Thermal loading test of a Wendelstein 7-X pumping gap panel

J. Boscary[1], F. Schauer[1], B.-E. Ghidersa[2], R. Krüßmann[2], M. Lux[2], M. Czerwinski[3], Z. Wang[1], C. Li[1], B. Mendelevitch[1], G. Ehrke[3], and the W7-X Team[4]

[1] Max-Planck-Institut für Plasmaphysik (IPP), Garching, Germany
[2] Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany
[3] Max-Planck-Institut für Plasmaphysik (IPP), Greifswald, Germany
[4] T. Klinger et al., Nucl. Fusion 59 (2019) 112004 doi: 10.1088/1741-4326/ab03a7

Abstract

For the upcoming long pulse operation phase 2 "OP2" of Wendelstein 7-X (W7-X), new water cooled non planar stainless steel panels have been manufactured to protect the wall of the plasma vessel behind the divertor pumping gap. Such a panel is made of a machined ground plate with channels which are covered by likewise machined sheets. The latter are electron-beam welded to the ground plates. There are 60 panels of 7 different types which are designed to remove a stationary heat flux of up to 100 kW/m². The specified water cooling conditions are: 2.5 MPa inlet pressure, 30°C inlet temperature, and 0.27 ℓ/s flow rate. A panel prototype has been manufactured to validate the design and manufacturing process. In order to verify the thermo-hydraulic calculations performed with ANSYS® CFX, a thermal loading test on the prototype was carried out in the SIRHEX test facility at KIT. The loaded surface of the prototype (about 0.11 m²) was black-finished, and thermocouples were installed at different positions. The prototype was placed in the vacuum tank and heated by an array of six infrared lamps (400 V, max. 16 kW per lamp). The deposited load of up to about 100 kW/m² was measured by calorimetry. The paper describes the loading experiment of the panel, and its results. A good agreement was found between calculations and test results, and thus the thermo-hydraulic panel design was well validated.

Keywords: Wendelstein 7-X, plasma facing component, panel

---

1. Introduction

The stellarator Wendelstein 7-X (W7-X) will start steady state operation with pulse length up to 1800 s., and continuous plasma heating with up to 10 MW electron cyclotron resonance heating (ECRH) in 2022. This phase with the full set of actively cooled plasma facing components (PFCs) [1, 2] is defined as operation phase 2 (OP2). The PFCs are: the divertor system (divertor target [3], baffle [4], divertor closures in the poloidal and toroidal directions) which have a total surface area of about 45 m² and the wall protection [4, 5]] with a total surface area of about 220 m². Pipes with a total length of about 3.5 km with water supply from 80 ports have been installed in the plasma vessel. The W7-X divertor has an open structure: A pumping gap between the vertical and horizontal divertor plates allows operation of cryo vacuum pumps which are placed under the horizontal target plates. The wall of the plasma vessel behind the pumping gap needs to be protected against radiative heat loads. Considering the location well away from the plasma, and expected stationary local heat fluxes in the range of 100 kW/m², the selected solution was to use actively water cooled panels made of stainless steel. In this area, no convective loads are expected. A first set of pumping gap panels was already installed for the first short pulse operation phase (OP1) [5]. This first set was produced before the completion of the design of the water cooled divertor. Due to lack of available space and a significant number of collisions, they had to be replaced by a new set of pumping gap panels. The technology developed for the first set of panels was not applicable any more because of the lower radius required for the new geometry. The arrangement of the panels had to be changed. In the previous design the panels were positioned side by side, and in the new design an overlap between neighbouring panels, which share the connection system with the wall of the plasma vessel, was introduced. This change was required to take into account the more restricted available space, and also to allow sufficient space and access for assembly in the plasma vessel . Therefore, a new technology was required. The results of the thermal loading test campaign of a full scale prototype of a new pumping gap panel to validate the design and manufacturing process are presented, and compared to FE (Finite Element) simulations.

2. Prototype design and fabrication

Fig. 1 shows the CAD design of a set of pumping gap panels installed in the plasma vessel from the back side. A set of panels of one unit has a surface of about 1.1 m²: 1.87 m long (toroidal direction) and 0.58 m wide. The panels are hydraulically connected in series. The gap between neighboring panels is 4mm. The panels are made of 316L stainless steel and their shape is not planar. The cobalt content of the material is specified < 500 ppm and the relative magnetic permeability < 1.01 (< 1.05 for the weld seams).

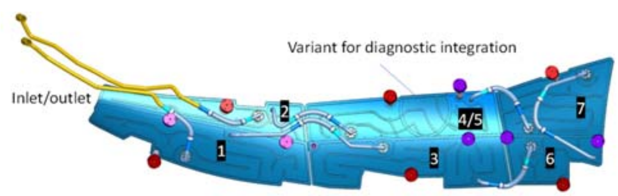

Fig. 1: Set of pumping gap panels. Mounting attachment system to the plasma vessel and hydraulic connection circuit are shown

The basic geometry is a conical surface made of two cones of different radii with coaxial axes (see Table 1). There are 60 panels (6 panels for each of the ten divertor units) and 7 types. The surfaces of the different panel types are shown in Table 1.

Table 1: Types of pumping gap panels

Type	1v	1h	2v1	2v2	2h	3v	3h
Surface [m²]	0,103	0,055	0,136	0,114*	0,12	0,095	0,13
Radii [mm]	540/ 250	470/ 260	490/ 320	490/ 320	500/ 330	470/ 85	500/ 100

*One variant was required in three divertor units for diagnostic port integration.

A panel is made of a machined ground plate with channels which are covered by likewise machined sheets (Fig. 2). The contour of the ground plate was firstly machined on both side up to 4 mm additional size with respect to the CAD model to check and correct a possible shape deformation. The cooling channel was machined according to the CAD model.

The latter are electron-beam welded to the ground plates positioned on dedicated jigs (clamped on supporting steel plates) to minimize deformation (Fig.3). After welding, a heat treatment in an oven at 490°C was performed to relieve residual strain in the welds. Afterwards, the plasma facing side of the panel was machined to reach the final specified surface geometry, and was finally straightened by using dedicated jigs to its final dimension.

Fig. 2: Machined ground plate and machined sheets for the type 1h before welding) (Courtesey of Z-Innovation GmbH)

After final geometric measurements, for one panel of each type the following tests were carried out at the site of the manufacturer: air pressure test at 4 MPa, cycling pressure test (between 1 and 2.5 MPa) for 200 cycles, pressure drop measurement, CT-scan (Computer Tomography) of all weld seams, measurement of the magnetic permeability of the plate and weld seams.

The delivered panels were scanned, and a CAD model using the best fit method was built to be compared with the specified CAD model. Not only the surface but also the position of the flanges (inlet and outlet) as well of the holes for mounting on the plasma vessel were checked.

The production of the panels was awarded to the company Z-Innovation GmbH, Germany. electron beam welding was performed under vacuum conditions by the company PTR Strahltechnik GmbH, Germany.

Fig. 3: Panels after electron beam welding of the likewise machined sheets to the ground plate. View from the back side of type 2v2 (prototype geometry) (Courtesy of Z-Innovation GmbH).

The maximal thickness of the ground plate is 12 mm. The depth of the cooling channel is 5 mm, and the width in the range 18-22 mm. The design of the cooling channel in the panels (parallel or serial) was optimized to reduce the total pressure drop. Reinforcing cylinders (Ø 8 mm) were inserted at different locations to increase strength and to get a more homogeneous flow distribution.

The type of panel selected for the prototype was the variant for the diagnostic port integration. Its surface is about 0.11m². The He tightness of the panel was tested at the site of the manufacturer at 4 MPa and tested between 1 and 2.5 MPa for 2000 cycles (frequency = 0.1Hz, 5s.)

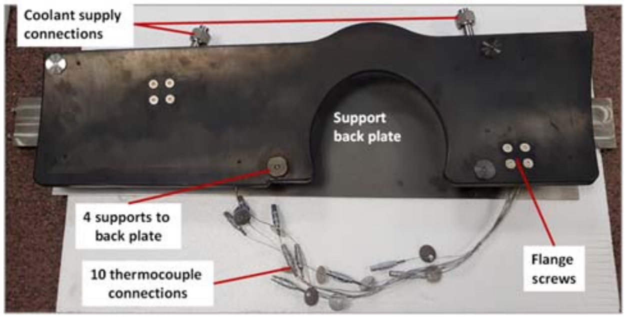

Fig. 4: Full scale panel prototype – View of the directly thermal loaded surface

The panel was prepared in the Integrated Technical Centre of IPP Garching before delivery to KIT. Fig. 4 shows the black finished surface of the panels to face the heating system. Ten thermocouples (type K) were brazed on the back side to measure the temperature evolutions at different positions (Fig. 7). Each panel has two CF-flanges for the water cooling connection. The flanges are located on the back side, its screws are also visible at the front surface. Before delivery to KIT, the following inspections were carried out at IPP Garching: visual inspection, pressure drop measurement, integral He leak testing in an oven (4 MPa at RT followed by 2.8 MPa at 160°C (5 min.). The specified water cooling conditions are: 2.5 MPa inlet pressure, 30°C inlet temperature, and 0.27 ℓ/s flow rate. Due to its curved surface, the panel was delivered already mounted on a support back plate made of stainless steel to ease the installation and positioning in the test facility. This attachment allowed to accommodate the thermal deformation of the panels during the loading test.

3. Test facility

Fig. 5 shows the open vacuum tank, 1.8 m diameter, of the SIRHEX (Surface Infrared Radiation Heating Experiment) test facility at KIT [6].

Fig. 5: Opened vacuum tank of the SIRHEX facility at KIT

The panel prototype was installed inside the frame as shown in Fig. 6. The heating system was positioned on the upper part of the frame. The walls of the frame are made of aluminium and are water cooled to protect the environment against thermal radiation. The heating system is made of an array of six infrared lamps (400 V, max. 16 kW per lamp), manufactured by the company Heraeus Noblelight GmbH. The total length of a lamp is 910 mm and the heated length of the tungsten filament is 710 mm. The lamps are closely positioned side by side and installed at a small distance to the surface of the panel to generate a homogeneous heat distribution on the whole surface. The quartz glass of the lamp facing away from the heated surface is coated to reflect back radiation.

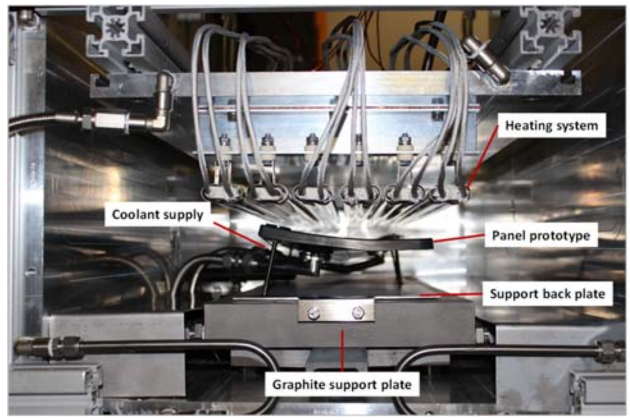

Fig. 6: Opened vacuum tank of the SIRHEX facility at KIT

3. Thermal loading tests

During the tests the pressure in the vacuum tank was about 1.4 Pa. The coolant was a mixture of 44-Vol-% Antifrogen® N (mono-ethylene glycol with a corrosion inhibitor) and water with a boiling point of 108°C at 0.1 MPa. During the tests the coolant pressure was maintained at about 0.35 MPa to avoid boiling. The different investigated cooling and heating conditions are summarized in Table 2. T_{in} and T_{out} are the inlet and outlet temperatures of the coolant, respectively.

Table 2: summary of testing conditions

Cases	Flow rate [kg/s]	T_{in} [°C]	T_{out} [°C]	Heat flux [kW/m²]
Case 1	0.26	18.2	29.4	105.2
Case 2	0.137	20.6	41.5	103.2

The measurement of inlet and outlet conditions allowed the calculation of the deposited power on the panel prototype by calorimetry. In spite of the black finishing of the heated surface, about 50% of the delivered power was reflected. Test duration allowed stationary conditions to be reached. Data acquisition frequency was 0.1 Hz.

4. Analysis of the thermal loading tests

The static CFD (Computational Fluid Dynamics) analysis was performed with CFX 2019R2 (part of ANSYS® 2019R2).

The model was meshed with 5 mm element size and had 538840 nodes and 2919080 elements. No boundary layer mesh was applied. The turbulence was modelled with K-Omega SST equations with automatic wall functions which is suitable for both coarse and dense near-wall meshes.

The global temperature distributions of the panel for the two cases defined in Table 3 are shown in Figs. 7 and Fig. 8, respectively. The theoretical positions of the thermocouples on the back side of the prototype are shown in Fig. 6 (red points), as well as inlet and outlet of the coolant. The thermocouples were positioned to provide indications at different locations with the worst cooling conditions: at the contour of the holes for the attachment system to the plasma vessel, (#2, 4, 6, 10), at other edges, (#1, 5, 7, 9), and in the largest regions inbetween the channels (#3, 8). During the tests, the measured temperatures of the different thermocouples were stable, and no thermocouple was damaged. The thermal equilibrium of the panel was achieved.

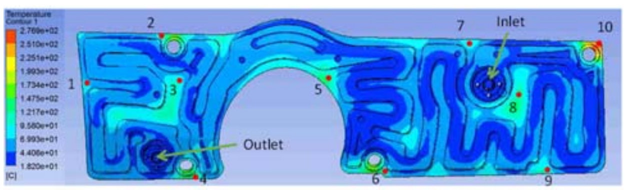

Fig. 7: Global temperature distribution, case 1

Table 3: Thermocouple (TC) measurements (M) and calculations (C) for case 1

TC	1	2	3	4	5	6	7	8	9	10
M	61	110	85	134	142	89	96	104	98	250
C	70	120	95	140	130	90	90	110	95	250

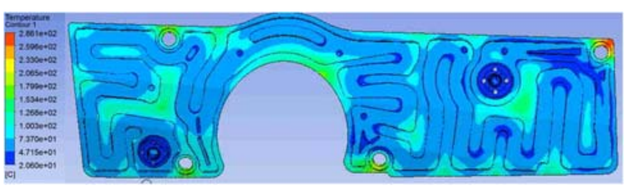
Fig. 8: Global temperature distribution, case 2

Table 4: Thermocouple (TC) measurements (M) and calculations (C) for case 2

TC	1	2	3	4	5	6	7	8	9	10
M	75	126	100	152	159	103	108	115	108	255
C	85	130	110	150	155	100	110	125	110	260

Tables 3 and 4 show a good agreement between the measured and calculated values of the thermocouples. Thus, the design of the cooling channels is validated. Figs. 6 and 7 confirm a quite homogeneous temperature distribution for the two cases. Part of the panel edges and the contour of the attachment holes reached higher temperatures. These poorly cooled small areas are acceptable for operation with no effect on the panel behaviour and function.

The exact comparison between measured and calculated temperatures of the thermocouples is tricky because the measurement point cannot be exactly defined. Since the TC covers a region rather than a point, it indicates more an average temperature of the brazed contact. This is illustrated by Fig. 9 which is representative for all thermocouples. The calculated value of 70°C for the thermocouple 1 in case 1 given in Table 3 is averaged considering the small measurement surface of the brazed area.

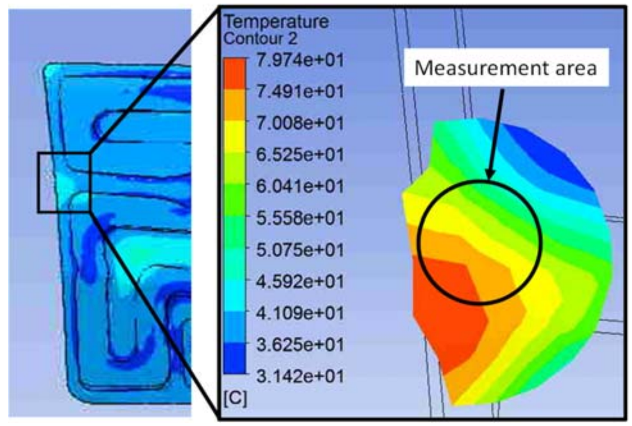

Fig. 9: Definition of thermocouple position for TC 1 in case 1 (left side of Fig. 5)

However, this accuracy is in the same order as the simulation results, and has been considered sufficient for the purpose of these tests to demonstrate that for the selected locations water cooling is sufficient.

After testing, the panels were inspected. The visual inspection did not detect any damages (area of weld seams), and the prototype successfully passed He leak testing in oven. No deformation of the panel was noticed.

5. Conclusion

A full-scale prototype of the new pumping gap panel of W7-X has been successfully tested in the SIRHEX facility at KIT. A good agreement between ANSYS® CFD simulations and measurements of the thermocouples located at different positions on the back surface of the panel has been found. The panel prototype performed as expected under 100 kW/m² stationary load, and cooling conditions similar to operation. The design of the cooling channels allows a quite homogeneous surface temperature distribution, and sufficient cooling at the edges. The results of the thermal loading test validate the design and manufacturing process of the pumping gap panels for the next operation phase OP2 of W7-X.

Acknowledgements

The authors would like to thank the Integrated Technical Centre of IPP-Garching for the preparation of the panel prototype, and the team of KIT for the installation and support of the loading tests.

References

[1] J. Boscary et al. 2011 *Fus. Eng. Design* **86** 572
[2] B. Mendelevitch et al. 2011 *Fus. Eng. Design* **86** 1669-1672
[3] J. Boscary et al. 2021 *Fus. Eng. Design* 166 (112293)
[4] B. Mendelevitch et al. 2013 *Fus. Eng. Design* **88** 1660-1663
[5] A. Peacock et al. 2011 *Fus. Eng. Design* **86** 1706
[6] A. Kunze et al., 2015 *Fus. Eng. Design* **98-99** 1345