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Boundary turbulence and transport in density scanning experiment on TH-7 tokamak*

Xu Guo-Sheng(徐国盛)†, Wan Bao-Nian(万宝年), and Song-Mei(宋 梅)

Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, *China*

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The boundary turbulence and transport in density scanning experiment were investigated using a fast reciprocating Langmuir probe in the HT-7 tokamak. With the increase of the central line averaged plasma density, an enhanced shear of the radial electric field was observed at plasma edge, which could account for the reduction of edge transport and the improvement of global particle confinement. The reduced particle transport was demonstrated by the increase of the particle confinement time and the decrease of the perpendicular diffusion coefficient. The features of the ionization-and-radiation-driven turbulence, $\tilde{T}_{\rm e}/T_{\rm e} \sim \tilde{n}_{\rm e}/n_{\rm e}$ and $\theta_\tilde{T}_{\rm e}\tilde{n}_{\rm e} \sim \pi$, were found in the plasma edge region, which suggests the importance of the ionization and radiation in the turbulence driving.

Keywords: turbulence, boundary plasma, density scanning, particle confinement
PACC: 5225, 5255

It is generally accepted that anomalous transport in a magnetized hot plasma is due to plasma turbulence.[1] However, the dominant free energy source responsible for the turbulence in the plasma boundary region has not yet been fully identified. It is now recognized that more than one single mechanism would be needed to explain all the experimental observations of turbulence in the plasma boundary region. Particular attention has been paid to the understanding of the impact of atomic physics processes on turbulence in recent years.[2] Atomic processes such as radiation and ionization can be drivers of instabilities that might cause anomalous transport in the plasma edge region. There are several experimental observations showing the important role of atomic processes in modifying the edge turbulence and flows.[3,4] Increasing the plasma density by feedback of gas puffing will increase the neutral influx, which influences the recycling, the impurity content and the boundary molecular and atomic physical processes. These processes are important in the plasma boundary region, and can affect plasma turbulence through turbulence driving and damping.[2] Sheared flow has been found to be important in explaining the suppression of turbulence and the reduction of transport.[5,6] The role of sheared flow in ohmic confinement scaling is an unresolved question. The confinement in ohmicly heated plasmas normally falls into ALCATOR scaling. In the linear ohmic confinement (LOC) region, both the energy confinement and the particle confinement are linearly improved with the increase of plasma density. These phenomena have been reported in most tokamaks, however the physics behind the phenomena is not fully understood. The results presented in this paper indicate that the enhanced shear of radial electric field possibly accounts for the reduced turbulent transport at a higher density.

HT-7 is a circular poloidal limiter superconducting tokamak[7] with a major radius R_0=122 cm and a minor radius a=27cm. Doped graphite with SiC gradient coating is used as limiter material. The liner is made of stainless steel with a radius of 33cm. This experiment was conducted in ohmicly heated deuterium plasmas under the similar discharge conditions: toroidal magnetic field B_ϕ=2.0T, plasma current $I_{\rm p} \approx$ 140kA. There was very weak sawtooth and Mirnov activity. The plasma discharge duration was typically 1s in a current flat top range of 200–800ms. A velocity shear layer naturally occurred at the plasma edge, resulting in a steeper pressure profile; however, the con-

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†Corresponding author. E-mail: gsxu@ipp.ac.cn

finement was still low and fell into ALCATOR scaling. In the velocity shear layer, fluctuation correlation was suppressed and turbulent transport was reduced.

The fast reciprocating Langmuir probe[8] was mounted on the top of the tokamak along the central line. It was driven by a pneumatic system and can rapidly scan over 8cm in 80ms. A square array[9] (with each side being 2mm) of four identical tips was used as a triple probe to measure the time-averaged and fluctuating electron densities (n_e, $\tilde{n}_e$), electron temperatures (T_e, $\tilde{T}_e$) and plasma potentials (ϕ_p, $\tilde{\phi}_p$). Each probe tip was made of tungsten wire, 2mm in length and 0.5mm in diameter. The probe tips were carefully orientated off the magnetic field lines to avoid the tips shadowing one another. Two toroidally separated tips were used as a double probe and biased at 180 volts. These two tips measured the ion saturation current I_s and positive biased potential ϕ_+. Neglecting the electron temperature fluctuation effect,[10-13] the fluctuation of the poloidal electric field $\tilde{E}_\theta$ was deduced from two floating potentials ϕ_{f1} and ϕ_{f2} measured with two tips poloidally separated by $\Delta_\theta = 2\sqrt{2}$mm (i.e. $\tilde{E}_\theta = (\tilde{\phi}_{f1} - \tilde{\phi}_{f2})/\Delta_\theta$). The electron temperature was derived as $T_e = (\phi_+ - \phi_f)/\ln 2$, where $\phi_f = (\phi_{f1} + \phi_{f2})/2$ represented the floating potential at the middle point of the two tips. The plasma potential was estimated from the formula $\phi_p = \alpha T_e + \phi_f$, where α=2.5 [14,15] was applied in this experiment. The particle flux driven by turbulence was calculated as $\Gamma_e = \langle \tilde{n}_e \tilde{E}_\theta \rangle / B_\phi$, where $\langle \cdots \rangle$ denoted an ensemble average.[16] The data were digitized at 1 MHz with 12-bit resolution using a multi-channel digitizer.

In this experiment, we increased the central line averaged plasma density by feedback of gas puffing. Feedback control ensured that the plasma current was fixed at a certain value. With the rise of plasma density, the electron density in the plasma boundary region increased accordingly, as shown in Fig.1(a), and the electron temperature decreased, as shown in Fig.1(b). An enhanced shear was observed on the profiles of floating potentials (Fig.1(c)). The electron pressure profile was steepened at the plasma edge, as displayed in Fig.1(d), which demonstrated the reduction of edge transport at a higher density. In Fig.2, the radial electric fields were calculated as the radial gradient of plasma potential ϕ_p. From this figure, one can see that with the increase of density, the shear of the radial electric field was enhanced at the plasma edge. This is consistent with the prediction of shear suppression theory.[5,6]

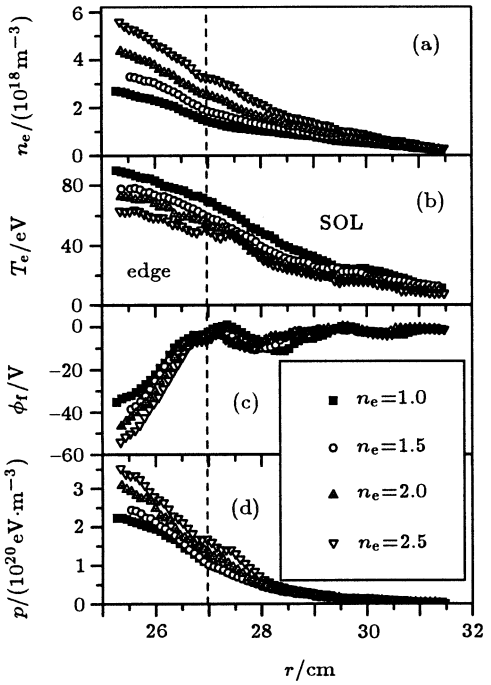


Fig.1. The radial profiles of (a) electron density, (b) electron temperature, (c) floating potential and (d) electron pressure in four central line averaged plasma density cases n_e=1, 1.5, 2, 2.5×10^{19}m^{-3}.

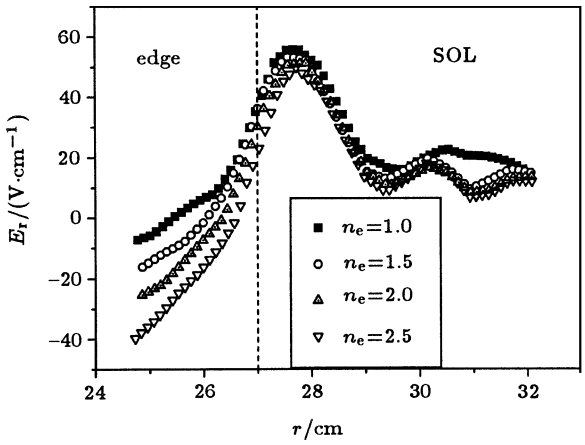


Fig.2. The radial profiles of the radial electric field in four central line averaged plasma density cases n_e=1, 1.5, 2, 2.5×10^{19}m^{-3}.

The electron density and temperature at the last closed flux surface (LCFS) are plotted in Figs.3(a) and 3(b) respectively. The electron density increased with the central line averaged plasma density, while the electron temperature decreased. The enhanced radiation is expected to account for the decrease of temperature at the plasma edge. The radial gradient of electron density at the LCFS increased, as shown in Fig.3(c), which indicates the improved particle confinement. In Fig.4, the relative fluctuation levels of electron temperature $\tilde{T}_e/T_e$, electron density

$\tilde{n}_e/n_e$ and plasma potential $e\tilde{\phi}_p/T_e$ are displayed together. These relative fluctuation levels were measured at r=25.5cm, about 1.5cm inside the LCFS. From this figure, one can see that the Boltzmann relation $\tilde{n}_e/n_e - e\tilde{\phi}_p/T_e$ was not satisfied at the plasma edge. The temperature fluctuations increased with density and reached the level of density fluctuations at a higher density. The relationship $\tilde{T}_e/T_e - \tilde{n}_e/n_e$ was approximately satisfied, especially in the higher density region. This is consistent with the prediction of the ionization-and-radiation-driven turbulence models.

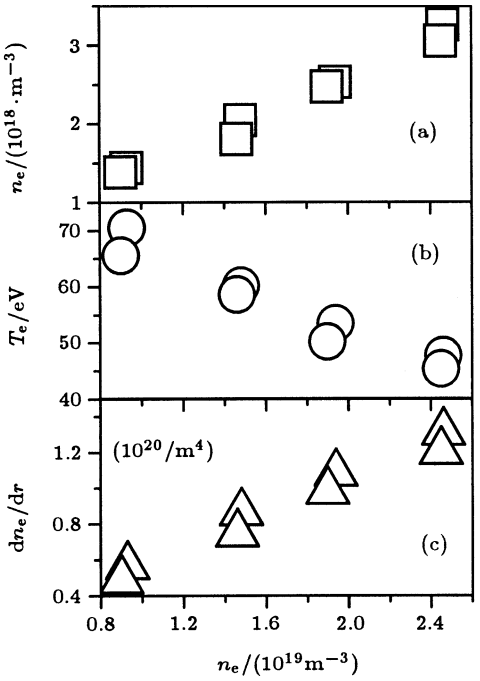


Fig.3. (a) The electron density, (b) the electron temperature and (c) the radial gradient of electron density at the LCFS plotted as a function of the central line averaged plasma density.

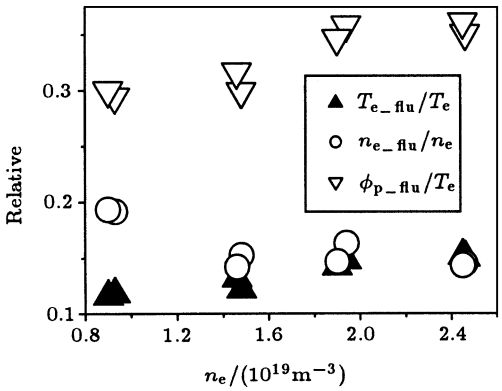


Fig.4. The relative fluctuation levels of electron temperature $\tilde{T}_e/T_e$(O), electron density $\tilde{n}_e/n_e$ (▲) and plasma potential $e\tilde{\phi}_p/T_e$(∇) measured at r=25.5 cm. The horizontal axis represents the central line averaged plasma density.

In Fig.5 (a), the e-folding decay lengths (L_n) of electron density were derived from the exponential fitting the density profiles in the SOL. It dropped with the increase of density, which denotes that the density gradient increased in the SOL. Figure 5(b) presents the turbulent particle fluxes close to the LCFS, which were calculated from probe fluctuation signals following the equation $\Gamma_e = \langle\tilde{n}_e\tilde{E}_\theta\rangle/B_\phi$. The particle flux driven by turbulence shows an increase trend with density but it is much slighter than that of the increase of density, so the calculated particle confinement time[8] increased, as shown in Fig.5(c). For comparison, the particle confinement time estimated from $H\alpha/D\alpha$ emission signals[17] is also plotted in this figure. It has a similar relationship with density. This result indicates that the global particle loss could mostly be accounted for by the electrostatic turbulence induced particle transport. Assuming that the turbulent transport measured at the top of tokamak could represent the poloidal averaged value of flux surface and this turbulent transport dominated the particle loss at the plasma edge, the effective perpendicular diffusion coefficient due to the turbulent transport can be estimated at $D_{turb} = \dfrac{\Gamma_e}{\partial n_e/\partial r}$. Figure 5(d) shows the D_{turb} measured at the location of LCFS. For comparison, the Bohm diffusion coefficient $D_{Bohm} = T_e/16B_\phi$ and the perpendicular diffusion coefficient $D_{SOL} = C_s L_n^2/2L_c$ from a simple SOL transport model[18,19] were calculated at the LCFS and are displayed in the same figure. L_c is the connection length and $C_s = \sqrt{kT_e/m_i}$ is the ion acoustic speed. Despite the uncertainties in the model and measurement they are the same in both magnitude and trend. These results indicate that, under such discharge conditions, the diffusion of Bohm type characterizes the edge confinement. The transport driven by electrostatic fluctuations plays an important role in particle confinement. The particle confinement improved with the increase of density was demonstrated by the increase of the particle confinement time and the decrease of the perpendicular diffusion coefficient.

The phase angle $\theta_T_e n_e$ between the temperature fluctuation and the density fluctuation was calculated using the correlation analysis technique [20] and a phase difference close to -π in the whole frequency range was observed in different density cases, as shown in Fig.6, where the phase difference $\theta_T_e n_e$ is plotted as a function of frequency. The measurements were carried out at r=25.5cm, about 1.5cm inside the

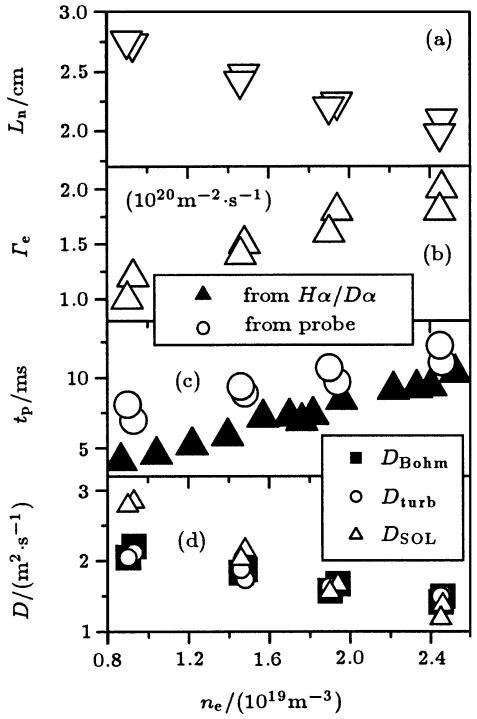


Fig.5. (a) The e-folding decay lengths (L_n) of electron density in the SOL, (b) the turbulent particle flux at the LCFS, (c) the particle confinement time estimated from $H\alpha/\alpha$ emission signals (▲) and from Langmuir probe signals (O), (d) the Bohm diffusion coefficient D_{Bohm} (■), the effective perpendicular diffusion coefficient due to the turbulent transport D_{turb} (○) and the perpendicular diffusion coefficient from a simple SOL transport model D_{SOL}(△). The horizontal axis represents the central line averaged plasma density.

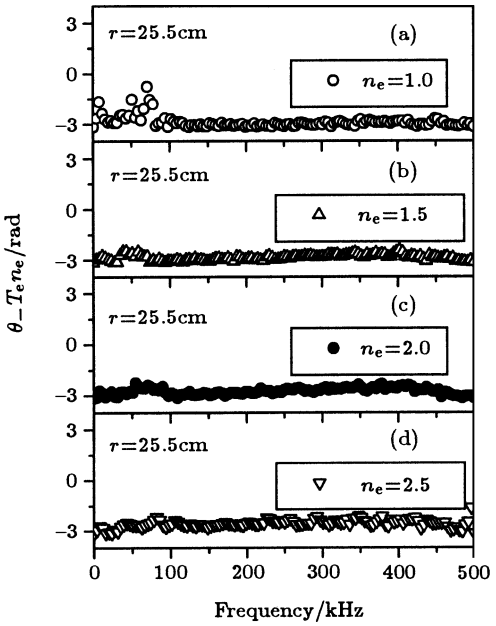


Fig.6. The phase difference spectra between the electron temperature fluctuations and the electron density fluctuations $\theta_T_en_e$ in four cases: central line averaged plasma density, (a) n_e=1×10^{19}m^{-3}, (b) n_e=1.5×10^{19}m^{-3}, (c) n_e=2×10^{19}m^{-3}, and (d) n_e = 2.5×10^{19}m^{-3}. The measurements were conducted at r=25.5 cm.

LCFS. The results indicate there seems to be no influence of the density on the phase difference $\theta_T_en_e$. The approximate -π phase difference between the electron-temperature fluctuation and density fluctuation and their close fluctuation levels ($\tilde{T}_e/T_e - \tilde{n}_e/n_e$) are two main features of the ionization-and-radiation-driven turbulence theory.[21] Although the results presented here cannot fully support the theory, they at least indicate the possible importance of the ionization and radiation to the edge turbulence in the HT-7 tokamak.

In conclusion, the boundary turbulence and transport in density scanning experiment were investigated using a fast reciprocating Langmuir probe in the HT-7 tokamak. With the increase of the central line averaged plasma density, an enhanced shear of the radial electric field was observed at plasma edge, which could account for the reduction of edge transport and the improvement of global particle confinement. The reduced particle transport was demonstrated by the increase of the particle confinement time and the decrease of the perpendicular diffusion coefficient. The features of the ionization-and-radiation-driven turbulence, $\tilde{T}_e/T_e - \tilde{n}_e/n_e$ and $\theta_\tilde{T}_e\tilde{n}_e \sim \pi$, were found in the plasma edge region, which suggests the importance of the ionization and radiation in driving the turbulence.

References

[1] Wootton A J *et al* 1990 *Phys. Fluids* B **2** 2879
[2] Hidalgo C 1995 *Plasma Phys. Control. Fusion* **37** A53
[3] Hidalgo C *et al* 1994 *Phys. Plasmas* **1** 3
[4] McCormick K *et al* 1992 *J. Nucl. Mater.* **196-198** 264
[5] Terry P W 2000 *Rev. Mod. Phys.* **72** 109
[6] Burrell K H 1998 Science **281** 1816
[7] Li J, Wan B N and Mao J S 2000 *Plasma Phys. Control. Fusion* **42** 135
[8] Wan B N *et al* 2001 *Nucl. Fusion* **41** 1835
[9] Lin H *et al* 1992 *Rev. Sci. Instrum.* **63** 4611
[10] Wang W H *et al* 2001 *Chin. Phys. Lett.* **18** 396
[11] Wang W H *et al* 2001 *Chin. Phys. Lett.* **18** 793
[12] Wang W H *et al* 2001 *Chin. Phys. Lett.* **18** 254
[13] Xu G S, Wan B N and Song M 2002 *Phys. Plasmas* **9** 150
[14] Xu G S *et al* 2002 *Chin. Phys. Lett.* **19** 1316
[15] Xu G S *et al* 2003 *Chin. Phys. Lett.* **20** 881
[16] Bickerton R J 1973 *Nucl. Fusion* **13** 290
[17] Xu G S *et al* 2003 *J. Nucl. Mater.* **313-316** 259
[18] Stangeby P C *et al* 1990 *Nucl. Fusion* **30** 1225
[19] Stangeby P C 2000 *Plasma Phys. Control. Fusion* **42** B271
[20] Ritz Ch P *et al* 1988 *Rev. Sci. Instrum.* **59** 1739
[21] Charlton L A *et al* 1994 *Phys. Plasmas* **1** 3871