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Long pulse operation with actively cooled limiters

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Abstract

We present here the major results obtained with actively cooled plasma facing components during long pulse operation (plasma duration $> 3 \times$ surface temperature time constant = steady-state). Shots up to 120 s have been achieved in Tore Supra when the plasma was leaning on the large inner toroidal actively cooled limiter with a moderate deposited power density heat flux (up to 0.3 MW/m^2). For larger power density heat flux up to 4.5 MW/m^2 (design value), modular limiters have been used. A prerequisite for any actively cooled limiter is the absence of any cooling defect (crack || to the surface in the tile or non-correct bonding). If a defect is present it leads to a super-brilliance event (with its corresponding local power heat flux increase) which propagates. This deleterious effect is unfortunately a runaway effect.

Keywords: Tore Supra; Boundary plasma; Energy deposition; Limiter; Sheath physics

1. Introduction

The achievement of steady state conditions in fusion devices requires a steady state power removal. A long pulse program (up to 120 s so far) has been pursued on Tore Supra and so actively cooled plasma facing components (PFCs) have been developed for this purpose [1]. This situation contrasts with existing machines where the pulse length is sufficiently short to store the energy delivered to the plasma in the inertial plasma facing components (cooled between shots). Actually the development of advanced axisymetric divertor scenarios for ITER relies on the assumption that the power heat flux on the recessed walls is < 0.5 MW/m^2 and < 5 MW/m^2 at the divertor plates. We present here results obtained in Tore Supra at this power heat flux range where the formation of localized hot spots are observed but not yet fully understood. Runaway impurity generation on graphite surfaces [2] is one possible mechanism for the production of carbon blooms. For some time, radiation enhanced sublimation (RES) [3] has been suspected to play a key role in these events. Thermionic emission [4] is involved in TEXTOR to explain the observations made on the strongly heated ($T > 2000$ K) test limiter [5] which leads to destruction of the debye sheath and a strong enhancement of the electron heat flux which reaches the surface. In Tore Supra thermal instabilities (sudden surface temperature excursions from 600°C to 1800°C, called 'super-brilliance' events), were previously observed [6] at the ridge of an actively cooled modular limiter (0.16 m^2) even at a moderate power load of 350 kW (design 700 kW) probably due to the fact that a number of tiles were poorly bonded to the cooling channel. Experiments have been carried out with a 'zero defect' limiter where the design power heat load was extracted routinely. One has to model these limitations, allowing an extrapolation which quantify the safety margins in terms of maximum surface temperature of the limiter, associated to the electron temperature at the plasma edge (T_s/T_e safe operational space).

2. Experimental results

We present here the results obtained with the first generation of actively cooled limiters: an inner toroidal limiter which represents a large surface with a moderate

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power heat flux capability (12 m^2, 1 MW/m^2) and a set of modular pump limiters (6×0.16 m^2, 5 MW/m^2).

2.1. Inner bumper operation

The inner limiter located on the high field side is composed by a set of about 8700 brazed graphite tiles brazed on an actively cooled stainless steel structure; the resulting time constant of the assembly is 15 s. The graphite itself represents a large toroidal structure of 12 m^2 designed to sustain a continuous 1 MW/m^2 heat flux. Up to 270 MJ were injected, mainly by the lower hybrid current drive (LHCD) system during a lower hybrid enhance plasma (LHEP) scenario ($H = 1.4$) lasting 120 s where 0.1 MW/m^2 was extracted by the inner wall, Fig. 1. One can see at the top of this figure, that at $t = 3$ s the current plateau is reached and that at $t = 4$ s the lower hybrid current drive power is switched on. The diagram shows that the electron density starts to rise slowly after one minute (mainly due to an O_2 plasma contamination), the ion temperature being stable. On the lower left of Fig. 1, the measured and L-mode predicted total energy in the discharge are shown. The electron energy content is also compared to the RLW prediction, showing a $H = 1.4$ enhanced confinement regime. The lower right of Fig. 1 shows the measured ion (triangles) and electron (circles) temperatures profiles just before ($t = 3$ s) the application of the LHCD power and after ($t = 15$ s). The ion temperature is not affected by the LHCD power while the electron temperature is more than doubled in the center of the discharge (normalised radius < 0.4).

In contrast to other machines, carbon blooms have not been observed so far during long pulse operation. However during the end of the shot one can see an outgasing of *non*-actively cooled recessed elements. The power exhaust is limited by defective tiles, incorporating braze flaws or cracks in the graphite material. Up to 1996, about 9% of the brazed tiles were damaged. A limited number of inner first wall panels, corresponding to a toroidal section of about 1.5 m^2 (40° toroidally) were sufficiently damaged to warrant replacement. It was decided to replace them by improved components of a new generation using CFC as tile material [1]. A rigorous manufacturing process and systematic non destructive inspection methods have been applied to this new components before installation in the machine. So far no defect has been observed after one year of operation (pulses of 2 min) on the newest generation. It is not clear so far if the power limitation can be attributed to the oldest generation of the inner wall, to the LHCD antennas or to a synergy effect of fast electrons which are produced by the LHCD system in the scrape off layer and the elements placed here. We have some evidences that 1% of the power injected is received locally by limiters (up to 4 MW/m^2) or by ICRF antennas lateral protection (up to 10 MW/m^2) in flux tube (2 cm poloidally and < 1 cm radially) connected directly to the LHCD grill rows (30 to 50 MW/m^2 perpendicular to the flux tube).

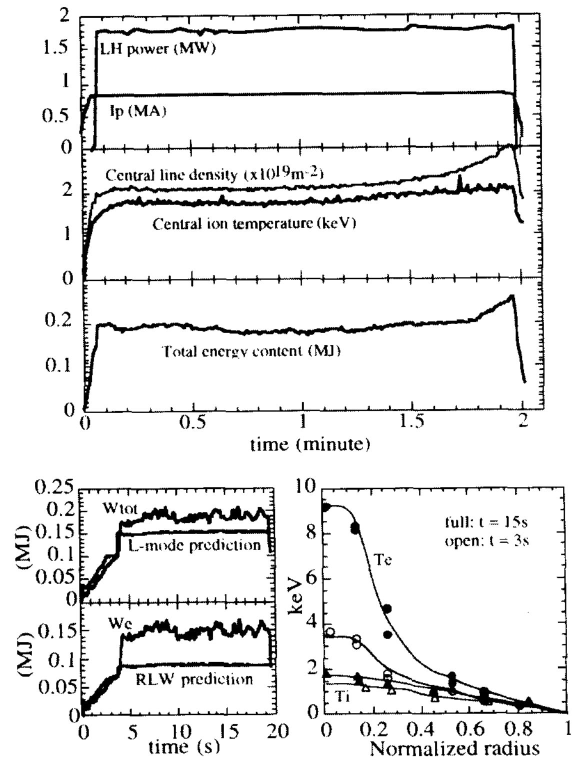

Fig. 1. Two minutes lower hybrid enhanced plasma (LHEP) discharge with improved confinement ($H = 1.4$) for a plasma leaning on the toroidal inner actively cooled limiter.

2.2. Modular limiter operation

A set of six actively cooled modular limiters were used to extract the power injected and to control at the same time the particle inventory for steady state operation. All the limiters used have a poloidal radius of curvature of 0.75 m and a small area 0.16 m^2 (time constant = 2 s). The maximum power load capability is in the range of 10 MW/m^2 leading to a maximum total power extraction of 4 to 5 MW. During these experiments, Tore Supra was operated in a large variety of plasmas: 1 MA $< I_p <$ 1.6 MA, 0.70 m $< r <$ 0.75 m, 1.5 T $< B_t <$ 3.85 T and was heated with up to 4 MW of lower hybrid current drive (LHCD). A typical set of discharge parameters are: $\langle n_e \rangle = 1 \times 10^{19}$ m^{-3}, $T_e(a) = 50$ eV, 2.4 cm $< \lambda n <$ 3.7 cm, $\lambda T = 3.7$ cm, 1 cm $< \lambda q <$ 1.5 cm ($\lambda_{n,T}$ are the electron e-folding length for density and temperature respectively and λ_q the power e-folding length). A discharge of 30 s (3 limiters used) heated with 2.2 MW of LHCD has been achieved (maximum power density = 4 MW/m^2).

The limiter front faces are surveyed with a set of infrared cameras calibrated to 2500°C (spatial resolution

< 10 mm = width of one of the 40 cooled tubes placed side by side to make up one limiter head). The steady state surface temperature allows to unfold the power load heat flux maps. The total power extracted by the actively cooled limiter is also deduced from the flow velocity ($\sim$ 10m/s) and the difference between the inlet and outlet water temperatures (< 50°C). The spectroscopic measurements (via relay lenses and optical fibers) were acquired on an intensified CCD-camera detector.

Thermal instabilities were reported [6] localized at the ridge of these limiters, called 'super-brilliance'. We have identified that these instabilities are triggered at locations where a tile defect is present, even if the defect is very small (1 mm^2) compared to the 1×1 cm^2 tile dimensions (2.5 mm thick). It is always localized at the ridge of the limiter where the electron temperature is the highest, T_e(LCFS) = 50 eV, and not at the leading edge of the limiter where the electron temperature is smaller (typically 3 times lower) and where the surface temperature is of the same order. This suggests that the event is strongly linked to the plasma electron temperature at the edge *and* to the surface temperature of the limiter. One has to note that the super-brilliance event leads to a new stable situation where the local power heat load and hence the temperature, are finite (no noticeable modification outside the overheated zone). These thermal instabilities could appear even when the extracted power by the limiter was half of the design value (P_{design} = 700 kW). A new limiter structure with improved heat removal capability has been built by assembling individual graphite brazed tubes, which have been selected following a non destructive inspection method such as X-ray imaging and transient infrared thermographic measurements. The main result of this experiment is that the routinely extracted power in steady state is increased, with up to 1.45 MW of LHCD additional power in the plasma, to its design performances: 700 kW steady state, 4.5 MW/m^2 on average, T_{max} = 600°C. However thermal instabilities occurred again on an increasing number of independent zones (up to 4) on the limiter ridge after a few shots with the same plasma parameters. The power extracted by the limiter then was $\sim$ 1.1 MW, 6.9 MW/m^2 average and 15 MW/m^2 maximum, leading to the cracking of some tiles or to the destruction of a part of the bonding joints. This leads, for the same heat flux, to a substantial increase of the surface temperature of some tiles. Once the super-brilliance event occurred at one location, then for the following shots it will always be anchored at the same place, but at a lower input power and/or earlier in the shot since a part of some tiles has been cracked (mainly || to the surface) during the event as seen from the cooling time constant of the tile. It has to be noted that the total surface involved in these events is small compared to the limiter surface (< 1%) and that no plasma bulk or plasma edge modification could be noted. In particular it does not evolve in a carbon bloom (poisoning of the core plasma by a large influx of carbon). We have observed super-brilliances lasting 5 s, the surface temperature of the limiter reaching quasi steady state values, up to 1900°C. The main observations made during these events [6] are: (1) a rapid local ($\sim$ 0.001 m^2 over 0.16 m^2 of the limiter surface) temperature excursion, Fig. 2, corresponding to a 2 to 3 fold local increase of power load reaching 15 MW/m^2 under steady sate conditions, (2) a propagation of the temperature excursion along the ridge of the limiter, (3) a significant increase of the extracted power (measured by calorimetry) from 700 KW to 1.1 MW during super-brilliances under the same plasma conditions, (4) a significant increase of H-alpha from the overheated zone only the first time the super-brilliance is taking place, (5) a 20% increase of the plasma density only the first time the super-brilliance is taking place (due to the overheating and outgasing of the graphite zone), (6) an 8-fold local increase of C-II emission from the overheated zones and (7) no increase of C-VI line, which suggests that the local source is too small (or that the screening is extremely efficient) to contaminate the plasma core.

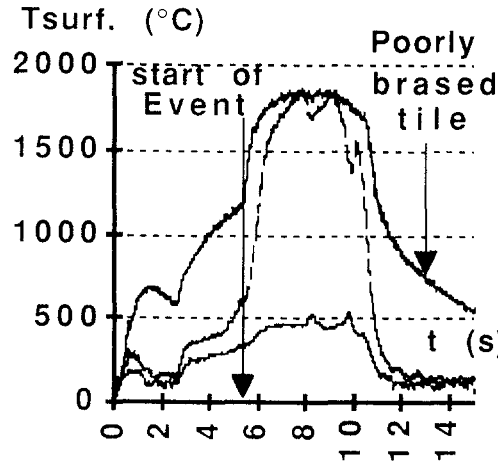

Fig. 2. Surface temperature time evolution of 3 points along the limiter ridge during a 4 s quasi steady-state super-brilliance event (time constant of the limiter = 1 s).

3. Modeling

A model for plasma and material behavior in this limiting regime has been developed. The main ingredients in the model are the CASTEM-2000 thermal analysis code and the BBQ scrape-off layer impurity generation and transport code. BBQ is a 3D Monte Carlo code which calculates the generation and penetration of chemical, RES and physically sputtered impurities. Since the generation rate depends sensitively on the surface temperature and since the graphite components are actively cooled, the 3D, time-dependent CASTEM-2000 code is used to calculate the temperature spatial distributions needed to evaluate sputtering yields. In turn, a physics-based heat flux model has been developed for CASTEM-2000 which derives the imposed heat flux self-consistently from scrape off layer plasma conditions and surface conditions.

The response of the limiter to the localized heat flux (including re-deposited heat) has been modeled with CASTEM. A self-consistent description of the imposed heat flux has been used, in which the sheath heat flux transmission factor (which depends on thermionic and secondary electron emission) is calculated as a function of the evolving surface temperature. The model calculates the condition of zero net electron current to the surface:

$$n_e v_e e e^{-e\phi/T}\beta/4 - J_T = \Gamma_i e \quad (1)$$

where

$$v_e = (8T_e/\pi m_e)^{1/2}, \text{ average electron velocity} \quad (2)$$

$$\Gamma_i = n_i V_s, \text{ average ion flux} \quad (3)$$

$$V_s = [(T_i + T_e)/m_i]^{1/2}, \text{ ion velocity} \quad (4)$$

$$\beta = (1-\sigma_e)/(1+\sigma_i) \quad (5)$$

and $\sigma_{e,i}$ are the secondary electron, ion emission coefficients. For high temperature cases, where there is strong thermionic emission, the thermionic current is:

$$J_T = AQ^2 e^{-B_{work}/kQ} \quad (6)$$

where

$$A = 120.4 \text{ A/cm}^2/\text{K}^2, \quad (7)$$

$$B_{work} = 4.5 \text{ eV}, \text{ electron extraction workforce} \quad (8)$$

$$Q = T_{wall} \text{ (K)}, \text{ surface temperature (K)} \quad (9)$$

Thus, the heat flux from the plasma to the wall is:

$$q_{ps} = \gamma\Gamma_i T \quad (10)$$

where

$$\gamma = 1 + \Phi + z_T, \text{ transmission sheath factor} \quad (11)$$

$$\Phi = e\phi/T = \ln\left[(m_i/\pi m_e)^{1/2}/z_T\right], \quad (12)$$

$$z_T = 2(1+y_T)/\beta, \quad (13)$$

$$y_T = J_T/e\Gamma_i \quad (14)$$

Calculations with this model show that the highly localized heat flux due to re-deposited impurities can be important in determining the behavior of the lower vertical limiter on Tore Supra, when this limiter is operated in the regime 4 $\text{MW/m}^2 < P_{lim} < 7$ MW/m^2. Sheath acceleration and re-deposited heat flux due to these impurities can lead to an overheating instability. It is a non-local effect (impurities ablated at one place are re-deposited in another) so the instability has a spatio-temporal character which cannot be treated by the usual global methods. The predicted operational regime in the space $T_{surf} - T_e$ (SOL), limited by runaway impurity generation, described for example in Ref. [2], has been revised through consideration of new

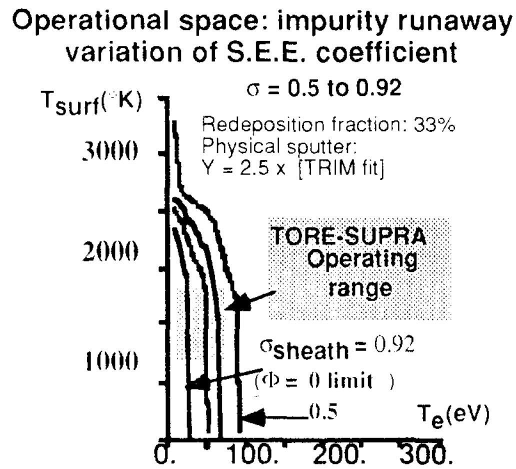

Fig. 3. $T_{surface}/T_{e\text{-LCFS}}$ stable operating range. The left of each curve is the stable domain and the right is the unstable region where a super brilliance is predicted to take place. The 4 different curves correspond to different secondary electron emission coefficients ranging from 0.5 to 0.92 where the sheath potential drops to 0.

data on athermal chemical [7], RES and physical sputtering [8] and by including the effects of thermionic emission at high temperatures [4]. The predicted operational space is found to be in reasonable agreement with limiting conditions observed in the Tore Supra experiments, Fig. 3, when:

- The physical sputtering yields are increased by 2.5 (middle of the experimentally measured range).
- The re-deposited fraction on the limiter is taken to be 0.33 (as indicated by BBQ code).
- The secondary electron emission is taken to be 0.86 (space charge limit for D plasmas).

Fig. 3 shows the predicted stable operating range (left domain of each curve) for 4 different secondary electron emission coefficients ranging from 0.5 to 0.92 (sheath potential = 0). For example if this coefficient is taken equal to 0.5 (curve on extreme right) then with a low surface temperature ($T_{surface} < 1700$ K) the maximum plasma electron temperature allowed is 70 eV otherwise the operating point is located in the unstable space, the right part of the diagram. We can observe as well that when the plasma electron temperature is low, 50 eV for example, the maximum allowed surface temperature is 1800 K before reaching the unstable region (the right of each curve).

While these processes all play a role in the evolution of the surface from discharge-to-discharge, detailed modeling has so far been unable to reproduce the super-brilliance effect using such effects alone. The further assumption of local defects is required, perhaps due to cracks [9] (|| to the surface) in the tile material or to erosion/re-deposition processes over several previous discharges. Fig. 4 shows a comparison of the local distributions of surface temperature (from the CASTEM-2000) code for a tube of the vertical limiter under the assumptions of a perfect sample and a tube with a localized region (1 mm) at the ridge with (i) reduced thermal conductivity and (ii) debonding of the graphite from the cooling tube in this 1 mm region. The case with the assumed imperfection shows the rapid rise of the observed temperatures.

The model must be compared with the observed phenomena:

(1) The material and cooling imperfection must be assumed to find a rapid local temperature excursion. Inclusion of self-consistent heat flux in the model then couples the surface temperature increase with the increase in heat flux to give the local increase of power load.

(2) The propagation of the temperature excursion along the ridge of the limiter can be understood. There are widely varying regions of (chemical and RES) impurity emission along each tube. The change in surface temperature from tube-to-tube along the ridge is sufficient to give rise to apparent propagation effects because of the simultaneous movement of the region of peak sputtering.

(3) Both the significant increase of H-alpha and small increase of the plasma density (first time) and the local increase of C-II emission from the overheated zones are consistent with a chemical sputtering (CD_4) source.

(4) No increase of C-VI line (located in the core plasma) occurs since chemical and RES sources are thermal, they penetrate less efficiently than physically sputtered impurities.

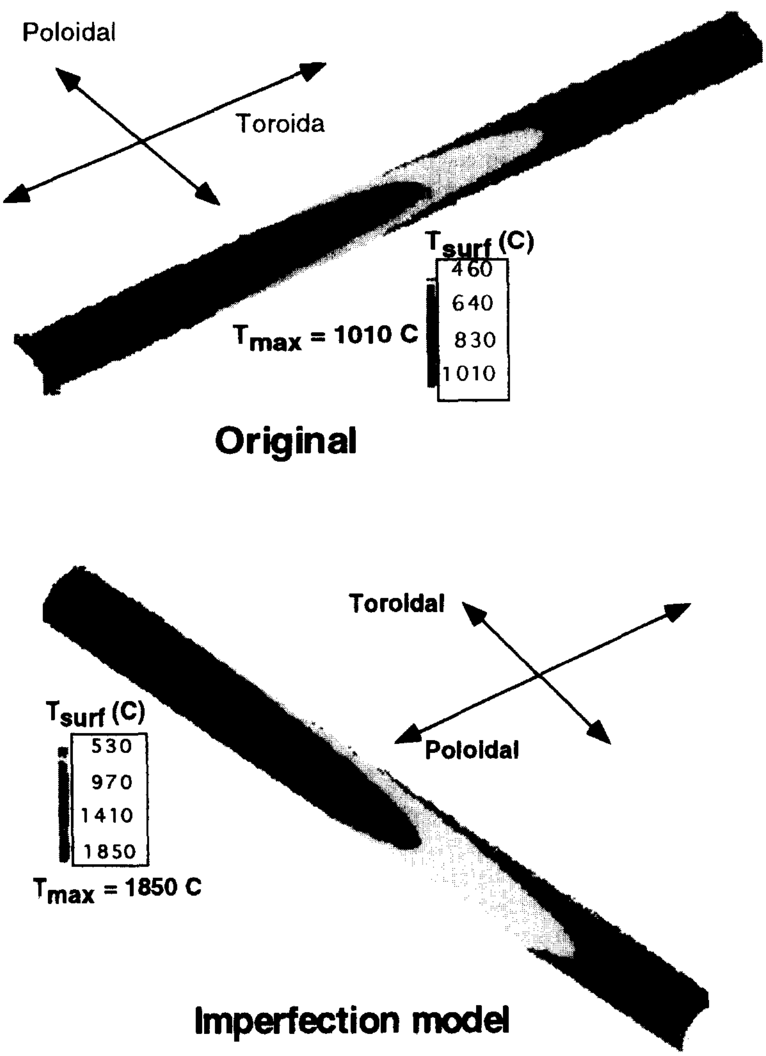

Fig. 4. Modeling of the steady state solutions, with an 'original' tube (T_{max} = 1010°C) and with an 'imperfect' tube (T_{max} = 1850°C). The imperfection is a 1 mm × 1 mm piece of uncooled graphite. Only one of the 40 tubes (20 cm long, 1.8 cm wide) constituting a limiter is presented here in both cases.

4. Conclusion

We have shown on Tore Supra that long pulse operation, up to 120 s, was possible (270 MJ injected by the LHCD system, LHEP mode) when the plasma was leaning on the large inner toroidal actively cooled limiter with a moderate deposited power density heat flux (up to 0.3 MW/m^2). For larger power density heat flux up to 4.5 MW/m^2 (design value), modular limiters have been used. A prerequisite for any actively cooled limiter is the absence of any cooling defect (crack $\parallel$ to the surface in the tile or non-correct bonding). If a defect is present it leads to a super-brilliance event (with its corresponding local power heat flux increase) which propagates. This deleterious effect is unfortunately a runaway effect.

While the individual phenomena occurring in the region of high heat flux can be understood, still a detailed prediction of the limiting conditions for future devices depends very sensitively on the details of construction of the plasma-facing component and the interaction with the basic processes discussed. This interaction is not yet sufficiently well understood.

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