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Customized Manufacture of Graphite Tiles According to the As-Built Situation of Wendelstein 7-X Interior

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After the first operation phase of Wendelstein 7-X, performed nearly without any graphite inside the vacuum vessel, completion of the vessel interior with the graphite tiles for the baffles and heat shields has been carried out. The tiles have been installed on the ready assembled cooling structures. Since the practically achieved alignment accuracy of the cooling structures does not fit to the required tight alignment tolerance of the tiles (for gaps between two tiles: 3 mm, +4 mm, -0.5mm; for steps: lower than 3mm) the as built position of the cooling structures was measured and the tiles were customized according to the as-built situation. The paper describes the measurement process inside the vacuum vessel and the reverse engineering process used for the adaptation of the tile CAD-models. In addition the machining process and the assembly of the tiles are presented.

Approx. 3000 out of 8000 graphite tiles have been customized. Finally all tiles could be installed inside the required tolerances. From the first scan to the installation of the last tile the complete process toke approx. 10 month. Due to a tight monitoring off all processes involved the installation of tiles could be completed in time.

Keywords: Wendelstein 7-X, assembly, metrology, graphite interior, as-built manufacture

1. Introduction

After a successful first Operation Phase (OP 1.1; from December 10th 2015 to March 10th 2016) Wendelstein 7-X (W7-X) went into a Completion Phase (CP 1.2a) which comes now to an end.

Goal of the first OP was a very early check of all main systems of the experiment as well as obtaining the first experience in the plasma physics behavior of W7-X. For the first OP the experiment was equipped with a fivefold symmetric limiter and only a set of vital diagnostics. Especially the divertor and most of the graphite interior were not installed.

The design of the limiter was chosen in such a way that most of the thermal energy of a plasma discharge is taken by the limiter and no risk of a thermal overload of other in vessel components exists. Since the limiter had been only inertial cooled the maximum energy per plasma discharge was restricted to 4 MJ in OP1.1. The longest discharges obtained in OP1.1 last up to 6 sec at a heat power of 0.6 MW. For shorter discharges the heat power could be increased up to 4.3 MW. The results of the first OP of W7-X are promising. All main systems worked properly [1]. The heat load on the limiter proves as estimated. No indication of an unsymmetrical head load distribution occurs. No structure in the plasma vessel showed damages due to plasma operation.

Especially the geometry of the magnet field turned out to be of a very high quality. Field line measurements at two cross sections of the main field showed the expected field topology in particular the forecasted position and shape of islands. The residual deviations of the as-built field compared to the design are smaller than one part in 100000 [2, 3]. The measured results confirm error field calculations made on the base of geometry measurements of the coils shape and position during manufacture and assembly of the magnet system [4].

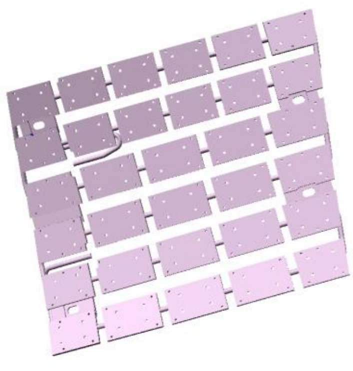

Fig. 1: CAD model of the cooling structure module of a heat shield. The size is approx. 650 x 600 mm². On each of the single heat sinks (approx 100 x 100 mm²) graphite tiles had to be installed

The main goals of the next OP (OP 1.2a) are the increase of energy per plasma discharge and the increase of the number of applicable magnet field configurations. In preparing of these goals the limiter had to be removed and the test divertor units (two units per each out of 5 modules of W7-X) have to be installed inside the vacuum vessel. In addition approx. 8000 graphite tiles have to be mounted on pre-installed cooling structures of the baffle and heat shields, which surrounds the divertor and should protect the plasma vessel walls from heat load coming out of the plasma.

Fig. 1 shows the CAD model of the cooling structure of a heat shield. In general the cooling structure of a heat shield consists of approx. 15 … 30 heat sinks of a size of approx. 100 x 100 x 12 mm³ made from Cu-Cr-Zr. The dimensions of a heat shield vary from approx. 300 x 800 mm² to 680 x 600 mm². The single heat sinks are connected to each other by stainless steel pipes of a dimension of 12 x 1 mm. Each cooling structure carries 4 … 6 geometric check points situated approx. 100 mm away from the edge of the component. In fig. 2 the arrangement of all cooling structures of the heat shields of one half module of W7-X (one half module is equal to 1/10 of W7-X) is shown.

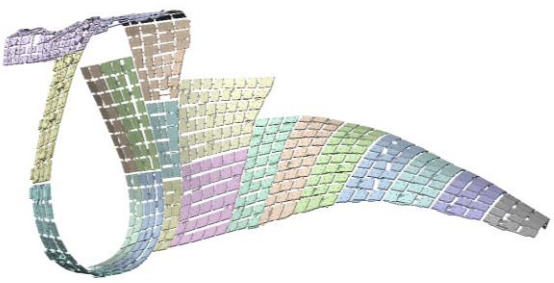

Fig. 2: CAD model of the cooling structures of heat shields of a half module of W7-X. Different colors represent different cooling structure modules

The cooling structures of the baffles are highly comparable with these of the heat shields, especially with respect to the graphite tile assembly.

2. Starting situation for graphite tile assembly

During construction of W7-X the prerequisites for the test divertor assembly and the graphite tile installation had been made. For the divertor assembly the mounting frames had been installed and adjusted. Thus, in the current completion phase the test divertor units have to be fixed only into their frames. A connection of the divertor units to the cooling water system which is necessary for steady state operation is foreseen only in one of the future completion phases (CP 2).

In comparison to the divertor assembly the initial situation for the assembly of the graphite tiles on baffle and heat shields proofed more complex. During construction of W7-X all cooling structures of the baffle and heat shields had been installed using brackets or weld studs to fix the components on the plasma vessel walls. Adjustment was made within a practical reasonable and trial tested tolerance sphere of dr <= 1.5 mm for each check point on the components. The application of smaller tolerances much more convenient for the later installation of the graphite tiles had to be refused since smaller tolerances result in inacceptable longer assembly times or make the adjustment itself impossible in many cases.

The shape of a tile is mainly trapezoid with sizes of approx. 150mm per dimension. Fig. 3 shows a CAD-model of a typical graphite tile designed for a heat shield.

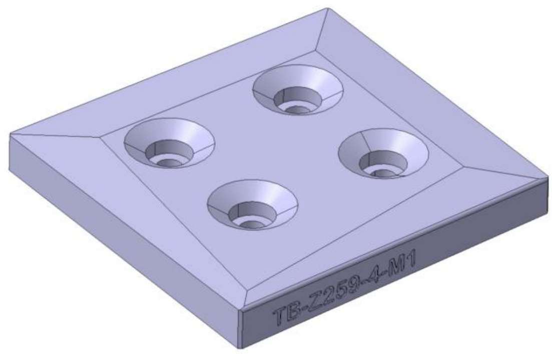

Fig. 3: CAD model of a typical tile used on heat shields (approx. 150x150x15mm³). Fixation with 4 x M6 screws allows a practical alignment of the tile of only some tenth of a Millimeter

All tiles for baffle and heat shields have been ready manufactured before starting of CP1.2a. Machining was done with tolerances of only some hundredth of a Millimeter.

The graphite tiles are fixed to the heat sinks by using 2 … 6 screws depending on the size of the tile. This gives a practical freedom in alignment of the tile in the order of only some tenth of a Millimeter.

From heat load reasons there are two main alignment criteria for tile installation: 1.) The gap between neighboring tiles has to be 3 mm with tolerances of minus 0.5 mm and plus 4 mm. 2.) The step between neighboring tiles has to be lower 3 mm.

For neighboring tiles of one and the same cooling structure the total tolerance chain is adequate and the alignment criteria are achievable by simple fixing the tiles onto the heat sinks.

Forced by the practically limited alignment accuracy of the cooling structures the alignment criteria for tiles on the edge of cooling structures cannot be met without further measures.

Especially the minimum size of the gap (2.5 mm) cannot be guaranteed by simple fixing the tiles on the cooling structures. Even a risk of clashes of neighboring tiles exists.

To cope with that situation a modification of the tile size according to the as-built situation of the cooling structure position became necessary. Modification of tiles toke place in three steps:

1. Measurement of the as-built position of cooling structures
2. Modification of CAD-models of the tiles according to the as-built-situation
3. Machining of prefabricated tiles or manufacture of new tiles according to the new CAD-models.

3. Scan of the actual cooling structure position

The measurement process of the actual cooling structure positions had to fit into the general workflow inside the vacuum vessel. Therefore the measurement process had to satisfy four criteria:

1. The accuracy of the gap and step size determination has to be better than 0.5 mm.
2. The measurement point grid has to be lower/equal than 1 x 1 mm².
3. The process time has to be as short as possible; especially the installation of a tripod or an adequate fixation structure for the measurement system has to be avoided.
4. Compatibility to vacuum environment and to the tide clearance inside the vacuum vessel

All these criteria can be fulfilled by the scan system HANDY SCAN 700. Since the system is hand guided there is no need for a tripod. The only prerequisite for a measurement is the installation of a rigid reference point system closed to the object to be measured. Fig. 4 shows the solution of such a reference point system used inside the vacuum vessel.

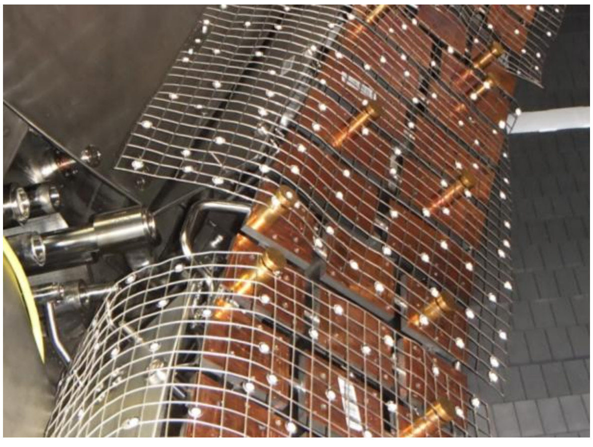

Fig. 4: Reference point system installad on cooling structures. The reference points (white points) are fixed in arbitary distances at a stainless steel wire grid

On a stainless steel wire grid the reference points are fixed in arbitrary distances with a maximum distance of 150 mm. The grid is fixed on the cooling structures using studs fitting into thread holes of the heat sinks. In pilot surveys it was shown that the installation of the reference point system is much faster than the installation of a tripod or a fixation bracket for a common measurement system. No removal of a ready installed component is necessary.

Fig. 5 shows the result of a scan of heat shield cooling structures. The scan process turned out to be easy manageable even for non professional metrology staff, no special treatment of the surfaces to be scanned is necessary (spraying).

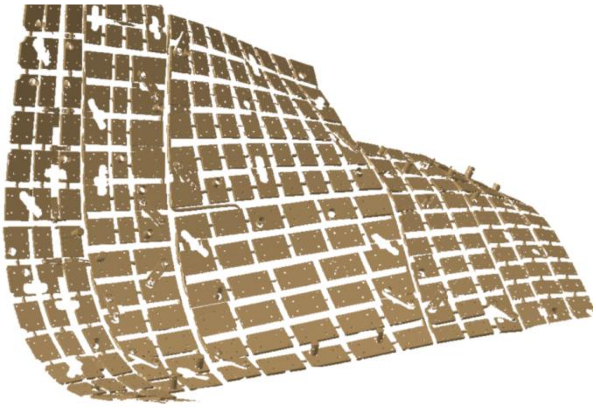

Fig. 5: Scan of as-built position of heat shield cooling structures.

4. Customizing of graphite tiles

The scans are used in a reverse engineering process to adapt the size of the CAD-models of the tiles if necessary. In a first step a virtual assembly of the tile models onto the scan is made (fig. 6). The models of corresponding tiles are cutted-off if the actual gap between them is to tide. In case of an oversized gap a new, bigger model of the tile is created. In all cases of gap modification the gap has to show parallel planes afterwards. In case of an oversized step a chamfer is modeled on one of the tiles.

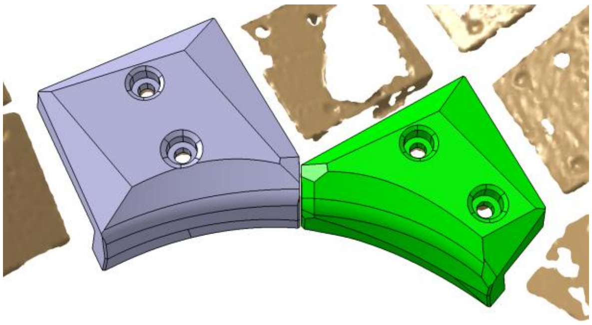

Fig. 6: CAD-models of tiles virtually fixed on a scan of cooling structures. After an analyze of the gap and step between the CAD-models the CAD-models are modified for a later machining.

The reverse engineering task was done by an external design office. In a period of 9 month approx. 110 scans of the cooling structures of baffles and heat shields have been analyzed. 3000 out of 8000 tile models have been modified whereas in most cases the models have been cutted to the right length. Only in a few number of cases the manufacture of new tiles became necessary from oversized material.

Machining of modified or new tiles toke place on a 5-axis-mill in a dry process (fig. 7). Depending on the complexity of machining two to ten tiles have been reworked or new manufactured per day.

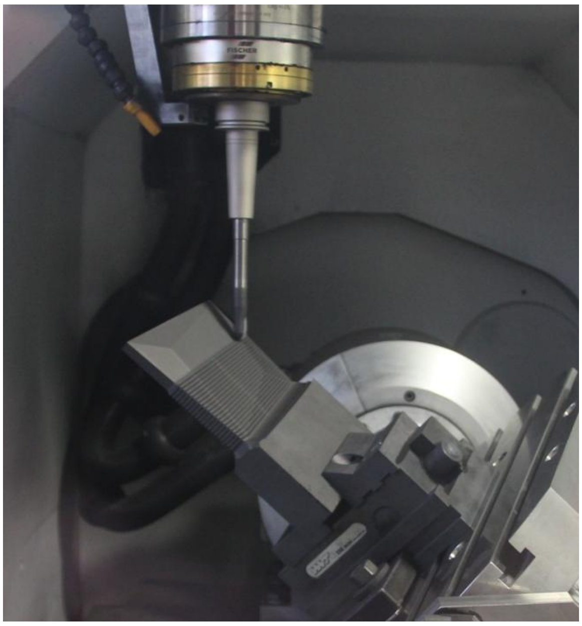

Fig. 7: Milling of graphite tiles on a 5-axis machining center in a dry process.

After machining, all tiles have been backed out under vacuum conditions at 2000°C to satisfy the cleanliness requirements of in vessel components.

Fig. 8 shows the assembly of the first graphite tile on a heat shield inside the plasma vessel of W7-X.

Fig. 8: Assembly of the first out of 8000 graphite tiles at W7-X

After installation of neighboring tiles the gap size and step high are always checked by means of a feeler gauge or a ruler.

In a period of approx. 3 month all graphite tiles have been installed with a rate of up to 180 tiles per day. Parallel work of up to three teams and an intense and well prepared logistic was necessary to meet the schedule.

5. Conclusion

The high requirements on the alignment tolerance of the graphite tiles (gap: 3mm, +4mm, -0.5mm; step: 0…3mm) does not match with the practical achievable alignment tolerance of the cooling structures (dr <= 1.5mm) acting as the carrier of the tiles.

In case of neighboring tiles of adjacent cooling structures the risk of undersized gaps or even clashes between tiles proofed to be as non negligible. Therefore a measurement of the as-built position of the ready installed cooling structures became necessary with a measurement accuracy of 0.5mm inside a volume surrounding at least two cooling structures.

A hand guided scanner (Handy Scan 700) proofs as an appropriated tool to measure the as-built position of cooling structures. No tripod or similar fixation structure is necessary which makes the hand guided scanner to a fast and flexible measurement tool inside the vacuum vessel.

The analysis of the as-built situation showed that 3000 out of 8000 tiles had to be customized. In most cases customizing could be performed using prefabricated tiles. Finally all graphite tiles inside the vacuum vessel were installed within the required tolerances for gaps and steps.

Measurement and analysis of as-built situation, modification of CAD-models, machining and installation of tiles toke approx. ten month. Only long and intense preparations of each single process step as well as a thigh and consequent monitoring, sometimes on a daily basis, ensured that the schedule for tile assembly has been met successfully.

Commissioning of OP1.2a started with evacuation of cryostat and vacuum vessel in time in May 2017.

6. Acknowledgement

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