of $\tan\delta = 1.3 \cdot 10^{-4}$ is 6.5 times higher than values which already have been measured in smaller size samples. However due to the phenomenal thermal conductivity, that was 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 pulse duration and higher power levels is foreseen in 1997.

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