Thermal Analyses of the W7-X Plasma Vessel for Operation Phase 2

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The W7-X plasma vessel (PV) is part of the cryostat wall and forms a vacuum and thermal barrier between the hot vessel interior and the superconducting coils. The vessel is thermally loaded from the inside and is actively cooled by numerous cooling water pipes in order to control its temperature.

However, due to the complex geometry and large number of different types of ports, the cooling pipes are distributed irregularly with varying distances in between them. So the temperature distribution of the PV becomes quite inhomogeneous even with homogeneous load density, and impermissible temperature hot spots >130 °C may arise. Particularly for the upcoming long pulse operation phase 2 (OP2), it is necessary to know the locally allowed thermal loads on the PV. Therefore, temperature distribution maps for different heat loads from 1 kW/m^2 to 12 kW/m^2 were calculated in order to determine the corresponding hot spots.

The available CAD geometry was not convenient for this extensive and complex analysis; therefore, a simplified shell-beam model was employed to get an approximate temperature distribution, and a correction formula was derived to calculate more accurate values at the positions of interest.

In some areas with large distances between cooling pipes, additional copper stripes are welded onto the PV to improve the heat transfer. For these regions local models were built to calculate the temperature distributions, and, in the course of this analysis, to judge the effect of the copper stripes.

The calculation results indicate positions to be additionally protected and will be used to determine safe operation limits.

Keywords: *Stellarator, Wendelstein 7-X, plasma vessel, heat load, thermal analysis*

1. Introduction

First plasma operation of the stellarator Wendelstein 7-X (W7-X) started at the end of 2015. During the two-year-long operation phase 1 (OP1), short pulses were carried out with an energy limit of 200 MJ. In the upcoming OP2, the pulse length shall reach 30 min and the total energy 18 GJ [1]. The W7-X plasma vessel (PV) is part of the cryostat wall and forms a vacuum and thermal barrier between the hot vessel interior and the superconducting coils, the latter are protected against thermal radiation by a cryogenic shield and multilayer insulation. This insulation system consequently covers also the outside of the PV. The vessel is loaded from the inside mainly from thermal and ECRH stray radiation, some conduction from the backside of the in-vessel components, and remaining plasma radiation from gaps between the latter. The PV is actively cooled by numerous cooling water pipes (Fig. 1) in order to control its temperature. For the long pulse OP2 it is necessary to know the locally allowed thermal loads on the PV and consequently also on the cryostat thermal insulation. Therefore, a numerical analysis was performed in order to determine the allowed local internal heat loads considering the varying distances between the cooling pipes.

Fig. 1. A plasma vessel (PV) section

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2. Hot spot calculation

The PV has a helically twisted shell geometry with mean major and minor torus diameters of 12 m and 8 m, respectively, and a wall thickness of 17 mm [2]. Due to this shape with its convexes and concaves, and the numerous port openings (in total 299), the cooling pipes are distributed irregularly. Because of this and the low thermal conductivity stainless steel (1.4429 equivalent to 316LN) wall material, hot spots over 130 °C may arise which are not permissible regarding the heat load on the cryogenic thermal insulation.

The W7-X PV design was performed some 20 years ago, iteratively with many corrections, using a CAD system which is outdated by now. The PV model was then transferred to the currently used CAD system. The pipes on the vessel were introduced later into this CAD model mainly by scanning and reverse engineering. The surface of this model contains, e.g., numerous small facets rather than a continuous smooth area, and the cooling pipes are broken into a great number of separated segments. It was thus not possible to perform a straightforward analysis in ANSYS [3].

Therefore, a shell-beam model was built in ANSYS (Fig. 2), in which the PV body is represented by shells, and the cooling pipes by beams; the model contains 2.6 million nodes.

Fig. 2. The shell-beam model of the PV

In reality, the cooling pipes are welded to the PV body, but in the analysis model there is a gap due to the CAD model simplification (Fig. 3). Therefore, a simplified method is used to apply the cooling boundary condition: The cooling pipes are projected to the PV body surface, and the cooling water temperature of 50 °C is assigned to the projection nodes. On the plasma side of the PV, a uniform heat flux ranging from 1 kW/m^2 to 12 kW/m^2 is applied which covers the possible operation scenarios. Fig. 4 demonstrates the way of applying the boundary conditions.

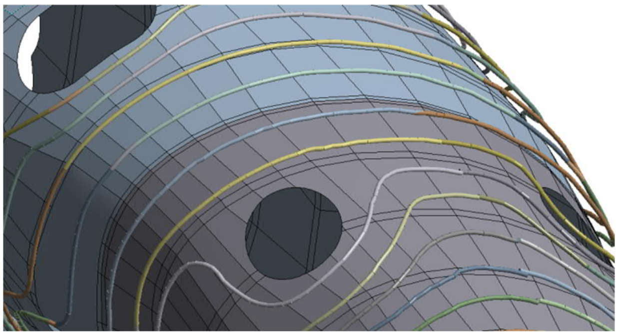

Fig. 3. Gap between the PV body and the cooling pipes

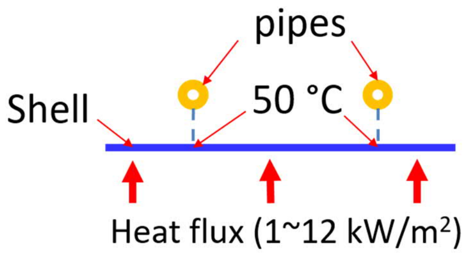

Fig. 4. Boundary conditions in the shell-beam model

Fig. 5 and Fig. 6 shows the temperature contours under 1 kW/m^2 and 12 kW/m^2, the hot area in which the temperature exceeds the 130 °C limit is marked in purple. When the heat load increases, the hot area grows larger. In Table. 1, the maximum calculated temperatures under different heat loads are summarized. From such temperature contours, the critical heat load at different locations can be inferred as a reference for the operation.

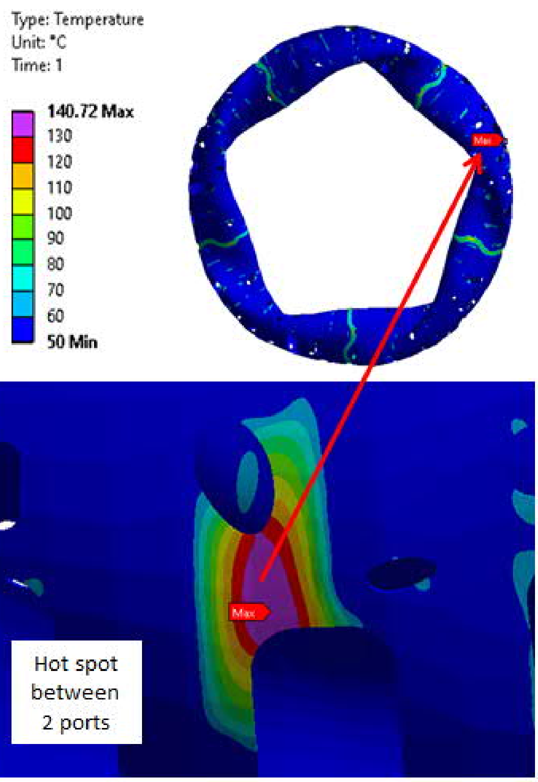

Fig. 5. Temperature contours under 1 kW/m^2, hot area > 130 °C is marked in purple

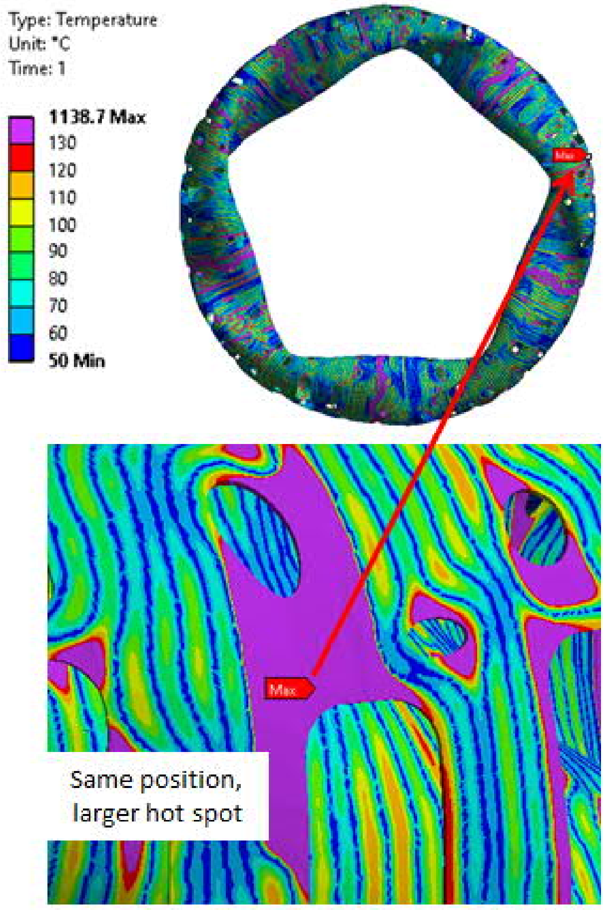

Fig. 6. Temperature contours under 12 kW/m^2 , hot area > 130 °C is marked in purple

Table. 1 Maximum temperatures under different heat loads

Head load (kW/m2)	**1**	**2**	**4.5**	**7**	**9.5**	**12**
Maximum temperature (°C)	141	232	458	685	912	1139

However, the shell model doesn't include all relevant issues, as there are:

1) The water temperature gradient between the inlet and outlet, and 50 °C is chosen to represent the average temperature.

2) The convection and weld heat transfer resistance are ignored, because the forced turbulent convection heat transfer is strong, and the weld size is small.

3) The radiation cooling to the surrounding components, this is excluded to be conservative.

In spite of these simplifications, the results are accurate enough for the intended purpose.

Since the pipes are attached on the outer (cryostat side) of the PV, the maximum temperature appears in the middle between two cooling pipes on the inner heated surface (Fig. 7). In the shell model, the temperature is uniform throughout the thickness, only the heat transfer resistance within the shell plane is considered. The difference between the shell model and the reality leads to an underestimation of the high temperature at the outer PV side (which is relevant for the heat load on the cryogenic thermal insulation).

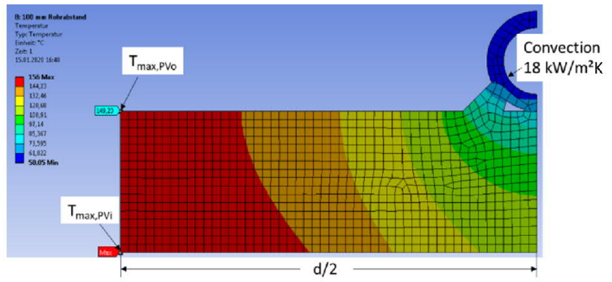

Fig. 7. Maximum temperatures at the center between two parallel cooling pipes (d = pipe distance; *PVi*, *PVo* = PV inside and outside, resp.) for 12 kW/m² heat load and d=100 mm.

To correct the shell model, an approximate formula was derived by fitting the temperature differences $T_{max,PVo}$ calculated with a parametric model according to Fig. 6, and the corresponding shell element model temperature, $T_{shell,max}$, which is simply be calculated by a 1D formula Eq (1)

$$\Delta T = \frac{p \cdot d^2}{8\lambda \cdot t}. \tag{1}$$

ΔT is the temperature difference between the projected cooling pipe temperatures (Fig. 4) and the max. shell temperature (T_{max_shell}) in °C; p the heat load in kW/m^2; d the pitch between 2 parallel cooling pipe centerlines in mm; λ the thermal conductivity, 15 W/(m·K); and t the wall thickness in mm.

The difference $T_{max,PVo}$ - $T_{shell,max}$ can be well fitted by a ruled surface with a standard deviation of the T-residuals of only 0.18 K (Fig. 8).

This fit leads to the formula for the corrected maximum temperature at the relevant PV outside

$$T_{max,\mathrm{PVo}} = T_{shell,\max} + \alpha \times p \times d \tag{2}$$

α=0.0337 K·m/W, p and d have the same units as in Eq (1).

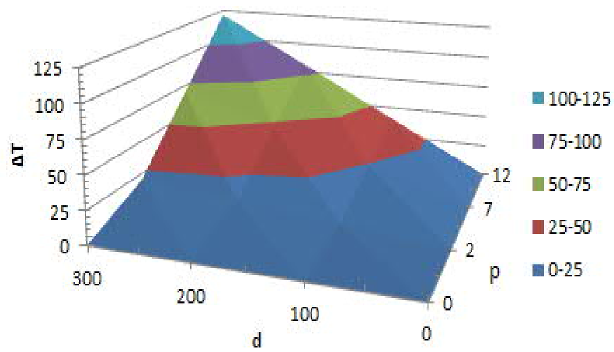

Fig. 8. Fit of $T_{max,PVo}$ - $T_{shell,max}$ for d = 100, 200, 300 mm and p = 2, 7, 12 kW/m².

The complete hot spot calculation procedure is:

1) Use the temperature contour from the PV shell model corresponding to a certain heat load p to locate the point of interest;

2) Measure the distance between the neighboring cooling pipes;

3) Calculate the corrected temperature $T_{max,PVo}$ in the middle between the pipes using the shell result $T_{shell,max}$ from the temperature contour.

4) In case of a critical hot spot, consider also the real water temperature of the PV cooling pipes in this area.

3. Cu stripe reinforcement

In order to reduce the worst temperature hot spots at positions between cooling pipes which are far apart from each other, Cu stripes were welded onto the PV outer surface to increase the local heat conduction.

In Fig. 9, a typical hot spot without Cu stripe is demonstrated on the left which is located at the center of a narrow uncooled area between two port holes, far away from the cooling pipes on both sides. On the right of this figure, the attached 2 mm thick Cu stripe is shown. There are in total five hot spots reinforced in this way. In this paper, the half-module #10 is introduced as a representative.

A local solid model was built to investigate the Cu stripe effect. In contrary to the simplified shell model, it includes heat transfer in all directions and supports more complicated boundary conditions. The high calculation cost of a solid model (~500 k nodes for each model) is not a problem for the small size local model.

Since the PV in that regions has large radii of curvature, the local model can be simplified to a planar geometry. The cooling pipes and the welds are explicitly modeled. The boundary of the local model is set away from the hot spot in order to eliminate the border influence.

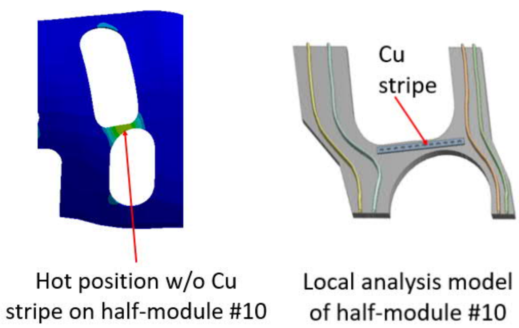

Fig. 9. Cu stripe reinforcement at hot spots

The heat load is applied on the local model in the same way as on the shell model, while the cooling boundary condition is a convection boundary instead of temperature in the shell model; this is more realistic and conservative. The convection heat transfer coefficient is 18 kW/m^2_K, and the bulk water temperature is 50 °C (Fig. 10).

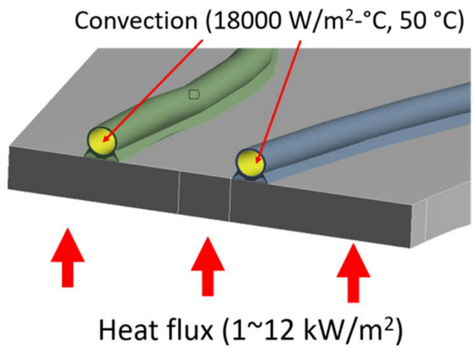

Fig. 10. Boundary conditions in the local model

There are two analyses for each position, one without the Cu stripe and the other with. The comparison indicates the effect of the reinforcement.

Fig. 11 shows the temperature contour comparison of half-module #10 under 1 kW/m^2. The maximum temperature without the Cu stripe is 118 °C, and 98 °C with the Cu stripe.

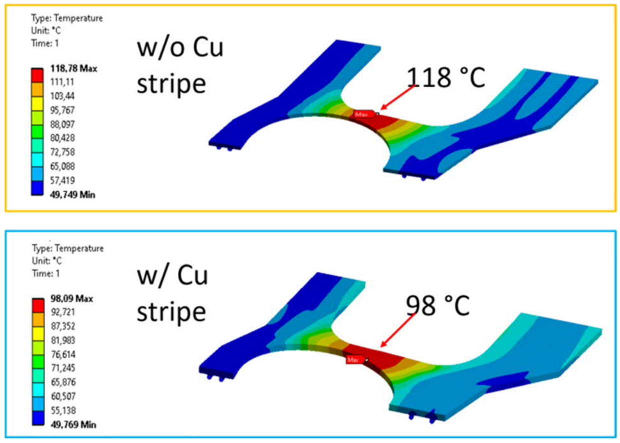

Fig. 11. Temperature contour of the half-module #10 model with/without the Cu stripe under 1 kW/m^2

This difference is naturally getting larger under higher heat loads. Fig. 12 lists the comparison for half-module #10 under different parametric heat fluxes. It can be seen that the maximal temperature decreases after applying the Cu stripes. Thus the reinforcements have some positive effect, and the operation space is correspondingly enlarged.

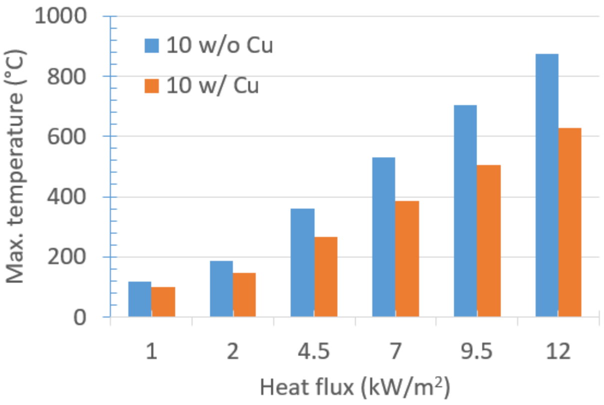

Fig. 12. Temperature comparison of the half-module #10 model without (blue) /with (orange) the Cu stripe

4. Conclusions

During the upcoming W7-X long pulse operation phase 2 the plasma will be operated with much more energy than in OP1, and it is necessary to determine the allowable local heat loads onto the PV to ensure safe operation of the machine.

The first step is to find out possible hot spots. A simplified shell model of the PV was analyzed under uniform heat loads ranging from 1 kW/m^2 to 12 kW/m^2, and the regions with temperatures above the allowed 130 °C can be located. However, the temperature from the shell model is not conservative because of the negligence of the temperature gradient through the PV wall thickness. Therefore, a correction formula was provided to close this gap for realistic maximum temperature estimates at any point and determination of allowable heat loads.

In some poorly cooled positions between large adjacent ports, Cu stripes were welded onto the PV to reduce temperatures of these hot spots. Comparative analyses were performed to assess the efficiency of this measure. It could be shown that some temperature reduction is achieved this way, however, these regions remain still critical and can be loaded only moderately with < 2 kW/m^2.

References

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