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Current measurements in the scrape-off layer of Tore Supra with the new CIEL limiter

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Abstract

The current flowing between the new toroidal pump limiter of Tore Supra and the inner wall components was investigated. The response of the current to a change of the wall clearance as well as to a variation of the poloidal and toroidal magnetic field was studied. A simple estimate of the thermoelectric currents resulting from the radial temperature gradient is presented. We find, that the dependance of the measured current on the wall clearance can be reproduced by prescribing a deviation of the plasma potential from the sheath potential.

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Keywords: Edge plasma; Currents; SOL; Tore Supra

1. Introduction

The tokamak Tore Supra has been equipped in the framework of the Composants Internes Et Limiteurs (CIEL) project with an actively cooled toroidal pump limiter (TPL) situated at the bottom of the machine [1,2]. The CIEL project is dedicated to plasma facing components design for steady state operation. The TPL plays a major role in controlling the plasma density in long-pulse discharges. It is designed to withstand a convected heat flux of up to 15 MW. The pumping throats of the limiter are open towards the high field side. A biasing system is foreseen in the future to increase the pumping efficiency by inducing a poloidal plasma rotation in the scrape-off layer [3,4]. We report in this paper about measurements of the current flowing between the limiter and the vessel wall. We have studied the influence of the wall clearance and the magnetic topology on this current. The experimental findings are compared to a simple analytical estimate based on thermoelectric effects.

The current between the TPL and the wall was measured via the voltage drop ΔV at a resistance of $R_\Omega = 1\ \Omega$ placed between the limiter and the vessel. Fig. 1(a) shows the structure of the TPL. The experiments in 2001 were performed with three of the six limiter sections already equipped with water-cooled carbon tiles. These parts of the limiter were in contact with the plasma, whereas the intermediate parts, which were left blank, were positioned 70 mm behind the last closed flux surface (LCFS). Thus the current collected at the final limiter parts differs from the current collected at the blank parts. Most of the data shown in this paper is the total current from all limiter sections which were electrically interconnected.

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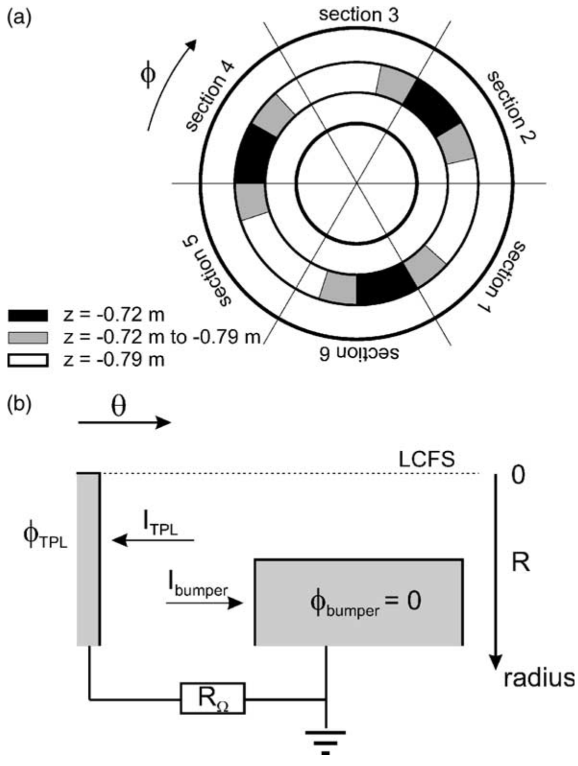

Fig. 1. (a) Schematic view on the TPL. The black parts are equipped with the final tiles, the grey parts are equipped with protection tiles and the white parts are blank. The vertical position is given in the legend, the plasma center is at $z = 0$. (b) Scheme of the scrape-off layer in the poloidal/radial plane. The current between the inner wall (especially the bumper limiter) and the toroidal limiter TPL was measured at the resistance $R_\Omega = 1\ \Omega$. The radial position of the bumper was changed in the experiment by a variation of the major radius.

2. Influence of the wall clearance

Fig. 2 shows the total current collected at the TPL during a variation of the major plasma radius. The plasma was first attached to the bumper limiter and than moved towards the low field side (LFS), with the TPL being the main limiter, until it touches the outer poloidal protection limiter. The plasma parameters were kept constant during this scan. The minor radius does not change as long as the TPL is the main limiter (wall clearance >0) and it shrinks when the plasma is attached to the bumper limiter or the poloidal protection limiter. We find for all major radii that the current is negative ranging from zero to −5 A and is thus flowing from the inner wall – mainly bumper and outer poloidal limiter – to the TPL. The current profile is qualitatively symmetric to the central position of the plasma. The deviations are expected to result from the toroidally non-symmetric protection limiter at the LFS. We will

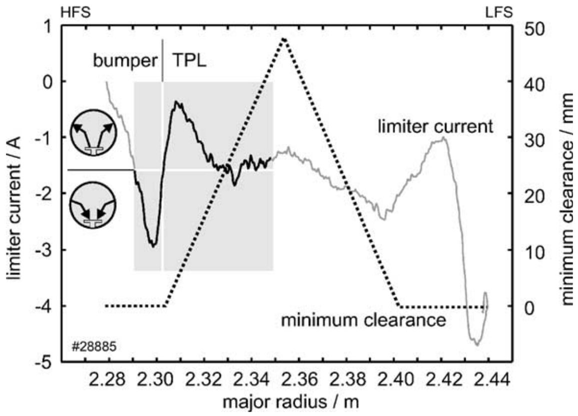

Fig. 2. Radial profile of the current flowing between the TPL and the vessel wall. Discharge in helium with a plasma current of 1 MA and an line integrated density of $5 \times 10^{19}\ \mathrm{m}^{-2}$. The plasma was shifted from the bumper limiter to the outer protection limiter LPA. The minimum clearance is either the wall clearance at the HFS or at the LFS.

concentrate on the part of the current profile in the vicinity of the bumper limiter which has toroidal symmetry. Provided that there are no poloidal temperature gradients we would expect, that the current is zero when both limiter – bumper and TPL – touch the LCFS. We attribute the observed offset to the different vertical positions of the TPL sections. We will see later that this offset vanishes if the current is collected only at the final limiter sections 2, 4 and 6 (Fig. 3). The expected offset

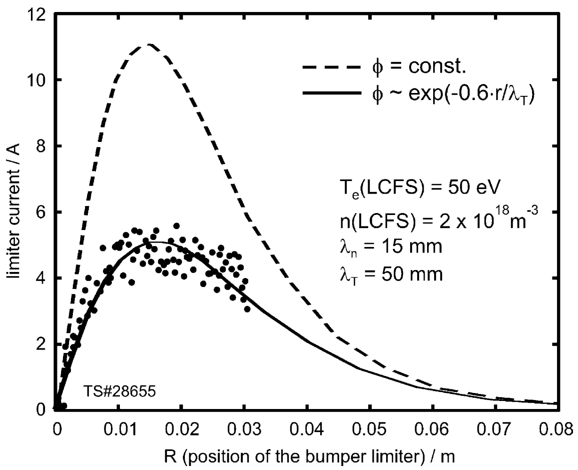

Fig. 3. Comparison of the measured current with model curves. The current resulting from a constant plasma potential and from an exponential potential profile with e-folding length $\lambda = 1.7\lambda_T$ is shown. The plasma parameters used in Eqs. (1) and (2) are given. The experimental points are the total current flowing between the equipped limiter sections (2, 4 and 6) and the wall.

and the main limiter – either bumper or TPL – is indicated in the grey box in Fig. 2. We will show in the following, that the current profile in this highlighted region can be reproduced using simple model assumptions.

For major radii less than $R_0 = 2.35$ m the current in the SOL flows mainly between the TPL and the bumper limiter. The current flowing to each of the limiter is defined by the boundary condition at the sheath entrance. This current would be zero if the plasma potential $\phi(r)$ equals the sheath potential $\phi_{sh}(r) \approx 3.2kT_e(r)/e$ for all radii r (T_e = electron temperature). A deviation $\Delta\phi(r) = \phi_{sh}(r) - \phi(r)$ leads to a finite current: either a net electron current to the limiter if $\Delta\phi(r) > 0$ or a net ion current for $\Delta\phi(r) < 0$. Integrated over the whole radial extent of the scrape-off layer, this current should be zero as long as only one limiter is in contact with the plasma. In the case of two limiter, which are electrically connected, the total current to both limiter should be zero. If the bumper limiter is at a radial position R with respect to the LCFS (Fig. 1(b)), the total current flowing to the TPL and the bumper limiter reads like

$$I_{\mathrm{bumper}}(R) = L \int_R^\infty j_{\mathrm{sat}}[1 - \exp\{e\Delta\phi/kT_e\}]\,\mathrm{d}r, \tag{1}$$

$$I_{\mathrm{TPL}}(R) = L \int_0^\infty j_{\mathrm{sat}}[1 - \exp\{e(\Delta\phi + \phi_{\mathrm{TPL}}(R))/kT_e\}]\,\mathrm{d}r, \tag{2}$$

with $j_{\mathrm{sat}} = enc_s/2$. The radial integration range extents over the whole SOL, starting from the LCFS ($r = 0$) to the wall, which is ideally at $r = \infty$. The resulting voltage drop at the resistance R_Ω is

$$\Delta V = -\phi_{\mathrm{TPL}} = -R_\Omega I_{\mathrm{bumper}} = R_\Omega I_{\mathrm{TPL}}. \tag{3}$$

The TPL potential ϕ_{TPL} has to enter in Eq. (2) since it is not negligible with respect to $\Delta\phi$ due to the choice of a relatively high R_Ω. The bumper limiter is connected to ground and its potential ϕ_{bumper} is defined to be zero. L is the effective toroidal length of the limiter taking into account the field line inclination. For $B_\theta < B_\phi$ this length is

$$L = k2\pi R_0 \frac{B_\theta}{B_\phi}, \tag{4}$$

with k being the toroidal fraction of the TPL where the current is collected (in the following we neglect the blank sections, thus $k = 0.5$).

A current profile can be extracted from the Eqs. (1) and (2) if the plasma potential is prescribed. We define the plasma potential to be $\phi = \phi_0 \exp(-r\alpha/\lambda_T)$, where α is a free parameter controlling the potential gradient with respect to the e-folding length λ_T of the electron temperature. The factor ϕ_0 is determined by the above equations. The plasma parameter density n and electron temperature T_e are taken as exponential profiles. Fig. 3 shows two current profiles resulting from the above equations for a constant plasma potential ($\alpha = 0$) and an exponential profile of the potential with $\alpha = 0.6$. The plasma parameters used in the calculation are typical for low density discharges without additional heating. The parameters measured with the reciprocating probe in such discharges are of the order [5]: electron temperature $T_e(\mathrm{LCFS}) \approx 50$ eV with e-folding length $\lambda_T \approx 50$ mm and electron density $n_e(\mathrm{LCFS}) \approx 2 \times 10^{18}$ m^{-3} with e-folding length $\lambda_n \approx 30$ mm. Only the e-folding length of the density had to be reduced by a factor 2 in the calculation in order to fit the measured current profile. However, the plasma parameters were measured far away from the limiter and it might be expected to have a poloidal variation of the density profile possibly leading to steeper gradients at the limiter. The experimental points in Fig. 3 represent the total current flowing between the equipped limiter sections (2, 4 and 6) and the wall. They are best fitted with $\alpha = 0.6$. Going back to Fig. 2, we see that the current profiles resulting from the above considerations qualitatively coincide with the profiles in the highlighted region. The reason for the difference in the absolute current values is the different configuration of the TPL. The values in Fig. 2 result from the summation of the current flowing to sections with different vertical positions but the same potential. In contrast, the values in Fig. 3 result only from the summation of the current flowing to the sections 2, 4 and 6 which were isolated from the blank parts of the limiter. The current profile measured with the plasma attached to the bumper limiter is expected to invert since the gap between the LCFS and the TPL increases and thus the current flows from the bumper limiter to the TPL. This situation is shown in Fig. 1(b) if one exchanges the labels 'TPL' and 'bumper'.

Fig. 4 shows the radial profiles of the plasma potential for $\alpha = 0.6$ and $\alpha = 0$ together with the floating potential. In the vicinity of the limiter tip the plasma potential is lower than the floating potential and a net electron current flows to the limiter. At radial position further outwards, the plasma potential is higher than the floating potential and a net ion current is collected by the limiter. Thus, the ion current flows away from the limiter tip and radially back to the TPL itself or to the bumper limiter. Such a radial profile of the potential difference $\Delta\phi$ is able to explain the current between the two limiter. The ad hoc assumption of an exponential profile of the plasma potential used here is of course very crude. The factor α implies so far no physical mechanisms. A detailed calculation of the potential is beyond the scope of this paper. A complete analysis would require to take into account the radial and poloidal currents in the SOL as it has been done for example with the TECXY code [6].

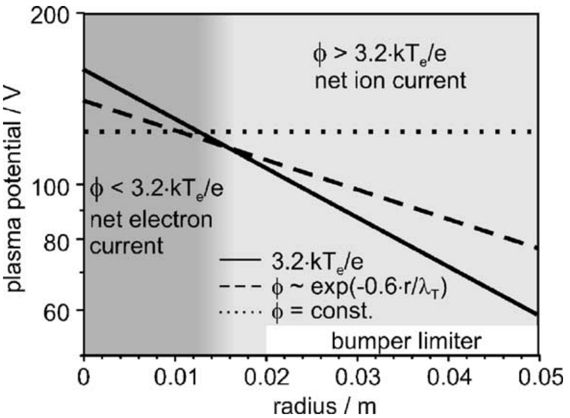

Fig. 4. Plasma potential profiles used in Fig. 3 for $R = 0.02$. If the plasma potential is lower than $3.2kT_e/e$, a net electron current is flowing to the limiter. This happens in the vicinity of the limiter tip. Radially further out the plasma potential is lower than the floating potential resulting in a net ion current to the limiter.

So far we discussed thermoelectric currents driven by radial temperature gradients and neglected those driven by poloidal temperature asymmetries in the SOL. Especially the latter type of thermoelectric currents is dominant in divertor machines which have strong temperature asymmetries between the inner and outer divertor (a survey is given in [7]). The temperature variation in parallel direction needed to built up the currents observed in the SOL of Tore Supra is in the range of a few percent. Such small gradients can certainly occur in this type of limiter SOL plasmas. We go back to the interpretation of the current profile shown in Fig. 3: the current is zero for both limiter at the same radial position, this means no poloidal temperature gradient. If the bumper limiter is retracted from the LCFS, the poloidal T_e profile has to change in order to explain the increase in the current, i.e. T_e at the bumper limiter must be lower compared to T_e at the TPL.

3. Influence of the magnetic topology

The dependence of the limiter current on the toroidal and poloidal magnetic field was investigated. These experiments were performed with all TPL sections electrically interconnected. A measurement of the absolute values of the current is therefore not possible due to the unknown offset. However, a characterization can be done by using the difference between the current maxima ΔI.

The magnetic field line inclination enters directly in the effective length L of the limiter. Provided that all other plasma parameters do not change – including the plasma potential – we find from the Eqs. (1) and (2) that

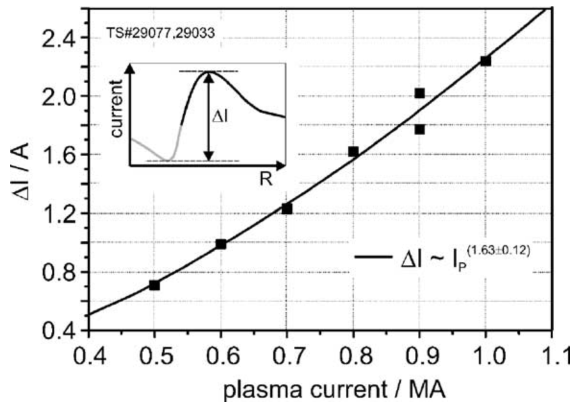

Fig. 5. Difference of the current maxima (cf. Fig. 2) as a function of the plasma current. The line integrated density was kept fixed to 3×10^{19} m^{-2}, the toroidal magnetic field was 3.85 T. All measurements were done in helium discharges.

the current scales at first order like $\Delta I \sim B_\theta B_\phi^{-1}$. Fig. 6 shows the current difference ΔI as a function of the toroidal magnetic field. We find, that the current scales like $\Delta I \sim B_\phi^{(-0.93\pm0.13)}$, which is indeed what we expect from the above considerations. From the probe measurements, we see no change in the edge electron density and temperature during this variation. The current plotted versus the poloidal magnetic field is shown in Fig. 5. ΔI increases more than linear: $\Delta I \sim B_\theta^{(1.63\pm0.12)}$. In contrast to the variation of the toroidal magnetic field we see a change in the edge density and its e-folding length during this current variation. The density increases within the shown B_θ range by about 35%, the e-folding length decreases by about 70% with B_θ. However, the trend fits in both cases quite well with what we would expect from our simple estimate.

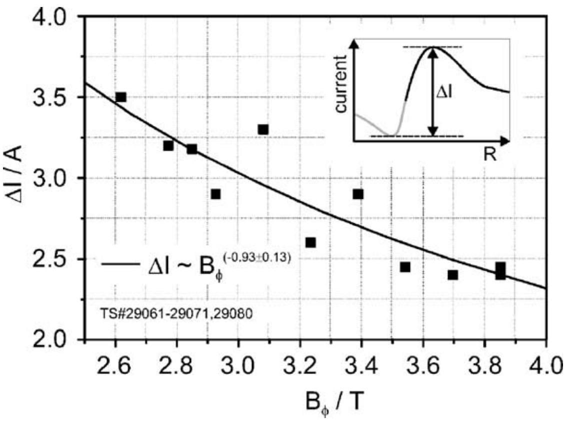

Fig. 6. Difference of the current maxima (cf. Fig. 2) as a function of the toroidal magnetic field. The line integrated density was kept fixed to 3×10^{19} m^{-2}, the plasma current was 1 MA. All measurements were done in helium discharges.

4. Summary

The current between the TPL and the wall elements is a function of the wall clearance. Thermoelectric currents driven by the radial temperature gradient can explain the observed current variation. We have reproduced the measured current for plasmas with the LCFS in the vicinity of the bumper limiter by prescribing a deviation $\Delta\phi$ of the plasma potential from the sheath potential. Such a deviation is expected to result from the radial and poloidal currents in the SOL. An exponential decay of the plasma potential at the sheath entrance is assumed and the resulting current is fitted to the measured values. This simple model shows, that the potential profile must have a larger e-folding length compared to the sheath potential profile in order to reproduce the measurements. Thus, the comparison between the model and the experiment gives evidence for a non-zero $\Delta\phi$. A quantitative analysis is difficult since the plasma parameters at the sheath entrances are unknown. Poloidal temperature gradients are expected to be small. Nonetheless, temperature variations of a few percent are sufficient to drive currents in the observed range. However, for the interpretation of the observed features this would mean a systematic variation of the poloidal temperature profile with the wall clearance. The variation of the limiter current with the toroidal magnetic field and the plasma current was investigated and can mainly be attributed to a change of the effective surface of the limiter.

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