Journal of Nuclear Materials 390–391 (2009) 1074–1077

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Measurements of scrape-off layer ion-to-electron temperature ratio in Tore Supra ohmic plasmas

M. Kočan [a,*], J.P. Gunn [a], J.-Y. Pascal [a], G. Bonhomme [b], P. Devynck [a], I. Ďuran [c], E. Gauthier [a], P. Ghendrih [a], Y. Marandet [d], B. Pegourie [a], J.-C. Vallet [a]

[a] CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[b] Nancy Université, BP 239, 54506 Vandoeuvre-lès-Nancy cedex, France
[c] Institute of Plasma Physics, Association EURATOM/IPP.CR, Prague 18200, Czech Republic
[d] CNRS/Université de Provence, Centre Saint Jérôme, case 232, F-13397 Marseille cedex 20, France

ARTICLE INFO

PACS:
52.40.Hf
52.70.−m

ABSTRACT

The scrape-off layer (SOL) ion (T_i) and electron (T_e) temperatures were measured in ohmic plasmas of the Tore Supra tokamak for a wide range of main plasma parameters. T_i increases strongly with the intensity of the toroidal magnetic field B_t, whereas T_e is nearly unaffected. The ion-to-electron temperature ratio $\tau = T_i/T_e \propto B_t^{2.5}$ and is a weak function of plasma density and plasma current. Close to the last closed flux surface $\tau = 2 \rightarrow 6$ so that equipartition is never reached. The SOL ion temperature *e*-folding length is about 30% greater than the electron temperature *e*-folding length meaning that τ increases with radius in the SOL.

1. Introduction

Ion (T_i) and electron (T_e) temperatures are key parameters of the scrape-off layer (SOL). They determine e.g. the amount of the heat flux convected to a surface, the relative importance of classical drift flows compared to turbulence driven flows, and physical sputtering rates. These are critical plasma parameters that constrain the design of plasma facing components in tokamaks.

While SOL T_e can be easily measured by Langmuir probes, SOL T_i is accessible only by complex electrostatic particle analyzers or, indirectly and with larger uncertainty, by e.g. charge exchange recombination spectroscopy (CXRS) [1–4], post mortem analysis of the ion deposition profiles on collector probes [5], or bolometers combined with Langmuir probes [6]. Consequently, due to the lack of systematic measurements, simple models (such as the famous two-point model [7]) assume that ions and electrons in the SOL are thermally well coupled (i.e. $T_i = T_e$). SOL measurements of T_i and T_e obtained in limiter [2,5,6,8] as well as divertor [1,3,4,9] tokamaks revealed ion-to-electron temperature ratios $\tau = T_i/T_e > 1$, which indicates that SOL ions and electrons can be thermally decoupled. However, systematic measurements of τ are sparse [10].

This paper reports on the measurements of τ in Tore Supra ohmic plasmas by a retarding field analyzer (RFA) [11]. Improving upon earlier studies, a more statistically significant database of SOL T_i and T_e is obtained for wide ranges of different plasma parameters. In addition, we report on a previously unobserved strong dependence of SOL T_i on the intensity of the toroidal magnetic field B_t. It is shown that in the SOL of Tore Supra the assumption of equal temperatures due to equipartition is not justified.

2. Experimental set-up

Tore Supra [12] is a large tokamak with a plasma of circular cross-section whose last closed flux surface (LCFS) is defined by its intersection with the bottom toroidal pump limiter. The RFA is mounted on a fast reciprocating drive which allows several insertions into the plasma during a single discharge (up to 15 until now) with a frequency of 1 Hz. Instrumental effects which lead to an overestimation of T_i by 4–12% [11] are taken into account. T_i is calculated assuming that fuel ions dominate the SOL plasma. T_e is measured by operating the RFA slit plate as a single Langmuir probe. Individual measurements of T_i and T_e are separated by ~0.5 ms. Each reciprocation provides a radial profile of T_i and T_e, typically up to 1–2 cm outside the LCFS, with a spatial resolution of about 1–2 mm and a temporal resolution of about 2 ms. The database obtained in six years of RFA operation consists of more than 600 radial profiles of SOL T_i and T_e measured in discharges with ohmic or RF heating up to 8 MW.

Fig. 1 illustrates radial profiles of SOL T_i and T_e measured by the RFA. In order to demonstrate good reproducibility of the measurements, data from 24 probe reciprocations (corresponding to 21 discharges measured in a time span of two years with 16 discharges

---

* Corresponding author.
E-mail address: martin.kocan@cea.fr (M. Kočan).

0022-3115/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2009.01.294

being measured during a single experimental session) in very similar plasmas are superimposed in one graph. Also shown in Fig. 1 is T_e measured inside the LCFS by electron cyclotron emission (ECE) and Thomson scattering (TS) diagnostics. Temperatures are plotted against the distance from plasma centre normalized to minor radius $\rho = r/a$.

One hundred and twenty-five probe reciprocations obtained from 79 discharges are analyzed. The range of the main plasma parameters is: $\bar{n}_e = 1.3 - 4.5 \cdot 10^{19}$ m^{-3}, I_p = 0.75–1.2 MA, Z_{eff} = 1.2–4.3, and B_t = 2.4, 3.1 and 3.8 T. Here $\bar{n}_e$ is the central-line-averaged density, I_p is the plasma current, and Z_{eff} is the central-line-averaged effective ion charge calculated from visible bremsstrahlung radiation. The Greenwald density fraction $\bar{n}_e/\bar{n}_e^{GW} = 0.22 \rightarrow 0.63$, where $\bar{n}_e^{GW} = I_p/(\pi a^2)$ (10^{20} m^{-3}, MA, m). Major and minor radii R = 2.39 m and a = 0.72 m, respectively. The working gas is deuterium. All database discharges are analyzed in a steady-state phase.

3. Results and discussion

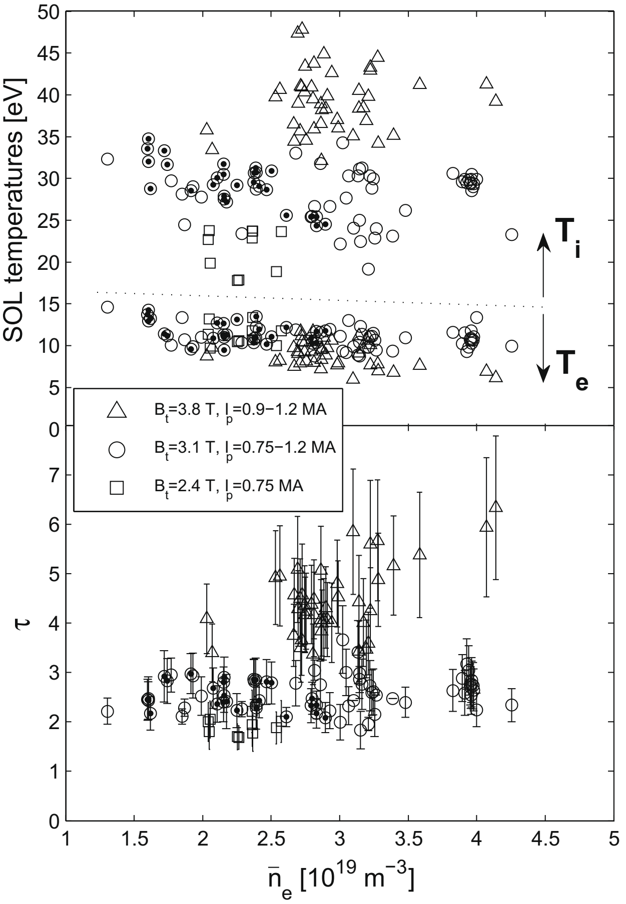

Fig. 2. Above: T_i and T_e measured 2–3 cm outside the LCFS, plotted as a function of the central-line-averaged density (dots: B_t = 3.1 T, I_p = 0.75 MA). Error bars are not plotted for clarity, but are typically 5–10%. Below: ion-to-electron temperature ratio τ. The error on τ is due to statistical errors on T_i and T_e.

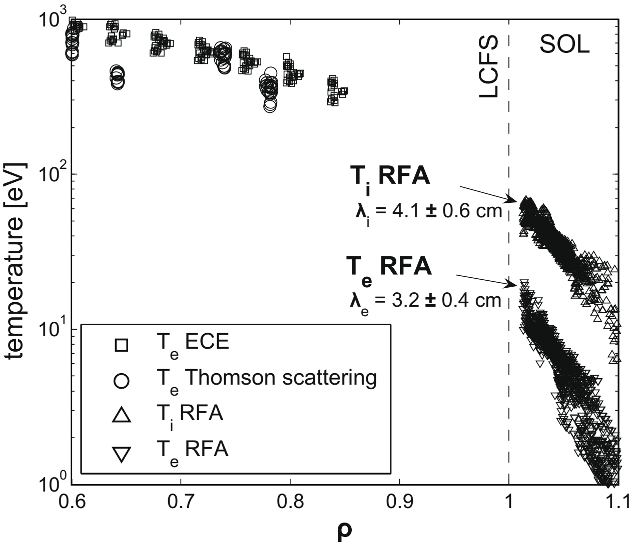

Fig. 1. Radial profiles of SOL T_i and T_e measured by RFA in 24 reciprocations characterized by similar plasma parameters, juxtaposed to T_e measured by ECE and Thomson scattering diagnostics. λ_i and λ_e are, respectively, the SOL ion and electron temperature e-folding lengths. $\bar{n}_e = 2.5 - 3 \cdot 10^{19}$ m^{-3}, I_p = 0.9–1.1 MA, and B_t = 3.8 T.

Fig. 2 shows T_i, T_e and τ plotted as a function of $\bar{n}_e$. For better statistics, measurements are averaged over a window of 1 cm, localized between 2 and 3 cm outside the LCFS. The width of the window is shorter than the typical ion and electron e-folding lengths (see below) so that it is reasonable to assume constant temperatures within the averaging region. Data are divided into three groups, characterized by different value of B_t. T_i increases with B_t, while the variation of T_e with B_t is insignificant. As a consequence, τ increases with B_t. Comparison of T_i measured at constant I_P = 0.75 MA and different B_t = 2.4 and 3.1 T (or at B_t = 3.1 T and different I_p) shows that the increase of T_i is due to an increase of B_t rather than of I_p. It should be noted that the variation of B_t (at fixed I_p) changes the degree of the probe head misalignment to the total magnetic field vector (with which the probe is supposed to be ideally perfectly aligned). For the database discharges the maximum misalignment due to B_t variation is less than 2°. As shown in [11], such misalignment should not affect T_i measurements. For B_t = 3.1 T and I_p = 0.75 MA both T_i and T_e decrease with $\bar{n}_e$. For other values of B_t and I_p the range of densities is too small to identify clear trends. The same applies for the dependence of SOL temperatures on I_p, as the data points measured at fixed B_t and $\bar{n}_e$ are characterized by a relatively small range of the plasma current. τ = 2 → 6 so that equipartition is never reached. An unconstrained non-linear least-square fit to the experimental values of τ with equal weight given to each point gives:

$$\tau = 0.095\,\bar{n}_e^{0.28\pm0.1} I_p^{0.08\pm0.1} Z_{eff}^{0.19\pm0.07} B_t^{2.5\pm0.2}. \qquad (1)$$

The only significant dependence is on B_t. The Pearson correlation coefficient of the fit is 0.89. Experimental τ is plotted against the fit in Fig. 3.

The only other parameter found thus far that strongly correlates with B_t is the core electron temperature. In Fig. 4, the measurements of SOL T_i and T_e are plotted against the electron temperature measured by ECE diagnostics at ρ = 0, $T_e(0)$. For the database discharges an empirical scaling $T_e(0) \propto B_t I_p/\bar{n}_e$ is found. Taken that in the steady-state $\tau_E = W_{dia}/P_{ohm} \propto nT/P_{ohm}$ and $P_{ohm} \propto I_p$, the increase of $T_e(0)$ with B_t roughly follows the empirical saturated ohmic energy confinement time scaling $\tau_E \propto B_t^{0.6\pm0.2}$ found in Tore Supra [13]. Here W_{dia} is the plasma energy obtained from diamagnetic measurements and P_{ohm} is the ohmic heating power. The correlation of SOL T_i with $T_e(0)$ is strong, whereas SOL T_e is practically independent of $T_e(0)$. Since the systematic measurements of core ion temperature $T_i(0)$ are not available in Tore Supra, we do not have any direct evidence how τ behaves in the core. We speculate that due to collisional coupling $T_i(0)$ increases similarly to $T_e(0)$, and that T_i in the SOL is simply related to $T_i(0)$ through radial

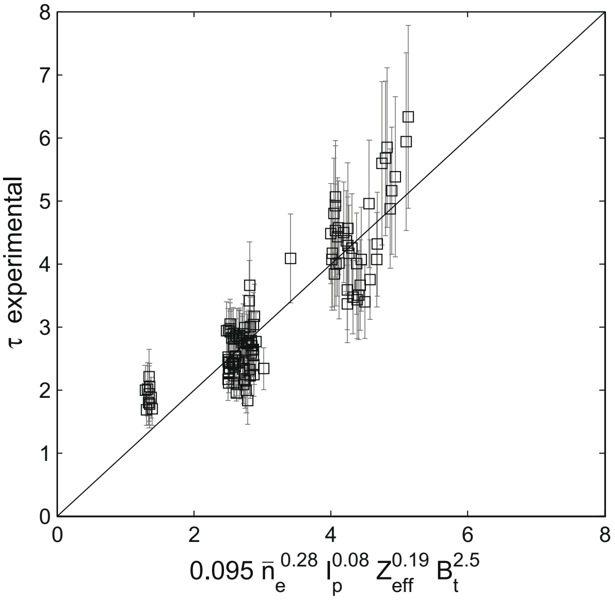

Fig. 3. Experimental values of τ plotted against the scaling law.

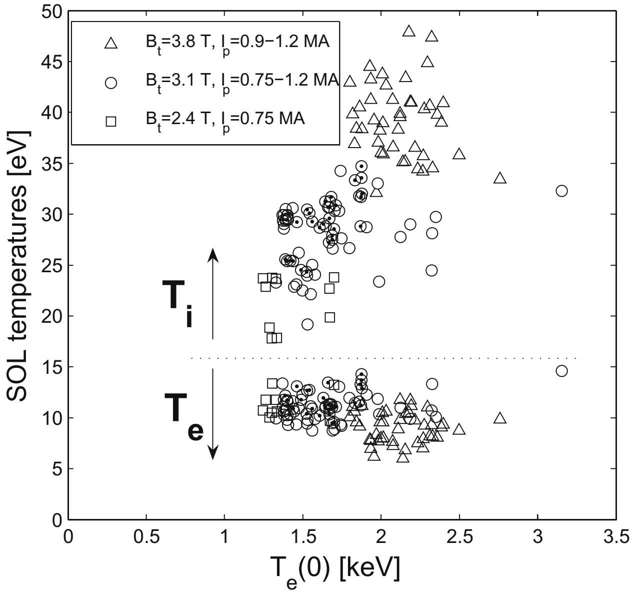

Fig. 4. SOL T_i and T_e measured 2–3 cm outside the LCFS plotted against the electron temperature $T_e(0)$ measured by ECE diagnostics at ρ = 0.

transport. A mechanism that would decouple the SOL electrons from the $T_e(0)$ needs to be identified.

It is worth noting that the database discharges were performed over a long time span that covers several experimental campaigns separated by e.g. boronization, machine opening, re-installation of the probe itself, so that the experimental conditions (in particular the charge state distribution and the amount of impurities in the SOL) could have changed. However, due to the lack of relevant measurements, it is not possible to quantify their effect on SOL temperatures. This can contribute to data scatter and confuse the scaling. In addition, as the analysis of the RFA current–voltage characteristics assumes Maxwellian deuterons, impurities with different charge-to-mass ratio can cause T_i inferred from RFA being underestimated. Separation of the components of the analyzed ion flux by charge state and temperature has been proposed in [10]. However, the model needs to specify the fractions of the total flux carried by ions with a given charge state as well as their temperatures. Such measurements are not available. The insertion of the probe into the plasma can itself modify the parameters being measured. The probe disturbance is expected to be significant if the ambipolar probe collection length L_{col} is larger than the magnetic connection length along the field line from the probe to the limiter L_{con}. For database discharges $L_{con} \cong 25 \rightarrow 40$ m. $L_{col} \cong d^2 c_s / 8D_\perp$ [14] where d = 0.04 m is the probe diameter, $c_s = \sqrt{e(Z_i T_i + T_e)/m_i}$ is the isothermal ion sound speed (with T_i and T_e in electron volts) and $D_\perp$ is the anomalous ambipolar cross field diffusion coefficient. Assuming $D_\perp$ = 1 m^2 s^{-1}, $L_{con} \cong$ 10 m so that finite connection length effects do not need to be considered.

The ion and electron temperature e-folding lengths for the database discharges, $\lambda_i \equiv T_i / |\nabla T_i|$ and $\lambda_e \equiv T_e / |\nabla T_e|$, respectively, has been evaluated from the data measured 1–4 cm outside the LCFS. The scatter of λ_i and λ_e values is relatively large without any clear trend. The average ion temperature e-folding length for the whole dataset, $\langle \lambda_i \rangle$, is by about 30% longer than $\langle \lambda_e \rangle$ ($\langle \lambda_i \rangle = 6.1 \pm 3.3$ cm, $\langle \lambda_e \rangle = 3.7 \pm 1.4$ cm), which implies that τ increases with radius in the SOL. The difference in the ion and electron temperature e-folding lengths can be easily understood as the energy removal at the sheath edge is smaller for ions than for electrons [15]. Other ion energy losses in the SOL due to e.g. ion-electron and ion-neutral collisions are negligible, as the ion-electron thermal coupling and the ion-neutral collisionality are small in the deuterium SOL plasma in Tore Supra.

Returning to general observation that T_i exceeds T_e in the SOL, this is usually explained by a filtering effect of the sheath which tends to remove fastest electrons from the distribution thus reducing effective SOL T_e [16]. Although the sheath effect can strengthen the tendency for $T_i > T_e$ in the SOL, there is increasing experimental evidence that, except at highest densities, in ohmic as well as in L-mode plasma $T_i > T_e$ a few centimetres inside the LCFS where no sheath effects exist. Values of τ = 3 → 5 at the LCFS were reported in [3,4,17,18], meaning that in some cases the sheath plays only a subsidiary role in strengthening the tendency for $T_i > T_e$ in the SOL. Similar results were obtained by Tore Supra RFA reciprocating up to the LCFS [19]. In addition, sheath filtering is governed by parallel transport, so it certainly cannot explain the strong variation of τ with B_t. Whether the fast drop of T_e compared to T_i in the edge plasma arises due to the difference in e.g. ion and electron heat/particle transport, volumetric power losses (like charge-exchange reactions, interaction of electrons with impurity ions and neutrals, etc.) is not well understood. More insight could be obtained from a simple radial transport model, provided that the relevant edge plasma parameters (e.g. ion and electron temperatures, effective ion charge, volumetric loss and source terms) are reasonably well known. Unfortunately, large uncertainties in such parameters (or lack of measurements thereof) lead to an error on the calculated variables of interest (e.g. edge profiles of the ion and electron cross-field heat diffusivities) which is much larger than their variation within the input parameter range.

4. Summary

The scrape-off layer ion and electron temperatures in a large number of ohmically heated plasmas were measured by a retarding field analyzer in the Tore Supra tokamak. T_i was found to be a strong function of the toroidal magnetic field B_t. SOL T_e is nearly independent of B_t. Variation of SOL T_i and T_e with B_t are not understood. The only other parameter found thus far which also correlates with B_t is the core electron temperature. The SOL ion temperature e-folding length is by about 30% greater than the electron temperature e-folding length so that τ increases with radius in the SOL. For 2–3 cm outside the LCFS the ion-to-electron temperature ratio $\tau = T_i/T_e \propto B_t^{2.5}$. Close to the LCFS $\tau = 2 \rightarrow 6$. This implies that e.g. the SOL plasma density calculated for $\tau = 1$ can by overestimated by a factor of 1.2 → 1.9, heat flux density conducted by ions (which is negligible for $\tau = 1$) is comparable or higher than the one conducted by electrons, the relative importance of the classical drift driven flows calculated by replacing T_i by T_e can be significantly underestimated compared to turbulence driven flows.

Simultaneous measurements of core and SOL T_i for a wider range of B_t and in diverted plasmas are needed in order to validate the scaling. Also important for the validation of SOL T_i and T_e measurements is to obtain overlapping profiles measured by RFA and by CXRS and TS or ECE, respectively.

References

[1] N. Asakura et al., J. Nucl. Mater. 241–243 (1997) 559.
[2] A. Huber et al., Plasma Phys. Control. Fusion 42 (2000) 569.
[3] M. Reich et al., Plasma Phys. Control. Fusion 46 (2004) 797.
[4] M. Reich et al., in: 31st EPS Conference on Plasma Physics, London, 28 June–2 July 2004.
[5] G. Staudenmaier, P. Staib, W. Poschenrieder, J. Nucl. Mater. 93 & 94 (1980) 121.
[6] P.C. Stangeby et al., J. Vac. Sci. Technol. A1 (1983) 1302.
[7] C.S. Pitcher, P.C. Stangeby, Plasma Phys. Control. Fusion 39 (1997) 779.
[8] G.F. Matthews et al., Nucl. Fusion 31 (1991) 1495.
[9] R.A. Pitts et al., Rev. Sci. Instrum. 74 (2003) 4644.
[10] R.A. Pitts, PhD thesis, University of London, 1991.
[11] M. Kočan et al., Rev. Sci. Instrum. 79 (2008) 073502.
[12] J. Jacquinot, G.T. Hoang, Plasma Sci. Technol. 6 (2004) 2101.
[13] X.L. Zou et al., Controlled fusion and plasma physics, in: Proceedings of 22nd European Conference, Bournemouth, 1995, vol. 19C, Part I, European Physical Society, Geneva, 1995, p. 41.
[14] P.C. Stangeby, J. Phys. D 18 (1985) 1547.
[15] P.C. Stangeby, The Plasma Boundary in Magnetic Fusion Devices, Institute of Physical Publishing, Bristol and Philadelphia, 2000. p. 160.
[16] P.C. Stangeby, The Plasma Boundary in Magnetic Fusion Devices, Institute of Physical Publishing, Bristol and Philadelphia, 2000. p. 96.
[17] A. Kreter, PhD thesis, Düsseldorf University, 2000.
[18] K. Uehara et al., Nucl. Fusion 38 (1998) 1665.
[19] M. Kočan, J.P. Gunn, J.-Y. Pascal, G. Bonhomme, C. Fenzi, E. Gauthier, J.-L. Segui, Plasma Phys. Control. Fusion 50 (2008) 125009.