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111Equation Chapter 1 Section 1 Numerical design approval of W7-X port liners

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Abstract

The world's largest operating stellarator, Wendelstein 7-X (W7-X) is operating since 2015. One of its final goals is the demonstration of steady-state operation capabilities with pulse-lengths of up to 30 minutes. Such pulses require a constant heating of the plasma due to losses by plasma-wall interactions, particle drift and radiation. The latter are assumed to occur with resulting loads of up to 10 MW in total on the surfaces of plasma-facing components (PFC) and ports. Thus, a shielding is required for the port walls, in order to avoid wall temperatures above 80 °C in average, which otherwise would cause unsustainable heat loads on the superconducting magnetic coil system of W7-X.

Furthermore, it is necessary to protect the sensitive weld seam, connecting ports and PV from direct thermal radiation. Plasma radiation would directly expose this weld, due to the gap between port and in vessel components. The paper presents the determination of the relevant heat loads, based on the 1-way ray-tracing code of S. Bozhenkov for the whole W7-X. On an exemplarily chosen port, the capability of the port-liner design to maintain the steady-state operation under the computed heat loads is demonstrated.

Keywords: Monitoring, Commissioning, Operation, Mechanical sensors

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1. Introduction

W7-X, the world's largest stellarator device, is currently in its second stage of operation with inertial cooled in-vessel components. Future operation stages, after an upgrade to actively cooled in-vessel components, focus on a significant increase of confinement time and density. However, all these goals require more heating power and longer exposure of the inner wall to radiation loads. Therefore, it is required to cover the remaining blank steel surfaces of the plasma-vessel (PV) with shielding devices not only in the major plasma chamber, but also in peripheral components, like the W7-X ports.

A port is a standard component, allowing the access from the Torus-Hall to the Plasma-Vessel, as sketched in Fig. 1. Most of the ports are circular shaped, but also more uncommon designs, like oval and rectangular shaped ports, are present. Some of them share intersected entries to the PV or split up into subsequent ports.

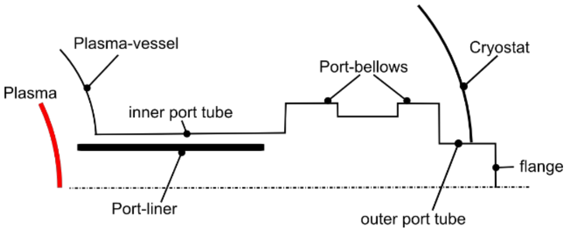

Fig. 1: Sketch of a port with port-liner

This article presents the work for the estimation of radiative heat loads on the port walls, and the subsequent application of the found radiation patterns and levels in thermomechanical and fluid-flow analyses of the port-liner and the port to specify design requirements.

2. Radiation model

The radiation load on the inner wall surfaces was computed with a ray-tracing code, written by S. Bozhenkov [1] and based on the work of T. Eich and A. Werner in 2010 [2]. The specialty of the code is that it is designed for radiation with energies above 10 *eV*, emitted by the plasma. Therefore, nearly complete absorption of the radiation power, by the first wall. This simplifies simplifies the calculations dramatically. Instead of solving the view–factor problem for radiation between surfaces, the problem reduced numerically to the computation and search of hitting points of rays onto a surface. This allows the buildup of comparably complex models with 1 million radiation sources, which leads to quiet good spatial resolutions in the radiation pattern. In our case, the radiation consists of one full module, with a spatial element resolution of approx. 2 cm within the ports. The total amount of elements for a complete module was then 3.2 million elements per module.

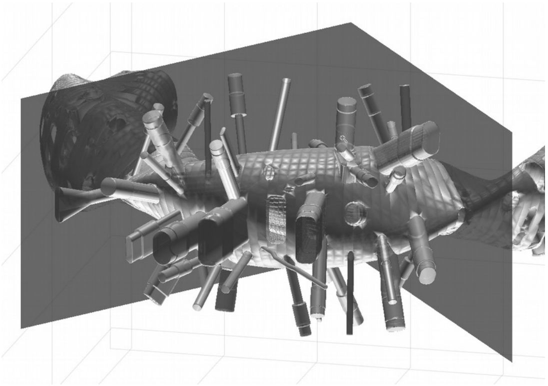

Fig. 2: 3D radiation model for 1-way ray-tracing

With respect to the desired accuracy of the port-loads within ±0.1 kW per port, the calculations were carried out with a total number of $n_s=1$ million radiation sources, each of them radiating 10 rays into randomly defined directions. The radiators itself were uniformly distributed on the x- and o-lines, as the central lines of the plasma islands and the inner-, central- and the last closed flux-surface, as the main surfaces of the plasma. as illustrated in Fig. 3. Each of these configurations characterized an independent load-case.

The total simulated radiation power is 10 MW for steady-state operation of W7-X, assuming a fully detached plasma. The power for each emitted ray in a module is then

$$q_r = \frac{P_0 \cdot (\varphi + 2 \cdot 0{,}05)}{2\pi \cdot 10 \cdot n_s}$$

,212* MERGEFORMAT (.)

with P_0 the total continuous radiation power loss, typically 10 MW and φ as the modelled angular portion of the W7-X, which was typically 72°, corresponding to one module. The extension of the angle to both neighboring half-modules until ±18° takes into account that a part of the radiation onto the components in the modelled module originates from these modules, as periodic boundary conditions are not implemented in the code yet.

The resulting heat load distribution, shown exemplarily in Error: Reference source not found for the large rectangular AEE port, allowed then the computation of the heat load received by a port. The integration was done by simply counting the hitting points per Area (A) and thus calculating the generated heat flux on the port walls

$$Q_P = \int q_r dA_P \, .$$

The maximum of all load cases was then used for subsequent calculations and analyses, like the port-liner length determination prescribed in the following section.

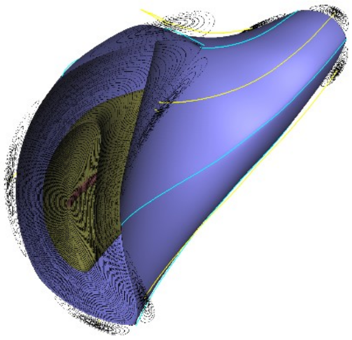

Fig. 3: Position of radiation sources. The sources are randomly distributed along o-lines (yellow-line), x-lines (blue line), the last closed flux surfaces (blue surface), the central flux surface (red) and a middle flux-surface (yellow surface). Image: S. Bozehenkov, IPP Greifswald

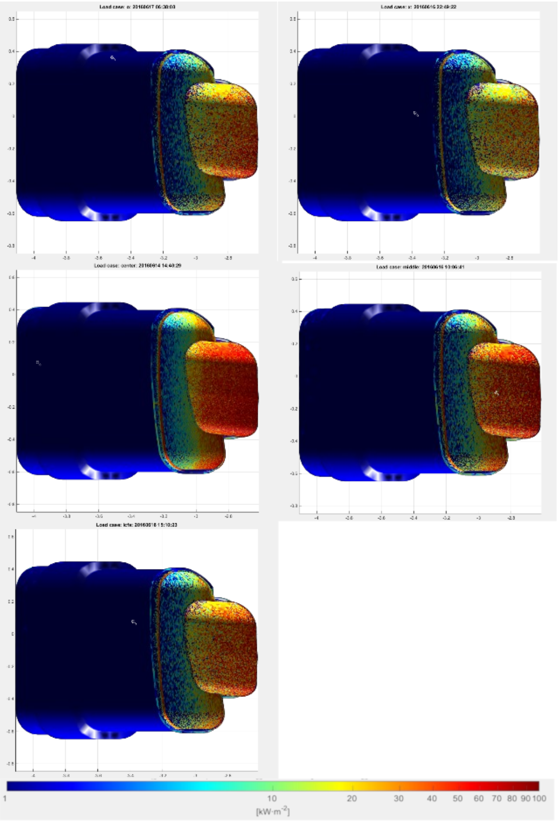

Fig. 4: Computed heat load distribution on an AEA port. The power densities for the named radiation scenarios (*from left to right and top to bottom*: o-lines, x-lines, central-, middle and last closed flux surface) are illustrated on a logarithmic scale.

3. Port-liner length estimation

The cumulative heat load, determined by the ray-tracing calculation, was used to estimate the required port-liner length. It has been the major input for the analytical calculation of the least required port-liner length, assuring the design criterion, that the perpendicular port wall heat flux must not exceed 2 kW·m^{-2}. The liner length was calculated by solving equation 1.2 [1]

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$$q_{wall}(l)=\frac{q_0}{2}\cdot\left(\frac{z^2+2}{\sqrt{z^2+4}}-z\right)+q_{ECRH,P}$$

with $z = l/r$ the dimensionless ratio between port-length and radius, q_0 the power density at the port entrance and $q_{ECRH,P}$ the constant background electron-cyclotron-stray-radiation (ECRH). The above given equation was solved with help of Matlab®'s symbolic toolbox capabilities, because the resulting solution expression is quiet unhandy. The calculated port-liner length gives a save estimate, as it does not take into account asymmetries in the radiation pattern. The asymmetry caused by the port its inclination, would usually lead to shorter port-liner lengths as estimated here, because the heat flux is more concentrated on the port-liner tip.

The resulting port-liner lengths vary strongly from 0,3 m for small ports until 1,6 m for large rectangular shaped ports. However, for the vast majority of the ports, the required lengths could be slashed significantly from the previously designed value of approximately 1 m, which is coincident to the average length of the inner port tube.

4. Port-liner fluid flow analyses

For the then proposed port-liner designs, thermal-hydraulic simulations were carried out, to obtain reliable data for the effective wall heat transfer coefficients, achievable by the design and for the fluid temperature. The calculations were carried out with the commercial ANSYS-CFX® package.

In order to do so, the radiation loads were transferred by interpolation of the calculated wall heat fluxes on the mesh surface of the port-liner. No ECRH-stray radiation was taken into account here, as it remains negligible compared with the direct plasma radiation loads. Fig. 5. shows coolant temperature within the channel for the first port-liner design proposal. The water temperature in the port-liner remains wit 67°C well below the allowed 80 °C.

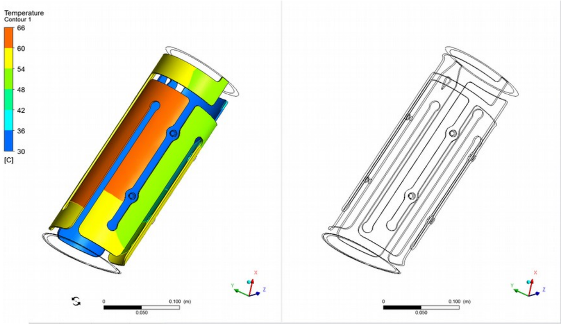

Fig. 5: Temperature distribution of the coolant (left) and geometry of the single cooling channel design (right) for a typical cylindrical port. Here: AEZ port.

The, with this model, numerically obtained average wall heat transfer coefficient α_w for such kind of channel design is about 14 kW·m^{-2}K^{-1}. This value was used for subsequent thermomechanical analyses of other port-liners as a proxy for the heat removal capacity of the design.

5. Port-liner thermal analyses

For selected ports, the above obtained wall-heat-flux patterns and the wall-heat transfer coefficients were used to calculate the thermal field within the assembly. This was done in a multiphysics simulation with the common FE-code ANSYS®. The thermal/meachnical models consisted of Solid70 elements solely and the properties of thin layer parts like ports were smeared.

In addition to the radiative heat loads, the ECRH stray radiation load was applied to all internal port surfaces, as it becomes more prominent and important the deeper the location in the port is. The average ECRH-stray radiation load was comparably sketchy taken into account by energy balance considerations. Since the distribution of the ECRH-stray-radiation is fairly uniform in the port volume. This is caused by the high reflectivity of metal surfaces for waves at 140 GHz frequency, which results in an absorption that is typically in the range of 1…3% only [5]. Thus, the ECRH load seen by a surface in a port is given by

$$q_{ECRH,p} = \frac{q_{ECRH,PV} \cdot A_E}{\sum_1^i \alpha_i A_i},$$

where $q_{ECRH,PV}$ denotes the stray-radiation density in the PV, A_E the open port entrance area and α_i describes the ECRH reflectivity of a specific surface A_i in the port, including the entrance area [6]. The ECRH-generated wall heat flux q_w on a specific surface in the port can then be determined by

$$q_w = q_{ECRH,P}\,\alpha_i\,.$$

The outside temperature of the ports, connected to the cryostat, was set to 22°C while the connection to the plasma vessel has been fixed at 80°C, which is the design value for the PV.

The calculations revealed that this design proposal for the port-liner, coming with only one meander cooling channel, was not sufficient. Because of its length, the water gets warm and the highest water temperature arises not at the tip, but at the end of the port-liner, as shown in Fig. 6. Hot spots in between the meandering cooling channel became also an issue, especially for larger ports and finally the feasibility and production costs set an end to this type of design.

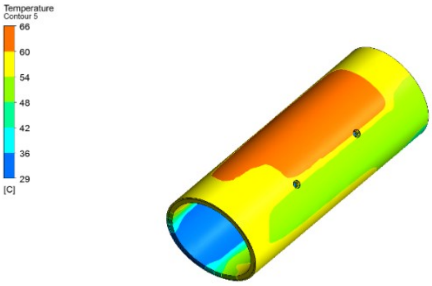

Fig. 6: Temperature of the AEZ31 port-liner

Therefore a new design approach, proposed by NTG, Neue Technologien GmbH & Co. KG, the final manufacturing company, was chosen. It splitted the port-liner into several pipes, each feeding cold water to its tips. Fig. 7 illustrates the new design. The temperature is very effectively kept below 80°C, right from the beginning. Only the metal sheets at the tip, required for closure of the gap between the first wall and the port-liner, will be notably heated up to 270 °C during steady-state operation. However, this is not of concern as the temperature limit is above 300 °C for these parts. The liner itself stays well below 80 °C, even at its highly loaded tips.

6. Conclusions

The article presents a typical work flow for he analyses of port liners of modern fusion devices. the accurate estimation of plasma radiation heat loads, as described, allows the reduction of requirements for the port liner length considerably. As a result, the W7-X port liner cost and manufacturing and installation efforts are significantly reduced.

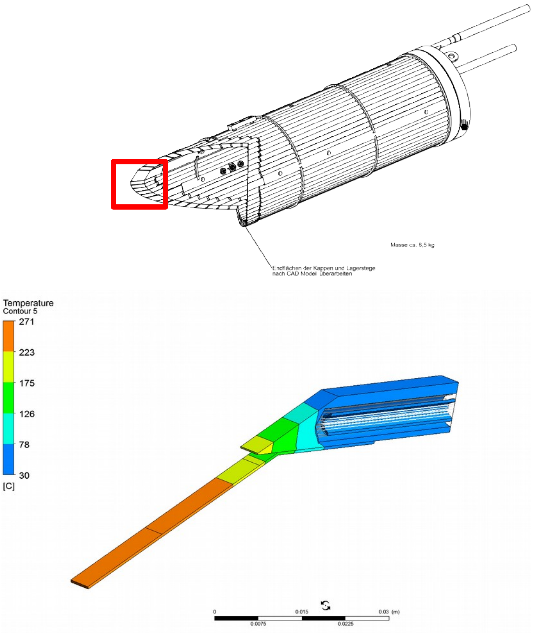

Fig. 7: Temperature of the final port-liner design with parallel feed cooling tubes (upper) and conductively cooled radiation gap closure sheets (AEB port). The outer side of the liner is well below 80 °C.

Acknowledgements

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