Results and consequences of high heat flux testing as quality assessment of the Wendelstein 7-X divertor

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The series manufacturing of the first 282 Wendelstein 7-X divertor elements was concluded in 2011. The divertor is designed to remove a steady-state heat load of 10 MW/m². 940 target elements of five different types made of CuCrZr heat sinks and covered with 16,000 CFC NB31 flat-tiles have to be produced. Additional to quality assessment during the manufacturing process, a final assessment of the delivered elements with operational heat load is indispensable to ensure a constant high thermal performance of the installed divertor.

Based on the results of the pre-series testing a statistical quality assessment method has been developed for the series production. The application of this method to the series elements ensures their thermal performance with reasonable high heat flux test effort.

Keywords: W7-X, Divertor, Plasma-facing components, High heat flux Tests, Statistics, Six-Sigma

1. Introduction

The actively water-cooled divertor will provide the stellarator Wendelstein 7-X (W7-X) with a steady-state power and particle exhaust. 890 so-called target elements form the ~20 m² highly heat loaded divertor plates. The elements are designed to remove 10MW/m² heat flux. These elements are made of carbon fibre reinforced carbon (CFC) tiles as plasma facing material bonded with 3 mm Cu bi-layer and welded onto a CuCrZr structure [1]. About 16,000 flat CFC NB31 tiles have to be bonded onto the cooling structures

Most of them, 14,000, are the thermally highest loaded standard CFC/Cu tiles on the top of the elements with dimensions of about 50 mm width, 25 mm length and 8 mm CFC thickness. This kind of elements was intensively high heat flux (HHF) tested during the pre-series phase. The most critical issue during operation is a possible debonding of the CFC from the cooling structure due to thermo-mechanical stress generated by the strong mismatch of thermal expansion coefficients of CFC and Cu. Only HHF testing can assess the thermo-mechanical behaviour of an individual CFC/Cu joint under realistic loading conditions. From this point of view, the assessment of the industrially fabricated components requires HHF tests complementary to the non-destructive examination and quality assessment employed at the manufacturer. The definition of a reasonable HHF test amount is a difficult decision balancing the assumed safety during operation and economic costs. The aim is to minimize the risk given limited resources for testing. The paper describes the applied methods and the results in detail for the manufacturing phase I and discusses the consequences for the testing of the second phase expected to be finished in 2014. In total 940 target elements (including 50 spare elements) have to be produced by PLANSEE SE.

2. Types and characteristics of target elements

There are 5 types of elements ranging from 250 to 600 mm length and 50 to 61.5 mm width [1]. In all types the top tiles are made of “standard tiles” with 25 mm length. The number of standard top tiles varies between 10 and 21 per element. The industrial manufacturing is split in two phases. In phase I, two types of elements covered with 10 and 13 standard tiles, respectively, have been manufactured (Fig. 1). The CFC tiles were manufactured from five batches of NB31with different properties and the delivery of the 282 phase I elements was completed in 2011 [2, 3].

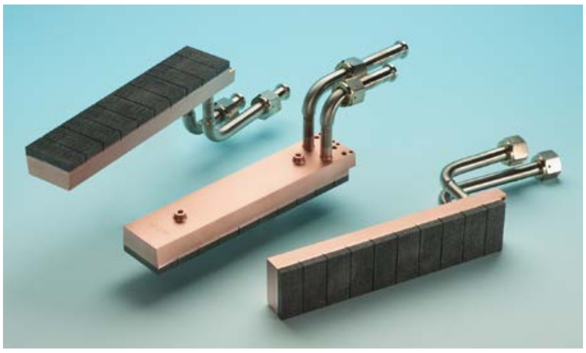

Fig. 1: Elements of manufacturing phase 1. Ten standard top CFC tiles cover the 250 mm long cooling structure. The bent water connectors are used for testing only.

Fig. 2 shows prototypes of the second manufacturing phase. 658 elements will be delivered until 2014. Typical for these elements is the design of the end CFC tiles [4]. Non-standard CFC tiles with various geometries are necessary to cover the end of the target exposed to particle flux due to the pumping gap of the divertor. The same standard CFC tiles as for phase I will be used as top tiles.

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Fig. 2: Elements of manufacturing phase 2. The elements are between 350 and 650 mm long.

3. Method of IR analysis

The CFC/Cu bonding quality of each individual tile is assessed by IR measurement of local temperature differences between the tile centre T_{centre} and the corresponding two opposite outer edges T_{edge} in the steady-state phase for each 10 MW/m² pulse. The outer edges of the tiles considered as individual samples are the locations where the highest stresses occur. The evolution of local temperature differences

$$\Delta T_N = (T_{edge} - T_{centre})_N - (T_{edge} - T_{centre})_1$$

after N cycles allows a reliable detection of growing defects for sufficiently high N [5]. Standard tiles without any indications of defects show a temperature increase of $\leq$ 50 K after 100 pulses. The upper specification limit (USL) of 75 K corresponds to clearly visible CFC/Cu delaminations of the order of several mm [6]. Further investigation (visual inspection) was specified to be performed for 50 K< ΔT < 75 K. The estimated noise of the temperature difference ΔT is approximately 5 K [7]. The criterion ΔT_{100} accurately describes the quality of the CFC bonding after 100 cycles at 10 MW/m².

4. Strategy of testing of the series elements

The launching of the series production was based on the results of the last 19 pre-series IV (PS-IV) tests. The successful HHF testing in the GLADIS [8] facility (10 MW/m² loading up to 10,000 cycles, 16 MW/m² cycling and screening tests up to 32 MW/m²) confirmed the robustness of the design, the manufacturing route, the process control methods and in particular the applied CFC/Cu bonding technology [9, 10]. The achieved agreement in the assessment results of the PLANSEE pulsed thermography facility ARGUS [9] and the HHF test results were an important step and essential for the clearance of the series production [7]. ARGUS is part of the quality assessment of the elements at the manufacturer and is systematically applied for all delivered elements.

To describe the achieved performance of the elements, a statistical analysis has been carried out on the results of PS-IV. The local surface temperature evolution of the CFC tiles during the initial test of the as-delivered elements with 100 heat pulses at 10 MW/m² and 10 s duration was analyzed. Based on these results a statistical quality assessment method has been proposed for the series production as part of the quality assessment of the delivered components [7]. The PS-IV testing has confirmed the stability of the manufacturing process and the applied quality control. Since the complete set of HHF test results of PS-IV established the connection between a stable production process in terms of ΔT100 and a high thermal performance, this statistical testing procedure is considered to be sufficient to ensure the functionality of the W7-X divertor.

Therefore it is not necessary to test all the delivered elements since a stable industrial process of a high number of components gives typically products whose measurable properties correspond to a Gaussian distribution. Two parameters, μ (mean) and σ (standard deviation), describe the Gaussian distribution. Statistical process control has been used in industry very successfully for maintaining a certain quality level of production processes. The Six-Sigma concept aims at reducing the variability of the process by monitoring the distance of a production parameter from lower and upper specification limits [11]. A distance of 6 σ results in about two parts per billion, which do not conform to the specification. Only the testing of sub-sets is necessary to detect quality deterioration. For long term production processes an empirical 1.5 σ shift is introduced in the calculation. Even if the mean would move by 1.5 σ in the future, there is still a high safety margin. The probability of a non-conforming tile is about 3.4 parts per million.

To include the possible broadening of the Gaussian distribution during the production process the chi-square χ^2-test is applied [11, 7]. A 20% increase in the variance of the ΔT_{100} distribution of the standard tiles could be detected at a significance level of 99.9% with the data of about 70 CFC tiles. Larger deviations (and shifts in the mean of the ΔT_{100} distribution) typically require even less tiles to be measured. To define the sub-sets of tested elements we have taken into account the five geometrical different element types.

The application of this method to the ΔT_{100} parameter of a sub-set of the series elements allows the reliable assessment of the stability of the production process with reasonable HHF test effort.

The statistically assessment for the series elements will be performed on “good” ARGUS tiles as follows:

A. Manufacturing phase I:

1. Loading with 100 pulses at 10 MW/m² of all CFC tiles of the first batch of 19 elements (reference batch).

2. Determination of the Gaussian distribution of the tested CFC tiles of the reference batch.

3. Comparison with the Gaussian distribution of the PS-IV (Table 1). The acceptance of the results from these first 19 elements as the reference distribution for the assessment of the series production based on the large distance between mean and USL.

4. Determination of the required sub-set of elements to be tested on the basis of a χ^2-test taking into account the two element types, the number of CFC batches and an acceptable deviation from the reference distribution according to the procedure published in [7].

B. Manufacturing phase II:

5. Test of sub-sets of elements of the remaining types according to 4.

6. To cover different element types and CFC batches we will assess statistically about 52 elements.

7. Tests of the lower loaded front and end tiles will be performed according to section 6.1. of this paper.

Additionally all questionable tiles after ARGUS will be tested in GLADIS as well as all repaired tiles.

5. Results of manufacturing phase I assessment

5. 1. Assessment of the reference batch with 100 cycles

The HHF test results of the reference batch are summarized in table 1. The distance between the mean of the ΔT_{100} distribution and the USL is very large and confirms the consistent high manufacturing quality. The highest value ΔT_{100}= 40.3 K is clearly within the 50 K range for tiles without any indication of defects. The quality of the reference batch is at the same high level as for the PS-IV. We apply this Gaussian distribution as the reference distribution for the series production.

5. 2. Alternative assessment of the reference batch after 25 cycles

An alternative proposal using 25 pulses instead of 100, which would allow the assessment of a higher number of elements with the same effort, was also evaluated. The statistical analysis of PS-IV shows that for this data set a reliable assessment of the bonding quality was not possible with this number of pulses [7]. Nevertheless, the possible applicability of this approach was further investigated for the reference batch after 25 HHF cycles. Assuming a linear dependence of ΔT_N as a function of the pulse number N the corresponding USL after 25 cycles should be reduced to 75 K/4=19 K. The threshold for further tile investigation is reduced to 12.5 K. The measured Gaussian distribution after 25 cycles has a mean of ΔT_{25}=3.0 K with a standard deviation of σ =5.5 K as shown in Fig.3. It is obvious that the standard deviation σ =5.5 K is very close to the 5 K noise of the signal. This approach does not allow a clear assessment of the tiles (samples located between the dashed green and red lines in Fig. 3) and appears not to be suitable for the analysis of the elements.

5. 3. Assessment of the remaining phase I elements

18 additional, randomly selected, elements taken from the remaining 263 elements were tested according to section 4. A. 4. In total, 13 % of the phase I elements have been tested. Fig. 4 shows that the distribution of ΔT_{100} of all tested elements of phase I can be matched well with a Gaussian distribution. All tiles clearly fulfil the specification. The bin width is 2 K. Mean and standard deviation are shown in Tab. 1.

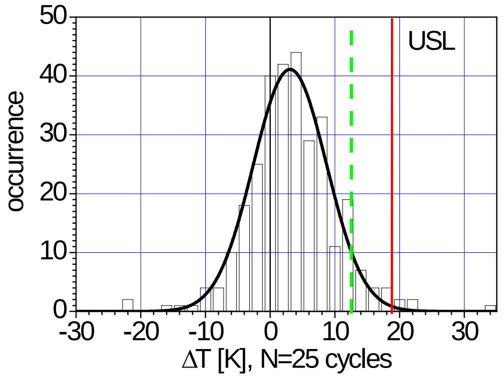

Fig. 3: Result of an alternative assessment after only 25 cycles at 10 MW/m² of the reference batch 1. The dashed line at ΔT=12.5 K marks the region for tiles with an unclear result.

The predicted number of undiscovered tiles exceeding the specification limit is about 1 × 10^{-7} tile. The risk of an undetected defect tile is very low. There is a narrower distribution but a small shift of the mean compared to the PS-IV results, however, well within the statistical variation of the data.

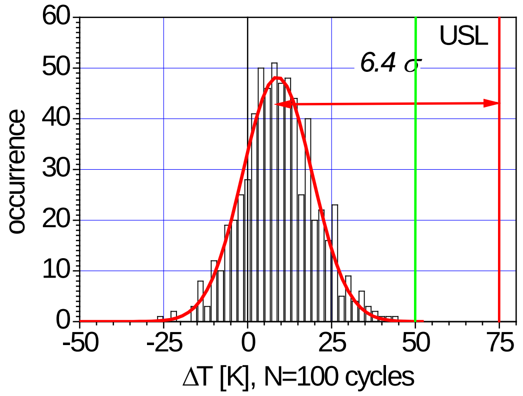

Fig. 4: Histogram of ΔT for all tested CFC tiles of manufacturing phase 1 after 100 cycles at 10 MW/m². The dashed line at ΔT=50 K marks the region for tiles without any indication of defect.

Four elements with a total of 5 questionable tiles after the final ARGUS tests were also tested in GLADIS. Their number corresponds to 0.2 % of the delivered tiles. The result of the test; maximum ΔT_{100} = 28 K, minimum ΔT_{100} = -2.6 K and a mean ΔT_{100}= 16.1 K, did not necessitate any further investigations.

	samples	Mean ΔT_{100} μ [K]	Standard deviation σ [K]	Distance to USL σ
PS-IV	*160*	*5.3 ±0.6*	*11 ±0.6*	*6.5*

Reference batch	304	8.6 ±0.4	9.7 ± 0.4	6.8
Phase I, total	**636**	**8.8 ±0.3**	**10.3 ± 0.4**	**6.4**

Table 1: Summary of the statistical parameters after the HHF tests with 100 cycles at 10 MW/m². The data of PS-IV are shown for comparison of the manufacturing quality.

6. Assessment of the phase II elements

Two-thirds of the remaining elements have to be assessed in the frame of phase II. Based on the statistical method, testing of the standard tiles of about 52 elements (8% of phase II) is required. Assuming an increase of ≤ 20 % in the variance of the ΔT distribution, the predicted number of an undetected standard top tile would be about 5×10^{-7} tiles.

6. 1. Assessment of non-standard tiles

621 of the phase II elements are covered with front tiles and end top tiles with a non-standard geometry. An improved manufacturing route for the front and end tiles was developed and HHF tested in preparation of phase II. The end top tiles are designed to withstand a reduced heat load on the top of an average 5 MW/m² descending to 2 MW/m² at the end. The corresponding front tiles are designed for ≤ 2 MW/m².

The 100 cycles HHF tests performed at 5.5 MW/m^2 on the end of the front top tiles has confirmed the robustness of the design. Loading with 100 cycles at 7 MW/m² initiated small cracks in the CFC/Cu interface. 8 MW/m² at the end of the element is the limit for single pulses to avoid larger defects at the CFC/Cu interface.

The assessment of the end top tiles will be performed within the standard tile testing with 3 MW/m² at the end of the element. Assessment criteria have still to be developed for the series testing of these top tiles.

The worst loading case for the end tiles, the simultaneously loading on the top and at the front surface was investigated. Pre-series elements were installed with an angle of 45° with respect to the beam axis according to the procedure described in [4, 8]. Cyclic HHF tests were performed at 4 MW/m^2 on the end of the top tile and the upper part of the front tile, respectively, without any indication of degradation. The maximum acceptable load of 7.5 MW/m² for single events resulted in a partial melting of the Cu.

The high safety margin of 2 between the power load design value and beginning delamination due to overloading allows an assessment of the series front tiles with reduced effort. A statistical assessment similar to the standard top tiles is not necessary. It is therefore foreseen to test the front tiles of only 2-4 elements per type.

7. Conclusions and outlook

The HHF testing of the W7-X divertor target elements of the first manufacturing phase has been concluded. The first delivered batch of 19 elements was completely HHF tested with 100 cycles at 10 MW/m². The analysis of the surface temperature evolution of each CFC tile confirmed the proposed statistical assessment method. The application of this method to the ΔT_{100} parameter of a sub-set of the series elements allowed the reliable assessment of the stability of the production process.

This analysis confirms the same high thermal performance as achieved in the last pre-series production. No degradation of the manufacturing quality resulting in a broadening of the Gaussian distribution was detected. After the statistical assessment of the results of 13% of the phase I elements the risk of an undetected defective CFC tile is considered to be very unlikely. A small number of tiles with questionable results after the final acceptance tests at PLANSEE passed clearly the 100 cycle test without any indication of defects.

The HHF tests of the delivered elements are imbedded in the quality assessment at PLANSEE SE and at IPP. Only the full set of all assessments performed both by the manufacturer and at IPP ensures the successful manufacturing of the W7-X divertor targets. On the basis of all these result the delivery of all 282 elements was accepted by IPP.

The statistical assessment will be applied to the delivery of the remaining 658 elements of phase II. The phase I results demonstrated the reliability of the statistical 100 cycle tests with reasonable HHF test effort. The remaining risk of defects during W7-X operation cannot be excluded by any conceivable testing strategy. Nevertheless, it is essential to continue the assessment of the remaining manufacturing to ensure the quality of the whole production.

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