

**Task Title: MONITORING AND ANALYSIS OF THERMAL FATIGUE TESTING OF DIVERTOR PROTOTYPES**  
**200 kW electron beam gun test**

**INTRODUCTION**

Thermal fatigue is one of the most important damaging mechanism for the plasma facing components (PFCs) of the ITER machine due to the high number of operating cycles (several thousands) and to the expected surface heat loads. Therefore an assessment of the behaviour of PFCs under cycling heat loads is essential to demonstrate the fitness for purpose of the selected design solutions. This contract concerns the monitoring and analysis of thermal fatigue testing of PFCs to be performed in the frame of the European R&D programme for ITER.

The thermal fatigue testing is performed in FE200 electron beam facility at Le Creusot, France, under a separate contract.

**2003 ACTIVITIES**

A Full Scale prototypical divertor Vertical target (so called VTFS), which included all the main features of the corresponding ITER divertor design, was manufactured by the EU companies Plansee AG and Ansaldo Ricerche and tested in FE200 facility. The test will continue in 2004.

This VTFS prototype consisted in 4 units with one cooling channel each. The overall length and width was about 1000 and 100 mm, respectively (figure 1).

The high heat flux part of the prototype has a lower straight region made of CfC NB31 (3 dimensional Carbon Fiber Composite manufactured by SEP) monoblocks and an upper bend region made of tungsten / lanthanum ( $La_2O_3$ ) lamellae monoblocks.

The internal tube is made of precipitation hardened CuCrZr copper alloy (ID/OD 10/12 mm).

The joining between the tube and the monoblocks has been done by:

- i) Active Metal Casting (AMC, Plansee).
- ii) Hot Isostatic Pressing (HIP) with 1000 bar at a maximum temperature of 550°C, which has been kept for 6 h before decreasing pressure and temperature.

The high heat flux was integrated onto the steel back plate via a mechanical attachment, which allowed the monoblocks to slide.

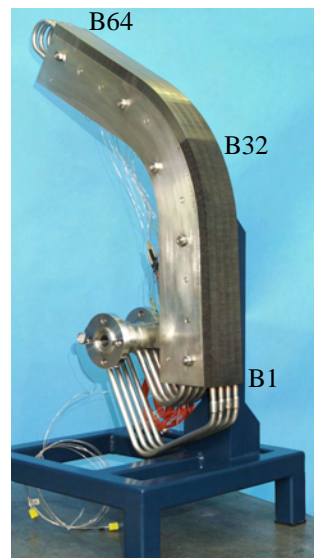
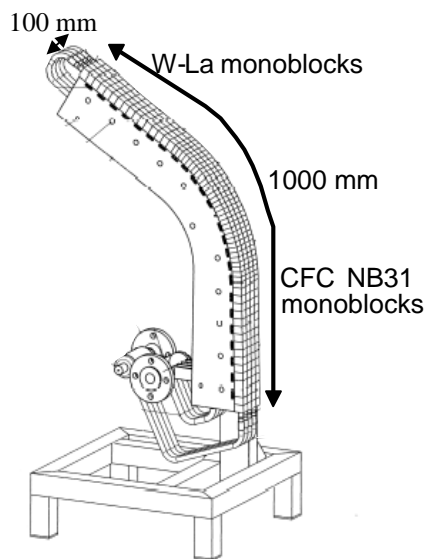


Figure 1 : View of the mock-up VTFS with block number (B1 to B64)

**A. TESTING PLAN**

The following testing plan was operated :

Table 1 : Testing Plan (foreseen and revised)

	Foreseen	Revised
Fatigue cycles CFC part	100 at 5 MW/m <sup>2</sup>	Done
	1000 at 10 MW/m <sup>2</sup>	Done
	2000 at 20 MW/m <sup>2</sup>	Done
	2000 at 20 MW/m <sup>2</sup>	Done at 23 MW/m <sup>2</sup>
Fatigue cycles W part	100 at 5 MW/m <sup>2</sup>	Done
	1000 at 10 MW/m <sup>2</sup>	Water leak after 636 cycles
	2000 at 15 MW/m <sup>2</sup>	To be operated
	2000 at 20 MW/m <sup>2</sup>	To be operated

**B. RESULTS ON CFC PART**

**Initial Screening**

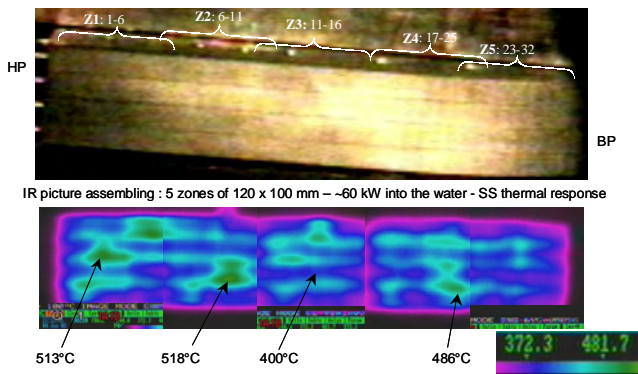


Figure 2 : CCD and IR view of the CFC part under 5 MW/m<sup>2</sup> flux, steady state

A first screening was performed at 5 MW/m<sup>2</sup> on the CFC part.

Maximum temperature calculated by FE calculations being 400°C, 2 blocks were detected hot (row 3 and 9, T<sub>surf</sub> > 500°C) but not enough to be considered as debonded, it was decided to operate the cycling at 10 MW/m<sup>2</sup> on one of these hotter blocks (row 3).

**Cycling at 10 MW/m<sup>2</sup> (cf. figure 3)**

A 10 MW/m<sup>2</sup> flux with a duty cycle (10 sec. ON/ 10 sec. OFF) was alternatively deposited on two areas of 120 mm x 92 mm (2 x 24 blocks).

No clear defect propagation was detected after 1000 cycles, even in the hotter row 3.

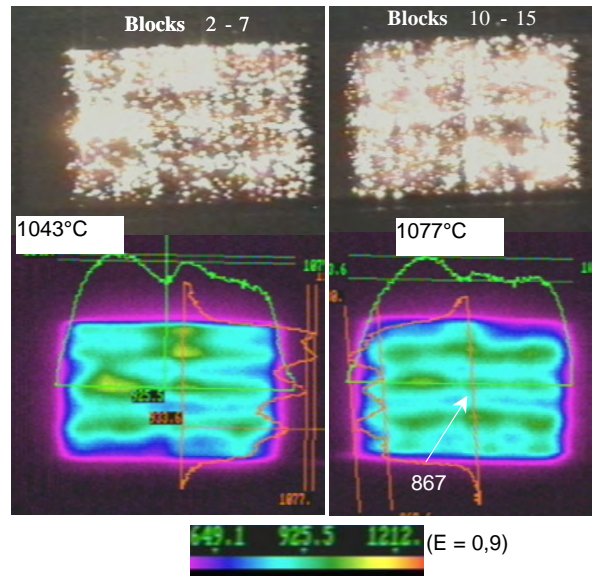


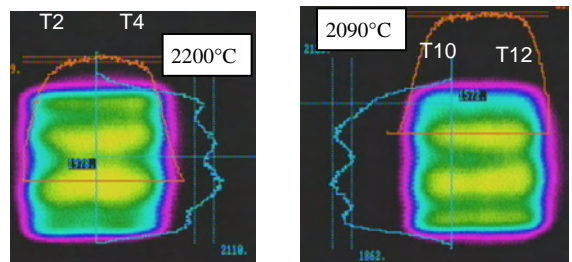
Figure 3 : Typical CCD and IR view of the CFC part under 10 MW/m<sup>2</sup> flux, steady state (Shot #2727 : 180th cycle)

**Cycling at 20 and 23 MW/m<sup>2</sup>**

Two successful tries at 20 MW/m<sup>2</sup>- 1000 cycles was performed on 2 x 18 blocks without defect propagation. Afterwards, looking for margins above 20 MW/m<sup>2</sup>, a 23 MW/m<sup>2</sup> flux with a duty cycle (10 sec. ON/ 10 sec. OFF) was alternatively deposited **2 times** on two areas of 60 mm x 69 mm (2 x 18 blocks).

No clear defect propagation was detected after 1000 cycles, for a typical surface temperature up to 2200°C. This step is particularly demonstrative of the CFC monoblocks robustness under cycling fluxes.

**10th cycle #2805**



**1000th cycle #2810**

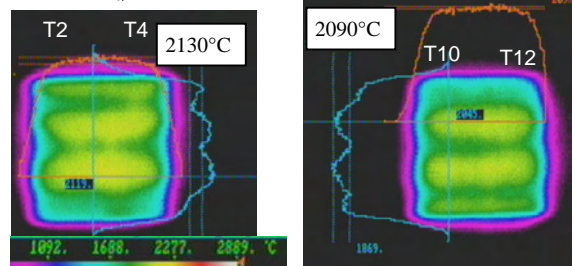


Figure 4 : Typical CCD and IR view of the CFC part under 23 MW/m<sup>2</sup> flux, steady state

**C. RESULTS ON W PART**

**Initial Screening**

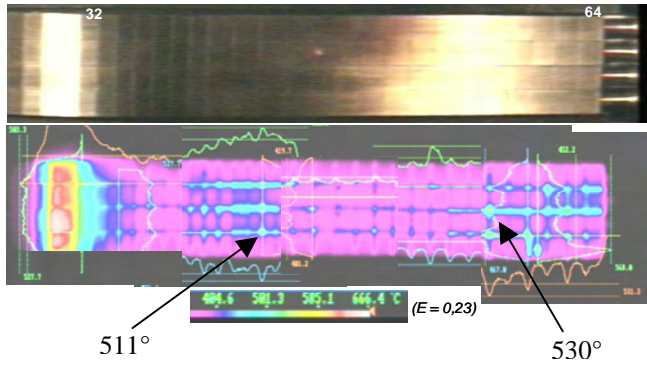


Figure 5 : CCD and IR view of the W part under 5 MW/m<sup>2</sup> flux, steady state

A first screening was performed at 5 MW/m<sup>2</sup> on the W part. Maximum temperature calculated by FE calculations was 550°C on the edges of the lamellae (blue lines on IR pictures) but as IR calibration on W is not validated today, only relative values (like 511 and 530°C) can be considered. No clear overheated zone or defect was detected.

**Cycling at 5 and 10 MW/m<sup>2</sup>**

After 100 cycles at 5 MW/m<sup>2</sup>, it was decided to start a cycling step at 10 MW/m<sup>2</sup> on 2 x 12 blocks of lamellae (NB. : 10 MW/m<sup>2</sup> is absorbed flux, meaning that incident heat flux is roughly the double). Unfortunately, after 636 cycles, a water leak appeared on the bended part (cf. figure 6).

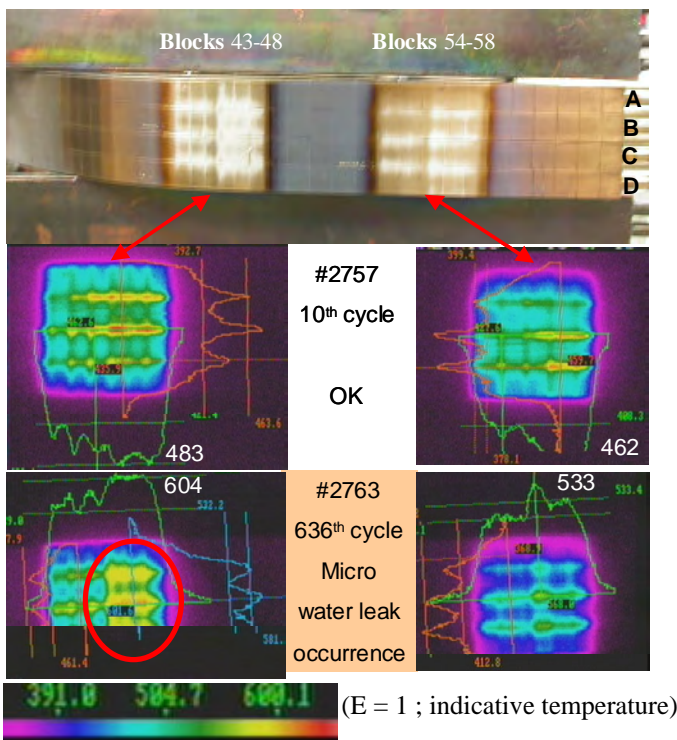


Figure 6 : Water leak occurrence on bended W part (into red circle)

A post mortem analysis of the damaged target was launched, it was found that i) there is no interaction between the leak and the swirl tape position, ii) the HIPped joint presents a weak point at the free edge and iii) it was observed an open crack into the CuCrZr coming from the outside and another crack coming also from the outside but not totally open, in the both cases, impurities (silicium ?) were noticed near the crack (figure 7).

These two radial cracks propagation may be attributed to the temperature gradient developed from the top of the lamellae to the water leading to a high level of mechanical stress at the OFHC/ CuCrZr joint.

Finite calculations are running to try to explain this phenomena. However a first analysis lead to recommend castellation of typically 1 mm gap between every block of lamellae.

The mock-up was mounted again on FE200 facility with 3 units and allowed the cycling step at 23 MW/m<sup>2</sup> on the CFC part. Cycling steps will continue in 2004.

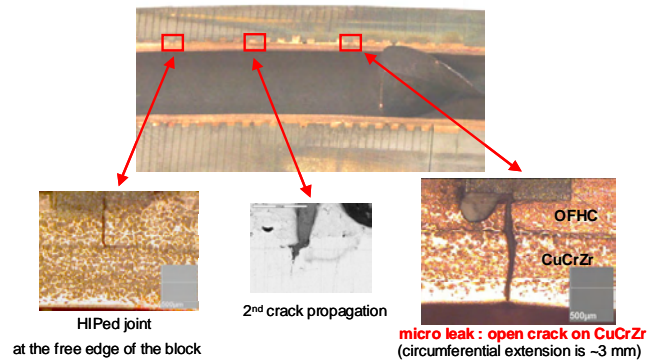


Figure 7 : Post mortem analysis of the water leak occurrence

**CONCLUSION**

A full scale prototypical mock-up of the ITER divertor vertical target was high heat flux tested in FE200 facility. The reference solution CFC monoblocks made of SEP NB31 tiles and CrCrZr tubes confirmed a good behaviour under fatigue testing.

The ITER goal of 20 MW/m<sup>2</sup> was exceeded with the HIP technology. Tungsten monoblocks with lamellae sustained well 100 cycles at 5 MW/m<sup>2</sup> and 600 cycles at 10 MW/m<sup>2</sup>, which is the double of the ITER design for the upper part of the vertical target.

Afterwards, a water leak occurred on the bended part showing a radial crack propagation coming from between two OFHC compliant layers to the internal CuCrZr tube. Analysis and calculations are running to tentatively explain this phenomena. High heat flux tests will continue in 2004.

## **TASK LEADER**

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Frederic ESCOURBIAC

DSM/DRFC/SIPP  
CEA-Cadarache  
F-13108 Saint Paul Lez Durance Cedex

Tél. : 33 4 42 25 44 00

Fax. : 33 4 42 25 49 90

E-mail : frederic.escourbiac@cea.fr

Not available on line

Not available on line

Not available on line

Not available on line



Not available on line

Not available on line

**Task Title: TW4-TVD-ACCEPT: ACCEPTANCE CRITERIA FOR THE ITER DIVERTOR**

**INTRODUCTION**

The fabrication defects in the plasma facing components (PFCs) of the ITER divertor components can be a major concern in regards to the performance of the machine.

The aim of this task is to provide an analytical and experimental basis for the definition of the acceptance criteria for the divertor vertical target elements. These elements are armoured by tungsten flat tiles on the upper curved part and by CFC monoblocks on the lower straight part, it was also decided to investigate a monoblock geometry for tungsten, which represents an alternative solution for the upper part. The heat sink structure is made of CuCrZr alloy and a compliant layer of soft copper is used to mitigate by plastic deformation the thermal expansion mismatch between the armour and the metallic heat sink.

The final outcome of this task should be the identification of the maximum acceptable defect size (probably as a function of its location), defined as the defect that is stable under HHF loading. The maximum acceptable defect shall be then correlated to its response under infrared examination and ultrasonic examination. The following joints shall be investigated: CFC/Cu joint, W/Cu joint, Cu/CuCrZr joint.

The task will be performed in 3 steps:

- Analysis of the existing database.
- Recommend a suitable testing procedure and establish by calculations the theoretical limit of detection taking into account the geometrical et material property uncertainties.
- Design a suitable number of mock-ups.

**2003 ACTIVITIES**

Since the call for tender for the procurement of the calibrated defective mock-ups to be used for the final validation tests had to be launched early in 2004, drawings of the samples were performed at the beginning of this task (4<sup>th</sup> term of 2003).

It was decided to manufacture only samples, which can be then installed side by side on a mock-up for high heat flux testing. The advantage of samples is to be able to control by visual inspection the integrity of the joints at the edges where is located the stress singularity.

The calibrated defects will be defined later in 2004 but early enough to be taken into account before delivery of the samples.

**SAMPLES FEATURES**

The following geometries will be investigated:

- 1) CFC monoblocks “short” (reference design for the ITER divertor vertical target).
- 2) CFC monoblocks “high” (out of the scope of this contract / for SATIR tests only).
- 3) W flat tiles (reference design for the ITER divertor vertical target).
- 4) W monoblocks (alternative solution for the upper part of the vertical target).

The table 1 summarizes the dimensions for each type of sample. The corresponding drawings are given figure 1 to 4.

*Table 1 : Dimensions of the mock-ups*

	<b>CFC monoblocks “short”</b>	<b>CFC monoblocks “high”</b>	<b>W flat tiles</b>	<b>W monoblocks</b>
Total height (mm)	25 <sup>(2)</sup>	50 <sup>(3)</sup>	40 <sup>(3)</sup> 40 <sup>(4)</sup>	40 <sup>(3)</sup>
Tile width (mm)	28	28	28	28
Tile axial length (mm)	20	20	28	12
CuCrZr tube ID/OD (mm)	12/15	12/15	12/15	12/15
CuCrZr tube overall length (mm)	120	120	120	120
Pure Cu interlayer <sup>(1)</sup> thickness (mm)	1	1	2	1

- (1) between the armour and the CuCrZr heat sink, to reduce the joint interface stresses
- (2) to enable the high heat flux testing while keeping the maximum surface temperature within acceptable levels
- (3) corresponding to the ITER divertor design
- (4) the W armour has a macro brush structure with four tiles separated by a ~0.5 mm gap

The manufacture of arrays of 7 samples, for 4 geometry and 2 joining technologies (HIP'ing and brazing), is foreseen. Each array shall be duplicated to check the validity of the high heat flux tests.

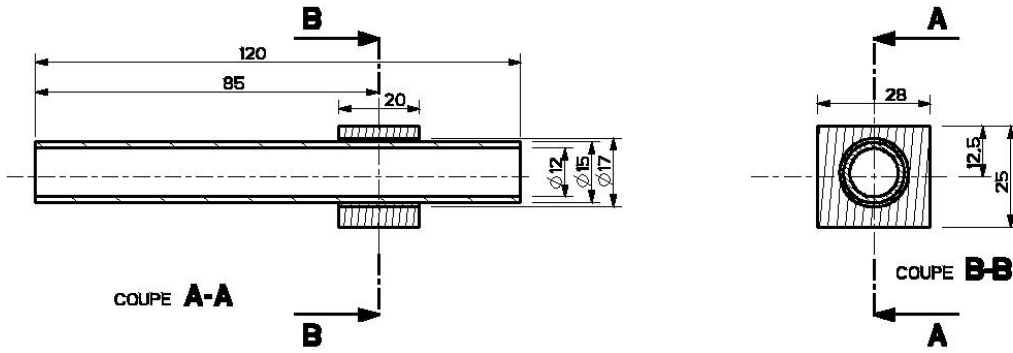


Figure 1 : CFC monoblocks « short »

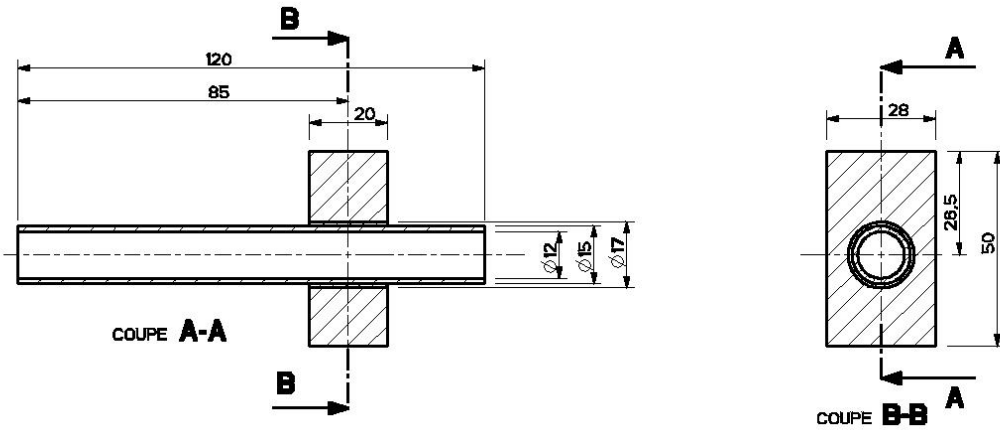


Figure 2 : CFC monoblocks « high »

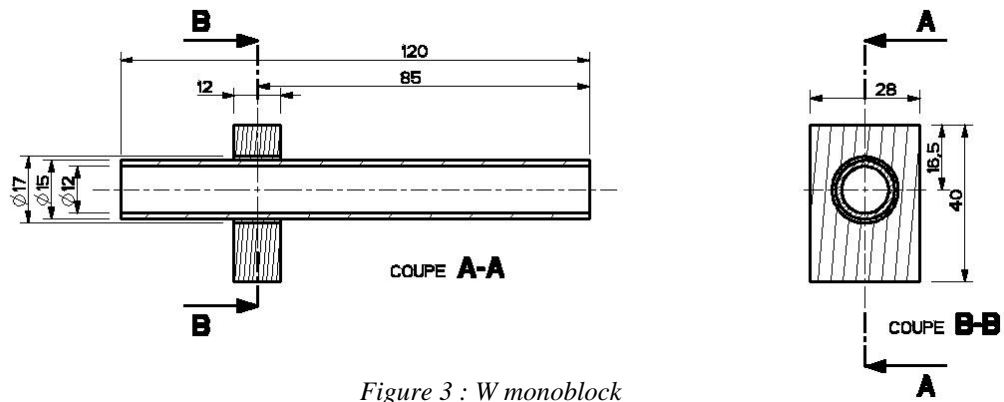


Figure 3 : W monoblock

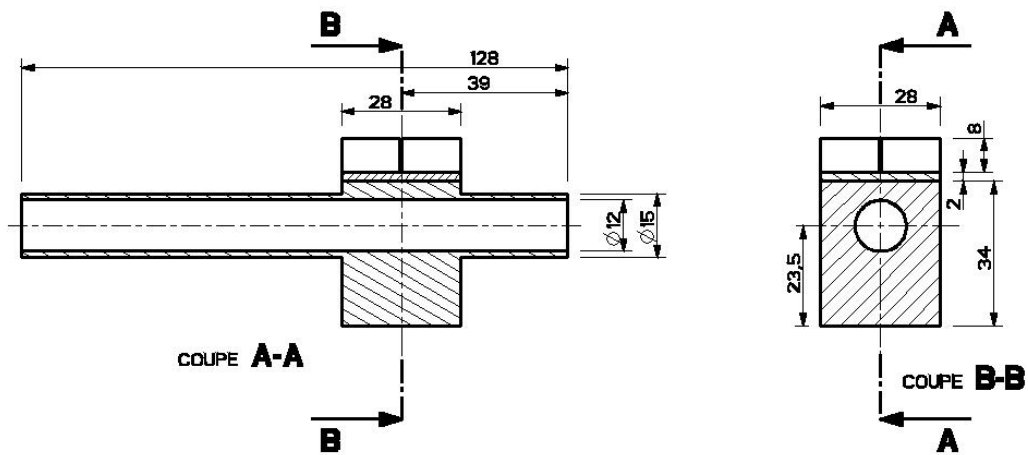


Figure 4 : W flat tiles

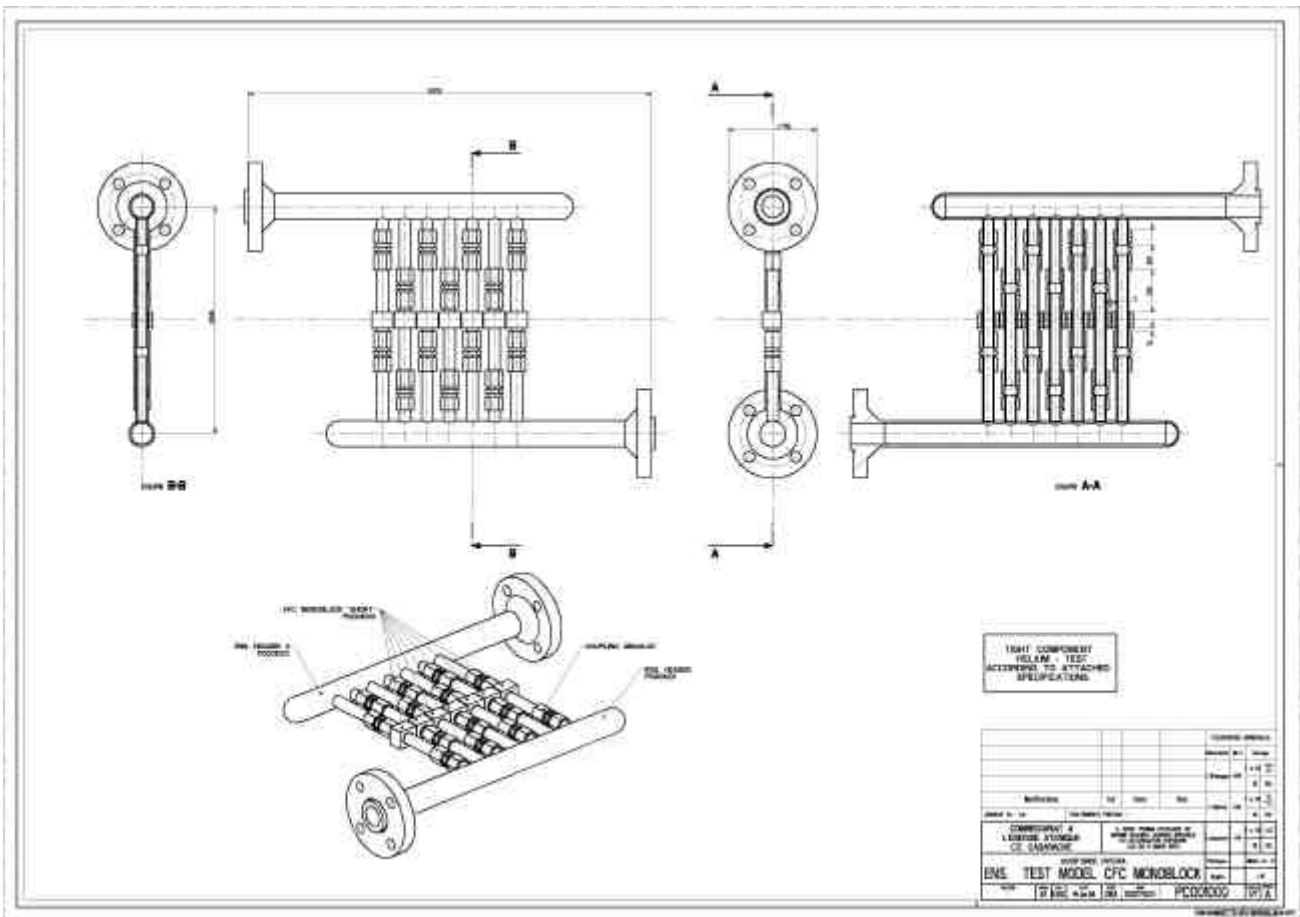


Figure 5 : CFC short monoblock assembly

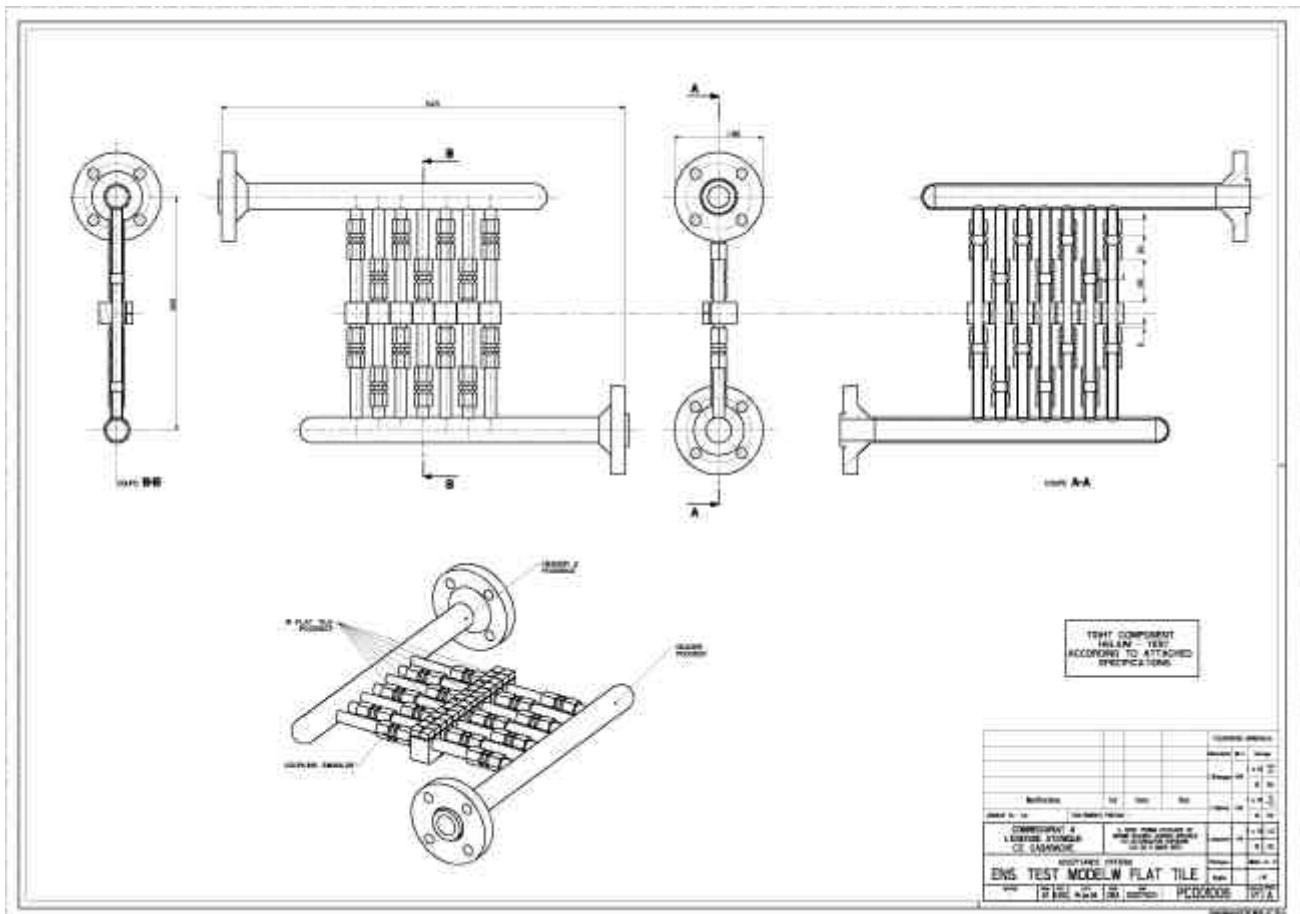


Figure 6 : W flat tile assembly

Hence it is expected to purchase  $14 \times 4 = 56$  samples for each of two manufacturing technologies. Which means 112 samples, however we may not need 14 CFC monoblocks “high”, but only 7 and with only one technology. In that case only  $14 \times 3 \times 2 + 7 = 91$  samples will be ordered.

We give on figures 5 and 6 the assembly in mock-up for monoblocks short and W flat tiles. More details are given in [1].

## CONCLUSIONS

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Four types of samples were designed in the frame of this task so that the call for tender can be launched. The task will be pursued in 2004 in order to provide an analytical and experimental basis for the definition of the acceptance criteria.

## REPORTS AND PUBLICATIONS

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- [1] S. Fouquet: Study on acceptance criteria for the ITER divertor, Intermediate report 1 : design of the samples for artificial defects. CFP/NTT-2004.003

## TASK LEADER

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Jacques SCHLOSSER

DSM/DRFC/SIPP/GICI  
CEA-Cadarache  
F-13108 Saint Paul Lez Durance Cedex

Tél. : 33 4 42 25 25 44  
Fax : 33 4 42 25 49 90

E-mail : jacques.schlosser@cea.fr

Not available on line

Not available on line



Not available on line

Not available on line

**Task Title: OPTIMIZATION AND MANUFACTURE OF HHF COMPONENTS**  
**Study of flat tile cascade failure possibility for high heat flux components**

**INTRODUCTION**

The object of this task is to evaluate the possibility of failure in cascade of flat tiles under convective heat flux with a glancing incidence.

Calculations and tests on the high heat flux (HHF) facility FE200 were planned.

Preliminary works in 1999 consisted in the definition of the geometry, the study of the feasibility of the tests by finite elements calculations and the definition of foreseen tests and mock-ups to be prepared.

In 2002 the mock-ups were delivered by Plansee: 2 of them armoured with NS31 CFC flat tiles and 2 of them with pure-W castellated flat tiles.

All these mock-ups were equipped with a hypervapotron heat sink. The tests were defined and launched on the FE200.

The mock-ups with CFC tiles were tested in 2002. The tests gave very good results with no evidence of cascade failure.

The high heat flux tests were continued in 2003 on the W mock-ups and good results were also obtained.

In addition post-mortem analyses of one CFC mock-up and one W mock-up were performed.

**2003 ACTIVITIES**

**RECALL OF THE OBJECTIVES**

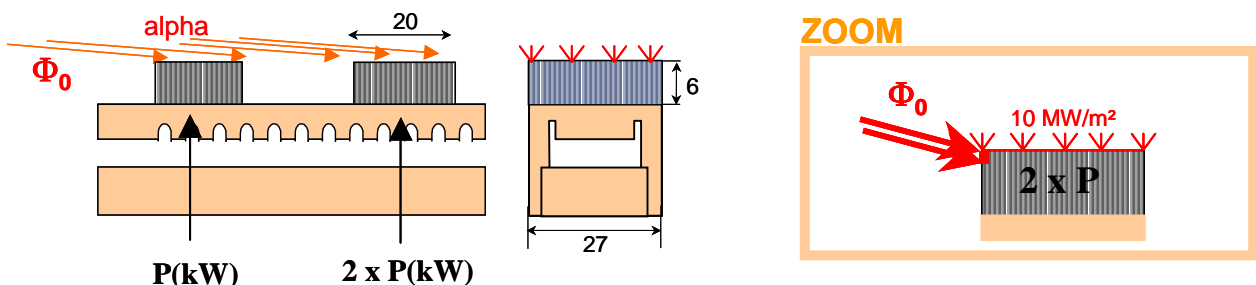
This technology has several advantages : existing industrial experience, possible repair process, dedicated non-destructive examination techniques. However, if one tile is missing on such a high heat flux component subjected to a convective flux with a glancing incidence, the thermal loading of the neighbour tile would be doubled leading to a possible cascade failure (see figure 1).

**TUNGSTEN MOCK UPS**

Among the four mock-ups delivered by Plansee Company in 2002 two of them were made of tungsten (W) flat tiles bonded to a hypervapotron CuCrZr heat sink. The armour is composed of 162 8.6 x 8.6 mm<sup>2</sup> tile teeth each of them being 6 mm thick except some tiles which are machined down to 5 mm (figure 2).



Figure 2 : The 2 W mock-ups W4 (upper) and W2 (down) assembled for HHF tests (armoured length = 460 mm)



Typical values : alpha = 3°, Φ = 10 MW/m<sup>2</sup>, Φ₀ = 190 MW/m<sup>2</sup>, 1 mm depth penetration

Figure 1 : Risk of cascade failure when a tile is missing: double power and high heat flux on the lateral of the neighbour tile

The overall dimensions are: 700 mm length (500 mm with armor), 27 mm width. A cross-view of the components is presented figure 3.

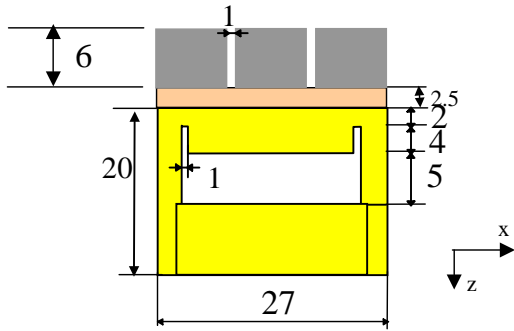


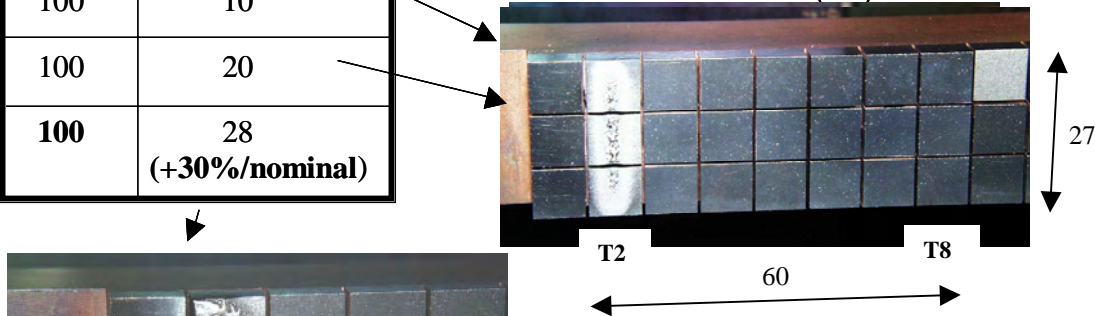
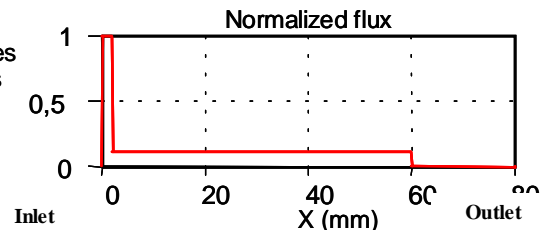
Figure 3 : Cross- view of W hypervapotron

**HHF FATIGUE TESTS WITH NORMAL INCIDENCE**

It was shown in 1999 that it can be possible to have almost the same heat flux with a normal incidence profile than with a glancing incidence of 3° for the CFC mock-ups. As normal incidence tests are routinely operated in the FE200 it was decided to perform first a normal incidence testing, at the same level as the CFC mock-ups. Two zones of the same mock-up (W4) were alternatively loaded during 100 cycles (T8-T2 and T54-T48). The 100 cycles were done 3 times with peaked heat flux of 43, 86 and 116 MW/m<sup>2</sup>. No tile detachment was observed. The high loaded tungsten tiles were immediately molten during the first cycling (43 MW/m<sup>2</sup>) and strongly molten during the last cycling (116 MW/m<sup>2</sup>), meaning that temperatures of 3100°C were reached (figure 4).

•300 pulses of 10 s alternatively on 2 surfaces of 60 x 27 mm, i.e. 3 tiles

Number of cycles	Power removed into the water (kW)
100	10
100	20
<b>100</b>	<b>28 (+30%/nominal)</b>



T2

**HHF FATIGUE TESTS WITH GLANCING INCIDENCE**

The 2 elements were positioned as shown on figure 5 at a 3° incidence with the e-beam.

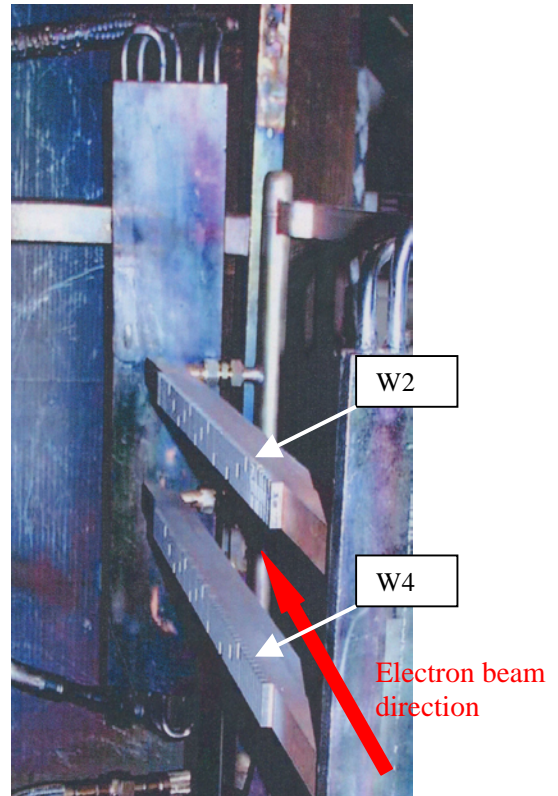


Figure 5 : Positioning at a 3° incidence with the e-beam

Figure 4 : Summary of the results obtained on W mock-ups with perpendicular incidence

Due to the high electronic reflective character of tungsten in glancing incidence position, it was found very difficult to increase the power absorbed into the water. The re-emitted power in the chamber led to several problems : pollution of the vacuum leading to short circuit, breaking of the glass-lead windows.

Finally a pulse of 120 sec. at nominal power +20 % was successfully performed without any tile detachment : the leading edges were immediately molten and light cracks developed on the surface in the direction of electrons incidence but no joint degradation was observed on the lateral edges.

The cracks on surface may be attributed to the brittleness of pure Tungsten. The use of an alloy of Tungsten/Lanthanum or Tungsten/Rhenium - more ductile - could be recommended.

Finally, up to 70 pulses of 10 s at full power were performed on the two mock-ups : no tile detachment was observed. The shape of the molten leading edges did not noticeably evolve after the first shot. Moreover, the visibility of the surface cracks was attenuated (figure 6).

**POST MORTEM ANALYSIS**

**CFC5 mock-up**

The tile 24 that sustained well 200 cycles at perpendicular peaked high heat flux (90 MW/m<sup>2</sup>) do not show any trouble at the CFC/Cu interface, despite an important erosion at the heated surface.

The tile 11 and 14 which sustained 200 cycles in glancing incidence (190 MW/m<sup>2</sup>) suffered at the interfaces with an crack opening longitudinally of 8.5 mm over 20 mm and transversally of 22 mm over 27 mm (figures 7 and 8).

Number of cycles	Power removed into the water (kW)	Local IHF (MW/m <sup>2</sup> ) on the edge
1 120 sec.	47 (+ 19% than nominal)	215 (+ 19% than nominal)
70 (10 sec. alternatively)	47 (+ 19% than nominal)	215 (+ 19% than nominal)

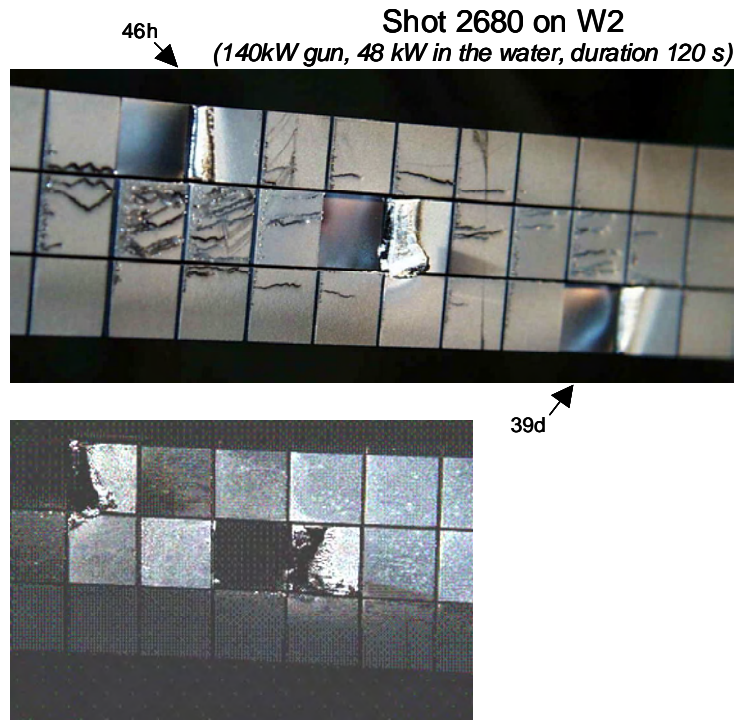


Figure 6 : W mock-ups after one pulse of 2 minutes and 70 pulses of 10 sec. at full power (+19%)

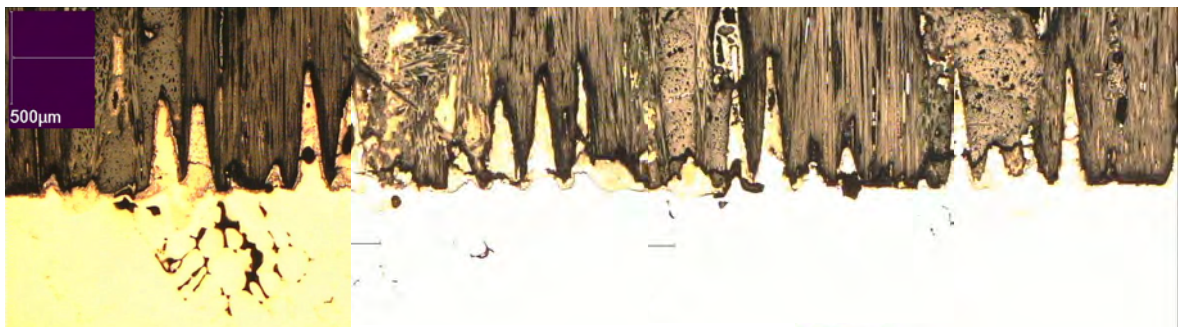


Figure 7 : Transversal cut of tile 11 interface



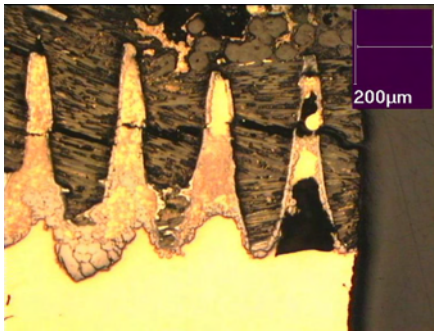


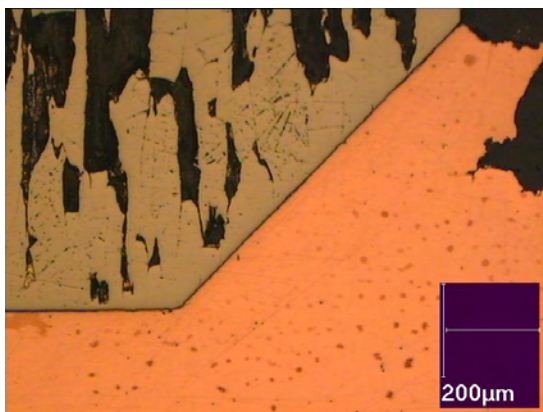
Figure 8 : Longitudinal cut of tile 14 interface

#### W4 mock-up

The post mortem analysis do not show important defect at the interface W/CU except for the high tooth of tile 53 which can be compared with the low tooth of the same tile.



(a)



(b)

Figure 9 : Damaged W/CU interface (a) compared with normal one (b)

## CONCLUSION

The expected phenomenon of cascade failure did not occur during the tests, showing that the hypervapotron cooling is very efficient. This concept of hypervapotron heat sink armoured with CFC or W flat tiles becomes then an attractive alternative design for the vertical targets of ITER. This task has been achieved in 2003, the report on HHF tests [1] and the final report [2] have been published. The results of this task have been the object of 2 presentations/publications [3][4].

## REPORTS AND PUBLICATIONS

- [1] I. BOBIN VASTRA Mock-up "cascade failure" (CEA 81), Rapport Framatome TFCW\_R\_03.885 B, 24/7/2003.
- [2] F. Escourbiac, J. Schlosser, EFDA Task GB8-DV4 Study of flat tile cascade failure possibility for high heat flux components, final report, CFP/NTT-2003.015, 2/7/2003.
- [3] J. Schlosser, F. Escourbiac, M. Merola, B. Schedler, P. Bayetti, M. Missirlian, R. Mitteau, I. Bobin-Vastra' Flat tile armour cooled by hypervapotron tube: a possible technology for ITER, Proceeding of 10th Carbon Workshop, Jülich, Sept. 17-19, 2003, to be published in Physica Scripta.
- [4] F. Escourbiac, M. Missirlian, J. Schlosser, M. Merola, I. Bobin Vastra, EXPERIMENTAL SIMULATION OF CASCADE FAILURE EFFECT ON TUNGSTEN AND CFC FLAT TILE ARMOURED HIGH HEAT FLUX COMPONENTS, Proc. of ICFRM 11, Kyoto, Dec. 8-12, 2003, to be published in Fus. Eng. And Des.

## TASK LEADER

Jacques SCHLOSSER

DSM/DRFC/SIPP  
CEA-Cadarache  
F-13108 Saint Paul Lez Durance Cedex

Tél. : 33 4 42 25 25 44  
Fax. : 33 4 42 25 49 90

E-mail : jacques.schlosser@cea.fr

## Task Title: DEVELOPMENT AND TESTING OF TIME RESOLVED EROSION DETECTING TECHNICS

### Development and implementation of an erosion redeposition diagnostic by means of speckle interferometry

## INTRODUCTION

Carbon based material is widely used as plasma facing component in present fusion device due to its good thermophysical properties. This is also the material that has been retained for the ITER divertor. Nevertheless, physical and chemical sputtering yield of carbon are important and this lead to high erosion rate. As a consequence, the large carbon source reacts with the plasma and creates a very complex Plasma Wall Interaction physic. In particular, redeposition may occur when carbon atoms or ion return to the wall; because of the reactivity of carbon with hydrogen, carbon layers are built up with a large hydrogen isotope content.

In the case of ITER, the tritium retention in these carbon redeposited layers may limit the operation for safety reason. So far, only basic erosion and redeposition measurements have been undertaken in present tokamak and none of them can provide in situ a time resolved erosion/redeposition measurement.

In the framework of the CIEL program [1], it is planed to obtain in Tore Supra high performances long time discharges (up to 1000 s). For such a duration, erosion of plasma facing components may become very significant. Therefore, Tore Supra being the only tokamak where erosion/redeposition for a single shot is similar to that expected to ITER, in situ diagnostic should be developed and tested in order to demonstrate the capability to monitor the codeposition process in ITER.

For a 1000 seconds discharge, the resulting gross erosion on the LPT in CIEL would be of about  $10^{20}$  Carbon per  $\text{cm}^2$  or  $10 \mu\text{m}$ . Due to local redeposition and from previous measurements on actively cooled carbon limiter on inner wall in Tore Supra [2], the net erosion rate can be reduced by 2 orders of magnitude. As a consequence, the erosion and redeposition process to measure should be in the range from  $0.1$  to  $10 \mu\text{m}$  for a single discharge. From bibliography analysis [3], Speckle interferometry has been retained as the most promising technique.

Preliminary experiments [4] showed the feasibility of such technique on a carbon fibre material and provided qualitative and quantitative information on surface displacement. It was also shown [5] that 2 wavelengths are required for a tokamak application. By using a second laser, the relative displacement and the shape of the object have been successfully measured [6].

## 2003 ACTIVITIES

From the results obtained with a 2-wavelength speckle interferometer at Saclay in 2002, we defined the technical specification for the procurement of the lasers. The system delivered at Cadarache at the end of 2002, is composed of a dye laser pumped by a pulsed Yag from Continuum, allowing to produce a variable wavelength with a large coherence length with an energy of  $150 \text{ mJ}$  at  $525 \text{ nm}$ , a pulse duration of  $20 \text{ ns}$  and a frequency of  $10 \text{ Hz}$ . These lasers have been mounted on an optical bench and installed in a clean room. Several arrangements have been required in the room in order to fulfil the safety regulations for operating class IV lasers. Operators have been trained for one week and received certification to work with such lasers. Lasers have been commissioned and are now fully operational.

Independently of the lab equipment, new experiments have been performed on graphite tiles covered with codeposited layer. With a high energy Ruby laser, ablation has been performed with 3 energy fluxes on 3 different positions on the tiles. The energy is measured with a calibrated Joulemeter installed in the optical bench (figure 1).

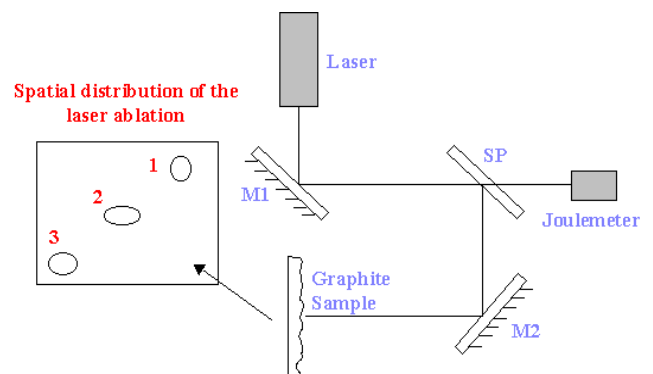


Figure 1 : Optical set-up to perform the laser ablations

After ablations, 2-wavelength speckle interferometer measurements have been realized using  $565$  and  $564.4 \text{ nm}$ , resulting in a synthetic wavelength of  $798 \mu\text{m}$  and an interfringe of  $399 \mu\text{m}$ . 3D measurements of the tile are obtained from analysis of 4 temporal phase shifted images and plotted on figure 2 (z axis represented on a grey scale). Profiles can be extracted from the 3D data, the figure 3 represents a horizontal profile across the ablation point "n°3" showing a depth of  $460 \pm 15 \mu\text{m}$  in the centre of the crater.

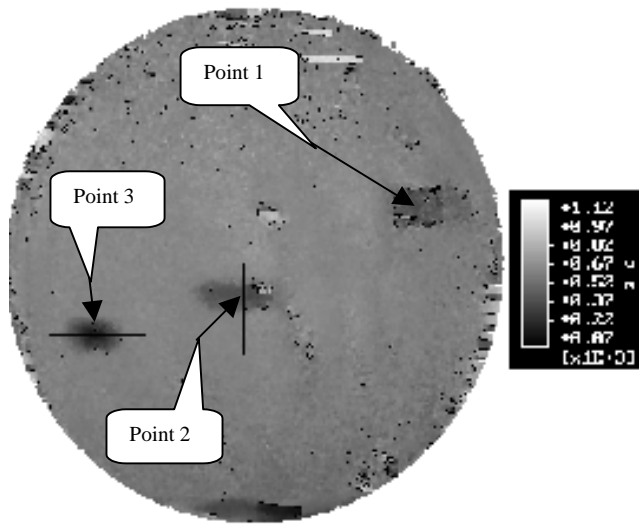


Figure 2 : Demodulated image with a 399 μm large interferfringe with 3 ablation zones

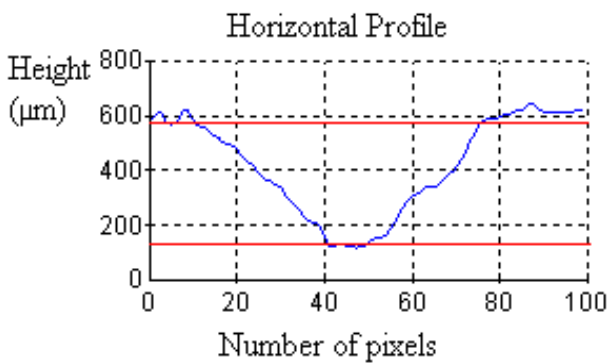


Figure 3 : Horizontal profile on ablation point n°3 extracted from figure 2

Independent measurements were undertaken on the same location by using sensor profilometer and a confocale scanning microscope: Profile obtained with the confocale microscope is plotted on figure 4.

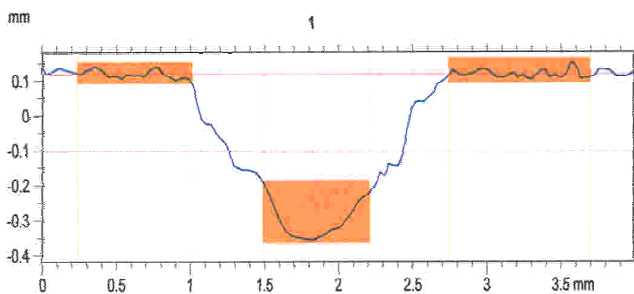


Figure 4 : Horizontal profile for the ablation n°3 measured with a confocale microscope

The depth of the crater, deduced from average distance of the orange area, is  $470 \pm 10 \mu\text{m}$ . Sensor profilometer gives a depth of  $430 \pm 20 \mu\text{m}$ . These two methods give similar results which confirm the value determined with speckle interferometer.

This is the first experiment which demonstrates that Speckle interferometer can provide quantitative erosion measurements on carbon materials on a micrometer scale. During the next months, we will try to reproduce these experiments on a larger scale by using a mock-up of the CIEL limiter installed on the speckle interferometer bench developed in Cadarache.

## CONCLUSIONS

Dye Laser pumped by a pulsed Yag laser have been delivered, mounted on a optical bench and installed in a clean room. Arrangements of the room has been performed according to the safety requirements. Ablation has realized on graphite tiles by using high energy Ruby laser. 2-wavelength speckle interferometer measurements provided 3D measurements of the erosion area.

The depth of the crater, in the range of  $450\mu\text{m}$  has been obtained from speckle interferometer and confirmed by using 2 other techniques: profilometry and confocale microscopy. This first erosion measurement demonstrates the capability of the 2-wavelength speckle spectrometry method which needs now to be validated on a larger scale and in the conditions observed in a tokamak environment.

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## **TASK LEADER**

---

Eric GAUTHIER

DSM/DRFC/SIPP/ICI  
CEA-Cadarache  
F-13108 Saint Paul Lez Durance Cedex

Tél. : 33 4 42 25 42 04  
Fax : 33 4 42 25 49 90

E-mail : [gauthier@drfc.cad.cea.fr](mailto:gauthier@drfc.cad.cea.fr)

## JET-EP-DHD-01 JW2-EP-DHD

### Task Title: JET EP MKII-HD DIVERTOR Tiles chamfering and power handling

#### INTRODUCTION

The JET HD Divertor is an upgrade of the MKII-GB divertor (radiatively cooled) consisting of two modified toroidal segments which are: a new Load Bearing SRP tile located at the septum position, and a High Field Gap Closure tile protecting the inboard divertor structures (see figures 1 & 2). The aim of this upgrade is to compare at high power the global divertor performances (with & without septum) and to study the high triangularity plasmas. The CEA activity performed in the framework of the JET MKII-HD divertor project has consisted in optimizing the tiles chamfering for the LB SRP and the HFGC tiles (edge shadowing) and to evaluate the power handling of these two tiles.

#### 2003 ACTIVITIES

##### TILE DESIGN

The LB-SRP and HFGC tile design is based on the unidirectional tile principle. Unidirectional tiles are tiles that have a slope in the toroidal direction, to hide any edge of the next tile from the impinging plasma.

The tiles are machined from blanks of C-C composite materials and are attached to the carrier through the JET usual system of dumbbell, tie rod and disc springs.

The precise design of the tile faces is based on 12 plasma configurations, 9 swept and 3 static, given by the JET team, and on two sets of tolerances, issued by the JET drawing office, which are provided depending if the two adjacent tiles (in the toroidal direction) are on a common carrier or are on two different carriers.

The PROTEUS code is used to calculate the various field lines angles, inputs of the chamfering calculation process. For each plasma face of the two designed tiles a single value of  $\alpha$  chamfering angle (alpha) has been calculated, except for the main face of the LB-SRP tile for which alpha varies linearly between inner and outer side on tile axis, and this for a power handling optimisation purpose.

After the calculation of the alpha values of each face, a checking exercise has been realised in collaboration with the JET drawing office.

The objective of this exercise is to check on the 3D CATIA models of the tiles put at their extreme tolerance positions if the shadowing is insured for a checking angle calculated to take into account the worst possibilities. Two iterations have been necessary to finalise this checking exercise.

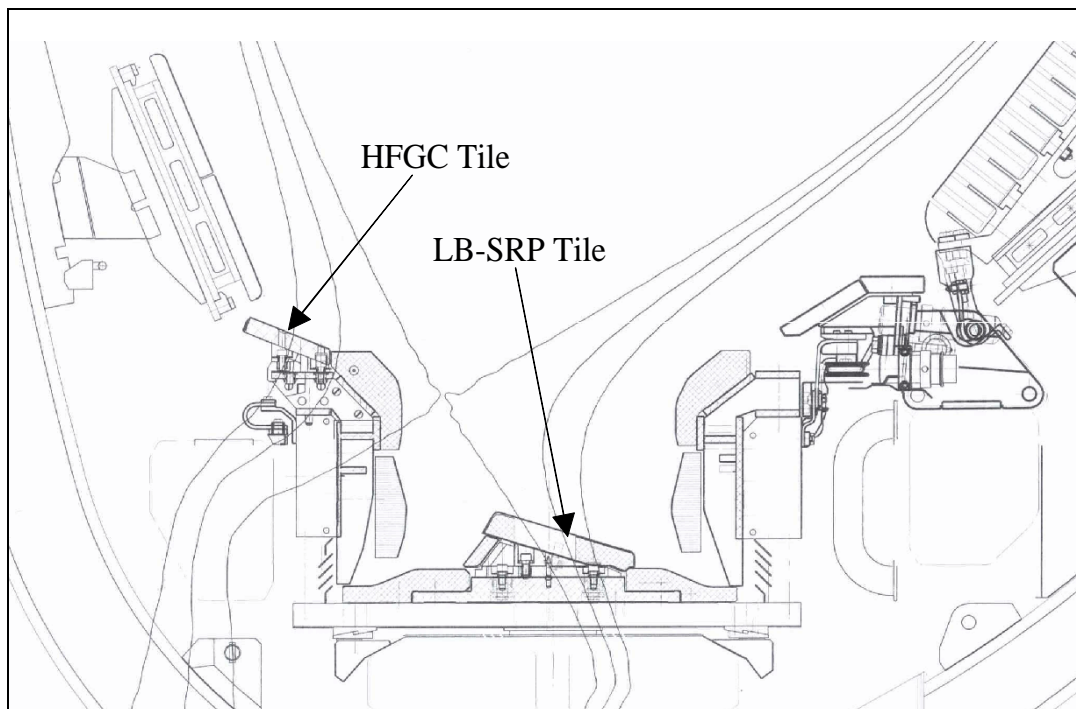


Figure 1 : Poloidal section of the MKII-GB Divertor with the new plates (LB SRP & HFGC)

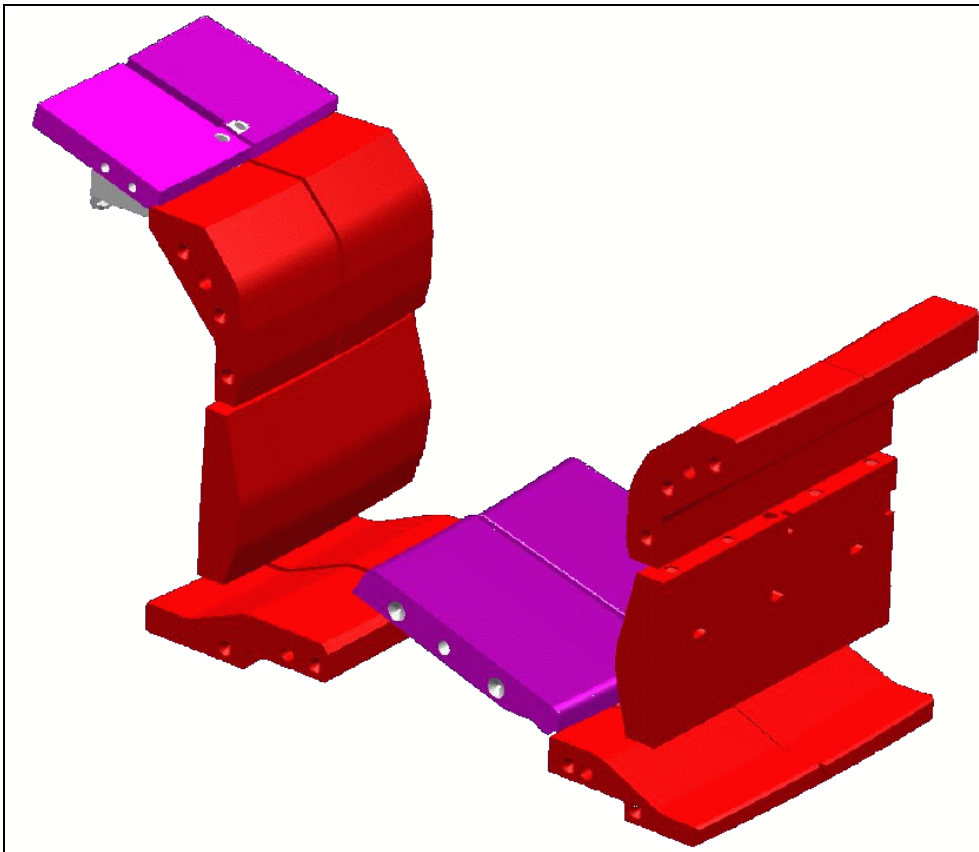


Figure 2 : 3D view of the MKII-GB Divertor with the new plates (LB SRP & HFGC)

## POWER HANDLING

With the final alpha value for each face, the power handling of the tiles has been estimated. Apart from specific assumptions, the general method used for the power handling estimation was based on the study performed for the HP Divertor [Ref. 1]. The main assumptions was the followings:

- Configurations (both static and swept) are issued from a JET reference document.
- The critical time is the time to reach 1800°C at the tile surface for a total injected power of 40 MW (70% convected to the divertor: 28 MW), and:
  - . LB-SRP tile: inboard/outboard power sharing: 2.5/3.5 so 20 MW on the outer leg,
  - . HFGC tile: inboard/outboard ½ power sharing corresponding to the case of reverse field operation:14 MW on the inner leg.
- $\lambda_Q = 5$  mm in the SOL and a decrease of power in the PFZ considering  $\lambda_Q/3$ .
- All calculations are 1-D, taking into account:
  - . LB-SRP tile: a 40 mm-thick Dunlop tile with lower conduction in the toroidal direction,
  - . HFGC tile: a 23 mm-thick A035 tile, with the bad conductivity in the thickness direction.
- Toroidal Wetted Fraction (TWF) is calculated point by point (particularly influent in the LB-SRP tile where the alpha varies along the tile profile).
- The effect of bowing has been assessed by comparison with a previous divertor study.
- The effect of Reverse flux is not taken into account (but some estimations have been made).
- For swept configurations, the incident flux considered for the thermal calculation is the maximum value of the average flux obtain in each point during the sweeping.
- For static configurations, the incident flux considered for the thermal calculation is the maximum value of the peaked static flux, but the critical time is corrected in order to take into account the difference between a flat and a peaked flux profile. Considering the very short critical times obtained with the nominal power, the results for the static configurations are presented in terms of maximum total injected power allowable for a 10 seconds run, but the correction constant/peak flux is also taken into account.

The power handling calculations for the LB-SRP tile have been performed before the checking exercise and take into account the first alpha angles calculation. Nevertheless the effect of the alpha value increase (after checking) has been calculated for only 3 significant configurations and show that the power handling varies less that 4 % in terms of flux justifying not to repeat all the calculations. Values obtained with the final alpha's are indicated in **(bold)** in the following result tables.

## RESULTS FOR LB-SRP TILE

Table 1 : Swept configurations Power handling  
(LB-SRP-tile)

Configuration	Flux (max av.)	Critical time
1MA5_hd	9.9 MW/m <sup>2</sup> <b>(10.2 after <math>\alpha</math> modif)</b>	8 s <b>(7.6 after <math>\alpha</math> modif)</b>
2MA5_hbhd	8.5 MW/m <sup>2</sup>	10.7 s
3MA5_hd	6.7 MW/m <sup>2</sup>	16.5 s
3MA5_ITER	9.7 MW/m <sup>2</sup> <b>(9.76 after <math>\alpha</math> modif)</b>	8.4 s <b>(8.2 after <math>\alpha</math> modif)</b>
4MA_hd	6.9 MW/m <sup>2</sup>	15.9 s
4MA_hd2	6.3 MW/m <sup>2</sup> <b>(6.45 after <math>\alpha</math> modif)</b>	18.3 s <b>(17.7 after <math>\alpha</math> modif)</b>
4MA_hdhx	6.0 MW/m <sup>2</sup>	20 s
4MA_hdlx	8.1 MW/m <sup>2</sup>	11.8 s
5MA_hd	9.5 MW/m <sup>2</sup>	8.7 s

Table 2 : Static configurations Power handling  
(LB-SRP-tile)

Configuration	Allowable total power for a 10 s run	Critical time (40 MW)
1MA5_hd	14.5 MW <b>(13.9 MW after <math>\alpha</math> modif)</b>	~ 1.2 s
2MA5_hbhd	33.4 MW	~ 8 s
3MA5_hd	22.5 MW	~ 3.2 s
3MA5_ITER	17.5 MW <b>(17.2 MW after <math>\alpha</math> modif)</b>	~ 2 s
4MA_hd	23.8 MW	~ 4 s
4MA_hd2	24. MW <b>(23.4 MW after <math>\alpha</math> modif)</b>	~ 4 s
4MA_hdhx	9.6 MW	~ 0.5 s
4MA_hdlx	35.6 MW	~ 8.5 s
5MA_hd	26.7 MW	~ 5 s
Extreme	7.4 MW	~ 0.2 s
H_4MA5_LT (*)	20.4 MW	~ 3 s (*)
ICRH (*)	22.7 MW	~ 3.5 s (*)

(\*) for these two configs, the reverse flux at the inner part of the LB-SRP front face is very important

**RESULTS FOR HFCG-TILE:** except for the "Extreme" configuration, which will have a limited critical time on HFCG tile (about 2 seconds, but already higher than the critical time for the LB-SRP for this configuration), no power handling limitation due the HFCG tile was expected.

## CONCLUSIONS

Chamfering angles for the new LB-SRP and HFCG tiles of the MKII-HD divertor have been calculated, optimised and checked in order to insure a good shadowing of the edges for each of the 12 reference plasma configurations. The consequent power handling has been estimated and gives promising results in regards to the JET EP project objectives.

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## TASK LEADERS

Jean-François SALAVY

DEN/DM2S/SEMT/BCCR  
CEA-Saclay  
F-91191 Gif-sur-Yvette Cedex

Tél. : 33 1 69 08 71 79  
Fax : 33 1 69 08 94 26

E-mail : jfsalavy@cea.fr

Philippe CHAPPUIS

DSM/DRFC/SIPP  
CEA-Cadarache  
F-13108 Saint Paul Lez Durance Cedex

Tél. : 33 4 42 25 46 62  
Fax : 33 4 42 25 49 90

E-mail : chappuis@drfc.cad.cea.fr



**Task Title: INTERNAL PFC COMPONENTS BEHAVIOUR AND MODELLING**

**INTRODUCTION**

The knowledge of power and energy flux impinging on the divertor during Edge Localised Modes (ELMs) is a crucial issue for ITER. In JET, during experimental campaigns, the temperature is measured with an infrared camera and heat flux is deduced from code computation.

During transient high heat loads the power calculated using standard material properties is over-estimated [1].

Indeed, the presence of a thin surface layer of codeposited material with low thermal conductivity induces a higher surface temperature for a given flux. In order to improve power estimation and provide tools for better power/energy measurements in tokamaks, model validation and experiments on divertor tiles are carried out using Castem code and JET NB test bed facility.

**2003 ACTIVITIES**

**PRE-TESTS 3-D THERMAL CALCULATIONS OF JET DIVERTOR TILES**

Two MKII divertor tiles, installed in JET during the 1995-1996 campaign, one from the inner side showing thick coating layer and one from the outer side showing erosion dominated and thin coating areas, have been selected to be exposed to power flux in the range from 5 to 80 MW/m<sup>2</sup>.

Both tiles were intended to be equipped with 12 thermocouples inserted at different depth from the surface allowing measuring the thermal diffusivity in the bulk and the total energy impinging on the tile. The surface temperature was to be recorded by using a fast infrared camera and a standard IR camera.

Pre-tests 3-D thermal calculations of JET divertor tiles have been performed in 2003. A detailed 3-D model (true geometry of tiles with dumbbell, ...) was developed using the CAST3M code (finite element code developed at CEA) to calculate the surface and in-depth temperature distribution on the actual JET divertor tiles during high frequency energy deposition (3 transient scenarios of heat loads 100 MW, 50 MW and 5 MW were considered). Finite element mesh and supposed power distribution on the exposed face are given in figures 1 & 2.

Different tiles configuration have been considered in the numerical simulations taking into account the possible modification of the surface of the tiles (erosion, re-deposition).

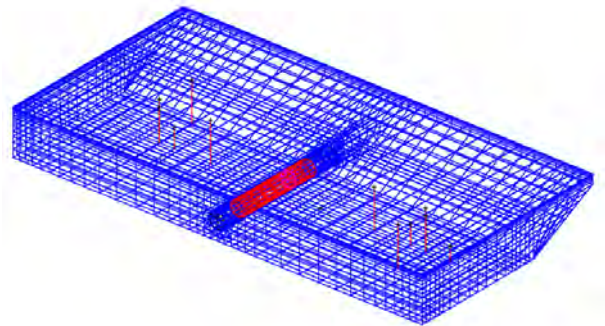


Figure 1 : Mesh of the tile with the dumbbell and the thermocouple positions

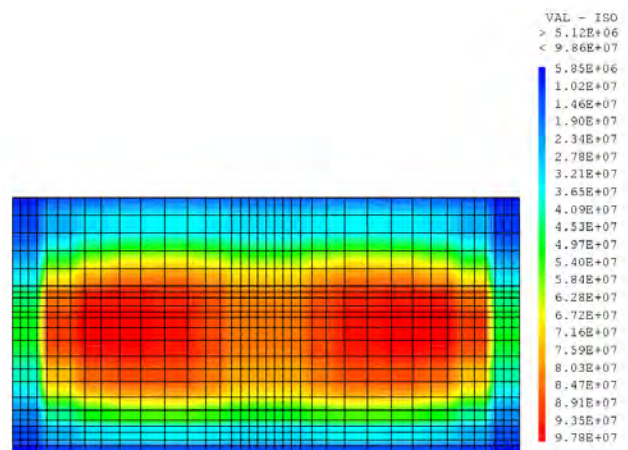


Figure 2 : Heat source distribution on the mesh

In table 1 are reported the maximum temperatures of the tile at various locations calculated with the two tiles configurations for the three different heat loads.

Table 1 : maximum temperatures obtained for the different calculations

	100 MW/m <sup>2</sup>		50 MW/m <sup>2</sup>		5 MW/m <sup>2</sup>	
Maximum T (°C)	Fresh tile	With erosion, re-deposition	Fresh tile	With erosion, re-deposition	Fresh tile	With erosion, re-deposition
Exposed face	932	1399	856	1166	684	803

Results of the calculations show that surface temperature obtained is higher for the model taking into account the possible modification of the surface of the tile.

Figures 3 & 4 give the calculated evolution of maximum temperature in the tile as a function of time for the two tile configurations (fresh tile and bulk + redeposited layer) and the 100 MW flux.



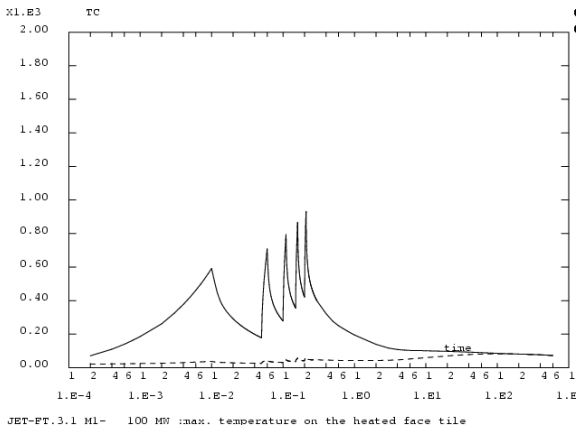


Figure 3 : 100 MW Max. temperatures on the heated face – Fresh tile

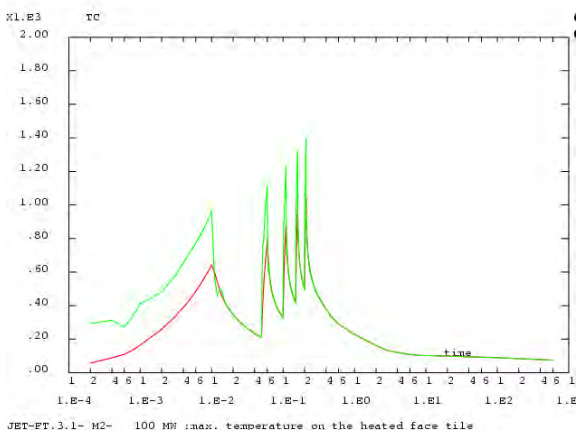


Figure 4 : 100 MW Max. temperatures on the heated face - Redeposited layer

All calculation results have been reported in [6] and will be validated in 2004 by comparing experimental data with modelling: tests were performed in July 2003 and data is now available since January 2004.

**POWER FLUX EXPOSURES ON DIVERTOR TILES IN THE JET NEUTRAL BEAM TEST BED FACILITY**

After several delays due to technical problems on the JET NBTB, the experiments have been performed in July and August 2003. Two tiles from the MKIIa divertor (tile 4 from inner side and tile 7 from outer side) have been exposed to power flux in the range from 5 to 100 MW/m<sup>2</sup>. In total, 648 shots have been realized using Deuterium and Helium beams. Several problems occurred during the experimental campaign.

First, the calorimeter was out of order and power flux distribution could never be measured. Secondly, the fast Infrared Camera, calibrated and implemented on the test bed especially for these experiments did not provide any data due to timing errors. Then, the visible spectrometer which has been successfully tested during the commissioning, has not been operated during the experimental campaign.

Nevertheless, a lot of useful data have been obtained with the thermocouples and with the standard IR camera. Both tiles were equipped with 12 thermocouples inserted at different depth from the surface (figure 5), allowing evaluation of the total energy impinging on the tile and the thermal diffusivity. The IR image showed clearly the influence of the codeposited layer on the surface temperature (figure 6).

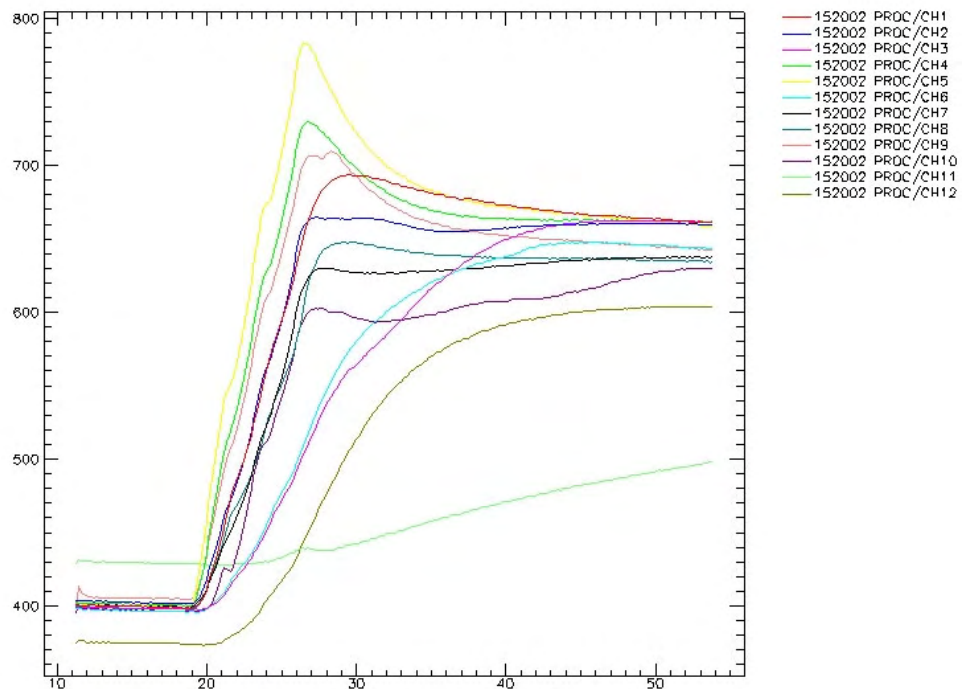


Figure 5 : Temperature evolution of the thermocouples at different depth with 5 MW/m<sup>2</sup> power flux during 3 cycles (2s/2s)

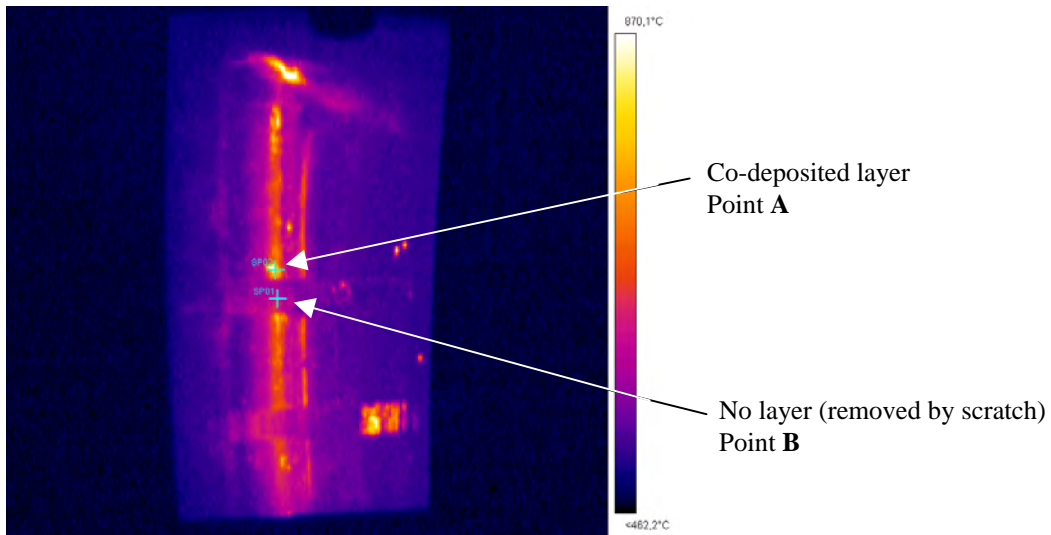


Figure 6 : Infrared image of tile 7 under  $5\text{MW/m}^2$  power flux, showing the codeposited layer pattern with a surface layer (point A) and without (point B)

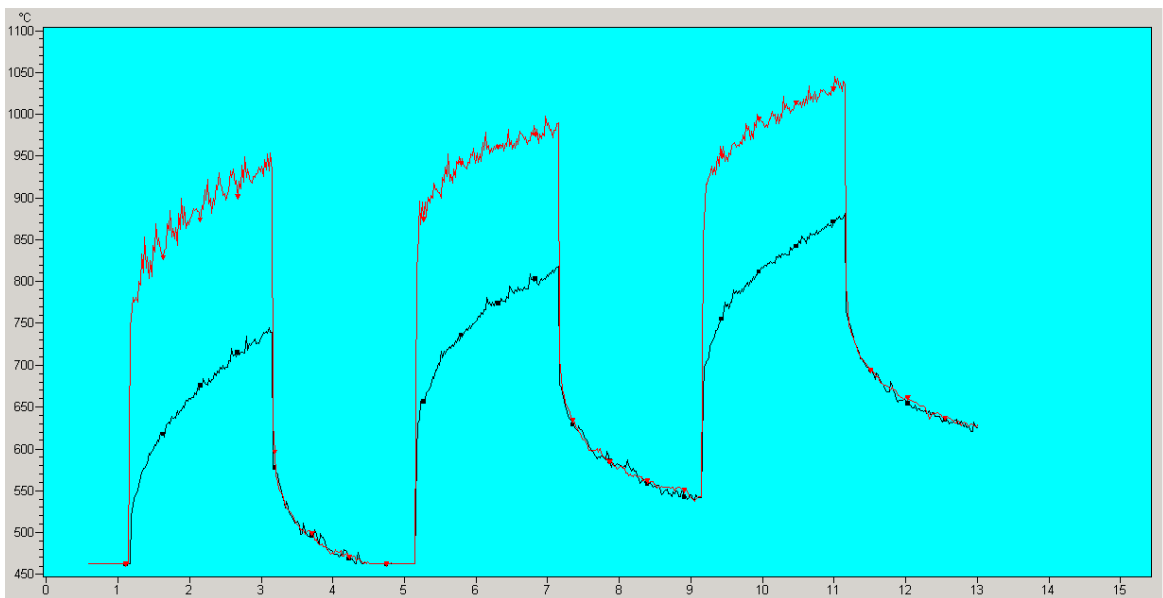


Figure 7 : Surface temperature evolution at  $5\text{MW/m}^2$  measured with the Infrared camera on point A (with a surface layer, red) and point B (without layer, blue)

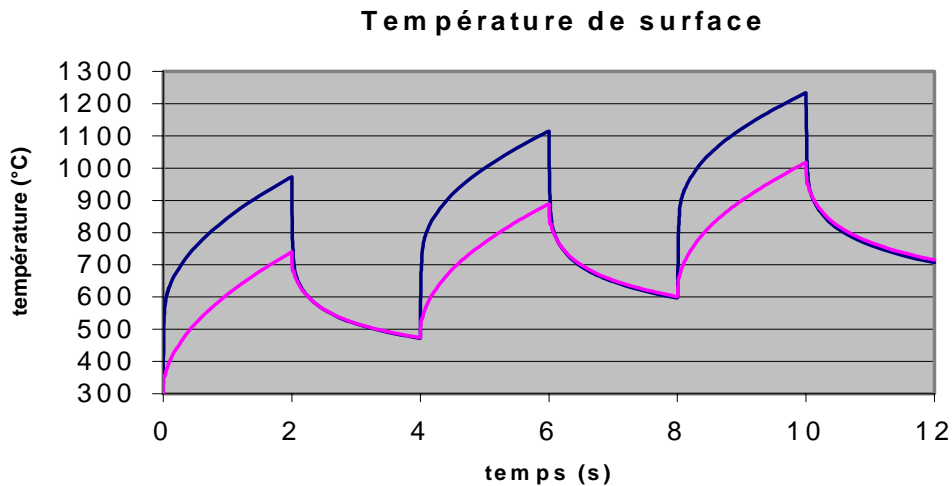


Figure 8 : Surface temperature evolution calculated with CAST3M at  $5\text{MW/m}^2$  with a surface layer (blue) and without (red)



Exploitation of the IR data has been delayed due to the absence of analysis software allowing extracting the surface temperature evolution. This point has been sorted out by the JET NBTB group at the end of the year 2003. The temperature evolution on two different locations (figure 7), one with codeposited layer and one with partly removed layer (scratch test) shows temperature difference in the range of 250°C under 5 MW/m<sup>2</sup> power flux exposure. The surface temperatures do not follow a square root of time dependence, as expected from a semi infinite model but they are in a good agreement with the simulated data obtained with the model developed for this purpose [Interim report FT3.1, 2003] as can be seen on figure 8.

Analysis and modelling are in progress to evaluate the thermal behaviour of tiles with codeposited layer under power flux of 5 MW/m<sup>2</sup> (2 s/2 s 3 cycles) and 50 MW/m<sup>2</sup> (17 ms/43 ms 10 cycles) in helium and deuterium. Results will be presented at the next PSI conference, in May 2004.

## CONCLUSIONS

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Pre-tests 3-D thermal calculations of JET divertor tiles have been performed in 2003. A detailed 3-D model was developed using the CAST3M code to calculate the surface and in-depth temperature distribution on the actual JET divertor tiles during high frequency energy deposition. Different tiles configuration have been envisaged in the numerical simulations taking into account the possible modification of the surface of the tiles (erosion, re-deposition).

Results of the different calculations will be checked in 2004 by fast infrared cameras and thermocouple measurements in order to quantify the impinging heat loads (tests have been performed in 2003 and data is available since January 2004). First available results show that temperatures up to 2500°C have been measured : comparison of experimental data with modelling results with 3D CAST3M code shows that no solution can be found with a single heat transmission coefficient. For post-test calculations to be performed in 2004, other models will have to be considered in order to reproduce experimental temperature measurements.

Power deposition experiments using the JET Neutral Beam Test Bed have been performed in 2004. Some technical problems occurred during the experiments but surface and internal temperatures have been recorded in several different experimental conditions. Modelling using Castem code with various material properties and different heat load conditions were performed. Experimental results are compared with modelling data in order to provide tools for better analysis of transient heat load during ELMS. Results will be presented at the next PSI conference

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## TASK LEADERS

---

Eric GAUTHIER

DSM/DRFC/SIPP/ICI  
CEA-Cadarache  
F-13108 Saint Paul Lez Durance Cedex

Tél. : 33 4 42 25 42 04

Fax : 33 4 42 25 49 90

E-mail : gauthier@drfc.cad.cea.fr

Laetitia NICOLAS

DEN/DM2S/SEMT  
CEA-Saclay  
F-91191 Gif-sur-Yvette Cedex

Tél. : 33 1 69 08 55 40

Fax : 33 1 69 08 86 84

E-mail : laetitia.nicolas@cea.fr

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