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Heat flux pattern on the toroidal pump limiter of Tore Supra: first observations and preliminary analysis

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Abstract

Tore Supra has re-started operation in 2001 with a partial toroidal pump limiter as the main plasma facing component. Assembled with actively cooled high heat flux elements, it has the shape of a toroidal ring. Thermal equilibrium is achieved within 4 s and the stabilised surface temperature is comparable to the design calculation. The observed heat flux pattern is similar to calculations realised beforehand with the heat deposition code TOKAFLU, and is dominated by the large toroidal field ripple. The power deposition is a combination of parallel convection and cross-field transport of similar magnitudes. The heat flux decay length is evaluated by three independent diagnostics to 10 mm. The excellent agreement between experiment and modelling indicates that the description of the power deposition mechanism is reasonable, although parameters such as the heat flux decay length and fraction of perpendicular power are still difficult to predict.

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Keywords: Heat deposition; Power exhaust; Limiter; Thermal load; Plasma facing component; Tore Supra

1. Introduction

Tore Supra has re-started operation in 2001 after a complete replacement of all plasma facing components [1,2]. The whole chamber is protected with actively cooled components (Fig. 1), the cooling being ensured by pressurised water. The toroidal pump limiter (TPL) is the main plasma facing component, located in the bottom of the vacuum vessel. It is made of 10 MW/m^2 high heat flux elements (the *fingers*) covered with carbon fibre composite (CFC) tiles and has a leading edge and a throat on the high field side (ion drift side) allowing pumping. The limiter was partial in 2001 with three 30° sectors at every 120° in the toroidal direction, terminated by large thermally inertial tiles [3]. It has been since completed to a total annular ring, and the 2001 experiments are representative concerning the finger performances and heat flux pattern.

Extensive power deposition modelling based on the cosine law has been performed on the TPL (code TOKAFLUX [4]). Cross field diffusion onto surfaces being parallel to the field lines is added as a perpendicular component of the heat flux. Shadowing effects are also taken into account [5]. The heat flux exponential decay length (λ_q in the following) in the scrape off layer (SOL) and the perpendicular fraction have been taken as free parameters.

The experimental campaign in 2001 focused on the qualification of the new components. ICRH and LH auxiliary heating allowed to test the limiter up to 3 MW in thermal steady state (up to 4.6 MW during 2.5 s).

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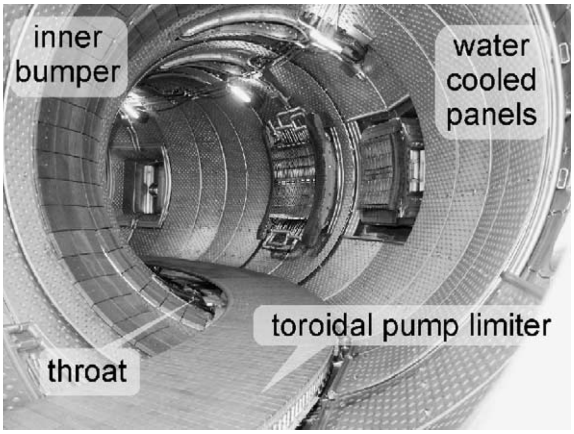

Fig. 1. Photo of the TPL installed in Tore Supra (2002).

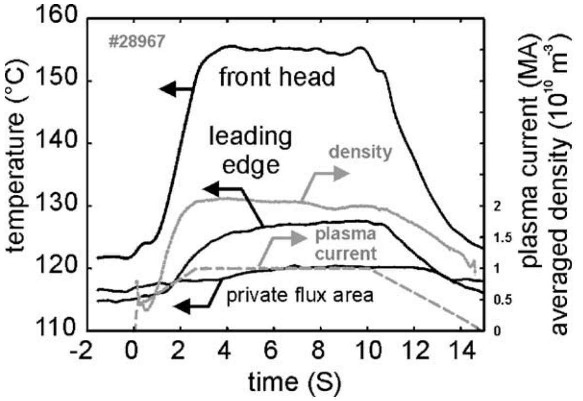

Fig. 2. Time evolution of the surface temperature of three characteristic areas, electron density and plasma current. The areas are described in Fig. 5(b).

2. Experimental procedure

The set of diagnostics used for the power deposition analysis on the TPL includes mainly:

- An infrared camera located at a vertical port. The field of view at the surface of the TPL was 36 × 30 cm. This allowed to observe seven tiles on 12 fingers, including the leading edge. Transmission of the optics and the sapphire window were taken into account. The emissivity of the CFC surface has been estimated to unity.
- Spatially and time resolved calorimetry of all components [6].
- Three CCD cameras inside the ports, allowing observations at 120° of the sectors of the TPL in visible light. The field of view was 2m × 2 m and gave a view of the whole actively cooled area.
- Five bolometric cameras with tomographic re-construction.

The heat flux pattern on the TPL is the sum of contributions of various phenomena. A first separation is made between radiation and convection (particles deposition). The convection can be separated into SOL convection and fast particles (ripples losses of trapped ions). Finally, hot spots assumed to be caused by dust particles were observed at the beginning of operation but vanished progressively during repetitive discharges with auxiliary heating. In the present work, the focus is set on the heat flux deposited by SOL convection and radiation which are the main channels of the power exhaust.

3. Thermal response of the limiter

Fig. 2 shows the surface temperature of three typical areas along with plasma current and density as a function of time. Thermal equilibrium was achieved in 4 s and surface temperatures are then constant. First measurements were smaller (a few video frames), indicating for a possible cleaning effect of the limiter surface [7]. This opened also the discussion on the precision of the infrared measure in tokamaks which is a topic on itself (errors bars of 10% are reasonable).

Fig. 3 shows the main results of this campaign obtained from representative infrared camera data. The surface temperature increases are presented as a function of the input power. Closed marks stand for the shots where thermal equilibrium was reached, while open marks stand for shots where thermal steady state was not reached. The two dashed lines recall design calculations with two hypotheses, a purely conductive case without core heat radiation (theoretical case) and 50% radiation. Square marks are a scan of ohmic shots which are in good agreement with the second hypothesis. The other points were obtained with auxiliary heating, and the dispersion of the points is larger. Up to 4.6 MW have

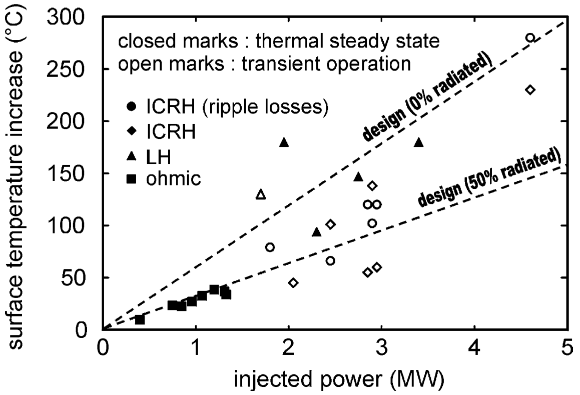

Fig. 3. Injected power and surface temperature increase of the TPL.

been injected by ICRH pulses in 2.5 s, resulting in the surface temperature increase of 290 °C on a pattern attributed to ripple losses. This input power is close to one third the design value of the TPL (15 MW). The temperature increase corresponds to a local heat flux density of 3 MW/m^2. The most powerful shots reaching steady state on the TPL were made with 3 MW of LH auxiliary heating. Some temperature increases with LH are higher than the design and would correspond to 2 MW/m^2, but this has to be confirmed and analysed more thoroughly.

4. Heat flux surface pattern

A complete view of the heat flux pattern was obtained on the image of the CCD cameras observing the recycling (Fig. 4(a)). The image is similar to design calculation given on Fig. 4(b). The leading edge is at the bottom of the image, appearing as a bright curved line. The areas close to the leading edge are located on the ion drift side, the farther ones on the electron drift side. Two main recycling zones are identified on the flat horizontal surface of the limiter. These localised areas of heat (and particle) deposition are caused by the ripple of the toroidal magnetic field, which induces a periodical oscillation of the impinging angle of the field lines on the limiter. Darker areas are private flux regions, where escaping field lines return to the limiter surface with short connection length (<1 m, see Fig. 6 in [4] for detailed explanations). This phenomenon is the limiter self-shadowing effect which is also a consequence of the large ripple in Tore Supra. These private flux areas are only exposed to radiation and charge exchange heat fluxes.

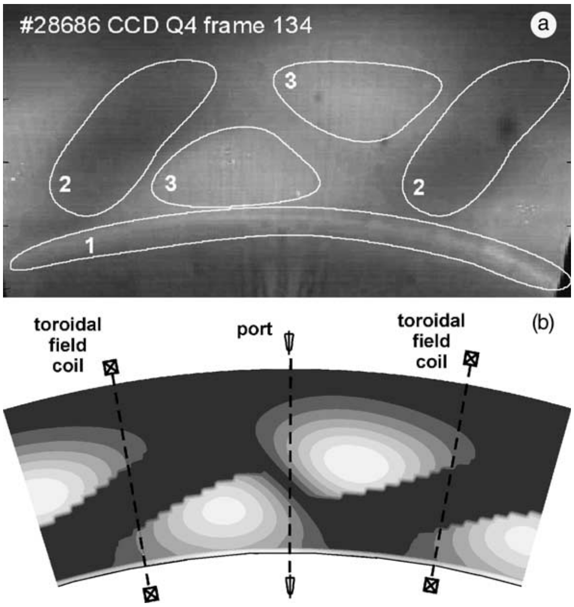

Fig. 4. (a) Light emission caused by the re-cycling at the surface of the limiter. The bright areas indicate a stronger interaction between the plasma and the limiter. (b) Heat flux pattern calculated with a TOKAFLU code (crenelation is due to finite element approximation).

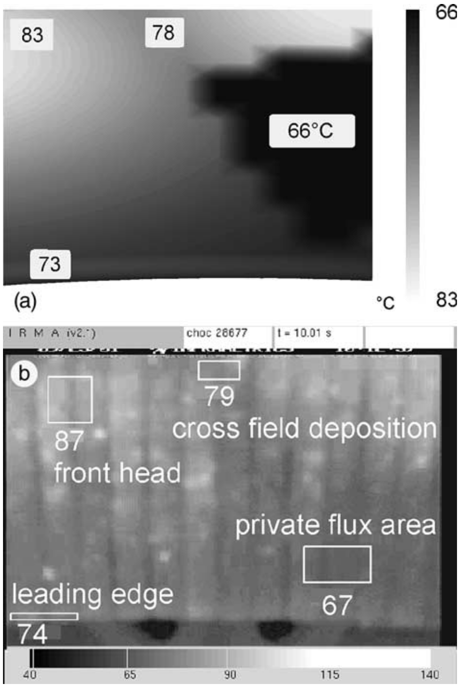

Fig. 5. (a) Map of surface temperature calculated with the heat flux code TOKAFLU. (b) Infrared image during #28677. The number in the figures show the temperature in the four characteristic areas.

Only a small fraction of this pattern was observed by the infrared camera, as shown in Fig. 5(b). The leading edge is here also at the bottom of the figure. The fingers are visible as vertical rows.

5. Quantitative analysis and comparison of modelling to observations

Emphasis is first set on the cross-field transport, observable where the field lines are tangent to the limiter surface. The heat flux should be limited there to radiation. However an excessive temperature increase is usually observed on large area limiters [8,9]. This is also the case on Tore Supra TPL. Fig. 6 shows the profile of the temperature increase along a line passing through the two temperature maxima. The solid line is the measurement, which should pass through zero (should the deposited heat flux be completely parallel, point line). Due to radiation, this local minimum can not be exactly zero but a few °C (radiation level is measured to be 2–3 °C in the private flux areas – see Fig. 2 – in

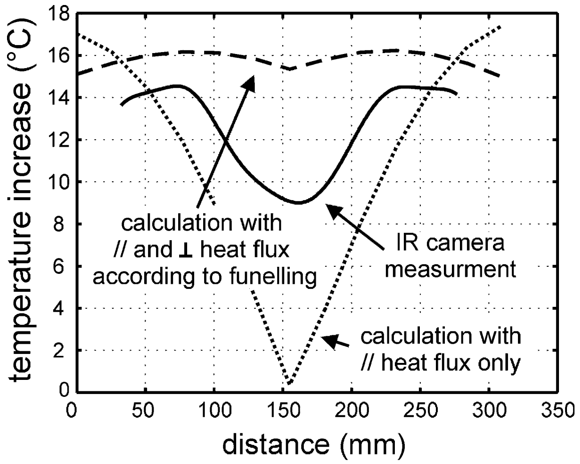

Fig. 6. Contribution of the perpendicular heat flux on the profile of the surface temperature increase.

accordance with bolometers measurements. Such temperature increases are however close to the quantification level of the acquisition system). The 10 °C measured is far beyond the radiation level. A calculation with cross-field diffusion according to Stangeby's funnelling effect [10] is also presented (dashed line) and overshoots the measure, but there are other experiments which are closer to it. According to TOKAFLUX code, this imply that the heat flux is distributed roughly equally between parallel and perpendicular components.

Another fundamental parameter of the power deposition is λ_q. Modelling has shown that the distance between the two hot areas of the limiter was directly related to λ_q and to the amount of perpendicular heat flux. This distance is measured by the image of the CCD cameras with the reasonable assumption that the recycling areas are close to the hotter areas. From the measurement of perpendicular heat flux, λ_q is evaluated to 10 mm. This value is consistent with the previous result (11 mm) analysed of the calorimetry of the individuals sectors during trim experiments [6]. It is also comparable to the value of 8 mm measured in TEXTOR with the ALT-II limiter [9] as well as other experiments [11]. During the experiments, λ_q is very stable, only a few millimetres variations were observed with the plasma current, toroidal field and plasma density.

The main parameters of heat flux deposition being measured, simulations are re-run with the correct values to check the quantitative coherence of the code with the experiments. An example is given with the temperature map calculated with the actual shot parameters (Fig. 5(a)) and the corresponding infrared image (5(b)). There are more measurements (including calorimetry of the individual sectors and the bolometry) than free parameters in the model, thus the code is constrained. The calculated surface temperature increases fit the infrared observations within 17% for areas as different as the front head, the leading edge, the private flux areas and the tangency point between the plasma and the limiter. The same coherence is obtained for the energy retrieved and the radiated heat flux.

6. Conclusions

The good agreement concerning the heat flux deposition between the calculated temperature and the various experimental results was shown. The TOKAFLUX parallel heat flux deposition code with its shadowing and cross-field diffusion add-on could predict the heat flux pattern and the power deposition both qualitatively and quantitatively. On Tore Supra TPL, the heat flux decay length was evaluated to be 10 mm, which is comparable to other machines with toroidal limiters. A heat flux caused by cross-field diffusion at the tangential point between the limiter and the plasma is observed as other tokamaks with large area limiters, and reduces the heat load on the leading edge. This heat flux level is comparable to estimations made with Stangeby's 'funnelling effect'. The heat pattern is stable even when plasma parameters vary, up to 4.6 MW of injected power. Other heat loads not related to SOL convection have been explained. The thermal time constant and stabilisation temperature are consistent with design calculation, and no evolution has appeared. The limiter is now complete (360 °C and no poloidal leading edge) and qualification work continues toward higher power. These preliminary results are encouraging with regard to ITER, which high heat flux targets remain a major technological challenge in a domain where the existing experience is rare.

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