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Measurements of Reynolds stress and turbulence in the boundary plasma of the HT-7 tokamak*

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Measurements of electric field fluctuations, Reynolds stress and poloidal flow have been performed in the boundary region of the HT-7 tokamak using a Langmuir probe array. Sheared radial electric field and poloidal flow have been found in the vicinity of the limiter and the turbulence has been clearly modified in this region. Furthermore, the electrostatic Reynolds stress component shows a radial gradient close to the velocity shear layer location. All results here indicate that the radial gradient of Reynolds stress may play an important role in the driving of poloidal flows in the plasma boundary region.

Keywords: Reynolds stress, poloidal flow, radial electric field, tokamak
PACC: 5225, 5235R, 5240, 5255

1. Introduction

The effect of sheared radial electric field E_r and $\boldsymbol{E}_r \times \boldsymbol{B}$ velocity on the L–H transition has been investigated and addressed in many experimental and theoretical works.[1−4] It has been found that the sheared poloidal flows play an important role in explaining the transition in magnetically confined fusion plasmas.[1] The shear in the rotation velocity can tear apart turbulent eddies and reduce the turbulent transport level. Many investigations on the fusion device are concerned with the edge plasma turbulence and poloidal flows.[5−9] Different mechanisms have been proposed to explain the creation of sheared poloidal flows in the edge plasma.[10−14] Among them, the generation of poloidal flows by plasma fluctuations via the Reynolds Stress has been investigated experimentally and widely accepted now.[15,16] It has been suggested that sheared poloidal flows can be generated in fusion plasmas due to radial variation of Reynolds stress.[17]

To investigate the role of Reynolds stress, high-resolution measurement is necessary and important. In this paper, we report the measured radial profiles of radial electric field E_r, poloidal electric field E_θ and the electrostatic Reynolds stress $R_{\rm e}$ in the plasma boundary region of the HT-7 tokamak and the clear modification of the edge turbulence by the poloidal flows and the important role of radial gradient of Reynolds stress on the driving of poloidal flows.

2. Description of the experiments

HT-7 is a medium-sized superconducting tokamak with major radius R=122cm and minor radius a=27cm defined by a graphite poloidal circular limiter.[18] The experiments are conducted in ohmic (OH) deuterium target plasma with the toroidal magnetic field B_t ∼1.9T, plasma current I_p ∼100kA, central line averaged density $\bar{n}_{\rm e}$ ∼1.5×10^{19}m^{-3}, central electron temperature $T_{\rm e}$ ∼1keV, edge electron density about 1.0×10^{18}m^{-3} and edge temperature about 30eV. The pulses last for more than 1s. Three probe tips made of tungsten wire, 0.5mm in diameter and 3mm in length, are well arranged to act as a Reynolds stress probe, as shown in Fig.1. The tip 1 and tip 2 are separated by $\Delta\theta = 2\sqrt{2}$ mm along the poloidal direction and both of them stick out radially Δr=5mm from the tip 3. The probe can be moved radially between two shots and the profiles are measured with a shot-to-shot scan during a series of identical discharges. All signals are digitized at 1MHz with 12-bit resolution using a multi-channel digitizer.

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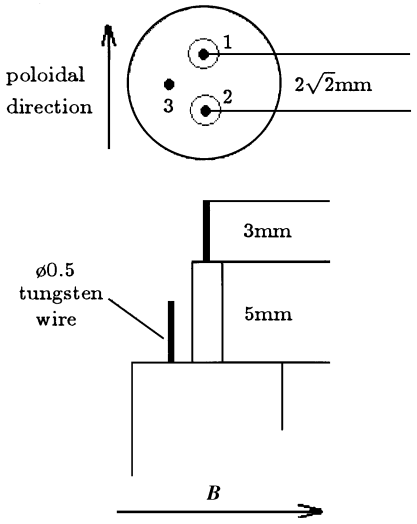


Fig.1. Schematic diagram of the three-tip Langmuir probe array acting as a Reynolds stress probe on the HT-7 tokamak.

With such a probe array, we can obtain the fluctuations of radial electric field $\tilde{E}_r$ and poloidal electric field $\tilde{E}_\theta$ from measured floating potentials by neglecting electron temperature fluctuation effects, namely $\tilde{E}_r = ((\tilde{V}_{f1} + \tilde{V}_{f2})/2 - \tilde{V}_{f3})/\Delta r$, $\tilde{E}_\theta = (\tilde{V}_{f1} - \tilde{V}_{f2})/\Delta\theta$.[19,20] Here we take the mean value of $\tilde{V}_{f1}$ and $\tilde{V}_{f2}$ as the fluctuation value of the floating potential at their radial position to reduce the phase shift error in poloidal direction. Neglecting the contribution of magnetic fluctuations, the Reynolds stress is determined by the electrostatic part, namely $R_e = \langle \tilde{V}_r \tilde{V}_\theta \rangle$, where $\tilde{V}_r$ and $\tilde{V}_\theta$ is the radial component and poloidal component of fluctuating velocity, respectively, and the angular bracket denotes the time average.[11] The $\langle \tilde{V}_r \tilde{V}_\theta \rangle$ term of Reynolds stress tensor is related to the $\boldsymbol{E} \times \boldsymbol{B}$ drift and can be calculated by the correlation between the poloidal and radial components of electric field fluctuation,[15,21] namely

$$R_e = \langle \tilde{V}_r \tilde{V}_\theta \rangle \cong -\langle \tilde{E}_r \tilde{E}_\theta \rangle \Big/ B_\phi^2. \qquad (1)$$

3. Results and discussions

The radial profile of radial electric field E_r, root-mean-square (rms) fluctuation of floating potential and its autocorrelation time t_s are shown in Fig.2. The radial electric field changes its sign in the proximity of the limiter radius location. The rms fluctuation shows an obvious drop trend when the probe is inserted into the plasma edge region while it increases radially inwards in the scrape-off layer (SOL). The relative fluctuations of electron density and plasma potential all reach their minimum values in the E_r shear region,[22] which means that the fluctuation is suppressed here. The autocorrelation time of fluctuations in the floating potential signal is also reduced inside the limiter, indicating the correlation of edge fluctuations is reduced.

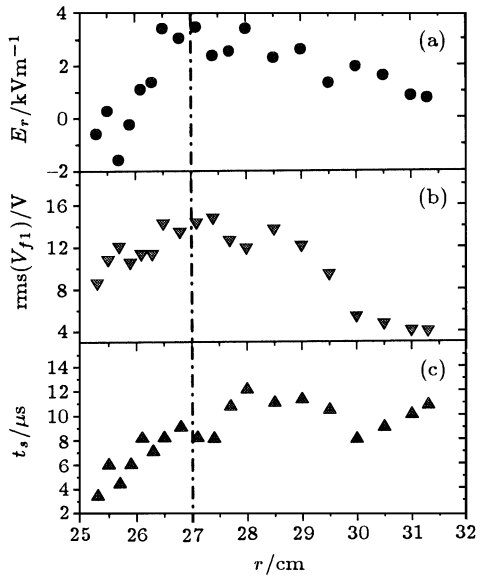


Fig.2. Profiles of (a) radial electric field E_r, (b) (rms) fluctuation of floating potential, and (c) its autocorrelation time t_s in the plasma boundary of the HT-7 tokamak.

Using a two-point correlation technique, we can obtain the spectral features and the poloidal phase velocity of fluctuations,[19,23]

$$V_{\rm ph} = \sum_{f,k} \frac{f}{k} S(f,k) \Big/ \sum_{f,k} S(f,k). \qquad (2)$$

It has been reported that the phase velocity of fluctuations in the laboratory frame of reference $V_{\rm ph}$ is determined by the $\boldsymbol{E}_r \times \boldsymbol{B}$ effects, $V_{\rm e} = E_r/B$.[7,24] From the comparison of them, as shown in Fig.3(a), we can see that the $V_{\rm e}$ and $V_{\rm ph}$ do have similar values and radial profiles. The profile of the poloidal phase velocity presents a clear change in the propagation direction of fluctuations from the ion diamagnetic direction in the SOL to the electron diamagnetic direction in the edge region. The cross point of the $V_{\rm ph}$ ($r \sim$26cm) is radially close to the zero point of the E_r and $V_{\rm e}$, which implies that the $V_{\rm ph}$ is dominated by the $\boldsymbol{E}_r \times \boldsymbol{B}$ rotation and the shear in $V_{\rm ph}$ is mainly attributable to the shear in $V_{\rm e} = E_r/B$. Furthermore, the experimental results suggest that the $V_{\rm ph}$ and the poloidal flow velocity V_θ have similar profiles in the boundary of HT-7 tokamak,[24] and therefore we use $V_{\rm ph}$ to estimate V_θ. The change of propagation direction of fluctuations also can be found in the profile

of the averaged poloidal wave number, as shown in Fig.3(b). From Fig.3(c) we can see that the spectrum of poloidal wave number is broadened in the shear layer. Correspondingly the calculated poloidal correlation length [Fig.3(d)] is obviously reduced in this region. All these show that the edge turbulence is modified by the shear.

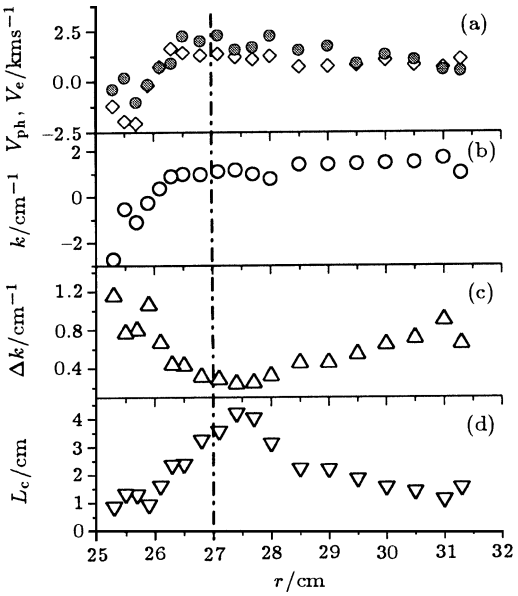


Fig.3. Radial profiles of (a) poloidal phase velocity $V_{\rm ph}(\diamond)$ and $\boldsymbol{E}_r \times \boldsymbol{B}$ rotation velocity $V_{\rm e}$ (●), (b) poloidal wave number k, (c) wave number broadening Δk, and (d) poloidal correlation length $L_{\rm c}$.

The electrostatic Reynolds stress in the boundary plasma has been computed by using the method mentioned above [Eq.(1)] and given in Fig.4(a). The electrostatic term of the Reynolds stress tensor, $\langle \tilde{V}_r \tilde{V}_\theta \rangle$, shows a radial gradient in the vicinity of the velocity shear layer location, indicating that this mechanism can play a significant role in explaining the physics of poloidal flows in the plasma boundary region. There is an obvious anomalous region (r=28–29cm) in the Reynolds stress profile. It could be input to the IBW antenna installed at r=30cm.[18] As a conductor in the tokamak, the antenna would lead to a poloidal asymmetry and influence the boundary flows. Figure 4(b) shows the fluctuation levels of the radial and poloidal velocities. Obvious suppression can be seen in the profiles of $\tilde{V}_r$ and $\tilde{V}_\theta$ near the velocity shear layer location, especially in that of $\tilde{V}_\theta$. The coherence and phase angle between them are also computed and given in Figs.4(c) and 4(d). Great modifications can be found in both the coherence and the phase angle. This means that the radial gradient in the Reynolds stress profile is not only determined by the fluctuation level of radial and poloidal velocity but also influenced by the coherence and phase angle between them.

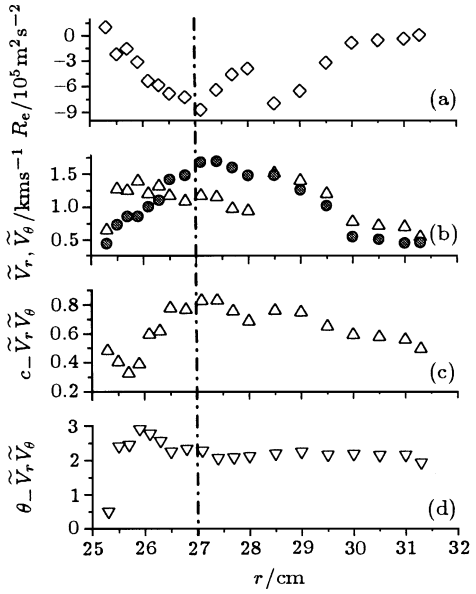


Fig.4. Radial profiles of (a) electrostatic Reynolds stress $R_{\rm e} = \langle \tilde{V}_r \tilde{V}_\theta \rangle$, (b) fluctuations of radial velocity $\tilde{V}_r$ (△) and poloidal velocity $\tilde{V}_\theta$ (●), (c) coherence between $\tilde{V}_r$ and $\tilde{V}_\theta$, and (d) phase angle between $\tilde{V}_r$ and $\tilde{V}_\theta$.

4. Conclusions

In this paper, we have reported the measurements of radial electric field, electrostatic fluctuations and Reynolds stress in the boundary region of the HT-7 tokamak using a Langmuir probe array. Sheared radial electric field and poloidal flow have been found in the vicinity of the limiter. In the shear layer region, the fluctuations have been evidently suppressed and the turbulence spectral features have been obviously modified. The electrostatic Reynolds stress component shows a radial gradient in the proximity of the velocity shear layer location. All results given in this paper indicate that the radial gradient of Reynolds stress may play an important role in the driving of poloidal flows in the plasma boundary region. Further investigations of the Reynolds stress parameter scaling and correlation with poloidal flows are needed to quantify its relative importance as compared with other mechanisms.

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