20th IAEA Fusion Energy Conference
Vilamoura, Portugal, 1-6 November 2004

IAEA-CN-116/EX/8-4Rb

Generation of Sheared Poloidal Flows by Electrostatic and Magnetic Reynolds Stress in the Boundary Plasma of HT-7 Tokamak

G.S.Xu 1), B.N.Wan 1), J.Li 1)

1) Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, P.R.China

e-mail contact of main author: gsxu@ipp.ac.cn

This is a preprint of a paper intended for presentation at a scientific meeting. Because of the provisional nature of its content and since changes of substance or detail may have to be made before publication, the preprint is made available on the understanding that it will not be cited in the literature or in any way be reproduced in its present form. The views expressed and the statements made remain the responsibility of the named author(s); the views do not necessarily reflect those of the government of the designating Member State(s) or of the designating organization(s). In particular, neither the IAEA nor any other organization or body sponsoring this meeting can be held responsible for any material reproduced in this preprint.

Generation of Sheared Poloidal Flows by Electrostatic and Magnetic Reynolds Stress in the Boundary Plasma of HT-7 Tokamak

G.S. Xu 1), B.N. Wan 1), J. Li 1)

1) Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, P.R.China

e-mail contact of main author: gsxu@ipp.ac.cn

Abstract. The radial profiles of electrostatic and magnetic Reynolds stress (Maxwell stress) have been measured in the plasma boundary region of HT-7 tokamak. Experimental results show that the radial gradient of electrostatic Reynolds stress (ERS) changes sign across the last closed flux surface, and the neoclassical flow damping and the damping due to charge exchange processes are balanced by the radial gradient of ERS, which sustains the equilibrium sheared flow structure in a steady state. The contribution of magnetic Reynolds stress was found unimportant in a low β plasma. Detailed analyses indicate that the propagation properties of turbulence in radial and poloidal directions and the profiles of potential fluctuation level are responsible for the radial structure of ERS.

1. Introduction

Sheared flows have been found to play a central role in explaining the transition to a variety of enhanced confinement regimes in magnetically confined fusion plasmas [1]. Finding the generation mechanism of sheared flows is crucial to understanding of the confinement transition and helpful for developing techniques to suppress turbulence and reduce transport. Recent progress in understanding the formation of the transport barrier in fusion plasmas reemphasized the importance of turbulence-driven flows via Reynolds stress (RS) [2]. In neutral fluids the RS not only leads to turbulence viscosities, but also generates a number of geophysical flows such as the quasi-biennial oscillation [3,4]. The importance of the RS as a flow generation mechanism in neutral fluids suggests that it should not be ignored in plasma turbulence. Since sheared flows suppress turbulence through the shear decorrelation mechanism [5], a feedback loop between turbulence and sheared flows will be closed, if flows could be driven by fluctuations. This feedback loop allows turbulence exist to in a self-regulated state, which might be able to self-consistently explain the spontaneous confinement mode transition when auxiliary heating power exceeds a certain threshold [6]. Both the nonlinear gyrokinetic simulations of plasma turbulence in the confinement region [7] and the nonlinear gyrofluid simulations of boundary turbulence [8] give prominence to the mechanism of flows generated by turbulence through the action of RS. In these simulations, the pressure gradient profile is input parameter and a static velocity shear always accompanies a steep pressure profile. What is interesting is on that the ion orbit loss mechanism for flow generation, which is caused by interaction with the materiel [9], is not included in above simulations. As a result, nonlinear turbulence simulations support the understanding that in steady state turbulence dominates the flow driven process. The measurement of RS in fusion plasmas is difficult but is crucial to a detailed understanding of transport barrier physics. So there is considerable interest in the quantitative investigation of the contribution of RS in the process of sheared flows generation, and, possible more important, to understand the radial structure of the turbulence RS. Up to now, the measurements of RS are not sufficient,[1] and no experimental result regarding the whole poloidal momentum balance with the complete RS expression has been reported so far. Experiments addressing this problem to date have only presented the estimation of the electrostatic Reynolds stress (ERS).[10,11] The role of magnetic Reynolds stress (MRS) in the poloidal flows driven has never been demonstrated in experiments and still need to be examined. This experiment presents the first measurement of the whole poloidal momentum balance with the complete RS expression. It is found that the flow shear generated by ERS can quantitatively account for the sheared velocity pattern observed at the plasma edge. And in this paper the first explanation of the radial structure of ERS is presented.

2. Poloidal Momentum Balance

To understand the behavior of poloidal flows, flow damping needs to be considered. The poloidal flow damping, called the neoclassical viscosity or magnetic pumping, arises from ion-ion collisions and the asymmetry of poloidal variation in a torus [12]. In this experiment, the profile of flow damping was calculated using measured profiles. We observed a poloidal velocity shear at the plasma edge, which results in the edge pedestal, could be explained by the ERS. The neoclassical damping of poloidal flow and the damping due to charge exchange processes are balanced by an accretion due to the radial gradient of ERS, which sustains the equilibrium sheared flow structure in a steady state. Almost all quantities in the poloidal flow evolution equation [13] $\frac{\partial V_\theta}{\partial t} = -\frac{\partial}{\partial r}\left(\left\langle \tilde{V}_r \tilde{V}_\theta \right\rangle - \frac{\left\langle \tilde{B}_r \tilde{B}_\theta \right\rangle}{\rho_m \mu_0}\right) - \mu V_\theta$ were measured in this experiment, where V_θ is the poloidal flow velocity in the laboratory frame, $\tilde{V}_r$ and $\tilde{V}_\theta$ are the radial and poloidal velocity fluctuations of turbulence, $\left\langle \tilde{V}_r \tilde{V}_\theta \right\rangle$ is the ERS tenser, the brackets $\langle \cdots \rangle$ denote an ensemble average, $\tilde{B}_r$ and $\tilde{B}_\theta$ are the radial and poloidal magnetic fluctuations dominated by small scale magnetic turbulence, $\left\langle \tilde{B}_r \tilde{B}_\theta \right\rangle$ is the MRS tenser, and μ is the damping rate of the poloidal flows. Elaborate measurements of the whole poloidal momentum balance with the complete RS expression were carried out in the boundary plasmas of HT-7 tokamak using a triple-tip-array Langmuir probe and an insert-able magnetic probe.

3. Experiment Setup

HT-7 is a superconducting tokamak [14] with two circular poloidal limiters separated in the toroidal direction by 180° and a high-field-side belt limiter. This experiment was conducted in ohmically heated deuterium plasmas with $R_0 = 122$ cm, $a = 27$ cm, $B_\phi \cong 1.98$ T, $I_p \cong 120$ kA, $\bar{n}_e \cong 1.5\times10^{19}$ m^{-3}, $T_{e0} \cong 0.7$ keV, $Z_{eff} \cong 1.9$ and loop voltage $V_l \sim 1.3$ V. The discharge duration was typically 1 s. The edge safety factor was $q_a \sim 4.9$ and there was very weak sawtooth and Mirrov activity. The poloidal β is not high ($\beta_p \sim 0.4$) as measured by magnetic diagnostics. A naturally occurring velocity shear layer exists at the plasma edge, which results in a steeper pressure profile; however, the confinement is still low and falls to ALCATOR scaling.

An insert-able magnetic probe with two perpendicular coils was mounted on the top of the tokamak along the central line. The two coils were used to achieve local measurements of $\tilde{B}_r$ and $\tilde{B}_\theta$. Graphite shields allowed reliable measurement 3 cm inside the last closed flux surface (LCFS). The ERS $\left\langle \tilde{V}_r \tilde{V}_\theta \right\rangle$ was measured with a triple-tip-array Langmuir probe with two tips poloidally separated by $\delta_\theta = 3$ mm and sticking out $\delta_r = 5$ mm from another tip. Each tip was 2 mm long and 0.5 mm in diameter and was used to measure floating potential (ϕ_{f1}, ϕ_{f2}, ϕ_{f3}). Then the poloidal and radial electric field fluctuations can be calculated as $\tilde{E}_\theta = \left(\tilde{\phi}_{f1} - \tilde{\phi}_{f2}\right)/\delta_\theta$ and $\tilde{E}_r = \left(\tilde{\phi}_{12} - \tilde{\phi}_{f3}\right)/\delta_r$, neglecting the contribution from electron temperature [11,15,16]. Note that $\tilde{\phi}_{12} = \left(\tilde{\phi}_{f1} + \tilde{\phi}_{f2}\right)/2$. Thus, the radial and poloidal E×B velocity fluctuations are calculated as $\tilde{V}_r = \tilde{E}_\theta / B_\phi$ and $\tilde{V}_\theta = \tilde{E}_r / B_\phi$. The probe was also mounted on the top of the tokamak along the central line and operated with shot-to-shot scanning. Both the probe tips and the shield tube were made of graphite. The data were sampled at 1 MHz with 12-bit resolution using a multi-channel digitizer.

4. Magnetic Fluctuations

Magnetic fluctuations were calculated from the integral of magnetic coil signals with mean value removed. As shown in Fig1(a) and (b), the auto power spectra of radial and poloidal relative magnetic fluctuations exhibit the typical broad band (1 ~ 200 kHz) feature. They peak at around 50 kHz and decay in both low-frequency and high-frequency regions. The decay index in the high-frequency region is about –2, which is close to that of electrostatic fluctuations. The spectra shape at plasma edge is similar to that in the scrape off layer (SOL). Mirrov activity is weak as shown in Fig1, especially in the SOL. As a result of low β, the fluctuation level is low, but increase monotonically inward (Fig1(c)). The electron thermal conductivity caused by magnetic fluctuations was calculated with the often-used quasilinear estimate [17] $\chi_e = qR_0 V_{Te}\tilde{b}_r$, where q is the safety factor, V_{Te} is the electron thermal velocity and $\tilde{b}_r = \tilde{B}_r / B_\phi$ is the relative amplitude of $\tilde{B}_r$. The calculated χ_e < 0.5 m^2s^{-1} in the measured region is much smaller than that estimated from power balance analysis at the plasma edge, which is larger than 5 m^2s^{-1} in such discharges [18]. But it increases monotonically inward (Fig1(d)).

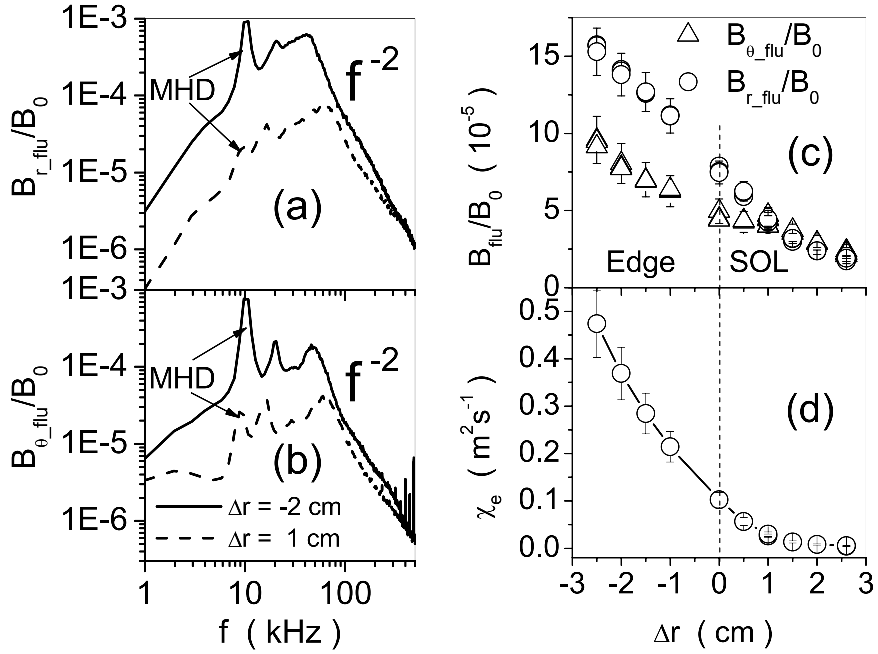

FIG. 1. The auto power spectra of (a) $\tilde{B}_r/B_0$, (b) $\tilde{B}_\theta/B_0$, at the plasma edge Δr = –2 cm and in the SOL Δr = 1 cm. The radial profiles of (c) $\tilde{B}_r$ and $\tilde{B}_\theta$ relative fluctuation levels (d) χ_e caused by magnetic fluctuations.

5. Electrostatic and Magnetic Reynolds Stress Profiles

Fig2(a) and (b) show the profiles of electron density and temperature respectively, which were measured with a reciprocating Langmuir probe [19]. The radial profile of MRS is plotted in Fig2(c). It shows a gradient in the proximity of the shear layer, however, the gradient (~ $3\times10^7 ms^{-2}$) is small compared to the gradient (~ $2\times10^8 ms^{-2}$) of ERS, as shown in Fig2(d). So the electrostatic component dominates the RS tensor in present experiment. A clear structure can be seen in the radial profile of ERS. Its gradient changes sign across the LCFS, which implies that mean flows driven by ERS have different directions on the two sides of the LCFS. A small jump in the profile can be found at $\Delta r = 1.5$ cm in the SOL, we found that the Faraday shield of ICRF antenna is located right there, which can account for the structure. The existence of Faraday shield reduced the connect length of magnetic field lines; this may influence the propagation properties of turbulence and results in a small structure similar to that close to the LCFS.

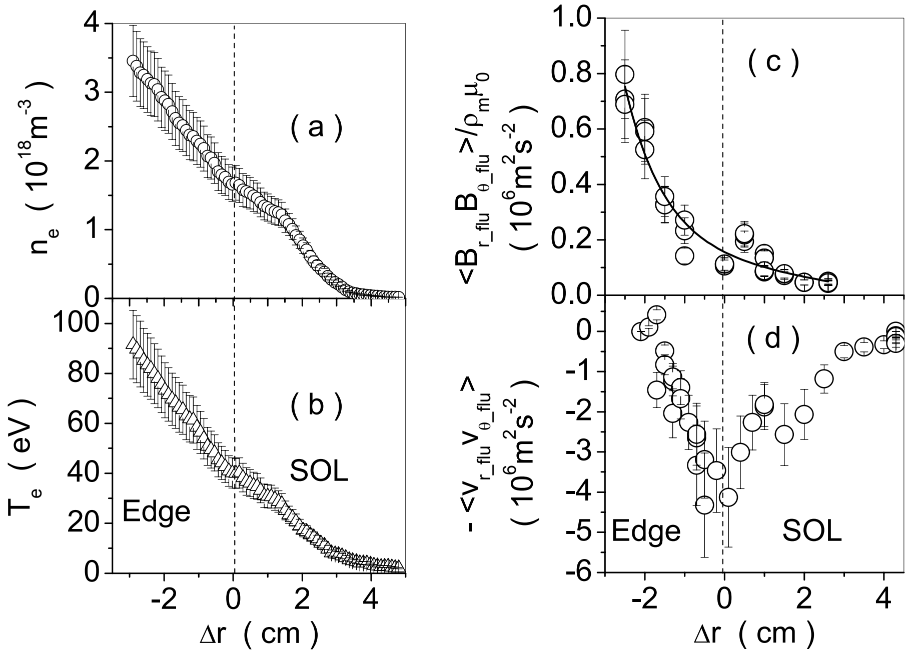

FIG. 2. The radial profiles of (a) electron density n_e, (b) electron temperature T_e, (c) magnetic Reynolds stress, and (d) electrostatic Reynolds stress.

According to the theory [2,20], for the RS to have a nonzero contribution, the radial wave propagation and radial asymmetry of turbulence are required. The standard two-point correlation analysis technique [21] was applied to the two radially separated fluctuations signals $\tilde{\phi}_{12}$ and $\tilde{\phi}_{f3}$ to investigate the radial propagation of electrostatic turbulence. It was found that turbulence is radially asymmetric and propagates in the radial direction. In poloidal direction, the turbulence propagates in the ion diamagnetic direction in the SOL (Fig3(a) $\Delta r = 1$ cm), changes to the electron direction at the plasma edge ($\Delta r = -0.2$ cm and $\Delta r = -0.9$ cm). At the plasma edge, the k_θ spectra are obviously broader than those in the SOL, which means the poloidal correlation is significantly reduced at the shear layer. In radial direction, the turbulence propagates outward in the SOL in this experiment (Fig3(b) $\Delta r = 1$ cm). When the probe top just across the LCFS, the turbulence is observed still propagating outward, but with a small averaged k_r (Fig3(b) $\Delta r = -0.2$ cm). When the probe top is inserted across $\Delta r = -0.5$ cm, the direction reverses and the turbulence is observed propagating inward in this experiment (Fig3(b) Δr = −0.9 cm). The delay between the reversion of k_θ and k_r is a result of the particular configuration of the triple tips array. Since tip1 and tip2 stick out 0.5 cm from tip3, when the tip1 and tip2 have just across the LCFS, the tip3 is still in the SOL. As a result, the conclusion is that both the k_θ and the k_r reverses across the LCFS in this experiment, in the SOL turbulence propagates in the ion direction and outward, while in the plasma edge region it propagates in the electron direction and inward. From Fig3(b), one can also see that at the shear layer the k_r spectra are slightly broader than those in the SOL. In the SOL the width of k_r spectra is approximately two times of that of k_θ spectra, while at the plasma edge two spectra have similar width, which implies the turbulence tends to be isotropic in the shear region. This observation is consistent with the prediction of shear decorrelation theory. Fig3(c) shows the ϕ_f fluctuation level. The decrease of fluctuation level at the plasma edge may be a result of the shear suppression. Assuming the boundary turbulence is a kind of drift wave, which propagates in both poloidal and radial directions, the ERS gradient can be analytically expressed as $\frac{\partial\langle\tilde{V}_r\tilde{V}_\theta\rangle}{\partial r}=\frac{\partial\langle\tilde{E}_\theta\tilde{E}_r\rangle}{B_\phi^2\partial r}\sim\frac{k_\theta k_r}{B_\phi^2}\frac{\partial|\phi^2|}{\partial r}$. Now, we can understand the radial structure of ERS and its gradient quite well. Since k_θ and k_r both change signs and the potential fluctuation level is always positive, the ERS does not change sign across the LCFS. Define outward and ion direction as the radial and poloidal reference directions respectively, in the equation $\frac{\partial V_\theta}{\partial t}=-\frac{\partial}{\partial r}\langle\tilde{V}_r\tilde{V}_\theta\rangle-\mu V_\theta=0$, $V_\theta > 0$. For the ERS gradient to balance the damping, $-\frac{\partial}{\partial r}\langle\tilde{V}_r\tilde{V}_\theta\rangle$ should be positive in SOL, just as shown in Fig2(d). In the SOL turbulence propagates in the ion direction and outward, $k_\theta > 0$ and $k_r > 0$, so the $-\langle\tilde{V}_r\tilde{V}_\theta\rangle$ is negative, as shown in Fig2(d). Similar sign relationship can be checked up at the plasma edge. In conclusion, the k_θ, k_r and the fluctuation level can qualitatively explain the radial structure of the ERS.

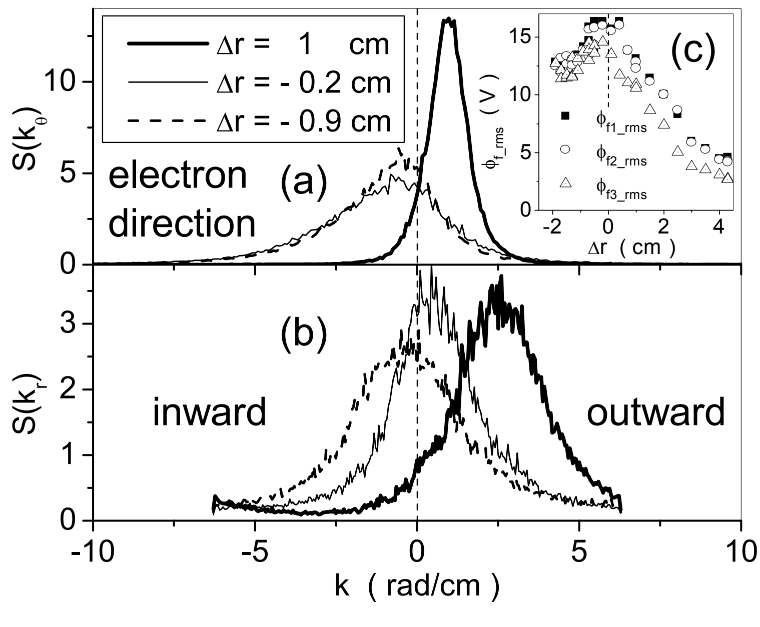

FIG. 3. (a) Normalized k_θ power spectra $S(k_\theta)$, (b) Normalized k_r power spectra $S(k_r)$; The inserted figure (c) shows the radial profiles of floating potential fluctuation RMS values measured by tip1, tip2 and tip3.

6. Poloidal Flow Damping

The RS gradient enables the turbulence to modify the radial transport of the poloidal momentum and generate sheared flows. To quantitatively estimate the importance of RS in generating sheared flows, a comparison with damping terms in the poloidal momentum equation is required. Neglecting the contribution of the MRS. In steady state, the poloidal flow profile is governed by the balance between the ERS gradient and the damping terms. The ion-ion collision frequency at the plasma edge can be estimated as $\nu_{ii} \sim 3$ kHz and the ion thermal velocity is $V_{th} \sim 50$ km/s. Thus the neoclassical transport condition for the plateau regime is satisfied $\varepsilon^{3/2} < \frac{R_0 q \nu_{ii}}{V_{th}} < 1$, where ε is the aspect ratio. First, considering the neoclassical viscosity drag in the plateau regime. The neoclassical damping term due to magnetic pumping in the plasma edge region can be expressed by the "Stix-like" model [22] as $\mu V_\theta = \left(\frac{\sqrt{\pi}}{2} \frac{q V_{th}}{R_0} \exp\left(-U_{pm}^2\right) + \frac{1}{2} \frac{\nu_{ii} q^2}{1 + U_{pm}^2} \right) \left(V_\theta - V_\theta^{Neo} \right)$, where $U_{pm} = -\frac{E_r}{B_\theta V_{th}}$, V_{th} is the ion thermal velocity and $V_\theta^{Neo} = -\frac{0.5}{eB_\phi} \frac{\partial T_i}{\partial r}$ is the neoclassical poloidal flow velocity in the plateau regime. The poloidal flow velocity V_θ can be estimated by the poloidal phase velocity of turbulence V_{ph}. All quantities in the above damping term expression can be computed from the measured profiles. Fig4 shows the profiles of V_{ph}, poloidal E×B velocity $V_{E\times B} = \frac{E_r}{B_\phi}$ and electron diamagnetic drift velocity $V_d = \frac{\partial P_e / \partial r}{e n_e B_\phi}$. The E_r was calculated as the radial gradient of plasma potential. From this figure, one can see the V_{ph} shear is dominated by the shear of E×B drift and the contribution from diamagnetic drift is small, and V_d is only slowly varying with radius. These phenomena were similar to those observed in the early TEXT experiment [23], including a slightly steepened density profile in the maximal shear region, as shown in Fig2. The boundary B_θ profile was directly measured with poloidal magnetic coil and agreed quite well with that calculated using a current density profile from an equilibrium model [24].

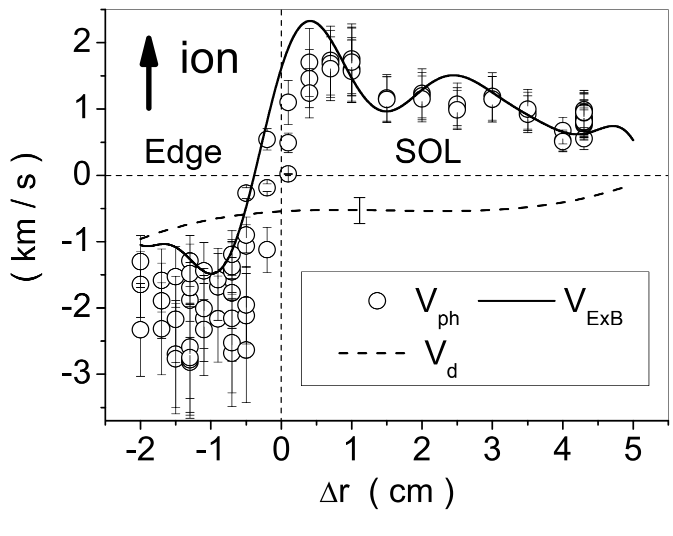

FIG. 4. The radial profiles of (circle points) the poloidal phase velocity of turbulence, (solid line) the poloidal E×B velocity, and (dash line) electron diamagnetic drift velocity.

Thus the experimentally measured profile of poloidal velocity damping term $-\mu V_\theta$ was computed and is plotted in Fig5. To form the sheared flow structure, a momentum source is required to drive plasma rotate in poloidal directions. Through the radial force balance, E_r profile is determined and as a result the E×B flows. Therefore the mechanism for inputting poloidal momentum in steady state is responsible for the reversed flow structure. Without the momentum source, the rotation will be damped and E_r will finally disappear. The ERS gradient is shown in Fig5 and compared with the damping term. Good agreement can be seen between the two profiles in both magnitude and structure. The ERS gradient reverses at the same radial location of the shear layer and balances the neoclassical damping. This indicates that the ERS might be the dominant mechanism to sustain the poloidal flow shear at the plasma edge. Fig5 also shows the radial gradient of total RS, the contribution of MRS is negligible, as a result of small magnetic fluctuation level in low β plasma.

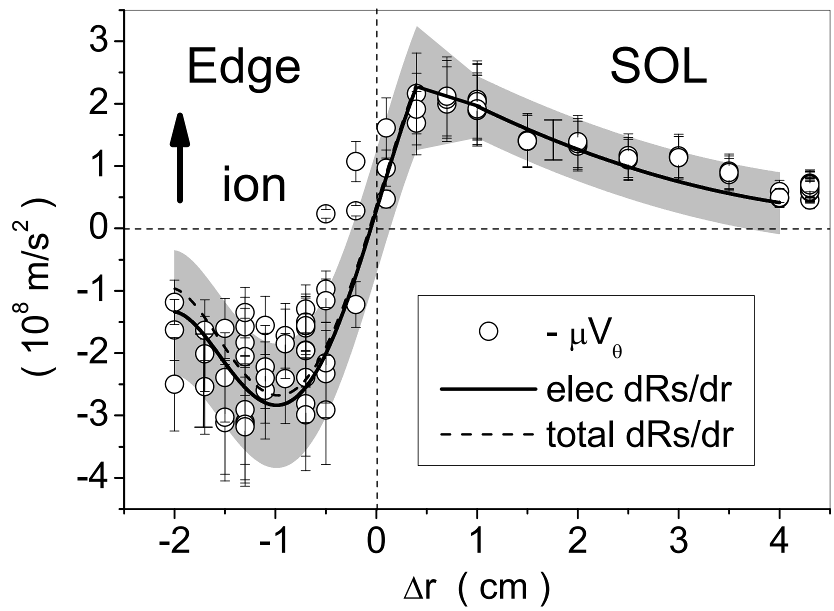

FIG. 5. The radial profiles of (circle points) the neoclassical viscosity damping term $-\mu V_\theta$, (solid line) the ERS gradient, and (dash line) the total RS gradient. The grey area is confidence interval.

Another possible damping term at the plasma edge is the friction force due to ion-neutral collision, the dominant contribution of which is charge exchange [25]. The damping of plasma rotation due to charge-exchange processes can be expressed as $\nu_{i0}V_\theta$, where $\nu_{i0} = \langle\sigma_{cx}v_i\rangle n_{0a}$ is the ion-neutral collision frequency. At the plasma edge, the mean charge exchange rate coefficient $\langle\sigma_{cx}v_i\rangle$ is about 3×10^{-14} m^3/s and the neutral density n_{0a} is close to 5×10^{16} m^{-3}, which was inferred from the Hα/Dα emission profile [26]. Thus, ν_{i0} is estimated as 1.5×10^3 s^{-1}. The V_θ at the plasma edge region is about 2 km/s, as shown in Fig4. It follows that the contribution of charge exchange to the poloidal momentum damping is about $\nu_{i0}V_\theta = 3\times10^6$ m/s^2. Since the present experiment shows that the dRs/dr term and the μV_θ term are both close to 3×10^8 m/s^2 at the plasma edge region, the $\nu_{i0}V_\theta$ term is thus 100 times smaller than the magnetic damping term. Therefore, it is concluded that the charge-exchange processes do not play a dominant role in the poloidal momentum balance for the parameters in this experiment.

Accurate description of the damping term is a crucial element for a complete understanding of poloidal momentum balance. The possible deviations from axisymmetry (such as that caused by toroidal field ripple), anomalous viscosity [27] (such as that caused by turbulence) and impurity friction may also contribute to flow damping, which are still problems and need further investigations.

7. Summary

The radial profiles of electrostatic and magnetic Reynolds stress have been measured in the plasma boundary region of HT-7 tokamak. Experimental results show that the radial gradient of ERS changes sign across the last closed flux surface, and the neoclassical flow damping and the damping due to charge exchange processes are balanced by the radial gradient of ERS, which sustains the equilibrium sheared flow structure in a steady state. The contribution of magnetic Reynolds stress was found unimportant in a low β plasma. Detailed analyses indicate that the propagation properties of turbulence in radial and poloidal directions and the profiles of potential fluctuation level are responsible for the radial structure of ERS.

References

[1] P. W. Terry, Reviews of Modern Physics **72**, 109 (2000).
[2] P. H. Diamond and Y. B. Kim, Phys. Fluids **B3**, 1626 (1991).
[3] J. R. Holton and R. S. Lindzen, J. Atmos. Sci. **29**, 1076 (1972).
[4] R. A. Plumb, J. Atmos. Sci. **34**, 1847 (1977).
[5] K. H. Burrell, Science **281**, 1816 (1998).
[6] R. D. Stambaugh *et al.*, Phys. Fluids **B2**, 2941 (1990).
[7] Z. Lin *et al.*, Science **281**, 1835 (1998).
[8] X. Q. Xu *et al.*, Nucl. Fusion **40,** 731 (2000).
[9] K. C. Shaing and E. C. Crume, Phys. Rev. Lett. **63**, 2369 (1989).
[10] C. Hidalgo *et al.*, Phys. Rev. Lett. **83**, 2203 (1999).
[11] Y. H. Xu *et al.*, Phys. Rev. Lett. **84**, 3867 (2000).
[12] K. C. Shaing and S. P. Hirshman, Phys. Fluids **B1**, 705 (1989).
[13] G. G. Craddock and P. H. Diamond, Phys. Rev. Lett. **67**, 1535 (1991).
[14] J. Li *et al.*, Nucl. Fusion **39,** 973 (1999).
[15] R. A. Moyer *et al.*, Phys. Plasmas **2**, 2397 (1995).
[16] G. S. Xu, B. N. Wan and M. Song, Phys. Plasmas **9,** 150 (2002). G. S. Xu, et al., Phys. Rev. Lett. **91**, 125001 (2003).
[17] A. B. Rechester and M. N. Rosenbluth, Phys. Rev. Lett. **40**, 38 (1978).
[18] X. M. Zhang, Chinese Phys. Lett. **18,** 1090 (2001).
[19] B. N. Wan *et al.*, Nucl. Fusion **41,** 1835 (2001).
[20] P. H. Diamond *et al.*, Phys. Rev. Lett. **72**, 2565 (1994).
[21] Ch. P. Ritz *et al.*, Rev. Sci. Instrum. **59**, 1739 (1988).
[22] J. Cornelis *et al.*, Nucl. Fusion **34,** 171 (1994).
[23] Ch.P.Ritz, et al., Phys. Rev. Lett. **65**, 2543 (1990).
[24] J. A. Wesson, Oxford University Press, Inc., New York, "Tokamaks", (1987).
[25] M.F.A.Harrison, in Physics of Plasma Wall Interactions in Controlled Fusion, NATO AS1 Series B, Vol. 131 (POST, D.E., BEHRISCH, R., Eds), Plenum Press, New York and London.
[26] B.N.Wan, et al., Nucl. Fusion, **39**, 1865 (1999).
[27] V.Rozhanskii, , et al., in Controlled Fusion and Plasma Physics (Proc. 18th Eur. Conf. Berlin, 1991), Vol. 15C, Part IV, European Physical Society, Geneva 287 (1991).