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# Performance of the W7-X ECRH gyrotron diamond output window at 2 MW operation

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ABSTRACT

The current electron cyclotron resonance heating (ECRH) system at the stellarator Wendelstein 7-X (W7-X) is in the phase to increase the gyrotron output power from 1 MW to 1.5 MW and, last, up to the target of 2 MW by different steps. The higher heating power shall allow achieving operating regimes with high plasma beta and low collisionality, required by the planned further experimental campaigns. Previous numerical analyses verified the design of the gyrotron diamond output window up to 1.5 MW operation, with temperature dependent material properties. The window must be cooled by water, to assure significant temperature reserve margins. In this work, the investigation of the window performance was further carried on for the target of 2 MW operation. Computational fluid dynamics (CFD) conjugated heat transfer and structural analyses were performed. The sensitivity of the design was checked with respect to different combinations of loss tangent and mm-wave beam radius. The operational limits of the window were also checked. The current design features conical cuffs and a slightly different cooling path with respect to the past. For the first time, the complete window assembly and both the thermal and other operational loads were considered in the analyses. They showed that the window design can work also at 2 MW operation. The maximum loss tangent value of the diamond disk that might be still tolerated is $5.7 \times 10^{-5}$, corresponding to an absorbed power of 2008 W, with a beam radius of 20 mm. Last, going to higher absorbed powers in the disk, maximum temperatures can be significantly reduced by increasing the beam radius within the limits which are however imposed by the window aperture.

## 1. Introduction

The performance of the chemical vapour deposition (CVD) diamond output window of the W7-X ECRH gyrotrons [1] was checked at 1.5 MW operation [2], when cooled by water and silicon oil Dow Corning 200(R) 5cSt at different values of absorbed power ($P_{abs}$) in the disk [3,4]. The conclusions were that water coolant provides significant temperature reserve margins, even at higher values of absorbed power, and temperature dependent properties shall be used. In fact, at high power level, the disk achieves temperatures for which, the degradation of the thermal conductivity in diamond becomes significant [5].

In this work, the window was further investigated to check the performance at 2 MW beam power [6] and define the operational limits of the design itself. CFD conjugated heat transfer analyses were carried out for different combinations of loss tangent (tanδ) of the disk and radius ($r_{beam}$) of the mm-wave beam. For the first time, structural analyses were subsequently run with the complete window assembly and the entire set of operational loads to obtain a real picture of the window performance at higher power operations.

## 2. Geometry of the window

Fig. 1 and Fig. 2 show respectively the window design and the geometry used in the analyses with the reference system, materials and nomenclature of the parts forming the window. With respect to the past [3], the window features conical copper cuffs brazed to the diamond disk. With one side of the cuffs parallel to the beam axis, the diamond disk is then tilted by 1.5° with respect to the mm-wave beam axis. This

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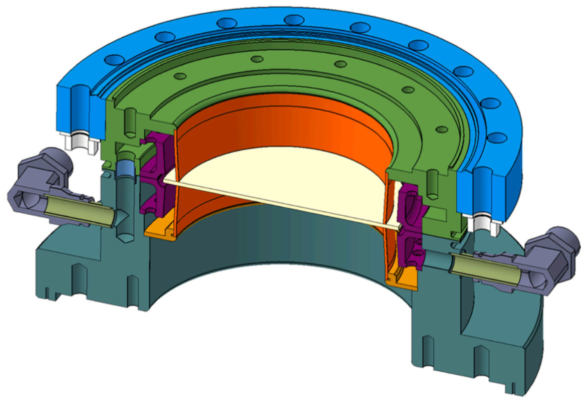

**Fig. 1.** Updated geometry of the W7-X gyrotron diamond output window design.

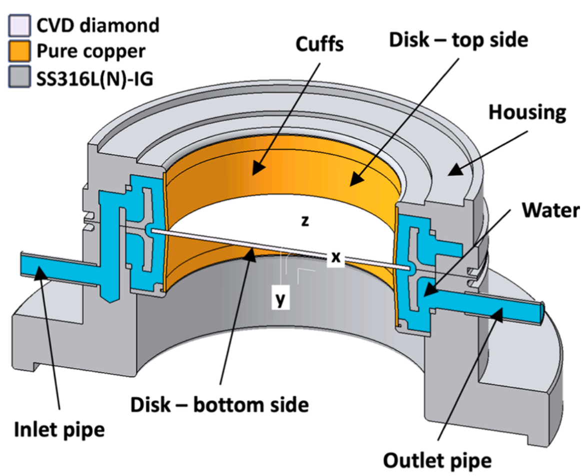


**Fig. 2.** Window geometry used in the analyses. The geometrical reference system, materials and names of the parts forming the window are indicated.

tilting is introduced to reduce the reflections of the beam back to the gyrotron cavity. As shown in Fig. 3, the window also features a slightly different cooling path aiming to make the temperature distribution in the structure more symmetrical around the beam axis. However, these changes had no significative impact on the window from the thermal and structural perspective. Small simplifications were carried out to generate a better mesh in the model for the analysis, e.g. removing small gaps. Both fluid and solid domains were considered in the CFD analyses

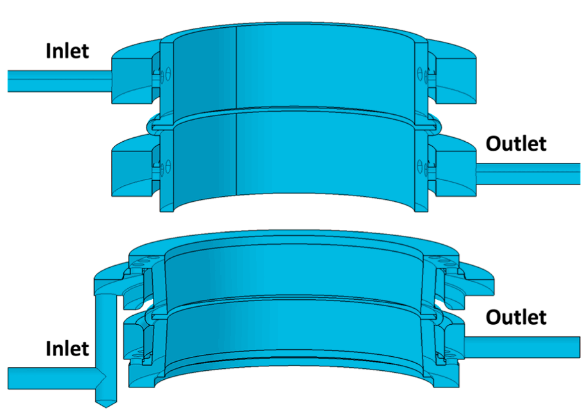


**Fig. 3.** View of the fluid domain in the past window design (top) and in the updated one (bottom). The surfaces in the symmetry plane were made transparent to enable the internal view.

while the fluid one was then suppressed when entering the structural analysis. For symmetrical reasons, only half of the window was modelled.

## 3. Analysis setup

A steady-state CFD conjugated heat transfer analysis was first carried out for a reference case with $r_{beam} = 20$ mm and $\tan\delta = 5.0 \times 10^{-5}$ by the code ANSYS CFX 2024 R2. The tanδ was considered constant over the area of the disk, with a conservative assumption and corresponding to an absorbed power in the disk of 1761 W, for 2 MW operation at 140 GHz and 1.8 mm thickness. Measurements of tanδ at Karlsruhe Institute of Technology (KIT) over 25 bare diamond disks mounted in the W7-X windows (for 1 MW operation) have led to average values of $2.10 \times 10^{-5}$ and $3.49 \times 10^{-5}$ respectively for D50 and D90 values (50% and 90% fractions of the inspected area in the loss tangent measurements [7]). A Gaussian mm-wave beam was considered. In the same fashion as the previous works, a water mass flow rate of 0.2 kg $s^{-1}$ at 25 °C was applied to the inlet of the cooling channel and a reference pressure of 0 Pa to the outlet. Temperature dependent properties for CVD diamond, pure copper and steel were taken respectively from [5,8] and [9]. The properties directly from CFX's library were used for water.

Second, the sensitivity of the window design was investigated for different combinations of $r_{beam}$ values (17, 20 and 23 mm) and tanδ ($2.0 \times 10^{-5}$, $3.5 \times 10^{-5}$ and $5.0 \times 10^{-5}$) aiming to check the maximum temperature achieved at disk center. The window aperture is 92 mm at disk location where the conical cuffs have the minimum radius. Since the beam radius shall not be larger than half of the aperture radius, $r_{beam} = 23$ mm was the upper limit value for the sensitivity study. The values of tanδ were selected based on the experimental measurements done at KIT.

Furthermore, the operational limits of the window were checked to identify the maximum value of tanδ that might be still tolerated at 2 MW gyrotron operation. Last, the resulting stresses due to the operational loads were calculated by plastic steady-state structural analysis of the window. The code ANSYS Workbench 2024 R2 was used. Fig. 4 shows the applied boundary conditions and the loads. Beyond thermal loads, also the coolant pressure (1 bar) and the atmospheric pressure acting on one side of the window were considered. Note that the latter was applied to the disk bottom side.

## 4. Results

### 4.1. Reference case

Figs. 5–7 show the temperature results for the reference case. As expected, the maximum temperature is located at the disk center and it amounts to 223 °C, with the coolant at 25 °C at the inlet. A temperature in the range 250 - 300 °C is generally assumed as limit for CVD diamond since beyond that, worsening of thermal conductivity and increasing of loss tangent occur with consequent higher losses in diamond. With respect to the past [4], the temperature distribution in the disk can be considered axial-symmetric, thanks to the new design of the cooling circuit. The temperature difference between the two edges of the disk at the symmetry plane is 6 °C only (Fig. 10). A maximum temperature of 66 °C is then achieved in the cuffs, in the contact region with the disk, while maximum temperature in the housing amounts to 37 °C.

The stress distribution in the copper cuffs is plotted in Fig. 8. The cuffs plastically deform at the brazing region and maximum stresses are in the range 50–62 MPa at the interface region with the disk. These stresses can be safely accepted considering a minimum ultimate tensile strength of pure copper of ~180 MPa at 70 °C [8]. It shall be mentioned that, in reality, the analysis and the comparison with the limits shall be done with stress-strain curves and ultimate tensile strength determined for copper subjected to the temperature cycle of the brazing process. However, this information is not available yet and properties from [8]

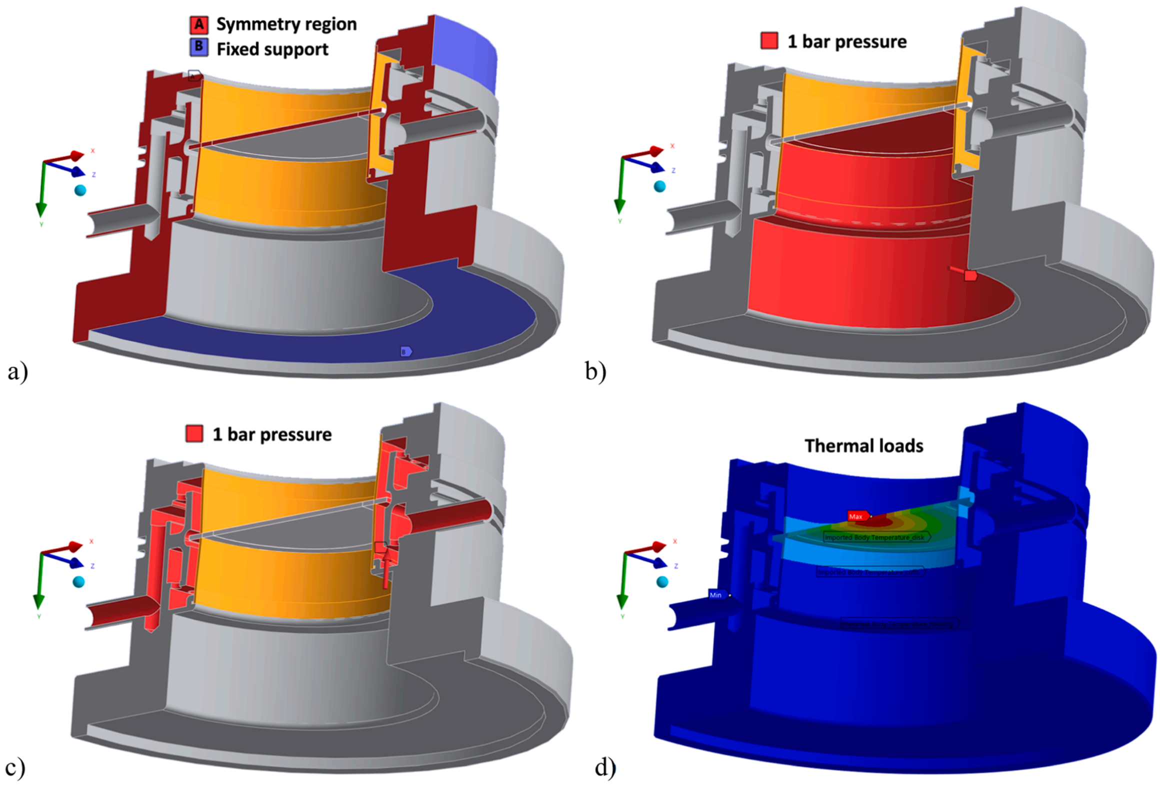


**Fig. 4.** Boundary conditions and loads applied to the window in the structural analysis: fixed support and symmetry region (a), atmospheric pressure on one side of the disk (b), 1 bar pressure of the coolant (c) and typical plot of the temperature distribution calculated by CFD analysis (d).

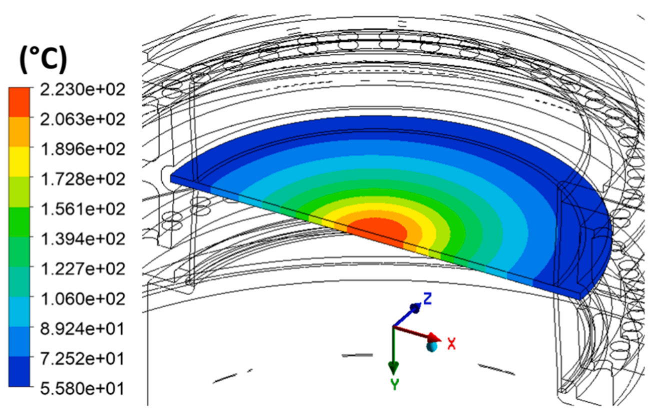


**Fig. 5.** Temperature distribution in the disk for reference case.

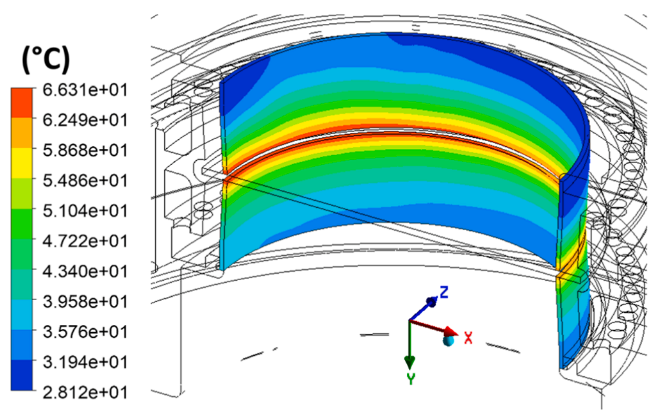


**Fig. 6.** Temperature distribution in the cuffs for reference case.

are used.

Fig. 9 shows the maximum principal stresses (describing the tensile component) in the diamond disk both when the single and combined loads are applied. As expected, the thermal loads only lead to a symmetrical distribution of the stresses between top and bottom surfaces of the disk, with maximum values in the range 60–76 MPa located in the outer region. The central area of the disk is instead under compression. Plotting the minimum principal stresses (describing the compressive stress component, not shown in this paper), it turns out a maximum compressive stress at disk center of ~120 MPa. The thermal gradients are in fact very steep with a temperature difference between disk center and side of ~160 °C, as can be deduced from Fig. 10.

The pressure loads only lead to a maximum stress of ~47 MPa at the disk center in the top surface which corresponds to the tensile side (pressure is applied to the bottom side). Stress is in the range 15–25 MPa in the outer region of the disk. When all loads are considered, it may be

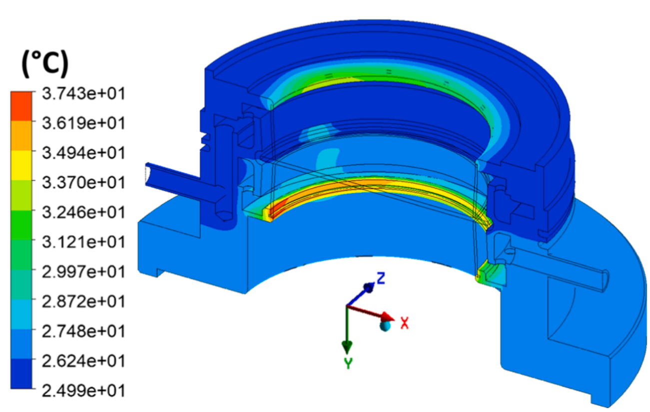


**Fig. 7.** Temperature distribution in the housing for reference case.

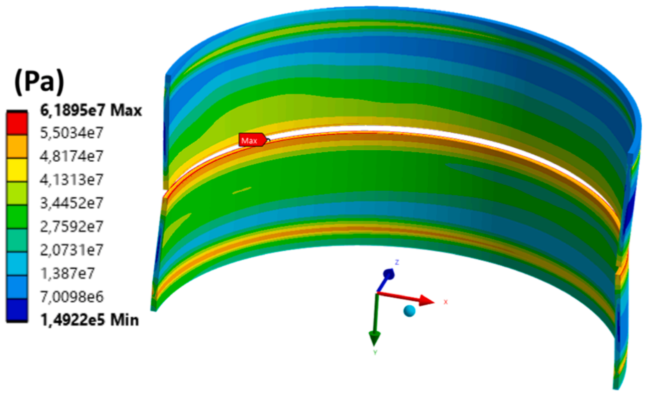


**Fig. 8.** Equivalent von-Mises stress distribution in the cuffs for the reference case with all operational loads.

observed that, on the top side, stress increases in the mid and outer region with a maximum value of 96 MPa. The stresses due to the single loads overlap. On the other hand, the central area of the disk remains under compression with a maximum compressive stress at center of ~70 MPa (minimum principal stress distribution, not shown in this paper). In the central area, the compressive state generated by the thermal gradients is so strong to overcome the tensile state generated by the pressure load of 1 bar. In this sense, it can be concluded that thermal loads rule the distribution of stress in the disk.

On the bottom side of the disk, the stresses relax when the pressure loads are added to the thermal ones, with maximum stresses in the range 40–60 MPa in the outer region. The stress generated by the combined loads can be anyway safely accepted, as lower than the allowable limit of 150 MPa generally assumed for CVD diamond. An ultimate bending strength of 280 ± 30 MPa was measured on the growth side of 1.89 mm thick CVD diamond samples (1.8 mm is the disk thickness in the window) while the strength turned to be 690 ± 95 MPa on the nucleation side of the sample (stronger side due to the smaller grain size) [10]. Last, the bow generated in the diamond disk is ~45 μm.

### 4.2. Parametric study and limit case

The thermal results of the parametric study concerning the loss tangent and the beam radius are respectively shown in Fig. 10 and Fig. 11. Maximum values of temperatures are provided by Table 1. In the case of $r_{beam}$ = 20 mm, the maximum value of tanδ that might be still

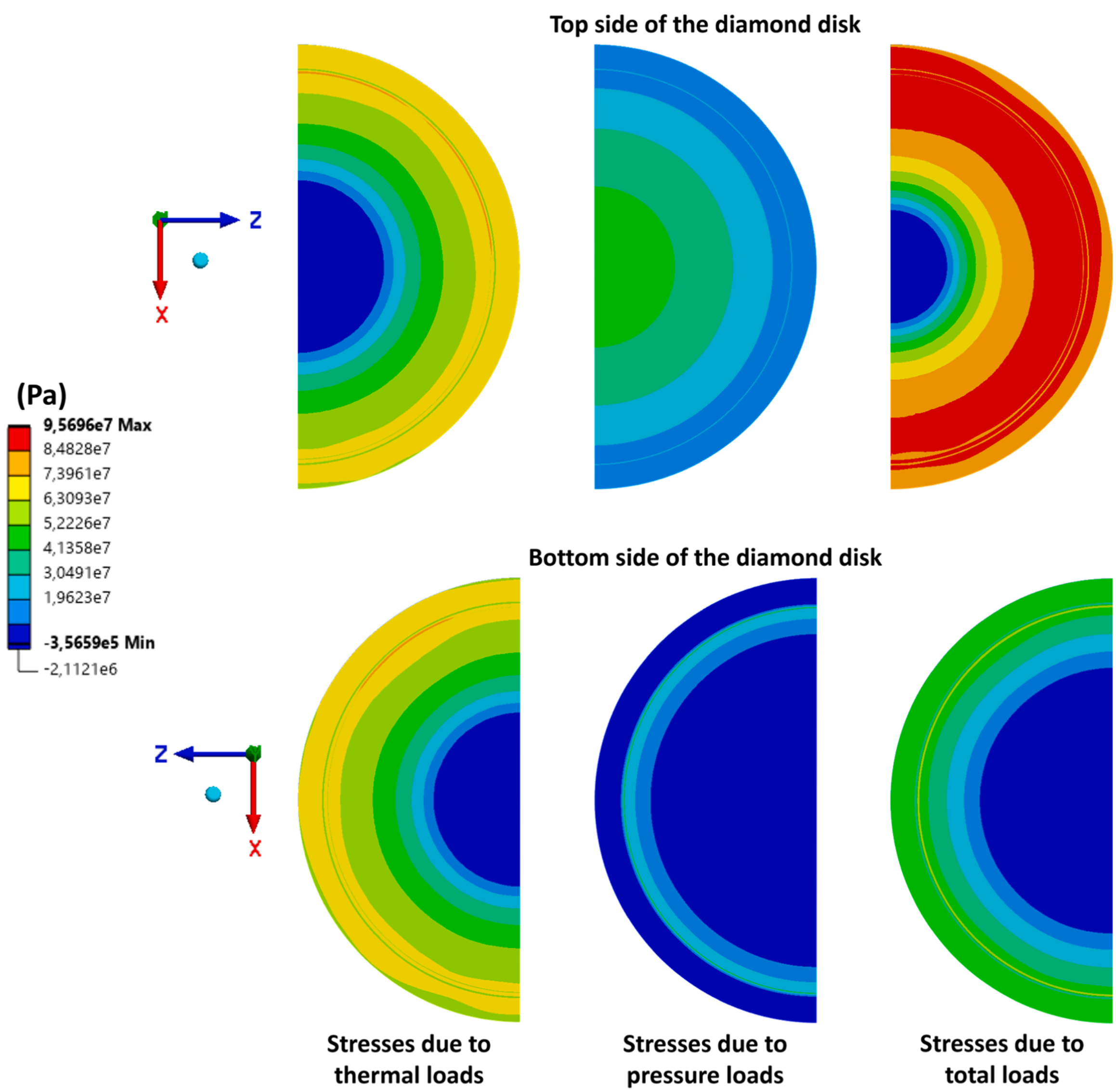


**Fig. 9.** Maximum principal stress distribution in the upper and lower surfaces of the diamond disk for the single and combined loads in the reference case. Top and bottom sides of the disk are shown in Fig. 2. Note that atmospheric pressure is applied to the bottom side of the disk (see Fig. 4b).

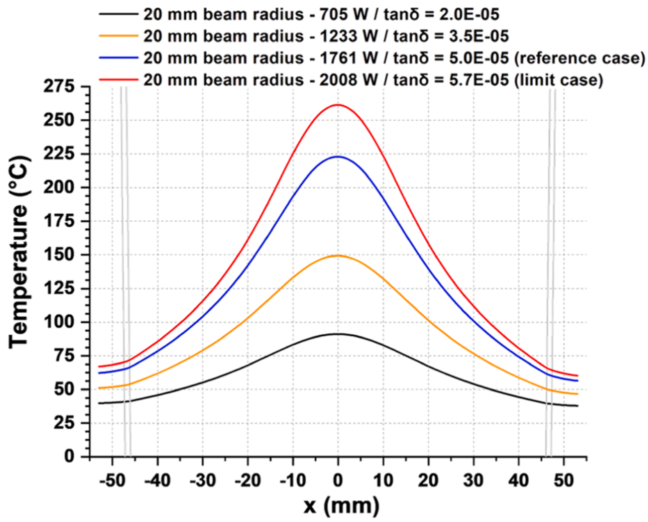


**Fig. 10.** Temperature profiles along the disk diameter for different values of loss tangent and constant beam radius of 20 mm.

tolerated by the diamond window at 2 MW operation results in 5.7E-5, corresponding to an absorbed power of 2008 W. As shown in Fig. 10 (limit case) and Table 1, the maximum temperature would go to 261.5 °C while a temperature difference between disk center and side of about 195 °C would occur. Stresses due to the combined loads would have the same distribution as in the reference case, but with a maximum value of 113 MPa in the disk and 62.5 MPa in the cuffs (lower anyway than the limits).

It can be stated from the thermal perspective that, looking at Fig. 11, going to higher values of absorbed powers, the selection of a greater beam radius may play a significative role in keeping the maximum temperature below the limit with a safety margin. For instance, in the case of $\tan\delta = 5.0 \times 10^{-5}$, going from 17 mm to 23 mm for the beam radius, the maximum temperature at disk center would decrease by about 40 °C. It can be also added that, the variation of the temperature profiles for the different beam radius affects a central area of the disk of about 40 mm diameter only.

However, the selection of a greater beam radius leads to greater electrical field strength at the edge of the disk surface inside the cuffs, which might introduce the risk of arcing. The strength of the field at the edge shall be lower than a dedicated threshold to avoid such a risk.

## 5. Conclusions

The W7-X gyrotron diamond output window was investigated by CFD conjugated heat transfer and structural analyses for 2 MW operation when cooled by water. The sensitivity of the design was checked with respect to different combinations of tanδ and $r_{beam}$. The operational limits of the window were also checked. The current design features conical copper cuffs and a slightly different cooling path with respect to the past. For the first time, the complete window assembly and set of operational loads were considered in the analysis.

It can be concluded that this window design was verified for 2 MW gyrotron operation. With a conservative assumption of $\tan\delta = 5.0 \times 10^{-5}$ (absorbed power of 1761 W) and $r_{beam} = 20$ mm, maximum temperature and stress are lower than the limits. The maximum tanδ value that might be still tolerated by the window is $5.7 \times 10^{-5}$, corresponding to an absorbed power of 2008 W, while keeping $r_{beam} = 20$ mm.

## CRediT authorship contribution statement

**G. Aiello:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **B. Gorr:** Project administration. **J. Jelonnek:** Project administration. **H.P. Laqua:** Project administration. **F. Legrand:** Resources. **A. Meier:** Resources. **T. Scherer:** Supervision, Project administration. **S. Schreck:** Data curation. **D. Strauss:** Supervision, Project administration, Funding acquisition. **M. Thumm:** Writing – review & editing, Conceptualization.

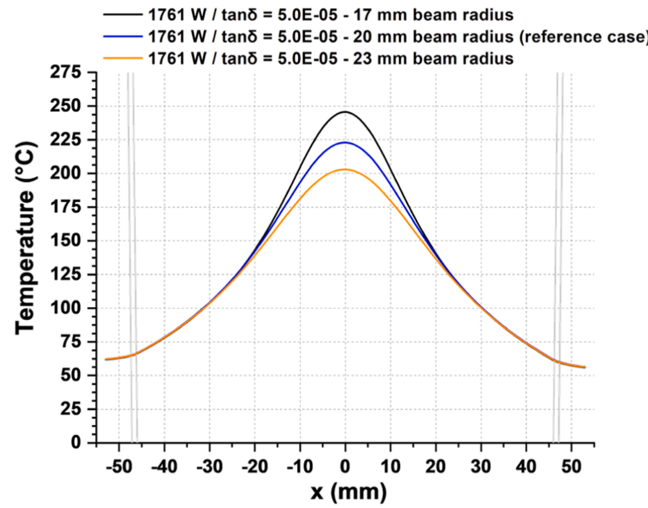


**Fig. 11.** Temperature profiles along the disk diameter for different values of beam radius and constant loss tangent of $5.0 \times 10^{-5}$.

**Table 1**
Maximum temperatures in the diamond disk for different combinations of beam radius and loss tangent.

| | $r_{beam} = 17$ mm | $r_{beam} = 20$ mm | $r_{beam} = 23$ mm |
|---|---|---|---|
| $\tan\delta = 2.0 \times 10^{-5}$ / $P_{abs} = 705$ W | 97.2 °C | 91.1 °C | 85.9 °C |
| $\tan\delta = 3.5 \times 10^{-5}$ / $P_{abs} = 1233$ W | 162.3 °C | 149.3 °C | 138.6 °C |
| $\tan\delta = 5.0 \times 10^{-5}$ / $P_{abs} = 1761$ W | 245.6 °C | 223.0 °C | 203.0 °C |
| $\tan\delta = 5.7 \times 10^{-5}$ / $P_{abs} = 2008$ W | - | 261.5 °C | - |

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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