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by

D. Guilhem
*Centre d'Etudes de Cadarache
Association EURATOM-CEA
sur la Fusion, France*

J. T. Hogan
*Oak Ridge National Laboratory
Oak Ridge, Tennessee USA*

R. Mitteau, V. Phillips
*Institut Für Plasmaphysik
Jülich, KFA*

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Observation and Interpretation of Thermal Instabilities at the Front Face of Actively Cooled Limiters in TORE-SUPRA.

D.Guilhem, J.Hogan[#], R.Mitteau, V.Phillips⁺

Association EURATOM-CEA sur la Fusion, Centre d'études de Cadarache FRANCE

[#]Fusion Energy Division, ORNL Oak Ridge, TN 37830 USA

⁺ Institut für Plasmaphysik, Jülich, KFA

1 Introduction:

In TORE-SUPRA, actively cooled modular limiters (time constant = 2 s) covered with carbon have been used to exhaust the convective heat flux continuously up to 700 kW steady state (design value) without thermal instability, i.e., 4.5 MW/m² on average. Steady state surface temperatures in the range 600°C (with 1.45 MW of Lower Hybrid waves) were routinely obtained. However, sudden surface temperature excursions from 600°C to 1900°C, called "super-brilliances", were observed during ohmic or heated plasmas, taking place locally over 20 ms, which led to a new equilibrium (figure 1). This new equilibrium correspond to a local increased power flux density to the limiter as confirmed by calorimetric measurements. Shot after shot, an increasing number of independent overheated zones (up to 4) were observed on the limiter ridge, the closest location to Last Closed Flux Surface (LCFS). The power extracted by the limiter then was ~1.1 MW (6.9 MW/m² average and 15 MW/m² maximum). Experimental data and possible mechanisms leading to a finite increased heat flux to the limiter surface are reviewed and comparisons with modelisation are made.

2 Experimental observations:

TORE-SUPRA was operated in a variety of D₂ and He plasmas: $\langle n_e \rangle = 3.10^{19} \text{ m}^{-3}$, 1 MA < I_p < 1.6 MA, 0.70 m < r < 0.75 m, 1.5T < B_t < 3.85 T, and was heated with up to 1.45 MW by Lower Hybrid waves. The actively cooled limiter is made of graphite and is observed with a set of infrared (3 - 5μm) cameras calibrated up to 2000°C (±150°C), with a spatial resolution ~ 10mm. The power extracted by the limiter is obtained by calorimetry. The spectroscopic measurements were recorded on an intensified CCD-camera detector (via relay lenses and optical fibers). A number of observations have already been made during super-brilliance events [1], some new results are added here. First of all, a rapid local (~10 cm² over 1600 cm²) surface temperature excursion is measured, figure 1, corresponding to a 2 to 3 fold local increase of power load reaching $P > 15 \text{ MW/m}^2$ under steady state conditions as shown by thermohydraulic analysis. The temperature excursion propagates along the ridge of the limiter, leading to a significant increase of the extracted power from 700 KW to 1.1 MW. A significant increase of H_α line radiation is observed from the overheated zone, *only the first time* the super-brilliance took place, correlated with a 20% increase of the plasma density (due to overheating and outgasing of the graphite zone). The super-brilliance always induces a local increase of C-II emission from the overheated zones (up to 8 fold), and no increase of C-VI line radiation, which suggests that the local source is too small (or that the screening is strong), to contaminate the plasma core. Super-brilliance events always take place at the ridge of limiter where the electron and surface temperatures are both maximum and never at the leading edge, although the surface temperature is equal or larger there than at the ridge but where the electron temperature is smaller. This suggest that the electron temperature is a leading parameter for thermal instabilities. However, inertial limiters with a smoother shape of the ridge have shown that if the surface temperature is small (in the range of 400°C) at the ridge of the limiter, no thermal instability is triggered in spite of high T_e there. This suggests that the event is strongly linked to both the electron and surface temperatures.

The super-brilliance leads to a new stable equilibrium where the local power heat load

reaches 15 M W/m^2 , and a surface temperature of 1900°C in the case of actively cooled limiters (no noticeable modification outside the small overheated zone). This large power heat flux density leads to cracking of some tiles or to destruction of a part of the bonding joints. A substantial increase of the surface temperature is observed at the beginning of the subsequent shot, for the same plasma parameter and hence heat flux (before the thermal instability occurrence). Once the super-brilliance has occurred at one location, for the subsequent shots, it remains anchored at the same place, but appears at lower input power and/or earlier in the shot (almost at the same surface temperature 1200°C to 1400°C) since a part of the tile has been cracked during the event as seen from the cooling time constant of the tile, figure 1. No plasma bulk or plasma edge modification could be noted probably due to the fact that the total limiter surface involved in these events is small compared to the limiter surface ($<10\%$). Super-brilliances lasting 5 seconds were observed, the limiter surface temperature reaching quasi steady state values, up to 1900°C .

3 Modeling of the super-brilliances:

A modelling effort has been undertaken to clarify the role of surface versus electron temperature in this thermal instability. The role of thermionic emission [2,3] and Secondary Electron Emission (SEE) are analysed as well as Radiation Enhanced Sublimation (R.E.S.), chemical and physical sputtering.

The BBQ time dependent Monte Carlo SOL impurity transport code has been used to examine the role of the redeposited impurity heat flux on the thermal instability which is observed on the actively cooled limiter ($n_e(a) = 4 \cdot 10^{18} \text{ m}^{-3}$ and $T_e(a) = 40 \text{ eV}$). Calculations show that the mean free path for the low energy impurities (chemical and RES produce thermal particles $E_L \sim 0.1 \text{ eV}$) is $0.3\text{--}0.6 \text{ cm}$, which is 15-30 times the magnetic Debye length. Hence the impurities which are redeposited are subject to sheath acceleration. BBQ calculations show that $\sim 30\%$ of the emitted low energy impurities are redeposited on the limiter. The maximum fraction of redeposited power is $\sim 15\%$ with respect to the direct SOL power. While this is not too large, it should be noted that the redeposited heat flux is quite localized at the region of the ridge of the limiter (the LCFS), this location is the radius of maximum T_e on the limiter, so that the sheath acceleration is also maximum there.

The response of the limiter to the localized redeposited heat flux has been modeled with the CASTEM 3-D, time dependent, thermohydraulic transport code, developed by CEA. A self-consistent description of the imposed heat flux has been used, in which the thermionic emission [2] and secondary electron emission are calculated as functions of the evolving surface temperature. For high temperature cases, there is a strong thermionic emission.

The BBQ impurity redeposition heat flux was added to that produced by the direct plasma heat flux, resulting in the *total* heat flux. The time evolution of the surface temperature of the actively cooled tube calculated with the self-consistent CASTEM model shows that the region of maximum chemical sputtering appears first near the ridge of the limiter, as T_{surf} starts to rise, then moves down the tube (toward the leading edge) as T_{surf} rises further, and the temperature rises above the peak of the chemical sputtering yield. At much higher temperature the RES yield begins to rise and a localized peak of impurity production again appears near the limiter peak.

The comparison of the fits in the model for treating physical sputtering with the actual measured data [4] shows that, while the maximum sputtering yield from the code fit is $Y_{\text{phys}} \sim 0.02$, the maximum for the data is $Y_{\text{phys}} \sim 0.06$. Thus, the actual physical sputtering data range amounts to a factor 3 increase over the code fits.

The incident heat flux is also a strong function of the SEE coefficient (σ_e) and σ_e , in turn, depends strongly on the surface hydrogen concentration for C:H layers [5]. During a discharge, we assume that the limiter surface has a H/C ratio near 0.4, and this ratio decreases with T_s , becoming 0.1 at $T_s > 1300 \text{ K}$. Taking the space charge limit in the range of allowed values, we have calculated both the resulting temperature evolution with the CASTEM self-consistent

model and the effect of enhanced SEE in restricting the safe operational $T_{\text{surf}}-T_e$ space.

4 Stable (T_e , T_s) operational space:

The safe operational space is defined as the space where there is no runaway impurity production ($Y_{\text{total-sputtering}} < 1$). This operating window depends on all the elementary processes which have been included in the model. Figure 2 shows the resulting accessible T_{surf} , T_e safe operational space which was found with the "conventional" work (old sputtering data, $\sigma_e = 0.5$, redeposited fraction = 1). This safe operational space was not consistent with that observed in experiments on the limiters, where $T_e \sim 50$ eV and $T_s < 2000^\circ\text{K}$ were found to be the approximate limiting values. Thus, a revision of this operational space was required.

The new physical data which are used have been previously discussed: (1) strongly localized redeposited heat flux due to C impurities near the peak of the limiter; (2) The recommended physical sputtering coefficients in the regime of the TORE-SUPRA limiters have been changed; (3) The incident heat flux is a strong function of the secondary electron emission (SEE) coefficient. The sensitivity to this coefficient has been explored. Figure 3 shows the sensitivity of the safe operational space to the assumed redeposition fraction for impurities. The cases shown are for $h = 0, 0.33, 0.66$ and 1 . BBQ calculations, as described earlier, show that only $\sim 30\%$ of the impurities are redeposited on the limiter. As seen in Figure 3, this effect would lead to an enlargement of the "conventional" operational space.

The next effect to be considered is the use of the laboratory measurements for the physical sputtering yield, to replace the use of fitting formulas. Figure 4 shows the effect of the new physical sputtering yields on the basis of recent results [4] (old values multiplied by factors up to 4). The largest factor (4.0) produces a maximum sputtering yield which passes through the maximum of the measurements. As can be seen, inclusion of this effect produces a significant reduction in the maximum safe operational $T_e(a)$ space, reducing it to the range observed in the actively cooled limiter experiments.

The next effect is that of the SEE coefficient. If we assume the physical sputtering yield to have the old fit values, i.e., if the multiplier factor = 1.0 in the cases shown in Fig. 4, then the revised safe operational space due to SEE is shown in Figure 5. The effect of using revised SEE values is to reduce the maximum value of T_s to the range observed in the experiments.

If we assume a physical sputter yield multiplier = 2.5 (middle of the experimentally measured range), then the variation of the SEE yield from lowest (clean graphite, $\sigma_e = 0.5$) to highest $\sigma_e = 0.92$ ($F=0$ limit) values produces the safe operational space shown in Figure 6. The value $\sigma_e = 0.86$ is probably the highest value to assume (space charge limit for D plasma) even though it is lower than laboratory SEE yield values.

5 Conclusion and prospectives:

The resulting operational space figure 6, seems at least reasonably consistent with that which is observed with the actively cooled limiter. As we can see, the operating window seems very narrow, especially for the acceptable electronic temperature T_e at the LCFS. The surface temperature range allowed can be, as well, very narrow, depending on the Secondary Electron Emission. The diagram fig. 6 shows that to avoid thermal instabilities we have to keep the edge electron temperature as low as possible (by using for example radiating layers). We have as well to keep the surface temperature of the plasma facing components as low as possible, by spreading the outward convective heat flux on large surfaces (decrease the power heat flux density). We have also to learn to make as "perfect" as possible high heat flux plasma facing components, robust enough to get through off normal events.

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Fig. 1: Surface temperature evolution of 3 locations at the ridge of an actively cooled limiter.

Fig. 2: "Conventional" stable space limited to 160 eV at Last Closed Flux Surface.

Fig. 3: Modification of the stable operational space with the fraction of redeposited Carbon.

Fig. 4: Modification of the stable operational space with sputtering yield.

Fig. 5: Modification of the accessible space with secondary electron emission coefficient.

Fig. 6: Revised Stable operational space for actively cooled limiters in TORE-SUPRA.