Technologies for the ITER Divertor Vertical Target Plasma Facing Components

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Abstract. The ITER divertor vertical target (VT) has to sustain heat fluxes up to 20 MW/m^2. The concept developed for this Plasma Facing Component (PFC) working at steady state is based on Carbon Fibre Composite (CFC) armour for the lower straight part and tungsten (W) for the curved upper part. The main challenges of such components are to be able to remove the high deposited heat fluxes and to join mechanically and thermally armour to the metallic heat sink, despite of the mismatch of the thermal expansions. Two solutions based on the use of CuCrZr hardened copper alloy and active metal casting (AMC®) process were investigated during the ITER EDA phase: the first one called "flat tile geometry" was mainly developed for Tore Supra pumped limiter, the second one called "monoblock geometry" was developed by the EU Participating Team for the ITER project. This paper presents a review of these two solutions and analyses their assets and drawbacks: pressure drop, critical heat flux, surface temperature and expected behaviour during operation, risks during the manufacture, controls of the armour defects during the manufacture and at the reception and possibility to repair defected tiles.

1. Introduction

The vertical target (VT) of the ITER divertor is one of the most critical Plasma Facing Components (PFCs). The present reference design foresees tungsten flat tiles armour on the upper curved part of the vertical target and carbon fibre composite (CFC) monoblocks on the lower straight part. The design specifications are 3 MW/m^2 for 3000 cycles on the upper part and 10 MW/m^2 for 3000 cycles and 20 MW/m^2 for 300 cycles on the lower part. The reference design for the cooling of the vertical target is a tube with a twisted tape insert in the lower straight part to increase the critical heat flux limit (FIG. 1).

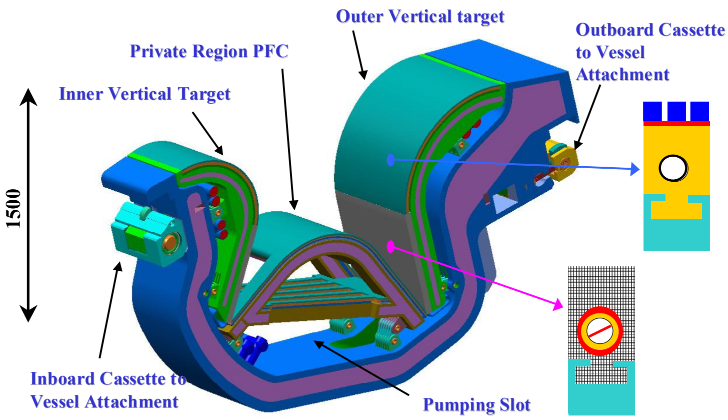


FIG. 1: Schematic view of the ITER divertor with cross sections of the VT

2. Previous experience with high heat flux plasma facing components

A large experience has been gained at Tore Supra for actively cooled PFCs working at steady state since 1989 and especially since 2002 in the frame of the CIEL project for which a toroidal pump limiter (TPL) was studied and developed [1] in order to sustain fluxes in the range of 10 MW/m^2. This last development, which represents a world-wide unique example of series production of high heat flux components (FIG. 2) has allowed a 6-minute plasma to be performed with a total injected energy of 1 GJ [2]. At the beginning of the 90's, brazing of CFC flat tiles onto a metallic heat sink was mastered in most of the cases [3]. For the CIEL project, a precipitation hardened copper alloy (CuCrZr) was selected for the heat sink [4] because of its good weldability and its better fracture toughness when compared to other copper alloys. To preserve its thermomechanical properties the so-called active metal casting (AMC®) technique to join the CFC tiles onto the heat sink followed by electron beam welding [5] was further developed and finally successfully implemented (FIG. 3).
However this manufacture was rather difficult and led to delays in the element deliveries. Many lessons were learned from this manufacture : technical ones (qualification of each batch of the pre-materials, improvement of manufacture processes margins, pre-commissioning of series manufacture processes, *repair processes to be developed prior to series manufacture*) and managerial ones (definition of supplier responsibilities, close collaboration between supplier and customer in the identification and solution of the various technical difficulties) [6]. These lessons are relevant for the next machines: W7X [7] and ITER.

3. Developments for the ITER vertical targets

The main difficulty of the ITER divertor vertical target is to sustain 20 MW/m^2 for 300 cycles at steady state in its lower straight part. The development of relevant concepts started in early 90's and are continuously pursued today.

3.1. Various thermal hydraulic concepts

A first important activity was launched into the use of hardened copper tubes cooled by a circular water channel with a swirl tape as a turbulence promoter. Many tubes and mock-ups were tested using mainly the electron beam facility FE200 in order to validate results and simulation tools. This led to the use of Bergles & Rosenhow and Thom-CEA correlations for the calculation of the heat transfer in the sub-cooled boiling regime and the development of a TONG75-CEA correlation for the prediction of the critical heat flux (CHF) [8]. At the same time a pressure drop correlation CEA98 was developed in order to better predict critical heat flux versus lineic pressure drop or pumping power [9].

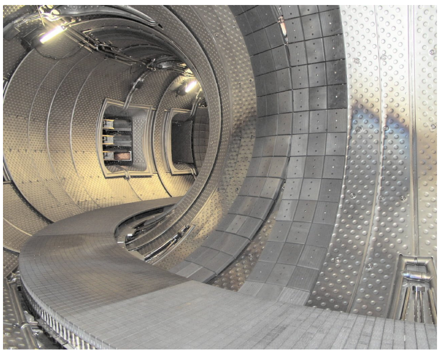


FIG. 2: View of actively cooled internal components of Tore Supra machine

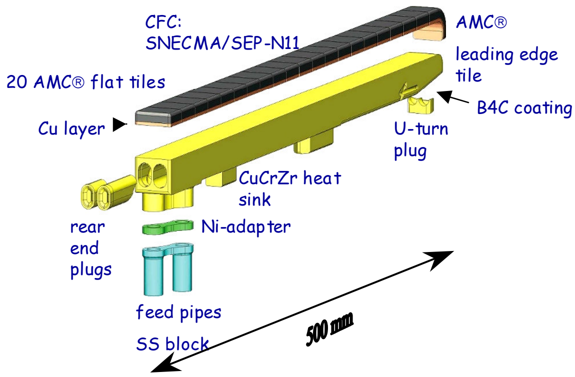
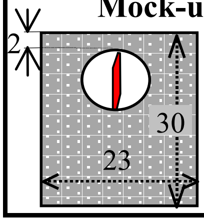


FIG. 3: Flat tiles onto CuCrZr heat sink using AMC technology

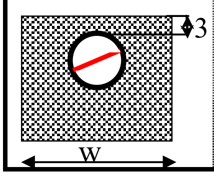
At the beginning the idea was of armouring the tube with a CFC flat tile but due to the high expected temperature at the CFC-Cu joint under 20 MW/m^2 a tube in tile concept (monoblock) was preferred [10]. Moreover a parallel work on flat tile armoured elements for Tore Supra emphasised the risk of tile detachment. The monoblock offers the safety of no risk of detachment even if, in case of defected joint, a hot spot can be observed.
Finally the thermal hydraulic study of swirl tubes culminated in 1998 [9] with tests on monoblock shaped tubes qualifying the thermal hydraulic of the monoblocks (TABLE 1).

TABLE 1: MAIN RESULTS ABOUT CRITICAL HEAT FLUX ON COPPER BLOCKS COOLED BY SWIRL TUBES

Mock-ups		Twist Ratio	Q	ICHF (MW/m^2)		Pressure drop	Pumping power
			kg/s	flat	peaked	(MPa/m)	(W/m)
	a	2	0.701	32.2	36.6	0.61	428
	b	3	0.70	27.1	28.4	0.45	316
	c	4	0.70	21.1	24.3	0.40	281

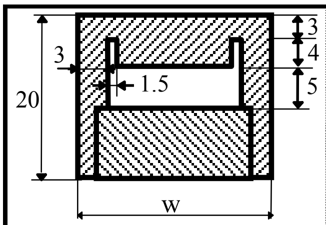
A very interesting critical heat flux campaign was then performed on CFC monoblocks cooled by swirled tubes (TABLE 2). The results are in good agreement with the previous campaign on Cu blocks and allowed the design of the monoblocks to be changed from a width of 23 mm to a width of 28 mm while increasing the tube dimensions from 10/12 mm ID/OD to 12/15 mm ID/OD.

TABLE 2: MAIN RESULTS ABOUT CRITICAL HEAT FLUX CFC MONOBLOCKS COOLED BY SWIRL TUBES

Mock-ups		W	Q	ICHF (MW/m^2)	Pressure drop	Pumping power
	ID/OD	mm	kg/s	flat	(MPa/m)	(W/m)
	10/12	23	0.70	22	0.59	433
	10/12	28	0.68	20	0.57	413
	10/12	33	0.69	17	0.58	423
	12/15	33	0.71	23	0.60	453

A second important activity was launched in 1995 in order to study in parallel alternative cooling concepts: performances of smooth tube, swirled tube, annular flow tubes and hypervapotron tube were compared [10]. This latter gave a very promising result (water velocity = 10 m/s, Q = 1.1 kg/s, ICHF= 38 MW/m^2, Pressure drop = 0.38 MPa/m, Pumping power = 378 W/m) and high heat flux tests were performed in 2001-2002 in order to study the hypervapotron (HV) concept at lower water flow (water velocity ranging from 2 to 6 m/s) [11]. The fins of the HV tubes are 4 mm high and 3 mm thick. This study confirmed the very good performance of the hypervapotron tubes (TABLE 3).

TABLE 3: MAIN CRITICAL HEAT FLUX RESULTS ON HYPERVAPOTRON TUBES (6 M/S)

	w	Q	ICHF (MW/m^2)		Pressure drop	Pumping power
	mm	kg/s	flat	peaked	(MPa/m)	(W/m)
	27	0.67	29.5	31	0.13	203
	40	1.02	25.5	30	0.10	103
	50	1.33	24.5	/	0.05	35

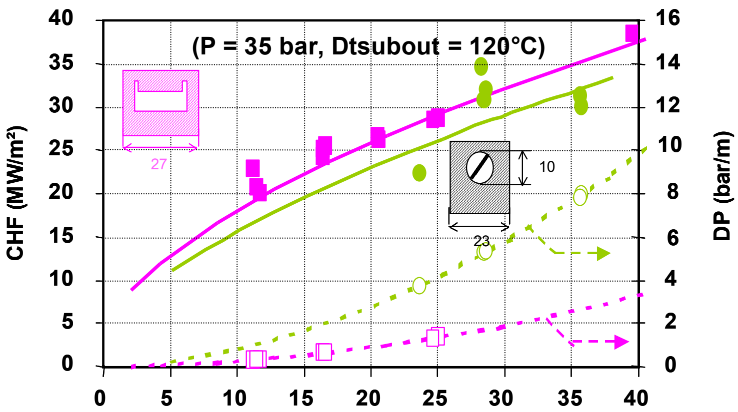


FIG. 4: Comparison of swirl and HV tubes versus water flow (kg/s/m^2)

A comparison between swirl tube and pressure drop is given on FIG. 4. The swirl tube and HV tube are about equivalent in terms of CHF but the HV tube would lead to lower pressure drop in the lower straight part of the VT. However, HV might require a higher water flow rate than the swirl tube (see § 3.3) and as a result, the total pressure drop and the required pumping power of the whole divertor system would be higher for the HV solution than for the swirl tube solution.

The reference solution (monoblock width of 28 mm and 12/15 mm ID/OD) foresees a total flow rate for the 54 divertor cassettes of 934 kg/s corresponding to a flow velocity of 9 m/s for the outer VT (design limit 1000 kg/s) and a total pressure drop of 12.2 bar (design limit 14 bar), the swirl tubes contributing to about 21% of the total pressure drop.

3.2. Qualification of the CFC monoblock concept and tungsten armour

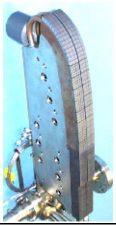
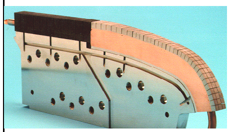
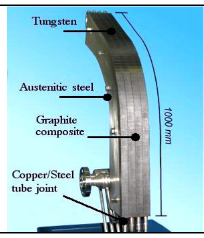
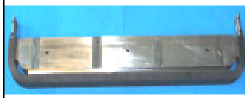
Many mock-ups were fabricated and high heat flux (HHF) tested to demonstrate the capability of the concept to reach the requirements. Besides samples, fabricated and tested in order to demonstrate the validity of manufacture processes, several medium-scale or full-scale mock-ups were manufactured and tested. The CuCrZr material was finally selected as heat sink material. A soft copper compliant layer of 1 or 1.5 mm was used between CFC and CuCrZr.

The main results on CFC monoblock large mock-ups are given TABLE 4 (*note that several of these mock-ups have also a W part*). Using the NB31 CFC from Snecma-Bordeaux (France) up to 2000 cycles at 20 MW/m^2 were sustained [12][13]. In general, the CFC monoblock quality improved during the mock-up manufacturing contract, but cracks continued to be observed at the top of CFC/Cu interface due to the shrinkage of the tube during joining-process cooling-down. Up to now the defects did not propagate dramatically during fatigue tests [14]. The tungsten armour of the curved upper part of the vertical target is not so critical because it is only exposed to lower heat fluxes (around 3 MW/m^2) however it was tested at higher values in order to investigate a full tungsten armoured divertor. Globally the W flat tile armours were able to sustain up to 1000 cycles at 10 MW/m^2, with only rare degradation of the W/Cu bond and even 1000 cycles at 14 MW/m^2 of absorbed heat flux [15][16].

Irradiation campaigns were launched first in mid 90s (Paride 1 and 2: 0.35 dpa [displacements per atom] 350 and 700°C) and then in 2000 (Paride 3: 0.2 dpa in carbon, 0.15 dpa in W, 200 °C and Paride 4: 1 dpa in carbon, 0.6 dpa in W, 200 °C).

It was not possible to test irradiated monoblocks at 20 MW/m^2 due to the decrease of CFC conductivity after irradiation (17 % of the un-irradiated value after 0.2 dpa). CFC monoblocks of Paride 3 and 4 were tested successfully 1000 cycles at 10 MW/m^2 plus 1000 cycles at 12 MW/m^2.

TABLE 4: MAIN RESULTS ON CFC MONOBLOCK LARGE MOCK-UPS

Mock-ups				
Name of Mock-up	VTMS	VTMSDEF	VTFS	BAFFLE
CFC part material	NB31	NB31	NB31	NB31
Top CFC thickness	13.5 and 7.5 mm	13.5 mm	5 mm	4 mm
Monoblock width	27 mm	27 mm	27 mm	27 mm
CFC/Cu Joint	AMC	AMC	AMC	AMC
Cu-Tube joint	Brazing	Brazing	HIPing	HIPing
Nb of cycles	1000*10 MW/m^2	1000* 12MW/m^2	1000*10 MW/m^2	**3000*10 MW/m^2**
	2000*20 MW/m^2		**1000*20 MW/m^2** **1000*23 MW/m^2**	Test in progress
		No propagation of cal. defects		

Irradiated W flat tile mock-ups did not survive 10 MW/m^2 cycling. This is thought to be due to irradiation induced diffusion processes. Due to these processes, vacancies are concentrated at locations of high mechanical stresses. As a result, the quality of bonding between copper and tungsten is reduced. In contrast W monoblocks, which were also fabricated and tested after irradiation, sustained well 1000 cycles at 18 MW/m^2 [17].

3.3. Qualification of CFC flat tile concept

In parallel to monoblock qualification, further developments were pursued to improve the limits of the flat tile technology by using a HV tube for cooling instead of a swirl tube. This change in the cooling scheme resulted in a substantial improvement of the fatigue performances that exceed the ITER requirements. As a result this solution could constitute a possible fallback solution to the present reference design (FIG. 5) [12]. Moreover this technology proved to be able to sustain under 10 MW/m^2 the loss of a tile without cascade failure effect [18]. Testing at 20 MW/m^2 needed to demonstrate the capability of the design to sustain transients was beyond the capabilities of the test facility. However, the tested HV geometry requires a higher flow rate than for the monoblock one (assuming a width of 28 mm, the water cross section is respectively 122 and 92 mm^2). One might think to vary the channel depth and hence the coolant velocity along the element in order to maintain an adequate margin on CHF and a suitable armour joint temperature in the region of the strike point, but this should be carefully assessed by HHF tests.

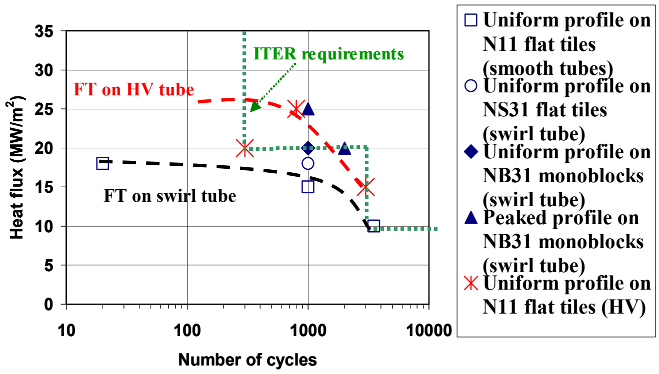


FIG. 5: Comparison of fatigue test results for CFC monoblock and flat tile concepts

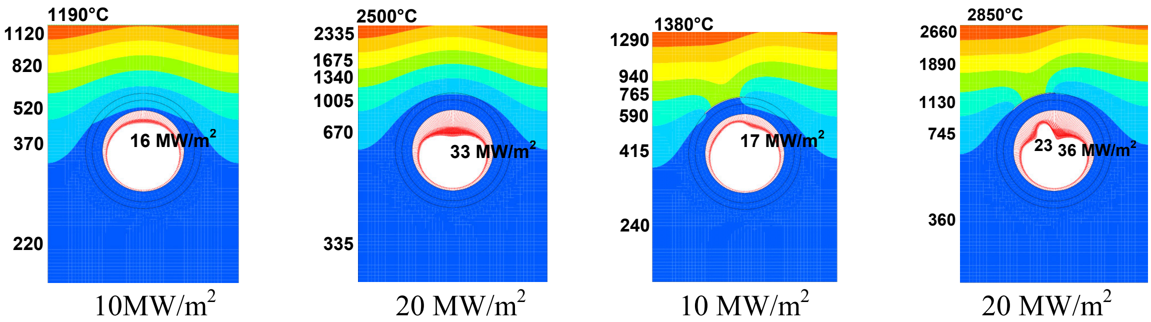


FIG. 6: Temperature iso-values for without- and with-defect monoblock (top CFC thickness 10 mm)

4. Acceptance Criteria

Feedback from TPL manufacture at Tore Supra shows it is essential to be able to test the elements during manufacture as well as at final delivery. To allow this to be done transient thermography and lock-in thermography have been developed [19]. The CFC thickness of 18 mm, foreseen for ITER, is rather unfavourable for theses methods. However, in the case of monoblocks, additional monitoring of the monoblock side surfaces contributes to improved detection, a 45° circumferential defect at the CFC/Cu interface being detectable [20]. But such a defect, even if it does not propagate rapidly under heat cycling, leads to a high surface temperature (FIG. 6) that would result in unacceptably high surface erosion if repeated on many of the divertor's monoblocks [20]. The aim of the acceptance criteria study is to identify the maximum defect that can be tolerated at the acceptance of the elements (not only taking into account the margins versus critical heat flux and surface temperatures but also the risk of crack propagation) and to determine means to detect such a defect. Developments are in progress in order to improve the thermography methods and at the same time monoblock samples with calibrated defects are under fabrication and HHF tests are scheduled in order to study the potential propagation of the minimum defect.

5. Repair Process

The fabrication of monoblock components is rather difficult. The most mature technology consists in the AMC of the CFC monoblocks followed by low temperature HIPing. The first step consists on the fabrication of AMC monoblocks: during the cooling down of the AMC process the shrinking of the copper can lead to a debonding of the CFC/Cu interface. The second step consists on the HIPing of a CuCrZr tube inside the monoblocks (470°C, 100 MPa inside and 100 MPa outside, several hours). Considering only this second step and assuming the residual stresses are completely relaxed during the heat treatment at 470°C one can evaluate the stresses in the CFC/Cu interface at the end of the HIP cycle. In fact, they may exceed the strength of the CFC which explains the observed defects in the monoblocks. In the full-scale vertical target prototype (4 tubes), manufactured and tested in EU, 107 monoblocks over a total of 108 were of acceptable quality, thus leading to an acceptance rate of more than 99% [13]. However it is prudent to develop a repair process of the monoblock before the launching of the series production for ITER because one defective monoblock can lead to the rejection of a complete tube.
In 2001, EFDA CSU Garching launched a feasibility study of the repairing process for the monoblock geometry. This study included an in-depth analysis of the various repairing processes. Five possible repairing modes have been investigated as shown in FIG. 7 (1. two horizontal half tiles with 1 mm gap filled by copper, 2. two horizontal half tiles with 1 mm

gap without adding copper in the gap, 3. two vertical half tiles with 1 mm gap, parallel to the CFC fibres with the highest thermal conductivity, 4. two horizontal half tiles with no gap, the two half tiles contacting each other during the final cool down, 5. two vertical half tiles with no gap).

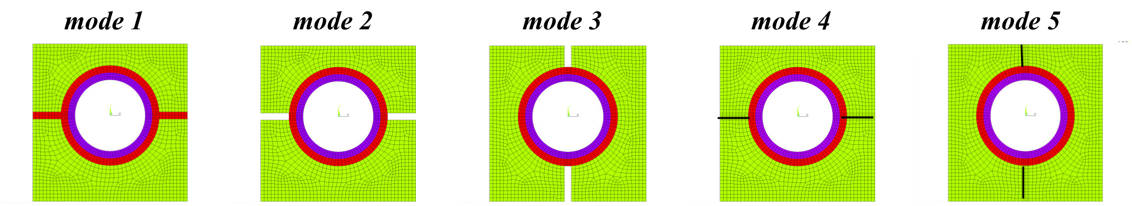


FIG. 7: Investigated repairs modes

When comparing the residual stresses of the repaired joint the fifth mode proved to be the best one. This mode does not allow a loss of a tile even in case of a complete joint failure. On the basis of this preliminary study, a technological R&D programme has been recently launched with the EU industry to manufacture "repaired" VT prototypes to be then high heat flux tested.
As a repair option, CEA proposes a saddle tile externally identical to the monoblock with a lock system at the rear to prevent the tile loss.

6. Discussion

The advantages and drawbacks of monoblock and flat tile concepts can be analysed with regards to the following design topics:
Pressure drop and critical heat flux: the HV tube has a better CHF performance but might require a higher water flow rate thus leading to an overall increase of the pressure drop in the whole divertor system.
Behaviour during operation: for flat-tiles on hypervapotron tubes, surface temperatures are lower under similar heat load whereas the CFC/Cu joint temperature is higher. Although tile detachment is possible, it has been experimentally demonstrated that this should not cause any cascade failure effect up to a heat load of 10 MW/m^2. The monoblocks provide a capability to avoid a tile detachment even after a complete CFC/Cu joint de-bonding and analyses demonstrated that a few of these events could be even tolerated during the ITER operation. Monoblocks proved to be a very robust solution under neutron irradiation whereas the capability of the flat tile solution to meet the ITER requirements after neutron irradiation appears uncertain.
Manufacture: the fabrication of monoblock components was demonstrated at prototypical level and EU industry is actively working to further improve the monoblock technology while manufacturing of flat tiles has already achieved the industrial level.
Non-destructive testing: infrared thermography of the CFC/Cu bond is difficult due to the CFC thickness (18 to 20 mm), however, monoblock geometry allows the bond to be investigated though lateral faces. Moreover ultrasonic controls of the CuCrZr/Cu bond are quite reliable for monoblocks.

7. Conclusion

The monoblocks have high defect tolerances and have better thermal fatigue behaviour even after neutron irradiations. From technical point of view, the main advantage of the monoblock concept is its strength under heat flux and its main drawbacks are a higher manufacturing difficulty than the flat tile and that the possibility of being repaired still needs to be fully demonstrated. Research and development activities are in progress, and will be continued, with the aim of bridging the gap between the demonstrated capabilities at the prototypical level and the required series production for ITER. In that respect, the flat tile concept may deserve continuous attention as a possible fallback solution to the reference design.

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