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Measurements of ion temperature in the scrape-off layer of Tore Supra

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1. Introduction

The ion temperature T_i in the tokamak scrape-off layer (SOL) is of key importance for modelling plasma surface interaction processes such as physical sputtering, reflection and impurity release [1], estimation of the amount of the heat flux deposited on the divertor tiles and main chamber walls by the ELM filaments [2], etc. These are critical parameters for designing tokamak plasma facing components.

While the SOL electron temperature T_e is easily accessible by simple Langmuir probes, T_i can be measured only by complex electrostatic particle analyzers or, indirectly, by charge exchange recombination spectroscopy. Consequently, due to lack of systematic T_i measurements, the models usually assume that SOL ions are in thermal equipartition with electrons (i.e. $T_i = T_e$) [3]. This is in contrast to what was measured recently in tokamaks TEXTOR [4], ASDEX [5] and CASTOR [6] or much earlier in DITE [7-9] and JT60 [10] (i.e. $T_i > T_e$).

This paper reports on measurements of SOL T_i and T_e during an ohmic density scan in Tore Supra tokamak. We show that the assumption of equal SOL temperatures due to equipartition is not justified, even at the highest densities for which ions and electrons are expected to be fully thermalized due to strong thermal coupling. The correlation between density fluctuations level and electron heat diffusivity in the edge plasma is analyzed.

2. Experimental set up

SOL temperatures were measured by a reciprocating probe system located in a top port at poloidal angle $\theta = 79°$ with respect to the outer midplane. The system was equipped with a retarding field analyzer (RFA) ([11] and references therein). The ions are transmitted through a thin slit into the analyzer and their parallel velocity distribution is analyzed by means of a retarding electric field applied to a grid, providing measurements of T_i. T_e is measured by operating the RFA slit plate as a single Langmuir probe. Temperatures can be measured up to 3 cm inside the last closed flux surface (LCFS) with a typical spatial resolution of ~1-2 mm and a temporal resolution of ~1 ms. Measurements of T_i and T_e are separated by ~0.5 ms.

The central-line-averaged density $\bar{n}_e \cong 0.7 \rightarrow 4.2 \cdot 10^{19}\,\mathrm{m}^{-3}$ was varied on a shot-to-shot basis. Feedback control on gas puffing was used to keep the density constant during each probe reciprocation. A database consisting of 90 reciprocations was assembled. The discharges were characterized by plasma current $I_p = 0.5$ MA and toroidal magnetic field $B_t = 3.8$ T. Major and minor radii $R = 2.38$ m and $a = 0.72$ m respectively. Helium was used as a working gas, since it provides higher density limit than deuterium. All discharges were ohmic.

T_i was calculated assuming that SOL plasma is dominated by He^{2+} ions. Ions with different charge-to-mass ratios affect T_i inferred from RFA [8, 9]. These can be singly charged helium ions He^+ (overestimating T_i), or impurities (mainly carbon and oxygen) which have a tendency to underestimate $T_{\rm i}$. At high densities, for which $T_{\rm e} < 10\,{\rm eV}$, the relative abundance of He^{+} can exceed that of He^{2+} [8]. The effect of impurities is expected to play an important role at lowest $\bar{n}_{\rm e}$ where their concentration relative to He^{2+} is highest. Separation of the components of the ion flux to the analyzer by charge state and temperature has been proposed [9]. 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. Indeed, it is reasonable to expect some underestimation (overestimation) of $T_{\rm i}$ at lowest (highest) $\bar{n}_{\rm e}$. The instrumental effects which accounts for overestimation of $T_{\rm i}$ by 4-12% [11] were taken into account.

3. Results and discussion

Figures 1a and 1b show SOL $T_{\rm i}$ and $T_{\rm e}$ as well as their ratio $\tau = T_{\rm i}/T_{\rm e}$ measured by RFA, plotted as a function of $\bar{n}_{\rm e}$. For better statistics the data are averaged over 2-3 cm outside the LCFS. For comparison, the simultaneous measurements of $T_{\rm e}$ by tunnel probe (TP) [12] installed in second reciprocating drive are also shown in Fig. 1a. RFA and TP are separated toroidally by 120°. TP values of $T_{\rm e}$ are in a good agreement with those measured by RFA.

$T_{\rm i}$ decreases by a factor ~3 with the increase of $\bar{n}_{\rm e} = 1 \rightarrow 4.2\cdot 10^{19}$. Within the same range of $\bar{n}_{\rm e}$, $T_{\rm e}$ decreases by a factor of ~2. The decrease of temperatures with density can be due to the fact that $\bar{n}_{\rm e}$ increases approximately two times faster than the total plasma energy content ($\propto nT$) obtained from diamagnetic measurements. For $\bar{n}_{\rm e} = 0.7 \rightarrow 1.2\cdot 10^{19}\,{\rm m}^{-3}$, $\tau = 4 \rightarrow 7$. For $\bar{n}_{\rm e} = 1 \rightarrow 2.8\cdot 10^{19}$ ${\rm m}^{-3}$, $\tau = 7 \rightarrow 4$. For $\bar{n}_{\rm e} > 2.8\cdot 10^{19}$ ${\rm m}^{-3}$, $\tau \cong 4$. In order to verify the reproducibility of $T_{\rm i}$ and $T_{\rm e}$ measurements, $\bar{n}_{\rm e}$ was steadily decreased during experiment ($\bar{n}_{\rm e} \cong 3.8 \rightarrow 0.7\cdot 10^{19}\,{\rm m}^{-3}$, light symbols in Fig. 1a) and last discharges were repeated at high densities ($\bar{n}_{\rm e} = 3.2 \rightarrow 4.2\cdot 10^{19}\,{\rm m}^{-3}$, heavy symbols). The temperatures measured in the initial and in the final phase of experiment are very similar. It is worth noting that $T_{\rm i}$ in helium plasma is up to a factor of 2 higher compared to $T_{\rm i}$ measured in deuterium plasma at similar conditions. Similar result was obtained in DITE tokamak and was attributed to the difference in the rate by which the ions lose their energy by charge-exchange collisions with neutrals in edge plasma [9] (in deuterium the reaction cross section can be up to an order of magnitude higher compared to helium). $T_{\rm e}$ measured in helium was found to be higher by up to 25% compared to those measured in deuterium. The statistical error on $T_{\rm i}$ increases monotonically with the decrease of $\bar{n}_{\rm e}$, up to 20% at lowest densities, which is due to the fact that the RFA signal level is proportional to density.

The ion temperature e-folding length ($7\pm 3\,{\rm cm}$) close to the LCFS was found to be about a factor of 1.4 longer than the electron temperature e-folding length ($5\pm 2\,{\rm cm}$).

Thermal coupling of SOL ions and electrons was estimated from the ratio of the ion parallel transit time to the ion-electron thermalization time, $R_{\rm th} = \tau^{\rm i}_{//}/\tau^{\rm ie}_{\rm th}$, where $\tau^{\rm i}_{//} \propto L_{\rm con}/\sqrt{T_{\rm i}+T_{\rm e}}$ and $\tau^{\rm ie}_{\rm th} \propto T_{\rm e}^{3/2}/n_{\rm e}$. Here $L_{\rm con} \approx q\pi R$ (with q being the safety factor at the LCFS) is the parallel connection length and $n_{\rm e}$ is the local electron density. $R_{\rm th} < 1$ implies thermally decoupled ions and electrons. $R_{\rm th} >> 1$ implies strong thermal coupling at which the ion and electron temperatures are expected to converge. $R_{\rm th}$ was evaluated at the LCFS radius from extrapolated RFA data. Fig. 1c shows $R_{\rm th}$ plotted against $\bar{n}_{\rm e}$. $R_{\rm th}$ varies from 0.1 up to

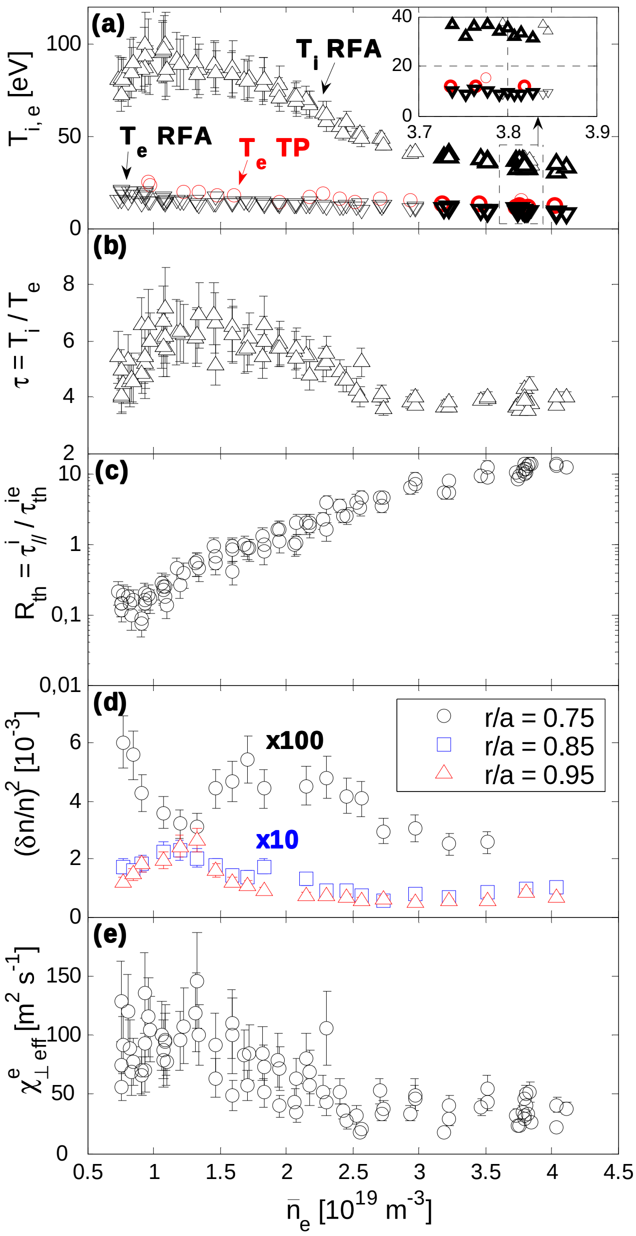

Fig. 1. (a) T_i measured by RFA. T_e measured by RFA and TP. Light symbols: high-to-low density scan. Heavy symbols: measurements of T_i and T_e repeated at high density. (b) Ion-to-electron temperature ratio τ. (c) Ratio of the ion parallel transit time to the ion-electron thermalization time R_{th}. (d) Density fluctuation level $(\delta n/n)^2$. (e) The effective cross-field electron heat diffusivity $\chi^e_{\perp eff}$ at the LCFS evaluated from RFA data and main plasma parameters. Data are plotted against the central-line averaged density $\bar{n}_e$.

15 at highest densities. For $R_{th} > 1$, τ decreases with the increase of R_{th}. For $R_{th} > 5$, τ remains at constant value of 4, i.e. far from full thermalization. The saturation of τ at highest densities can be explained by the balance between ion-electron collisions (which tends to decrease τ) and the tendency for $T_e < T_i$ on open field lines due to higher parallel thermal conductivity of electrons compared to that of ions ($\chi^e_{//}/\chi^i_{//} \propto \sqrt{m_{He}/m_e}\tau^{-5/2}$). On the other hand, the saturation of τ might also be explained by the overestimation of T_i (by up to a factor of 2) due to an increase of He^+/He^{2+} with $\bar{n}_e$.

The properties of the electron heat transport in edge plasma were analyzed by comparing the effective cross-field electron heat diffusivity $\chi^e_{\perp eff}$ with the density fluctuation level $(\delta n/n)^2$ obtained from reflectometry [13]. $\chi^e_{\perp eff}$ was evaluated combining RFA data and the main plasma parameters. $\chi^e_{\perp eff} = q_e/(en_e \nabla T_e)$ where q_e is the electron heat flux density at the LCFS and e is the elementary charge. Assuming poloidally and toroidally uniform q_e, $q_e \cong (P_{ohm} - P_{rad})/4\pi^2 aR$ with P_{ohm} and P_{rad} being the ohmic heating power and the radiated power inside the LCFS, respectively. Power lost by electrons due to ion-electron collisions inside the LCFS P_{ei} (typically less than $0.2\,P_{ohm}$ at the LCFS [14]), as well as the other electron power losses and gains, were neglected. n_e and ∇T_e were obtained from RFA data measured 2-3 cm outside the LCFS. Since the electron density and temperature increases towards the LCFS, $\chi^e_{\perp eff}$ is likely to be about one order of magnitude higher compared to electron heat diffusivity at the LCFS. Figures 1d and 1e show $(\delta n/n)^2$ at $r/a = 0.75$, 0.85 and 0.95, as well as $\chi^e_{\perp eff}$, plotted against $\bar{n}_e$. The fluctuation level increases strongly with radius ($\delta n/n$ up to 3-5% at

$r/a = 0.95$). $\chi^{\mathrm{e}}_{\perp\mathrm{eff}}$ decreases with the increase of density up to $\bar{n}_{\mathrm{e}} = 2.5\cdot10^{19}\,\mathrm{m}^{-3}$, and than saturates. The saturation of $\chi^{\mathrm{e}}_{\perp\mathrm{eff}}$ coincides with the saturation of the energy confinement time obtained from diamagnetic measurements. The difference between $\chi^{\mathrm{e}}_{\perp\mathrm{eff}}$ measured at high and low $\bar{n}_{\mathrm{e}}$ is expected to be even larger if P_{ei} is included in q_{e}, as P_{ei} is an increasing function of density. The change of $(\delta n/n)^2$ at $r/a = 0.95$ and 0.85 with density is correlated with similar variation of $\chi^{\mathrm{e}}_{\perp\mathrm{eff}}$ (the Person correlation coefficient is 0.78 and 0.77, respectively). At $r/a = 0.75$ the correlation is only 0.24. This suggests that at low densities the edge turbulence increases which leads to strong increase of electron heat diffusivity. Since $\chi^{\mathrm{e}}_{\perp\mathrm{eff}}$ and $(\delta n/n)^2$ are not evaluated at the same radial position, a certain self similarity between the radial profiles of $\chi^{\mathrm{e}}_{\perp\mathrm{eff}}$ and $(\delta n/n)^2$ is assumed.

4. Summary

Ion and electron temperatures in the SOL of Tore Supra tokamak were measured by a retarding field analyzer in ohmic density scan. SOL T_{i} was found to be by a factor of 4-7 higher than T_{e}. The ion-to-electron temperature ratio decreases with the increase of density and saturates at high densities. At low densities the edge turbulence increases significantly and leads to a strong increase of electron heat diffusivity. The saturation of the electron heat diffusivity coincides with the saturation of the energy confinement time. Similar observations has been already reported in [15, 16].

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