ELSEVIER

Journal of Nuclear Materials 266–269 (1999) 788–792

journal of nuclear materials

The generation of poloidal pressure gradients in the SOL of TdeV by plate biasing

C. Boucher [a,*], B.C. Gregory [a], J.-L. Lachambre [c], J.P. Gunn [d], B.L. Stansfield [a], M. Tendler [e], TdeV Team [b]

[a] TNRS- Énergie et Matèrianx, Varennes, Qué., Canada
[b] Centre canadien de fusion magnétique, 1804 boulevard Lionel-Boulet, Varennes, Qué., Canada J3X 1S1
[c] Hydro-Québec, Varennes, Qué., Canada
[d] CEA-Cadarache, Saint-Paul lez Durance, France
[e] Alfven Laboratory, NFR, Royal Institute of Technology, Stockholm, Sweden

Abstract

In the TdeV tokamak, the convection of the plasma towards the divertors can be studied by changing the radial electric field in the scrape-off-layer (SOL) through biasing the divertor plates relative to the vacuum vessel wall. Electrostatic probes were used to determine the plasma parameters on both the outboard midplane and the bottom of the discharge. From these measurements, poloidal differences in the electron kinetic pressure were seen to arise due to the application of the biasing voltage on the neutralizer plates and that these pressure differences were correlated to the changing radial electric field. By using a linear relation between the poloidal kinetic pressure drop and the radial electric field averaged between the two observation points, an experimental value of 8.8×10^{-3} $(\Omega\ \mathrm{m})^{-1}$ is obtained for the perpendicular conductivity. A comparison with current models would tend to favor inertia and viscosity over friction with neutrals to counterbalance the $j \times B$ force during biasing although the scaling of the conductivity with the toroidal magnetic field, plasma density and plasma current should be verified to confirm this conclusion.

Keywords: Tokamak; Scrape-off-layer; Particle transport; Ion mobility

1. Introduction

A key in the search for fusion power is understanding, in a divertor tokamak, the transport of energy and particles in the scrape-off-layer (SOL) towards the divertor plates. In particular, a radial electric field across flux surfaces in the SOL, combined with the magnetic field, plays a role in the convection of particles and energy in that the resulting drifts modify the plasma flow. Biasing experiments [1,2] involving the variation of the radial electric field by changing the voltage difference between the plates and the wall are possible in TdeV due to the fact that the divertor plates are electrically insulated. This feature allows the investigation of the role played by the electric field and the resulting radial currents in the SOL.

We will start by describing the experimental set-up, the probes and how the measurements were performed. We will then discuss the results in view of available models.

2. The experiment

TdeV [3] is a medium size tokamak with a major radius of $R = 0.86$ m and minor radius $a = 0.27$ m. The experiments were performed on two sets of upper single null discharges that were produced at a line average density of 2.5×10^{19} m^3, a toroidal field of 1.5 T, a plasma current of 190 kA, and divertor coil currents of

* Corresponding author. Tel: +1-514 652 8710; fax: +1-514 652 8625; e-mail: boucher@ccfm.ireq.ca

PII: S 0 0 2 2 - 3 1 1 5 (9 8) 0 0 5 5 0 - 9

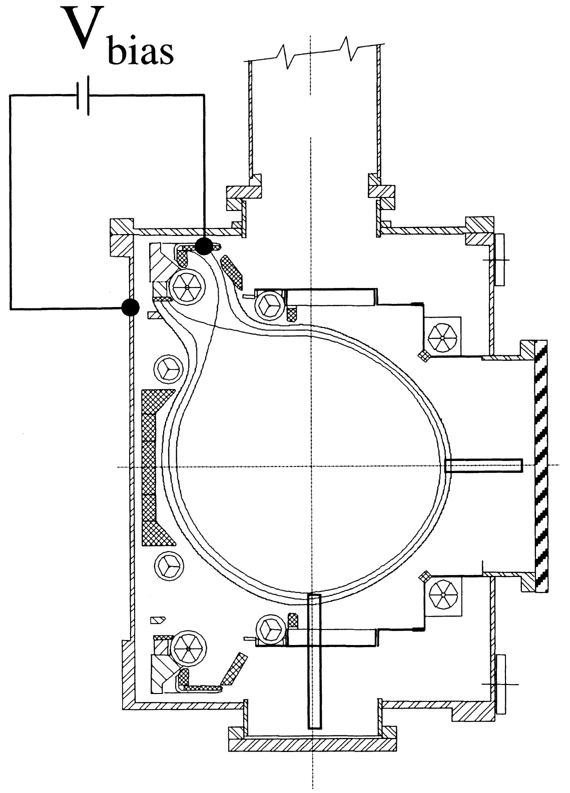

Fig. 1. Biasing circuit and probe positions.

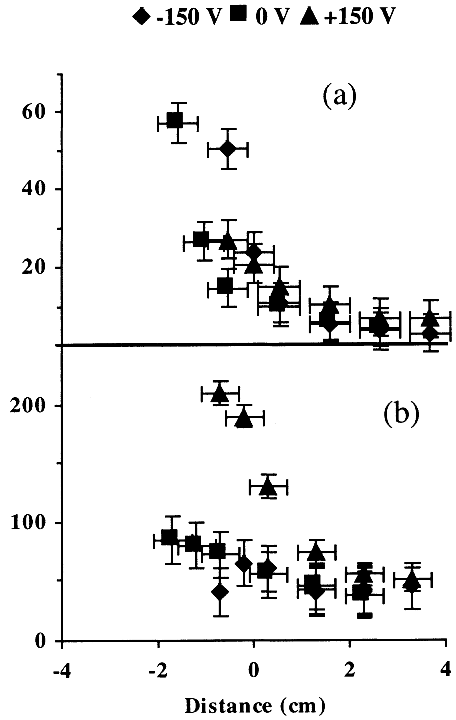

Fig. 2. (a) Pressure in J/m^3 and (b) plasma potential in Volts. Profiles in the midplane centered at $R = 1.14$ m for a divertor coil current of 6.5 kA.

6.5 and 7.5 kA. For each configuration, values of voltage between −150 and +150 V on the divertor plates were used to vary the electric field (Fig. 1).

The plasma parameters in the SOL, namely the density, temperature, potential and Mach number were measured using electrostatic probes. On the outboard midplane a probe system referred to as Gundestrup [4] was used. On the bottom of the discharge (Fig. 1), a set of standard cylindrical Langmuir probes and a Mach probe were used. The density, temperature and potential profiles were constructed from shot to shot for any given set of conditions. Fig. 2 illustrates the kinetic pressure, defined as the produce of the locally measured n_e and T_e and potential profiles obtained on the midplane for biasing voltages of −150, 0 and +150 V. Fig. 3 summarizes how the pressure and electric field varied with the biasing voltage. In these figures, it is clear that the application of the biasing on the neutralizer plates has a pronounced effect on either the pressure or the electric field. We assume that the radial electric field is radially constant over a few centimeters at or near the separatrix and can therefore be calculated from the plasma potential profiles by a linear fit through the data.

Finally, Fig. 4 summarizes the experimental results. There is a clear correlation between the pressure drop and the average radial electric field. After the theoretical discussion, the differences will be used to calculate an effective or phenomenological conductivity.

3. Theory

Current theories [5–7] of the SOL relate the poloidal distribution of kinetic pressure p and the radial ion current density j_r in the form

$$j_r B_\theta = \frac{-\Theta}{a}\left(\frac{\delta p}{\delta \theta}\right), \tag{1}$$

where $\Theta = B_\theta / B_\phi$ and a is the minor radius. This expression results from the consistent analysis of the parallel and toroidal ion momentum equations. For example, Rozhansky and Tendler [5], in the parallel component of the ion momentum equation, balance anomalous inertia and viscosity with the projection of the pressure gradient along B while the $j \times B$ contribution is strictly zero. In the toroidal equation, anomalous inertia and viscosity are balanced by the toroidal projection of $j \times B$ while the contribution due to the pressure gradient is strictly zero because it is strictly poloidal, given the assumption of toroidal uniformity of

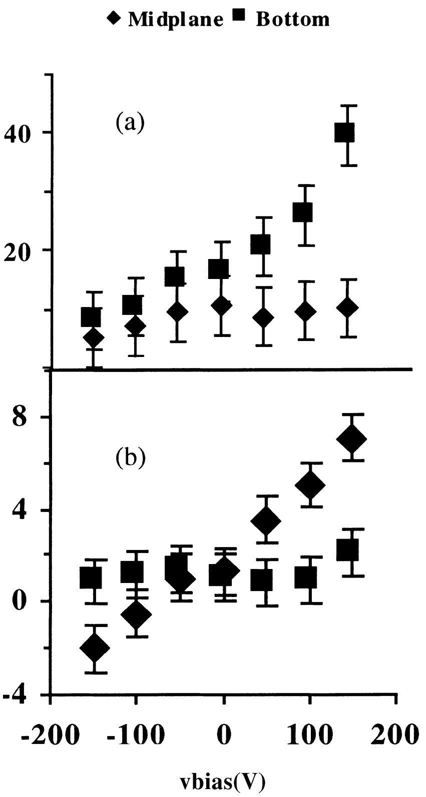

Fig. 3. (a) Pressure in J/m^3 and (b) radial electric field in kV/m as a function of the biasing voltage. Results at $R = 1.14$ m (midplane) and $Z = -0.28$ m (bottom) for a divertor coil current of 6.5 kA.

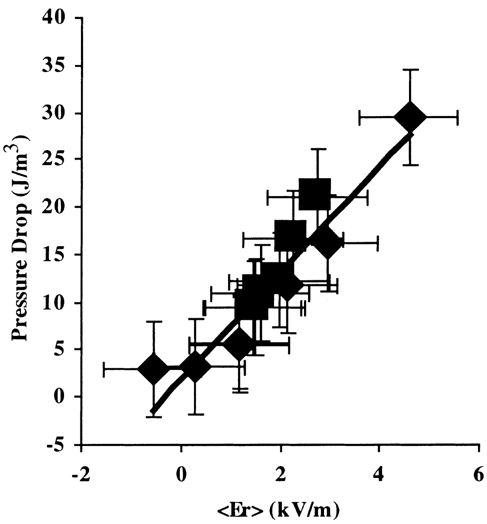

Fig. 4. Pressure drop between the bottom and midplane as a function of average electric field. The diamonds are for a divertor coil current of 6.5 kA and the squares for 7.6 kA.

the pressure. It is important to understand how the $j \times B$ force, applied perpendicular to B in the SOL plasma can affect the parallel motion. Under the action of the $j \times B$ force, a pressure gradient develops solely in the poloidal direction due to the toroidal symmetry. In turn, the parallel component of this gradient induces a parallel motion in the opposite direction, thus slowing down the sonic parallel flow and even reversing it at sufficient biasing levels. However, the amplitude of the resulting parallel (~toroidal) angular momentum has to be balanced by a force resulting from the transport of the angular momentum. This force is provided by (1) anomalous viscosity and inertia, (2) friction with the primary neutrals arriving directly from the wall, at rest in the laboratory frame of reference, (3) perpendicular viscosity due to Coulomb collisions and (4) surface dissipation on collecting surfaces and side walls. Since $v_{//} \sim v_\phi$, almost the same terms emerge in the parallel component, where the force provided by anomalous viscosity and inertia has to be balanced by the poloidal component of the pressure gradient. Thus, it has been asserted in Ref. [5] that the poloidal pressure gradient dominates on open field lines and therefore has to balance the $j \times B$ force. Although the result of a slightly different treatment, the same relation between j_r, B_θ and the poloidal variation of the pressure is obtained in Ref. [7] and is also used and discussed in Ref. [8].

In order to verify experimentally Eq. (1), we integrate it between the equator and the bottom of the single null discharge to obtain

$$p_{bot} - p_{MP} = \left(\frac{\pi}{2}\right)\sigma a B_\phi \langle E_r \rangle, \qquad (2)$$

where the subscripts bot and MP refer to the bottom and midplane, respectively. The integration is performed in the coordinate system (r,θ,ϕ), where the positive radial direction is outward from the center, the positive poloidal direction is towards the bottom from $\theta = 0$ at the outboard midplane and the positive toroidal direction is counterclockwise when looking at the torus from the top. To get Eq. (2), we have written a linear relation between the ion current density and the radial electric field in the form $j_r = \sigma E_r$. Also, $\langle E_r \rangle$ is the average value of the radial electric field between the midplane and the bottom, the two observation points. Since j_r is here the ion current density, σ is a phenomenological or effective electrical conductivity and the results could also be presented and discussed in terms of an ion mobility [9].

4. Results

Using the measurements at $R = 1.14$ m on the equator and $Z = -0.28$ m below the center of the plasma, we obtain Fig. 4. As suggested by Eq. (2), and within error bars estimated at ±5 J/m^3, the drop in kinetic pressure between the midplane and the bottom varies linearly when plotted against the average radial electric field for both values of the current in the divertor coil. The slope of the linear regression (continuous line) between the pressure drop and the average electric field can be used to calculate an effective electrical conductivity using

$$\sigma = \frac{S}{\left(\frac{\pi}{2}\right) a B_\phi}, \tag{3}$$

where S is the slope obtained in Fig. 4. The procedure is valid as long as the calculation is performed on the same flux surface. Since it is known that there are uncertainties in the position of the flux surfaces as calculated by equilibrium codes (see Ref. [8] for example) we tested the sensitivity of the calculated conductivity on the alignment of the profiles by 'shifting' the bottom profiles relative to the midplane profiles. The pressure drop was calculated for the bottom pressure using the expression:

$$p_{\mathrm{bot}} = p_{0,\mathrm{bot}} \exp\left(\frac{-x}{\lambda}\right), \tag{4}$$

where x is the position on the profile used to calculate the pressure drop, $x = 0$ being the $Z = -28$ cm and λ the e-folding length of the exponential fit for a given set of divertor coil current and biasing voltage. On the midplane, we take the value of pressure at $R = 1.14$ m. The resulting effective conductivities are shown in Fig. 5 as a function of the position. The experimental value obtained for $Z = -28$ cm is represented by a circle while those obtained using the fitted profiles by the continuous line.

On the other hand, Eq. (24) of Ref. [5] gives a relation between the total biasing current and the electric field. This equation yields, for the electrical conductivity, the theoretical relation

$$\sigma = \frac{K n m_i v_{thi}}{a B_\theta B_\phi}. \tag{5}$$

For a constant $K = 2$, using values for the density and temperature ($T_i = T_e$) for $R = 1.14$ m and Z between -30 cm and -26 cm, Eq. (5) yields the values lying in the region represented by the horizontal lines. The value of K is chosen from an analysis of the I–V curves of the biasing plates [5]. For comparison, we also include in Fig. 5 the values obtained applying Eq. (10) of Ref. [9] (vertical lines) where the $j \times B$ force is assumed to be counterbalanced by friction with neutrals [6] instead of inertia and viscosity as in Ref. [5]. The density of atoms is estimated to be 5×10^{16} atoms/m^3 as suggested by H_α measurements with a charge exchange rate of approximately 3×10^{-14} m^3/s.

This Fig. 5 shows indeed that the determination of the effective conductivity, and therefore the interpretation of the results, is sensitive to the relative radial positions of the measuring points. These results, although imprecise, nevertheless suggest that the procedure can give an order of magnitude estimate for the conductivity (or ion mobility).

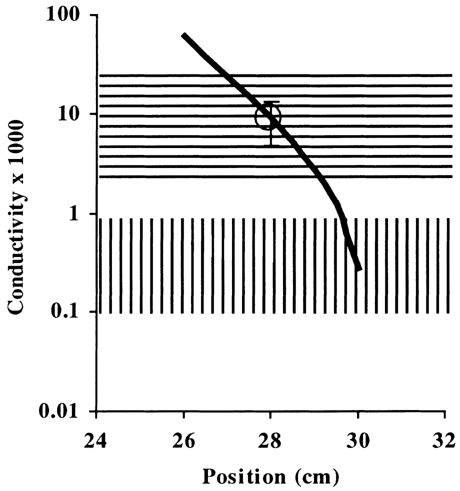

Fig. 5. Behavior of the effective conductivity in (W m)$^{-1}$ as the bottom profiles are shifted for the determination. The horizontal lines represent an estimate using the inertial and viscosity model and the vertical lines the model using friction with neutrals.

5. Discussion

We note first that the model calls for averaging on open flux surfaces, over the biased circumference of the SOL, such that if j_r is a sensitive function of the poloidal position, the result will depend on the poloidal positions observation points and the distance between them. Also, this comparison was done assuming $T_i = T_e$. If $T_i > T_e$ there are two consequences. The theoretical expression of Eq. (2) varies as $T_i^{1/2}$ so that an increase in T_i would increase the theoretical prediction of the electrical conductivity. We must remember, on the other hand, that the experimental results were obtained from probes interpreted by using $T_i = T_e$ so that taking $T_i > T_e$ would increase the ion sound speed implying that for a given ion saturation current one would get a lower density. The experimental pressures would then become a product of a reduced density with an increased temperature so that the change in temperature would result in a net increase of the experimental estimate of the conductivity as well. The net result from these two considerations is that taking $T_i > T_e$ would not change appreciably the comparison between theory and experiment although the absolute value of the electrical conductivity would be increased.

6. Conclusion

In conclusion, the above results suggest that poloidal pressure gradients exist in the SOL during biasing, that they are modified by varying the bias voltage and that the distribution of the pressure is directly related to the radial electric field. This variation implies a relation with flows along the magnetic surface and with radial currents. Furthermore, given the comparisons in Fig. 5, the present experiment would tend to favor, at least in TdeV, inertia and viscosity over friction with neutrals to counterbalance the $j \times B$ force during biasing. This tentative conclusion could be verified by determining the scaling of the conductivity (or mobility) with the toroidal magnetic field, plasma density and plasma current [9].

References

[1] B.C. Gregory et al., in: K.H. Spatscheck, J. Uhlenbush (Eds.), Contributions to High-Temperature Plasma Physics, Akademie Verlag, Berlin, 1994, p. 34.
[2] G.M. Staebler, J. Nucl Mater. 220–222 (1995) 158.
[3] R. Décoste et al., Plasma Phys. Contr. Nucl. Fusion Research 1992, vol. 1, Würzburg, Germany; International Atomic Energy Agency, Vienna, Italy, 1993 p. 383.
[4] C.S. MacLatchy et al., Rev. Sci. Instrum. 63 (1992) 3923.
[5] V. Rozhansky, M. Tendler, Phys. Plasmas 1 (1994) 2711.
[6] R. Weynants, R. Taylor, Nucl. Fusion 30 (1990) 945.
[7] A.V. Chankin, P.C. Stangeby, Plasma Phys. Control. Fusion 38 (1996) 1879.
[8] S.K. Erents et al., The location of the separatrix in the JET divertor and SOL, 22nd EPS Conference on Controlled Fusion and Plasma Physics, Bournemouth, 1995.
[9] J.-L. Lachambre et al., Nucl. Fusion 34 (1994) 1143.