Manufacturing and Testing of Vertical Target Qualification Prototypes for ITER

T. Huber*, H. Traxler*, L.S. Sigl*,
B. Riccardi**, M. Merola***, F. Escourbiac****

*PLANSEE SE, Reutte, Austria

**Fusion for Energy, Barcelona, Spain

***ITER Organization, Cadarache, France

****CEA Cadarache, Cadarache, France

Abstract

Within the ITER fusion reactor one of the most challenging components is the divertor, whose main function is to extract the power from the scrape-off layer of the plasma and to maintain plasma purity. The main divertor components are (i) the inner and outer vertical target (IVT, OVT), (ii) the dome liner and finally the cassette body which integrates the two targets and the dome. The IVT comprises various materials which form a composite, highly resistant to cyclic thermo-mechanical loads. The armour, i.e. the plasma facing subcomponent, is made either of carbon fibre reinforced carbon composite or tungsten and is joined to an actively cooled heat sink, consisting of precipitation hardened CuCrZr. The individual components of the IVT are joined by technologies such as copper casting, active metal casting, electron beam welding and hot isostatic pressing.

Two qualification prototypes for the divertor's IVT were manufactured by Plansee. The manufacture and the non-destructive testing (NDT) methods, which have been applied to assure specified quality requirement of the components, are described. NDT is an integrate part of the manufacturing chain and allows "online monitoring" of product quality. High heat flux (HHF) tests were performed to check for the cyclic thermo-mechanical performance. The components were exposed to heat loads of up to 5 MW/m² at the tungsten part and 20 MW/m² at the CFC part, respectively. HHF test results are presented and discussed.

Keywords

ITER Vertical Target, CFC, Tungsten, Joining, Non-Destructive Testing, High Heat Flux Testing.

Introduction

The ITER divertor (Fig. 1) is among the components which face the highest thermal loads within the ITER fusion reactor system. Therefore the ITER Organization (IO) decided to perform a qualification phase for the inner/outer vertical targets as well as for the dome liner prior to procurement activities. In the qualification phase a potential supplier needs to demonstrate its technical capability to comply with technical tasks, required quality assurance and projected timetables [1]. Significant R&D efforts have been invested to develop appropriate acceptance criteria for the high heat flux units of the divertor components [2]. The acceptance criteria are mainly based on the evaluation of the armour to the heat sink joint, carried out by non-destructive testing such as ultrasonic examination and infrared thermography.

The present reference design foresees two different types of armour, (i) tungsten monoblocks on the upper curved section of the VT and (ii) carbon fibre composite (CFC) monoblocks on the lower straight section (Fig. 2). Furthermore an additional alternative armour design option was built, which comprises tungsten flat tiles on the upper curved section instead of monoblocks (Fig. 3). Both designs comprise precipitation hardened CuCrZr tubes which allow the coolant to pass through the composite just below the hot armour. To increase the capacity for heat removal and thus the critical heat flux limit, a twisted tape is inserted into the lower straight section of the tube.

Accordingly to the acceptance criteria, the divertor plasma facing components (PFC) shall withstand 3.000 pulses of 400 seconds duration at nominal parameters, including 300 disruptions at full power and 300 at slow transients [3]. During normal operation conditions the vertical target is expected to receive a surface heat flux limited to about 10 MW/m^2 at the strike point region and less than 5 MW/m^2 at the baffle region. Under conditions of slow transient thermal loading the divertor's lower vertical target region has to endure a surface heat flux of up to 20 MW/m^2 for sub-pulses of less than 10s. Therefore, the high heat flux tests programme for the vertical target qualification prototypes was chosen to be 1000 cycles at 3 and 5 MW/m^2 at the curved tungsten section and 1000 cycles at 10 and 20 MW/m^2 at the straight CFC section, respectively.

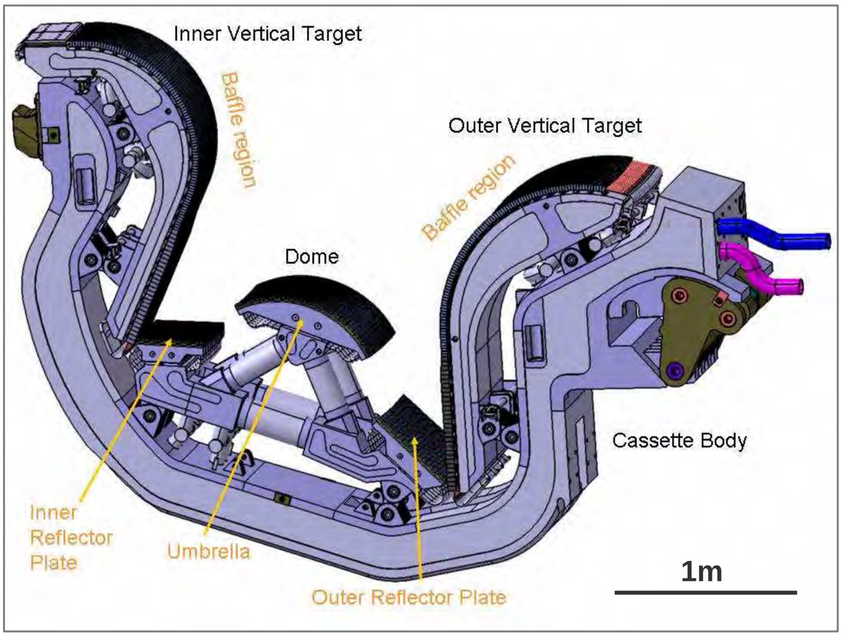

Fig. 1: Schematic view of the ITER divertor.

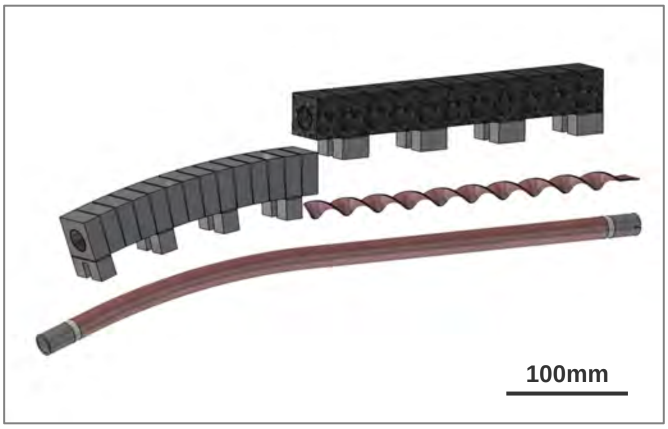

Fig. 2: Design of a single VT full monoblock heat flux unit.

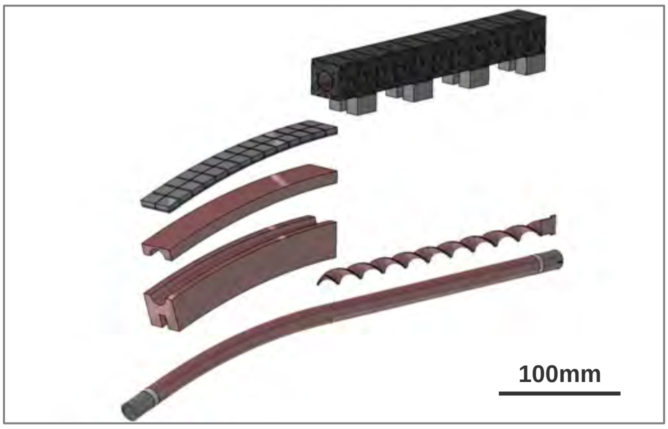

Fig. 3: Design of a single VT mono flat tile heat flux unit.

Manufacturing

Each vertical target qualification prototype consists of three single high heat flux units, mounted to a stainless steel structure (Fig. 4 and Fig. 5). In both designs the straight part consists of CFC monoblocks. Two design options were selected for the curved section of tungsten parts, resulting in (i) tungsten monoblocks (full monoblock option) and (ii) tungsten flat tiles (mono flat tile option). The cooling tube is made of a precipitation hardened CuCrZr copper alloy, which is extended by stainless steel tubes on both ends. The fixation of the single high heat flux units to the support structure is performed via stainless steel attachments at selected monoblocks. The joining technologies employed are copper casting of tungsten, active metal casting of CFC and hot isostatic pressing of the armour to the cooling tube. For monitoring the quality of joints, several 100% non-destructive tests by means of radiographic and ultrasonic inspection were performed in accordance with EFDA specifications.

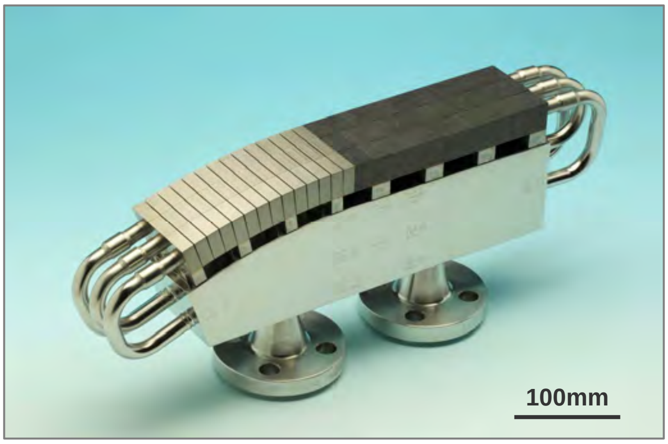

Fig. 4: IVT full monoblock qualification prototype.

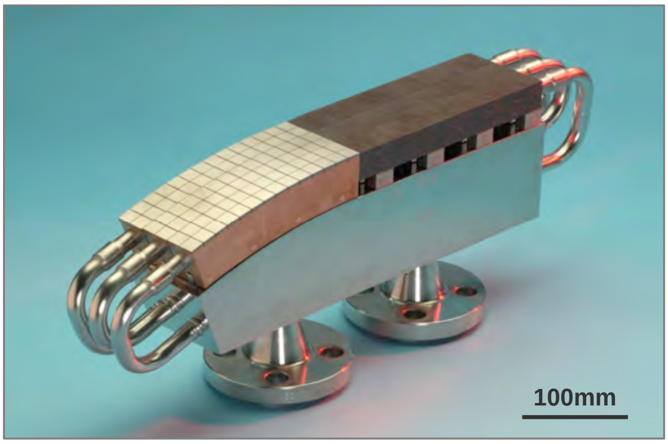

Fig. 5: IVT mono flat tile qualification prototype.

Joining of the CuCrZr cooling tubes to the 316L stainless steel tube extension is accomplished by electron beam welding. A small slice of the high temperature resistant, nickel-chromium based super-alloy Inconel 625 is used as a welding adapter between CuCrZr and 316L (Fig. 6) to overcome the limited weldability of the two materials. Welding of Inconel is quite difficult due to a tendency for cracking and microstructural segregation of alloying elements in the heat affected zone. However, Inconel 625 is capable to overcome these problems. Improvements on this joint have been highly important for the manufacturing of the prototypes [4]. The quality of the welds was verified by radiographic inspection and helium leak testing. After corrective bending to the specified shape, the CuCrZr tube section is nickel plated to support diffusivity for a better bonding during hot isostatic pressing.

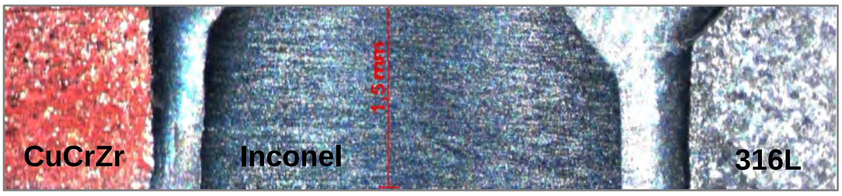

Fig. 6: Cross section of electron beam welded CuCrZr/Inconel/316L transition.

Europe's material choice for CFC is NB41, a CFC grade produced by Snecma Propulsion, France. Inside the NB41 the ex-pitch fibres are perpendicular to the plasma facing surface. Subsequent processing of the CFC monoblocks uses two technologies developed by Plansee, (i) laser structuring of the CFC surface prior to joining, followed by (ii) active metal casting® (AMC). These processes are crucial and contribute significantly to the resistance of the CFC/Cu interface against cyclic thermo-mechanical loads. Applying laser surface treatment to the monoblocks drills several hundreds of small cones into the CFC joining surface. This increases the total joining surface and at the same time forms a gradient layer between CFC and the cast Copper. The method for joining copper to CFC is accomplished by active metal casting, which is a copper casting process, performed in the presence of carbide forming elements. This process produces an AMC® layer (Fig. 7) which consists of pure copper, containing small quantities of Si and Ti compounds.

The CFC/Cu transition is examined non-destructively by radiographic testing using an adequate reference block. Thus, small flaws down to Ø 3 mm and even non-filled laser cones can be detected. Unfortunately, cracks can not be found, because ultrasonic inspection is not applicable due to the porosity of the CFC.

Manufacturing of the tungsten monoblocks and flat tiles is performed by direct casting of copper to the tungsten surface, which results in a pure copper layer on tungsten (Fig. 8). The monoblocks and flate tiles are oriented such that the grains are parallel to the heat-flux direction. Both, monoblock and flat tile cast interfaces are examined by ultrasonic inpsection using an adequate reference block. Thus, small flaws in the cast interface larger than Ø 3 mm can be detected.

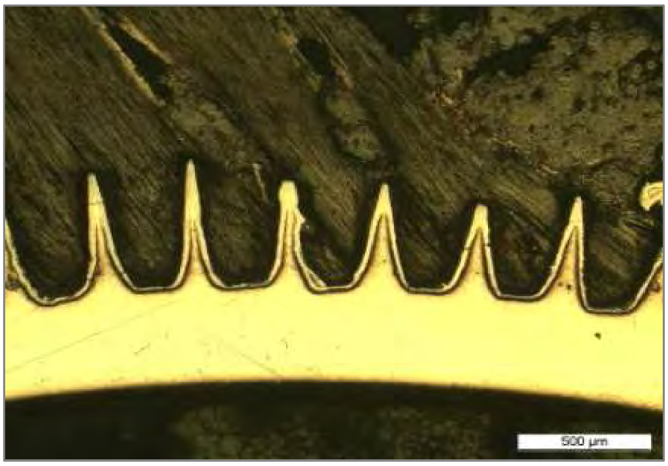

Fig. 7: Cross section of active metal cast CFC/Cu interface.

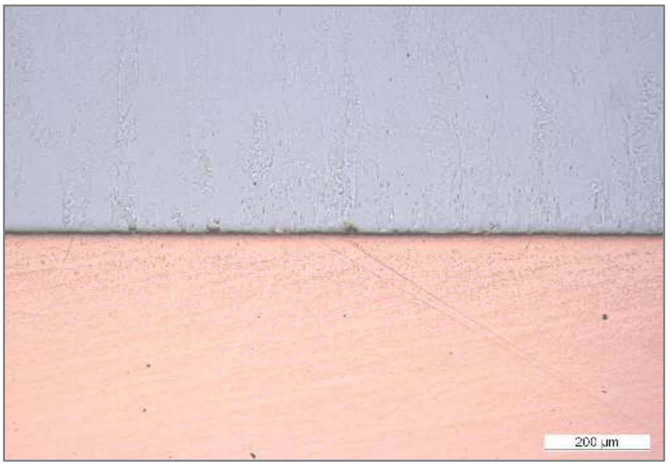

Fig. 8: Cross section of cast W/Cu interface.

Joining of the 316L steel attachment to the AMC layer (CFC monoblocks) and to the copper layer (W monoblocks) is performed by high temperature brazing with a nickel base braze alloy (BNi-2) at approximately 1040 °C. The braze alloy is silver-fr ee and can withstand high temperatures up to 970 °C . These temperatures occur during hot isostatic pressing and subsequent annealing steps. All the brazed interfaces are finally examined by ultrasonic inspection using an adequate reference block. Again, flaws in the brazed interface larger than Ø 3 mm can be detected.

Manufacturing of the single high heat flux units is performed by hot isostatic pressing. The single CFC/Cu and W/Cu monoblocks are assembled on the cooling tube to form the full monoblock option. In case of the mono flat tile option, the single CFC/Cu monoblocks and the W/Cu flat tiles are assembled to the cooling tube via two CuCrZr half shells. Subsequent to this assembly step, all components are enclosed into a steel can for hot isostatic pressing. Based on extensive evaluations of different sets of HIP parameters, e.g. low temperature HIP at 550 °C up to high temperature HIP in the range of 900 °C, the high temperature HIP process revealed significantly higher levels of reliability. Thermal treatment follows the HIP process to re-adjust the properties of the CuCrZr alloy (solution annealing at 970 °C for 30 min, gas quenching and age hardening at 475 °C f or 3 h). The HIP interface is finally NDT examined by inner tube ultrasonic inspection; a typical UT pattern is shown in Fig. 9. Small flaws in the interface of larger than Ø3mm can be detected. Tightness of the components is confirmed by He leak testing.

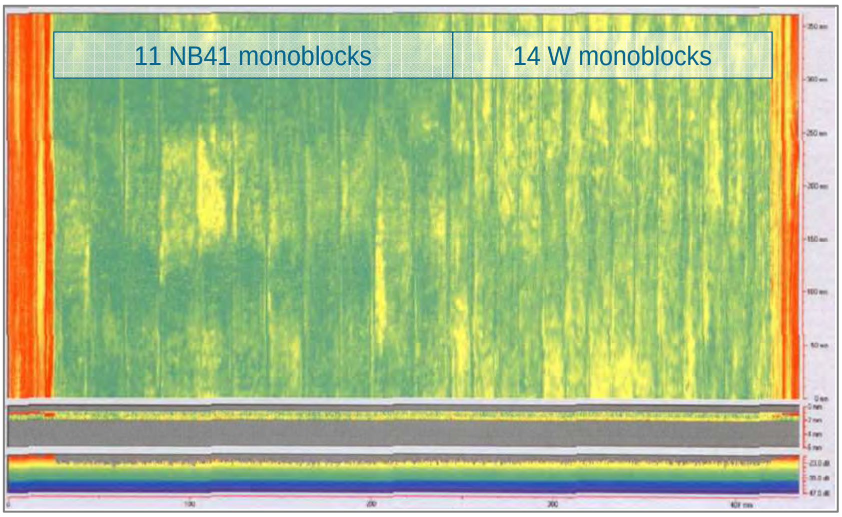

Fig. 9: Ultrasonic scan of the HIP interface of CFC/Cu and W/Cu monoblock armour to cooling tube.

Within the last two decades extensive R&D work has been performed in close collaboration between the European Fusion Development Agreement (EFDA) and PLANSEE. As a result of these development activities, high levels of reliability of the different joining technologies applied have been achieved. Single components, like monoblocks or flat tiles and even more essential, the fully assembled and hot isostatically pressed heat flux units show a very high rate of yield, i.e. rejection rates of single monoblocks or flat tiles are less than 5 %. Hot isostatic pressing of fully assembled components was performed without rejection due to flaws or leaks. From a manufacturing point of view, there is obviously no technical limitation for any of the two options. However, in case of assembly work for HIP, the flat tile option is more delicate. Therefore the full monoblock option is considered the most reliable option with reduced risks of manufacturing.

Thermographic Inspection

One of the most challenging issues in the NDT of divertor components is the inspection of the CFC/Cu monoblock joint with respect to interface cracks which do disturb the heat transport. Standard NDT methods like ultrasonic inspection or radiographic inspection cannot be applied to detect interface cracks. Experience gained in previous divertor projects show that thermographic inspection is the most appropriate tool for this purpose [5, 6]. Two thermography test methods have been applied during manufacture of the QVTPs, i.e. the ARGUS method and the SATIR method, respectively.

Industrial thermography inspection requires a rapid method which can be applied at any stage of production. This is possible by using an external heat source. In the frame work of the Wendelstein 7-X divertor target project, extended experience with pulsed thermography testing (PTT) was obtained and turned out to be the most effective method to fulfil the required defect resolution required [7]. So far, only flat tile divertor components where inspected with PTT. In the frame of the production of the vertical target prototypes the application to CFC monoblock components was demonstrated. The experimental setup developed in the Plansee testing laboratories was named ARGUS and is shown in Fig. 10.

The power supply of the heat source used for PTT releases an electrical energy of 12 kJ within 50 ms. One pair of flash bulbs transforms the electrical power to a flash of light and thermal radiation which is directed towards the surface of the part under inspection. The cool down of the component after the flash is recorded by an infrared camera containing a high thermal resolution matrix detector (noise equivalent temperature difference at 30 °C = 20 mK). Via fast Fourier transformation the time dependent cool down behaviour of each pixel is transformed into the frequency domain. The results are two series of images, the amplitude and the phase image, respectively. The phase image of the first harmonic frequency is chosen for NDT of the CFC/Cu interface. For the heat transport polar cracks are critical, whereas CFC fibre separations at the side surface of the components are considered to be negligible.

The monoblock design requires the inspection from four sides to check for defects in different locations. The influence of defect size on the PTT image has been derived by finite element modelling [8]. The dependence of the phase image on the radial defect extensions is shown in Fig. 11.

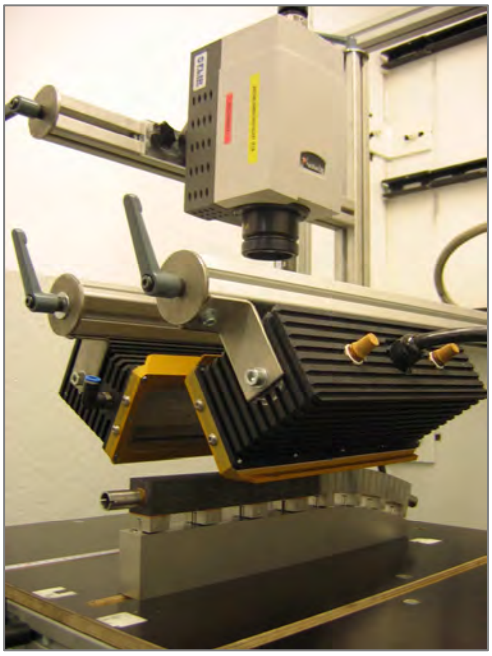

Fig. 10: Experimental setup of ARGUS facility.

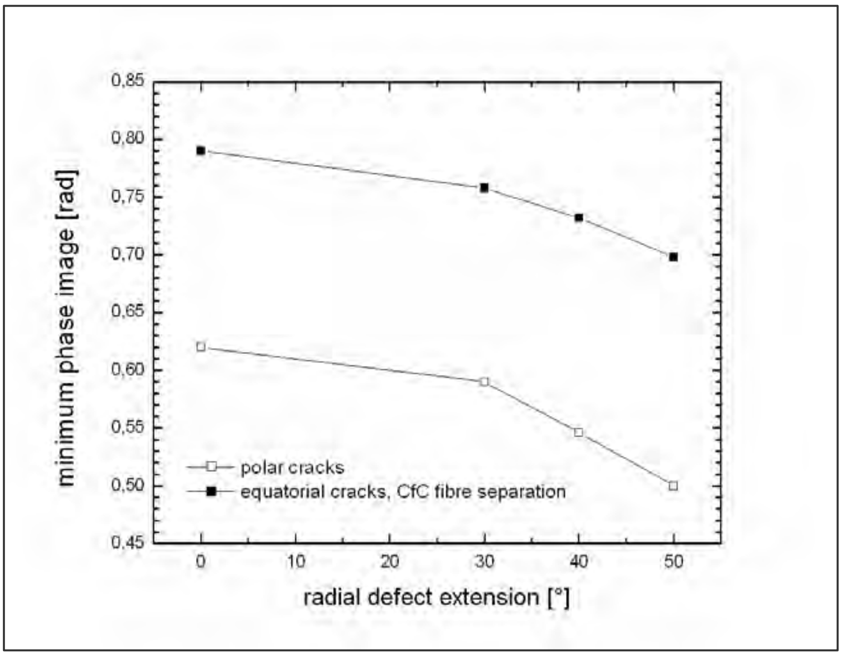

Fig. 11: Dependence of the PPT phase image on the radial defect extensions.

This information is the base for the definition of acceptance criteria for different defect classes as defined by the ITER specification [7]. The PTT inspection was performed on all Plansee vertical target qualification prototypes. The biggest defects observed are shown in Fig. 12.

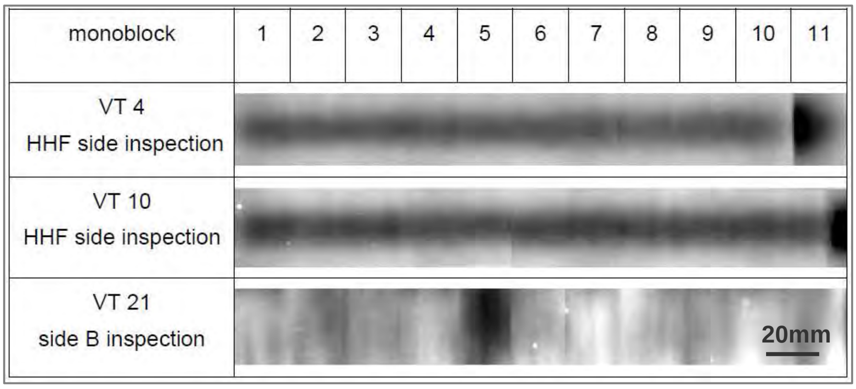

Fig. 12: Biggest defect indications (dark areas of phase image) observed by PTT on the ITER vertical target prototypes.

Since the experience in the inspection of monoblock design components is yet fairly limited, the defect indications can not be classified. Thus, the vertical target prototypes where investigated additionally by computed tomography (CT). The CT results confirm the PTT defect indication. The PTT defect size appears systematically smaller than the defect size derived from CT. This can be explained by the irregular shape of the cracks. Small branches of the cracks may be recognized by CT but do not influence the PTT phase image. However, less than 2 % of monoblocks contain such defects.

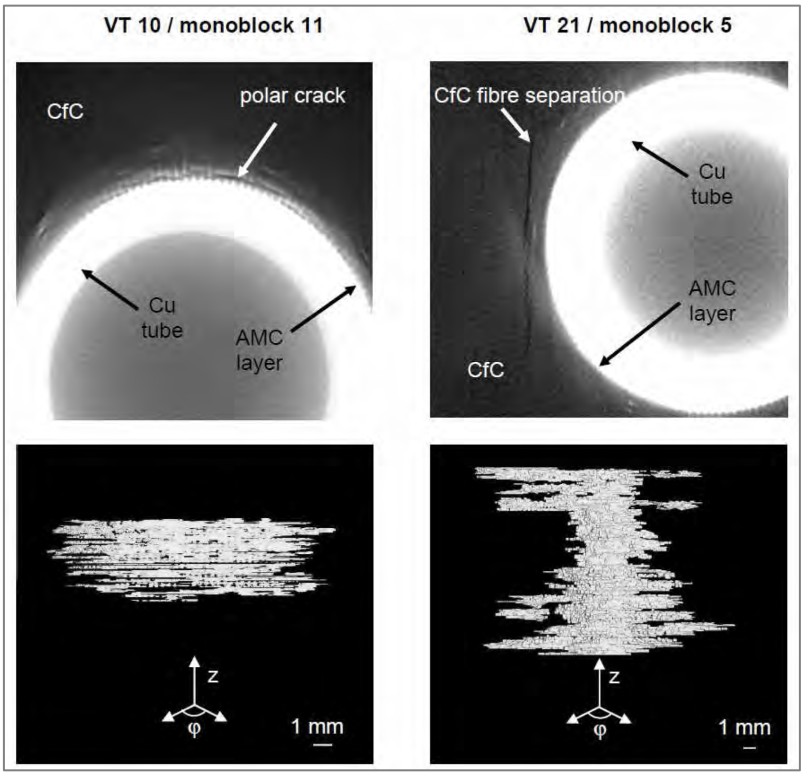

Fig. 13: Results of CT of two defect indications observed by PTT. The cross section slice (top) and the shape of the defect (bottom) are shown for VT10/monoblock 11 (left) and for VT21/monoblock 5 (right).

In addition to the ARGUS technique, an inspection with the so-called SATIR facility was performed at CEA Cadarache after the manufacture of the single HHF units, but prior to insertion of the twisted tape [9]. The principle of the SATIR active thermography technique [10] is based on the detection of a time delay of the surface temperature, which evolves during the fast decrease of the water temperature in the cooling tube. An imperfection at any joint or material would increase thermal resistance, thereby inducing an increased delay during the transient thermal regime. This delay is assessed by comparing the thermal behaviour with a “defect-free” reference component. The maximum value of this delay, called DTref_max

(°C), is calculated for each pixel on the infrared images. SATIR is a functional technique which can be used both for W and CFC materials. In this study, the technique was applied to CFC monoblock samples only. Thermal responses of a CFC monoblock are measured on the three sides (left-top-right).

The physical relation between DTref_max and the radial extension and position of the CFC/Cu joint was established both by finite element modelling, taking into account property variation of materials and the background noise of the test bed, and by tests on samples with calibrated defects, which were defined in the framework of the acceptance criteria definition for the ITER Divertor [2] (Fig. 14).

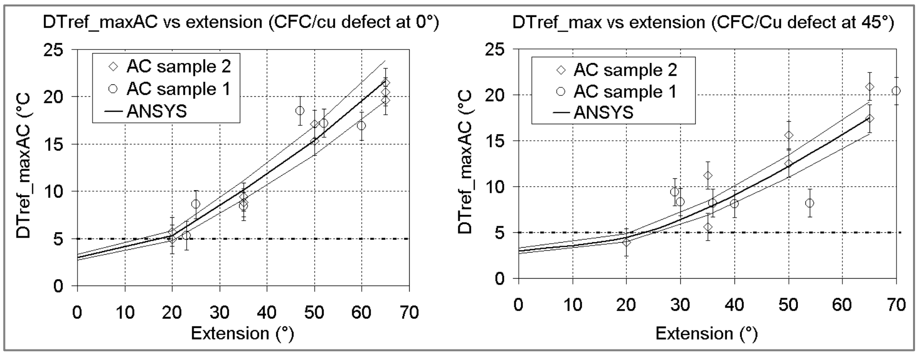

Fig. 14: Comparison between measured and calculated DTref_Max obtained on top surface for defects at position 0° and 45°.

The radial extension of a defect is estimated via the reversed geometric projection of the defect at the interface from the DTref_max cartography, taking into account the orthotropic ratio of the CFC thermal properties. The error of the estimate of the defect position is about ± 5°. The axial length of the de fect is also estimated by this data processing technique.

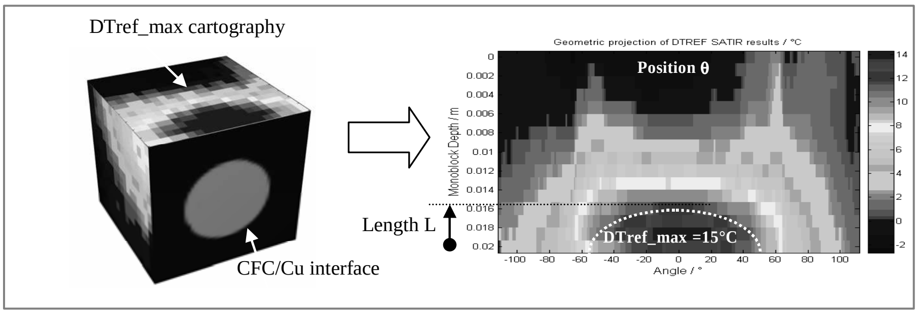

Fig. 15: Geometric projection of the three DTref_max cartographies of the monoblocks #11 (VT4 prototype) at the CFC/Cu interface to define the defect position θ (=0°) and axial length L (1/5Lmonoblock).

It was found during previous studies [2] that a 50° maximum radial extension of CFC/Cu joint defect is acceptable with respect to thermo-mechanical fatigue requirements. 54 CFC monoblocks among 55 inspected fulfilled this criterion. The largest indication of defect was obtained on the CFC block #11 of the VT4 prototype (Figs. 15 and 16).

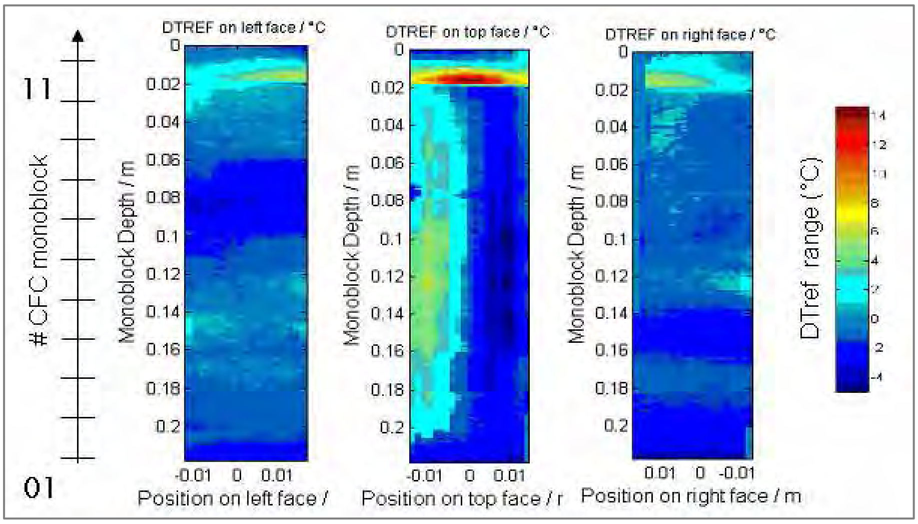

Fig. 16: DTref_max cartographies of the VT4 prototype.

High Heat Flux Testing

The two vertical target qualification prototypes were subjected to high heat flux (HHF) tests in the frame of the qualification phase for the procurement activities. The tests were performed by the Russian Domestic Agency at the TSEFEY-M facility [11] under a task agreement with the ITER Organization.

The high heat flux test programme is essentially the heating of the armour side of the prototype with an electron gun of 200 kW power. The prototype was placed in a vacuum chamber, actively cooled with pressurized water (typically 35 bar; 3,3 kg/sec; 11 m/s; 50-120 °C) and protected by copper masks so that the heated area was precisely defined and could be observed with a camera and infrared diagnostics (Fig. 17). The pulse duration was set at 15 sec., so that the surface temperature could reach thermal equilibrium. Heat flux density was derived from calorimetric measurements (2 sets of 4 K-type thermocouples immersed into the water at the inlet and outlet flanges).

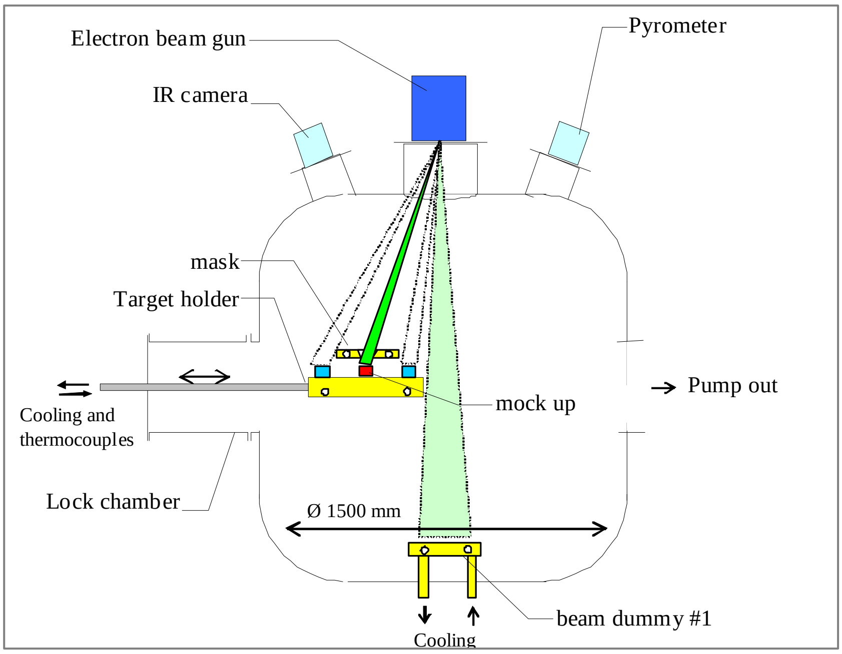

Fig. 17: Schematic view of TSEFEY-M vacuum chamber.

Prior to and after each step of cycling, thermal mapping at 1 MW/m² (W part) and 5 MW/m² (CFC part) was performed. As a general rule, a cycling step was considered successful, if the increasing of surface and water temperature between the thermal mapping steps was lower than 50 %.

Both W flat tiles and W monoblocks successfully sustained HHF cycling at 3 and 5 MW/m² for 1000 cycles each. 100 % of the W surface was tested and no increase of the surface temperature was observed. A typical surface temperature of W was measured in the range 300-380 °C for monoblock option and a 440-550 °C for flat tile option (Fig. 18). Visible light on the sides of the IR pictures does not signify overheating but reflections from the copper masks.

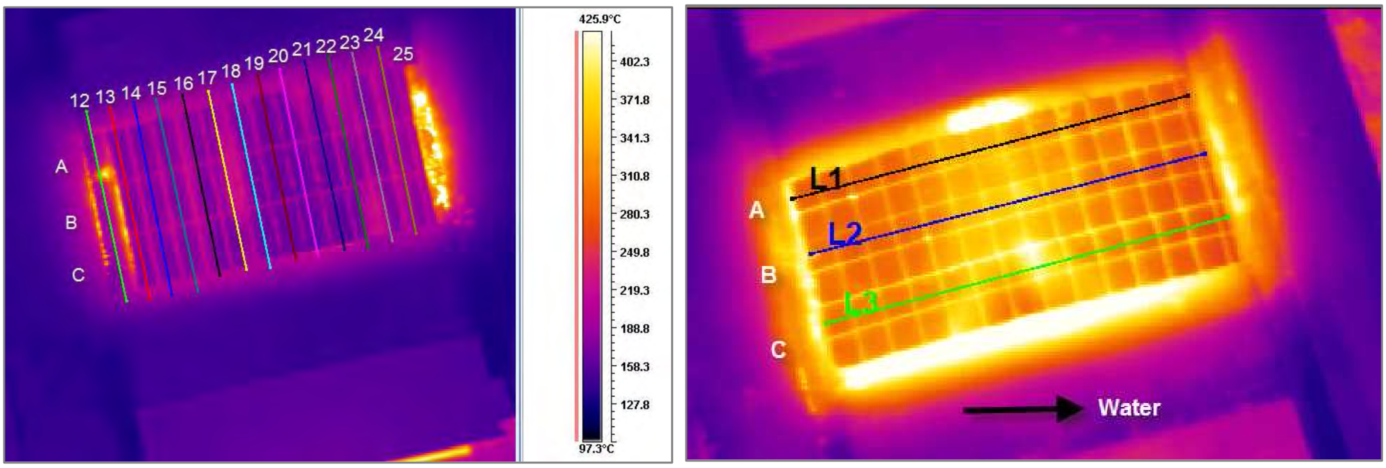

Fig. 18: Surface temperature map of the W region under a eat flux of 5 MW/m²
(left: monoblock option, right: flat tile option).

The CFC monoblock regions of both prototypes successfully survived the testing steps at 10 MW/m², 1000 cycles. The heated surface consisted of 5 blocks x 3 tubes on 2 areas, thus 30 CFC monoblocks were tested effectively. No increase of the surface temperature during the cycling steps was observed. The surface temperature of CFC was typically ranging from 500 to 600 °C, which is consistent with fini te element thermal calculations.

For HHF testing at 20 MW/m² the CFC monoblock region of the full monoblock prototype was divided into three test areas, each containing 3x3 monoblocks. During testing the surface temperatures were in the range 2300-2500 °C, whereas the finite element analysis calculated maximum surface temperatures of 1800 °C. Eroded CFC areas at the edges of the mo noblocks (Fig. 19) gave evidence that the incident heat flux was higher than 20 MW/m².

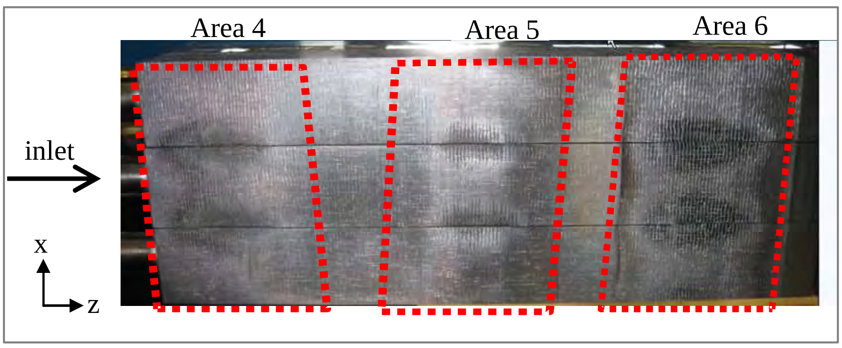

Fig. 19: Zoom on the CFC monoblock surface after testing.

A three-dimensional thermal analysis was performed with the ANSYS finite element code to determine the heat flux pattern, taking the swirl insert and sub-cooled boiling into account [12]. Radiation was implemented too, and a perfect contact between blocks was assumed. SNECMA NB41 properties were taken from ref. [13] up to 800 °C, extrapolated as for SNECMA NB31. Solving the reverse thermal problem, it was found that the maximum heat flux was in the range of 25 MW/m² on the eroded parts (Fig. 20) with a surface temperature comparable to experiments (Figs. 21 and 22).

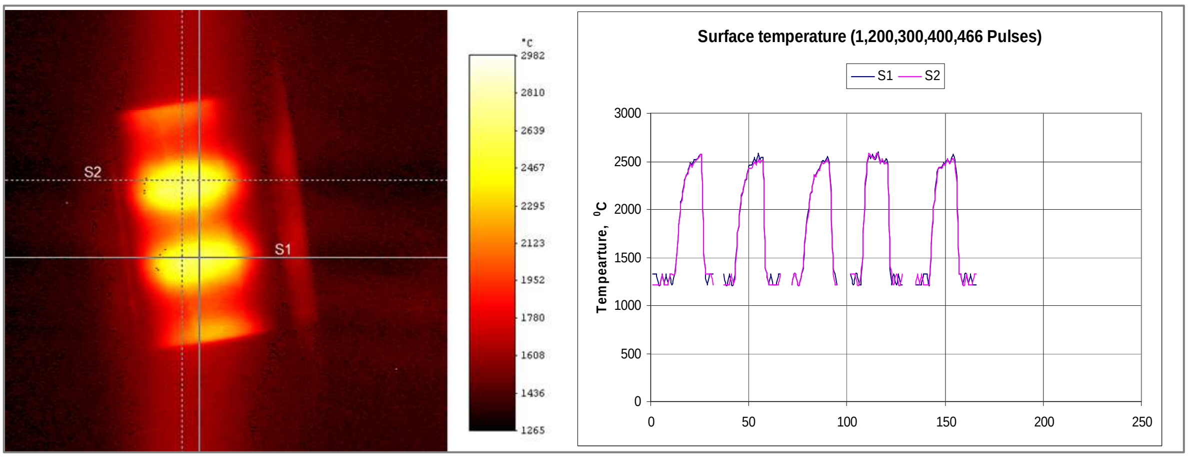

Fig. 20: Measured surface temperature at 20 MW/m² average absorbed heat flux and 25 MW/m² max. incident heat flux.

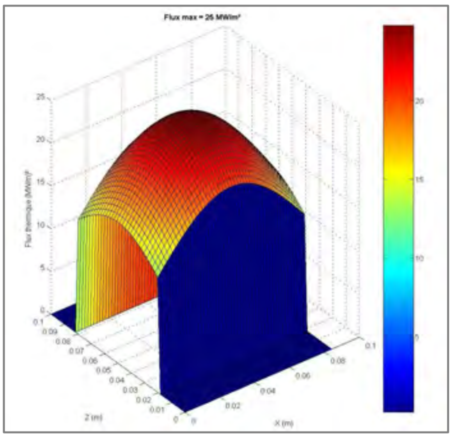

Fig. 21: Estimated heat flux pattern deposition (MW/m²).

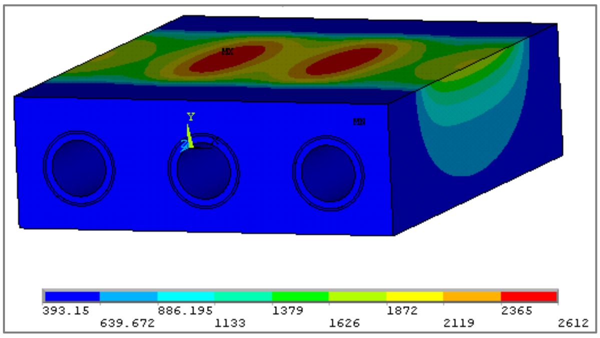

Fig. 22: Calculated surface temperature for 20 MW/m² average absorbed heat flux and 25 MW/m² maximum incident heat flux.

During the experiments, vacuum was lost in the test chamber (from nominal 10^{-4} mbar to 10^{-2} mbar) during testing of areas 4, 5 and 6 after 996, 510 and 472 of 1000 cycles respectively. Furthermore helium leakage was detected after HHF testing. The development of micro-cracks in the cooling tube, caused by fatigue is a likely cause for the vacuum degradation. Destructive examination will have to be performed in order to confirm this assumption.

Based on this result, it was decided to cut slots in-between the CFC monoblocks, which permit unconstrained thermal expansion of single blocks, thereby reducing the transmission of fatigue stresses to the CuCrZr tube. Slots were machined by wire-cutting of 4 mm depth, 0.7 mm width every 20 mm at the level of plane of contact in-between the CFC monoblocks (Fig. 23). Furthermore, sweeping of the electron beam was changed to obtain a more homogeneous incident heat flux on across the tested area.

Fig. 23: Top view of the CFC region of the mono flat tile prototype after slot machining (castellation).

Fatigue testing at 20 MW/m² and 1000 cycles was split into 5 sub-steps: The heated surface consisted of 2 blocks x 3 tubes (Fig. 24). The test was successful in the sense that no overheating was observed. During the 5th sub-step, vacuum degradation occurred after cycle #800, yet vacuum could be recovered by increasing the turbo-molecular pumping speed. Surface examination of the monoblock “A1” after this step revealed the presence of an axial crack in the CFC material (Fig. 25). This crack was not present at the beginning of the test. Its cause remains unclear and will be investigated by destructive examination.

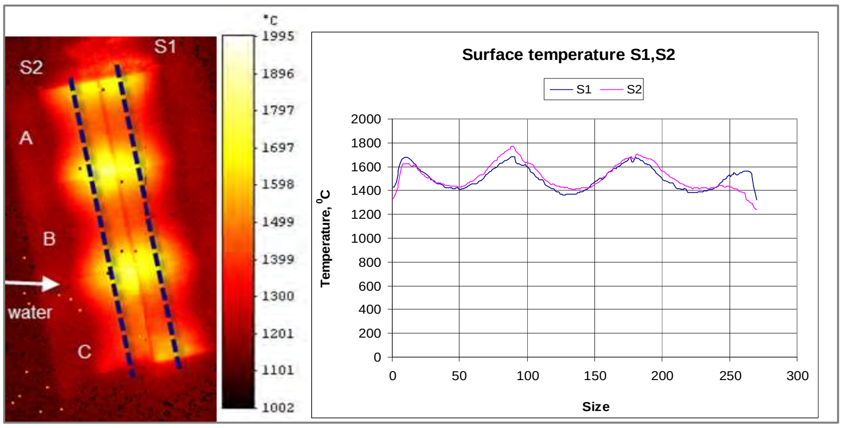

Fig. 24: Surface temperature cartography of CFC monoblocks at 20 MW/m² heat flux. S1 and S2 show a maximum T_{surf} of ~1800 ℃ (T_{calc} = 1780 ℃).

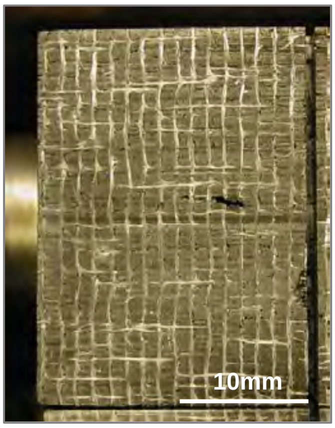

Fig. 25: Crack in the CFC monoblock “A1”, observed after 1000 cycles at 20 MW/m².

Concluding Remarks

Within the qualification programme of vertical target prototypes, the capability to manufacture W/CFC full monoblock and W flat tile / CFC monoblock components was demonstrated. As main joining techniques, active metal casting of CFC, copper casting of tungsten and hot isostatic pressing of the armour / cooling tube joint were applied with high reliability. Special attention was paid to non-destructive testing, including ultrasonic and radiographic inspection as well as leak tightness inspection of all joints at each manufacturing step. Two thermographic inspection methods were applied to assess the heat transport capability of the components. While the hot water test SATIR can be applied at the end of manufacture only, the flash light system ARGUS supplied valuable information at all stages of production.

Both the W flat tile and the W monoblock option survived the loading up to 5 MW/m² and 1000 cycles, i.e. satisfied the ITER requirements for the W part. For the CFC part, the load up to 20 MW/m², 1000 cycles was successfully attained on the prototype containing slots on the axial section between the CFC monoblocks. For an incident heat flux of 25 MW/m², vacuum degradation was observed after having reached more than 500 cycles. Manufacturing and high heat flux testing of the Plansee qualification vertical target prototypes can be considered successful, with clear potential for further improvements.

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