Lessons learned from the design and fabrication of the baffles and heat shields of Wendelstein 7-X

B. Mendelevitch[a], A. Vorköper[b], J. Boscary[a], Ch. Li[a], N. Dekorsy[a], A. Peacock[c],
O. Sellmeier[a], R. Stadler[a], H. Tittes[a]

[a]Max Planck Institute for Plasma Physics, EURATOM Association, Boltzmannstr. 2, 85748 Garching, Germany
[b]Max Planck Institute for Plasma Physics, EURATOM Association, Wendelsteinstr. 1, 17491 Greifswald, Germany
[c]European Commission c/o Max-Planck- Institute for Plasma Physics, EURATOM Association, 85748 Garching, Germany

The baffles and heat shields of the wall protection of the Wendelstein 7-X stellarator are actively water cooled components based on the same technology. Fine grain graphite tiles are clamped onto a CuCrZr heat sink, which is vacuum brazed to a stainless steel tube. The baffles are part of the divertor and improve the divertor pumping efficiency. The heat shields protect the plasma vessel wall, water piping, cables and the integrated diagnostics. The 170 baffles with 25 variants and 162 heat shield modules with 85 variants comprise a total surface of 33 m^2 and 51 m^2, respectively. Design guidelines enabled as much as possible the standardization of the fabrication to allow for a more efficient work organization. Individual jigs have been manufactured for each variant in order to weld, bend and mill the different parts of the baffles and heat shields to the required 3D accuracy. At the end of the manufacturing process, each component has been checked and documented according to a detailed quality plan.

Keywords: W7-X, plasma facing components, design analysis, manufacturing

1. Introduction

The long pulse operation of the stellarator Wendelstein 7-X requires actively cooled plasma facing components (PFCs) [1, 2]. Among the different PFCs installed in the plasma vessel of the W7-X machine, the baffles and heat shields have different functions. The baffles are part of the divertor and improve the divertor pumping efficiency. The heat shields protect the plasma vessel wall, water piping, cables and the integrated diagnostics. The baffles and heat shields are based on the same technology. Fine grain graphite tiles are clamped onto a CuCrZr heat sink, which is vacuum brazed to a stainless steel tube. A Sigraflex® compliant layer is placed between the tile and the heat sink to improve the thermal conductivity (Fig. 1 & 2).

The challenge of the design of these components is to reproduce by a series of 2D elements the required 3D shaping of the W7-X helical plasma contour and to define a set of design guidelines which allow an efficient work organization, and, allow the achievement of the demanding accuracy of the final components.

2. Design criteria

The baffles and heat shields consist of 170 and 162 modules with a total surface of 33 m^2 and 51 m^2, respectively. The baffles have nominally 17 different types corresponding to the 10 divertor units of the machine. Due to the requirements of diagnostics, heating systems and a diversity of ports, 8 additional variants for the baffles and 85 variants for the heat shields have been manufactured.

The major design criteria are the specified radiative thermal loads, which depend on the function and on the position of the components in the plasma vessel, as indicated in Table 1.

Table 1: maximum design radiative loads for baffle and heat shields *per module, **per tile (LWH: Lower loaded Heat Shields - HIH: Higher loaded Heat Shields)

Component	Surface	Average load*	Local load**
	[m^2]	[kW/m^2]	[kW/m^2]
Baffle	33	250	500
LWH	31	150	500
HIH	20	250	500

The HIH are more loaded than the LWH because they are located at the inboard side of the vessel which has the highest curvature and is closer to the plasma. The maximum allowable temperature of CuCrZr of 400°C in operation defines the performance limit of the component.

A second criterion is the water cooling conditions, which are the same for the baffles and heat shields: an axial velocity of 6 m/s, a maximum pressure drop of 1 MPa with a static pressure of 1 MPa, a maximum temperature increase of 50K with room temperature of the inlet water. The inner

---

author's email: boris.mendelevitch@ipp.mpg.de

diameter of the pipe is 10 mm with a wall thickness of 1 mm. The total foreseen flow rates are 221 and 282 m^3/h for the baffles and heat shields, respectively.

3. Design guidelines

The design guidelines summarize the information coming from physics inputs, tests and calculations, to enable as much as possible standardization of the fabrication. They define also the interfaces with other in vessel components.

The maximum allowable water temperature increase of 50K, which depends on the average heat flux, defines the dimensions of the modules. The maximum surface of the LWH and baffles is 0.3 m^2, the surface of the HIH ranges between 0.3 m^2 and 0.6 m^2. A total of 111 manufactured modules have a surface lower than 0.3 m^2. This dimension results also from the restricted available space at certain locations due to ports and diagnostics. The hydraulic arrangement (in parallel or in series) depends on the size of the modules and the available space for the piping through the allocated ports of the machine for the cooling. The heat shields are mostly cooled in parallel, with a few exceptions in particular areas for the protection of diagnostics. The baffles are cooled either in parallel or in series, depending on the location along the divertor.

The maximum specified heat loads and local profile of the plasma define the dimensions of the individual tiles and heat sinks, and the geometrical ratio between the tile and the heat sink, indicated in Fig. 1 and Table 2.

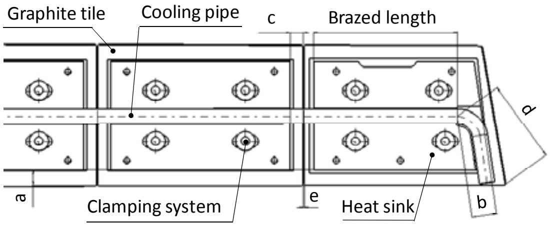

Fig. 1: Guidelines for design baffle and heat shields

Table 2: Geometrical dimensions in mm of the tiles and heat sinks (T: Target, P: panels)

Dimension	a	b	c	d	e
Baffle-T	12	12	21	62	1
Baffle-P	15	15	24	68	1
LWH	12	12	21	62	1
HIH	20	15	24	68	1

The boundaries of the baffles are the target elements of the divertor [3] and the panels of the wall protection [4]. In the region adjacent to the target elements, the heat flux is locally higher, therefore, the distance between the tiles and the heat sinks are reduced in this area to allow a more efficient cooling.

The design of the clamping system between the tiles and the heat sink is detailed in Fig. 2.

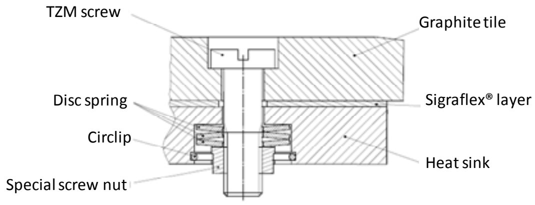

Fig.2 Design clamped components

Two different graphite grades have been selected and used for the graphite tiles: FP 290 produced by Schunk and R 6510 produced by SGL. A TZM screw creates a contact pressure of 0.25 MPa at RT (0.2 MPa at operating temperature) to ensure a heat transfer coefficient of 2000 W/m^2 K at the interface between the graphite tile and the heat sink over a surface of 0.003 m^2 [5]. This area defines the number of screws required for each heat sink. The pre-load force is 700 N and the tightening torque 3 Nm. The head of the M6 screw is shadowed inside the hole of the tile against energetic particles with an angle up to 3° to reduce the thermal load and thus its temperature in operation. The disc spring and the circlip are made of Inconel 718. The maximal temperature of the disc spring in operation is ~700°C. The screw nut is made of 1.4980 stainless steel because it maintains its properties at increased temperatures. The thickness of the Sigraflex® interlayer is 1 mm. The thickness of the CuCrZr heat sink is 9 mm and 11 mm for the heat shields and baffles, respectively. At some special locations facing the neutral beam injection systems, the thickness of the graphite tiles of the heat shields is increased to 20 mm to offer a better protection against shine-through effects. The thickness of the graphite tile ranges between 6 and 10 mm. The tiles are machined with facets to allow the adjustment of the surface of the modules to the helically twisted shape of the plasma and to prevent leading edge exposure.

4. Manufacturing

The different steps of the manufacturing process (Fig. 3) of the baffles and heat shields are: the machining of the CuCrZr heat sinks, the brazing of the cooling pipes to the heat sinks, the welding between the different parts of the pipes and the 3D shaping of the modules, the final inspections of the manufactured component. The graphite tiles will be clamped onto the heat sinks only once the cooling structure is mounted and positioned in the plasma vessel. Therefore, the graphite tiles and the clamping parts will be delivered separately.

The technology and procedures for the brazing were selected during the prototyping phase. The brazing of the heat sink subassemblies was performed at Reuter Technologie GmbH, Germany. The heat sinks placed horizontally in an oven are brazed with the tubes using a LN_2 braze. Before brazing, the surface of the pipes, made of 1.4441 stainless steel, is electro-polished and cleaned. Following the brazing temperature cycle, a heat treatment is applied to recover the CuCrZr properties by precipitation hardening @ 480°C for 3 hours. The brazing quality has been controlled by X-ray on a random basis and a total of 15-20% of the individual elements of each oven charge has been inspected. The sampling rate is based on experience with the manufacturing of ASDEX Upgrade components, which was verified by the results of the present project. The acceptance criteria are: a wetting surface > 95% with fault diameter < 1.5 mm. The hardness of the heat sinks is 100% controlled and documented after brazing. The acceptance criterion is: HB = 85 ±10%.

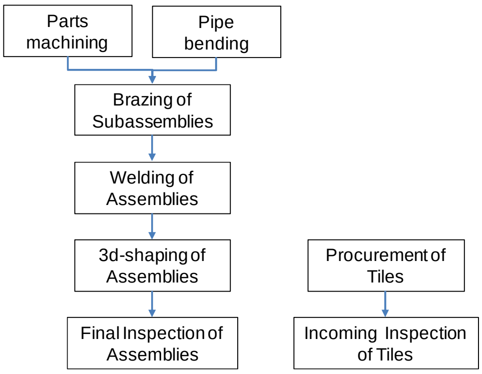

Fig. 3 Manufacturing process

The next step is the 3D shaping of the different parts of the cooling structure. The arrangement and the manufactured jigs are illustrated in Fig. 4.

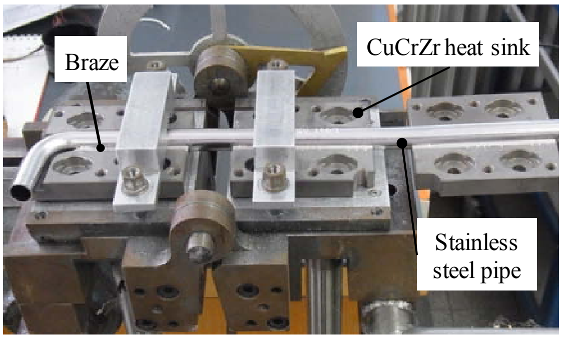

Fig. 4 Bending jigs for cooling row

This system allows the bending up to 12° and twisting up to 3° without damaging the brazed connection.

In a final stage, the different parts are assembled together to build the module, as shown in Fig. 5.

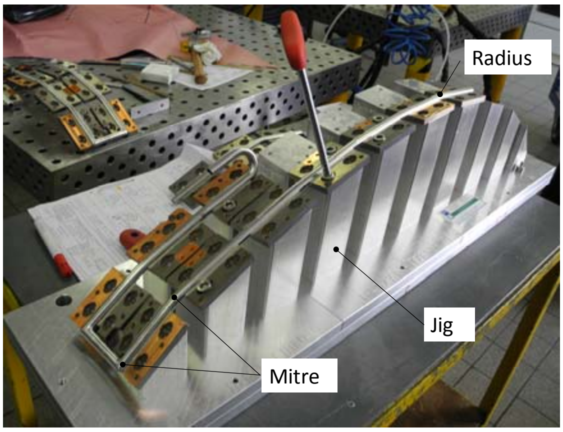

Fig. 5 Jigs for montage heat shield

Individual jigs have been manufactured for each variant in order to weld and bend the different parts of the baffles and heat shields to the required 3D accuracy: 84 jigs for the heat shields, 38 jigs for the baffles. The jigs have been carefully manufactured and 3D measured. The following accuracy needs to be achieved: a step ≤ 0.1 mm between two neighbouring heat sinks and ≤ 0.5 mm for the completed module, a required flatness tolerance of 0.01 mm on the side of the heat sink facing the graphite tile.

The favored technological solution for the piping is the orbital welding of the different tubes. A total of 6000 welds were necessary for the fabrication of these components, and this technology proved to be reliable for the production of the W7-X PFCs. However, this method cannot be systematically applied, as shown by Fig. 5, when the bending angle is > 12° or when the distance between the heat sink and the baffle has to be reduced. In these cases, a mitred joint is used and the two parts are TIG welded.

The main difference between the heat shields and the baffles is the larger stiffness required for the baffles because they have to accommodate larger average heat fluxes while providing a higher stability during operation. This requirement causes a distinction between baffles and heat shields at this stage of the fabrication. The heat sinks of the heat shields are machined from an 11 mm to a 9 mm thickness after the brazing process. The assembly with the jigs allows the specified geometry within the required tolerances to be achieved because the element is not too stiff. For the baffles, the manufactured 38 jigs consist of 19 jigs for the assembly and 19 jigs for the milling. Once assembled, the module is positioned on another special jig and the heat sinks are individually milled from a 13 mm to an 11 mm thickness within the specified accuracy.

An example of a completed baffle module is shown in Fig. 6 from the back side and Fig. 7 from the plasma side. These pictures illustrate the typical type of difficulties encountered during the design, for example, for the integration of a port.

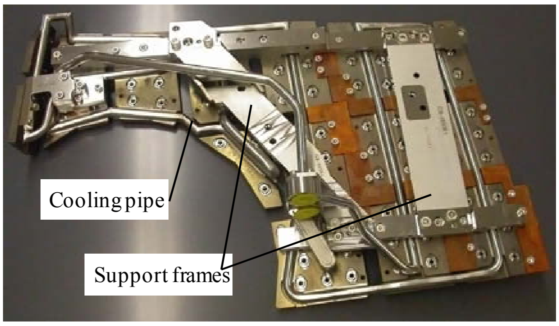

Fig. 6 Completed baffle module - View from the back side

The baffle module needs various shapes of heat sinks with the corresponding graphite tiles to achieve the required geometry. The cooling pipe consists of a simple geometry of straight and bent pipes (right side of Fig. 6) and a more complex arrangement including mitred joints (left side of Fig. 6) to provide the necessary cooling at the boundary of the port.

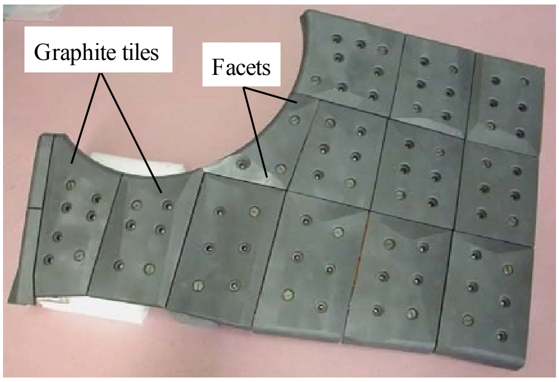

Fig. 7 Completed baffle module - View from the plasma side

At the end of the manufacturing process, each component was checked and documented according to a detailed quality plan. The geometry of the completed modules is systematically measured. The baffles have been 3D measured with a 3D measurement machine and compared to the CAD model. The heat shields have been carefully positioned on the jigs. The jigs have been previously 3D measured. The gaps between the heat shield and the jig are measured with a gauge. The mounting of the graphite tiles onto the cooling structure has been also checked for one series of baffles and heat shields of each variant. The pressure drop has been measured for one series element for each variant of heat shields and baffles, and compared with calculations. The acceptance criterion is an agreement between measurements and calculations within ±15%. For some variants, the pressure drop of all produced series modules has been measured at different flow rates to check whether the scattering of the measured values remain within ±10%. When the pressure drop test was not performed, a so-called “ball” test was performed. A sphere of 7 or 8 mm diameter is air propelled in the cooling pipe at the inlet and has to reach the outlet. The purpose is to check whether all seam welds between the different tubes have been adequately joined without creating a local restriction which may reduce the local heat transfer capability. The leak testing inspections has been systematically performed for all components with pressurized Helium. The maximal allowed Helium leak rates are: 5 10^{-7} Pa.ℓ/s @ room temperature and 4 MPa, 5 10^{-8} Pa.ℓ/s @ 160°C and 2.5 MPa.

5. Conclusion

The selected technology and manufacturing processes proved to be adequate and reliably reproducible for the production of the baffles and heat shields of W7-X. The challenge of the design was to reproduce the specified 3D shape of the components with 2D parts as the heat sinks are vacuum brazed onto flat pipes. The design guidelines allowed a more efficient work organization, which has a direct impact on the time schedule and costs because the baffles are made of about 110.000 parts and the heat shields of about 120.000 parts. The complexity of the fabrication was not only determined by the manufacturing process of the modules within a high level of accuracy but also by the production of the required jigs corresponding to each variant of baffles and heat shields. The quality of the delivered components has been guaranteed by a series of inspections performed according to a detailed quality plan. Presently, the production of the baffles and heat shields is nearing completion and the next step is the installation of these components inside the plasma vessel of W7-X.

References

[1] R. Stadler et al., The in-vessel components of the experiment Wendelstein 7-X, Fus. Eng. Design 84 (2009) 305-308

[2] J. Boscary et al., Design and technological solutions for the plasma facing components of Wendelstein 7-X, Fus. Eng. Design 86 (2011) 572-575.

[3] J. Boscary et al., Design improvement of the target elements of Wendelstein 7-X divertor, Fus. Eng. Design 87 (2012) 1453-1456.

[4] A. Peacock et al, The procurement and testing of the stainless steel in-vessel panels of the Wendelstein 7-X stellarator, Fus. Eng. Design 86 (2011) 1706-1709.

[5] H. Greuner et al, Final design of W7-X divertor plasma facing components-test and thermo-mechanical analysis of baffle prototypes, Fus. Eng. Design 66-68 (2003) 447-452.