

# Design verification of the gyrotron diamond output window for the upgrade of the ECRH system at W7-X

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The 10 MW electron cyclotron resonance heating (ECRH) system at the stellarator Wendelstein 7-X (W7-X) currently relies on the successful operation of continuous wave (CW) 1 MW, 140 GHz gyrotrons which have chemical vapor deposition (CVD) diamond output windows cooled by the industrial silicon oil Dow Corning 200(R) 5cSt. The window features a 1.8 mm thick diamond disk brazed to two copper cuffs with an aperture of 88 mm, which are then integrated in a steel housing. In the context of the upgrade of the ECRH system towards higher microwave power, this gyrotron design has been significantly advanced to fulfill the requirement of 1.5 MW CW operation, still at 140 GHz. A prototype of this new gyrotron is under development at Thales, France. This paper reports the computational fluid dynamics (CFD) conjugated heat transfer and structural analyses of the diamond window performed using the commercial code ANSYS V19.2 to investigate its performance at 1.5 MW operation. Furthermore, sensitivity studies were also carried out with respect to the absorbed power in the disk and the mm-wave beam radius at the window location. These analyses showed that the window design of the existing 1 MW gyrotrons still works quite well at higher power operation, thus verifying the performance of the window. Even in the worst case scenario of 1.5 kW absorbed power, the maximum temperature of 215°C at the disk center can be safely accepted, being below the conservative limit of 250°C for CVD diamond. In addition, the non-axial symmetric thermal gradients due to the geometry of the cooling channels lead to thermal stresses in the disk and the cuffs. However, they are much lower than the limits. The copper cuffs experience plasticity deformation in the region of the interface with the diamond disk up to a value of about 1.5 mm.

Keywords: Stellarator Wendelstein 7-X, ECRH system, gyrotron diamond output window, CFD analyses, FEM analyses, silicon oil Dow Corning 200(R) 5cSt.

## 1. Introduction

The reliable ECRH system at W7-X currently consists of 10 conventional cavity gyrotrons with a successful output power of 1 MW each in CW operation at a frequency of 140 GHz [1]. However, an upgrade of this output power is required to achieve operating regimes with high plasma beta and low collisionality. Therefore, the existing gyrotron design has been upgraded to 1.5 MW CW operation with significant improvements and the construction of a prototype has been already started at Thales Electron Devices SAS, Vélizy-Villacoublay, France [2].

As shown in Fig. 1, the existing gyrotrons feature CVD diamond output windows with a 1.8 mm thick and 106 mm diameter CVD diamond disk brazed to two copper cuffs of 1 mm wall thickness, which, in turn, are welded to a stainless steel housing. The window has an aperture of 88 mm and the edge of the disk is directly in contact with the coolant [3]. In order to prevent any corrosion of the brazing material, the window coolant is the industrial silicon oil Dow Corning 200(R) with the kinematic viscosity 5cSt (named later on as DC200) [4]. Past CFD conjugated heat transfer analyses showed that this oil is a good alternative to water in the case of the W7-X gyrotron output window at 1 MW operation [5].

First, this paper deals with the CFD conjugated heat transfer analyses aiming to investigate the window performance at 1.5 MW operation from the thermal perspective, in comparison to the 1 MW case. Subsequently, it presents sensitivity studies with respect to the mm-wave beam radius at the window location and, in particular, to the absorbed power in the disk by using loss tangent ( $\tan\delta$ ) values obtained as average over measurements done in the past for W7-X bare disks at the laboratories of Karlsruhe Institute of Technology (KIT). Finally, the paper reports the structural analyses carried out to verify the window design against the applicable stress limits.

## 2. CFD conjugated heat transfer analysis

### 2.1 CFD model

In the same fashion as in [5], a steady-state CFD conjugated heat transfer analysis was carried out by modelling the fluid domain and the solid domain, the latter formed only by the diamond disk and the copper cuffs. In fact, the steel housing does not give any significant contribution to the removal of the heat absorbed in the disk during the mm-wave beam transmission. As shown in Fig. 1, for symmetry reasons,

only half of the window was modelled. The flow path is described in [5].

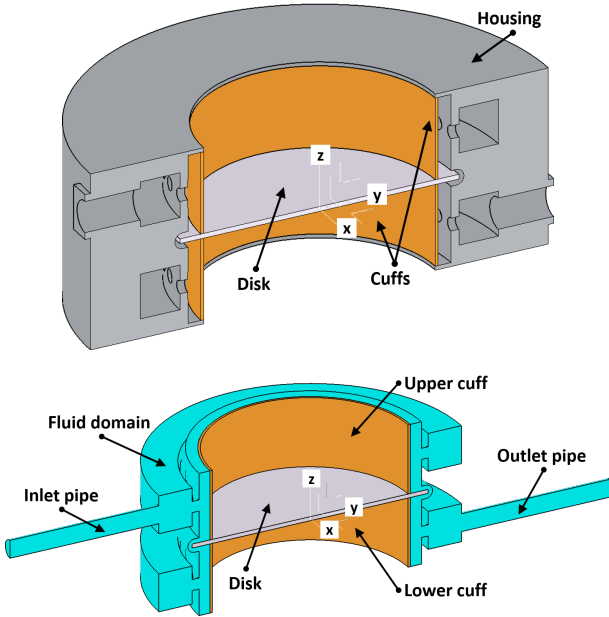


Fig. 1. Section view of the W7-X gyrotron diamond output window (top) and geometry in the CFD analysis (bottom). The reference system is placed at the disk center with y-axis oriented towards the outlet.

The code ANSYS CFX V19.2 was used for the analysis. Constant properties were used. The ones for the pure copper were taken directly from the CFX's library while the ones for the DC200 and the CVD diamond were derived from [4] and [6] respectively. A mass flow rate of  $0.2 \text{ kg s}^{-1}$  was applied to the inlet of the cooling channel ( $0.1 \text{ kg s}^{-1}$  in the symmetric model) while a reference pressure of  $0 \text{ Pa}$  was applied to the outlet. The inlet temperature of the oil was set to  $25 \text{ }^\circ\text{C}$  while the fluid pressure to  $1 \text{ bar}$ . A Gaussian mm-wave beam was considered and, for comparison reasons to the  $1 \text{ MW}$  case, the absorbed power in the disk was at first increased from  $1$  to  $1.5 \text{ kW}$  (see §2.4 for discussion on  $\tan\delta$ ). The heat load was applied to the disk in terms of volumetric power density given by:

$$q'''(r) = \frac{P_{tot}}{2\pi\sigma^2 t} e^{-\frac{r^2}{2\sigma^2}}$$

where  $q'''(r)$  is given in  $\text{W m}^{-3}$ ,  $P_{tot}$  is the total absorbed power,  $t$  is the disk thickness,  $r$  is the radial coordinate,  $\sigma$  is half of the beam radius ( $R_{beam} = 20 \text{ mm}$ ). The Gaussian distribution was normalized in order to obtain in the disk the total absorbed power of  $1.5 \text{ kW}$ . Finally, the k-omega shear stress transport (SST) model was selected as turbulence model and smooth walls were considered at the cooling interface.

## 2.2 Thermal results and comparison to 1 MW case

Fig. 2 shows the temperature distribution in the disk and cuffs for the  $1.5 \text{ MW}$  beam case. As expected, the maximum temperature is located at the disk center and amounts to  $215 \text{ }^\circ\text{C}$ , with the coolant at  $25 \text{ }^\circ\text{C}$  at the inlet. This temperature can be safely accepted, being well below the conservative limit of  $250 \text{ }^\circ\text{C}$  assumed for diamond. The cuffs experience a maximum temperature in the range  $117\text{-}126 \text{ }^\circ\text{C}$  at the region in contact with the disk, going towards the outlet. The cooling configuration of the window does not lead to an axial-symmetric temperature distribution. This can be better observed in Fig. 3 where the temperature profiles in the disk at the symmetry plane (the  $zy$ -plane) are compared between the two beam power cases. Going to  $1.5 \text{ MW}$  operation, the maximum temperature in the disk increases by  $\sim 70 \text{ }^\circ\text{C}$  and, as expected, the temperature gradients become steeper. The temperature difference center – edge increases by  $\sim 53\%$  on the inlet side of the disk and  $\sim 48\%$  on the outlet side. The asymmetry in the profiles becomes thus stronger. In fact, the temperature difference between the two edges of the disk at the symmetry plane raises from  $\sim 11 \text{ }^\circ\text{C}$  to  $\sim 20 \text{ }^\circ\text{C}$ .

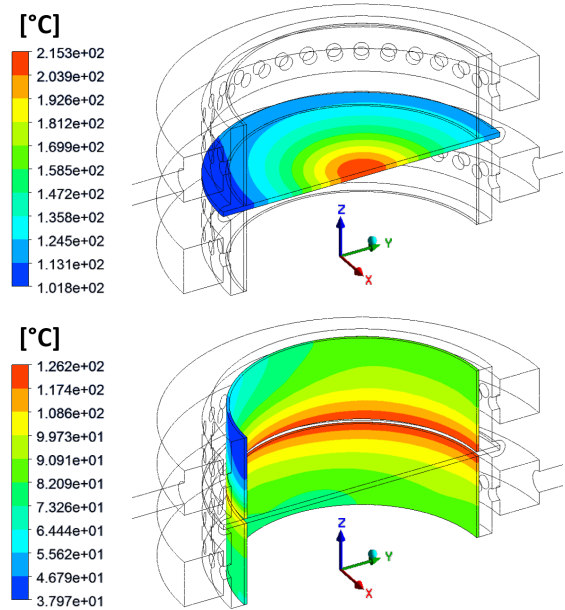


Fig. 2. Temperature distribution in the disk (top) and cuffs (bottom).

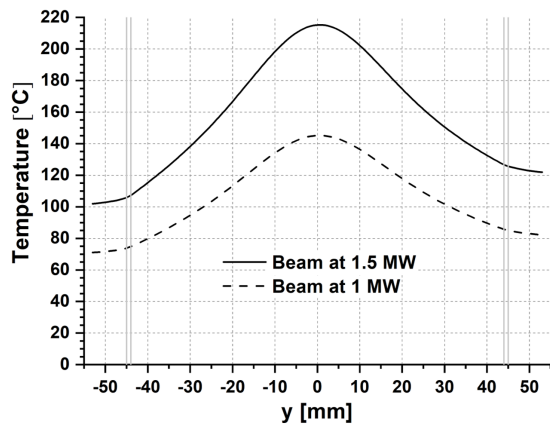


Fig. 3. Temperature profiles along the disk diameter (y-axis of Fig. 1) for the two mm-wave beam power cases. The vertical lines represent the cuffs brazed to the disk.

As already reported in [5], the thermal gradient is steeper on the inlet side of the disk due to the high turbulent kinetic energy of the fluid right after the inlet pipe. Structural analyses were therefore required to check the stresses induced by these more severe non-axially symmetric thermal gradients (see §3). Finally, the temperature increase of the oil at the outlet results in 4.4 °C only.

### 2.3 Mesh convergence study

With respect to [5], considering the more advanced computing power that is available nowadays, a mesh sensitivity study was performed to show the independency of the results from the grid. The steady-state CFD analysis related to the 1.5 MW case was run using three different meshes: (a) the one used in [5] with  $2.87 \times 10^6$  elements, (b) the mesh with  $15.5 \times 10^6$  elements used to generate the results shown in §2.1 and (c) an even more refined mesh with  $27.3 \times 10^6$  elements. The temperature profile in the disk was used as output parameter to check the grid independency. The mesh (b) turned out to be the optimum, as a further mesh refinement did not pose any significant change in the results. A global mesh size of 0.5 mm was applied and a very much finer mesh (inflation layer with first element size of 10  $\mu\text{m}$ ) was generated at the boundary layer to model properly the near wall interactions (heat transfer).

### 2.4 Sensitivity study for loss tangent and beam radius

As mentioned in §2.1, for comparison reasons to the 1 MW case, the absorbed power in the disk was at first increased from 1 to 1.5 kW to investigate the window performance at 1.5 MW operation. A  $\tan\delta$  of  $5.68 \times 10^{-5}$  for the diamond disk turns out when a power of 1.5 kW is dissipated in the disk of the W7-X gyrotron window. This can be easily calculated by the formula that provides the absorbed power in a disk being

perpendicular to the direction of propagation of the millimeter wave beam [7]. The  $\tan\delta$  is provided by the experimental measurements performed at KIT with Fabry-Perot resonators on the diamond disks and the resulting values are given, with reference to bare disks, respectively for the 50% (D50) and 90% (D90) fractions of the inspected area of the disk [8]. In the past,  $\tan\delta$  values were measured for 25 bare diamond disks to be mounted in the W7-X windows and the average over these measurements led to a  $\tan\delta$  of  $2.10 \times 10^{-5}$  for the D50 and  $3.49 \times 10^{-5}$  for the D90. The steady-state CFD analysis was therefore re-run considering the absorbed powers of 554.5 W and 921.4 W, corresponding to the D50 and D90 values, in order to perform a sensitivity study with respect to the  $\tan\delta$  parameter. The results of this sensitivity study are reported in Fig. 4. With a  $\sim 3$  times lower  $\tan\delta$ , the maximum temperature at the disk center reduces from 215 °C to 95 °C and the thermal gradients in the disk become consequently much more relaxed.

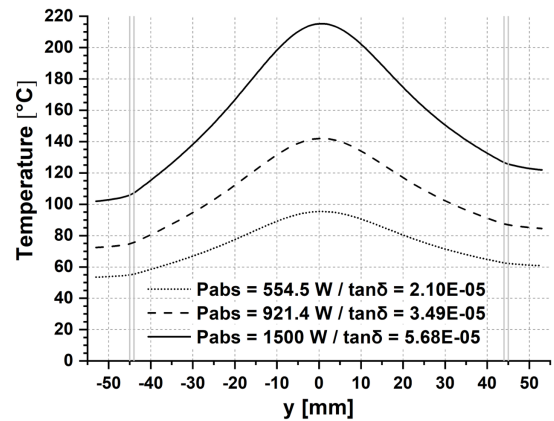


Fig. 4. Temperature profiles along the disk diameter (y-axis of Fig. 1) for three values of loss tangent.

The assumption of 1.5 kW absorption results thus conservative with respect to the  $\tan\delta$  experimental measurements, which however do not account for the potential degradation of the  $\tan\delta$  caused by the brazing process between disk and cuffs and the manufacturing of the window itself (a good margin is so assured against the uncertainties due to the potential degradation of the disk quality).

Finally, a sensitivity study with respect to the mm-wave beam radius was carried out. The CFD analysis was re-run for  $R_{\text{min}} = 15$  mm and  $R_{\text{min}} = 24$  mm, which respectively led to a maximum temperature in the disk of 234 °C and 203 °C. Latest calculations have shown that the expected beam radius at the window plane is about 22.5 mm. Since  $R_{\text{min}} = 20$  mm was used in the analysis setup, the results shown in §2.2 and §3 can be thus considered slightly conservative.

## 3. Structural analysis

The temperature distribution on the window calculated by the CFD analysis in §2.2 was given as input to a structural analysis to assess the thermal stresses in the disk and cuffs at 1.5 MW operation and check if the stresses are within the allowable limits. The code ANSYS V19.2 was used. In the region of the cuffs close to the disk, the cuffs plastically deform as the resulting stresses are greater than the yield strength of copper for the temperature range of interest (minimum yield strength of copper for plate products is ~55 MPa in the range 90–130 °C [9]). A plastic steady-state structural analysis was thus performed with the geometry shown in Fig. 5 and the material properties for diamond and pure copper taken respectively from [6] and [9]. Temperature dependent properties were defined and the multilinear isotropic hardening was used as plasticity material model with stress-strain curves given for plate products at different temperatures (up to 250 °C). Symmetry was applied to model only half of the window and the structure was made isostatic to assess first only the stresses due to the thermal gradients.

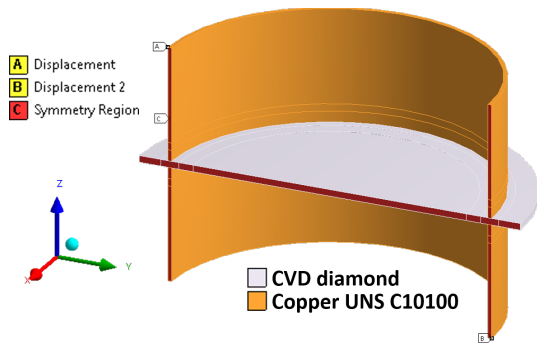


Fig. 5. Window geometry in the structural analysis.

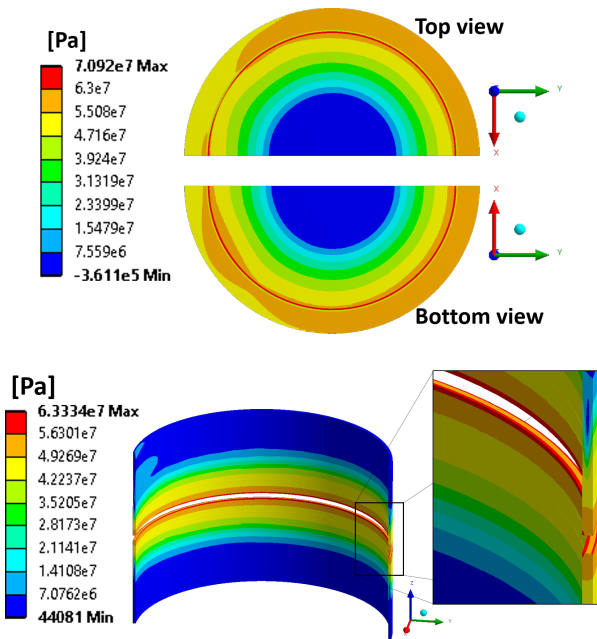


Fig. 6. First principal stress (top) and equivalent von Mises stress (bottom) distribution in the disk and cuffs.

The stress results are shown in Fig. 6. The distribution is only slightly asymmetric and the maximum principal stress in the disk amounts to 71 MPa, well below the conservative limit of 150 MPa assumed for diamond (ultimate bending strength is 450 MPa [10]). Exactly at the interface diamond-copper, there are the maximum stresses, in the range 63–71 MPa. Most part of the thermal load is absorbed by the plasticity in the copper, leading to relatively low stresses in the disk. In the cuffs, the maximum stresses are in the range 50–63 MPa in the region from the interface with diamond to a distance of ~2.5 mm, then the stress reduces to 20–50 MPa. These stresses can be safely accepted as the minimum ultimate tensile strength of pure copper is ~175 MPa in the range 90–130 °C [9]. The plastically deformed region extends from the interface to a distance of ~1.5 mm and the equivalent plastic strain is 0.1–0.2% for the most part.

In reality, the cuffs are not completely free to expand as they are constrained by the housing (Fig. 1), thus additional stresses occur from blocking the expansion of the cuffs. For this reason, the analysis was again run with a fixed support applied to the upper and lower cuffs. Since the cuffs are plastically deformed close to the disk, no significant stress change occurred in the disk and the portion of cuffs close to diamond. With respect to the previous analysis, instead a greater plastic strain was obtained (0.1–0.7% for the most part in the same region of interest) and, in the cuff region where no plasticity occurs, also greater stresses were found, but still well below the limits. In conclusion, the real stress state in the disk and the cuffs is in between the stress distributions obtained with the isostatic boundary condition and the fixed support one. In fact, the cuffs are not entirely free to expand because of the housing, but they are also not completely fixed as, during the beam transmission, the housing partially also heats up and moves accordingly.

#### 4. Conclusions

The W7-X gyrotron CVD diamond output window at 1.5 MW operation was investigated by analyses. Even in the worst case of 1.5 kW absorbed power in the disk, the resulting temperatures and stresses are well below the limits, verifying thus the performance of the window in the context of the analyses carried out in this work.

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