

European divertor target concepts for DEMO: Design rationales and high heat flux performance



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ABSTRACT

The divertor target plates are the most thermally loaded in-vessel components in a fusion reactor where high heat fluxes are produced on the plasma-facing components (PFCs) by intense plasma bombardment, radiation and nuclear heating. For reliable exhaust of huge thermal power, robust and durable divertor target PFCs with a sufficiently large heat removal capability and lifetime has to be developed. Since 2014 in the framework of the preconceptual design activities of the EUROfusion DEMO project, integrated R&D efforts have been made in the subproject ‘Target development’ of the work package ‘Divertor’ to develop divertor target PFCs for DEMO. Recently, the first R&D phase was concluded where six (partly novel) target PFC concepts were developed and evaluated by means of non-destructive inspections and high-heat-flux fatigue testing. In this paper, the major achievements of the first phase activities in this subproject are presented focusing on the design rationales of the target PFC concepts, technology options employed for small-scale mock-up fabrication and the results of the first round high-heat-flux qualification test campaign. It is reported that the mock-ups of three PFC concepts survived up to 500 loading cycles at 20 MW/m² (with hot water cooling at 130 °C) without any discernable indication of degradation in performance or structural integrity.

1. Introduction

One of the R&D focuses in the European fusion energy program is to establish a physical and technological basis for reliable power exhaust during entire operational situations of a demonstrational power plant (DEMO) [1–3]. The divertor target plates are the most thermally loaded in-vessel components in a fusion reactor where high heat fluxes (HHFs) are produced on the plasma-facing components (PFCs) by intense plasma bombardment, radiation and nuclear heating by neutron irradiation [4]. In this context, the paramount engineering challenge is to develop robust and durable divertor PFCs with a sufficiently large heat removal capability and longevity. The lifetime of the PFCs is affected by possible material degradation, cracking [5], plastic fatigue [6], erosion of armor and corrosion of cooling pipe [7]. In designing PFCs, a particular attention should be paid to materials degradation by neutron irradiation (e.g. embrittlement by lattice damage and transmutation)

[8–10].

Since 2014 in the framework of the EUROfusion Consortium, integrated R&D efforts have been performed in the work package “Divertor” (WPDIV) where one of the major missions is to deliver a feasible design concept(s) and applicable technology solutions for the divertor target PFCs of DEMO at least with a preconceptual maturity taking the envisaged thermal and nuclear loads into account [11,12]. To this end, a comprehensive set of R&D activities has been carried out in the subproject ‘Target development’ including design guidelines, design studies, failure modeling, materials production (if not commercially available), mock-up fabrication, nondestructive inspection, HHF tests, post-examination of damage, corrosion protection, and neutron diffraction study of stress, etc. This article presents a brief overview on the recent achievements of this subproject focusing on the design requirements, logics of the PFC concepts, manufacturing technologies, mock-up production, inspection and the first round HHF qualification

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test campaign.

2. Design background for the water-cooled DEMO divertor targets

Water cooling (low-temperature operation of the coolant: $<150\text{ }^{\circ}\text{C}$) is the baseline option for the entire divertor system (PFCs and cassette body) while gas cooling (high-temperature operation of the coolant: $>500\text{ }^{\circ}\text{C}$) is only regarded as a back-up option subject to long-term development.

2.1. Operation conditions

Up to now there is no fully consolidated quantitative prediction of the surface heat flux profile. Thus, the heat flux profile specified for the ITER divertor targets was adopted in WPDIV as a tentative specification where the peak heat flux was assumed to be 10 MW/m^2 for the quasi-stationary operation (2 h) and 20 MW/m^2 for slow transient events ($<10\text{ s}$) [12,13]. Moreover, a safety margin of 50% is reserved in the heat flux specification for normal operation assuming that the peak heat flux on the targets even could reach 15 MW/m^2 for an extended time period in normal operation. The temperature and pressure of the coolant in the cooling circuit of the divertor targets was specified to range from $130\text{ }^{\circ}\text{C}$ (inlet) to $137\text{ }^{\circ}\text{C}$ (outlet) and from 5 MPa (inlet) to 3.5 MPa (outlet), respectively [10,14]. This cooling condition was determined as a compromise between two competing design requirements, namely, 1) that the coolant temperature should be kept as low as reasonably achievable to assure the specified minimum margin (40%) to the critical heat flux (CHF) at the cooling pipe apex with an acceptably low coolant velocity ($<15\text{ m/s}$) [12] and 2) that the temperature of the cooling pipe (e.g. CuCrZr alloy) should be kept high enough to avoid severe embrittlement by neutron irradiation. In a previous irradiation test study, it was shown that CuCrZr alloy exhibited acceptable ductility when irradiated (up to 5dpa) and tested at $150\text{ }^{\circ}\text{C}$ or above [15]. The cooling parameters were fine-tuned by full 3D thermo-hydraulic simulations for the entire target systems [14]. It is noted that a localized nucleated boiling should be allowed if there is still an enough margin to the CHF.

2.2. Baseline design model

In WPDIV seven different design concepts of target PFCs are currently under development for HHF application. Five of them have a generic geometric form of the array of rectangular monoblocks of tungsten with a cooling pipe as heat sink at the middle. This tungsten monoblock type design concept (see Fig. 1) was inherited from the ITER divertor target design [13]. In WPDIV, copper-base cooling pipes are employed for the water-cooled PFCs. The combination of tungsten (as plasma-facing armor) with a copper alloy or composites (as structural heat sink) is currently deemed to be the only feasible materials option for HHF application in a nuclear environment [16,17].

In the 1st design phase (2014–16) the initial thickness of the armor (to the plasma-facing surface) was set at 5 mm while in the 2nd phase (2017–18) at 8 mm. This thickness range was specified taking the ITER

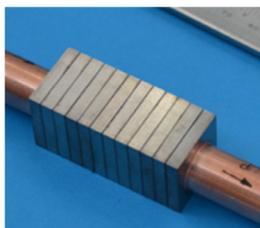


Fig. 1. A divertor target PFC mock-up of the ITER-like reference design model considered for DEMO showing a tungsten monoblock type configuration (armor block width: 23 mm, height: 25 mm, pipe outer diameter: 15 mm).

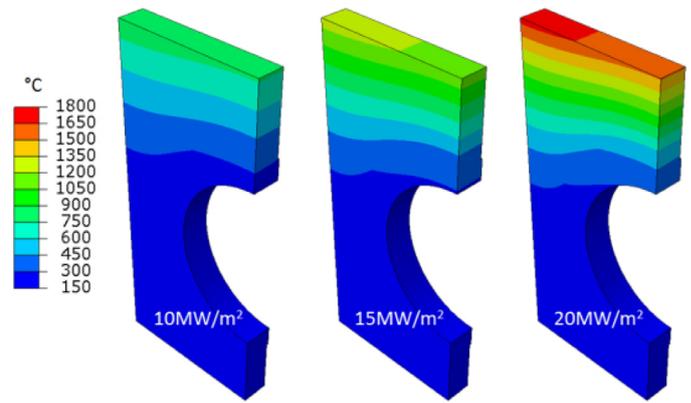


Fig. 2. Temperature fields of the ITER-like reference divertor target PFC (only the left half is shown) in thermal equilibrium under HHF loads of 10 (left), 15 (middle) and 20 MW/m^2 (right) (coolant: $150\text{ }^{\circ}\text{C}$).

divertor target PFC design as preliminary reference [13]. It is noted that an accurate assessment of surface erosion rate of tungsten armor for DEMO plasma operation conditions is currently difficult as the physical conditions and scenarios of ELM instabilities (which have the most impact on the erosion rate of the tungsten armor) are not established yet. In WPDIV, the envisaged lifetime (i.e. replacement period) of a DEMO divertor target was specified to be 2 full-power years (fpy). The section width of the armor blocks was set at 23 mm (the reason for this is explained in Section 3.1). The inner diameter of the cooling pipe was set at 12 mm and the thickness 1.5 mm. The diameter was determined by an engineering compromise between the thermohydraulic efficiency of heat removal, thermal and mechanical loading and the manufactural feasibility of PFCs for the given block section width [18]. The chosen pipe thickness of 1.5 mm was deemed thick enough for assuring the specified lifetime even in the presence of corrosion (protection coating shall be used). The peak velocity of the coolant was limited up to 15 m/s to mitigate erosion damage by coolant [14].

In Fig. 2 the temperature fields of the ITER-like reference divertor target PFC in thermal equilibrium under HHF loads of 10 (left), 15 (middle) and 20 MW/m^2 (right) are illustrated (coolant: $150\text{ }^{\circ}\text{C}$). Only the left half is plotted. It is seen that a very steep vertical temperature gradient builds up mostly within the tungsten armor but above the cooling pipe. The huge temperature difference building up in the armor block implies that the critical material and design issues related to irradiation-induced embrittlement (lattice damage, gaseous transmutation, formation of brittle phase) will need to be separately considered depending on local temperature and stress intensity. The structural integrity problem of embrittled tungsten armor is beyond the scope of this paper.

2.3. Structural design issues

In Fig. 3 the equilibrated temperature fields of the cooling pipe in the reference (ITER-like) PFC model under the three specified HHF loads are plotted (left column). The corresponding stress fields (hoop component) are also plotted for the HHF loading (middle column) and the cooling phase at $150\text{ }^{\circ}\text{C}$ (right column). It is noted that although 20 MW/m^2 was specified as a (slow) transient load, the assumed pulse duration of 10 s was long enough for the PFC to reach a thermally equilibrated state making no difference from the steady state from mechanical point of view. Steady state temperatures of the cooling pipe read off at selected positions are listed in Table 1. It is noted that the upper allowable temperature limit of CuCrZr alloy for PFC application was once specified to be around $300\text{--}330\text{ }^{\circ}\text{C}$ considering irradiation creep [16,19]. The table shows that for the peak stationary load of 15 MW/m^2 the temperature in the top region (apex) locally exceeds the allowed upper temperature limit near the outer bond interface while

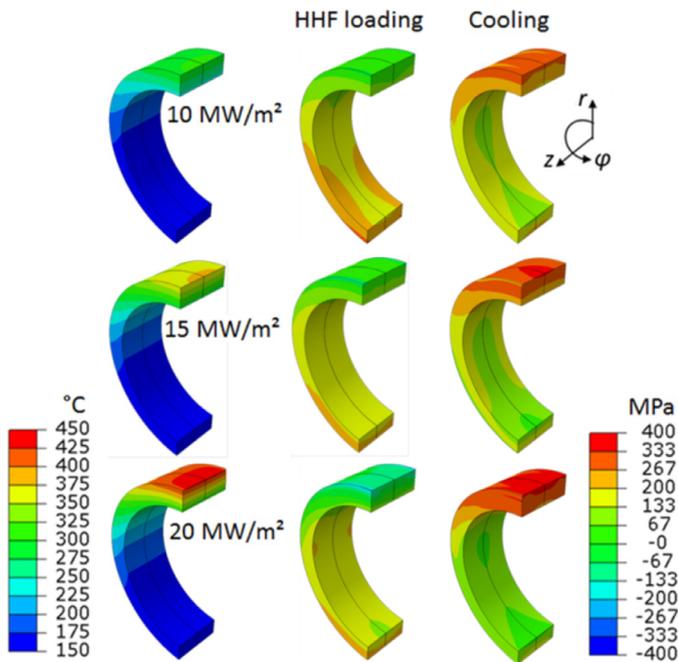


Fig. 3. Equilibrated temperature fields in the pipe of the reference (ITER-like) PFC model under three specified HHF loads (left column) and the corresponding thermal stress fields (hoop component) during the HHF loading (middle column) and in cooling phase at 150 °C (right column). The thermal stresses are mostly produced by the mismatch in differential thermal strains between the tungsten block and the copper alloy pipe.

Table 1

Steady state temperatures (in °C) of the cooling pipe read off at selected positions.

Positions at the pipe	10 MW/m ²	15 MW/m ²	20 MW/m ²
outer interface (top)	301	376	432
inner wall (top)	240	284	304
outer interface (side)	186	204	228
inner wall (side)	173	184	200
interface (bottom)	150	150	150

the most part of the pipe still remains well below the limit. For 20MW/m², however, the entire apex region experiences temperature much higher than the limit. Should the total number of slow transient pulses be so high that the total accumulated time of excessive thermal excursions is long enough, an irreversible microstructural change may take place leading to degradation (e.g. tertiary creep, softening). In this circumstance, a proper material solution is required [16]. The thermal stress in the pipe is produced mostly by the mismatch in differential thermal strains due to the different thermal expansion coefficients (CTE) between the armor block (tungsten) and the heat sink pipe (copper) under temperature variations.

3. Design concepts of DEMO divertor target PFCs

In this chapter the design concepts of target PFCs being developed in WPDIV are described. For brevity, only the PFCs for HHF application are discussed here (currently, a PFC concept of reduced activation for medium-heat-flux application is also developed in WPDIV). The key features and design rationales of the individual PFC concepts are summarized in Table 2.

3.1. ITER-like tungsten monoblock

For the time being, the ITER-like tungsten monoblock concept is the

baseline design in WPDIV. Fig. 4 shows the photographs of fabricated mock-ups of the ITER-like design for DEMO (top) and the original ITER design (bottom) together with a schematic of the cross-section, respectively. While inherited from the ITER divertor target design as preliminary reference (see Section 2.2), the current baseline design has a reduced cross-section dimension (width: 23 mm instead of 28 mm, block thickness: 4 mm instead of 12 mm) [18,20]. The reason for this is explained later. The inner diameter and thickness of the cooling pipe was 12 mm and 1.5 mm, respectively. The copper interlayer was 1 mm thick. The presence of the thick soft copper layer is widely thought to be needed to relax the residual stress after fabrication which would be otherwise quite high.

For joining tungsten blocks to copper pipe the HRP (Hot Radial Pressing) technique was applied (temperature: 600 °C, pressure: 60 MPa) [20]. The mock-ups were fabricated at ENEA in Frascati using a dedicated facility. It is noted that the HRP process causes a reduction of plastic strength of the precipitation-hardened CuCrZr alloy.

In the previous HHF qualification test program conducted for the ITER full-tungsten divertor targets, a number of small scale mock-ups produced with different joining technologies have been tested. While no appreciable structural failure (e.g. pipe rupture) was observed, the tungsten armor blocks mostly exhibited deep cracking at 20MW/m² after several hundreds of loading cycles [21,22].

In a recent study, the mechanism of the observed deep cracking of tungsten armor was theoretically elucidated and attributed to the plastically induced local tensile residual stress field near the surface occurring upon cooling following the compressive plastic yield of the recrystallized (thus softened) surface layer during a transient HHF loading (> 20 MW/m²) [23]. It is noted that during HHF loading the recrystallized surface layer remains ductile as the temperature is much higher than the ductile-to-brittle transition temperature. It was shown that the reduced monoblock size (23 × 25 × 4 mm³) brought clear benefits by reducing the driving force of crack growth in the armor [24,25]. This feature is illustrated in Fig. 5 where J-integral values (a measure of the stress intensity at crack tip) are plotted as a function of the extending crack size from the surface for four different armor block dimensions (t: axial thickness, w: section width). The compared J-integral values exhibit a clear trend that the surface crack in a smaller block is less loaded as the corresponding stress intensity is significantly reduced.

3.2. Tungsten monoblock with a thin graded interlayer

The primary motivation of this concept was to replace the thick (~1 mm) copper interlayer with a very thin bond coat for armor-to-pipe joining in order to avoid the potential risk of fast fracture of the copper interlayer to be embrittled. A previous study on irradiation testing (neutron dose: 1×10^{22} n/cm²) of pure copper in a fast neutron reactor (BOR60) showed that the uniform elongation of irradiated copper at $T_{irr} = T_{test} = 340 \pm 5$ °C was drastically decreased down to 2.5% due to the segregation of transmuted helium (2 appm) at grain boundaries fostered by concomitant recrystallization [26]. The test temperature was comparable to the service temperature of the copper interlayer of the ITER-like target PFC in DEMO. Such pronounced embrittlement of copper interlayer could be a potential source of component failure, thus the reasoning of the present concept. Another benefit of this concept is the fact that armor temperature is decreased as the distance of heat conduction path is shortened. This effect significantly mitigates recrystallization of the armor surface layer. On the other hand, the absence of an initially soft copper interlayer may cause bonding defects or failure during fabrication as a result of high residual stress produced by CTE mismatch [27]. To realize a joining technique with a sufficiently high bonding strength is the major engineering challenge in this concept.

To this end, prior to joining the bore wall of the tungsten blocks was coated with a compositionally graded thin (25 μm) film of a binary W/

Table 2
Key features of the individual PFC design concepts being developed for DEMO divertor targets.

Target concepts	Coolant	Armor	Interlayer	Heat sink	Design logics
ITER-like baseline (ENEA)	H ₂ O	W block (23 mm)	Thick Cu (1 mm)	CuCrZr pipe	Avoid deep cracking via reduced dimension
Thermal break layer (CCFE)	H ₂ O	W block (22 mm)	Thick Cu with holes	CuCrZr pipe	Mitigate heat flux peaking, Reduce thermal stress
Composite block (IPP)	H ₂ O	W tile (22 mm)	None	Wp/Cu composite block (50/50 vol.%)	Enhance toughness, Reduce thermal stress
Composite pipe (IPP)	H ₂ O	W block (23 mm)	None	Wf/Cu composite pipe (15/85 vol.%)	Enhance strength, Reduce thermal stress
Thin graded interlayer (CEA)	H ₂ O	W block (23 mm)	Graded W/Cu film	CuCrZr pipe	Avoid thick Cu interlayer, Enhance joining quality
W flat tile (KIT)	H ₂ O	W tile (23 mm)	Thin Cu	CuCrZr block	Enhance toughness & flexibility in cooling concept
Pipe multi-jet (KIT)	He	W block (23 mm)	Thin Cu	W laminate pipe	Enhance efficiency by high operation temperature

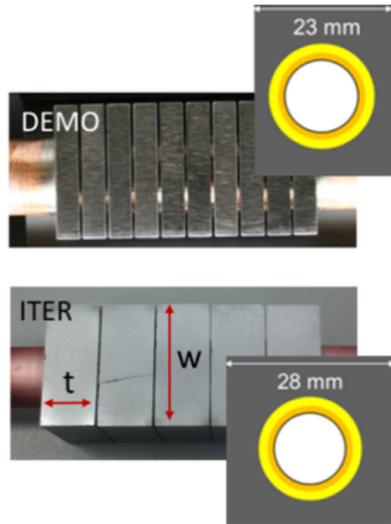


Fig. 4. An ITER-like PFC mock-up developed for DEMO divertor targets (top) and a PFC mock-up for the ITER divertor targets (bottom).

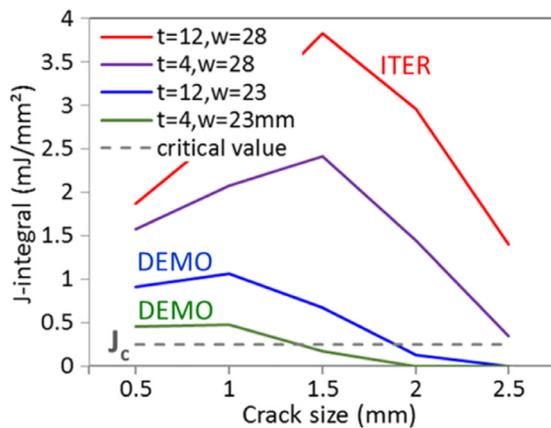


Fig. 5. J-integral values calculated at the crack tip plotted as a function of the growing crack size from the surface for four different block dimensions (t: axial thickness, w: section width) [9].

Cu pseudo-alloy as bond coat by means of physical vapor deposition in the company DEPHIS, Étupes, France [28]. The tungsten blocks were joined to the copper alloy pipe by hot isostatic pressing (HIP) technique and subsequently heat-treated for precipitation hardening of CuCrZr by CEA in Cadarache [29]. A fabricated mock-up is shown in Fig. 6(a) and a tungsten block with coated bore wall in (b). The dimension of the mock-up size was 22 × 23 × 4 mm³.

Fig. 7 shows a SEM image of the bond interface region revealing the compositionally graded W/Cu bond coat layer (a) and the EDX concentration profiles of W and Cu measured across the coating thickness (b).

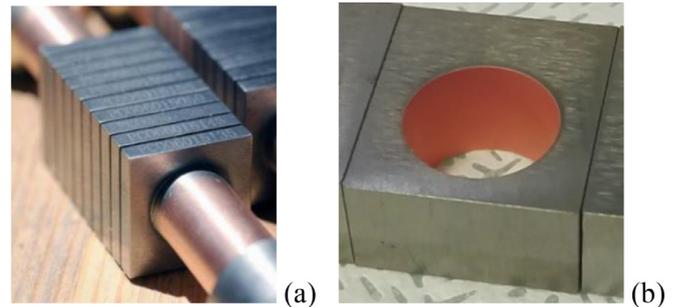


Fig. 6. Tungsten monoblock type PFC mock-up joined using a thin graded bond coat layer without thick Cu interlayer (a) and tungsten block with a coated bore wall before joining (b). (armor block width: 23 mm, pipe outer diameter: 15 mm).

3.3. Tungsten monoblock with a thermal break interlayer

The underlying idea of this concept is to mitigate the local concentration of heat flux at the cooling pipe apex by introducing a local thermal break layer between the armor and the pipe. This effect is demonstrated in Fig. 8 where the local heat flux distributions are plotted along the outer periphery of the pipe (the origin of the polar coordinates is set at the apex position) during a stationary heat flux loading at 10MW/m² for five different areal coverage fractions of the thermal break layer of any kind (thermal conductivity: < 20 W/m·K) inserted along the interface. It is clearly shown that the peak heat flux at the pipe is significantly decreased even for the smallest areal coverage fraction (25%). The same trend applies to the pipe temperatures.

According to the theoretical design study, the presence of such a thermal break layer brings several beneficial effects as follows [30]:

- 1) The thermal margin to the critical heat flux (CHF) is increased since the local peak heat flux at the pipe is reduced,
- 2) Tungsten block is more uniformly heated as the by-passing downward heat flow around the pipe is increased, which is particularly desirable for a lower-temperature water-cooled PFC.
- 3) Being endowed with lower elastic stiffness, the thermal break layer can also act as a stress break.

It is an inevitable consequence, however, that the surface temperature of the armor is much higher compared to the other companion concepts posing a design concern in terms of tungsten degradation by recrystallization.

Initially, highly porous metals (e.g. foam or felt) were considered as thermal break material, which turned out to be less feasible [12]. Recently, a structured copper interlayer was employed which is characterized by axial holes and spokes cut into an otherwise solid interlayer to reduce heat conductance. An extensive design study has been carried out to optimize the geometric feature by exploring various design variants. The final design (edge section view) is shown in Fig. 9(a) [31]. The blocks were deep-notched from the top surface to reduce thermal stresses.

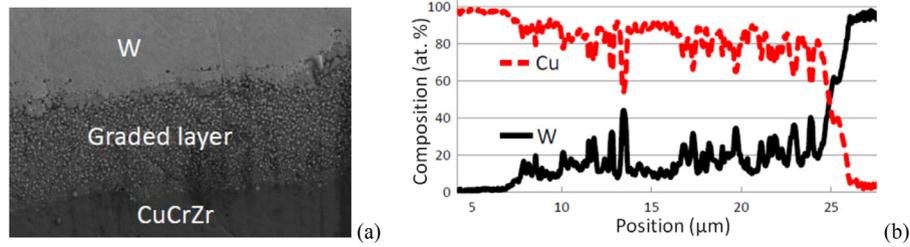


Fig. 7. Composition profiles of W and Cu through the coating thickness measured by EDX scan (a) and SEM image of the same scan region (b).

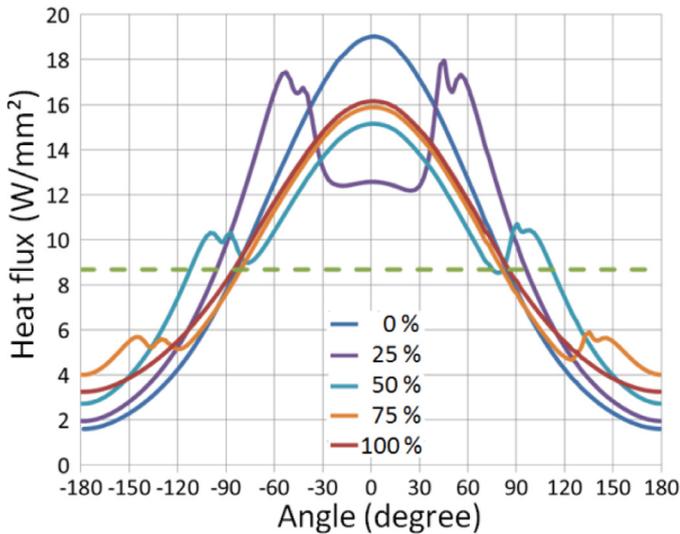


Fig. 8. Local heat flux distribution plotted along the pipe periphery (the top position is the origin of polar coordinates) during stationary heat flux loading at 10 MW/m² for five different areal coverage fractions of the thermal break layer along the bond interface.

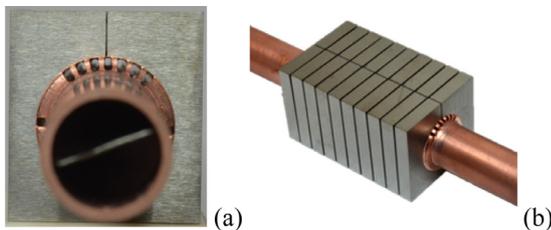


Fig. 9. (a) Edge section view of a tungsten monoblock type PFC mock-up with a thermal break interlayer and (b) a fabricated PFC mock-up with a thermal break interlayer. (armor block width: 23/27 mm, pipe outer diameter: 15 mm).

The PFC fabrication technology was developed by CCFE in Culham. Mock-ups were joined using a two-stage vacuum braze process [31]. A copper sleeve (interlayer) was first brazed to the CuCrZr pipe and the

hole/spoke structure was machined into the outer surface. The central bore of the tungsten blocks were cast with copper and the copper cast was then machined out to leave a thin copper layer, which was needed to facilitate the subsequent brazing to the pipe/sleeve assembly. In the current proof-of-concept study, a gold-copper alloy braze was used for demonstration purpose, but a further R&D is needed to replace gold as gold is transmuted to liquid mercury by neutron. A fabricated mock-up is shown in Fig. 9(b). Finally, the complete mock-up joint was subjected to an ageing heat treatment for hardening of CuCrZr.

3.4. Tungsten monoblock with a composite cooling pipe

In this concept the PFC is equipped with a special cooling pipe made of a long tungsten fiber-reinforced copper matrix composite (W_f/Cu). The purpose of using the W_f/Cu composite pipe is to exploit the high mechanical strength of the composite at elevated temperatures beyond the upper limit allowed for irradiated CuCrZr alloy (<330 °C). The unique combination of superior strength, toughness and high thermal conductivity of the W_f/Cu composite enables to significantly extend the upper operation temperature limit of the heat sink. For instance, the ultimate tensile strength of a W_f/Cu composite (fiber: 40 vol.%) reaches 500 MPa at 650 °C and the failure strain more than 5% [32]. The origin of the outstanding strength is the strong and refractory tungsten wires. The tensile strength and ultimate strain of commercially available W wires (e.g. OSRAM) amount around 2.7 GPa and 3%, respectively [16,33]. The copper matrix provides structural stability, ductility and thermal conductivity. This beneficial combination of properties is a common characteristic of long fiber-reinforced metal matrix composites [34]. Another advantage of this concept is that macroscopic thermal stresses are considerably relaxed thanks to the reduced mismatch in CTE between the armor and the pipe while additional thermal stresses are produced in the composite on the mesoscopic scale [35,36].

The W_f/Cu composite pipes were developed and fabricated by IPP Garching in close collaboration with industry partners (Deutsche Institute für Textil- und Faserforschung Denkendorf, Germany and Louis Renner GmbH, Bergkirchen, Germany) [37]. Fig. 10 shows the braided W wire preform in cylindrical shape (a), the microscopic architecture of the braided wire preform (b) and the cross section cut (one quarter part) of the pipe fabricated by centrifugal melt casting technique (c). The wire diameter was 50 μm and the volume fraction

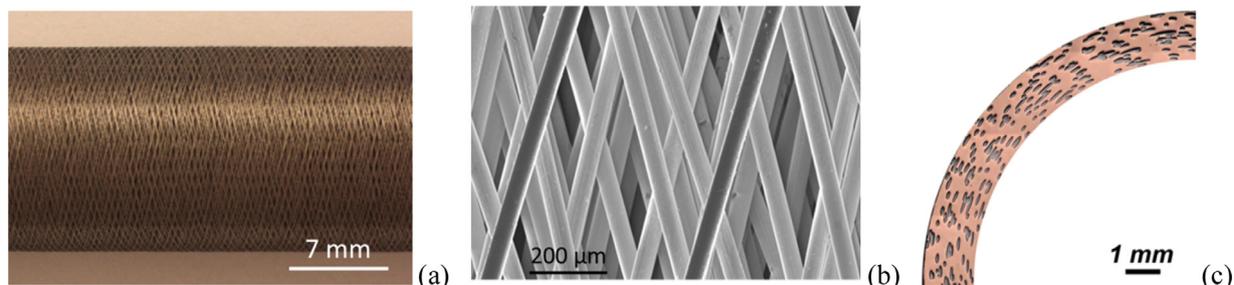


Fig. 10. (a) Braided wire preform in cylindrical shape, (b) braided architecture of the wire preform and (c) cross section cut of the pipe fabricated by melt infiltration process [37].

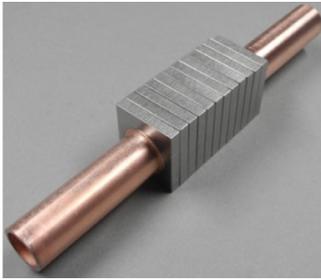


Fig. 11. A PFC mock-up with a W_p/Cu composite cooling pipe joined by brazing. (armor block width: 23 mm, pipe outer diameter: 15 mm).

amounted roughly 15%. Visually perfect infiltration was achieved while the wires remain ductile. It is noted that the tensile strength and plastic modulus of wire-reinforced metal matrix composites are normally much higher (roughly by one order of magnitude) in the wire axial direction (in the present pipe geometry, the strength was optimized in the hoop direction) than transverse directions.

A monoblock-type PFC mock-up with the W_p/Cu composite cooling pipe was fabricated by means of brazing (see Fig. 11). For the first trial to deliver the proof-of-concept, a binary Cu-Au alloy braze was used. Currently, a further R&D work is ongoing to replace the Cu-Au braze with a radiation-resistant braze alloy.

3.5. Tungsten flat tile with a copper alloy heat sink block

A PFC model armored with tungsten flat tiles joined to a (water-cooled) copper alloy heat sink block is another PFC design concept which has already been applied for the ITER divertor dome [13]. This design concept allows a relatively straightforward fabrication process and a robust structural stability owing to the bulky heat sink part. Moreover, armoring a heat sink block with flat tungsten tiles allows designers more flexibility in choosing the cooling scheme, for instance, to apply innovative cooling concepts such as heat pipe or hypervapotron. On the other hand, the global structural integrity of the component relies sensitively on the local joining quality since a failure of a single tile could trigger a cascade failure of neighboring tiles.

In the ITER R&D activities, the eligibility of this concept was demonstrated for a medium heat flux range (5–11 MW/m²) [13]. For applications to DEMO-relevant HHF loads, a matured joining technology with irradiation resistance will be needed to assure reliability. In parallel, a design optimization with a modified geometry is also pursued to relax the singular stress concentration occurring at the free edge of the bond interface which is the weakest site [38].

In an effort to address this critical issue, an improved HIP-based joining technique was developed by KIT in Karlsruhe where a number of technical details were elaborated to improve the joining quality. Fig. 12 shows flat-tile type PFC mock-ups which are currently under testing in the HHF test facility for preliminary evaluation. The first test

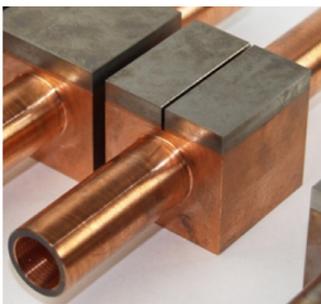


Fig. 12. Flat-tile type PFC mock-ups where the tungsten tiles are joined to the CuCrZr heat sink by HIP.

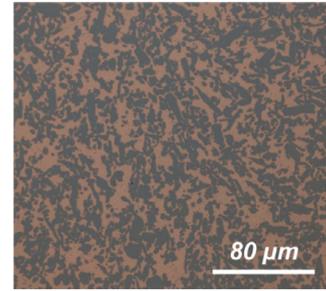


Fig. 13. Optical microscopic image of the microstructure of a W_p/Cu composite [37].

result showed that the mock-up underwent a premature failure by macroscopic cracking where the crack was initiated and propagated in and through the tungsten tile near the bond interface while the interface itself remained intact.

3.6. Tungsten flat tile with a composite heat sink block

The risk of interfacial cracking (or armor cracking near the interface) for flat-tile type PFCs can be mitigated if the CTE mismatch between the armor tile and the heat sink block is reduced [39]. To this end, a novel composite heat sink block was developed using a tungsten particle-reinforced copper matrix composite (W_p/Cu) which has a much lower CTE value and higher tensile strength than copper alloys. [34,40,41]. An optical microstructure image of a W_p/Cu composite sample (50 vol.%) is shown in Fig. 13 where a percolated tungsten skeleton in the copper matrix is seen. The composite material was manufactured by an industrial melt infiltration process (Louis Renner GmbH in Bergkirchen, Germany).

The ultimate tensile strength (UTS) and CTE data of the W_p/Cu composites with three different copper contents (legend in weight percent) are plotted in Fig. 14(a) and (b), respectively [42]. For the copper content of 30 wt.% (roughly 50 vol.%) the UTS ranges from 520 MPa (150 °C) to 350 MPa (450 °C) in the envisaged temperature window of the cooling pipe. On the contrary, the UTS of age-hardened CuCrZr alloy ranges from 370 MPa to 250 MPa in the same temperature range [19]. The tensile elongation was larger than 5% for temperatures below 430 °C. The average CTE lay around 10 microstrain per degree Celsius exhibiting a significant reduction effect compared to the copper alloy (17 microstrain/°C). The W_p/Cu composite possessed a reasonably high thermal conductivity ranging from 220 (400 °C) to 240 (20 °C) W/mK following the rule of mixture [37].

A dedicated manufacturing process for this PFC concept has been developed by IPP in Garching in cooperation with an industry partner (Louis Renner GmbH in Bergkirchen, Germany) [37]. A test mock-up was fabricated by means of the melt infiltration technique where the production of the W_p/Cu heat sink block and the joining to the tungsten armor tiles took place simultaneously in a single casting process. The fabricated mock-up is shown in Fig. 15. The W_p/Cu composite has also been developed as a thick (3 mm) functionally graded interlayer with three composition steps and applied to a water-cooled flat-tile PFC which exhibited a reasonable HHF loading performance [43].

3.7. Tungsten monoblock for helium-cooled PFC

In WPDIV a gas-cooled PFC concept is also developed as a potential alternative to water-cooling. Currently, the applicability of a gas-cooled PFC for HHF application seems rather limited (to about 5–10 MW/m²) depending on design concept and maturity of technology [44]. Provided advanced plasma operations (e.g. very large portion of radiative power dissipation) or advanced divertor magnetic configurations (e.g. enlarged plasma wetting area on the targets) could enable a strong reduction of peak heat flux (say, down to 5 MW/m²), gas-cooled PFC

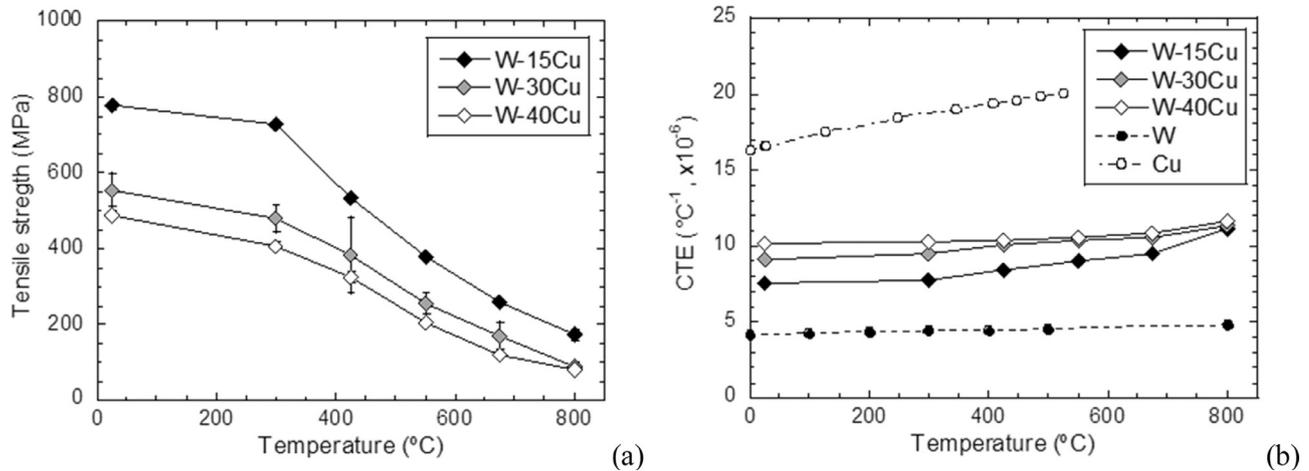


Fig. 14. Ultimate tensile strength (a) and CTE (b) data measured for the W_p/Cu composite with three different copper contents (15, 30 and 40 wt.%) [41,42].

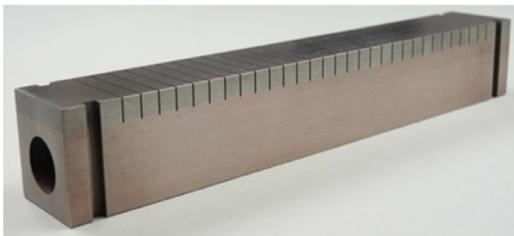


Fig. 15. A flat-tile armor type composite PFC mock-up fabricated with a W_p/Cu composite heat sink block. (section width: 23 mm, cooling channel diameter: 15 mm).

concepts would be an option.

Helium-cooled PFCs offer advantages over the water-cooled counterpart, e.g., chemical inertness of coolant (no corrosion of cooling pipe, no risk of volatile oxidation of tungsten in the event of accidental coolant ingress), the absence of coolant transmutation, no boiling crisis, and the compatibility of the cooling circuits with the helium-cooled breeding blankets (if applied). Operating at higher temperature levels, the helium-cooled concept would allow higher efficiency of the power conversion system. In addition, the thermal recovery of irradiation damage (dpa) expected at the helium operation temperatures will keep the structural material in a ductile regime. On the other hand, the relatively limited power handling capability (compared to the water-cooled PFCs) is deemed the most critical shortcoming, particularly in terms of the compatibility with slow thermal transients ($\sim 20 \text{ MW/m}^2$).

In WPDIV, a helium-cooled PFC concept has been developed by KIT in Karlsruhe where the concept was based on the generic tungsten monoblock-type design with a cooling pipe made of either Eurofer steel for medium/low heat fluxes ($1\text{--}5 \text{ MW/m}^2$) or W laminate composite (W_1/Cu or W_1/W_1) for higher heat fluxes (10 MW/m^2). The use of a steel pipe or a W-laminate pipe allows higher coolant operation temperature ranging between 300 °C and 600 °C . To achieve the required cooling performance, the helium-cooled PFC concept relies on utilizing the jet-impingement technique. In the pipe-monoblock concept, the jets are generated via a perforated tubular cartridge locating inside the main cooling pipe.

Fig. 16 shows a cut-section of a manufactured PFC mock-up joined to a W-laminate pipe (a) and 120 mm-long validation mock-ups (b). Currently R&D efforts are focused on improving joining quality between the steel pipe and W-monoblocks, where a considerable progress has been achieved by means of HIP technique. A PFC mock-up with a steel pipe manufactured recently using HIP is shown in Fig. 17 together with the HIP capsules.

A recent CFD study of the thermo-hydraulic performance of a

helium-cooled PFC predicted that the maximum temperature reached 670 °C at the apex of the steel pipe (diameter: 16 mm, thickness 1 mm) and 1070 °C at the armor surface for the applied surface heat flux of 5 MW/m^2 where the coolant inlet temperature and pressure was set at $300 \text{ °C}/10 \text{ MPa}$ and mass flow rate at 20 g/s . The local peak heat flux at the pipe reached 6.2 MW/m^2 , while the average convective heat transfer coefficient and average temperature on the pipe wall amounted $66 \text{ kW/m}^2\text{K}$ and 394 °C , respectively. When the pipe thickness is reduced to 0.5 mm (diameter: 14 mm), the peak temperature of the pipe was decreased to 580 °C . The predicted pipe temperatures indicate that ODS (Oxide Dispersion Strengthened) Eurofer steel (max. allowable service temperature: $650\text{--}700 \text{ °C}$) will have to be used as pipe material (especially for the thick pipe) so that the helium-cooled PFC concept can be eligible for stationary peak heat flux up to $4\text{--}5 \text{ MW/m}^2$.

Similar studies done for the W-laminate concept showed that, at the surface heat loading of 10 MW/m^2 , the peak temperature of the pipe reached roughly 1000 °C and the surface temperature of the tungsten block 1860 °C , which were similar to the ones obtained for the earlier HEMJ finger concept [44]. Note that these results were obtained for a slightly larger tungsten block, the heated surface being 32 mm wide and 13 mm in thickness.

4. Nondestructive inspection

All produced PFC mock-ups were subjected to a series of non-destructive inspection to evaluate the fabrication quality (particularly joining quality) and to sort out defective mock-ups prior to HHF testing. Two different kinds of ex-situ inspection techniques were applied, namely, ultrasonic reflectometry [20] and infrared thermography. Additionally, two kinds of in-situ diagnostic techniques were applied for screening during HHF testing, namely, infrared thermography and optical imaging using a CCD camera.

4.1. Ultrasonic test

The ultrasonic tests were carried out by ENEA in Frascati by means of a standard testing procedure which was calibrated according to the norm prescription EN583-1. The frequency of the pulser (and the receiver) of the ultrasonic probe was set at $5\text{--}20 \text{ MHz}$. The resolution of C-scan images was about 1 mm. In this testing a mock-up is immersed in a water bath and an ultrasonic pulse is transmitted into the hollow of the cooling pipe. The pulse is deflected towards the pipe wall by a mirror positioned in the hollow and reflected back by the solid and transmitted back to the receiver mounted in the probe. Any perturbation of reflected echoes caused by acoustic scattering at defects is detected and visualized as a scan image along axial positions.



Fig 16. Helium-cooled PFC mock-ups based on W/Cu laminate pipe: (a) cut section view and (b) 120 mm long validation mock-ups.

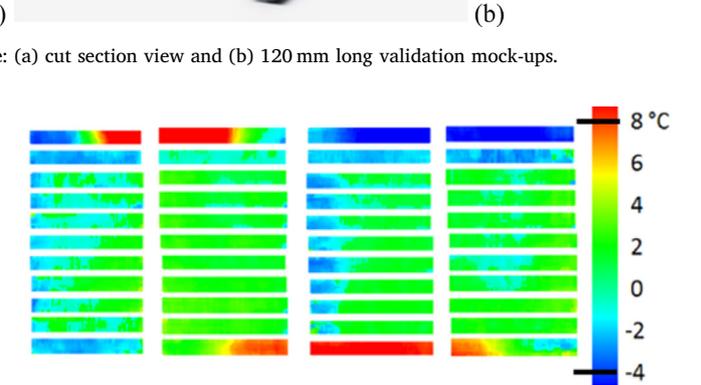
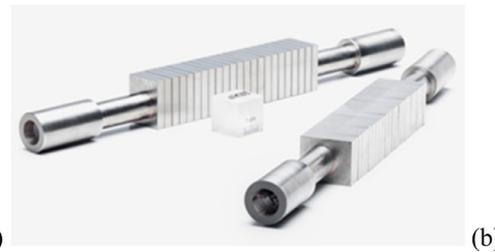


Fig. 19. Relative difference in surface temperature between respective individual blocks and the reference block (the third block from the bottom) mapped on the four side faces of all blocks.

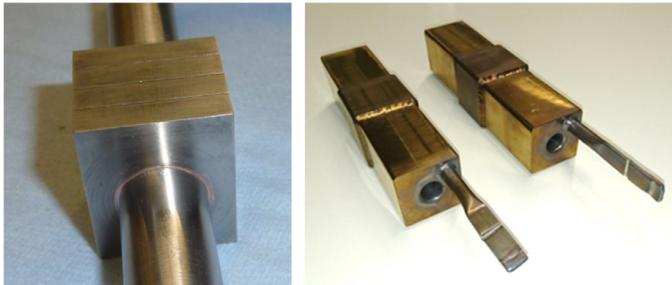


Fig 17. Helium-cooled PFC mock-up based on steel cooling pipe manufactured through HIP technique (left), HIP capsules used for the joining (right).

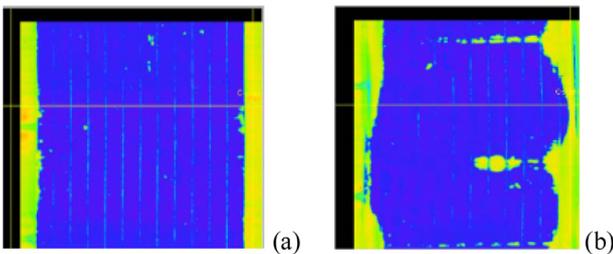


Fig. 18. Two exemplary ultrasonic C-scan images of ITER-like PFC mock-ups illustrating a mock-up with a perfect joining quality (a) and one with several bonding defects (b) where the defective regions are indicated by light green color (or bright tone in grey scale). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 18 shows two exemplary ultrasonic C-scan images of two ITER-like PFC mock-ups either (a) with a perfect joining quality indicated by blue color (or dark tone in grey scale) or (b) with several isolated bonding defects indicated by the islands of light green color (or bright tone in grey scale). The bright green stripes at both edges indicate the copper pipe. It is noted that ultrasonic testing served as quick and economic inspection tool with a reasonable spatial resolution.

4.2. Infrared thermography

As a further inspection tool infrared (IR) thermography was applied using a dedicated facility SATIR operated by CEA in Cadarache. In this facility the cooling pipe of a PFC mock-up is connected to a water loop where the temperature of circulating water can be quickly changed. This inspection method makes use of the difference in transient thermal response between the armor blocks of a mock-up during an abrupt drop of water temperature (typically from 110 °C to 10 °C). The surface temperature of the blocks is measured using an IR camera on the four side faces. Next, the relative difference in surface temperature between respective individual blocks and the related blocks of the reference mock-up is calculated and mapped on the four side faces of all blocks (see Fig. 19). The reference mock-up is selected in such a way that it exhibits the best thermal contact to the heat sink which is judged by the speed of transient thermal response.

Then, the map of the relative surface temperature difference is

numerically projected onto the cylindrical face of the pipe-to-armor interface (Fig. 20a). The data of relative temperature difference projected on the interface is compared with the threshold value which corresponds to a critical defect size which may lead to a global failure of the PFC. The threshold value is determined by a series of preceding HHF tests where several mock-ups of the same kind each with a machined interfacial pre-crack of different sizes are loaded to failure under a specified HHF load and the critical crack size and the corresponding surface temperature is correlated for calibrating the critical temperature at surface hot spots. Finally, the areas where the relative surface temperature difference exceeds the calibrated threshold value are identified as so-called equivalent thermal imperfection. In the current study, 8 °C was considered to be threshold value according to the previous qualification specification applied for ITER divertor PFCs [45]. Fig. 20b illustrates the defective area (marked in red color) identified by the present procedure.

5. High-heat-flux qualification tests

5.1. Testing conditions

The HHF testing was conducted by means of a high power hydrogen neutral beam facility GLADIS operated by IPP in Garching. The technical data of the facility can be found elsewhere [46]. The beam spot diameter was 70 mm (section span of at least 80% peak heat flux) corresponding to 150 mm full width at half maximum. In the present testing campaign, cold (20 °C, 1 MPa) as well as hot (130 °C, 4 MPa) water was used as coolant for both screening tests and HHF fatigue tests. Each HHF fatigue test was preceded by a screening test to check the initial integrity of the mock-up prior to a fatigue test. In the screening tests heat flux was increased incrementally from 5 to 25 MW/m² where 5 loading cycles were applied at each individual heat flux step. The main HHF fatigue tests were carried out at 20MW/m² with hot-water cooling up to 500 loading cycles. In some cases, preliminary HHF fatigue tests were carried out in advance at lower heat flux loads (up to 100 cycles) or using cold water cooling in order to carefully check the possibility of abrupt failure of mock-ups. The cooling condition with hot-water coolant (130 °C, 16 m/s, 4 MPa) applied to the HHF testing was equivalent in hydraulic effect to that of the actual PFC

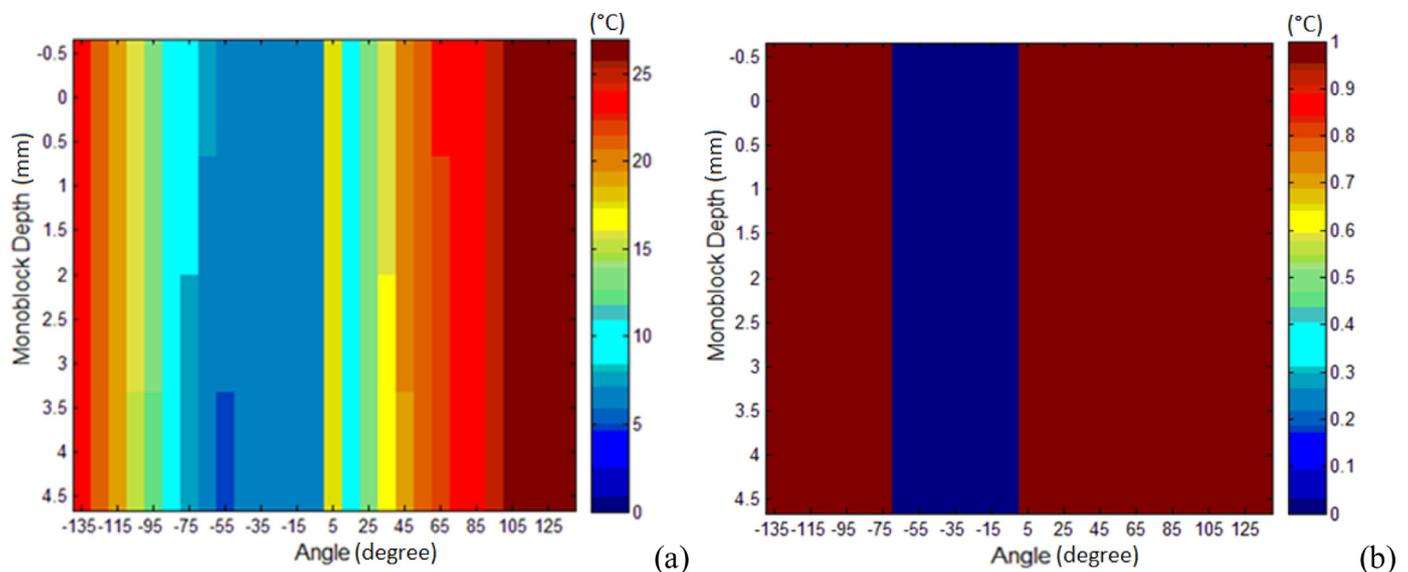


Fig. 20. (a) Map of the relative surface temperature difference projected numerically onto the cylindrical face of the pipe-to-armor interface (abscissa: angular position along the periphery, ordinate: armor block thickness), (b) identified defective area (marked in red color). The spatial resolution ranged from 1.1 to 1.7 pixels per mm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

operation at the strike point specified for a DEMO reactor ($<150\text{ }^{\circ}\text{C}$, $<16\text{ m/s}$, 5 MPa). The pulse duration time was 10 s where thermal equilibrium was almost reached within 6–7 s.

5.2. Diagnostics for in-situ failure detection

For in-situ observation of defect evolution and failure of the mock-ups during cyclic HHF testing, two different kinds of optical diagnostic instruments were employed: two IR pyrometers with different wavelength range (one-color: $2.0\text{--}2.2\text{ }\mu\text{m}$, two-color: $1.4\text{--}1.7\text{ }\mu\text{m}$) and high-resolution CCD cameras. It is noted that the IR thermography could not deliver accurate absolute temperature values in higher temperature range due to changing emissivity by surface modification (e.g. by removal of oxide films causing a decrease of emissivity depending on wavelength and temperature). Nevertheless, the relative change in surface temperature in the course of cyclic loading could be measured with a high accuracy. Any significant change in the color scale (IR thermography) or brightness at hot spots (CCD camera) can be interpreted as an optical indication of developing defects (e.g. cracks in the bond interface) which affects thermal conduction through the interfacial regions. In the present testing campaign, the HHF performance was evaluated mainly in terms of structural integrity after 500 loading cycles where structural integrity was judged by in-situ observation of surface temperature evolution and by microscopic examination of metallographic sections. The latter work is still on-going and thus not reported here.

5.3. Test results

The results of HHF fatigue tests are summarized in Table 3. Fig. 21 displays a collection of the corresponding images of IR thermography and CCD camera captured at the first and the 500th load cycle (IR) and at 500th load cycle (CCD), respectively (heat flux: 20 MW/m^2 , coolant: $130\text{ }^{\circ}\text{C}$). The test result of the “Flat tile” concept is not included here since the HHF testing has not been completed yet.

Three of the five tested PFC concepts survived 500 HHF loading cycles at 20 MW/m^2 with the hot-water cooling remaining intact without any indication of macroscopic failure as can be seen in Fig. 21. These mock-ups were of the “ITER-like”, “Composite pipe” and “Thin FGM interlayer” concept. On the contrary, the mock-ups of the “Thermal break” and “Composite block” concept exhibited a formation

of hot spots on the armor surface after 300 cycles and 360 cycles, respectively, followed by a progressive increase of the hot spot temperature (see Fig. 22). It is recalled that the HHF qualification criterion specified for the ITER divertor targets requires that mock-ups should not fail at least until 300 loading cycles at 20 MW/m^2 (with cold-water cooling at $70\text{ }^{\circ}\text{C}$) [13]. In this HHF qualification test practice, a mock-up is regarded as being failed if the surface temperature of any block in a mock-up becomes by 20% higher than the average temperature of the other blocks of the mock-up or increases more than by 15% compared to that of the initial load cycle [47]. In this sense, even the mock-ups of the latter two concepts might be regarded as having fulfilled the basic quality requirement.

It is noted that the tungsten armor blocks of all tested mock-ups showed no visible cracks on the surface after the full cumulative loading cycles at various heat flux loads up to 20 MW/m^2 . This empirical finding supports the reasoning explained before w.r.t. Fig. 5 that the reduction of block size (particularly the section width) would lead to a mitigated risk of vertical deep cracking of the armor under slow transient heat flux loads (20 MW/m^2). It is recalled that the impact of the axial thickness of the armor block is less significant than that of the section width (see Fig. 5).

5.4. Outlook

All tested mock-ups shall be subject to metallographic post-examination in near future where those blocks which are suspected of being damaged will be selected and prepared for detailed microscopic investigation.

Currently, the second phase R&D activities for optimizing the PFC technologies are on-going where the second batch of mock-ups of all PFC concepts are produced and tested in the second round HHF qualification campaign, possibly with an improved joining method, modified design or novel material. After the conclusion of the second phase HHF testing campaign, a down-selection of the PFC concepts will be made on the basis of the test results. The selected PFC concepts will be qualified for the next (and the last) stage of the preconceptual phase (2019–20) where the R&D efforts shall be focused on the technology for upscaling. The schedule of the down-selection is envisaged in October 2018.

Table 3
Summarized results of the HHF fatigue testing campaign of the 1st R&D phase in WPDIV.

PFC concepts	Coolant temp. (°C)	Screening (MW/m ²)	Fatigue (MW/m ²)	Results 100 cycles	Results 300 cycles	Results 500 cycles
ITER-like (ENEAC)	20	6–20	10, 15	no failure		
	130	6–20	20	no failure	no failure	no failure
Thermal break (CCFE)	20	6–25	10, 15, 20	no failure		
	130	6–20	10, 15, 20	no failure	no failure	failed
Composite block (IPP)	20	6–22	20	no failure	no failure	failed
Composite pipe (IPP)	20	6–25	10	no failure		
	130	6–20	20	no failure	no failure	no failure
Thin FGM interlayer (CEA)	20	6–25	10, 15, 20	no failure	no failure	
	130	6–20	10, 15, 20	no failure	no failure	no failure

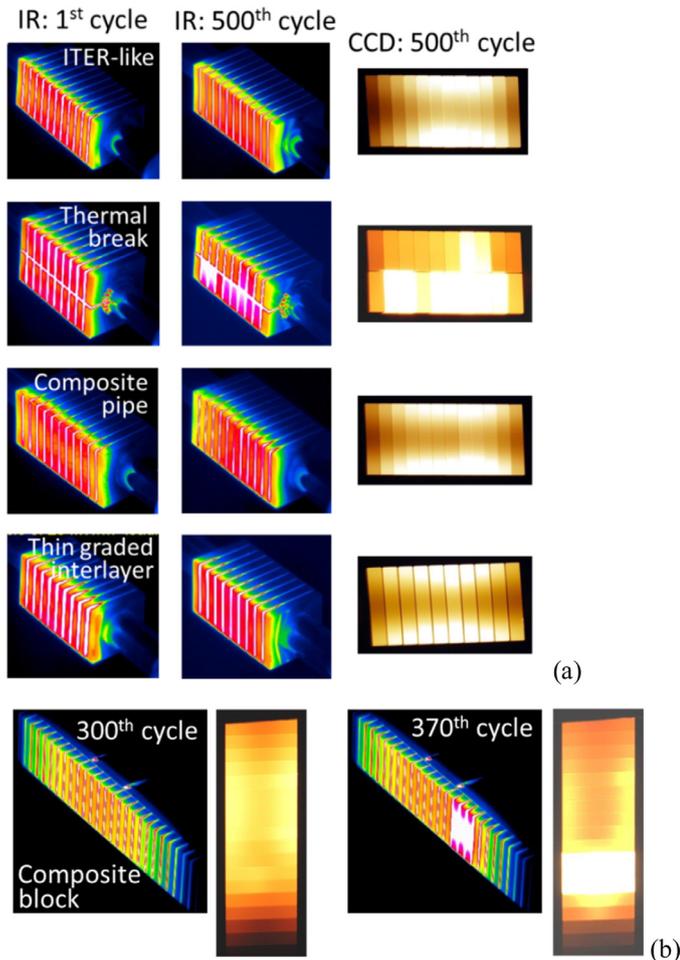


Fig. 21. (a) IR thermography images of four different types of divertor target PFC mock-ups at the first and 500th load cycle and CCD camera images at 500th load cycle produced during the HHF fatigue testing (heat flux: 20 MW/m², coolant: 130 °C) and (b) IR thermography images of the composite block PFC mock-up at 300th (left) and 370th (right) load cycle together with the corresponding CCD camera images produced under the same HHF testing condition as (a). In the IR images the hot spots where defect formation is suspected are displayed in white areas.

6. Summary and conclusions

In the framework of the preconceptual design activities of the EUROfusion DEMO project, integrated R&D efforts have been made in the work package ‘Divertor’ to develop PFCs of divertor targets for high-heat-flux applications. Recently, the first R&D phase was concluded and as of late the second phase started where PFC mock-ups are tested with

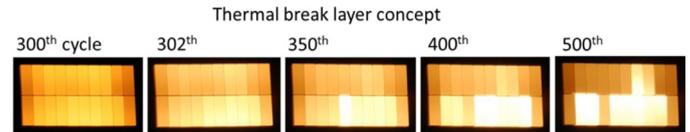


Fig. 22. Evolution of the surface luminance distribution on the tungsten armor blocks of the “Thermal break concept” mock-up in the course of a cyclic HHF fatigue test at 20 MW/m². The images were captured by a CCD camera (visible light) where the illumination (brightness scale) was automatically adjusted respectively for each individual imaging.

optimized geometry and improved joining techniques. The major achievements of the first phase activities in the subproject ‘Target development’ are as follows:

- 1 One conventional and six novel PFC design concepts were developed for DEMO divertor targets on the basis of dedicated design requirements and innovative technology options. The primary driver of R&D was the necessity of enhanced thermal capability (higher coolant temperature) and mechanical reliability (higher irradiation dose, long pulse operation, higher service temperature) under DEMO-specific loading conditions.
- 2 Key technological elements for manufacturing novel materials and mock-ups were developed.
- 3 A number of small-scale mock-ups were produced mostly with a good joining quality as verified by the non-destructive inspection (ultrasonic test and IR thermography) applied to all mock-ups.
- 4 HHF fatigue tests were carried out using cold and hot water coolant at several heat flux levels up to 20 MW/m². The mock-ups of five PFC concepts survived 300 loading cycles and three thereof even 500 loading cycles without any discernable defect formation at 20 MW/m² with hot-water cooling.
- 5 Practical guidelines were developed as a generic platform for FEM-based design study, failure modeling and structural design criteria specialized for joined PFCs. This item is beyond the scope this article and is partly dealt with elsewhere [48].

The key message of the outcomes from the first R&D phase of this subproject is that a couple of PFC design concepts and associated technology options were verified in terms of fabrication quality and HHF performance which seemed comparable to the ITER HHF technology at least for the applied test conditions. This statement should be seen as a preliminary conclusion since it is based on the HHF tests in unirradiated state while a final judgment will need to be supported by relevant irradiation test data on materials and/or mock-ups.

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