Advanced Qualification Methodology for Actively Cooled High Heat Flux Plasma Facing Components

A.Durocher 1), F.Escourbiac 1), A.Grosman 1), J.Boscary 2), M.Merola 3), F.Cismondi 1), X.Courtois 1), JL.Farjon 1), M.Missirlian 1), J.Schlosser 1), R.Tivey 3)

(1) Association Euratom-CEA, CEA/DSM/DRFC Cadarache, France
(2) IPP Garching, Germany
(3) ITER Team, Garching, Germany

E-mail contact of main author: alain.durocher@cea.fr

Abstract: The use of high heat flux plasma facing components in steady state fusion devices requires high reliability. These components have to withstand heat fluxes in the range of 10-20 MW/m2 involving a number of severe engineering constraints. Experience feed back of various industrial manufacturing showed that the bonding of the refractory armour material onto the metallic heat sink causes generic difficulties strongly depending on materials qualities and specific design. As heat exhaust capability and lifetime of plasma facing components during plasma operation are directly linked to the manufacturing quality, a set of qualification activities was performed during the component development phases following a qualification route. The paper describes the major improvement stemming from better measurement accuracy and refined data processing and analysis recent developments aim at investigating the capability to qualify the component in situ during its lifetime.

1. Introduction

High heat flux plasma facing components (PFC) in steady state fusion devices will have to reach very high performance such as accepting thermal fluxes as high as 20 MW/m². They require in addition high reliability. This can be only guaranteed through a very high level of qualification obtained with a rigorous acceptance inspection protocol. To meet the PFC power exhaust requirements during plasma operation imposes the control of their thermal and mechanical integrity. PFC are systematically controlled before their installation in fusion machine detecting and localising defects inside material and welded junctions and qualifying their capacity to be cooled. Such systematic acceptance tests obviously need tools for process development and qualification of critical parts. The major issue is to detect thermal discontinuities in the element, such as material flaws like cracks and debondings. These can cause hot spots on the component surface and may even lead to the destruction of the PFC e.g. critical flux event. A set of qualification activities should be performed very early during the component development and subsequent manufacturing phases. The paper aims at pointing out the qualification route, which has been followed in order to define an acceptance criterion for flat tile target elements joining for the Tore Supra Toroidal Pumped Limiter (TPL) series production [1] and more recently for the WENDELSTEIN 7-X (W7-X) component pre series production [2]. Investigations for the International Thermonuclear Experimental Reactor (ITER) divertor elements, which are more challenging due to the thicker armour material and the more complex monoblock geometry, are now prepared and will be done shortly (see FIG.1). A long-term effort has been undertaken, from analysing the principles of the non-destructive examination (NDE) techniques to their implementation at an "industrial level". An assessment of the qualification methods was achieved, resulting in a more accurate qualification and in improvement of the methods. They now imply the combination of various techniques. Recent developments aim at investigating the capability to qualify the component in situ during its lifetime. They are summarized in the last section.

Tore Supra TPL targets *Wendelstein 7-X targets* *ITER mock-up (CFC and W parts)*

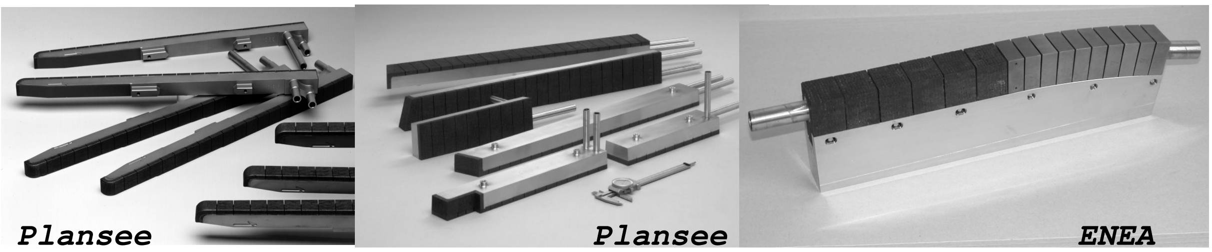

FIG. 1. Various high heat flux plasma facing components.

2. Plasma facing component challenge

A plasma facing component has to withstand heat fluxes in the range of 10-20 MW/m2, such as in ITER [3] involving a number of severe engineering constraints: (i) the armour materials must be refractory and compatible with plasma wall interaction requirements; (ii) the heat sink should have a high thermal conductivity, high mechanical resistance and sufficient capability to assembly techniques; (iii) the cooling system, which is up to now based on a circulation of pressurized water in the PFC heat sink, must offer a high thermal efficiency and margins to failure modes; (iv) the joint of the refractory armour material onto the metallic heat sink, which suffers strong constraints during the assembly.

A development is done where high heat flux tests are complemented by non-destructive evaluation. For instance Tore Supra TPL manufacturing, thermal fatigue tests at 10MW/m² were performed and showed a high increase of surface temperature with an uncertainty zone between 2000 and 3000 cycles, observations showed that degradation appeared well over 3000 cycles (fig. 2). This study allowed roughly to define a steady state surface temperature limit of 1200°C at 10MW/m² for TPL targets [4]. The ability to predict the evolution of flaws assembling need a thermal fatigue analysis which is a challenging problem including both experimental activities based on development of dedicated NDE, such as active infrared thermography technique or High Heat Flux (HHF) testing and thermo mechanical modelling activities.

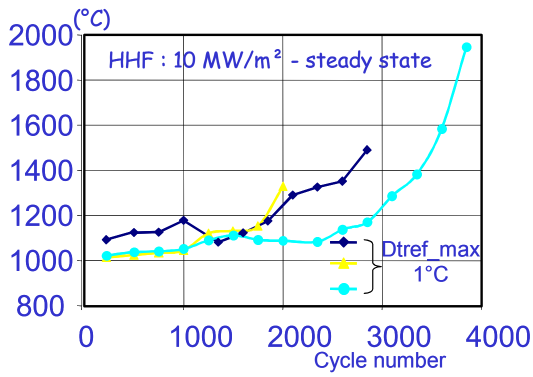

FIG. 2. Fatigue ageing: evolution of surface temperature (TPL)

3. Qualification methodology

3.1 The SATIR test and its limits

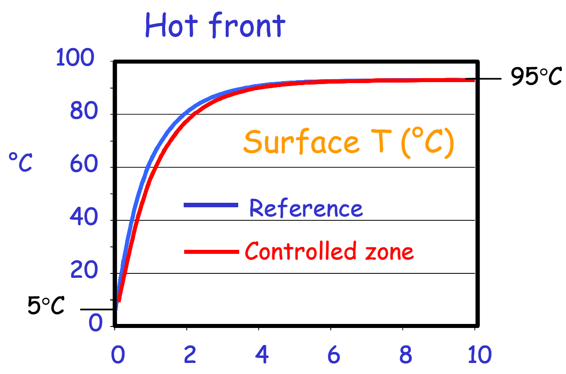

FIG.3. Surface temperature evolution: tested and reference element

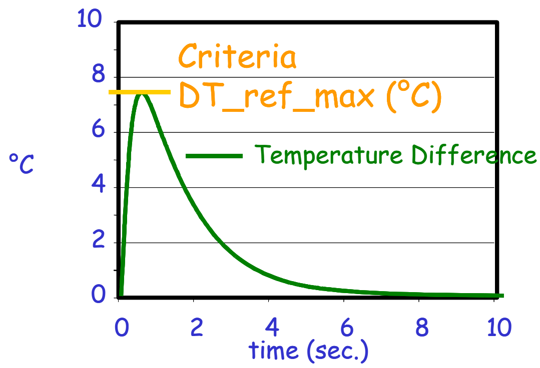

FIG.4.DT_ref_max definition

The SATIR test is based on the detection of a delay in the surface temperature evolution produced through an abrupt variation of the water temperature flowing in the cooling tube [5,6]. This delay is actually measured in comparison to the behaviour of a reference element. This is realised by an alternate flow of cold (5°C) and hot (95°C) water into the cooling channels (FIG.3). The principle is based on the comparison of the surface temperature evolution of the inspected component with that of a so-called "defect-free" reference one. In the case of the Tore Supra TPL, two elements were tested in parallel to a reference and a DTref criterion (Maximum of the transient temperature difference: FIG.4) was stated to 3K maximum mismatch with respect to this reference. The connection between this mismatch and defect size was established both by means of finite element modelling, taking into account material physical properties, thickness effect and the background noise of the facility, and by tests of calibrated defects. Considering the SATIR performances during TPL reception, it was considered that corner defects larger than 6 mm required detection with confidence.

The mismatch extent was derived from the uncertainties in the material characteristics and the measurement (±0.5 K for ±5% on the CFC conductivity, 0.1 K for ±lmm on the CFC thickness, ±2.1 K for ±0.7 mm on the copper thickness, 0.2 K for IR camera). An optical examination allowed to quantify the correlation of the SATIR DTref value to free cracks extent. This finally gave access to the minimum value detectable heat transfer efficiently degradation has been assessed (FIG.5). Such value must be lower than the maximum acceptable value defined by design conditions [4]. It appeared that the margin although acceptable needed improvement to meet the challenge of very large statistics: even for the Tore Supra TPL, the number of tiles exceeded 10000 and in a few cases elements not meeting the criterion requirements were accepted and installed in the tokamak, taking the advantage that not all the PFC are subjected to the maximum heat exhaust design value.

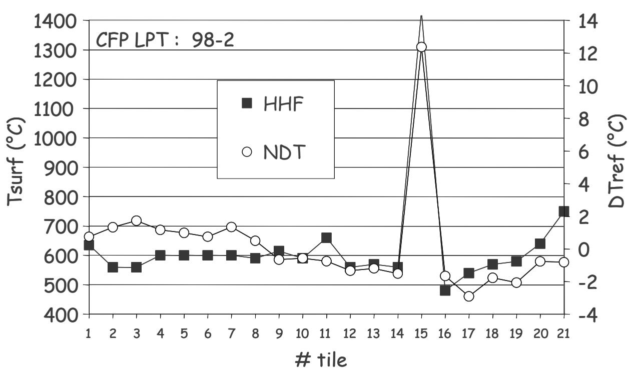

FIG.5. Example of SATIR and HHF test correlation

3.2 Improvement of the SATIR test

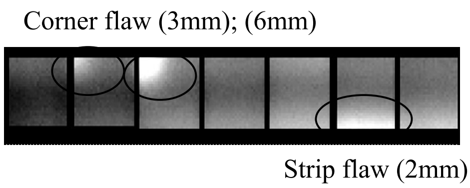

FIG.6. Example of SATIR DTref cartography on TPL target (CFC flat tile)

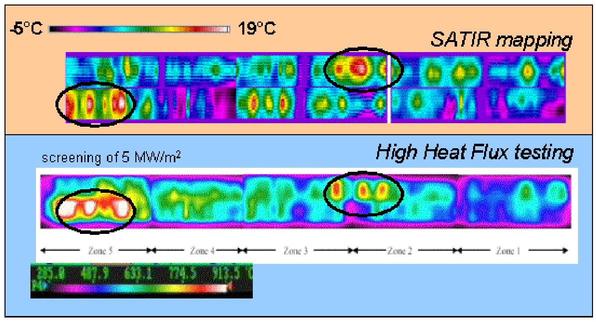

FIG.7.Good agreement between SATIR infrared image and high heat flux testing (CFC monoblock)

In order to improve the defect detection capability of the SATIR test bed, several possibilities have been considered and assessed and some of them already implemented. In particular the installation in 2003 of a digital infrared camera and the improving of the thermal signal processing, has led to a considerable improvement of the performances as the spatial resolution was increased by about an order of magnitude. The emissivity correction of the measured surface took an important part in this improvement; a pixel normalisation algorithm has been developed and allows the detection threshold to be reduced. In fact both the normalisation and the DTref by pixel allowed increasing the spatial location and sensibility of detection by a factor 2. In the case of Tore Supra TPL element, corner defect of 3mm and strip defect of 2mm can be easily detected at the CFC/Cu bonding (FIG.6). The advanced data processing was highlighted on SATIR image of a CFC baffle panel from ITER monoblock technology and image of the same tested component exposed to high heat flux of 5MW/m². Similar default patterns (shown by a black circle) are observed with both techniques (FIG.7). The good agreement between SATIR infrared image and high heat flux testing allowed to propose the active infrared thermography method as an ITER relevant method. In addition the so-called DTref criterion could be improved by using signal processing methods. After a spatial-temporal filtering of the signal, a treatment based on spatial image autocorrelation allows a better location of the bond defect. The qualitative improvement of the defect detection obtained by signal processing methods is combined with a quantitative estimation accomplished by analytical simulation of the thermal behaviour of a PFC tested on SATIR test bed; thus a digital reference replaces the element reference without introducing any bias. A 1D model based on thermal quadruples theory, allows to quantify the defect in terms of thermal contact resistance [7]. This methodology has been applied to the qualification tests of W7-X PFC (FIG.8).

FIG.8.Defect detection (energy of autocorrelation function) and estimation (thermal contact resistance:Rc): SATIR experimental measurement without reference

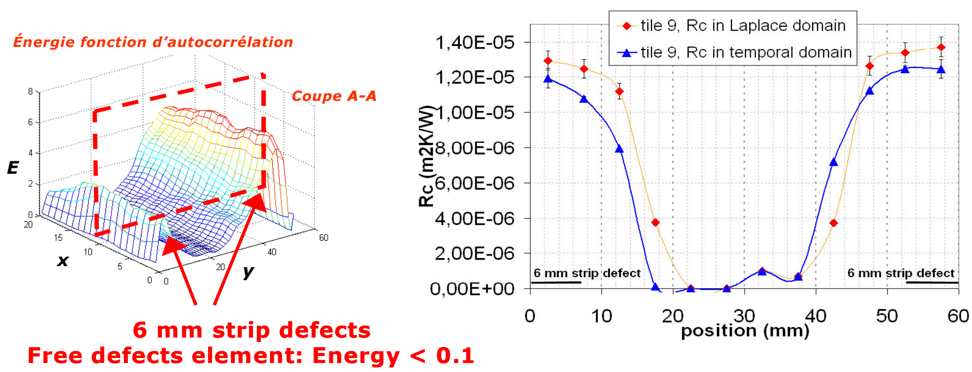

FIG.8 shows the analysis of faulty tile (2 artificial 6mm strip defects) of an asymmetrical diagnostic element. Image processing and analytical model yield complementary information on defect detection and estimation. The CFC thickness of W7-X PFC is 8mm.

3.3 Application of multiple NDE techniques for recent projects such as W7-X

The divertor of the Stellarator W7-X is composed of 890 actively cooled target elements with a total area of 19 m², and was designed to withstand heat fluxes up to 10 MW/m² in steady state operation. The selection of the material combination of the target elements is a 3D carbon fibre reinforced carbon composite (CFC grade Sepcarb® NB31), joined to a heat sink of CuCrZr alloy. The definition of acceptance criteria is based on manufacturing and qualification experiences obtained during a pre series fabrication representing about thirty mock-ups. A crosschecking analysis, between the high beat flux performance tests (mainly carried out in the ion beam facility GLADIS [8] at IPP-Garching), and the non-destructive infrared thermography examination bas been performed. It allowed to set a DTref detectable limit for SATIR close to 1.5°C as well as to define an acceptance limit of about 4°C for the standard elements, corresponding to a surface temperature increase of about 30% under a heat flux of 10 MW/m² (FIG.9). The defined acceptance criteria for the flat tiles target elements may applied for reception of the W7-X divertor targets during series fabrication [6]. To avoid taking decisions, which are doubtful when in particular, the threshold is only slightly exceeded; it appeared that the use of a second technique probing again the thermal response of the component might help. Modulated photothermal thermography and lock-in detection (to be summarized hereafter as “LOCKIN”) consists of the exposure of the component tile surface by a periodic external thermal source while recording its temperature response by infrared thermal imaging, and then calculating the phase shift between the measured signal and the source by synchronous demodulation (FIG.10) [9]. The phase-shift of the thermal response depends on the thermal conductivity and diffusivity along the heat path, thus on the presence of any thermal discontinuity within the material, leading to a localized modification of diffusivity. This allows to detect strong thermal resistances such as produced by cracks or debonding, provided they are large enough compared to the distance to the temperature measurement surface so as to maintain the 1D character of the analysis modelling. Note that other thermal stimulation (e.g. pulse) can be used and have been implemented [10]. In any case, the definition of criterion will be limited by the rather poor statistics that one can derive from results obtained in pre series where about 100 elements might be tested and submitted to high heat flux tests. Nevertheless, criteria may be guessed defining the boundary of a zone of confidence to a zone of semi confidence and of the latter to a zone of non-confidence.

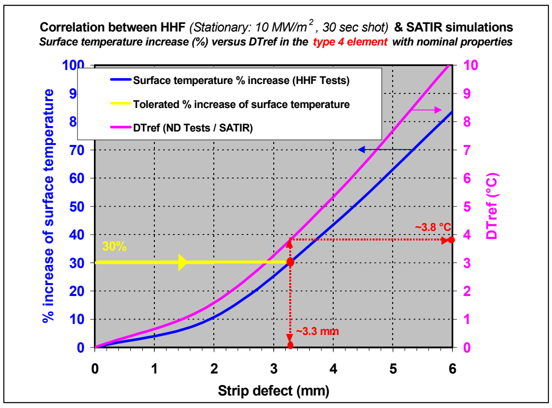

FIG.9. Acceptance criteria evaluation for Standard W7X target

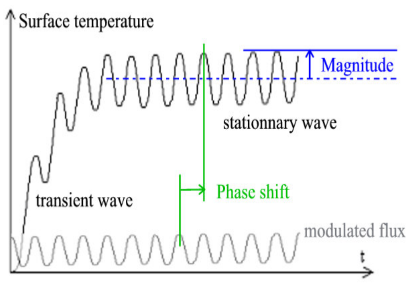

FIG.10. Sinusoidal thermal stimulation: Lockin Thermography target

3.4 Data merging

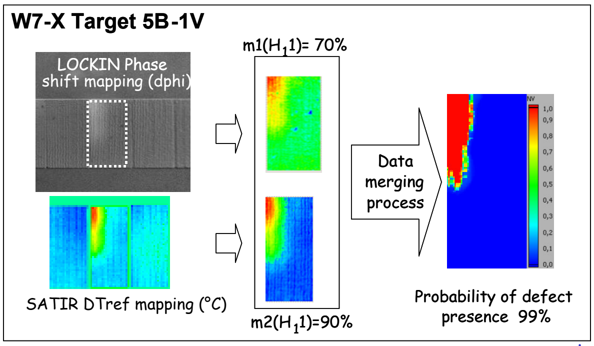

FIG.11. Infrared data merging (SATIR and LOCKIN) on a W 7-X element tile

Data merging from the above quoted techniques appeared to improve significantly the detection sensibility and reliability of defect location and size. This original study, using fuzzy logic through a Dempster-Shafer's model, showed a detection improvement of LOCKIN and SATIR methods (FIG.11). The data merging method is now in operation at CEA [11]. From the experimental know-how gained during the development of each individual NDE method, it will be possible to implement a data merging process with fairly reduced training. This data process brings an improvement even for a method that is already very reliable like the SATIR method. In the future the merging of additional NDE on ITER monoblocks, like the ultrasonic inspection or heat flux examination data should improve the reliability of the decision-making.

3.5 ITER prospects

SATIR inspection is proposed as the basis test to decide upon the final acceptance of the ITER divertor qualification prototypes. So as to provide a statistical basis, an extensive study is undertaken under EFDA auspices for the ITER divertor vertical target composed by 112 samples of W and CFC armoured HHF PFC with calibrated defect located at the interfaces are being manufactured in Europe both for advanced NDE validation and HHF testing [12].

4. Operational assessment of the PFCs

A new trend is to try to investigate the operational modes of the component including the failure modes in view of the limitation of the component described above and also to check the capability to assess the component thermal and mechanical status in situ. The major endeavours we are pursuing are investigations on the erosion phenomenon of elements with poor active cooling, in situ monitoring of PFC. In the case of ITER divertor, the CFC monoblock in the vertical target is the most loaded part of the plasma facing surfaces, hence a significant risk of failure; if the monoblock is expected to retain the CFC around the tube even after debonding, the possibility of a strong erosion could happen and should be assessed. A program has been developed with the aim of understanding the impact on the erosion lifetime and on the probability of a critical heat flux event in the heat sink of a combination of two main effects: the material property variations and the presence of joining defects. In assessing erosion, the finite element (FE) calculation takes account of geometry and sublimation, physical and chemical erosion of the CFC armour. The programs have been validated by comparison with analytical and experimental data. A FE calculation of physical erosion at 10 MW/m² performed on nominal ITER monoblock geometry with calibrated interface defects showed that the surface temperature reached to 2250°C [13]. In the next step, the model shall aim at modelling the macroscopic behaviour of a divertor element and especially check the eventuality of catastrophic failure such as critical flux event or strong reduction of the component lifetime by CFC ablation.

Because it is difficult to prevent the creation or evolution of defects, it is essential to relate the quality of the component to its possible evolution in operation. For instance, non-destructive testing devices - as the lock-in thermography technique – may be applied to observe, in between plasma campaigns, the evolution of defects in the Tore Supra TPL CFC/Cu joints [14]. In the case of Tore Supra TPL elements, the quality of the elements was controlled on 100% of the delivered batches. In order to integrate the TPL, a new relaxed acceptance criteria for flat tiles was applied to delivered elements. Some elements, with tiles outside the criteria range, but accepted nevertheless, were installed on the limiter sectors with lower power densities taking into account the shadowing on the TPL due to the Shafranov shift and the ripple effect. These shadowed zones have been experimentally confirmed during the 2001 campaign [14].

LOCKIN has been implemented in situ (see FIG.12) through an external sinusoidal thermal excitation generated by a set of modulated halogen lamps. The thermal response of the inspected component is recorded during the stimulation with the help of an infrared device. Magnitude and phase-shift of the response, which is calculated with a synchronous demodulation, may indicate the presence of cracks failure into the component, but also the presence of coatings due to co deposition phenomena of plasma component mainly C and D. Reliable measurements of magnitude and phase contrast were obtained on a limiter element with calibrated flaws machined at the bonding CFC/Cu [15]. The resulting cartography of a TPL sector shows 6 tiles at least with probable reduced heat transfer efficiency (FIG.13). The results are still preliminary and may suffer from the non-appearance of defective tiles as the Tore Supra TPL is used below its design thermal heat exhaust design values.

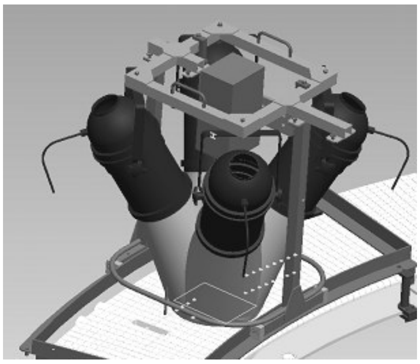

FIG.12. LOCKIN test device set up on TPL in Tore Supra vacuum vessel (electronics and computer are set-up outside the vessel)

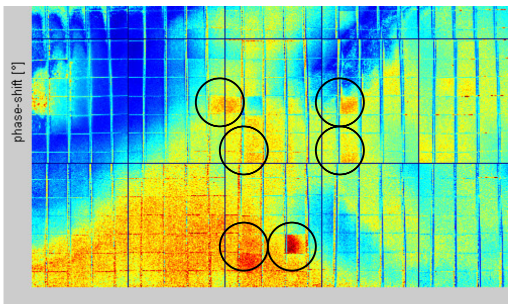

FIG.13. Phase-shift LOCKIN map of Tore Supra Q6A sector

5. Conclusion

Actively cooled plasma facing components sustaining high heat flux must be controlled following thermal and mechanical criteria. The major risk is that the heat loads can induce a partial or entire bond fracture between the refractory tile and the heat sink if any large cracks remain. Consequently, advanced non-destructive inspection and original in-situ monitoring techniques were developed for the qualification of PFC including R&D and the definition of acceptance criteria. This could be achieved by putting together various NDE methods and defining a methodology where the poor statistics may be used at its best by a strong effort on the modelling, data analysis and processing. The results are encouraging in view of the ITER challenge. In situ assessment of the PFC is now investigated; the studies are still in a preliminary phase.

6. Acknowledgments

This work, supported by the European Communities under the contract of Association between EURATOM/CEA, was partially carried out within the framework of the European Fusion Development agreement. The views and opinions expressed herein don't necessarily reflect those of the European Commission.

7. References

[1] J. SCHLOSSER et al., Experience feedback from high heat flux component manufacturing for Tore Supra, Fusion Engineering and Design, vol. 56-57 (2001), pp. 309-313.
[2] J. BOSCARY et al., Applied technologies and inspection for the W7-X pre-series target elements, Fusion Engineering and Design 75-79 (2005), pp. 451-455
[3] M. MEROLA et al. EU R&D on divertor components, Fusion Engineering and Design, vol. 75-79 (2005), pp. 325-331.
[4] J.J. CORDIER et al. Preliminary results and lessons learned from upgrading the Tore Supra actively cooled plasma facing components, Fusion Engineering and Design 66-68 (2003), pp.59-67
[5] A.DUROCHER et al., Quality control of plasma facing components for Tore Supra, Fusion Engineering and Design, vol. 66-68 (2003), pp. 305-309.
[6] A.DUROCHER et al., Development of an original active thermography method adapted to ITER plasma facing component control, Fusion Engineering and Design, vol. 75-79 (2005), pp. 401-405.
[7] F.CISMONDI et al., Etude méthodologique des tests non destructifs des liaisons Composite à Fibre de Carbone / Cuivre par thermographie infrarouge. 6éme colloque international francophone, Méthodes et techniques optiques pour l'industrie - Marseille (France), 21/11/05 - 25/11/05.
[8] H. GREUNER et al., Design, performance and construction of a 2 MW ion beam test facility for plasma facing components, Journal of Fusion Engineering and Design 75-79 (2005), pp. 345-350
[9] F. ESCOURBIAC et al., Application of Lock-in technique to CFC armoured plasma facing component inspection, to be published in Journal Of Nuclear Materials (ICFRM 12th)
[10] M. MISSIRLIAN et al., Infrared thermography inspection methods applied to the target elements of W7-X divertor, proc. of 24th SOFT (2006) Warsaw-Poland, to be published in Fusion Engineering and Design
[11] A.DUROCHER et al., Infrared images data merging for plasma facing component inspection, proc. of 24th SOFT (2006) Warsaw-Poland, to be published in Fusion Engineering and Design.
[12] S. FOUQUET et al., Acceptance criteria for the ITER divertor vertical target, Fusion Engineering and Design, Volume 81, Issues 1-7, February 2006, Pages 265-268
[13] E. D'AGATA et al., Behaviour of the PFC tiles on the ITER divertor under critical loading conditions, Fusion Engineering and Design 66-68 (2003), pp. 329-334
[14] R. MITTEAU and al. Power exhaust and edge control in steady state Tore Supra plasma 19th, IAEA Fusion Energy Conference, Lyon (France), Oct.14-19, 2002
[15] X. COURTOIS et al., In-Situ Monitoring of Actively Cooled Plasma Facing Components Using Acoustic and Thermal Methods, proc. of 11th PFMC Greisfwald Germany (2006), to be published in Physica Scripta