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.

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1. Introduction

W7-X, the world's largest stellarator device, is currently in its second phase of operation with inertial cooled in-vessel components. Future operation phases, 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 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. 2. 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.

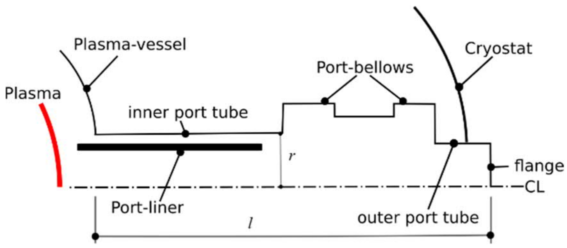

Fig. 2: Sketch of a port with port-liner

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 coolant flow analyses of the port-liners.

2. Radiation model

The radiation load on the inner wall surfaces is 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 code is specifically designed for radiation with energies above 10 *eV*, emitted by the plasma. This type of radiation is nearly completely absorbed by the first wall and therefore no reflection needs to be taken into account.

Thus the radiating plasma surface is replaced by a set of n_s uniformly distributed points on defined plasma flux surfaces or strike lines, from which radiation is emitted into k randomly generated directions, as illustrated in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

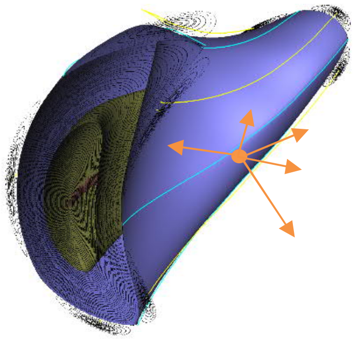

Fig. 1: Position of radiation sources. Example for randomly distributed sources along o-lines (yellow-line), x-lines (blue line), the last closed flux surfaces (blue surface), the central flux surface (red) and a middle flux-surface (yellow surface). Image: S. Bozhenkov, IPP

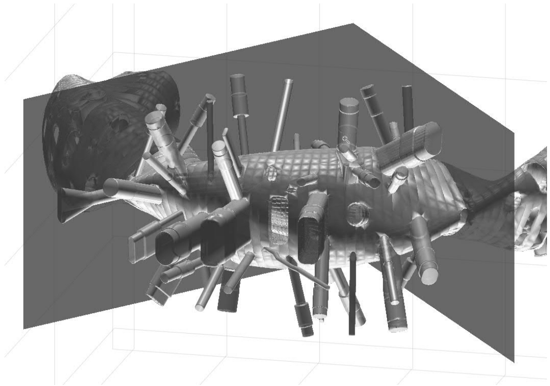

Fig. 3: 3D radiation model for 1-way ray-tracing

With respect to the chosen accuracy limit of the port-load of ±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 $k=10$ rays into randomly defined directions. The accuracy limit allows an interruption of the calculation, if the limit is reached. This ensures that the major heat-load on a port does not differ by more than 2% from the final value in average. A value, accurate enough for further applications.

The total simulated radiation power is 10 MW for steady-state operation of W7-X, assuming a fully detached plasma, causing only radiative loads on the first wall. The power for each emitted ray in a module is then

$$q_r = \frac{P_0 \cdot (\varphi + 2 \cdot 0.05)}{2\pi \cdot 10 \cdot n_s} \quad ,(1.1)$$

with P_0 the total continuous radiation power loss, typically 10 MW and φ as the modelled angular portion of the W7-X, which is typically 72°, corresponding to one module. The extension of the angle to both neighboring half-modules by ±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, yet.

The geometry model for the first wall consists of one full module. The spatial element resolution within the ports is approx. 2 cm. The resulting total amount of elements for a complete module is then approximately 3.2 million elements per module.

The resulting heat load distribution, shown exemplarily in Fig. 4 for the large rectangular port, named AEE-port, allowed then the computation of the heat load received by a port. The integration is 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 is used for subsequent calculations and analyses, like the port-liner length determination prescribed in the following section.

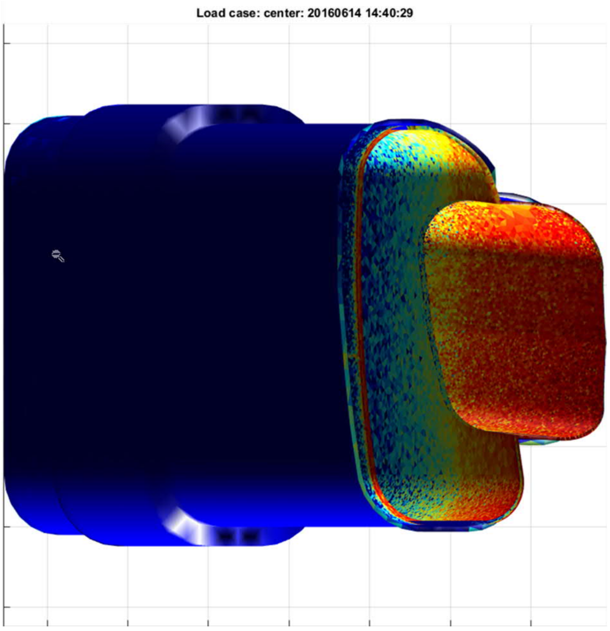

Fig. 4: Computed heat load distribution in a rectangular port, for a selected load-case. The power density on the port wall is colored on a logarithmic scale (blue=0, red=100 kW·m^{-2}, max. 70 kW·m^{-2}).

3. Port-liner length estimation

In order to reduce costs and material resources, the port liner should be as short as possible whilst still fulfilling its desired function. Therefore, it is necessary to determine the minimum length needed to satisfy this. The cumulative heat load, determined by the radiation calculation, is used to estimate the required port-liner length. It has been the major input for the analytical calculation of the minimum required port-liner length, assuring the design criterion, that the perpendicular port wall heat flux must not exceed 2 kW·m^{-2}, to ensure that the cryogenic cooling of the port is not overloaded. The liner length is calculated, by solving equation 1.2 [1]

$$(1.2)\quad q_{wall}(l) = \frac{q_0}{2} \cdot \left(\frac{z^2+2}{\sqrt{z^2+4}} - z \right) + q_{ECRH,P}$$

with $z = l/r$ as the dimensionless ratio between port-length and radius, q_0 the plasma radiation power density at the port entrance, derived from the preceding radiation calculation and $q_{ECRH,P}$ as the constant background electron-cyclotron-stray-radiation (ECRH). The latter term is only important for the heat load deep inside the port, whereas the plasma radiation is governing at the port entrance until approx. $z > 2-3$. The ratio $q_0/q_{ECRH,P}$ is typically at 20:1 – 50:1 at the entrance of the port and quickly decreasing in favor of $q_{ECRH,P}$. The above given equation is solved with help of Matlab®'s symbolic toolbox capabilities. The calculated port-liner length gives a conservative estimate up to 1.6 m as it does not take into account asymmetries in the radiation pattern. The asymmetry caused by the port's inclination, would usually lead to shorter port-liner lengths as estimated here, because the heat flux is more concentrated on one side of the circumference.

The resulting port-liner lengths vary from 0.3 m for small ports, up to 1.6 m for large rectangular shaped ports. However, for the vast majority of the ports, the required lengths reduced significantly from the initial design value of approximately 1 m.

4. Port-liner coolant flow analyses

For the 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 resulting coolant temperature. The calculations were carried out with the commercial ANSYS-CFX® package.

In order to do so, the radiation load is transferred by interpolation of the calculated wall heat fluxes on the mesh surface of the port-liner. No ECRH-stray radiation is taken into account here, as it remains with <2.2 kW·m^{-2} negligible compared with the direct plasma radiation loads. Fig. 5. shows the coolant temperature within the channel for the first port-liner design proposal. The water temperature in the port-liner remains with 67°C well below 80 °C, which is the maximum allowed coolant temperature in the return line .

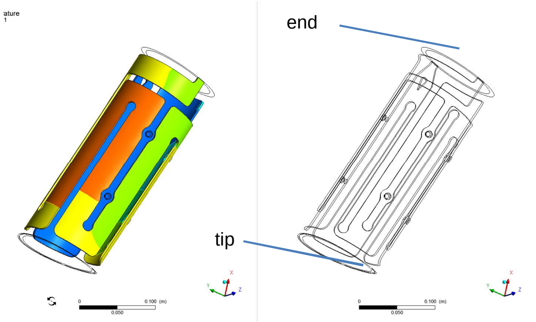

Fig. 5: Temperature distribution of the coolant (left) and geometry of the single cooling channel design (right) for a typical cylindrical port. Here: AEZ port. Blue=30 °C, Red=65 °C.

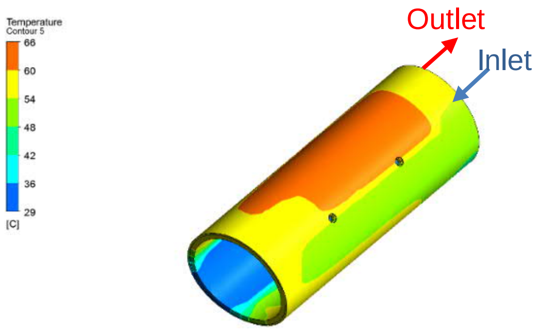

Fig. 6: Temperature of the AEZ31 port-liner. blue=29 °C, orange=66 °C.

The heat transfer coefficient α_w obtained numerically with this model is about 14 $kW{\cdot}m^{-2}K^{-1}$. This value is 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 coefficient is used to calculate the thermal field within the assembly. This is done in a multiphysics simulation with the common Finite-element-code ANSYS®. The thermal/mechanical models consist of Solid70 type elements solely and the properties of thin layer parts like ports are smeared.

In addition to the radiative heat loads, the ECRH stray radiation load is 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 is taken into account by energy balance considerations, as shown in eq. 5.1. The distribution of the ECRH-stray-radiation is nearly uniform in the port volume, caused by the high reflectivity of metal surfaces for waves at 140 GHz frequency. The resulting absorption of metals at these frequencies is typically in the range of 1-3% only [5]. Thus, the ECRH load seen by a surface in a port can be calculated by

$$q_{ECRH,p} = \frac{q_{ECRH,PV} \cdot A_E}{\sum_{1}^{i} \alpha_i A_i}, \qquad (5.1)$$

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 absorptivity of a specific surface A_i in the port [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 temperature of the port-ends, connected to the cryostat, is set to 22°C while the connection to the plasma vessel is 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, is 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 **Fehler! Verweisquelle konnte nicht gefunden werden.**. 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.

Therefore, a new design approach, proposed by NTG, Neue Technologien GmbH & Co. KG, the final manufacturing company, was chosen. The port-liner is split into several pipes, each feeding cold water to a single tip. Fig. 7 illustrates this new design. The temperature within this port-liner can be effectively kept below 80°C. Only the metal sheets at the tip, required for the closure of the gap, between the first wall and the port-liner, would notably heat up to 270 °C during steady-state operation. However, this is not of concern, as the temperature limit is at 300 °C for these parts.

6. Conclusions

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

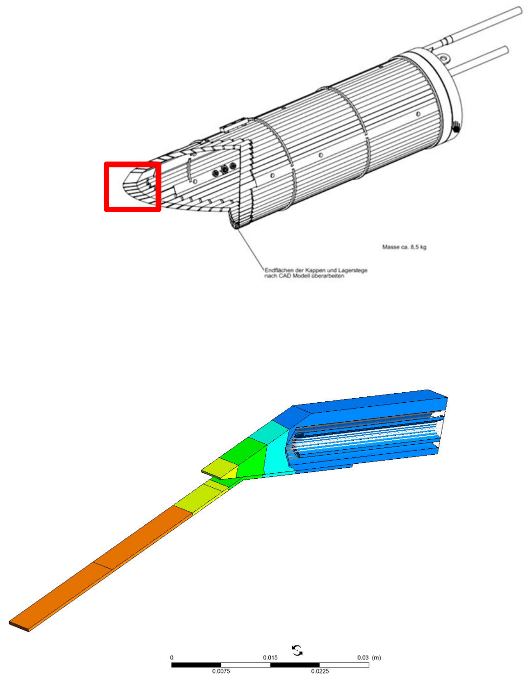

Fig. 7: Temperature of the final port-liner design with parallel feed cooling tubes (upper) and conductively cooled radiation gap closure sheets (AEB port). The outer side of the liner is well below 80 °C. (blue=30 °C, orange=270 °C)

Acknowledgements

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