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Manufacturing and testing of a prototypical divertor vertical target for ITER

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Abstract

After an extensive R&D activity, a medium-scale divertor vertical target prototype has been manufactured by the EU Home Team. This component contains all the main features of the corresponding ITER divertor design and consists of two units with one cooling channel each, assembled together and having an overall length and width of about 600 and 50 mm, respectively. The upper part of the prototype has a tungsten macro-brush armour, whereas the lower part is covered by CFC monoblocks. A number of joining techniques were required to manufacture this component as well as an appreciable effort in the development of suitable non-destructive testing methods. The component was high heat flux tested in FE200 electron beam facility at Le Creusot, France. It endured 100 cycles at 5 MW/m^2, 1000 cycles at 10 MW/m^2 and more then 1000 cycles at 15–20 MW/m^2. The final critical heat flux test reached a value in excess of 30 MW/m^2.

1. Introduction

An extensive R&D activity has been carried out in the EU aimed at developing robust solutions for high heat flux components (HHFCs) for the ITER reactor. Table 1 summarises the typical operating conditions of a next step fusion machine. The research effort was focused on the development of suitable armour materials and armour to heat sink joints [1].

As far as the divertor vertical target is concerned, a carbon fibre reinforced carbon (CFC) armour has been selected for the lower part. Advanced 3D CFCs were developed (namely, SEP NB31 and the Si-doped NS31) with excellent thermal conductivity and high resistance to thermal shocks and neutron induced swelling [2]. The upper part of the vertical target is covered by tungsten (W) due to its lowest sputter yield in regions, where resistance to charge exchanged neutrals dominates. A commercial grade was used (Plansee WL10) which contains 1% of La_2O_3 and has an easier machining, lower cost and higher recrystallisation temperature when compared with pure W.

A number of small scale mock-ups have been manufactured and high heat flux tested to develop a robust armour to heat sink joint. Unirradiated and irradiated (0.3 dpa at 350°C) CFC monoblocks survived 1000 cycles at 24 and 15 MW/m^2, respectively [3]. A highly castellated W flat tile mock-up ('macro-brush') started failure close to 1000 cycles at 16–18 MW/m^2.

After the above-mentioned extensive R&D activity, a prototypical medium-scale divertor vertical target was manufactured and tested. It includes all the main features of the corresponding ITER component (Fig. 1).

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Table 1
Main operating conditions of the next step HHFCs

	Divertor target	Baffle	Start-up limiter
Normal operation			
Peak surface heat flux (MW/m^2)	10	3	10
Duration (s)	<450	<450	<50
Number of cycles	30 000	30 000	30 000
Peak particle flux (10^{23}/m^{2}s)	~10	TBD	TBD
Off-normal operation	Slow transient	Marfe	Marfe
Peak surface heat flux (MW/m^2)	20	1.0 (IB) 0.5 (OB/top)	Same as for Baffle
Duration (s)	10	3	Same as for Baffle
Number of events	3000	3000	3000
Disruptions	Thermal quench		Thermal/current quench
Peak surface heat load (MJ/m^2)	100	4	1/2
Duration (ms)	1	1	1/30
Number of events	3000	3000	3000
VDE (*Full power*)			Loss of control
Peak surface heat load (MJ/m^2)	N.A.	<25	120
Duration (ms)	N.A.	0.3	0.3
Number of events	N.A.	300	300
Run-away electrons (<20 MeV)			
Peak surface heat load (MJ/m^2)	N.A.	~50	TBD
Duration (s)	N.A.	~0.3	TBD
Number of events	N.A.	<3000	TBD

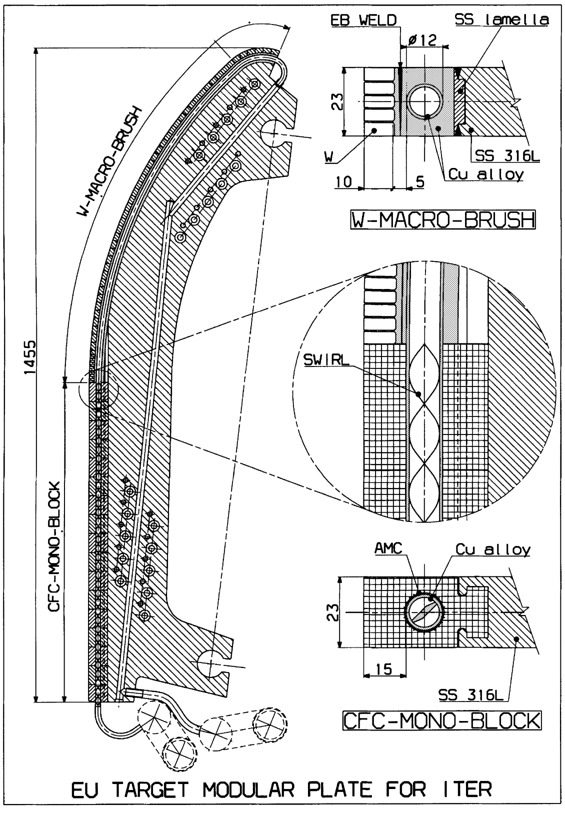

Fig. 1. ITER divertor vertical target.

The aim of the medium-scale component is to qualify the manufacturing processes of the full scale prototype, which is also being built by the EU Home Team, and to investigate some critical issues of the vertical target envisaged during the ITER divertor design activities. Furthermore, the medium-scale prototype is aimed at checking the divertor component performance and lifetime under heat flux.

The vertical target design features which required to be assessed and qualified were the following:

- the armour-heat sink joining utilising two different armour materials (CFC and W) on the same heat sink;
- the heat sink bending with the required accuracy;
- the deformation induced by the welding;
- the steel back deep drilling;
- the welding between Cu alloy and stainless steel;
- the insertion of the swirl tube;
- the non-destructive examinations of the armour-heat sink joints.

The aim of the present paper is to describe the manufacturing process, non-destructive testing and high heat flux testing of the medium-scale vertical target prototype.

2. Manufacturing

The divertor vertical target medium-scale prototype consists of two units with one cooling channel each,

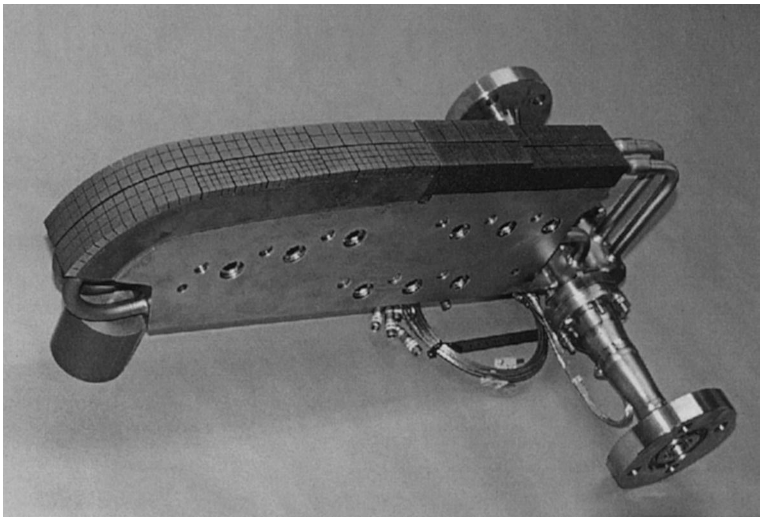

Fig. 2. Divertor vertical target medium-scale prototype.

assembled together and having an overall length and width of about 600 and 50 mm, respectively (Fig. 2).

The high heat flux part and the 316L steel back plate was manufactured by Plansee and Ansaldo, respectively. The integration between the two parts was carried out by Ansaldo.

The high heat flux part has a lower straight region made of carbon monoblocks and an upper bend region with a W macro-brush armour. The heat sink material is a dispersion strengthened copper (DS-Cu) alloy by OMG Americas (GlidCop AL-25, Cu + 0.25% Al_2O_3). In the upper region, it consists of a hollow bar (obtained by two half shells) where a DS-Cu tube (10/12 mm ID/OD) is inserted. The tube then continues in the lower monoblock region. The transition between the DS-Cu tube and the stainless steel tube is performed via a nickel sleeve electron beam (EB) welded at both ends. The steel tube is then TIG welded to the steel back plate on the top of the component and to the inlet and outlet manifolds on the bottom. Thus the steel back plate is actively cooled by the return water flow from the high heat flux part (Fig. 1). A twisted tape with a twist ratio of two is inserted in the monoblock region to enhance the critical heat flux limit.

The armour of the upper region is made of both pure W and W–1% La_2O_3 with different castellations. The thickness is 10 mm. A pure copper interlayer is inserted between the W armour and the DS-Cu heat sink to alleviate the joint interface stress due to the thermal expansion mismatch. In this region, the heat sink is attached to the steel back plate via a 316L steel lamella EB welded onto the back plate (Fig. 1).

The lower region of the vertical target (CFC monoblock) is integrated onto the steel back plate via a dove-tail mechanical attachment which allows the monoblocks to slide. The carbon material is a 3D CFC (SEP NB31) which is joined onto the DS-Cu tube by Active Metal Cast®. This well-established technology was developed by Plansee in 1995 [4] and consists in casting a pure copper interlayer (about 0.5 mm thick) onto a laser structured surface of the CFC tile. Then the copper interlayer is brazed onto the DS-Cu tube at 880°C by means of a Ti-based eutectic. The 11 CFC armour tiles per unit have a thickness of 14 and 8 mm (5 and 6 tiles, respectively). The lower thickness has been introduced to allow the heat flux testing at 20 MW/m^2 without impairing the proper running of the test facility due to a too high CFC surface temperature.

The manufacturing steps can be summarised as follows:

- Machining of the two DS-Cu half shells and of the steel lamella.
- Bending of the DS-Cu tube after having EB welded the nickel sleeves at both ends.
- Assembly of the two DS-Cu half shells, the DS-Cu tube and the steel lamella and canning with a stainless steel sheet; HIP'ing at 700°C, 150 MPa.
- Machining of the W and W–1% La_2O_3 tiles, casting of the pure copper interlayer and EB welding onto the DS-Cu heat sink.
- Active Metal Cast of the CFC tiles.
- Brazing of the CFC tiles onto the DS-Cu tube.
- Insertion of the thermocouples and assembly of the two units.
- TIG welding of the two inlet and the two outlet cooling tubes into the inlet and outlet manifold, respectively.

Before manufacture could start, a development work was carried out aimed at ensuring that the component was fabricated with the required quality, in an efficient and timely manner and with minimum tolerances. All the manufacturing processes were qualified by means of standard procedures, when applicable, or by ad hoc procedures when any standard was not available. In particular, the transition between the DS-Cu tube to stainless steel tube was qualified and characterised by means of tensile tests, torsion shear tests, rotary bending fatigue tests and burst tests.

3. Non-destructive testing

A number of non-destructive tests were carried out on the divertor vertical target prototype during the manufacturing process and are summarised hereinafter.

Ultrasonic inspection by Plansee of the W macro-brush according to the ASME Code, Sect. V, Subsect. A, Art. 5. To this aim, an ad hoc calibration block was manufactured.

Radiographic examination by Plansee of the pure Cu interlayer Active Metal Cast into the CFC tiles. To this

Table 2
Thermal fatigue test results of the vertical target prototype

Test	Results
Screening at 4 MW/m^2	No damage, stable surface temperature
5 $MW/m^2 \times 100$ cycles on CFC and W	No damage, stable surface temperature
10 $MW/m^2 \times 1000$ cycles on CFC and W	No damage, stable surface temperature
15 $MW/m^2 \times 1000$ cycles on W	No damage, stable surface temperature; after additional 100 cycles two W tiles detached
20 $MW/m^2 \times 2000$ cycles on CFC	No damage, no temperature evolution; erosion of the CFC tiles
Critical heat flux tests with a peaked heat flux profile	A peak absorbed heat flux of 30.2 MW/m^2 was reached without observing any CHF event; the test was stopped due to excessive surface temperature (>2500°C)

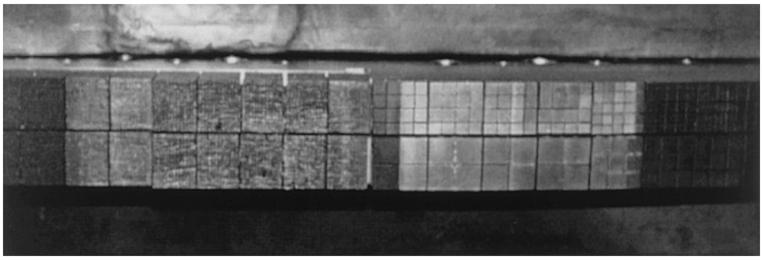

Fig. 3. Vertical target heated surface after the fatigue cycling at 5 MW/m^2.

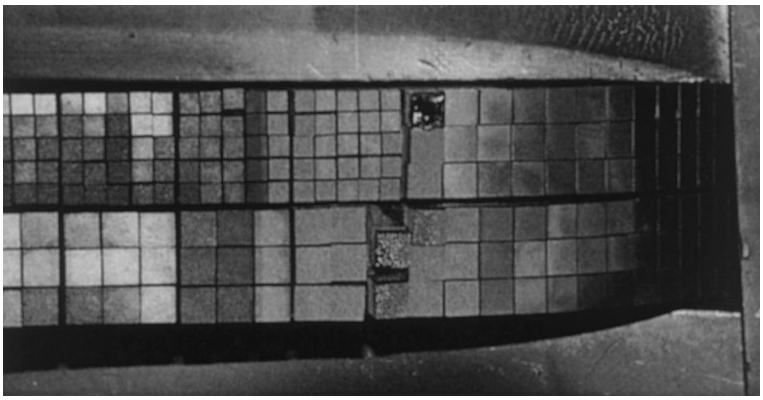

Fig. 4. W armoured part after 1100 cycles at 15 MW/m^2.

purpose an ad hoc calibration block was manufactured according to the ASME Code, Sect. V, Subsect. A, Art. 2.

Ultrasonic inspection by the Austrian research centre at Seibersdorf of the brazed joint between the CFC monoblock and the DS-Cu tube. For this purpose, an ad hoc calibration block was manufactured according to the ASME Code, Sect. V, Subsect. A, Art. 5. An appreciable improvement of the overall quality of the joint was observed when compared with previous monoblock components.

Ultrasonic inspection by Plansee of the HIP'ed steel lamella to heat sink joint.

Thermographic examination by Plansee by means of water at room temperature and 6 MPa and subsequent water steam at 250°C, 4.4 MPa. The infrared camera has a resolution of 320×240 pixels and an image acquisition rate of 20 Hz.

Thermographic examination by CEA Cadarache (SATIR test) by means of refrigerated water at 5°C and subsequent water flow at 95°C [5] and comparison with the screening test under high heat flux.

Preliminary He leak test of the assembled vertical target before the water pressure test by Ansaldo.

Pressure test of the assembled vertical target by Ansaldo at 6 MPa, 20°C for 30 min.

He leak test of the assembled vertical target after the water pressure test by Ansaldo according to the ASME Code, Sect. V, Art. 10, App. V. The detected leak rate was well below the specifications, namely 1.38×10^{-10} mbar l/s (1.38×10^{-11} Pa m^3/s).

Dimensional measurements by Plansee to check the geometrical shape and tolerances.

4. High heat flux test

To assess the thermal fatigue performances of this divertor prototype, a high heat flux test was started in June 1999 in the electron beam facility FE200 at Le Creusot, France and operated by Framatome and CEA Cadarache.

Table 2 summarises the test results. Fig. 3 shows the component surface after the successful completion of the cycling at 5 MW/m^2. The water cooling conditions were 120°C, 3.5 MPa and 12 m/s.

After the completion of the high heat flux test, preliminary investigations showed no appreciable differences between pure W and W–1% La_2O_3 as far as the thermal fatigue behaviour is concerned. The detachment of the two W tiles after 1100 cycles at $\sim$15 MW/m^2 seems to be due to creep damage of the pure copper interlayer and concerned only the area with a coarse castellation (Fig. 4).

5. Summary and conclusions

A medium-scale vertical target prototype has been successfully manufactured with all the main features of the corresponding ITER divertor design. Different joining techniques have been used during the manufacturing process, namely: Active Metal Cast and brazing for the CFC tiles, metal cast and EB welding for the W tiles, HIP'ing for the DS-Cu heat sink, EB welding for the integration of the high heat flux part onto the steel back plate, EB welding for the DS-Cu to stainless steel tube transition via a nickel adapter, TIG welding for the coolant connections.

Emphasis was also put on the non-destructive testing which includes: X-ray, ultrasounds, He leak test, pressure test and dimensional test.

An extensive high heat flux testing was carried out in FE200 electron beam facility at Le Creusot, France. The component endured 100 cycles at 5 and 1000 cycles at 10 MW/m^2. Then the W armoured part was successfully tested for more than 1000 cycles at 15 MW/m^2 and the CFC armoured part for 2000 cycles at 20 MW/m^2. The final critical heat flux test, performed on the CFC armoured part, reached a value in excess of 30 MW/m^2.

References

[1] G. Vieider, M. Merola, F. Anselmi, J.P. Bonal, P. Chappuis, G. Dell'Orco, D. Duglué, R. Duwe, S. Erskine, F. Escourbiac, M. Fèbvre, L. Giancarli, M. Grattarola, G. Le Marois, H.D. Pacher, A. Pizzuto, L. Plöchl, B. Riccardi, M. Rödig, J. Schlosser, A. Salito, B. Schedler, C.H. Wu, Invited paper at the Fifth Symposium on Fusion Nuclear Technology, ISFNT-5, Rome, Italy, pp. 19–24 September 1999.

[2] C.H. Wu, C. Alessandrini, J.P. Bonal, H. Grote, R. Moormann, M. Rödig, J. Roth, H. Werle, G. Vieider, J. Nucl. Mater. 258–263 (1998) 833.

[3] M. Rödig, R. Duwe, W. Kühnlein, J. Linke, M. Scheerer, I. Smid, B. Wiechers, J. Nucl. Mater. 258–263 (1998) 967.

[4] T. Huber, L. Plöchl, N. Reheis, in: Proceedings of the 16th IEEE/NPSS Symposium on Fusion Engineering, Champaign Illinois, USA, 1995, pp. 716–719.

[5] A. Durocher, P. Chappuis, R. Mitteau, L. Moncel, in: Proceedings of the 20th Symposium on Fusion Technology, Marseille, France, 7–11 September 1998, vol. 1, pp. 121–124.