Design and thermo-mechanical analysis of a double disk window for step-tuneable gyrotrons

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Abstract

The state of the art of output windows for Megawatt gyrotrons relies on edge cooled windows equipped with a single large area CVD diamond disk of resonant thickness. For step-tuneable gyrotrons, this concept does not satisfy the required minimum reflection conditions and is therefore replaced by a double disk window design. The paper presents the mechanical design and thermo-mechanical simulation of a double disk window for multi-frequency Electron Cyclotron Heating at ASDEX-Upgrade operated at four distinct frequencies at ~ 105…140 GHz. For the two intermediate frequencies (around 115 and 125 GHz), the minimum reflection will be achieved by high precision tuning of the distance between the two CVD diamond disks (adjustment tolerances ± 5µm). A small working distance of 4… 6 mm is realised by single face cooling. Cooling chambers for direct face cooling are prepared by a double ring configuration realised by joining two concentric copper cuffs to the diamond faces using an Ag-based braze. The flow distribution of the pressurised water through the specific cooling structure has been modelled and the temperatures obtained for center and the edge of the disk. Averaged effective heating transfer coefficients have been obtained as the function of the water consumption to quantify the efficiency of the cooling concept and to couple simulation models. Thermally induced stress and deformation in the window structure have been determined by FEM analysis, they are shown to be compatible with the specified limits.

1 Introduction

Since the successful operation of high power gyrotrons with CVD diamond windows, Megawatt gyrotrons for single frequency output are normally equipped with a single large area CVD diamond disk of resonant thickness [1]. The thickness condition is set to ensure minimum reflection at the output window (power reflection factor R < 1%) and fulfilled when the disk thickness is equal to integer number of half wavelength in material:

$$t = \frac{\lambda_1}{2} n , \tag{1}$$

where n = 1, 2, 3… is an integer number of the half wavelengths in the disk, $\lambda_1 = \lambda_0 \sqrt{\varepsilon_r}$ is the wavelength in material, λ_0 is the wavelength in vacuum. Equation (1) is normally reformulated in terms of operating frequencies:

$$f_n = n \frac{c}{2t\sqrt{\varepsilon_r}} , \tag{2}$$

with the light c velocity and dielectric permittivity ε_r (ε_r = 5.67 for diamond).

Multifrequency Electron Cyclotron Heating (ECH) bears particular potentials in nuclear fusion technology especially for studying tokamak operation with different equilibria and plasma currents or the suppression of neoclassical tearing modes (NTM). An advanced ECH system is presently under development for related plasma experiments at ASDEX-Upgrade (Garching, Germany) that will operate between ~105…140 GHz [2]. Step-tuneable gyrotrons are bound to provide 1 MW power at 4 distinct frequencies. As shown in Fig. 1, the thickness of a single-disk diamond window can be chosen such that the minimum reflection condition for the radiofrequency (RF) power can be met at the boundaries of the frequency interval, however the intermediate frequencies (around 115 and 125 GHz) will then create off-resonant conditions in window operation. This fact excludes the use of the present single disk windows for step-tuneable gyrotrons.

The transmission spectrum can be adapted by setting up a double disk window using two parallel disks of equal thickness. The resulting Fabry-Perot resonances, which strongly depend on the disk separation, create a more complex spectrum. For such an arrangement, minimum reflection conditions are not only met for resonant thickness but also for distinct intermediate frequencies which can be selected by fine tuning the window separation. This principle is exploited for the design of transmission windows for step-tuneable gyrotrons. The paper presents the mechanical design and thermo-mechanical simulation for the development of a double disk window.

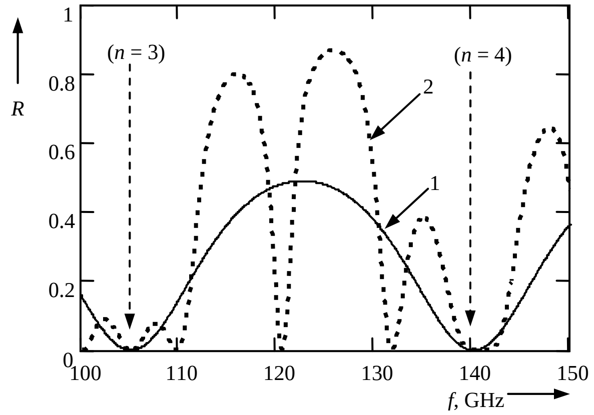

Fig.1 Power reflection factor *R* for window configuration based on diamond disk(s) of thickness *t* = 1.797mm: 1 - Single- disk window; 2 - Double-disk window: separation *l* = 10mm ($f_{n=3}$ = 105.1 GHz, $f_{n=4}$ = 140.1 GHz) [2].

2 Design concepts

To reach the minimum reflection conditions with a double disk window, the two large area diamond disks and their arrangement have to fulfil specifications imposed by the modelling of the MW transmission [3]. Accordingly the main requirements for actual double window design were specified as follows:

- Operating bandwidth: 35 GHz (105…140 GHz);
- Disk thickness: 1.80 mm, identical within ± 30 µm;
- Disk separation: about 5 mm (to cope with the typical frequency drift in long pulse gyrotrons ≈100 MHz);
- Mechanical tuning range ≈ ± 1.0 mm;
- Setting accuracy: ± 5µm;
- Vacuum at disk interspace: $p < 10^{-6}$ mbar (to cope with standing wave enhancement of the field amplitude (factor 2.4)).

The design for a double disk window with standard edge cooling geometry can not fulfil the tight requirements for the disk separation because of the inevitable use of cooling areas on both faces of each disk. Therefore a new cooling geometry was developed to allow direct face cooling. The underlying idea is to braze a double copper ring structure onto the diamond face which provides the formation of a cooling chamber on one side of each CVD diamond disk. Integration of the disk into window housing is made by a second brazing step in which also central liners are inserted to force the cooling water flow in the vicinity of the diamond surface (schematically shown in Fig. 2).

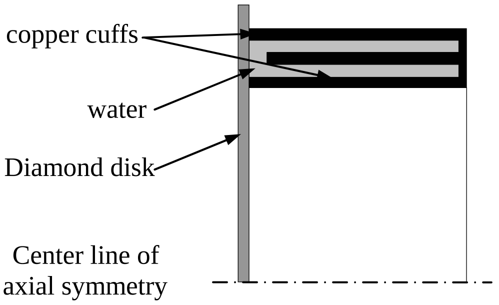

Fig. 2 Sketch of the direct face cooling concept.

The window housing is arranged to allow remote adjustment of the window separation over the range of 4 – 6 mm with a setting accuracy of ± 5 µm. This is achieved by 3 motor driven shafts and 3 additional guiding shafts (cf. Fig. 3). Spring forces will provide the counteracting mechanism to allow the displacement of the atmospheric pressure side of the double disk window unit relative to the torus vacuum side.

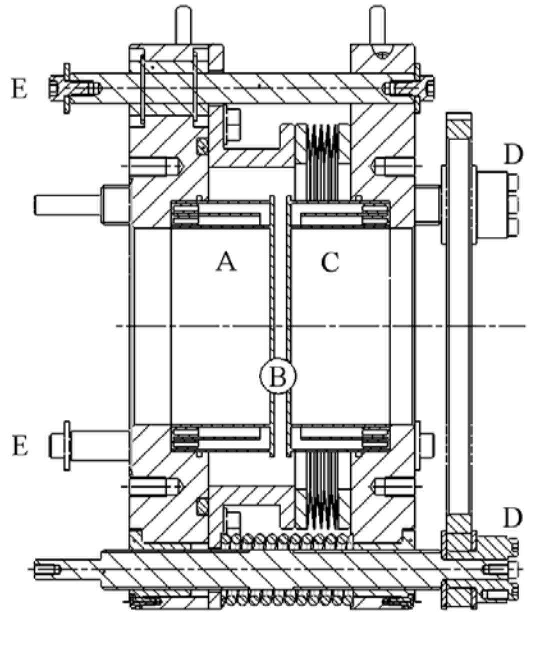

Fig. 3 Schematic arrangement of the double disk window housing with the integrated basic window disk unit: A is Torus vacuum; B is Interspace vacuum; C is atmospheric pressure side; D is 2 (of 3) shafts for gap adjustments; E is 2 (of 3) guiding shafts.

To form the CVD diamond window units, copper cuffs (OFHC) with inner diameters of 80 mm and 100 mm (thickness: 1 mm) were brazed by the reactive

Ag(Cu) brazing technology at 840°C on both faces of each disk (Fig. 4).

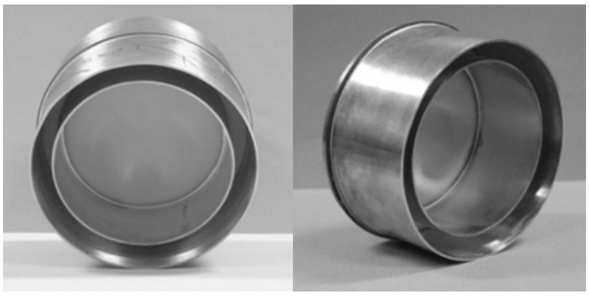

Fig. 4 Basic window disk unit after brazing and removal of the double ring structure at the counter-face.

The symmetrical arrangement of the cuffs during the brazing process was chosen to avoid any axial anisotropy of the stresses in the disk. The brazing process proved to be very critical with respect to vacuum tightness: even in 5 brazing runs at least one braze was not leak tight. However a manageable arrangement was achieved for one face where both the inner and the outer cuffs were vacuum tight. Then the leaky set of cuffs was cut off to provide the direct cooling arrangement.

3 Thermo-hydraulic analysis

The power absorption of 350 Watt per disk leads to the heating of the structure. In order to demonstrate the efficiency of the cooling concept as well as to assign the water consumption, thermo-hydraulic analysis (using ANSYS Flotran CFD) was provided. For our consideration the following beam parameters were applied:

Window aperture	d_{eff}	80 mm
Radius of the RF-beam	w	25.7 mm
Absorbed power (P_0 =1 MW, $\tan\delta = 2\cdot 10^{-5}$, f = 140 GHz)	P_{abs}	350 Watt

The 3D finite element thermo-hydraulic analysis assigns the temperature field (absolute value of the temperature in each node of the meshed structure) for different water consumption. Although the temperature field has a complex 3D distribution, it is possible to summarize the key results in terms of the temperature of the center and edge of the disk (T_{center}, T_{edge}, see Table 1). From thermo-hydraulic analysis, it follows that the water consumption of 10 *l*/min provides an effective cooling of the disk. Increasing of the consumption above 10 *l*/min has no major effect on T_{center} but it improves the temperature homogeneity in the metal of the cooling cuffs. In this case, the temperature along circumference of the cooling structure becomes constant. It means that it is possible to obtain an effective heat transfer coefficient which corresponds to an axi-symmetrical (i.e. 2D) temperature distribution. This step couples 3D thermo-hydraulic and 2D axi-symmetrical thermostatic models allowing later to provide 2D axi-symmetrical thermo-mechanical analysis of the structure. Heat transfer coefficient α_T was calculated in FEMLAB in a way that center temperature T_{center} is the same in both models. In order to document limits of the cooling concept infinite α_T was applied to 2D thermostatic model.

Table 1. Results of the thermo-hydraulic analysis

Parameters	Water consumption, *l*/min				Limit
	3	10	18	30	-
T_{center}, K	338	322	320	318	312
T_{edge}, K	317-321	301-303	298-303	296-300	293
ΔT, K	17-21	19-21	17-22	18-22	19
α_T, $Wm^{-2}K^{-1}$	-	5000	7500	12500	∞

T_{center} is expected to be about 320 K (47°C) and temperature gradient between center and edge of the disk ΔT = 19 K. A typical value of heat transfer coefficient α_T = 6000 $Wm^{-2}K^{-1}$ which corresponds to water consumption between 10 and 18 *l*/min was chosen to provide thermo-mechanical analysis of the structure.

4 Stress analysis

There are three main technology and operation factors that introduce stresses in the structure: brazing process, pressure and absorption of the microwave power in diamond. In order to avoid both inelastic deformation of the cooling cuffs and breaking of the diamond during window operation maximum stresses must be below the critical limits.

4.1 Brazing

The Ag-based brazing process for the double disk window was performed at Thales Electron Devices (Velizy, France). After the brazing deformations of about 15 μm (from center of the disk to its edge) were measured despite the brazing symmetry. Also inelastic deformations occurred in copper cuffs near the brazing area. The removal of copper cuffs in one side of the disk caused no additional deformations. This allows to conclude, that no residual stresses in the whole structure were left after the brazing. The reason is very soft OFHC copper (Yield Stress of 50 MPa). That means that the condition of the structure after the brazing can be assumed as a stress-free reference.

4.2 Pressure

During operation 0.1 MPa pressure and in off normal events 0.2 MPa overpressure will have to be tolerable. Maximum pressure introduces stresses of about 50 MPa in the center of the disk and 60 MPa in brazing area. Additional displacement of the center of the disk relative to its edge can reach 27 μm.

4.3 Microwave absorption

In order to calculate thermal induced stresses results of thermal analysis using the technique of model coupling described in part 3 were applied. Maximum stress in diamond due to microwave absorption is 18 MPa arises near the brazing area of the outer cuff. A similar stress arises in outer copper cuff. Displacement of the disk center due to this effect is 2 μm. Total effect is summarised in the table 2.

Table 2. Analysis on stress. 1st column: stresses due to pressure; 2nd column: stresses due to absorption.

Place		Principal stress S_1, MPa			
		1	2	total	Limits
Diamond	Inner brazing	60	15	67	100-150 1/3 of ultimate bending strength
	outer brazing	4	18	22	
	center	53	-	46	
	displ. μm	27	2	29	
Cuffs	Inner	16	7	24	50 Yield stress
	Outer	4	16	21	

5 Conclusion

The specifications set for adequate mm-wave transmission through windows in multi-frequency ECH systems fed by step-tuneable gyrotrons can be fulfilled by double disk windows with a specifically developed direct face cooling concept.

The double disk window was analysed by thermo-mechanical simulation tools (FEMLAB, ANSYS) to assign the temperature distribution in the window under high power operation and stresses in the full window structure. It was found that for 1MW RF power (P_{abs} = 350 W), the maximum center temperature arises up to 320 K for water consumption grater than 10 *l* /min. Thermally induced stresses as well as stresses due to overpressure (0.2 MPa) have a maximum value of about 70 MPa in diamond and 25 MPa in copper cuffs which is well below the admissible limits.

6 Literature

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