Power Deposition Pattern on Plasma Facing Surfaces in TEXTOR-94

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Introduction

The power deposition at the divertor target plate may be a serious problem in a future fusion reactor. To overcome the heat load problem in present day devices, the power density on the surface of divertor target plates or limiters is minimised by selecting a very shallow angle of inclination between the material target and the magnetic field lines. The angle of incidence amounts typically to few degrees only. It is the aim of this contribution to investigate whether the conventionally assumed power deposition pattern, the "exponential sine law" $Q(r-ro) = Q_{//} exp[-(r-r_o)/\lambda] sin((\alpha)$ remains valid all over the deposition area. Here $Q_{//}$ is the parallel heat flux per unit area at the last closed flux surface LCFS, r_o is the radius of the last closed flux surface, λ is the power decay length and α is the angle of incidence.

It was found experimentally that for angles $\alpha < 3°$ this law is violated in several devices. Especially on machines using the inner wall as a large area limiter like TFTR [1] and TORE-SUPRA [2], the flux is never zero at the tangency point as the 'sine law' predicts. However, these results could be represented by a 'modified sine law' that takes a large heat flux perpendicular to the magnetic field into account [3]: The additional perpendicular heat flux amounts to one third of the parallel heat flux and a large power decay length of more than 3 cm was used to fit experimental data with this formula. Another approach to describe the heat flux to surfaces parallel to the magnetic field is reported from TFTR [4]. It is shown that a 'funnel effect' channels flux to the surface parallel to the magnetic field. In contradiction to the experiments performed at TORE SUPRA and TFTR the sine law holds for angles down to 0.3° at misaligned divertor tiles on the DIII tokamak [5]. These phenomena show that a general theory describing the energy flux onto plasma facing components under oblique angles is still a matter of dispute.

Experimental set-up at TEXTOR-94

As shown in Fig. 1 TEXTOR-94 is equipped with a full toroidal belt limiter (ALT-II limiter) located at a poloidal angle of 45° below the outbound mid-plane. The limiter consists of eight individually movable blades. Each blade carries 28 graphite tiles. A detailed description of the ALT-II limiter can be found in a special issue of Fusion Engineering and Design [6]. To optimise the particle exhaust, the projected radial thickness has to be small, however, there are limitations due to the incident heat flux. New tiles were designed to cope with the maximum heat flux of TEXTOR-94 (6 MW convected power over 12 s). The tiles are about 20 mm thick. The whole limiter surface would receive a relatively uniform heat flux if the magnetic ripple could be neglected. The selected shape has two big advantages for the evaluation of the radial distribution of the heat flux since 1) the plasma positioning enters less critically into the evaluation than with the previous tile design and 2) the enhanced heat flux on parallel surfaces as discussed in the introduction is no longer an important issue. The tiles are curved also toroidally to distribute the heat load more evenly. Several of the end tiles of

each blade are also more recessed than before providing the desired maximum heat flux. Due to the large wetted area, the angle of incidence of the magnetic field is smaller than 1° in the first 10 mm of the SOL. The blades form a roof type toroidal limiter where the area around θ = 45° is parallel to the last closed flux surface over a poloidal width of 3 mm of the limiter surface. For the following measurements the blades are positioned at a = 44 cm such that the individual blades have their ideal toroidal curvature; also the plasma has been radially shifted to its optimum position with respect to a symmetric tile contact. Most of the tiles consist of fine grain isotropic graphite (IG-430U); only the edge tiles of each blade consist of felt type carbon-carbon composite (CX-2002U) with an enhanced heat conductivity in the radial and poloidal directions.

The measurements were performed with a newly developed digital thermography system with a spatial resolution of about 2 mm and a thermal resolution of 12 bit with adjustable temperature range and offset.

Analysis

Aim of the measurements is to deduce the power flux along the magnetic field lines as a function of the radius from the observed surface temperature of the tiles. To reach this aim, the following steps are performed [7]: a) A 1D or 2D heat diffusion code is applied in order to evaluate the incoming local power density from the evolution of the surface temperature of the graphite tiles; the observation over the poloidal direction of the tiles contains the information of the radial power distribution, because the tile surface bends away radially from the tangent line. b) The projection effect from the direction along the magnetic field lines to the tile surface - i.e. the factor $sin\alpha$ of the first formula - has to be taken out again. For this purpose at first the geometry of the tile surface and its exact location relative to the plasma column have to be considered. Then in addition, the detailed structure of the magnetic field - i.e. B_t, B_t-field ripple and B_p at the intersection points with the surface - have to be determined. All effects such as field ripple, plasma positioning and limiter positioning enter critical into the analysis because the angle of incidence is so small. Finally also the existence of private flux zones of self shadowing of the field lines (stemming from the field line ripple) has to be considered. After these preparations, the radial distribution of the power flowing along the magnetic field lines can be calculated.

Results

To avoid errors caused by different emissivities of coated and uncoated areas, freshly cleaned limiter tiles were installed before the campaign. Fig. 2 shows the heat flux profile along the poloidal section of the limiter during the flat top time of a discharge. The heat flux caused by radiation from the plasma was calculated by bolometric data and is indicated in the figure and has been subtracted prior to the calculation. It can be seen that the upper tile gets a higher heat flux than the lower tile which is predicted by the modelling including the field ripple. The lower tile shows a fast decrease of the flux with increasing distance from the centre of the blade. This is an indication of the shadowed regions on the tile. Small perturbations can be seen at the poloidal position of the bolts. The temperatures are measured in the middle between the bolts but although the bolts are 2 cm away from the observation point, there is a small perturbation.

To derive the radial power decay law for the upper tile, the heat flux along the field lines was calculated by multiplying the measured heat flux with the sinus of the angle between the surface and the magnetic field line ('simple sine law'). This heat flux was plotted in a diagram as a function of the distance to the LCFS with logarithmic y-scale. If the simple

exponential decay is valid, the points should follow a straight line. Fig. 3 shows the result for the same discharge as in Fig. 2. It can be seen that the points seem to form two straight lines with different power decay lengths rather than one. This behaviour was observed for all evaluated discharges; the results can be fitted with a superposition of two exponential functions with different power decay lengths λ_1 and λ_2. For all cases λ_2 is in the range of 1 cm and therefore in accordance with values measured in earlier experiments with test limiters [8], the ALT-II limiter [9] with a previous set of tiles and with data of the SOL density and temperature.

The grey curve in Fig. 3 shows that the superposition of two exponential decay functions describes well the heat deposition on the upper tile whereas the heat flux is underestimated for the lower tile. As the field lines are almost parallel to the surface on the lower tile it was tried to add an additional perpendicular transport in the model to get a better fit. This caused, however, a large error for the upper tile. as the field line structure on the lower tile is very complicated (partly shadowed) and most of the energy is deposited on the unshadowed tiles, the heat load on shadowed tiles was not further considered. It can be seen that a considerable fraction of the heat flux is concentrated on a rather small area close to the roof tip of the limiter.

The decay length λ_1 was determined for the unshadowed tile and is shown as a function of plasma density in Fig. 4. It can be seen that the power decay length is in the range of 1 to 3 mm and increases with increasing density. The effect of the short power decay length is dominant in the first few mm of the SOL and at larger radii the effect of the usual power decay length takes over. The integrals over the two superposed functions showed that about 50% of the energy is deposited according to the short decay length. The power deposition in form of two exponential with roughly equal energy content has been observed for all types of discharges: for ohmic discharges, for L-mode discharges, for H-mode discharges and even during the disruptive power pulses. So far there is no complete theory to explain this phenomenon. It is speculated that the unexpected power deposition at the roof of the limiter is caused by the magnetic presheath effect at very shallow angles of incidence.

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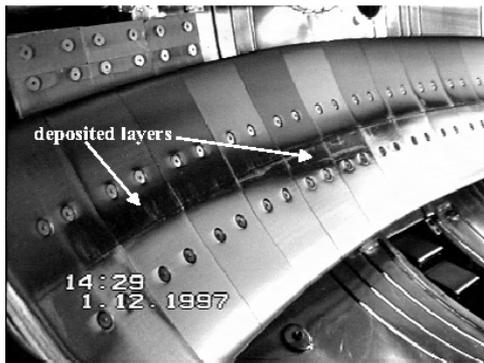[9] Finken, K.H., Baek, W.Y., Dippel, K.H., J. Nuc. Mat. **196-198** (1992) 220

Fig. 1: View to the ALT-II pump limiter. Each of the 8 blades is covered with 28 graphite tiles, which are bolted to an Inconel base plate. After long TEXTOR operation, the tiles become covered by deposited layers indicating areas of high power deposition. Before the measurements were taken, the tiles were carefully cleaned.
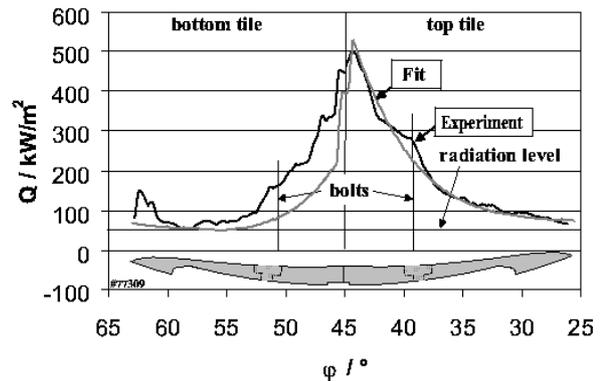

Fig. 2: Heat flux along a poloidal line of the ALT-II tiles. The top blade (45° to 27°) receives a "normal" heat flux while the lower tile (63° to 45°) is in a self shadowed region which is not accessible to the evaluation of a radial power decay function
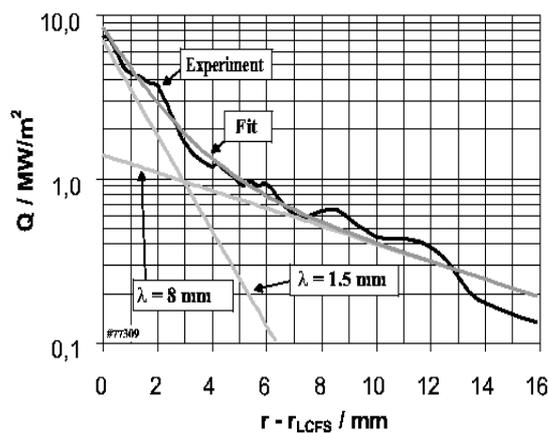

Fig. 3: Heat flux along the magnetic field lines as a function of the distance from the last closed flux surface. The radial heat flux can well be described by two exponential functions with decay lengts of 1.5 mm and 8 mm
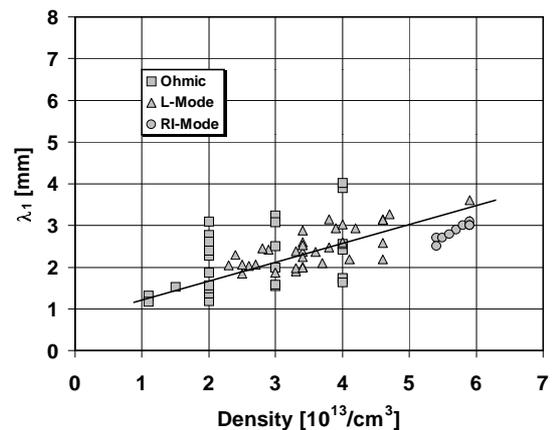

Fig. 4: Short power decay length as a function of the electron density for different modes of operation. The doubly structured decay function is found for all modes of the TEXTOR discharges.

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