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The W7-X ECRH gyrotron diamond output window: Oil and water cooled window performance at 1.5 MW operation

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ABSTRACT

The 140 GHz 1 MW gyrotron (Thales TH1507) for the electron cyclotron resonance heating (ECRH) system at the stellarator Wendelstein 7-X (W7-X) is being upgraded to 1.5 MW continuous wave operation to increase the total heating power for achieving operating regimes with high plasma beta and low collisionality. The design of the new 1.5 MW gyrotron (Thales TH1507U) has been significantly improved to the new power target. It features a chemical vapor deposition (CVD) diamond output window cooled by the silicon oil Dow Corning 200(R) 5cSt, in direct contact with the circumference of the diamond disk. The oil has been selected to prevent any corrosion of the brazing material between diamond disk and copper cuffs. Previous analyses verified the suitability of the window design for both, operation at 1 MW and at 1.5 MW if assuming constant properties for diamond and copper. In this work, the window is investigated by computational fluid dynamics conjugated heat transfer and structural analyses with temperature dependent material properties to assess its performance if cooled by water and oil at different absorbed powers in the disk. Temperature dependent properties are assumed as, at those power levels, the disk achieves temperature ranges at which, the reduction of the diamond thermal conductivity becomes remarkable. Otherwise, the maximum achieved temperatures are deeply underestimated. Both water- and oil-cooled window cases work up to about 1.2 kW absorbed power in the disk, with temperatures and stresses lower than the maximum allowed limits. However, it is of fundamental importance to assure high temperature reserve margins in the window to counteract any potential degrading factor of the disk quality from microwave transmission perspective. Water-cooling represents the only solution as it provides significant margins, even at higher values of absorbed power. In the worst-case scenario of 1.5 kW absorption, the maximum temperature in diamond is 173 °C while the oil-cooling option would lead to temperatures well above the 250 °C design safe limit.

1. Introduction

The gyrotrons of the ECRH system at W7-X [1] feature a diamond output window with the CVD diamond disk in direct contact with the coolant [2]. The disk is brazed to the copper cuffs. To prevent any corrosion risk of the brazing material, the silicon oil Dow Corning 200 (R) 5cSt has been so far selected as coolant [3]. It is an industrial silicon oil, chemically inert, with the kinematic viscosity 5cSt (named later only DC200).

Past computational fluid dynamics (CFD) conjugated heat transfer analyses showed that this oil is a good alternative to water in the case of 1 MW gyrotron operation [4]. Then, additional CFD and structural analyses verified the performance of the oil-cooled window at 1.5 MW operation [5,6] showing that, even in the worst-case scenario of 1.5 kW absorbed power, the maximum temperature at the disk center results in 215 °C [7]. However, a real picture of the window performance was not obtained yet as constant material properties for diamond and copper (no dependency on temperature) were used in these works. This led to underestimate the temperatures in the window, even by >50 °C. Maximum temperatures would be thus close or even higher than the materials limits. Consequently, the option of a cooled-water window has been re-considered to be within the limits and, even more to have high reserve

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temperature margins to counteract unwanted factors like potential loss tangent (tanδ, the parameter that characterizes the microwave absorption in a material) degradation in diamond. In case of potential corrosion at the brazing diamond-copper due to direct contact with water, it might be prevented by dedicated control of water chemistry.

First, this paper shows CFD conjugated heat transfer analyses carried out for the window at 1.5 MW operation, with temperature dependent properties for diamond and copper, to support the change from oil to water cooling and check the temperature reserve margins of the design with respect to tanδ variation. Values of tanδ obtained as average over measurements done in the past for W7-X bare disks at Karlsruhe Institute of Technology (KIT) are used. The code ANSYS CFX 2024 R2 is used. The impact with respect to the previous works (1.5 MW, constant properties) is assessed. Finally, structural analyses by the code ANSYS Workbench 2024 R2 are shown to verify the window design against the applicable stress limits with respect to the thermal loads.

2. CFD conjugated heat transfer analyses

2.1. Analysis setup

Fig. 1 shows the window geometry with the flow path of the coolant. Only half of the window is modelled. The diamond disk has a thickness of 1.8 mm and diameter of 106 mm. It is brazed to two copper cuffs with 1 mm wall thickness. In a first instance, a steady-state CFD conjugated heat transfer analysis is carried out, first with water as coolant and, second, with oil, in both cases considering an absorbed power in the disk of 1.5 kW. The assumption of 1.5 kW is conservative and derives from the need to compare the results of the analyses with the previous works, where oil as coolant and constant material properties are considered. Temperature dependent properties for pure copper and CVD diamond are taken from [8] and [9], respectively. The properties directly from CFX's library are used for the water coolant while the properties of DC200 are taken from [3]. For convenience, the properties of both coolants are reported in Table 1.

In the same fashion of the previous work [7], a mass flow rate of 0.2 kg s^{-1} is applied to the inlet while a reference pressure of 0 Pa is applied to the outlet. The inlet temperature is set to 25 °C while the fluid pressure to 1 bar. As dealing with a gyrotron window, a Gaussian mm-wave beam with a 20 mm radius is considered. The heat load is applied to the disk in terms of volumetric power density as a function of the radius. The Gaussian distribution is normalized to obtain the total absorbed power of 1.5 kW in the disk. The k-omega shear stress transport (SST) model [10] is selected as turbulence model as it usually provides good results for cases in which there are near wall interactions like heat transfer between solid and coolant.

In a second case, the sensitivity of the window design with respect to the tanδ parameter is investigated both for water and DC200 in accordance with the values provided by Table 2 and the temperature dependent material properties. In Table 2 the absorbed power is calculated by [11]:

$$P_{abs} = \frac{P_{beam}\,\pi\,f\,t\,tan\delta\,(1+\varepsilon_r)}{c}$$

where P_{abs} is the absorbed power in W, P_{beam} is the beam power (1.5 MW), f is the operating frequency (140 GHz), ε_r is the dielectric constant of diamond (5.67), t is the disk thickness (1.8 mm) and c is the speed of light. The dielectric loss factor tanδ is provided by the experimental measurements at room temperature performed at KIT with the FABRY-PEROT resonators on the diamond disks. The values of tanδ are given, with reference to bare disks, respectively for the 50% (D50) and 90% (D90) fractions of the inspected area of the disk [12]. In the past, values of tanδ were measured for 25 bare diamond disks to be mounted in the W7-X windows and the average over these measurements are also reported in Table 2.

The average residuals, obtained by the root mean square (RMS) applied to the mesh elements through the model, turns out to be lower than the default target of 1×10^{-4} for all solved equations, except for the fluid energy equation. This target is used in many engineering applications dealing with complex geometries [10]. As recommended by guidelines, the high residual of the fluid energy equation ($\sim 7 \times 10^{-4}$ in the case of water) was checked by running a transient analysis with a small time step of 0.05 s. The transient case confirmed the results of the static case while a drop of the residual of the fluid energy equation to $\sim 4 \times 10^{-5}$ was observed. The overall results of the analyses may be thus considered accurate.

Table 1
Properties of the coolants at 25 °C used in the CFD analyses of the window.

Coolant	Density [kg m^{-3}]	Dynamic viscosity [Pa s]	Specific heat [J kg^{-1} K^{-1}]	Thermal conductivity [W m^{-1} K^{-1}]
Water	997	8.899×10^{-4}	4182	0.607
DC200	915	45.75×10^{-4}	1639	0.142

Table 2
Values of the tanδ and corresponding absorbed powers in the diamond disk considered in the analyses.

	tanδ [-]	Absorbed power [W]
Conservative assumption	5.68×10^{-5}	1500
Measurements for disk 89DB1	4.55×10^{-5}	1200
D90, average on 25 bare disks	3.49×10^{-5}	921.4
D50, average on 25 bare disks	2.10×10^{-5}	554.5

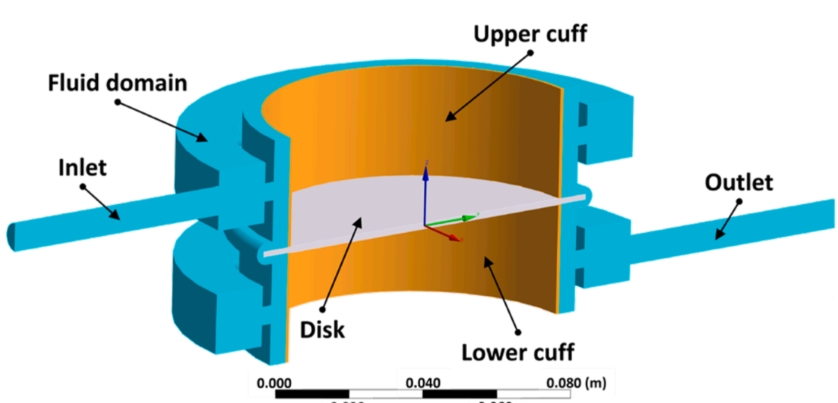

Fig. 1. Geometry of the W7-X gyrotron diamond output window used in the CFD analyses. The reference system is placed at the disk center with y-axis oriented towards the outlet.

2.2. Comparison silicon oil - water

Fig. 2 shows the temperature distribution in the disk and cuffs for the water- and oil-cooled window at 1.5 kW absorption by considering temperature dependent properties for diamond and copper. The comparison between the two cases is also shown in Table 3. As expected, the maximum temperature is located at the disk center. It amounts to 173 °C and 278 °C respectively for the water- and oil-cooling, with the coolant at 25 °C at the inlet. A temperature of 250 °C is generally assumed as design safe limit for CVD diamond as beyond that, worsening of thermal conductivity and increasing of loss tangent occur with consequent higher temperatures in diamond. In contrast to [7], it can be concluded that oil-cooling is not an option for the window at 1.5 kW absorption. In the water case, the cuffs experience a maximum temperature in the range from 51 °C up to 57 °C at the region near the disk, going towards the outlet, while in the oil case, higher temperatures in the range from 110 °C up to 128 °C are achieved. It can be stated too that in both cases the cooling configuration of the window does not lead to an axial-symmetric temperature distribution.

The non-axial symmetry can be better observed in Fig. 3 where the temperature profiles in the disk at the symmetry plane are compared between the two cooling cases and always at 1.5 kW absorption. The asymmetry is stronger in the oil case as the temperature difference between the two edges of the disk at the symmetry plane raises from ~12 °C in the water-cooling to ~22 °C (Table 3). Fig. 3 also shows temperature gradients that are steeper in the oil case and worse on the inlet side of the disk. The water-cooled window has a better performance from the thermal perspective with respect to the oil-cooling option. This can be explained by Table 1. With respect to water, the DC200 is in fact chemically inert, but it has about 5 times larger viscosity while heat capacity and thermal conductivity are reduced respectively by about 60% and 77%. The heat removal by oil is to some extent degraded with respect to water and additionally results in a higher pressure drop of about 1.3 times. It can be also noted in Table 3 that the ratio between the power fractions removed by diamond and copper, about 50–50% in the oil case while to 60–40% in the case of water, is different between the two cooling options. It means, that in the oil-cooling, more power is transferred to the cuffs by the brazing region and this contributes to the high temperatures obtained in the copper with respect to the water-cooling (Fig. 2).

Fig. 3 also shows the temperature profile in the disk for the oil-cooled window obtained with the constant properties for diamond and copper. It can be observed how the maximum temperature in the disk goes from 215 °C up to 278 °C, i.e. ~ 30% increase, if the temperature dependent material properties are used in the analyses. The temperature jump can be explained mainly by the variation of the thermal conductivity with temperature in diamond [9]. In fact, from room temperature up to 200 °C, the thermal conductivity reduces by about 42% leading to the higher temperature peak observed at the disk center, with respect to the case of constant material properties. For completeness of information, the variation of the thermal conductivity in copper is not significant. At 200 °C, it reduces by only ~ 3% [8].

2.3. Parametric study for loss tangent

The sensitivity of the water- and oil-cooled window was then investigated with respect to the tanδ parameter in accordance with the values provided by Table 2. Fig. 4 shows the temperature profiles in the disk for the water case while, for both cooling cases, Table 4 provides the values of the maximum temperatures in the disk and the corresponding reserve margins with respect to the design safe limit of 250 °C. With a lower absorbed power of about 3 times, the maximum temperatures at the disk center reduce by about 58% and 64% respectively in the water- and oil-cooling cases, with consequent more relaxed thermal gradients and stresses in the disk. It can be stated that, with respect to oil, the water-cooling provides by far significant temperature reserve margins, even at higher values of absorbed power in the disk. It is very important to keep high reserve margins in the window to counteract any potential factor leading to a degradation of the microwave transmission capability of the diamond disk.

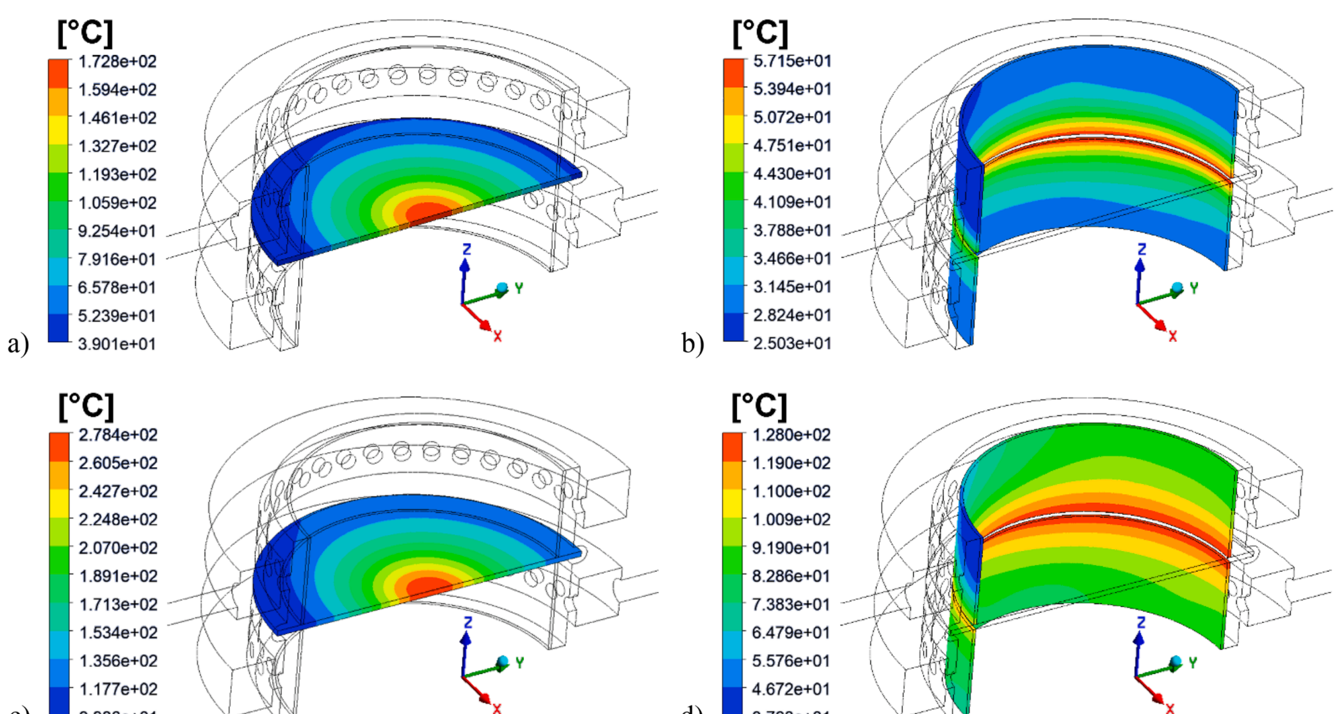

Fig. 2. Temperature distribution for water-cooled window at 1.5 kW absorption power in the disk (a) and cuffs (b) and corresponding temperature distribution for oil-cooled window in the disk (c) and cuffs (d). Temperature dependent material properties were used.

Table 3
Comparison between water and oil cooling performances of the window at 1.5 kW absorption power with temperature dependent material properties.

Coolant	Pressure drop [bar]	ΔT fluid inlet-outlet [°C]	Max T in disk [°C]	Max T in cuffs [°C]	ΔT disk edges [°C]	Power fraction removed by diamond [-]	Power fraction removed by copper [-]
Water	0.15	1.75	172.8	57.2	11.8	58 %	42 %
DC200	0.20	4.47	278.4	128.0	22.4	48 %	52 %

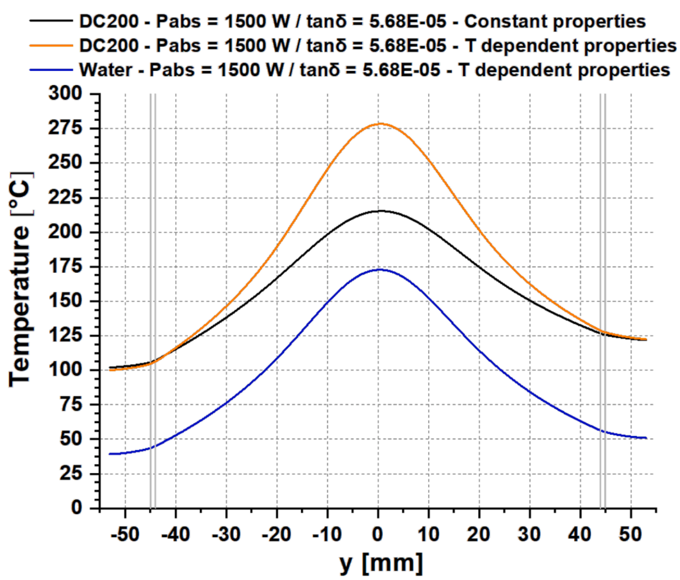

Fig. 3. Temperature profiles along the disk diameter (y-axis in Fig. 1) for oil and water at 1.5 kW absorption power. The curve related to oil obtained with constant material properties in [7] is also shown. The vertical continuous lines represent the cuffs brazed to the disk.

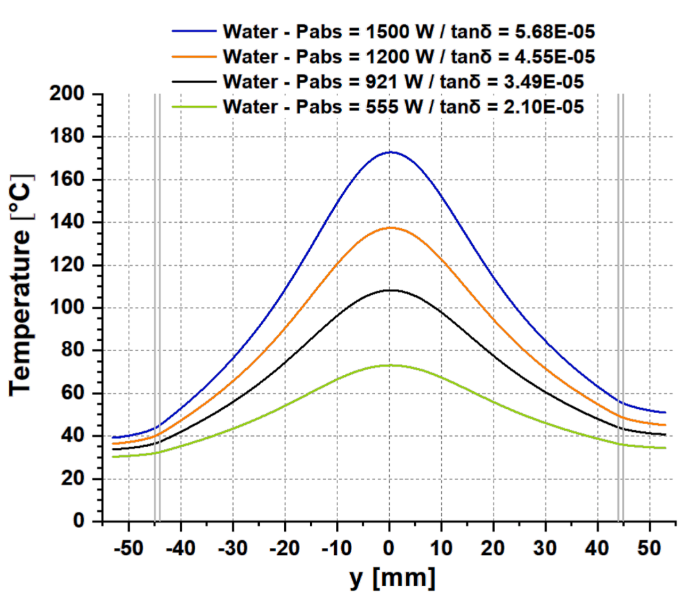

Fig. 4. Temperature profiles along the disk diameter (y-axis in Fig. 1) for different values of tanδ in the case of water-cooled window and temperature dependent material properties.

3. Structural analyses

The thermal stresses generated in the disk and cuffs by the power absorbed in the disk were checked first by structural analyses for both water- and oil-cooled window, considering the case of 1.2 kW. An additional analysis was then run to check the stresses in the case of water-cooling at 1.5 kW absorption. As the cuffs plastically deform at the brazing region, a plastic steady-state analysis is performed with the multilinear isotropic hardening as plasticity material model. The temperature distributions from the CFD conjugated heat transfer analyses are applied as load and the stresses are taken in terms of first principal stresses for diamond (brittle material) and equivalent von-Mises stresses for copper.

Table 4
Maximum temperatures in the disk of the water- and oil-cooled window for the different values of absorbed power in the case of temperature dependent material properties. Temperature reserve margins are shown with respect to the assumed temperature limit of 250 °C for diamond.

Absorbed power in disk [W]	Water		DC200	
	Max T in disk [°C]	Reserve margin [°C]	Max T in disk [°C]	Reserve margin [°C]
1500	172.8	77.2	278.4	–
1200	137.4	112.6	213.1	36.9
921.4	108.2	141.8	159.3	90.7
554.5	73.11	176.9	100.7	149.3

The comparison of the stress distribution between the two window cooling cases at 1.2 kW power absorption is shown in Fig. 5. First, it can be observed the non-axially distribution with greater stresses towards the outlet side of the disk (see Fig. 1 for axis orientation). For the same power absorbed by the disk, in the water case, the stresses in the disk are lower and the maximum values amount to 38–49 MPa at the interface diamond-copper. On the contrary, in the oil case, the maximum stresses in the disk are in the range 51–66 MPa. The reason lies in the more relaxed temperature distribution in the window obtained by water-cooling, with a maximum temperature of 137 °C against a value of 213 °C in the oil case (Table 4). However, in both cases, the stresses are below 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) [13].

With reference to the cuffs, it can be observed that in the water case (Fig. 5c), the maximum stresses are in the range 44–57 MPa and they are located only in the region from the interface with diamond up to a distance of ~1 mm. On the contrary, in the oil case (Fig. 5d), a region up to ~6 mm from the interface is affected by maximum stresses in the range 45–58 MPa. However, in both cases, the stresses can be safely accepted considering a minimum ultimate tensile strength of pure copper of ~170 MPa at 100 °C [8]. It can be also stated from the analyses that the plastically deformed region of the cuffs extends from the interface up to ~0.5 mm in the water case with an equivalent plastic strain lower than 0.1 %. On the contrary, in the oil case, the plastically deformed region extends up to ~2 mm from the interface with an equivalent plastic strain lower than 0.3 % for the most part. The strain is in the range 0.3–0.5 % only in a small portion of the region.

Finally, for the water-cooled window at 1.5 kW power absorption, no significant changes occur with respect to the 1.2 kW power case. The maximum stresses in the disk amount to 43–56 MPa while the stresses in the cuffs to 46–59 MPa.

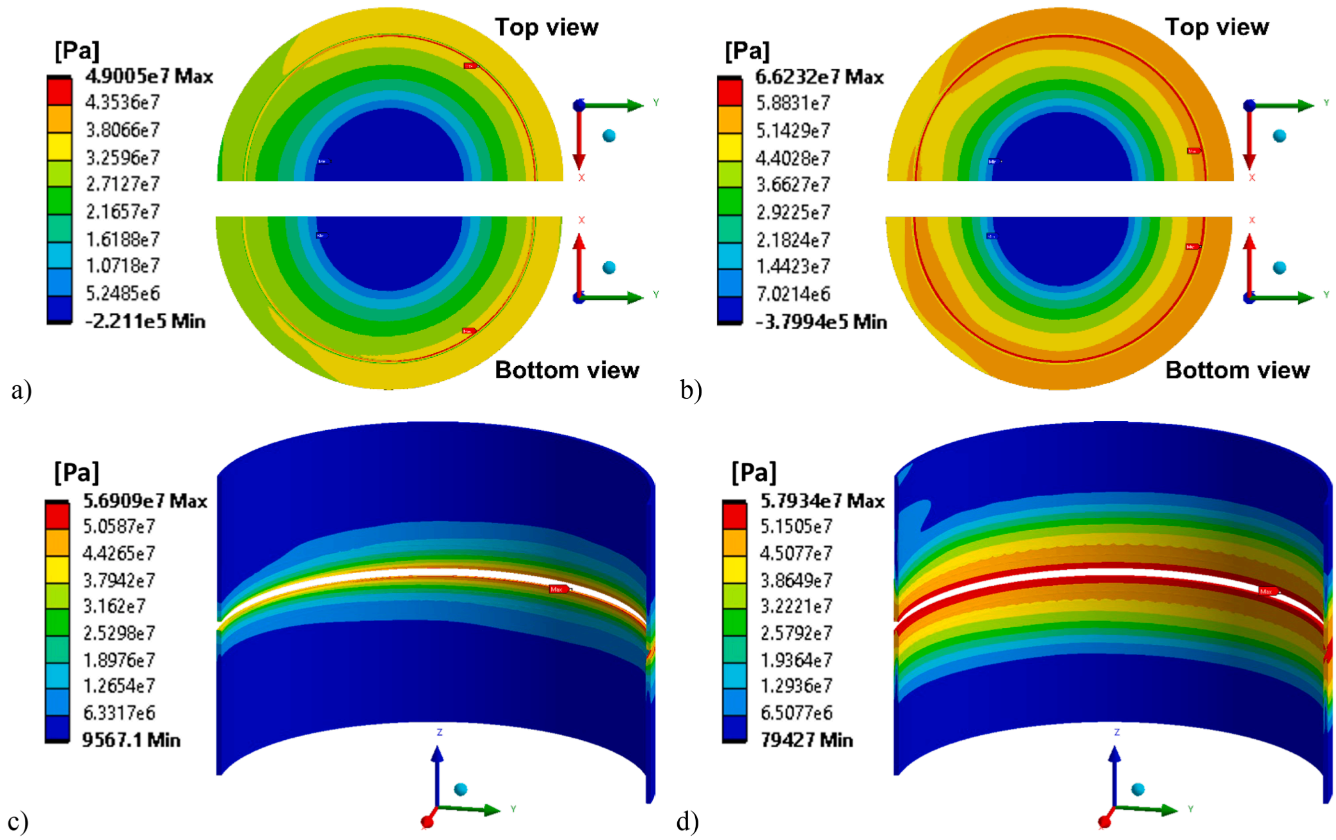

Fig. 5. First principal stress distribution in the disk of the water- (a) and oil-cooled (b) window at 1.2 kW power absorption and related equivalent von-Mises stress distribution in the cuffs of the water- (c) and oil-cooled (d) window.

4. Conclusions

The W7-X gyrotron diamond output window is investigated by CFD conjugated heat transfer and structural analyses to assess its performance if cooled by water and, alternatively, silicon oil DC200 at different values of absorbed power in the disk. With respect to previous work, temperature dependent properties for diamond and copper are used and the impact is assessed. Temperature reserve margins of the window design are calculated with respect to the variation of tanδ, with values obtained by experimental measurements. It can be concluded that up to 1.2 kW absorbed power in the disk, both water- and oil-cooled window cases work, as temperatures and stresses are lower than the limits. However, it is of fundamental importance to assure high temperature reserve margins in the window to counteract any potential factor leading to a degradation of the disk quality from the microwave transmission perspective. The water-cooling represents a much better option than oil as it leads to lower temperatures and thermal gradients, with consequent lower stresses in the window.

The oil cooling is not an option for the window at 1.5 kW absorption, being the latter a worst-case scenario. The maximum temperature in diamond goes well above the limit of 250 °C while, on the contrary, the water-cooling option leads to a temperature of 173 °C. Water-cooling provides thus significant temperature reserve margins, even at higher values of absorbed power in the disk. Temperature dependent properties shall be used to obtain a real picture of the window performance as, at these power levels, the disk achieves temperature values for which, the degradation of the thermal conductivity in diamond becomes significant. Otherwise, especially for absorbed powers in the disk of about 1 kW and above, maximum temperatures in the window would be strongly underestimated.

CRediT authorship contribution statement

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

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Gaetano Aiello reports financial support was provided by EUROfusion Consortium. If there are other authors, they 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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