Thermal insulation of the Wendelstein 7-X superconducting magnet system

Schauer F., Nagel M., Bozhko Y., Pietsch M., Shim S.Y., Kufner F*, Leher F.*, Binni A*., Posselt H.**,

Max-Planck-Institut fuer Plasmaphysik, Greifswald Branch, Euratom Association, Wendelsteinstrasse 1, D-17491 Greifswald, Germany
* MAN DWE GmbH, Dpt. AB – Plant Construction, Werftstrasse 17, D-94469 Deggendorf, Germany
** Linde AG, Engineering Div., Dr.-Carl-von-Linde-Strasse 6-14, D-82049 Hoellriegelskreuth, Germany

The cryostat thermal insulation of the stellarator Wendelstein 7-X (W7-X) is being built by MAN DWE and its main sub-contractor Linde AG. Development and engineering of the plasma vessel (PV) insulation is finished and production is starting. The complex geometry and narrow gaps to the superconducting coils require innovative solutions concerning the multi-layer insulation (MLI) as well as the shield and its supports. Crinkled Al-coated Kapton® foils with glass paper spacers were chosen as MLI, and the shield consists of epoxy-glass resin containing copper meshes for temperature equalisation. Shield supports are made of Torlon® which exhibits extremely low thermal conductivity and good mechanical strength.

INTRODUCTION

The main assembly activities of Wendelstein 7-X at the Max-Planck-Institut fuer Plasmaphysik, Greifswald Branch, start this autumn with stringing the first superconducting coil over a plasma vessel (PV) sector which by then must be thermally insulated with multi-layer insulation (MLI) and an actively cooled thermal shield [1]. Subsequent insulation of the other cryostat components has to be performed step by step in accordance with the machine assembly until the torus is completed in 2009.

Basically, three regions with different conditions have to be discerned: Firstly, the PV and adjacent "inner" port sections (ports allow access to the plasma vessel from the outside world) are exposed to strong magnetic field changes in case of coil emergency switch-offs. Space is extremely restricted there, and the insulation has to endure occasional PV baking at 150°C. Secondly, the "outer" port sections adjacent to the outer vessel are exposed to relatively small stray fields but they are also baked. Thirdly, the outer vessel always remains at room temperature and encounters small stray fields only.

In order to keep insulation effort and costs within reasonable limits, the heat flow from the MLI-covered cryostat walls being at 300 K to the shield at around 60 K is specified to relatively undemanding 6 W/m². This limit increases to 9 W/m² at the PV and port walls when they have an average temperature of 60°C during plasma operation. Since the shields of the inner port sections are cooled indirectly only, some hot spots there can reach up to 150 K. Some layers of MLI are thus applied at those shields also to their cold sides. Generally, heat influx from the shields to the coils and their support structure is ≤1.5 W/m².

Following the assembly sequence of the W7-X basic device, the PV insulation and corresponding port interfaces have to be manufactured first. Therefore, development work has been concentrated onto these components. Now the critical issues are solved and production is starting. This summer, the thermal insulation components will be ready to be assembled onto the first PV segment before stringing over the first coil. The insulation of the outer vessel, the ports, and other components like feedthroughs, pipes, instrumentation wires, etc., are considered to be less demanding and less time critical. The insulation concepts for these constituents basically exist; the detail engineering is straightforward and will be based on experience from current work with the plasma vessel insulation, from the Demo-Cryostat [2], and from general know-how in the field.

THERMAL INSULATION OF THE PV

W7-X assembly starts with mounting the first coil in the middle of the 1st PV half-module (HM) which is delivered in two sectors. After insulating segment 1 (Fig. 1) on top of the larger sector and stringing the middle coil over, both PV parts are welded together. Then insulation segment 2 is mounted and the next coil strung over, etc. Every plasma vessel HM insulation is built up from four segments. Each segment in turn is sub-divided into shield and corresponding MLI panels, adding up to 4 x 5 panels in poloidal and toroidal directions, respectively, per HM. Each panel is cooled by two tubes as indicated in Fig. 1.

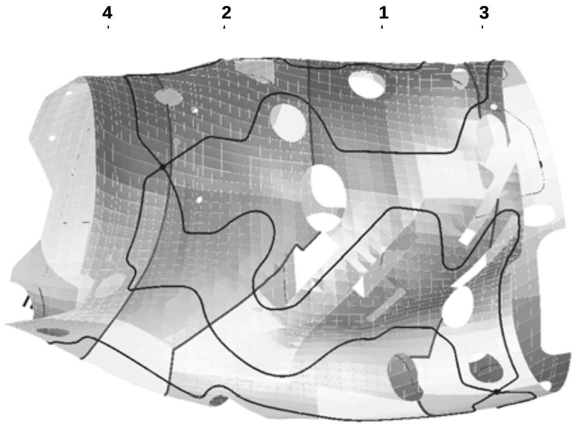

Figure 1 Insulation of a plasma vessel HM. The segment assembly sequence is indicated

MLI of the PV

The most challenging requirements to the MLI of the plasma vessel are adaptability to the complex PV surface and heat resistance. This lead to the choice of aluminized crinkled polyimid (Kapton®) foils with glass paper layers (DBW Type 50111) in between. The low thermal conductivity within the foils allows simple overlap design between panels, and undemanding interfaces to the port tube insulation. This MLI is also flame retardant, and eddy current forces caused by magnet emergency discharges are negligible.

The MLI of the PV is built up from panels consisting of two shifted mats. Each mat contains ten crinkled Al-coated Kapton®-foils, alternating with glass paper. This MLI is well adaptable to the PV surface which is not developable into a plane (Fig. 2).

Figure 2 Crinkled Kapton® MLI prototype mat adapts easily to the PV surface

The MLI panels are laid into corresponding shield panels and are fixed by plastic pins. The MLI mats are then cut to right size, and these assemblies are mounted onto the PV surface with optically tight overlaps.

Loss tests of a 20-layer MLI system were performed by Linde Co. on a 0.32 m diameter, 3.4 m long cylinder at 80 K. In one case the MLI was laid perfectly loose with a thickness of about 15 mm, and with one overlap (two narrow gaps) along the cylinder length. In the second case, the insulation was compressed to a thickness of 10 mm, and the overlap gaps were opened to 10 mm width. At the cylinder ends, a PV to port insulation interface was simulated. In the first experiment, the losses were 0.62 W/m², and in the second, realistic one, the losses were 0.93 W/m². These excellent results were better than expected.

Thermal shield of the PV

Following the experience from the Demo-Cryostat, the first idea was to use panels made up by canted stainless steel stripes approximating the PV surface. Attached copper stripes were planned for temperature equalization. This steel – copper combination avoids excessive eddy currents and associated forces in case of a magnet emergency shut-off. However, during the detail design phase it turned out to be quite difficult to fulfill the stringent tolerance requirements, and this concept was dropped.

One promising alternative appeared to be "dieless forming", a process where a spherically tipped forming tool incrementally presses securely clamped metal sheets over a stationary swage into the complex shapes. The final panel contour has to be cut out of the formed sheet. Experiments were performed with stainless steel and brass. However, the required tolerances could not be achieved without elaborate measures for compensation of spring-back. In both cases, the sheet was out of tolerance already after forming, and subsequent annealing was required to avoid spring-back during cutting the panel out of the formed sheet. As expected, brass was easier workable. This material has the additional advantage that its thermal and electrical conductivities are such that copper stripes for thermal equalization can be omitted and eddy currents can be kept within acceptable limits at the same time.

In parallel, the possibility to use epoxy-fiber panels containing copper meshes was investigated. After optimization of small samples, a real size glass-fiber epoxy panel was built (Fig. 3) with excellent surface tolerances of ± 1.5 mm. The copper net was tightly integrated within the homogeneous laminate. No cracks or any signs of disintegration appeared after many thermal shocks in liquid nitrogen.

Figure 3 Epoxy-glass resin PV shield panel not yet cut to final shape, without Al coating

Technical and economical evaluation led to the decision to use epoxy-glass resin laminates for the PV shield to be produced by the sub-contractor Wethje Co. Each panel contains three copper mesh layers for sufficient thermal conductivity. Every copper layer will be cut into two or three electrically insulated parts in order to reduce eddy currents. FEM analysis confirmed the thermodynamical, electrodynamical and mechanical behaviour of this shield [3]. The emissivity of the panel surface facing the cold coils will be reduced by applying adhesive aluminium tape.

<u>Shield supports</u>

Stringent space requirements call for short shield supports (Fig. 4). They must be rugged in order to withstand eddy current forces as well as the weight of assembly personnel stepping on it, and must exhibit at the same time low thermal conductivity.

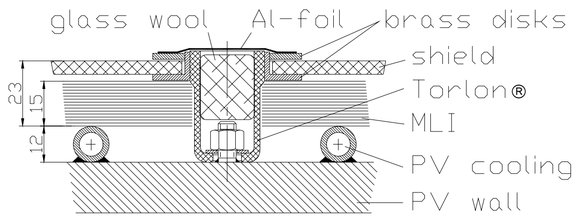

Figure 4 PV thermal insulation with shield support

One type considered uses thin polyimid ropes (Kevlar®) as supporting elements (Fig. 5, left). Two U-shaped steel stripes are arranged coaxially in opposite. The bottoms and tips of the U's are connected by ropes to each other, respectively, to prevent any in-axis movements. Forces perpendicularly to the axis are supported by the skewed arrangement of the ropes. These tensile-loaded support elements can be made very thin and thus with low thermal losses.

The second - and finally selected - spacer consists of the polyamid-imid Torlon 4203® (Fig. 5, right) whose thermal conductivity is extremely low and varies almost linearly from $0.08\ \mathrm{Wm^{-1}K^{-1}}$ at 30 K to $0.25\ \mathrm{Wm^{-1}K^{-1}}$ at 300 K [4]. Also the mechanical properties, measured by FZK, are excellent: tensile strength ≥ 155 MPa at 7 K and 300 K, and fracture toughness K_{IC} ranging from $4.3\ \mathrm{MPa{\cdot}m^{1/2}}$ at 7 K to $5.7\ \mathrm{MPa{\cdot}m^{1/2}}$ at 300 K. The design of the support can be gathered from Figs. 4 and 5: A thin-walled Torlon® tube is bolted at its warm bottom to the PV, and at the cold end the shield is being inserted between two circular brass disks which are screwed onto the tube.

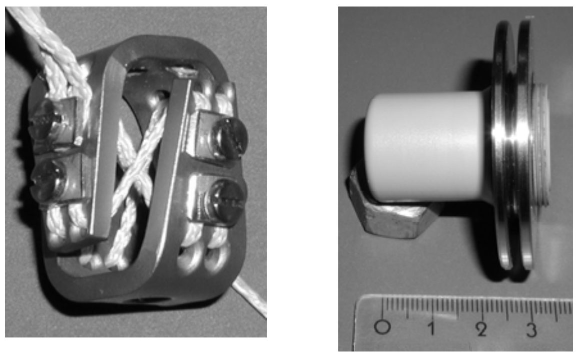

Fig. 5 Kevlar® (left) and Torlon® shield supports

Each shield panel has a firm support near its center of gravity, and a few additional "loose" supports which allow sliding of the shield between the brass disks for thermal contraction compensation. The tube OD is 22 mm, and its wall thickness is 2 mm and 1 mm for the fixed and loose supports, respectively. Both support types were tested under real thermal and mechanical conditions, inter alia with forces perpendicular to the tube axes. The resulting breaking strengths were ≥ 4.9 kN and ≥ 2.5 kN which by far exceed the specified fixed point load of 1.0 kN.

<u>Cooling circuit</u>

The four toroidal shield panel rows of a half-module are cooled in series via two parallel He-tubes each which merge at the HM ends (Fig. 1). The meandering shape of the tubes results from evasion of ports and constrictions between PV and coils. Flexible copper braids are soldered to the tubes, and at the other braid ends, attached cable shoes are riveted elastically to the shield. Sufficient heat transfer is provided by thermally conductive paste between the cable shoes and the glass-fiber epoxy panels.

THERMAL INSULATION OF THE PORTS

The port tubes welded to the PV are insulated using the same MLI system as at the PV. The interface between the MLIs of the PV and a port is basically performed by cutting staggered strips into the port MLI, and by overlapping these strips with the PV-MLI for an optically tight cover of the intersection.

The shield of this "inner" port section is made of brass which is loosely bolted to the PV shield panel(s) such as to allow sliding for thermal contraction compensation. On the other end, the inner port shield is fixed by spacers. It will be cooled indirectly from the PV and the OV shields.

The "outer" port section adjacent to the outer cryostat vessel contains bellows for compensation of PV movements and thermal expansion. The insulation of this assembly adjoins to the OV. Since the magnetic field is small in this region, copper is allowed as shield material. MLI and shields of the inner and outer port parts are overlapping such as to allow relative movements of almost 30 mm in any direction.

THERMAL INSULATION OF THE OUTER VESSEL

The MLI of the outer vessel is not yet finally decided, it will be either the same as on the PV or consist of pure aluminum foils having also glass paper spacer layers in between. The low magnetic field in this area allows copper as shield material. The shield will be divided into 5 x 4 panels per module toroidally and poloidally, respectively. The same Torlon® supports will be used as described above. Also the cooling loops will be in principal the same as with the PV shield. Each panel will be cooled by two tubes in parallel, and the tubes of a panel-row merge at each end of a half-module. The four poloidal HM panel-rows are cooled in series. The cooling tubes are soldered via copper adapters to the copper shields. Corresponding PV and OV half-module cooling loops are connected in series. Each such HM shield cooling loop can be controlled by a valve.

SUMMARY

Development and detail engineering of the main components of the plasma vessel thermal insulation and the interfaces to adjacent port tubes is finished and production is starting. The chosen MLI system is crinkled Kapton® foils with vapor deposited aluminium on both sides, and with glass paper as spacers in between. The actively cooled thermal shield consists of epoxy-glass resin panels which contain three copper mesh layers each for sufficient thermal conductivity. Eddy current induction is controlled by one or two cuts per copper mesh. The surface facing the coils is covered by ahesive Al-foil in order to reduce emissivity. Each shield panel is supported by one firm support near the center and several "loose" supports which allow in-plane gliding for thermal contraction compensation. The shield supports consist of Torlon® tubes. They are bolted to the PV, and at the cold ends the panels are clamped between two disks. Each panel is cooled by two cooling pipes which are thermally contacted via flexible copper braids.

Concepts were worked out for the thermal insulation of the ports and outer vessel. Detail design and assembly tests of critical components will be performed in a sequence corresponding to the overall W7-X mounting activities.

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