Thermal and Mechanical Analysis of Wendelstein 7-X Thermal Shield

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The thermal insulation of Wendelstein 7-X cryostat consists of multi-layer insulation (MLI) and a thermal shield. The shield is cooled by helium gas flowing in pipes which are attached to the shields via copper strips or braids. The paper presents the basic thermal and mechanical layout of the thermal shield. The design is strongly influenced by the tight design space.

Main mechanical loads on the shield are electromagnetic forces resulting from rapid shut down of the magnet system and the self weight. Design and calculations were performed iteratively. Copper and brass were checked in combination with different electrical isolation variants. The induced eddy currents will be reduced if the upper and the lower half shells of the cryostat are electrically isolated against each other. The cryostat shield and the port shields are made of brass.

The expected heat loads on the shield were estimated. The resulting temperature distribution was then calculated for brass and copper shield panels. The average shield temperature is below 85 K and fulfills the thermal requirements.

Keywords: thermal insulation, finite element analysis, eddy currents, Wendelstein 7-X

1. Introduction

The stellarator fusion experiment Wendelstein 7-X (W7-X) is currently being built in Greifswald (Germany). The cryostat of W7-X consists of an inner and an outer stainless steel vessel. The inner vessel is a plasma vessel (PV) and encloses the hot plasma. The outer vessel (OV) contains the superconducting magnet system that confines the hot plasma in a magnetic cage, the dedicated support structure, the PV and the 254 ports. The ports connect the outside of the cryostat with the insides of the PV. They are used for various plasma diagnostics and for supply lines. The magnetic field of W7-X has fivefold symmetry. Correspondingly the machine is divided in 5 modules. The status of the construction and assembly of the thermal insulation is given in reference [1].

The superconducting magnet system requires an operation temperature of about 4 K. According to the cooling design the maximum heat load on the coils must be below 1.5 W/m². The cryostat is evacuated during operation to avoid heat transfer by convection from the warm components to the cold structures. Supports and feedthroughs are designed to minimize the heat load caused by conduction. All warm surfaces are covered with a thermal insulation, these include the PV (190 m^2), the OV (427 m^2) and the ports (332 m²). The paper describes the basic design of the thermal insulation and gives details of the thermal and electro-mechanical analysis that were carried out with finite element programs using the commercial software ANSYS.

2. Design of the thermal insulation

2.1 Thermal insulation concept

The thermal insulation is made of 20 double sided aluminized thin Kapton layers with silk like glass spacers as radiation shields and an actively cooled thermal shield as shown in Fig. 1. The shields are fixed on the warm cryostat surface with hollow cylindrical supports made of Torlon® (polyamide-imide). This material offers a low thermal conductivity (0.1 W at 70 K) combined with good mechanical properties (yield strength of 66 MPa at room temperature).

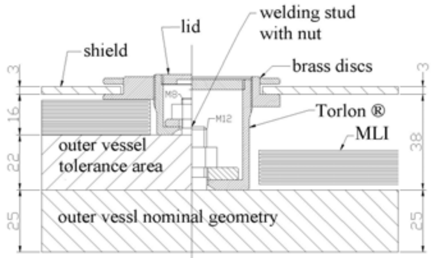

Fig. 1: Layout of the OV-thermal insulation consisting of MLI blankets and a thermal shield. Torlon supports fix the shield to the cryostat wall (22 mm radial tolerance).

2.2 PV and OV insulation

The PV shields were made of pre-impregnated laminates of glass fibre epoxy. Three annealed copper meshes were embedded in the glass fibre compound. The 3 meshes correspond to a copper sheet with a thickness of 0.314 mm. Each panel is connected to two parallel cooling pipes attached at the cold panel side via copper tresses. Two module halves are connected in parallel.

The outer vessel shields are made of 3 mm rolled brass panels. Two cooling pipe loops from the upper and two loops from the lower shell are connected in series resulting in two parallel circuits for a module. The pipes are mechanically and thermally connected to the

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OV-panels with copper strips. The strips are welded to the panel and soldered to the cooling pipes.

2.3 Port insulation

Ports are circular, oval or rectangular tubes with diameters varying between 150 mm and 1200 mm. They run from the OV to the PV inside the cryostat. They are equipped with bellows to compensate the thermal movements between the PV in reference to the OV.

The port shields are divided in two parts allowing lateral and axial movements relative to each other. The inner tube is fixed axially on the PV and in radial direction on the ports itself with pin-like supports made of Torlon. The outer tube is welded to the outer vessel shield. The welding seams cover about 30% of the circumference. This ensures enough mechanical stability and reduces the heat load on the OV-panels during the welding process.

The port shields are made of 2 mm sheet metal. The inner tube is cooled indirectly from the PV shield via copper tresses. The outer tube is coupled via welding connections. Both port shield tubes are also thermally connected via copper tresses that are fixed by riveting and soldering.

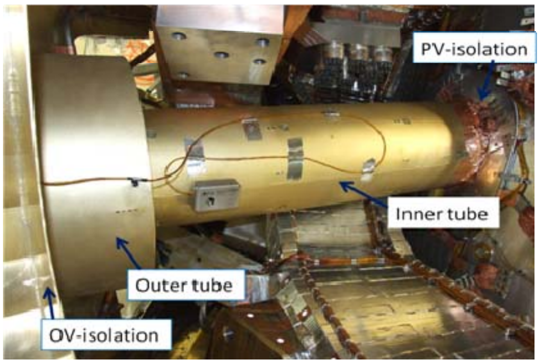

Fig. 2: Port insulation. The inner tube shield is fixed at the plasma vessel and at the port. The outer tube is fixed at the outer vessel shield.

3. Thermal analysis

3.1 Heat loads

Heat loads are based on heat load measurement for a test cryostat for W7-X modelling a half module of the cryostat with its complex geometry including domes, ports, and feedthroughs [2]. The MLI was made of thick, compressed MLI packages (90 compressed layers) using aluminum foil together with glass silk spacers. The test resulted in an average heat load of 4 W/m^2. This value includes heat conduction through the supports, the heat transfer through the MLI packages, loads due to imperfect overlap at the edges of MLI packages and of errors during the assembly. A safety factor of 1.5 was then used to define the design value of 6 W/m² for cryostat surfaces operating at room temperature. PV and ports have an operation temperature of about 333 K. The specified heat load on the shields was scaled to 9 W/m^2.

Handling of the MLI, very tight space requirements and sensitivity of heat loads caused by temperature perturbations at the edges of MLI blankets resulted in a change of the material. It was decided to use double sided aluminized Kapton with 20 layers and glass silk as spacer material. The aluminum coating and the Kapton sheets have a thickness of 25.4 µm and 600-800 Å, respectively. A test of the MLI carried out by Linde AG Hoellriegelskreuth resulted in a performance of 0.62 W for uncompressed MLI (15 mm) and 0.93 W for slightly compressed MLI (10 mm).

The MLI of a panel is made of two blankets with 10 layers each. The blankets are shifted against each other at edges to neighbouring panels to allow a blanket overlap (see Fig. 3). The influence of the gap between the blankets on the temperature profile and therefore on the heat transfer within the MLI was numerically checked with a 2D-finite difference method ESATAN v8.9 (European Space Agency Thermal Analysis Network). A gap of 2 times 10 mm results in an additional heat load of 0.25 W/m panel edge for the outer vessel and 0.4 W/m for the plasma vessel panels. An analysis of the MLI surface and of the overall length of the edges results in a heat load of about 400 W per module.

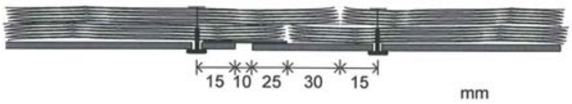

Fig. 3: MLI overlap between the two neighboring panels. Two blankets are shifted against each other.

The heat conduction from the cryostat walls to the panels through the supports is determined by the number, the geometry and the material properties. Different variants of supports were designed to cope with the tight space requirements and the acting forces. Most supports are hollow cylinders according to Fig. 1. The lengths of the supports vary between 24 to 60 mm. The heat transfer trough the supports was calculated using a FE-method. Only the heat conduction was considered. The heat conduction varies between 0.2 to 0.5 W per support. 700 supports on the PV- and OV-shields producing a heat load of 210 W. The 49 port shields of a module are fixed with 170 fixed supports and 590 pin-like loose supports. The overall heat load through the port supports by conduction is 200 W.

Based on this data new design values of 4.5 W/m^2 for the OV-insulation, 3.5 W/m^2 for the PV-insulation and 7 W/m^2 for the port shields were derived.

3.2 Temperature distribution on the shields

In a next step the temperature distribution on the thermal shields was calculated. The thermal shield of a half module was modelled with shell elements containing the OV- shields, the PV- shields and the port shields (see Fig. 4). The glass fibre epoxy panels of the PV-shield were allocated an effective thermal conductivity that is dominated by the copper mesh. The cooling pipes were not modelled. A temperature of 70 K is applied at the nodes close to locations where the copper tresses or braids of the cooling pipes are connected with the panels. The applied temperature corresponds to the helium outlet temperature of the cooling loops and is therefore a conservative value. The thermal connections between the plasma vessel shield and the port shield as well as the connection between the inner port shield and the outer port shield were modelled with conducting bar elements (LINK33). Numbers and cross section of the elements were chosen to describe the effective heat transfer.

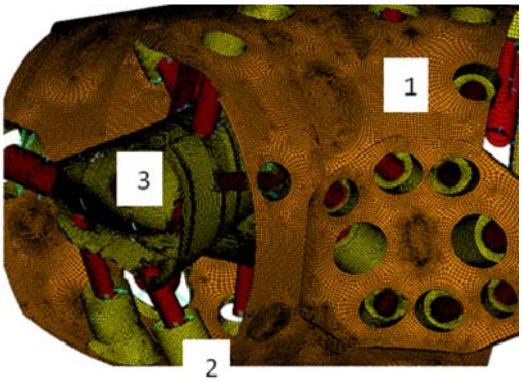

Fig. 4: Finite element model for calculation of the temperature distribution on the shields.
1 = OV-shield, 2 = port shield, 3= PV shield

Two different load cases were calculated. In case 1 the original design values for the heat load were used. In load case 2 the derived heat loads were applied instead. Both cases were calculated with copper and brass as material for the outer vessel shields. Port shields were always considered as made of brass. The results of the calculation are summarized in table 1.

Table 1: Average and maximum temperatures on the shields for different load cases (load case 1: original design values; load case 2: derived heat loads).

Load case	OV-shield	PV-shield	Port-shield	All shields
	T_{aver} [K]	T_{aver} [K]	T_{aver} [K]	T_{max} [K]
Target	85	85	100	120
1 (brass)	78	77	104	133
1 (copper)	71	76	97	119
2 (brass)	75	74	93	112
2 (copper)	71	73	88	102

The lowest shield temperatures can be achieved using copper panels. When brass is used instead of copper, the average temperature rises by 5-8 K. For load case 1 with brass as material for the port shields and OV-panels an average temperature of 78 K was calculated. The port shield temperatures vary between 70 K and 120 K. One critical port even has a temperature of 133 K. Based on the analysis of the current shield design heat loads according to load case 2 are expected. In that case the maximum temperature on the brass shields drops to 112 K. The target values for the design are achieved.

4. Eddy current calculation

The magnet system of W7-X will be shut down in case of an emergency with a time constant of 3 s (e.g. a quench of a coil or a coil group). In that case eddy currents are induced in all conducting shield parts that are exposed to the magnetic field. The influence of the induced current was investigated on the thermal shield. The magnetic field is up to 3 T on the plasma axis depending on the magnetic load cases of W7-X. The PV shields and the inner parts of the port shields are exposed to the highest field. The outer port shields and the OV-shields are outside the toroidal field coils and see only to the stray field that rises up to 1 T.

An electromagnetic calculation was carried out with ANSYS for one half module of the OV shields and the outer port shields. The results for the plasma vessel shields together with the inner port shields were discussed elsewhere [3]. The PV shields are fabricated of glass fiber reinforced epoxy. The surfaces of the panels are completely covered with epoxy and are therefore non-conducting. There is not any electrical contact to the neighboring port shields. Consequently the OV shield can be treated independently to the PV shield.

SOLID97 elements were used to model the panels of the OV shields together with the outer port shields. All free conducting surfaces with no neighboring elements were covered with 2 additional layers of non conducting elements. Vector potential data was applied as boundary conditions on the outside nodes of the non conducting elements. This vector potential data was calculated assuming steady state condition for the outside nodes. The calculation was carried out with the computer program EFFI [4] that is based on the Biot-Savart law. Then the data was applied in the ANSYS model assuming that the field decays with a time constant of 3 s. A feed back of the induced current on the applied field was neglected.

The size of the electromagnetic forces depends on the concept of electrical connected areas and on the material of choice. Maximum electromagnetic forces are expected in case no electrical isolation is foreseen between different components of the shield allowing the current to form big eddies along the shield surfaces. Smaller forces will be generated if all panels are isolated against its neighbors. This requires that all shield components must be isolated completely against the panels like port shields and dome shields, cooling pipes, etc. Another option is to isolate only the separation lines between the shields of the upper and the lower half shells of a module. Ports and domes on the separation lines must also be isolated against the panels. Copper and brass were considered in the calculation as two possible materials for the thermal shield. Brass has an electrical resistance of 4.69E-8 Ohm·m at 80 K that is about 10 times the value of copper with a residual resistivity ratio of RRR=10.

The induced current densities and the electromagnetic forces were calculated. The forces depend on the local magnetic field that differs considerably from place to place. Table 2 shows the forces per unit area acting normal to the panel surfaces. The maximum and the average values are listed. The results are given for two isolation variants (no isolation within a module and isolation of the lower shell against the upper half shell). The maximum pressure on the copper panels with electrical isolation is about 10 kN/m². The corresponding value for brass panels is 0.9 kN/m².

Table 2: Maximum and average forces normal to the copper panel surfaces for two isolation variants (no isolation within a module and isolation of the lower shell against the upper shell). Additionally the values for brass panels are given.

	No isolation	With isolation	With isolation
	copper	copper	brass
Average pressure [kN/m²]	4.55	0.386	0.035
Maximum pressure [kN/m²]	56.6	9.98	0.862

5. Mechanical Analysis

In a next step a mechanical analysis of the shields was carried out. The shields were modelled with shell elements (type SHELL63). Supports were not modelled at their positions but considered as boundary conditions for shield nodes. Displacements were set to zero normal to the panel surfaces for loose supports and in all directions for fixed supports. A panel with an average size of 3.3 x 2.0 m² has about 8 loose supports, one fixed support and one semi fixed support. A semi fixed support allows only a panel movement in the direction of the fixed point. No rotation is possible. The outer port shields are connected with the OV shields.

The electro-magnetic forces were applied at the nodes calculated with the eddy current model. The forces and stresses for a shield made of copper were calculated for the two isolation variants. The corresponding values were also calculated for brass shields with electrical isolation between the upper and the lower half shell. The maximum forces are listed in Table 3. Additionally results are listed for fully isolated copper panels for comparison (no electrical contact to neighbours).

Based on these results it was decided that brass will be chosen for the port shields and for the OV panels. Electrical isolation of all panels was rejected. The effort for isolating all components against each other was considered as to time consuming and not practical. Additionally this would also have an impact on the thermal coupling of connected pieces. The maximum forces on the supports for brass panels are below 1 kN for the fixed supports and below 0.5 kN for loose supports. The equivalent stresses in the brass shields are below 100 MPa. This value is below the yield strength for brass (about 180 N/mm² for CuZn37).

Table 3: Maximum and average forces on the supports for copper panels for different isolation variants (no isolation within a module, isolation of the lower shell against the upper shell, fully isolated panels). Additionally values for brass panels with isolation are given.

	No isolation	With isolation	With isolation	Fully isolated
	copper	copper	brass	copper
Average force [kN]	7.05	0.85	0.13	0.39
Maximum force [kN]	49.5	8.89	0.77	4.96

6. Summary

The thermal and mechanical layouts of the outer vessel shield including the outer port shields were analysed based on finite element models. Different electrical isolation variants and two different materials for the outer vessel shield were investigated. It was decided to make the shields out of brass and to isolate electrically the shields of the lower half shell from the upper half shell. The modules are isolated against each other as well. The resulting forces on the fixed supports are below 1 kN and the stresses are below 100 MPa. The impact of brass on the temperature distribution was also checked. The average shield temperature is about 92 K. Heat loads derived from the current shield design give lower numbers than the primary loads. In that case the average shield temperature is somewhat lower (about 85 K).

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