

# Performance assessment of high heat flux W monoblock type target using thin graded and copper interlayers for application to DEMO divertor

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For the development of a divertor for DEMO, the European WPDIV project is underway since 2014. The first phase of the project (2014–2016) aims to provide mock-ups adapted to DEMO operation requirements and the second phase aims to furnish mock-ups, with standardized geometry, which fulfill phase 1 requirements. Within the WPDIV project, several options are under development. One of these aims to replace the thick copper interlayer, used for ITER divertor components, with a very thin coat (functional gradient material or pure copper) for armor-to-pipe joining. One of the benefits is related to armor temperature which is decreased as the distance of heat conduction path is shortened. Some blocks equipped with thin functional gradient material as interlayer proved, in 2016, to handle high cycling performances without any degradation (no surface change aspect and no decrease of thermal heat exhaust capability). This article gives a brief overview on the recent achievements of the development of thin interlayer concept focusing on the design, mock-up production, inspection, high heat flux (HHF) qualification testing and post-examinations.

Keywords: DEMO, Divertor, Plasma-facing component, thin interlayer, functional graded material, Non-destructive examinations

## 1 Introduction

The design of divertor target component is a key issue for fusion reactor [1]. Tungsten (W) is considered as the best option as armour plasma facing material. CuCrZr is considered as a heat sink material for components subjected to 20 MW/m<sup>2</sup>. The baseline DEMO divertor concept is the ITER divertor one [2] which is based on the use of a CuCrZr cooling pipe armoured by a W block. This concept uses CuOFHC (~1 mm) as interlayer between W and CuCrZr. Additionally to this concept, several other designs are being developed within Eurofusion WPDIV project [1]. As an option, it is proposed to use thin coat (~20 µm) interlayer between W and CuCrZr [3] [4]. One of the motivations is to avoid the potential fast fracture of copper under neutron irradiation. With this concept, another advantage is to decrease the armor temperature, as the distance of heat conduction path is shortened. Such mock-ups have high thermal fatigue performance since they handled, without any degradation (no surface change aspect and no decrease of thermal heat exhaust capability), 1000 cycles at 20 MW/m<sup>2</sup> [3]. This article presents the recent results being obtained on this concept focusing on the design, mock-up production, inspection, high heat flux (HHF) qualification testing and post-examinations.

## 2 Requirements and scope

Within WPDIV project, the baseline divertor to be developed is constituted of tungsten as armor material and CuCrZr as heat sink [3] [4]. Water is used to cool plasma facing components (PFCs) and cassette body.

The temperature and pressure of the coolant is 130 °C and 5 MPa, respectively [5]. The inner wall heat flux has to be lower than the critical heat flux with a 1.4 margin. In normal operation phase it is assumed that surface heat flux reaches 15 MW/m<sup>2</sup> [5]. Considering the geometry requirements of developed WPDIV concepts, the initial thickness of the armor (minimum distance from the interlayer to the plasma-facing surface) was set at 5 mm [6], in the 1<sup>st</sup> phase of the project (2014–16), while in the 2<sup>nd</sup> phase (2017–18) it was set at 8 mm [5]. Considering the ITER-like concept as reference [7, 8], it was decided to use, for the 2<sup>nd</sup> phase, as much as possible the same geometries as the ITER-like ones.

Three types of mock-ups are considered in this paper (Table 2): mock-ups with thin FGM interlayer developed during the 1<sup>st</sup> phase (here later called FGM-Phase1), mock-ups with thin FGM interlayer developed during the 2<sup>nd</sup> phase (here later called FGM-Phase2) and mock-ups with thin Cu interlayer developed during the 2<sup>nd</sup> phase (here later called Cu-Phase2). Block dimensions are 22 mm (width) \* 23 mm (height) \* 4 mm (depth), for FGM-Phase1 mock-ups. Block dimensions are 23 mm (width) \* 26 mm (height) \* 12 mm (depth), for FGM-Phase2 and Cu-Phase2 mock-ups. Tube inner diameter is 12 mm. Tube outer diameter is 14 mm and 15 mm for Phase1 and Phase2 mock-ups, respectively. Phase1 and phase2 mock-ups are composed of 10 blocks and 4 blocks, respectively.

## 3 Performance assessment simulations

Inputs for performance assessment simulations are presented in [4]. Monoblock elastic analysis procedure

(MEAP) is used to define reserve factors [8] (Table 1). For FGM-Phase1 mock-ups, calculated reserve factors [4] are higher than the ones calculated for Phase-2 mock-ups. It can be deduced that FGM-Phase1 mock-ups should have a better thermomechanical behavior compared to the Phase2 ones. This is mainly due to the tube outer diameter, the block and armor thicknesses, which are higher for Phase2 mock-ups compared to Phase1 ones. Moreover, the higher the armor thickness is the higher is the maximum temperature in tungsten. Phase2 mock-up tungsten blocks will consequently be more prone to recrystallization compared to Phase1 mock-up ones.

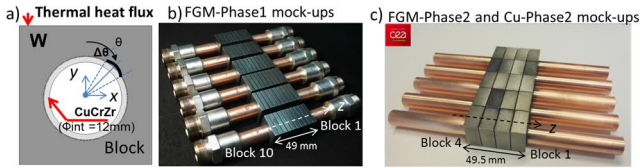


Fig. 1: Block dimensions (a) pictures of FGM-Phase1 mock-ups (b) and FGM-Phase2 and Cu-Phase2 mock-ups (c)

## 4 Fabrication and examinations

### 4.1 Mock-up fabrication

W and CuCrZr properties comply with the DEMO requirements. W plate is supplied in stress relieved condition. For each phase of the project, a dedicated batch was delivered. CuCrZr raw material, provided in solution annealed condition, is a bar with an outer diameter of 42 mm (Le Bronze Industriel, CRM16 TER grade).

FGM interlayer is realized with physical vapor deposition (PVD) in order to obtain a coating at the inner surface of the bore hole of tungsten blocks [3]. At the W interface, the coating consists of 100 at% of W from where the W concentration is decreased continuously up to the interface with the tube. At this position, the deposit is composed of 100 at% of Cu. Cu interlayer fabrication is also realized with PVD. Methods to characterize the deposits are presented in [4]. For FGM-Phase1 mock-ups, mean thickness is 21.5  $\mu\text{m}$  and the standard deviation is 4.6  $\mu\text{m}$  [3]. For FGM-Phase2 mock-ups, mean thickness is 23.1  $\mu\text{m}$  and standard deviation is 3.5  $\mu\text{m}$ . For Cu-Phase2 mock-ups, they are estimated to be 25  $\mu\text{m}$  and 7.6  $\mu\text{m}$ , respectively.

Final joining of tungsten blocks to tube is realized with hot isostatic pressing (HIPping; 950  $^{\circ}\text{C}$ , 120 MPa, 2 h) [3]. Thermal ageing (3 hours) has been applied on the component at 475  $^{\circ}\text{C}$  after HIPping in order to partially recover thermal-mechanical properties of CuCrZr

Table 2. Geometries, material grade and MEAP results for manufactured mock-ups

Mock-up type- (Mock-up name)	W batch	W thickness / mm			Interlayer		CuCrZr external diameter / mm	Pipe ratchetting (451MPa)	Pipe fatigue (6000 cycles)	Pipe max. temp. (350 $^{\circ}\text{C}$ )	Wall peak heat flux (44.4MW/m $^2$ )	Armor Max. Temp. (1800 $^{\circ}\text{C}$ )
		T	p	L	Composition	Thickness / $\mu\text{m}$						
FGM-Phase1 [3] [4] (Mock-ups 2 and 4)	1	5	4	4	FGM	25	14	0.68	2.04	1.35	3.1	2.2
FGM-Phase2 (Mock-ups 9 and 10)	2	8	3	4	FGM	25	15	0.61	1.18	1.12	2.11	1.36
Cu-Phase2 (Mock-ups 7 and 8)	2	8	3	4	Cu	25						

material. In total, 10 mock-ups were manufactured for testing (6 for FGM-Phase 1, 2 for FGM-Phase2 and 2 for Cu-Phase2).

### 4.2 Non-destructive examination after manufacturing

A global thermal assessment test with SATIR/STING facility [9] was performed. With this test-bed, thermal imperfection is reported in terms of probable thermal imperfection located at the external surface of the tube, being quantified by its extension ( $\Delta\theta$ ) and its position ( $\theta$ ) [10] (Fig. 1). Ultrasonic tests (UT) in ENEA were also performed.

SATIR tests revealed that 94% of the monoblocks constituting FGM-Phase1 mock-ups have no thermal imperfection [4].

Defects detected with non-destructive examinations (NDEs) for FGM-Phase2 and Cu-Phase2 mock-ups are presented in Table 2. No defect was observed after fabrication for ~65% of the blocks, corresponding to no defect for 50% of the mock-ups. Detected defects are wide and UT testing reveals that they are always located inside tungsten blocks. When comparing results obtained from UT and IR, one can note that defects are detected with both technics. Some differences, in terms of position and extension, are noticed which may be due to the defect detection methods which are different for these two NDEs. For two mock-ups, not quantifiable detachments are detected only by UT at the free end of 2 blocks (1 and 4 for mock-up 7).

Table 1. Thermal imperfection position and size ( $\theta$ ,  $\Delta\theta$  see Fig. 1) detected after manufacturing (measured by infrared thermography (IR) and ultrasonic testing (UT))

Block		Cu-Phase2 (Mock-up 8)		FGM-Phase2 (Mock-up 10)			
		4	1	2	3	4	
IR	$\theta$	24 $^{\circ}$	-5 $^{\circ}$	-27 $^{\circ}$	0 $^{\circ}$	-20 $^{\circ}$	
	$\Delta\theta$	288 $^{\circ}$	195 $^{\circ}$	215 $^{\circ}$	170 $^{\circ}$	245 $^{\circ}$	
UT in W	$\theta$	8 $^{\circ}$	-39 $^{\circ}$	1 $^{\circ}$	5 $^{\circ}$	-11 $^{\circ}$	
	$\Delta\theta$	288 $^{\circ}$	274 $^{\circ}$	169 $^{\circ}$	152 $^{\circ}$	198 $^{\circ}$	

### 4.3 HHF tests

Thermal heat exhaust capability is checked with high heat flux testing. One mock-up from FGM-Phase1 (Mock-up-2) was tested up to 1000 cycles at 20 MW/m $^2$  with cold water cooling (70 $^{\circ}\text{C}$ , 30 bar, 12 m/s) in JUDITH-2 facility [3]. 3 blocks were tested up 1000 cycles while 3 blocks, on the same mock-up, were tested up to 500 cycles.

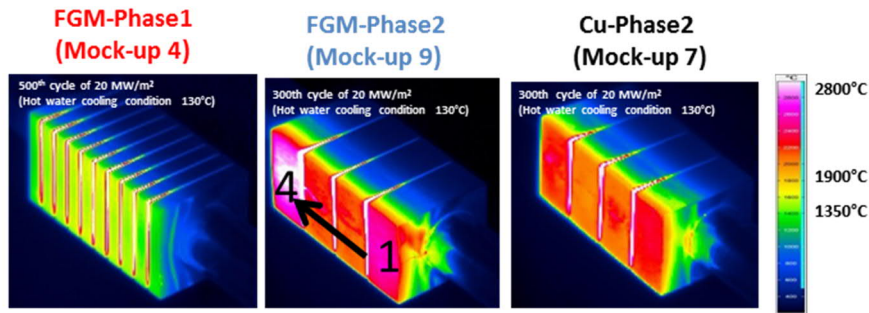


Fig. 2 : Infrared pictures from high heat flux tests (latest cycle at 20 MW/m<sup>2</sup>)

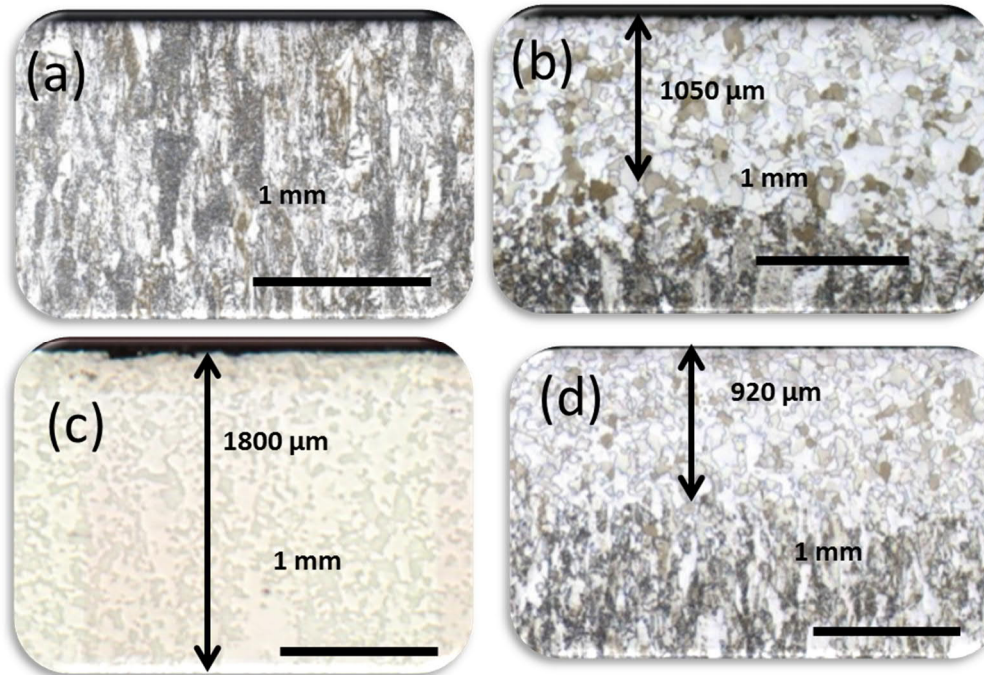


Fig. 3: SEM images of tungsten related to FGM-phase1 mock-ups: after the complete manufacturing process, (a) after 1000 cycles at 20 MW/m<sup>2</sup> (b and c) and after 500 cycles at 20 MW/m<sup>2</sup> (d).

The other mock-ups were HHF tested in GLADIS facility [11]. Two ranges of HHF tests are performed: under cold (20 °C, 10 bar, 12 m/s) and hot (130°C, 40 bar, 16 m/s) water cooling conditions [3]

For FGM-Phase1 mock-ups, hot water condition tests consist in performing 500 cycles at 20 MW/m<sup>2</sup>. After the HHF testing campaign of FGM-Phase1 mock-ups no damage was observed.

For FGM-Phase2 and Cu-Phase2 mock-ups, cold water tests in GLADIS consisted in: screening tests up to 25 MW/m<sup>2</sup> followed by 100 cycles at 10 MW/m<sup>2</sup>. Hot water condition tests consist in performing 300 cycles at 20 MW/m<sup>2</sup>. For these mock-ups, as expected, the blocks with the manufacturing defects did not pass the HHF tests under cold water cooling condition. Consequently HHF test with hot water cooling condition were not possible to be performed for these mock-ups. Mock-ups, which presented no defect during cold water cooling conditions were tested with hot water cooling. With this conditions, damages were observed on 2 blocks of Cu-Phase2 and FGM-Phase2 mock-ups, for which small detachments were observed by UT at the free end of

blocks. After the emergence of these defects, HHF tests were stopped even if non-damaged blocks could have pursued the HHF tests. The same range of number of cycles at 20 MW/m<sup>2</sup> (~130) are reached for FGM-Phase2 and Cu-Phase2 mock-ups. The infrared picture of the last cycle performed at 20 MW/m<sup>2</sup> is presented in Fig. 2. Some further investigations are needed to understand the reason of damage propagation and to define if FGM-Phase2 and Cu-Phase2 mock-ups can have equivalent performance under HHF tests.

#### 4.4 Metallographic examinations

Metallographic examinations are performed, on some blocks presenting no damage during HHF tests. The recrystallized thickness at the upper part of the cooling tube (

Fig. 3.B, C and D) is checked. For comparison, raw W grains (shape and size) related to FGM-Phase1 mock-ups are presented in

Fig. 3A. For FGM-Phase1 mock-ups, presenting an armor thickness of 5 mm, one can note a tungsten recrystallized layer of 1050 µm and 1800 µm (resp. 920

µm) for a loading at 1000 cycles (resp. 500 cycles). As expected, the greater the number of cycles is, the thicker the recrystallized layer is. Two different recrystallized layer thicknesses are obtained after 1000 cycles. This difference, could be partially be explained by the difference of cooling conditions during HHF testing. As comparison, recrystallized tungsten layer of ITER-like mock-up after 1000 cycles@20 MW/m<sup>2</sup> is 2000-4000 µm [12]. Recrystallized layer of FGM-Phase2 mock-up (mock-up 9) is ~4380 µm due to the 8 mm armor thickness.

It is not presented here, but interfaces (FGM to W and FGM to CuCrZr) are free of crack.

## 5 Conclusions

For DEMO divertor target components, different concepts are developed and two R&D phases have been completed in the WPDIV project since 2014. One of proposed concepts uses thin interlayers (functional gradient material (FGM) or copper) between tungsten armor material and tube. The first phase of the project (2014-2016) led to the successful production of mock-ups with FGM as interlayer, for which no degradation at the interface was noticed under DEMO relevant testing conditions. As expected, a low recrystallized tungsten layer is noticed (~1050 µm).

For the 2<sup>nd</sup> phase of the WPDIV project, mock-up geometries were standardized. Mock-ups equipped with thin interlayer were manufactured. As for mock-ups from first phase, some defects were detected after manufacturing, being always located inside tungsten.

All Phase2-mock-ups were HHF tested and half of them passed successfully the cold cooling HHF tests (screening test up to 25 MW/m<sup>2</sup> followed by 100 cycles at 10 MW/m<sup>2</sup>). Damaged blocks observed during HHF tests are consistent with the ones detected by non-destructive examinations after their manufacturing. Mock-ups which passed successfully the HHF tests with cold cooling were HHF tested with hot water cooling conditions. No damage was observed up to ~130 cycles at 20 MW/m<sup>2</sup> and well-fabricated blocks did not show significant degradation under HHF tests. The complete characterization of these damages blocks will be performed in the future, by means of metallographic examinations.

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