High heat flux actively cooled plasma facing components development, realization and first results in Tore Supra

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The development, design, manufacture and testing of actively cooled high heat flux (HHF) Plasma facing components (PFCs) has been an essential part of the Tore Supra programme towards long powerful tokamak operation. The Tore Supra PFC programme has culminated in the installation and operation of a toroidal pump limiter, since 2002, which already allowed to reach new world records in steady state operation (1GJ injected in a 6 minutes discharge). The HHF PFCs development and manufacturing was achieved through a long lead development and industrialisation programme (about 10 years) marked out with a number of challenges. The major technical topics cope with bonding technology analysis involving an adequate material selection and procurement, repair processes development and implementation, development of destructive and non destructive testing methods, and more generally industrialisation assessment. All these lessons are relevant to the ITER divertor PFCs manufacturing, although the technical solution adopted for Tore Supra (flat tiles concept) is different from the one proposed for the ITER divertor (monoblock concept).

The routine operation of the actively cooled toroidal pumped limiter (TPL), capable to sustain up to $10MW.m^{-2}$ of nominal convected heat flux, is described. Up to now, the limiter fulfills its objectives in terms of heat exhaust. However, the thermographic monitoring exhibits unexpected behavior of the surface temperature. Particle exhaust control displays a complex pattern, due to the high fraction of the injected deuterium which remains in the wall. The first experimental results with a full actively cooled wall gives access to ITER relevant information on wall conditioning, hydrogen plasma density and vacuum vessel inventory control, carbon erosion and redeposition and capability of in situ monitoring in a completely actively cooled environment.

1. Introduction

The steady state aspects of tokamaks discharges is still essentially a “terra incognita”. One of the major difficulties is that among the many time constants at stake, most of those involved in plasma wall interaction physical processes are difficult to estimate and could likely be extremely long. Tore Supra (R=2.36 m, a=0.72m) is the first fusion experiment designed for long pulse operation with a high level of additional power (~20 MW, 30s then 1000s) [1]. This requires integrated physics and technology solutions of such components with particular attention to the plasma facing components (PFCs). Indeed, the full integration is a very demanding process, involving complex R&D, an industrial manufacturing route and specific implementation requirements for the system to be installed inside the plasma vessel. The first generation of high heat flux actively cooled plasma facing components exhibited some weaknesses that were due essentially to the difficulties encountered in joining carbon to a metallic substrate [2] ; this was even more difficult when more complex designs had to be implemented [3]. A new project (so-called CIEL for Internal Components and Limiters in French) was launched to install a new generation of reliable high heat flux (HHF) Plasma Facing Components (PFCs), based on hardened copper alloy heat sink structures covered by a carbon fiber composite (CFC) armour, able to exhaust large enough power. This resulted in a state of the art actively cooled high heat flux component, the so called finger element, which is able to handle up to 10 MW/m^2. A schematic representation is displayed in figure 1. In the framework of CIEL project, about 600 of such high performance parts have been manufactured to build the 7.6 m^2 Toroidal Pump Limiter (TPL) [4]. This assembly has been operated in Tore Supra since Spring 2002, strongly contributing to a new world record of a 6 min. long discharge, involving the injection of more than 1GJ [5].

In spite of a well defined R&D programme, and a robust design [6], some difficulties occurred during the manufacturing phase, resulting in delivery delay. The experience gained is a unique input for the fusion community and is summarized in section 2. It especially stresses the importance of the R&D, including test facilities availability and development, but also the attention to be paid to material specification and to industrial relationship. Obviously this effort aims at the access to the integrated physics of long discharges: this paper will address in section 3, the heat flux monitoring and control issue but also the progress made in our understanding of the deuterium retention in long discharges in conditions which are partly ITER relevant.

2. Lessons to be taken from industrialisation

a. The Tore Supra programme aims

By developing a unique capability to run long plasma discharges , Tore Supra yields access to a specific technical and physical integration. The supraconducting toroidal field is obviously the basis of this integration and the magnet has proved to work satisfactorily since the operation beginning [7]. In tokamaks, the second essential tool is the capability to non inductively drive the plasma current : this is achieved on tore Supra by lower hybrid current drive, the actual limitation being the actual available power, which results in a plasma current limitation at 0 loop voltage of about 0.6 MA. The CIMES project will allow a strong extension of the device capacity [8]. At the first step, 0 loop voltage plasma will be reached at higher values of the plasma current,, allowing to approach edge safety factor values q of about 3. A second step will eventually give access to another scenario class at higher densities approaching the Greenwald density, for which a significant part of the plasma current will be produced by bootstrap. This will also involve the capability to continuously inject about 10 MW of Ion cyclotron resonant Heating (ICRH).

A third element had to be implemented and Tore Supra developed actively cooled plasma facing components (PFCs) from the very beginning, as achieving long plasma discharges require the in-vessel integration of such PFCs,. A high pressure water loop, so called 'B30' (3 MPa at 150 C) is devoted to the cooling of Tore Supra PFCs. The first generation plasma facing components main limitations stemmed from the difficulty to produce them without a significant number of faulty tiles; the techniques used to join the carbon substrate to the metallic heat sink, i.e. brazing, proved to be unreliable at an industrial level. [3]. Operational limitations may even be more stringent in view of unforeseen peaked heat deposition. Note that for long discharges, unavailability of adequate density control resulted in another (radiative) energy limit due to heating of uncooled part of the inner vessel (20% of its area) and consequently water desorption [9]. A new project should provide a reliable HHF component and a complete coverage of the vacuum vessel with actively cooled elements.

b. The CIEL Project description and R&D

To accommodate the total power, i.e. about 20 MW, a corresponding heat exhaust capability has been implemented through the CIEL Project. The CIEL project consists in a set of new, high technology plasma facing components able to exhaust 15 MW of convected power on the TPL (peaked flux up to 15 MW/m2). Moreover, the concept of the TPL associated to radiative power (10 MW) induced by long plasma discharges up to 1000 s, led to a complete re-design of the inner vessel protection by adding a set of water cooled panels, covering as much as possible (98%) the inner wall of the vessel in order to protect it against thermal radiation. The necessary gas flow rate to be extracted (4 Pa m^3 s^{-1}) in order to ensure the particle control during long pulse is pumped using turbomolecular pumps. The permanent control of PFC's surface temperature all along the discharge is performed by a set of six actively cooled infrared endoscopes. The CIEL project was designed in order to provide a reliable High Heat Flux (HHF) component and a complete coverage of the vacuum vessel with actively cooled elements. The HHF proved to be the most challenging item by far. When considering the difficulties encountered with the previous HHF PFCs of Tore Supra, efforts were devoted to improve the elements design and to find an alternative to brazing. This endeavour finally was a flat and modular element, the so called "finger". The second involved a R&D effort, for which the industrial input became essential. A new concept developed by the Plansee Co. in 1995 through a CEA R&D contract aimed at performing a HHF component with a structural hardened copper alloy heat sink (CuCrZr) : the surface of the CFC tile to be joined is laser treated to obtain micro holes that increases the bonding surface and links better the copper to the CFC. Molten OFHC copper is casted onto the tile surface and then machined to form a 2-mm thin interface layer. This concept was called Active Metal Casting (AMC©) [10]. Each individual tile is controlled by X-ray process before its assembly to the heat sink. The 21 tiles (composite element CFC/copper) are then electron beam welded to the heat sink. Other more conventional operations are still needed, such as coolant channels deep drilling, and joining the hardened copper structure to stainless steel pipes. The full R&D effort lasted 5 years from 1992 to 1996 when successful prototypes could be produced.

The development of such components requires qualification tests in a high heat flux facility. For this purpose in 1991 in collaboration with the NET team, CEA and Framatome Co. developed a 200 kW electron beam facility, named FE200 [11]. The testing campaigns were mainly devoted to thermal hydraulic tests (critical heat flux study) and to fatigue tests. Another development proved to be essential : a major acceptance test. It consists of an infrared thermography aiming at controlling the interface quality between tiles and heat sink. This test involves transient thermographic measurements on the so called SATIR test bed developed at CEA in 1994 [12] when a hot water followed by a cold-water flow in the heat sink cooling channel induces surface tile temperature time evolutions which witnesses the thermal transfer quality from the water to the surface. Any large enough mechanical and thermal defect can be detected. Correlation between high heat flux and SATIR tests has proved to be satisfactory but will need improvements, both practical and conceptual, since the future acceptance tests should be based on a realistic appreciation of the HHF PFC operational specification and since the measurement is very sensitive.

c. Toroidal pump limiter manufacturing

The TPL elementary components manufacture (600 'standard' and 60 'neutraliser') was launched in 1997. The two first batches (100 elements) were delivered in June 1999. The ratio of accepted elements based on thermal criteria for each tile (developed by CEA on the SATIR test bed) was as high 95%.The increase of tile failures was observed both by CEA and the manufacturer on following batches (40% of rejected elements). As each finger element is composed of 21 tiles, the individual tile failure rate is indeed much lower (~3%). This increase has led to many investigations in order to understand the defects [13], and to some delay for the full limiter completion. However, the manufacturing resulted in an achievement by end of 2001.

d. Major issues and lessons

Meeting the HHF PFC challenge requires the implementation of "extreme" techniques and materials. As far as the latter are concerned, the rather recent progress result in much better capability but also in a relative lack of knowledge concerning the material specifications and involved techniques. Even when the information is accessible, it may not be easy to lead to effective implementation. In addition, the material supplier are scarce and the manufacturing process may be complex and long, limiting their ultimate availability. Both used specific material (CFC and CuCrZr) proved to provide specific difficulties.

The CFC material has a complex manufacture route and is found to display rather inhomogeneous characteristics, once delivered : the scattered values of the strengths together with variability of the density can lead to unexpected faults in the bonding process results [14]. Two different CFC-N11 fabrication batches were used for the TPL, with significant different mechanical and thermal material properties, so as to influence the attachment quality of the tiles.

Electron beam (EB) welding of CFC/Cu AMC© tiles induces high stresses at the bond, that could lead to cracks that appear mainly after welding in the CFC close to the bond. Margins concerning the reliability of the EB welding of AMC© tiles have to be increased, in order to integrate the likely inhomogeneity of the CFC mechanical properties. More generally CuCrZr is far from a conventional material ; much remains unknown in terms of material and manufacturing process specifying, i.e. component design (in particular weld joint configuration/flexibility) and detailed material composition ,mechanical properties, grain-size and manufacturing route. Component manufacturing procedures such as material condition during welding need to be carefully checked and then monitored [15]. This should obviously be verified by testing full-scale prototypes, and not only mock-ups. Eventually, the definition of EB homogeneous welding criteria for CuCrZr alloy would help but implies a long term research effort, that will prove valuable if this material is extensively used in future fusion devices such as W7-X [16] and ITER.

The development of a repair process appears highly valuable in response to the many difficulties and uncertainties which are described above. This might be considered early in the design phase, in order to avoid unacceptable delays and/or costs. The TPL finger element design allowed the replacement of flat and/or leading edge tiles. A new electron beam process was developed by the Plansee Co.

in order not to damage adjacent well bonded tiles during the EB welding of the replacement tiles. Thanks to this repair process, the last batch of TPL elements was finally delivered on site at the end of 2001, with a delay of ~1 year when compared to the expected CIEL project schedule.

In addition to these numerous technical elements, it clearly appeared that adequate relationship with the industrial partners is also a challenge, which definitely needs to be met. This of course relies on an in depth quality management. However, the close collaboration between supplier and customer proved to be essential during manufacturing in our case. The R&D and industrialisation phases provide specific challenges in this specific relationship. In our case, our rather good technical preparation (early definition of acceptance criteria, anticipation of the quality control needs, involvement validation of manufacturing processes), were essential in forging the success.

3. Specific plasma wall interaction physics in Tore Supra

Among the major objectives of the CIEL project, a strong priority was given to the TPL surface temperature monitoring control and safety. Another specific field of interest relates to the active particle control in steady state. In addition to the pumping system, conventional gas fuelling system and advanced ones such as pellet injection were implemented [17].

a. Infrared thermography system implementation

The infrared thermographic system has been designed in order to monitor the whole TPL surface (7,5 m², 15m long) and the 5 additional heating antennae [18]. A set of 7 infrared actively cooled endoscopes, are equally spaced around the torus. The measured spatial resolution is ~ 9 mm, which is to be compared with the width of the smallest element constituting the TPL, 20 mm. Each endoscope, is equipped with 3 viewing lines, two for 2 TPL sections of 35° (including a 5° crossover), and one line for one antenna. Each viewing line involves more than 30 optical elements, while the external tube is cooled with the same pressurized water as the PFCs while the internal part supporting the relay lenses is also actively cooled by another water loop at 25°C. Thus, the error bar affecting the blackbody temperature measurement is estimated to be < 10% even at low temperatures 100°C. Note that the temperature range is pretty large from 100 to 1500C, thanks to the development of controlled exposure time of the camera IR detector. Along with this new set of digital cameras, a feed-back and safety system is being implemented, which will allow to use in real time calculated criteria from the temperature images to react on the plasma.

A fibre system observing the neutralisers was also developed [19]. It uses optical fibres either made of silica transparent up to 2 µm or by ZrF_4 fibres transparent up to 4µm. The measurement is done for all fibres simultaneously with a focal plane array infrared camera of a sensitivity range of 1-5 µm with about 30-50 independent measurement points per fibre covering the spectral range 1-4 µm and 15 – 20 points per fibre in the 1-2µm range.

b. Surface temperature measurement interpretation

Heat deposition on the TPL was very early calculated based on a simple model where the flux decreases exponentially in the scrape off layer with a characteristic length depending of the square root of the connection length of the field lines from the limiter to the limiter. This was implemented in the Tore Supra geometric configuration using the TOKAFLU procedure[20]. On Tore Supra , the magnetic field ripple induces important zones of “self shadowing”, i.e. with very short connection length, and consequently nearly 0 flux. They can be easily seen on figure 2 a, where the expected flux is shown on one TPL sector. Figure 2 b displays an infrared image of the same sector. It may be easily recognized that if the overall pattern (mainly the private flux regions) can be identified, it is much more tricky to relate the high heat flux zones. This stems from the presence of deposited materials on the limiter surface (see figure 3). Those “deposits” may correspond to various forms. Some “dust” appears in the form of sub-millimetric flakes ; it is in large part not well attached to the surface. But one can also find hard layers on each side of the tiles. The two varieties of deposits are mixed up. Note that in both cases, the deposit grows in areas displaying some kind of shadowing from the plasma.

Quantitative infrared measurements are in good agreement with the presence of deposits. The thermal time constant, which can be easily derived from situations where the power flowing to the limiter is rapidly decreased, appears in such locations to be about 0.2 - 0.5 s, significantly shorter than the element expected one, typically 0.7-1s.

The deposits thermal behaviour modelling can be achieved along 2 main lines : either isolated, layer with a purely radiative cooling, corresponding to the loose dust, or a conductive layer, corresponding to the hard layer. In the first case, the dust temperature reaches a value determined by its radiation. The second case introduces a thermal resistance compared to of a regular structure. A general remark is that, in both cases the deposit leads to higher surface temperatures than expected. The thermal time constant does not allow to discriminate the cases to lead to the incident heat flux or to evaluate the possible over-estimation. However, the location of the deposits can be expected and checked by experience since the erosion and deposition could be clearly determined when the edge plasma characteristic are known [21]. The spatial resolution allows to determine the tile centre temperature, which should not exhibits such deposits.

Another difficulty may arise from the “non blackbody” character of the IR radiation emitted by the carbon surfaces. This could be studied by using the IR fibres described above. The measurement in the 1-2µm range led to temperature values much higher than expected. This could be linked to the growth of deposits on the TPL neutraliser plates [22]. However, the spectrum measurement indicated that it did not exhibited the foreseen Planck law shape. Measurements achieved in a wider bandwidth (1-4µm) led to interpretative model where hot spots, likely due to the carbon roughness under plasma sputtering, plays a role [23]. However, measurements at higher wavelength may largely alleviate such problems.

c. TPL performance in Tore Supra

The experimental campaigns which have been carried out in Tore Supra since the complete upgrade of all plasma facing components, proved that the TPL allows reliable steady state operation at significant injected power (up to 9.5 MW peak, 6 minutes at 3 MW). The surface temperature remains constant (the thermal time constant being about 1s) at a relatively low temperature (about 540 K for the above quoted longest discharges) due to the low CFC thickness. Figure 4 shows that the average surface temperature varies as expected.

A simple 1D thermal calculation tool linked to the database has been developed and is used to allow flexible analysis of the ageing of the bond between the tile and the metallic cooling structure from the surface temperature measurement [24]. So far, no evidence of ageing has been observed after the three first years of operation. It gives confidence in the bonding technology used to manufacture the high heat flux components of Tore Supra.

d. Deuterium retention in the Tore Supra plasma facing components

Particle control still remains a major concern in view of ITER. This generally addresses two major issues. The first one is erosion, which can hardly be studied on a macroscopic scale in Tore Supra. The other one deals with retention of hydrogenic species in a carbon-dominated device. A major asset of the experiments in Tore Supra stems from the full active cooling of the plasma facing components, as it allows both achievement of long discharges, thus exceeding some first order limits (see below), as well achievement of those discharges in conditions where the components' surface temperature remains constant. This appears to considerably ease the interpretation of the experiments which are generally much more complex, if one should include surface temperature effects playing a prominent role in primary processes such as carbon chemical sputtering, or deuterium desorption.

A major finding from all the long discharges in Tore Supra, with duration exceeding 2 minutes is that a constant build up of the deuterium vessel inventory, independent of previous conditioning or discharge history [25]. This phenomenon is studied with very reliable particle balance based on pressure measurements : it seems to be very robust, and depends only slightly on the gas fuelling method. In the long discharges, for which the operational window is actually very narrow due to the low current drive capability now available, the injected fuelling rate amounts to about 2 10^{20} s^{-1}. From this, about half is finally pumped during the discharge, while the rest is “buried”. Figure 5 displays the D flux retained in the wall during 3 long discharges. Two phases have been identified in the time behaviour of the trapped particle flux (see figure). In the first phase (up to 100 s), it decreases (from 4 10^{20} D s^{-1} to 2 10^{20} D s^{-1}), and in the second phase, remains constant throughout the pulse, with a typical value of 2 10^{20} D s^{-1}, showing no sign of wall saturation even after more than 6 minutes. The wall inventory then becomes simply proportional to the pulse duration. The highest value reached so far is 7.8 10^{22} D, out of which the excess trapped during the first phase (corresponding to the hatched area on the figure) is around 5 10^{21}. One could relate this to a codeposition (C + D) mechanism. However, it is extremely difficult to find a physical situation where the amount of carbon needed is sputtered, neither to find post mortem deposits which could completely support this hypothesis. It is why, other phenomena are envisioned, such as pore retention.

On shorter time constants (typically the first 100s), an additional loss term is recorded which is likely linked to implantation up to saturation on areas accessible to both ion and charge exchange neutral flux.

It is worthy to note that Tore Supra long discharges yield access to this long time constant phenomena, while surface conditions might anticipate the one in ITER ,especially for the actively cooled plasma facing components.

4. Conclusions

A continuous R&D and industrialisation undertaking led to the achievement of a reliable high heat flux component in Tore Supra. This is a significant step before implementing similar component in W7-X and ITER. This industrialisation achievement involved a capability to accurately specify materials and define intermediate and final acceptance criteria and to develop a repair capability, but also to well consider the involved contractual and managerial aspects, so as to possibly a adequate relationship during the manufacturing. The further anticipation of problems encountered within the CIEL project will ease the realisation of the future PFCs manufacturing.

The toroidal pump limiter appears to behave satisfactorily during the Tore Supra operation, albeit at about 50% of its heat exhaust capability. A straightforward assessment of its surface temperature and even more of the impinging plasma heat flux is complicated by the actual properties of the carbon surface. However, the understanding of the involved mechanisms is in progress.

The implementation of actively cooled plasma facing components and long discharges allow to address specific questions such as C erosion and D retention in ITER (partly) relevant conditions. Continuous D retention, is given evidence ; codeposition has been investigated to explain this but appears only a marginally reason. Other more involves processes should then be pursued. However, in situ control diagnosis (heat exhaust, deuterium retention) remains still challenging.

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Figure Captions

Figure 1 : Break up view of the “finger” element of the Tore Supra toroidal pump limiter stressing the material assembly.

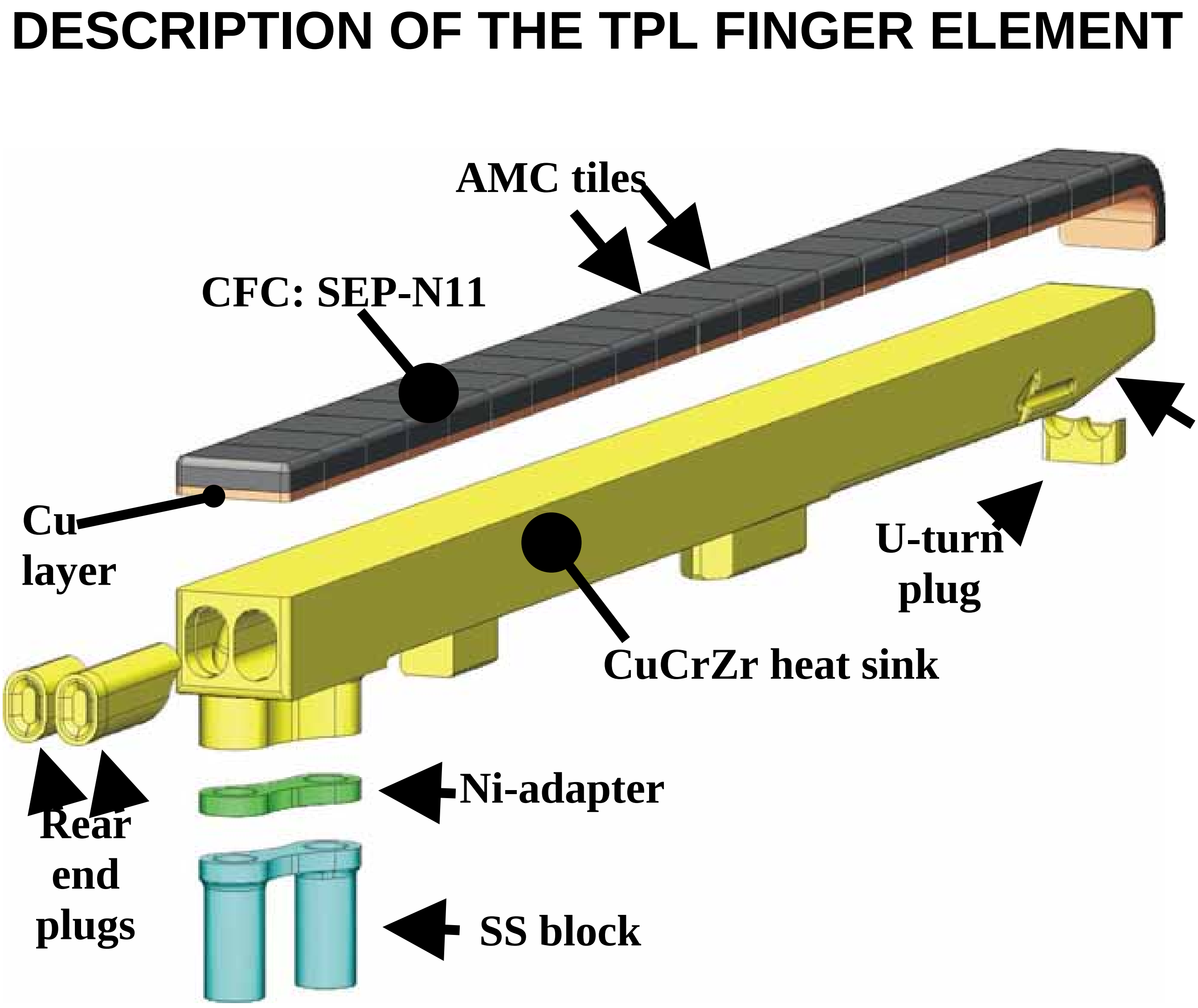
Figure 2 : Comparison of the expected TPL surface temperature (TOKAFLU calculation) (top: a)with the actually measured one for a 35° sector (bottom : b): “distortions” are mainly induced by the deposited materials

Figure 3 : In vessel view of the TPL exhibitingthe two types of deposited material mentioned in the text

Figure 4 : Averaged tile surface temperature as a function of injected power align along the TPL design line.

Figure 5 : Dynamic wall retention rate calculated from particle balance for 3 successive long discharges in Tore Supra

Figure 1



DESCRIPTION OF THE TPL FINGER ELEMENT
AMC tiles
CFC: SEP-N11
Cu layer
U-turn plug
CuCrZr heat sink
Ni-adapter
Rear end plugs
SS block

Figures 2a and 2b

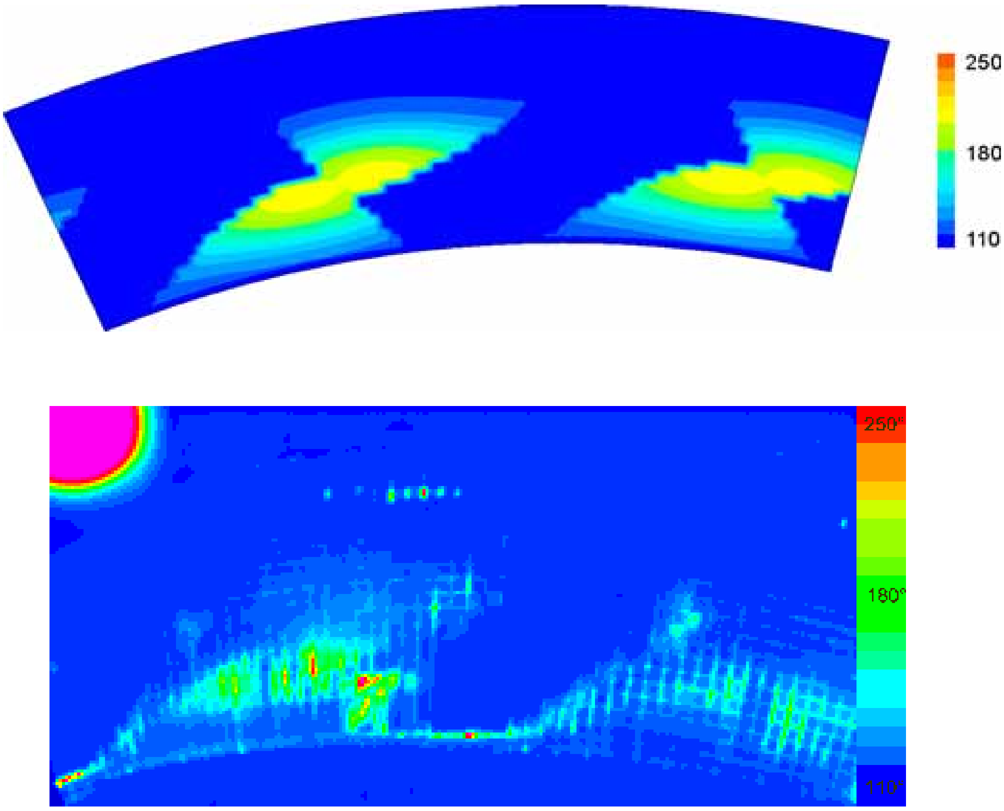


Figure 3

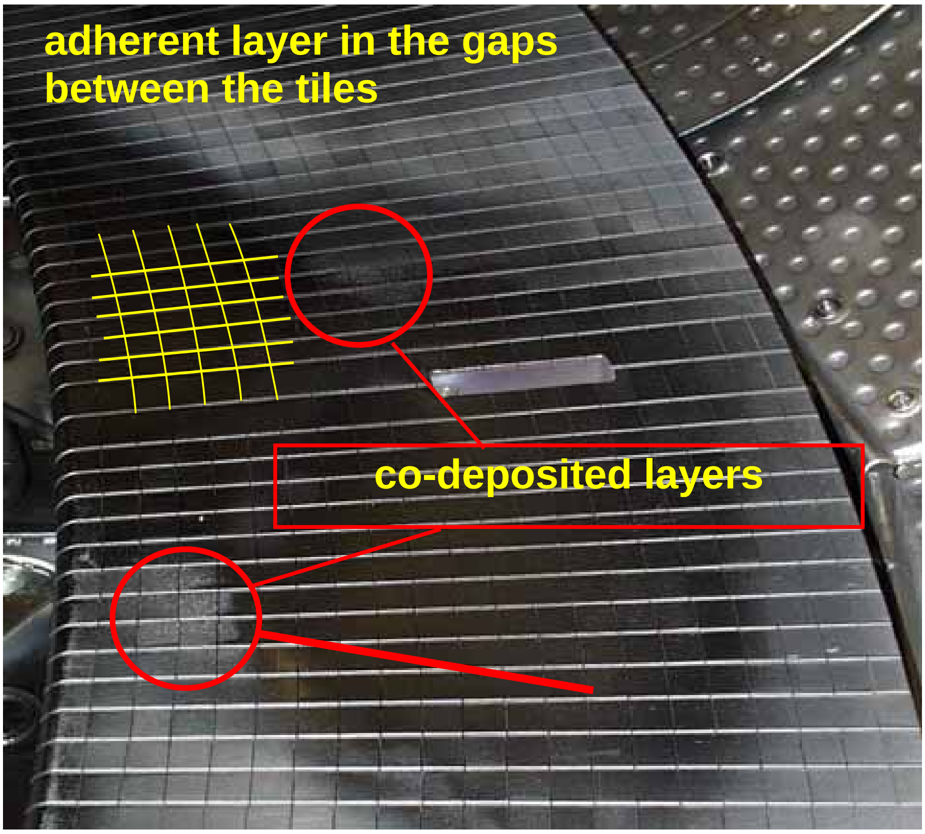
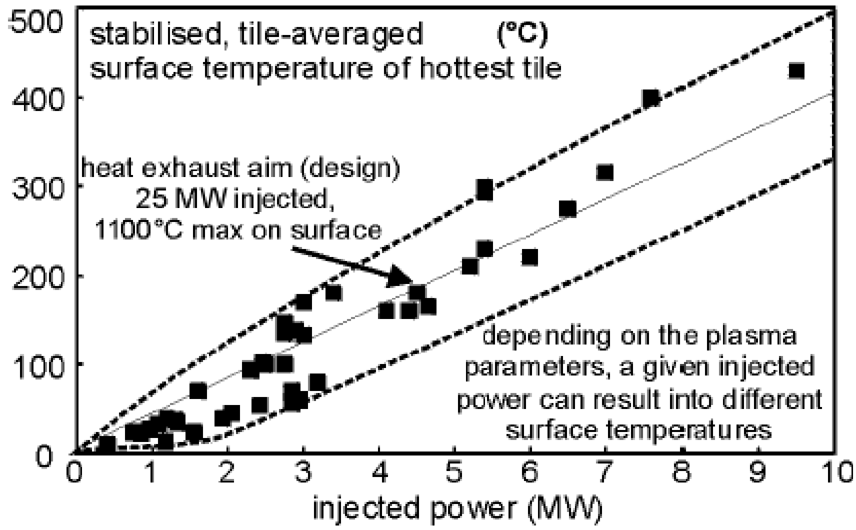

adherent layer in the gaps
between the tiles
co-deposited layers

Figure 4



stabilised, tile-averaged (°C)
surface temperature of hottest tile
heat exhaust aim (design)
25 MW injected,
1100°C max on surface
depending on the plasma
parameters, a given injected
power can result into different
surface temperatures
0
100
200
300
400
500
0 1 2 3 4 5 6 7 8 9 10
injected power (MW)

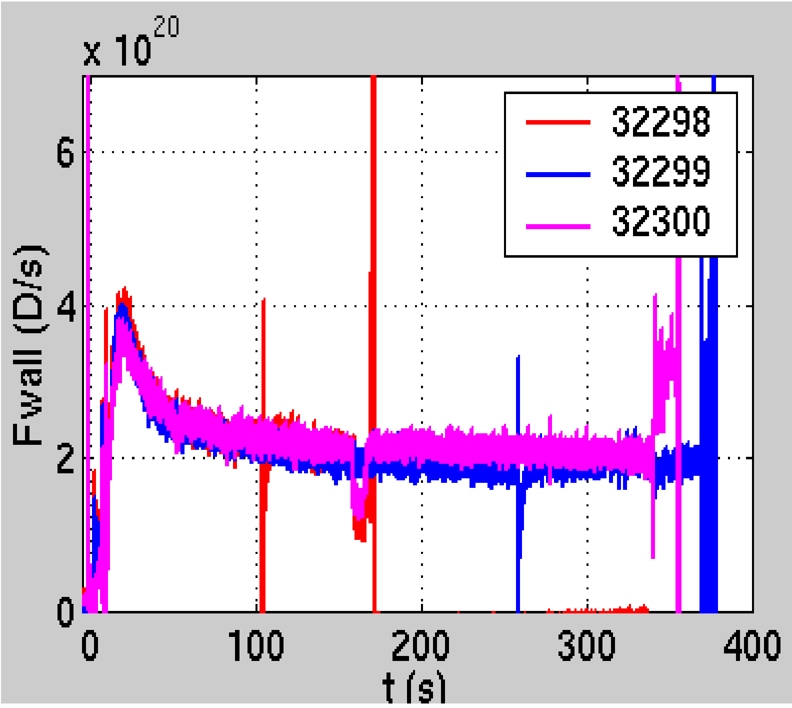


Figure 5