Non destructive tests on tungsten coated JET divertor CFC tiles in the electron beam facility JUDITH-2

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P111

ABSTRACT

In the ITER like wall project, the JET tokamak will employ tungsten coated CFC tiles for the outer and inner divertor tile rows. In order to assure the performance under thermal loads at the JET divertor high heat flux (HHF) tests are performed for the qualification during the series production of the W coated tiles, some of which might be carried out in the JUDITH-2 facility of FZJ. The electron beam facility JUDITH-2 consists of an electron beam gun (EB-gun), a process chamber with vacuum system (vacuum chamber extension) and different cooling circuits.

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1. Introduction

The initial choice of ITER materials is a full beryllium (Be) main chamber wall with Carbon Fibre reinforced Composites (CFC) at the strike points and tungsten (W) at the dome and the upper part of the divertor vertical targets. In order to study the armour material combination in a tokamak, the ITER-like Wall (ILW) Project has been launched at the JET tokamak [1]. In the ILW Project, the JET tokamak will employ tungsten coated CFC tiles for the outer and inner divertor rows. In order to assure the performance under thermal loads at the JET divertor, high heat flux (HHF) tests are performed for the qualification of the W coated tiles during the series production. This paper reports the preparatory steps and demonstration experiments of the qualification tests in the JUDITH-2 facility [2] of FZJ. A schematic overview of the testing facility JUDITH-2 is given in **Fig.1**.

A fraction of the 700 tungsten coated CFC tiles (largest tile size 172 mm x 375 mm) might be tested in the electron beam facility JUDITH-2 during a limited period. Due to the large number and the size of tiles, an optimized test scheme was developed including the upgrade of the JUDITH-2 vacuum chamber. In this scheme, eight standard size (~200mm x ~200mm) divertor tiles are mounted on copper adapter blocks and fixed on actively cooled copper plates by a specially designed clamping fixture. The loading pattern in the test scheme is designed to be rectangular with a reduction of the heated area of 20 mm on each edge of the tested tile. The maximum surface temperature was aimed to be not higher than 800^{o}C during the qualification test.

On completion of the hardware procurement for the tests, a demonstration test was performed on a pre-production tile. In this test, one tile was loaded at an absorbed power density of 2.9 MW/m^2 (Beam Power of 84 kW) for a loading time of 10.2 s. The surface temperature reached 800^{o}C level after two loading cycles and cooled down to 200^{o}C in approximately 5 minutes. This allows 10 thermal cycles to be applied on four tiles in one hour. An IR camera based emergency switch-off system is used to protect tiles from overheating due to possible machine failure or operating errors. In parallel, the electron beam was characterized in detail to obtain optimized machine parameters for the acceptance tests.

2. Electron beam facility JUDITH 2 for JET tests

The JUDITH-2 facility is equipped with a commercial electron beam (EB) generator (high power electron beam gun EH 800 V, from ARDENNE Anlagentechnik GmbH). This type of powerful EB-gun facility is mainly used for surface heat treatments. The maximum JUDITH-2 beam power now is 200 kW.

2.1 Two different beam gun modes

The acceleration voltage is variable in the range between 40 to 60 kV. Whereas the maximum power is only reached with an electron beam voltage range above 50 kV. The EB-gun of JUDITH-2 has two options of electron beam power regulation. Generally one is for lower power range 0 – approx. 30 kW, TL-mode (temperature limited mode) and one for higher power range 30 – 200 kW. The high power mode is called SL-mode (space charge limited mode) [3]. In SL-mode the cathode is kept at maximum temperature. The distance between cathode and anode is labelled d_{ka}. In [3] it has been shown that the maximum d_{ka} is reached at 45 mm (position equal to minimum power), while the minimum d_{ka} is close to 15 mm (position equal to maximum power). That means that the EB power P is proportional to $1/d_{\mathrm{ka}}$. The software adjusts the resulting power. In SL-mode the power set points are reached a lot quicker than in TL-mode. This is based on the fact that in the former mode the control of the electron emission is done by mechanically changing the distance between cathode and anode before starting with EB-loading procedure. All Jet tests were done in SL-mode.

2.2 Vacuum chamber

The process chamber was produced by TRINOS Vacuum-Systeme GmbH and is of cylindrical shape with 800 mm diameter and a length of 1800 mm (1200 mm + 600 mm extension). A double wall cooling design allows to dissipate the heat caused by the reflected electrons (electron reflection of tungsten is 45%). The tested materials and components are mounted on a numerical controlled carrier system (x, y cross-table) fixed to the door of the vacuum chamber. The observation windows for IR camera was made by CaF_2 glass and for two-colour pyrometer silica glass was used.

The JUDITH-2 facility is equipped with several separate cooling loops. The turbo molecular pumps and the EB-gun are cooled by a 2 kW water circuit [2]. With a flow rate of v_1 = 10 m^3/h up to P_1 = 40 kW of thermal heat can be dissipated from the JUDITH-2 vacuum chamber [2]. The experimental cooling circuit with a water flow rate of v_2 = 18 m^3/h at 25 bar is designed to remove up to P_2 = 150 kW from active cooled test components [2]. An ARDENNE Company own tool is supplied for controlling the guidance and other parameters of the beam. On the PC screen all important parameters, such as power, percentage of d_{ka}, acceleration voltage and lens currents, as well as processes parameters of vacuum pumps and valves are monitored. The pressure in different segments of the vacuum chamber can be observed and has also some influence of the EB-diameter [3].

2.3 Beam control and EB-diameter

The sweeping of the electron beam (EB) is controlled by a special beamguidance software. With this special software it is possible to define different kinds of patterns, repeat the patterns, let the patterns run on a defined path or simply set single points.

The generation of heat load patterns is based on freely programmable figures. These figures consist of up to 2600 points with x- and y- co-ordinates each, the beam dwell time for these points can be defined between 5 µs and 1 s [2]. Extensive tests to characterize the EB-diameter were carried out (influence of parameters as EB-power, acceleration voltage, lens settings and vacuum pressure inside different segments of EB-gun chamber [3]). As a result of these tests the focused EB-diameter can be adjusted between 2.6 mm (EB power approx. 15 kW) and 16.7 mm (EB power approx. 130 kW) at an acceleration voltage of 50 kV [3]. The power distribution has been calculated under assumption of a Gaussian beam profile [3]. For all JET tests in the JUDITH-2 facility, a defocused EB-diameter has been used.

2.4 Observation systems

Observations with various diagnostics are performed through a number of windows oriented directly and indirectly towards the EB testing-area (**Fig. 1**). The surface temperature of all tiles during EB loadings (one set = 4 tiles) was monitored continuously by an IR camera (type SC 6000 from FLIR, wavelength 3 – 5 µm, with 640 x 512 pixels). A surface temperature protection system was realised by using this FLIR-IR camera together with a special software (IRControl and DASYLab). For most of the test with W/Re coated CFC tiles the switch-off condition has been set to a maximum temperature of $T_{MAX} \leq 800°C$.

For additional temperature controlling a two-colour pyrometer (type: Maurer QKTR 1075) was used beaming to the centre of one of the loaded tile. The temperature range for this two-colour pyrometer was between 300°C and 900°C (1000°C). Furthermore a video camera for recording of image sequences during the EB-loading was installed.

3. Benchmark test on JET G7-like W/Re coated CFC tile

Five W coated CFC tile types were tested in the JUDITH-2 facility, their JET tile designations are: G7-like (benchmark test), G1, G3, G4, G8. The G7-like tile consisted of CFC, coated with 14 µm W/Re. The other CFC tiles were coated with W only ~30 µm. All tiles were coated by PLANSEE Company. In this paper only the Benchmark Test on the G7-like tile will be discussed.

Uncoated FGG samples W/Re and W coated CFC tiles were fixed on numerical controlled x, y cross-table with slideways inside the JUDITH-2 vacuum chamber. Four Cu-cooling plates are installed on the slideways and followed by special Cu-adapter blocks on top. For getting more efficient heat transfer from every coated CFC tile the Cu adapter block and from Cu adapter block to the Cu cooling plates a thin graphite foil (Papyex, thickness 0.2 mm) was installed. For the mechanical fixing of all thes components INCONEL 625 / 617 and stainless steel 316 parts (dumbell shafts, dumbell barrel ends, tie bars and disc springs) were used.

The sweeping of the electron beam (EB) is controlled by the ARDENNE beam guidance software. For all JET tests a special pattern of meander structure was used

(**Fig. 2**). The distance between the electron beam loading points (EBLP) in x direction was approximately 4.2 mm, the distance in y-direction was only 3.75 mm. The EBLP-time was 10 µs (**Fig. 2**).

After establishing an acceptable heating pattern on geometric equivalent FGG prototypes, the W coated CFC tiles were tested. In case of the W/Re coated G7-like benchmark tile, the EB loaded area was A_L = 0.0162 m^2 (**Fig. 2**, heating area reduced by 20 mm on each edge of the tile) and a heating time of 10.2 s on each tile was used per cycle. With 4 x G7-like W/Re coated tiles, the time of one total cycle becomes to 40.8 s (= 10.2 s + 3 x 10.2 s).

The G7-like tile bench mark test pointed out that the critical temperature level of 800°C was reached after 4 cycles at an incident power of P = 43.8 kW and after 2 cycles at an incident power of P = 84 kW (**Fig. 3** and **Fig. 4**).

For the interesting 84 kW bench mark test the average power density was $p_1 = P / A_L$ = 84 kW / 0.0162 m^2 = 5.2 MW/m^2, the absorbed average power density can be calculated as $p_{ABSORBED}$ = 0.55 x p_1 = 0.55 x 5.2 MW/m^2 = 2.86 MW/m^2.

Finally under the assumption of an EB-diameter of approximately d_e = 17.6 mm the absorbed power density (defocused e-beam) on 14 µm W/Re coated CFC G7-like tile was $p_{AB\text{-}EB}$ = 0.55 x P / (π/4 x d_e^2) = 0.55 x 84 x 10^3 W / 2.44 x 10^{-4} m^2 = 0.19 GW/m^2 < 5.66 GW/m^2. The latter is the allowed absorbed power density for negligible damages in tungsten (p x sqrt (t)-law and energy density limit of 0.4 MJ/m^2 in 0.5 ms [4]).

The whole EB-loading and cool-down situation is shown in **Fig. 4**. For the temperature-time behaviour two curves are shown. The surface temperature reached the maximum after two loading cycles and cooled down to 200°C in approximately 5 minutes (**Fig. 4**, black curve in case of TB). This allows 10 thermal cycles to be applied on four tiles in one hour (10.38 = 3600 s / [4 x 10.2 s + 306 s]).

The gray curves in **Fig. 3** and **Fig. 4** are the temperatures which were measured by the two colour-pyrometer during two cycles. At the end of the 2nd cycle the maximum temperature was near 1000°C. This corresponds also to the real temperature switch-off limit during the benchmark test (instead of 800°C)- due to an unfavourably assumed emissivity of ε = 0.55 [5] in the IR protection system.

The black temperature-time curves (TB) in **Fig. 3** and **Fig. 4** are the results of analytical calculation with a pyrometer-correction equation as follows [6]:

$$T\mathrm{B[K]} = C_2\,(C_2/T - \lambda\, ln\, \varepsilon\,)^{-1} \qquad (1)$$

Here C_2 is the second PLANCK constant (C_2 = 1.44 x 10^{-2} m K), T is the measured temperature in [K], λ the used average wavelength (λ = 4.0 µm) and ε the emissivity (here unfavourably ε = 0.55) of “correction” procedure. TB is also the temperature which was received by the IR camera protection system based on the unfavourably used emissivity of ε = 0.55. Under this condition the maximum of temperature was in the acceptable range of 800°C. In **Fig. 3** and **Fig. 4** the black curve TB = f(t) with TB < 800°C is also the proof of active protection system. In future JET tests with the IR camera protection system it would be better to use a tungsten emissivity value in the range of ε < 0.3 [6].

4. Conclusion and consequences

In the frame of JET ITER like wall project NDT tests with defocused beam in the JUDITH-2 facility were performed on 14 µm W/Re coated CFC G7-like tile (Benchmark Test) with a local power density limit of 1.9 GW/m^2 for 10 µs (2 cycles, 84 kW, defocused EB-diameter approximately 17.6 mm). Additional tests on different ~30 µm W coated CFC tiles have been executed at a higher power level of 132 kW and 1500°C surface temperature ranges.

Acknowledgement

The authors would like to acknowledge the assistance of K. Dominiczak, K.J. Breuer and M. Lowis in the JUDITH-2 experiments. We also would like to thank the JET organisation Culham, UKAEA for the friendly relinquishment of the G7-like FGG, W/Re coated CFC- and other W coated CFC tiles.

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Figure captions

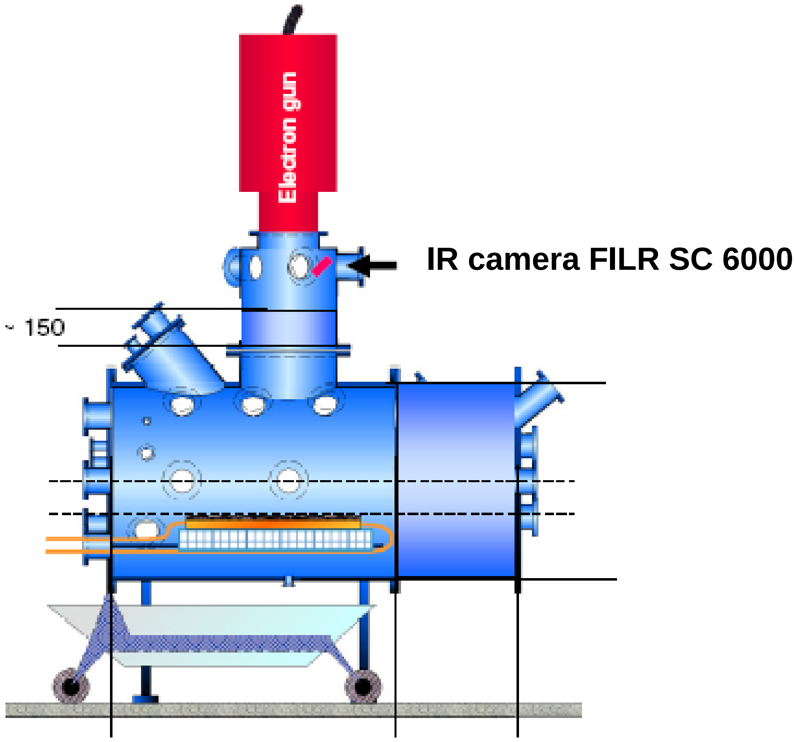
Fig. 1: Representation of new JUDITH 2 electron beam facility after upgrading.

Fig. 2 Schematically example of cyclic electron beam heating meander figure for a G7-like tile.

Fig. 3: Representation of power (P) and temperature (T) vs. time (t) curves during cyclic e-beam loading of W/Re coated CFC tile at 84 kW (EB-gun pre-setting's: P = 80 kW, U = 50 kV, $L1$ = 96% and $L2$ = 30%).

Fig. 4: Representation of temperature (T) vs. time (t) curves during cyclic e-beam loading of W/Re coated CFC tiles at 84 kW. Cooling down temperature to TB = 200°C was extrapolated with equation *(1)*.

FIGURES



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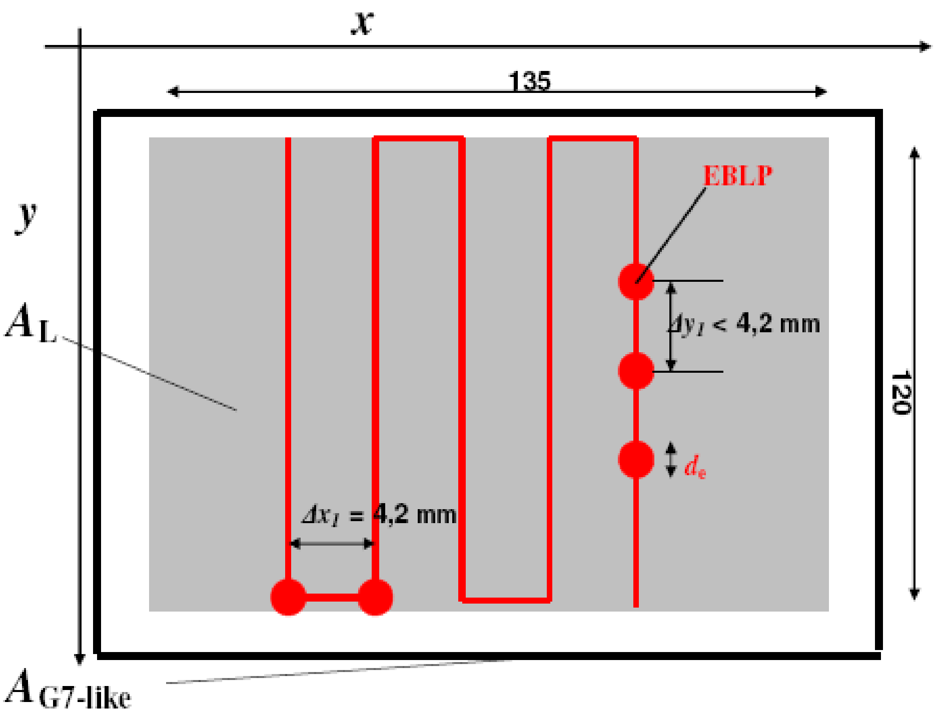

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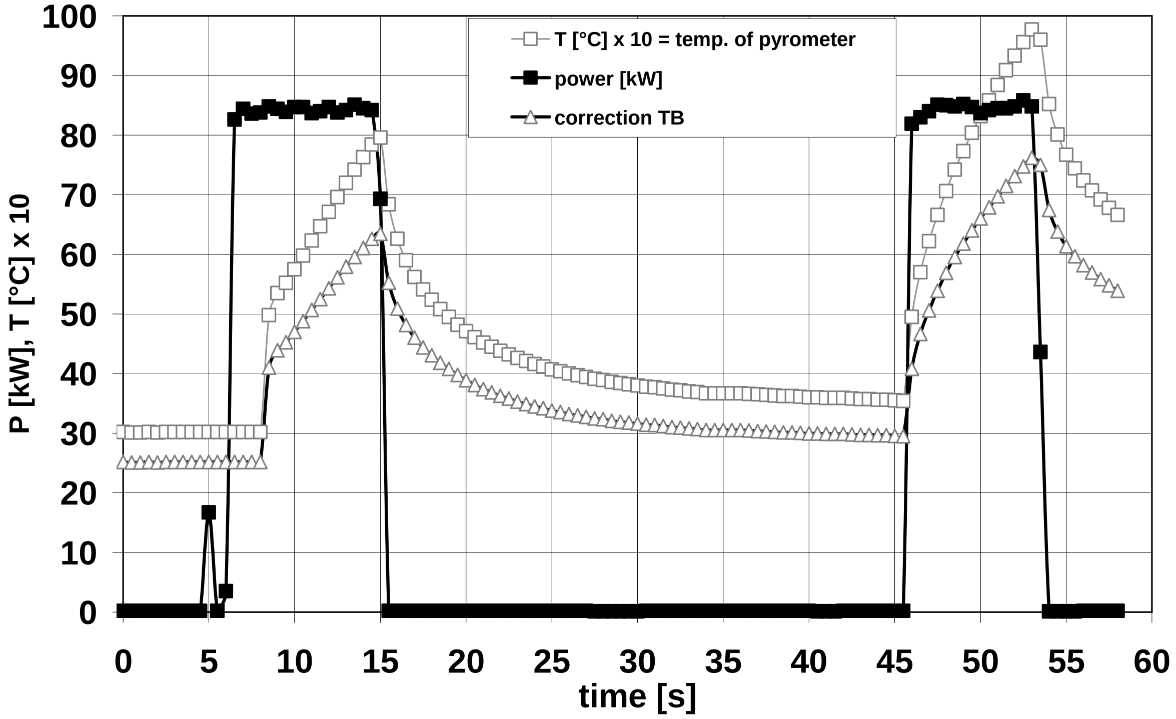

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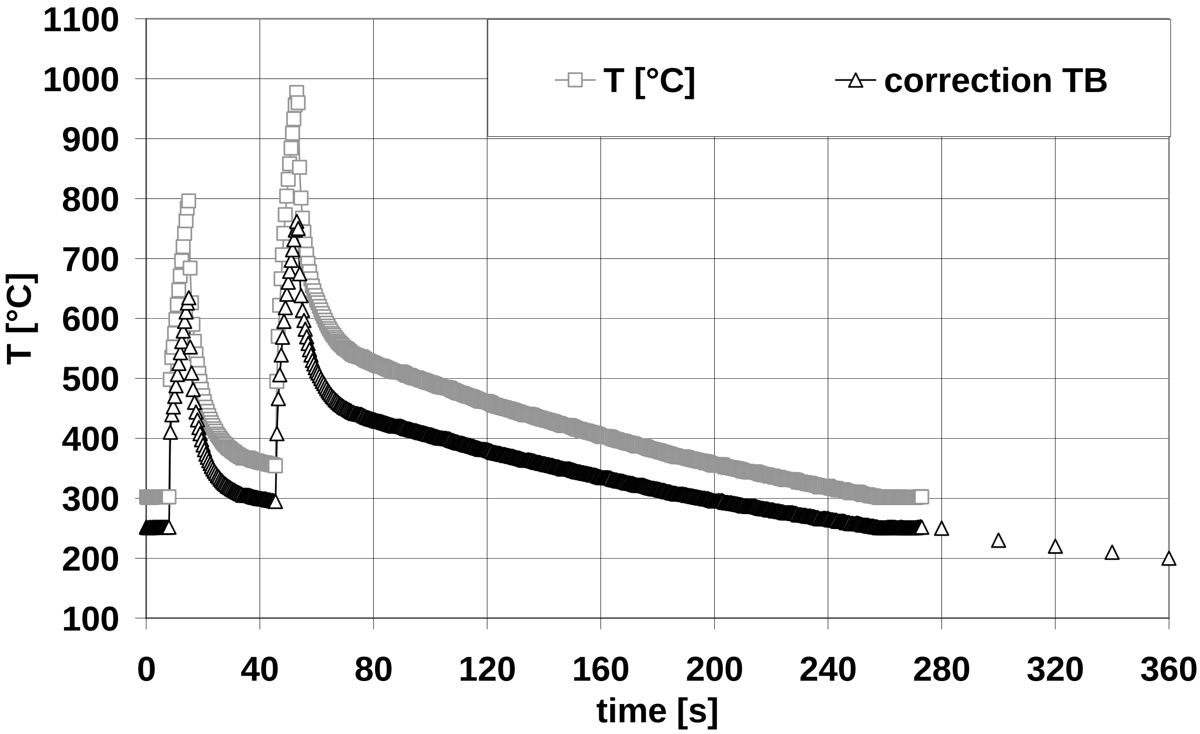

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