

Power Exhaust and Edge Control in Steady State Tore Supra Plasma

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Abstract. Tore Supra is operated since 2001 with a toroidal limiter designed to remove continuously a heat power of 15 MW at a maximum (ITER relevant) heat flux density of 10 MW/m². The limiter is located in the bottom of the vacuum vessel and is actively cooled by a pressurised water loop. For an injection of 6 MW of additional power, the limiter extracts 3.6 MW and the surface temperature stabilises typically at 400°C in 5 seconds during discharges lasting up to 260 seconds. The maximum heat flux density reach 3 MW/m² which is still modest compared to the design value, but nevertheless enables a comparison to the modelling. Heat flux and deposition pattern are in very good accordance with design simulations. Additional heat load concentrations specific to radio-frequency heating superimpose to the convection heat load at levels that are commensurable with the elements thermal capability. Insights on the tiles behaviour are given. Operation with such a large size high heat flux component sets an renewed emphasis on issues such as feed back systems, active security, cooling parameters and in situ assessment of the elements. These issues are dealt with in this paper.

1. Introduction

The Tore Supra tokamak has been designed from the very beginning for long pulse operation (super conducting toroidal field coils, actively cooled plasma facing components (CFP), quasi steady state additional heating allowing for fully non inductive current drive). Drifting density during previous long discharges and limited performance of the CFP during high power operation led to the CIEL project (French acronym for Composants Internes Et Limiteur) aiming to overcome these issues [1]. Operation re-started in 2001 after a complete replacement of all internal CFP [2]. The whole chamber is now protected with a new generation of actively cooled components with a more than 99% coverage of the vessel (Fig. 1.).

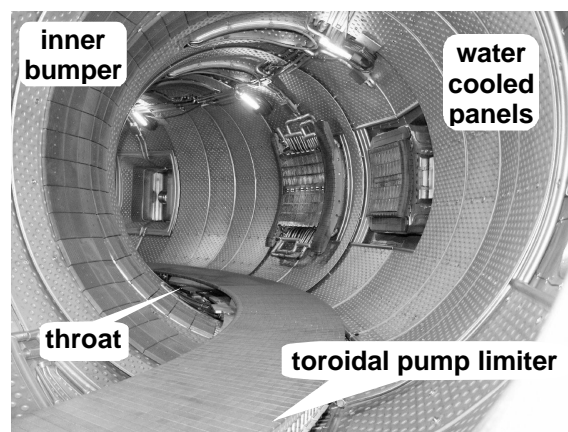


Fig. 1. Photo of the actively cooled first elements installed in Tore Supra.

The main active plasma facing component is a toroidal pump limiter (TPL) located at the bottom of the vacuum vessel. The choice of a toroidal limiter was dictated by the circular cross section of Tore Supra vessel, which reduces exaggeratedly the interest of an axisymmetric divertor. The geometry of the toroidal limiter is best suited to sustain the plasma power

because of the shallow impinging angles on the whole surface ($<5^\circ$) but still result in heat flux densities of the order of those expected in ITER (5-20 MW/m²).

The TPL has a throat and a leading edge on the high field side (ion drift side) allowing pumping. The flat surface is favourable for the easiness of fabrication nevertheless completion of the fabrication while maintaining a sufficient quality standard proved a daunting task. The limiter is made of 574 high heat flux elements (the fingers, [3]) which are the result of more than 10 years of developments that culminated in the creation of the active metal casting (AMC) bond by the Plansee society (Austria). The limiter is covered with carbon fibre composite (CFC) tiles. The cooling is ensured by a water loop at 120°C and 2.4 MPa. The limiter was partial in 2001 (start-up limiter) with three 30° sectors at every 120° in the toroidal direction, terminated by large thermally inert tiles. It has been since then completed to a total annular ring. The TPL is movable between shots. Target neutraliser fingers are located beneath creating a plenum space communicating with the pumps. At two toroidal locations on the limiter, one finger is replaced by two larger ones with a slit in between allowing for optical diagnostics to cross over the plasma.

Other secondary components deeper in the scrape off layer are installed to protect specific elements : the inner bumper (runaway electrons during disruptions), the inner vessel protection (radiated heat flux and charge exchange), ripple protections (electronic ripple losses toward the top of the vessel) and an outboard limiter (runaways on antennas protection for start up and end phase and retractable in between). These components are not described here.

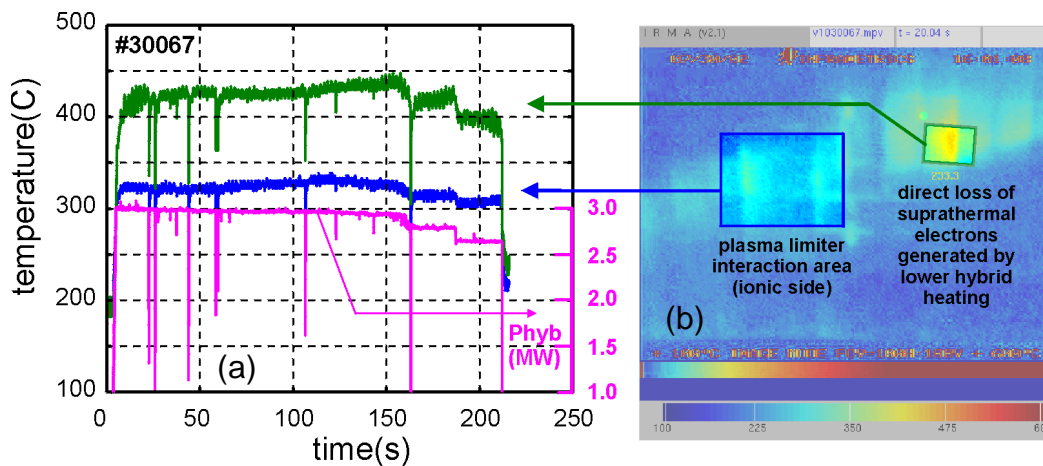


Fig. 2a. Time evolution of TPL surface temperature. 2b. infrared view during the shot #30067 at 20s

Working with actively cooled components is a permanent challenge against temperature. The aim is to retrieve continually the heat power in the coolant. This is illustrated Fig. 2. for a 3 minutes 40 seconds long discharge. The maximum surface temperature extracted from the blue rectangle stabilises here at 330°C (green rectangle is dealt with in §3). The short thermal stabilisation time of the order of 5 seconds is observable at the beginning and at the end of the pulse. Short breakdowns of the lower hybrid (LH) power are immediately visible as negative spikes of the surface temperature cooled by the structure.

Off normal events are a main concern with actively cooled component. Armour tiles are thin (6 mm for the TPL) so that a not too high thermal gradient builds up in the tile : this allows reasonable surface temperature ($<1100^\circ\text{C}$) in steady state which are favourable with regards to mechanical resistance and sputtering. However, the drawback of thin structures is their poor ability to store unexpected amount of thermal energy during off normal events. In such cases, the components may undergo some damages such as surface melting or crack propagation in the heterogeneous bond. The off normal events encompass a large variety of phenomena : disruptions which can lead to runaways electrons, ripples losses of trapped particles may focus on a small area, direct loss of suprathermal electrons etc...[4]. Plasma scenarii and

experience tend to minimise such events, but of course they still occur in tokamaks where a large operational window is explored. Because of the dramatic consequences [4], the operation aims at a as good as possible control of the edge, particularly from the point of view of the heat fluxes. The "control" encompasses mostly that of the edge knowledge, particularly of heat fluxes : how the power distributes among and on the components, how to avoid excessive heat fluxes from the design of the scenarii. When the knowledge is insufficient, the operation goes toward feed back control, and a real time feed back loop based on the surface temperature measure can trim the additional power before damaging the components.

2. Heat flux monitoring and associated diagnostics

The control of the heat flux on the components raises the need for diagnostics that are devoted to this task. The ambiguity appears between systems favouring the security (simple, robust, straightforward interpretation, non parametrable, production of data easily injectable into the feed back control loop) and systems favouring a wide analysis of the physics (versatile, less stringent requirement on the robustness). Some weight is put on "non plasma" diagnostics such as infrared cameras and calorimetry, which are investment preserving systems for the high cost actively cooled elements. They are described shortly hereunder.

2.1. Infrared cameras

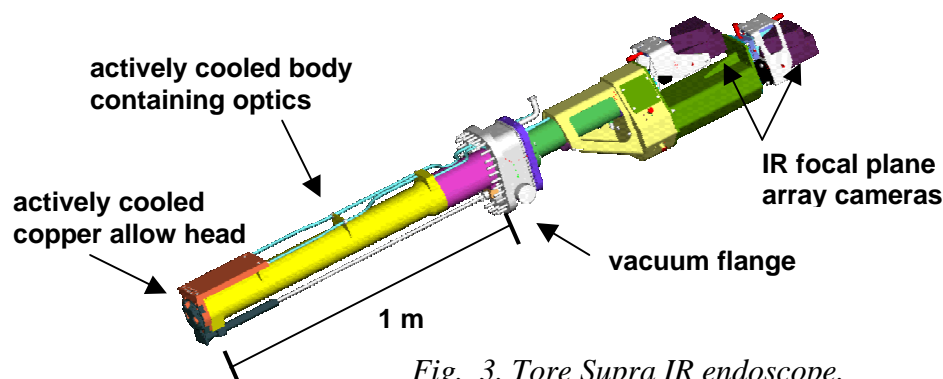


Fig. 3. Tore Supra IR endoscope.

A new infrared endoscope has been developed and is now in operation on Tore Supra (Fig. 3). The body is actively cooled and contains a second separately cooled body at room temperature hosting three optical channels that transport the images out of the vessel. The camera is a infrared focal plane feeding a fully numerical acquisition system. 60° toroidal degree of the TPL are observed after reconstruction of two channels and an ICRH antenna or LH grill are observable [5]. A full coverage of the TPL with 6 endoscopes is aimed at. Feed back function were accounted for from the beginning of the project, by sending the maximum temperature of predefined areas into the control loop.

Conventional infrared scanner cameras were also installed with 3x telescopes to monitor a reduced portion of the TPL and three antennas (2 LH grills and one ICRH antenna). The field of view on the TPL is 270*200 mm², allowing to observe 7 tiles on 12 fingers, including the leading edge. The spatial resolution on the limiter surface is 4 mm which allows to distinguish individual tiles. This limited IR diagnostic was enough to start the limiter but going to higher power will require more coverage by new endoscopes.

Infrared cameras authorise feed back control on the surface temperature of the components. This was already demonstrated in 1999 [6] and again in 2002. This function was used during the long pulse discharges. Surface temperature limit was set at 500°C with a first triggering of the modulation of the LH power at 470°C, but it never had to operate.

2.2. calorimetry

The calorimetry of the cooling loop is based on 47 flowmeters and 128 platinum temperature probes, some being installed in pipes inside the vacuum vessel [7]. The imposed constraints makes these probes a technological challenge on itself (overall dimensions, vacuum tightness). The number of probes allows a spatial resolution component per component, and even module per module for the TPL and the inner vessel protection. A limited redundancy allows for cross checking. Calorimetry is a diagnostic which precision can be tuned : reducing the flow (into limits constrained by the CFPs security) increase the water temperature rise during the discharges, improving the signal to noise ratio. Trim experiments were carried out at a reduced regime to benefit from a maximum precision, and the final setting of the TPL toward the magnetic field was set according to these measures (less than 1 millimeter discrepancy to geometrical triangulation).

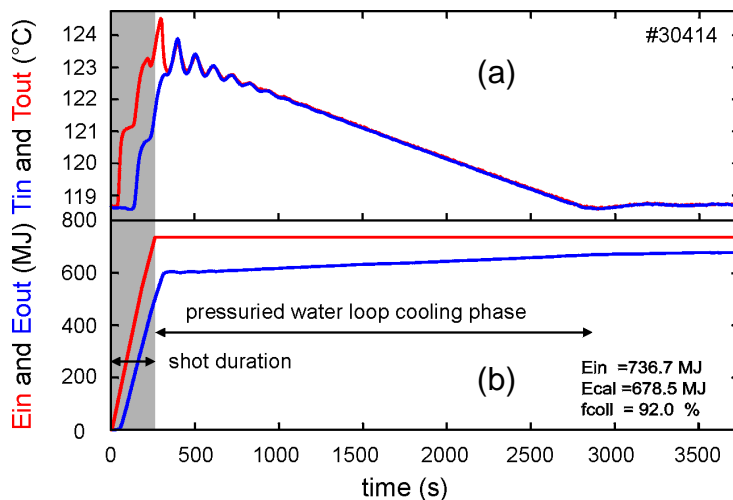


Fig. 4. (a) Inlet and outlet temperature during 4 minutes 30 seconds record discharge, (b) Energy injected in the plasma and extracted energy from the internal elements.

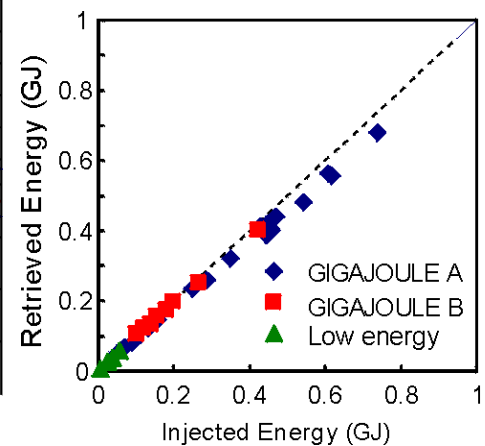


Fig. 5. Energy injected in the plasma versus extracted total energy from the internal elements.

Input (in blue) and output (in red) temperatures are given Fig.4a. The loop is a closed circuit with a 80 seconds cycle period so that 3 passages are recorded during such a long shot and the water temperature builds up progressively in the loop. After 260 seconds, the discharge is over and the difference between outlet and inlet becomes very small. At that stage, the majority of the heat power is stored into the water which cools progressively in the external heat exchanger during more than 2500 seconds. The oscillations are a reminder that the water is not homogenous in the circuit, and are damped in the components. Figure (a) shows that 7 cycles are done before the water is fully homogenised in the circuit. Almost one hour is necessary here before the feed back control gets back to the required temperature. (The cooling has since then been enhanced.) 92% of the injected energy are recovered here (Fig. 4b and 5). Integration errors and structural effects may occur on so long periods, explaining the increasing discrepancy.

2.3. fibre monitoring in the near infrared

Neutraliser target fingers located under the TPL share a common behaviour with the TPL fingers. They are even more at risk as they undergo the same heat flux level as the finger tips, added with a enhanced heat flux caused by electrons accelerated in the near field of lower hybrid grills [8]. Although they lie deep in the scrape off layer (>2 cm), the incidence angle

on the tip is high (45°). Their monitoring is complicated because they are underneath the TPL which forbid a direct view from a port. A novel diagnostic based on infrared fibres has been designed, built and installed [9]. The analysis of the data has to account for a progressive deformation of the spectral luminance curve with the accumulation of shots. Effects of thin resistive layers or a semi-transparent wall are investigated.

3. Assessment of the heat flux on the TPL

3.1. Heat flux pattern

The surface temperature pattern observed from the conventional IR scanner is given Fig. 6&7 and is a direct result of the surface heat flux distribution. It results from the cosine law (combination of the impinging angle on the surface with an heat flux exponential decay length) modulated by the ripple of the toroidal field (TF). It has a periodicity of 20° which is imposed by the TF coils (snake skin effect, [10].)

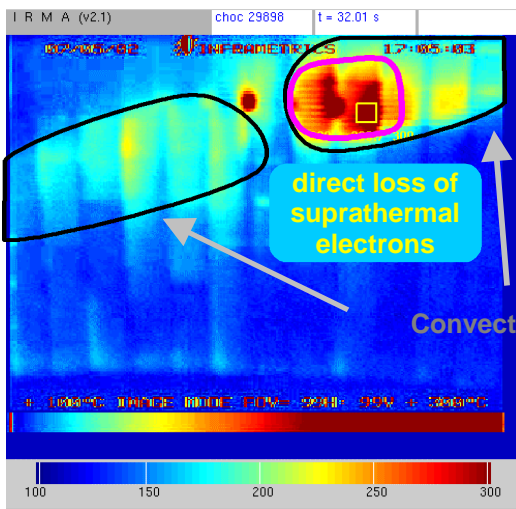


Fig. 6. Heat flux pattern during LH heating.

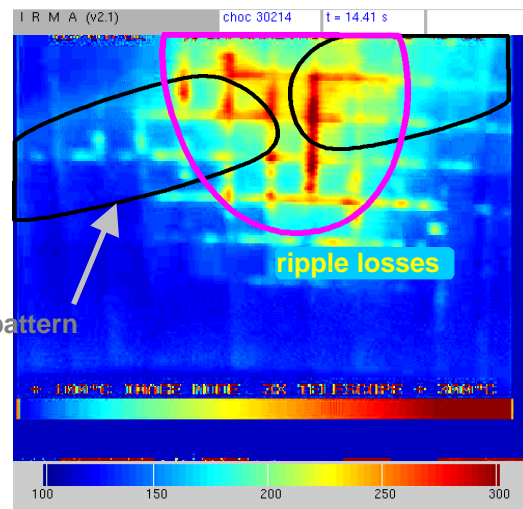


Fig. 7. Heat flux pattern during ICRH heating.

Two heat flux concentrations are observed, one on the ion drift side, the other on the electron drift side. Private flux areas appear on the limiter above the TF coils as the result of a self shadowing phenomenon. They are exposed only to radiation and charge exchange neutrals. This pattern has been obtained previously as the result of extensive modelling [11] and was confirmed during the 2001 campaign. The pattern is the superposition of two components, one "normal" with a heat flux decay length of 5 mm and one short that can be described either as perpendicular heat flux or as parallel with a λ_q to 1 mm. This apparition of a short component is a reminder of axisymmetric divertor [12,13] and was also present on Tore Supra previous main limiter, the inner first wall [14].

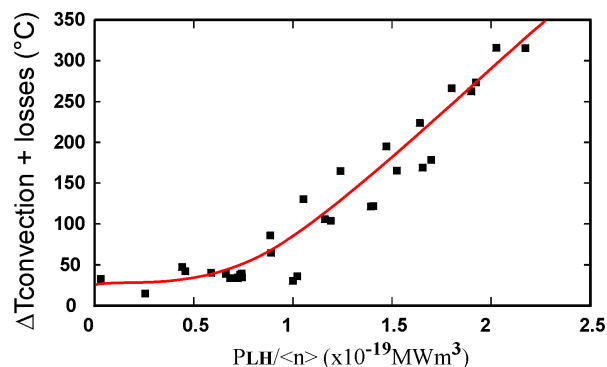


Fig. 8. Maximum surface temperature increase (convection + suprathreshold losses).

Regular use of auxiliary heating in 2002 allow to document the new heat flux patterns specific to RF heating. Shots with LH (Fig. 6) result in a surface temperature pattern that has a similar shape as the previous one, but a additional contribution appears on 4 tiles on the electronic side. The excess heat flux is attributed to fast electrons impinging the wall and was expected at that location [15,16]. The maximum surface temperature increase scales well with the ratio of lower hybrid power to the density (Fig. 8.) and remain at a level that is tolerable with respect to the capability of the tiles. With ICRH auxiliary heating (Fig. 7), the ions ripple losses superimpose to the convection pattern. The surface temperature analysis have to decorrelate the different heat flux patterns which is currently under way.

3.2. Heat flux decay length

The heat flux decay length (λ_q) is measured on the recycling pattern [10]. It was measured to 10 mm on a partial TPL in 2001. **This value was confirmed** by calorimetry during trim experiments which set the modules at different depth in the SOL, and also by the simulated reconstruction of the infrared image where λ_q influences the ratio of the temperature increase between the limiter head and tip.

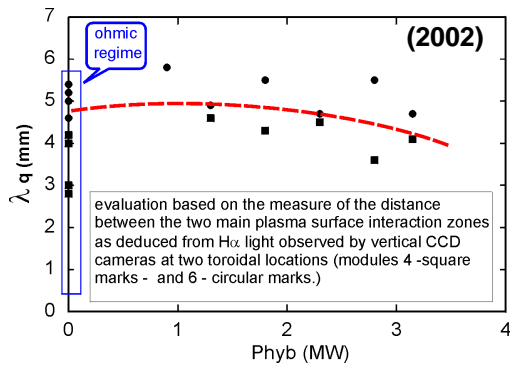


Fig. 9. I_q as a function of LH power on the full 360° limiter.

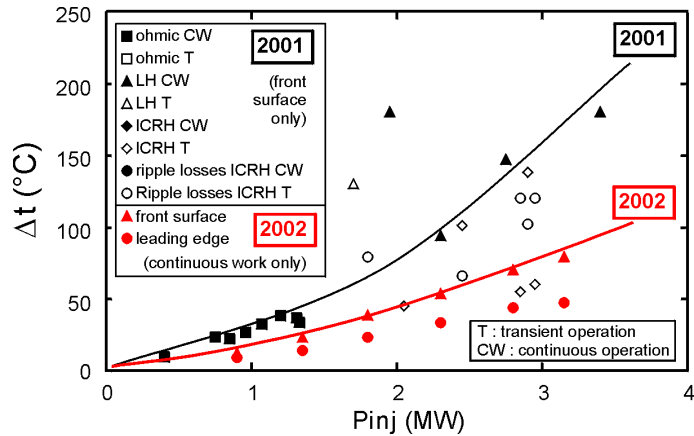


Fig. 10. Average surface temperature increase

The 2002 complete toroidal limiter show a λ_q reduced to 5 mm (Fig. 9.). The 12 modules (whereas the start-up TPL was made of 3) causes a 4 fold increase of the toroidal coverage (and hence the interception of the SOL field line). This corresponds to an equivalent reduction of the connection length. This is consistent with a λ_q reduction of a factor of 2 (λ_q is inversely proportional to the square root of the connection length). λ_q appears almost constant with increasing LH power (Fig. 9). However, the λ_q cited here is specific to the TPL : other evaluations (by fast moving langmuir probes and outboard limiter calorimetry) converge on a value between 20 and 30 mm far from the TPL. The shorter λ_q on the limiter does not however translate into higher stabilisation temperature. The 4 fold area increase between 2001 and 2002 remain dominant, and convective areas surface temperature are smaller (Fig. 10.). Those results gives confidence that the limiter will behave well up to the 15 MW nominal power.

4. thermal behaviour of the tiles and ageing monitoring

The weak points of the limiter, from a thermo-mechanical point of view and in the order of importance, are the tips of the diagnostic fingers, the leading edge of the fingers, the edges of the slit and the leading edge of the neutraliser which represents a whole problem on its own. Safe operation imposes to limit the heat flux on these areas. A variety of rupture modes

caused by excessive heat flux actually exist : debonding of the tile (with or without tile detachment from the metallic structure providing the active cooling), critical heat flux and erosion of the CFC surface. In reverse order of importance, erosion appear the least severe because it arrives progressively. Moreover, it can be kept low by maintaining the working surface temperature under 1100°C . This is achievable as the surface temperature is monitored by IR cameras. Critical heat flux comes in second and is avoided by the setting of the cooling loop parameters. The corresponding design calculations required extensive testing and some hypothesis [17]. More difficult is the assessment of the bond fatigue. Monitoring the surface temperature is not a sufficient criterion to prevent accidents as bond damage can occur (600°C) well below maximum working surface temperature (1000°C for nominal operation, and up to 1500°C for the neutraliser target tips). A first approximation is to link directly the steady state surface temperature increase to the heat flux (contrarily to inertial components, the surface temperature reach a steady state under a continuous heat load). The resulting equilibrium is only a function of the thermal resistance between the surface and the cooling channel. However, the surface temperature pattern reflects mainly the shape of the applied heat flux (Fig. 6., the leading edges of the individual tiles are visible). The right parameter to evaluate the bonds is more probably the **averaged heat flux** passing through it, the averaging unit being there the tile. However, bond thermal resistance (for example created by a localised crack) can in return influence the surface temperature profile so that the link is not straightforward. The other key parameter is the thermal time constant. Longer stabilisation times indicate tiles that are less actively cooled. The non destructive examination (NDE) of the tiles followed that principle (All 12054 tiles have undergone thermal NDE prior to their installation [18] to ensure a correct thermal response under high heat flux). Fig. 11. summarise these properties by giving the thermal time constant and the stabilised temperature increase as a function of the (constant) heat flux and bond resistance. The left axis give the response (temperature versus heat flux) of nominal tiles. With increasing damage, tile progress toward the right of the abacus, the main consequence being longer time constant. Almost inertial tiles are mainly cooled by radiation and have time constants around 10 seconds. So far, all observed tiles stay in the green rectangle and no measurable evolution has been observed. Another issue is the experience feed back of the NDE testing of the elements. The criterion was set at 3°C based on design calculations (a few fingers with reference defects were also manufactured). The level to noise ratio is unfavourable, so that the results of the NDE appear as a statistics : a tile with a given ΔT has a given probability to fail in one cycle at 10 MW/m^2 . Around 6.5°C , this probability approaches 1. Operation in the machine is an opportunity to feed the statistics and decide whether some elements slightly above the design criterion need replacement before going to high power operation.

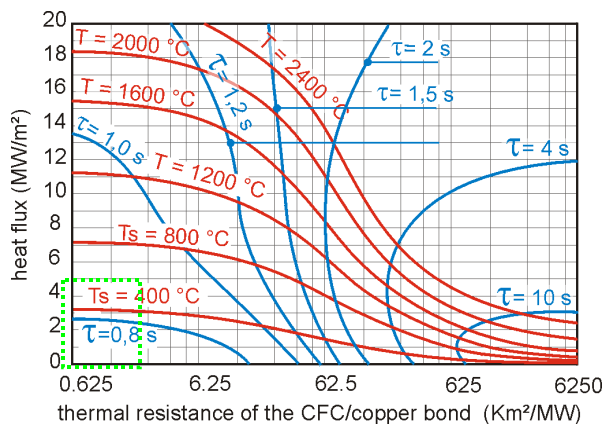


Fig. 11. Abacus of the stabilisation temperature and the thermal time constant of TPL tiles.

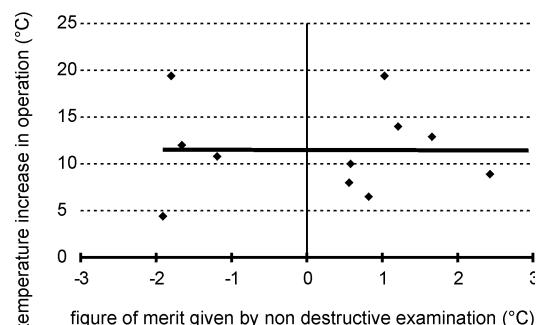


Fig. 12. Comparison of the response of the tiles of the leading edge between operation with plasma and non destructive examination.

The IR scanner camera observes however only elements meeting the criterion ($|\Delta T| < 3^\circ\text{C}$). No correlation is observed between the surface temperature increase (temperature increase was normalised according to design calculations) and the figure of merit of the NDE (Fig. 12.). This result indicates that all tiles meeting the design criterion have until now a similar behaviour under plasma heat flux. A more interesting statistic will be enabled by the new IR endoscope which observe tiles exceeding slightly the design criterium.

5. Conclusion

The Toroidal Pump Limiter is the first large area ($>7\text{m}^2$), actively cooled, plasma facing component capable to sustain high heat fluxes (up to 10 MW/m^2). Design and fabrication of this component are proving full of leanings from technological as well as operational aspects. The integration from design calculations, fabrication and diagnostics are an all-days necessity. It draws the sketches of the challenges that will arise when ITER will go toward continuous operation.

6. references

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