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Infrared thermography on Tore-Supra, the French experimental Tokamak on nuclear controlled fusion

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Abstract

Nuclear fission and fusion are exoenergetic reactions. Fission is largely entered in its industrial age. Controlled nuclear fusion is still under development before building an experimental reactor of industrial power plant size . Tore-Supra is *the French* experimental reactor, member of the large size Tokamaks' family. The most significant experimental results are presented and particularly the temperature maps of the limiters, components in direct contact with the plasma. The thenmographic system is a major diagnostic of Tore-Supra: its main role is to prevent from deterioration or destnuction of the components directly exposed to the plasma. The comparison between the thenmal maps of components obtained during shots and a model of plasma edge physics. So, we have measured the characteristic length of power deposition on plasma facing components for various experimental conditions. This is essential to check the adequacy between the conception of plasma facing components submitted to high heat ñuxes and their ability to face and sustain such a plasma. Three of the actively cooled limiters have been successfully tested in a steady state regime with surface temperatures under 1 000°C. The design value for power removal has been obtained. Peak power fluxes of 10 MW.m^{-2} (3.5 MW.m^{-2} on average) have been estimated. This represents a breakthrough for high heat flux components since critical heat flux and burnout with subcooled ñow boiling are major aspects for this kind of design. The time constant to reach a stabilized temperature on the whole head is less than 2 s (shot duration = 10 s) as expected from modelling of heat transmission through the thin 2.5 mm graphite layer tile, to the water through the brazed joint.

1. Introduction

Plasma Facing Components (PFC) are one of the key *issues* for the next step generation of Tokamaks, for intrinsic plasma performances (plasma dilution) and availability. We have to bear in mind, that PFC will be exposed, as far as we know, up to 30 MW/m^2 during initial phase with 10^4 pulses lasting 400 s. That means: PFC will have to be *Actively Cooled* (AC) during shots, to prevent them from reaching unacceptable temperatures.

Nowadays, among the biggest Tokamaks, D-III, JET, JT60, TFTR, and ToreSupra, the latest is the only one which operates with Actively Cooled Plasma Facing Components (ACPFC) [1]. The others relie on adiabatic heating of PFC, reaching temperatures up to 2 800 °C on some small and localized surfaces (compared to the whole surface of the PFC) [2 and 3]. The energy, conducted to the PFC, is stored in the bulk of the material which is massive. Then, during the long time between two pulses, it is realeased to the cooled PFC support structures or is radiated on cooler surfaces in the machine. On the contrary, PFC in Tore-Supra are all actively cooled (200 °C, 40 bar) during and between the pulses, so that their temperatures reach the equilibrium value after few seconds, depending on the thickness of the tiles. In this

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paper, we will present pure graphite vertical limiters. Some of them, semi-inertially cooled between shots, have been used for plasma scrape off characterization, the others are actively cooled during shots. Their thermal time constant is less than 2 s.

2. Semi-inertial limiters for plasma scrape off characterization

A semi-inertially cooled limiter has been used to characterize plasma edge interaction with plasma facing components. It is made of thick graphite blades (EK-90 Le Carbone Lorraine), bolted to an actively cooled mechanical stnucture. *A* model taking into account of:

- the geometry of the limiter,
- the heat transfer through the thick blade,
- the heat transfer through the bond down to the water,
- the field lines including the ripple (field line modulation),
- an exponential e-folding length for power deposition (for the power to decrease by a factor e=2.7),

has been developed to calculate limiter surface temperatures. The code has been run for a wide range of parameters:

- e-folding length from 0.5 to 2.5 cm, λ_q,
- Q, the incident heat flux at the last closed flux surface (LCFS), from 0.5 to 40 MW/m^2.

Figure 1 presents the results of the code for λ_q=1.2 cm, Q_{LCFS}=10 MW/m^2 at time t=2, 5 and 8 s. This is to be compared to the measurements (*colour figure A*)*made with an infrared camera *(Inframetrics Model-600)* looking at the limiter during a shot where 3 MW of Lower Hybrid Current Drive (LHCD) has been applied for 4 s. Comparing code results with measured surface temperatures, we can unfold the e-folding length and the power incident to the limiter. The e-folding length λ_q for power deposition on these components has been studied (*figure 2*) for different plasma parameters. It varies from 1.0 to 2.4 cm. It seems almost independent of electron density ($10^{19}m^{-3} < n_e < 5x10^{19}m^{-3}$), of power Lower Hybrid level, up to 4 MW, and of toroidal magnetic field (1.5T < B_t < 4T):

$$\lambda_q = 7.3\ Te^{1/4}\ Ip^{-1/2} \quad \text{with: } \lambda_q\text{(m)},\ Te\text{(eV)},\ Ip\text{(A)}$$

This variation is consistent, in the absence of a strong source of neutrals, with ions flowing in a flux tube to the limiter with ion sound speed velocity along magnetic field lines, $Cs = [k(Te+Ti)/mi]^{1/2}$ and a Bohm like cross field diffusion, $Db \sim Te/B_t$, which leads to an exponential e-folding length for

- density: $n = n_{LCFS}\exp(-x/\lambda_n)$

x is the distance in the scrape off layer from the last closed flux surface,

- temperature in the SOL:

$$T = T_{LCFS}\exp(\ x/\lambda_T)$$

- and in consequence for power deposition on PFC:

$$Q = Q_{LCFS}\ exp(-x/\lambda_T) = [n\ T]^{3/2}$$

This exercice is essential to check the adequacy between conception of plasma facing components submitted to high heat fluxes and their ability to face and sustain such a plasma. On Tore-Supra, PFC have been build for an e-folding length of 1 cm.

3. Actively cooled limiters

A set of six actively cooled vertical limiters is installed to operate in a steady state regime. The limiter head consists of graphite tiles in direct contact with the plasma, brazed on a

* *The colour plates of this article 5 are located on page I of the colour gathering, at the end of the book*

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copper tube bank. The thicknesses of tiles, the copper tube and the hydraulic system have been designed to remove 10 MW/m2. Surface temperatures reach an *equilibrium after 2 s.* The power handling is 0.7 MW for each vertical limiter in a DC regime. Codes have been developed to predict surface temperatures. The same procedure as for semi-inertial limiter has been used but we improved it by adding a third dimension since the individual cooling tubes are circular. *Figure 3* presents the results of such a code when the incident power is $Q_{I\,CFS}$=100 MW/m2.

Three of the actively cooled limiters have been successfully tested in a steady state regime with a surface temperature less than 1 000 °C. The design value for power removal has been obtained. Peak power fluxes of 10 MW/m2 (3.5 MW/m2 on average) have been estimated This represents a breakthrough for high heat flux components since critical heat flux and bumout with subcooled flow boiling are major aspects for this kind of design. The time constant to reach a stabilized temperature is under 2 s (shot duration = 10 s) as expected from modelling of heat transmission through the thin 2.5 mm graphite layer tile, to the water through the brazed joint. The power extracted by each limiter does not seem to depend on the number of limiters; that is *natural* when there is no short parallel connection between. It increases linearly with available power. This is verified on Tore-Supra by complete power balance on ACPFC. Almost all the tiles on limiters are well bonded to the copper cooling tubes. Nonetheless some do not have a very good thermal contact with the cold sink (*figure 4* and *colour figure B*). Their temperature can go up to 1 800 °C in a standard shot. This is due to a thermal runaway phenomenon occuring locally on a small part (100 cm2) of the limiter head (1600 cm2). That induces some deterioration of the properties of the plasma (particularly the carbon content of the discharge). This phenomenon which always starts on a non well brazed tile (10 mm x 18 mm) spreads on a wider surface. The size of such a surface depends strongly on plasma current and hence on power and particles fluxes at the plasma edge. We tried to correlate this sudden event with plasma parameters. So far, no significant correlation has been found. The only correlation is with the temperature of the non-well brazed tile which reaches 1 100 °C. The time to reach this temperature depends on available power in the machine and hence on particles flux to the limiter. We know that, when this phenomenon occurs, the carbon influx from this zone increases by at least a factor 8, with some signs of carbon influx in the discharge. On the other hand, the local molecular or atomic hydrogen / deuterium influx is not modified, except the first time it appeared. Once, the zone has been outgazed by an overheating, no more sign can be seen on plasma density. Langmuir probes do not indicate any change of the ion flux during this phenomenon. Modelling of critical heat flux event indicates that the time constant of this event is too small compared to what we observed. The only explanation seems to be that Radiation Enhance Sublimation (RES) [4 to 6] sets in. Most of the carbon influx is tum back to the limiter by friction forces. The ions store up energy through the sheath and give it up to the tile front face (and to adjacent tiles) [7]. This is still under investigation. Locally, the deposited energy goes from the initial 10 MW/m2 to at least 20 MW/m2. This is close to the critical heat flux. Indeed, we know that the surface temperature is very high, up to 1 800 °C, as indicated by infrared thermographic measurements and by continuum near Hydrogen and Carbon lines emission (656.3 nm, 657.8 nm) interpreted as radiation issued from a blackbody.

4. Long pulse operation

Achieving long (>60 s) tokamak pulse discharges is difficult since all the parameters of the machine must be kept constant during this lapse of time. It is difficult to perfonm such discharges as not only technology but also plasma physics are involved. In Tore Supra, one minute experiments have been achieved with a 1 MA plasma cunrent and a 3.9 T magnetic field. Lower Hybrid Cunrent Drive technique (2.5 MW) has been used to provide 80 % of the plasma cunrent. Since the total energy spread over the torus is 170 MJ, plasma facing components have to be actively cooled. We used the inner bumper limiter wall (representing 10 to 15 m2of *weated* area) which is able to sustain 6 MW of conducted power with a 0.5

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MW/m2 maximum power density. This wall is made of 5000 tiles (7 cm by 2 cm), 1 cm thick, brased on actively cooled stainless steel tube banks. Some of the tiles are not *well brased* some others are cracked because of the release of thenmal stresses during brasing. This kind of problems must imperatively be solved in order to achieve long pulse discharges. Indeed, as tiles are no longer actively cooled, they are adiabaticaly heated and, in consequence, they can reach unacceptable temperatures. Some melted brasing material, falling tiles and large carbon influxes can pollute the plasma. Figure 5 shows the time evolutions of the temperature of three inner wall tiles. One is not *well brased:* it reachs 800 °C. The others are actively cooled and get to a steady state in 10 s.

The inner bumper wall must be replaced in 1993. We are developing new concepts with new materials (carbon composites and reinforced carbon) for the realization of this new wall.

Non destructive controls (particularly infrared themmographic measurements) will be extensively used in order to attain the *zero defect option.* That is necessary for long pulse operations.

5. Conclusions

We showed that analysing infrared surface temperatures in conjunction with modelling of heat deposition on plasma facing components can be extremely valuable. It allowed us to unfold the e-folding length for power deposition on high risk elements of the French experimental nuclear fusion reactor Tore-Supra.

Actively cooled limiters have been successfully tested, up to 10 MW/m2, in a steady state regime. We must not forget that any small area thermally insulated from the cold sink will be a source of local increase of deposited power. If the safety margin is not large enough, critical heat flux will occur [8], though, the *zero defect option is* indeed a necessity for these high heat flux components.

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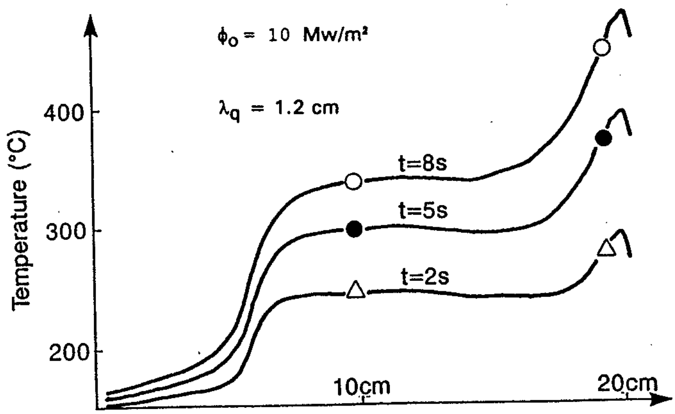

Fig. 1 - Predicted surface temperature profiles at times t=2, 5 and 8 s of one blade of a semi-inertially cooled limiter (half of the limiter extension).

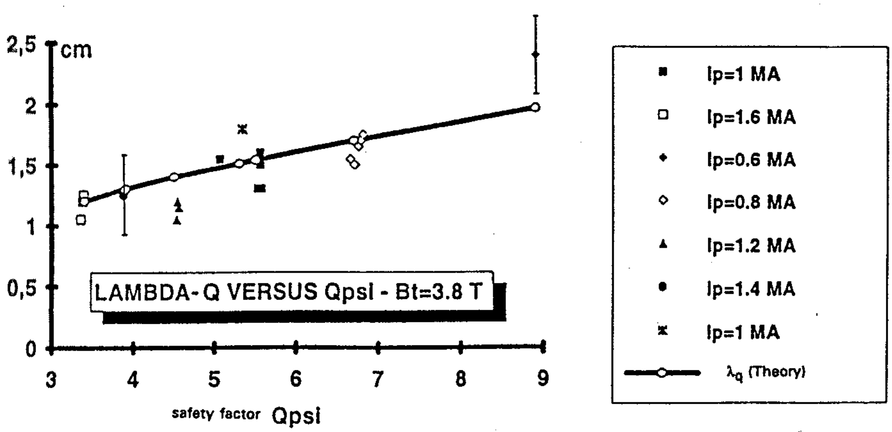

Fig. 2 - Power deposition e-folding length as function of plasma current I_p and safety factor at the edge Q_{psi}.

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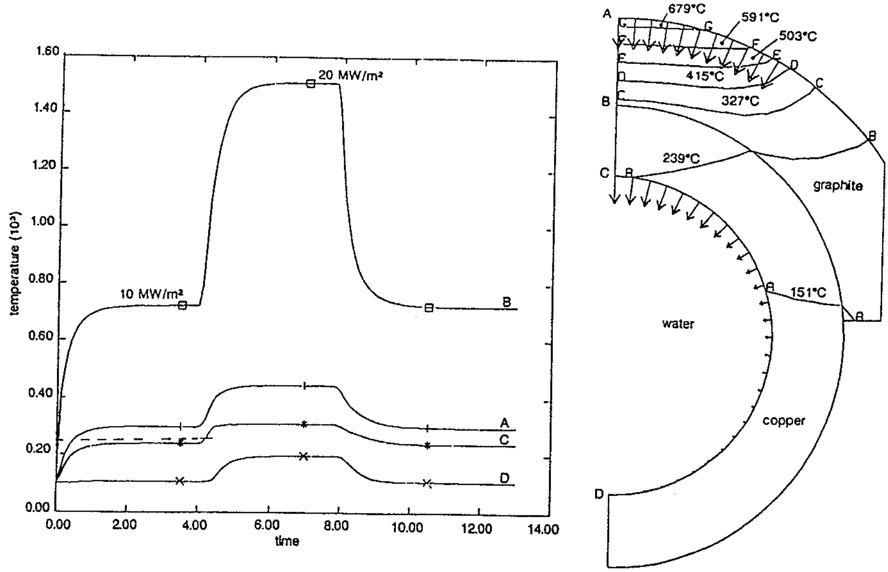

Fig. 3 - Half section of one actively cooled tube (10 MW/m2; steady state conditions) and code results when 10 and 20 MW/m2 are applied.

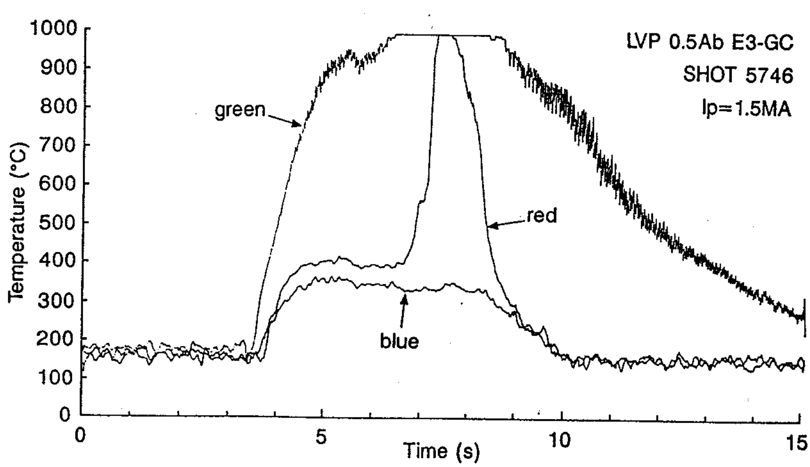

Fig. 4 - Time dependence of the temperature of 3 points on the limiter head (see *color Fig. B* for locations).

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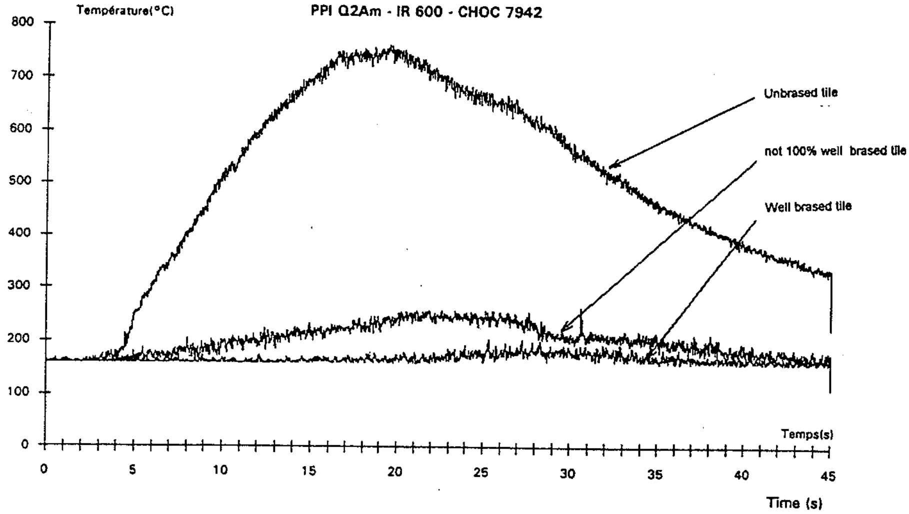

Fig. 5 - Temperature time dependence of three representative tiles of the inner wall.