Radial Structure of Reynolds Stress in the Plasma Boundary of Tokamak Plasmas

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The radial profile of Reynolds stress has been measured in the plasma boundary region of the ISTTOK tokamak using a multiarray of Langmuir probes. The electrostatic Reynolds stress component, proportional to the cross correlation of radial and poloidal fluctuating electric fields, shows a radial gradient close to the velocity shear layer location. It is shown that this mechanism may drive significant poloidal flows in the plasma boundary region.

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Sheared poloidal flows have been found to play an important role in explaining the transition to improved confinement regimes in magnetically confined fusion plasmas [1]. If a radial electric field is spatially nonhomogeneous, plasma volumes on neighboring magnetic surfaces rotate with different $\mathbf{E} \times \mathbf{B}$ velocities. Such a shear in the rotation velocity tears apart turbulent eddies elongated in the radial direction and reduces the turbulent transport level. Several investigations of edge plasma turbulence and poloidal flows have been reported in fusion plasma devices [2–11]. Different mechanisms have been proposed to explain the generation of sheared poloidal flows in the plasma edge region. An important mechanism is the ion orbit loss caused by interaction with the limiter [12]. A complementary explanation is the generation of poloidal flows by plasma fluctuations via the Reynolds stress [13–15] and the poloidal spin-up of plasmas from poloidal asymmetry of particle and momentum sources [16]. Turbulent Reynolds stress plays a linking role between the turbulence and averaged flows. It has been suggested that sheared poloidal flows can be generated in fusion plasmas due to radially varying Reynolds stress [17,18]. The formation of a core transport barrier by ion Bernstein wave heating in the Princeton Beta Experiment-Modified (PBX-M) tokamak is consistent with this interpretation [19]. Reynolds stress may also play a role in the *L-H* transition [20,21]. The importance of toroidal effects has also been addressed [22].

This Letter reports the measurement of the radial profile of Reynolds stress in the plasma boundary region of the ISTTOK tokamak.

Neglecting the contribution of magnetic fluctuations, the Reynolds stress (Re) was determined by $\mathrm{Re} = \langle \tilde{v}_r \tilde{v}_\theta \rangle$ [14]. The $\langle \tilde{v}_r \tilde{v}_\theta \rangle$ term of the Reynolds stress tensor can be related to the $\mathbf{E} \times \mathbf{B}$ velocities, $\langle \tilde{v}_r \tilde{v}_\theta \rangle \propto \langle \tilde{E}_r \tilde{E}_\theta \rangle$, $\tilde{E}_r$ and $\tilde{E}_\theta$ being the radial and poloidal components of the electric field, respectively. The brackets ($\langle\,\rangle$) mean time average. It should be noted that only in the case of poloidally homogeneous turbulence are the Reynolds stress, computed as the time averaged product of fluctuating radial and poloidal velocities, and the flux surface average Reynolds stress [13,14] equivalent. The Reynolds stress measures the degree of anisotropy in the structure of fluctuations. In the case of radial poloidal nonisotropic turbulence, the Reynolds stress component $\langle \tilde{v}_r \tilde{v}_\theta \rangle$ is not zero. Radially varying Reynolds stress allows the turbulence to rearrange the profile of poloidal momentum, generating sheared poloidal flows.

Measurements were carried out on the small-size ISTTOK tokamak ($R = 0.46$ m, $B \approx 0.5$ T, $I_p \approx 6$ kA) [23]. Around the limiter radius (a_{limiter}) the electron temperature is about $T_e \approx 20$ eV and the electron density is $n_e \approx 0.5 \times 10^{12}$ cm^{-3}. Measurements were taken at different radial positions, both in the edge ($r < a_{\mathrm{limiter}}$) and in the scrape-off layer (SOL) ($r > a_{\mathrm{limiter}}$) plasma regions.

The experimental setup consists of two arrays of three Langmuir probes, radially separated by $\Delta_r \approx 6$ mm (Fig. 1). Probes were located in the equatorial plane of the device. Two tips of each set of triple probes,

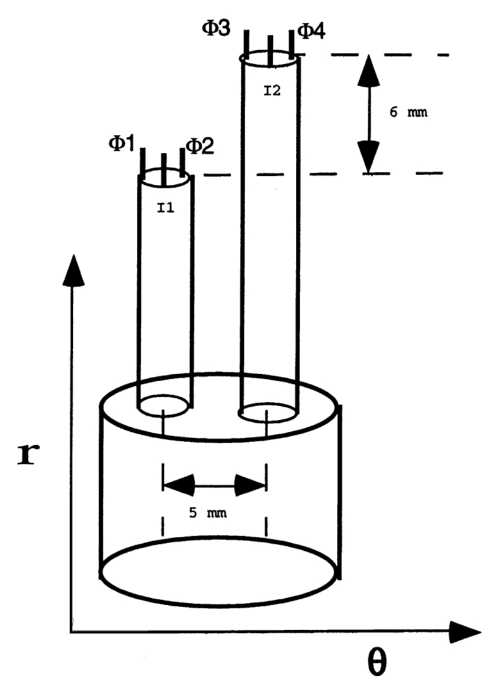

FIG. 1. Experimental setup.

aligned perpendicular to the magnetic field and separated poloidally ($\Delta_\theta \approx 3$ mm), were used to measure fluctuations of the poloidal electric field $\tilde{E}_\theta$, as deduced from the floating potential (ϕ_f) and neglecting electron temperature fluctuation effects [i.e., $\tilde{E}_{\theta 1} = (\tilde{\phi}_1 - \tilde{\phi}_2)/\Delta_\theta$ and $\tilde{E}_{\theta 2} = (\tilde{\phi}_3 - \tilde{\phi}_4)/\Delta_\theta$]. The third tip was biased at a fixed voltage in the ion saturation current regime (I_S). The radial electric field was estimated from floating potential signals measured by radially separated probes (i.e., $\tilde{E}_r = (\tilde{\phi}_3 - \tilde{\phi}_2)/\Delta_r$). The probes were oriented with respect to the magnetic field direction to avoid shadows between them [24]. With these approximations, the electrostatic component of the Reynolds stress proportional to $\langle \tilde{E}_r \tilde{E}_\theta \rangle$ has been computed in the plasma boundary region.

The radial profile of the floating potential and the corresponding (rms) fluctuations are shown in Fig. 2. The floating potential becomes more negative when the probe is inserted into the plasma edge and the radial electric field changes its sign in the proximity of the limiter radius location. There is a significant gradient in the rms fluctuation level and its value increases radially inwards.

Figure 3 shows the radial and poloidal coherence of fluctuations and the poloidal phase velocity. From the $S(k,\omega)$ function, computed from the two-point correlation technique using two floating potential signals, the poloidal phase velocity of fluctuations is defined as $v_\theta = \Sigma_{\omega,k}(\omega/k)S(\omega,k)/\Sigma_{\omega,k}\, S(\omega,k)$ [25]. The poloidal phase velocity presents a clear change in the propagation direction of fluctuations from the ion diamagnetic direction in the outer edge of the plasma behind the limiter to the electron direction inside the limiter radius. The measured poloidal coherence is in the range (0.8–0.9) for probes separated poloidally by 3 mm, and the radial coherence ranges from 0.6 in the proximity of the plasma limiter radius to 0.8 in the plasma edge region for probes separated radially by 6 mm. The decrease in the radial coherence in the plasma region where the radial electric field changes sign could be interpreted in terms of shear decorrelation effects on fluctuations.

The electrostatic Reynolds stress has been computed as $\langle \tilde{E}_r \tilde{E}_\theta \rangle$, where $\tilde{E}_\theta$ is the mean value of $\tilde{E}_{\theta 1}$ and $\tilde{E}_{\theta 2}$ (see Fig. 1). In this way the poloidal and radial components of the electric field are estimated, approximately, at the same plasma position. The computed value of $\langle \tilde{E}_r \tilde{E}_\theta \rangle$ is very similar to those deduced using the values of the fluctuating poloidal electric field measured by the inner ($\tilde{E}_{\theta 2}$) or outer ($\tilde{E}_{\theta 1}$) probes. Figure 4 shows the $\langle \tilde{v}_r \tilde{v}_\theta \rangle$ radial profile. The $\langle \tilde{v}_r \tilde{v}_\theta \rangle$ term of the Reynolds stress tensor shows a radial gradient in the proximity of the velocity shear layer location.

A quantitative estimate of the importance of the fluctuation-induced flows in the evolution equation of the poloidal flow requires a comparison with the magnitude of the poloidal flows damped by different mechanisms (i.e., magnetic pumping and charge exchange).

The damping term due to magnetic pumping in the plasma edge region can be expressed as $\gamma_{mp} v_{i\theta}$, where $v_{i\theta}$ is the ion poloidal velocity [26]. For the ISTTOK edge plasma parameters, γ_{mp} is expected to be in the range of 10^4 s^{-1} [26]. Assuming $v_{i\theta}$ of the order of the $\mathbf{E} \times \mathbf{B}$ poloidal velocity ($v_\theta \approx 10^3$ m s^{-1}), the contribution

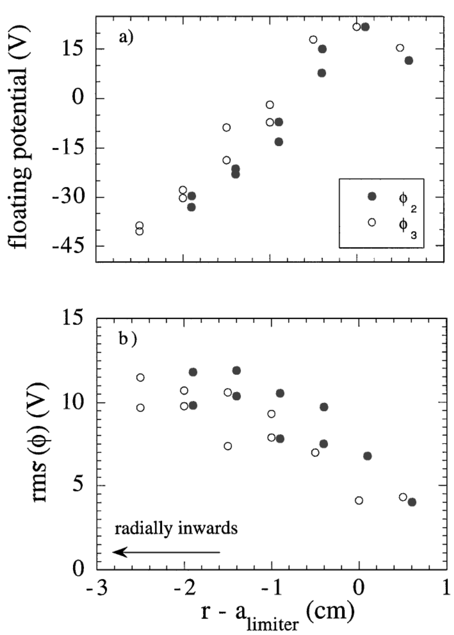

FIG. 2. Radial profile of (a) floating potential and (b) root mean square (r.m.s.) value of fluctuations (rms $\tilde{\phi}_f$).

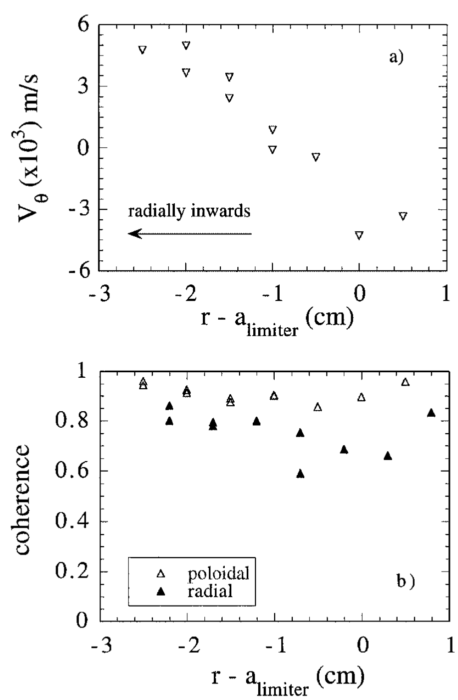

FIG. 3. Radial profile of (a) poloidal phase velocity of fluctuations and (b) the radial and poloidal coherence of fluctuations.

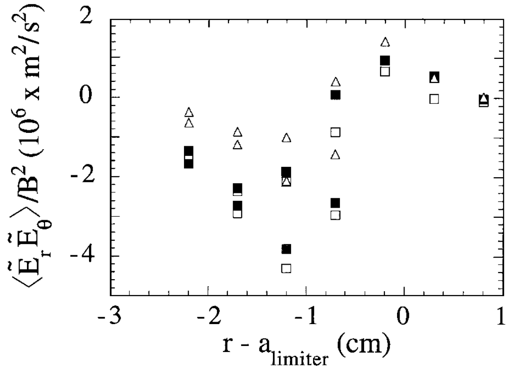

FIG. 4. Radial profile of the electrostatic Reynolds stress in the plasma boundary region of the ISTTOK tokamak.

of magnetic pumping to the time evolution of the poloidal flow is about 10^7 m s^{-2}. The damping of the plasma rotation due to atomic physics mechanisms (charge exchange) can be expressed as $\nu_{iCX} v_{i\theta}$ (ν_{iCX} being the momentum loss rate). For ISTTOK, ν_{iCX} is estimated to be of the order of 10^4 s^{-1}. It follows that the contribution of atomic physics to the time evolution of the poloidal flow is about 10^7 m s^{-2}. The present experiments show that the radial gradient of $\langle \tilde{v}_r \tilde{v}_\theta \rangle$ (i.e., $d\,\mathrm{Re}/dr$) is of the order of 10^7–10^8 m s^{-2} in the plasma boundary region. This suggests the importance of fluctuation-induced flows in the plasma edge region of ISTTOK tokamak.

There are different effects which should be considered in the computation of the Reynolds stress. In particular, electron temperature fluctuation effects can modify the absolute value of the measured electrostatic Reynolds stress. However, taking into account that the radial profile of the floating potential fluctuations has been found to be closely correlated with the level of the plasma potential fluctuations [27,28], $d\,\mathrm{Re}/dr$ is not expected to be significantly modified by T_e fluctuation effects.

In conclusion, the present experiments point out that the electrostatic Reynolds stress (proportional to $\langle \tilde{E}_r \tilde{E}_\theta \rangle$) shows a radial gradient in proximity to the velocity shear layer, indicating that this mechanism can play a significant role to explain the physics 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 (such as ion orbit losses and Stringer spin-up).

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[1] K. Burrel, Phys. Plasmas **4**, 1499 (1997).
[2] S.J. Zweben and R.W. Gould, Nucl. Fusion **25**, 171 (1985).
[3] C.P. Ritz, H. Lin, T.L. Rhodes, and A.J. Wootton, Phys. Rev. Lett. **65**, 2543 (1990).
[4] C. Hidalgo *et al.*, Nucl. Fusion **31**, 1471 (1991).
[5] T.P. Rempel *et al.*, Phys. Rev. Lett. **67**, 1438 (1991).
[6] H.Y. Tsui *et al.*, Phys. Fluids B **5**, 2491 (1993).
[7] G.R. Tynan *et al.*, Phys. Plasmas **10**, 3301 (1994).
[8] R.A. Moyer *et al.*, Phys. Plasmas **2**, 2397 (1995).
[9] H. Toyama *et al.*, in *Proceedings of the 15th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Seville, 1994* (International Atomic Energy Agency, Vienna, 1995), Vol. 1, p. 575.
[10] M. Endler, H. Niedermeyer, L. Giannone, E. Holzhauer, A. Rudyj, G. Theimer, N. Tsois, and the Asdex Team, Nucl. Fusion **35**, 1307 (1995).
[11] B.E. Chapman, C-S. Chiang, S.C. Prager, J.S. Sarff, and M.R. Stoneking, Phys. Rev. Lett. **80**, 2137 (1998).
[12] K.C. Shaing and E.C. Grume, Phys. Rev. Lett. **63**, 2369 (1989).
[13] P.H. Diamond and Y.B. Kim, Phys. Fluids B **3**, 1626 (1991).
[14] B.A. Carreras, V.E. Lynch, and L. García, Phys. Fluids B **3**, 1438 (1991).
[15] L. García, B.A. Carreras, V.E. Lynch, and P.H. Diamond, in *Proceedings of the 14th Conference on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg* (International Atomic Energy Agency, Vienna, 1993), Vol. 2, p. 225.
[16] A.B. Hassam, T.M. Antonsen, J. Drake, and S.C. Liu, Phys. Rev. Lett. **66**, 309 (1991).
[17] G.G. Craddock and P.H. Diamond, Phys. Rev. Lett. **67**, 1535 (1991).
[18] H. Bigliari *et al.*, in *Radio Frequency Power in Plasmas*, edited by Donald B. Batchelor, AIP Conf. Proc. No. 244 (AIP, New York, 1991), p. 376.
[19] M. Ono *et al.*, in *Proceedings of the 15th Conference on Plasma Physics and Controlled Nuclear Fusion Research, Seville* (International Atomic Energy Agency, Vienna, 1995), Vol. 1, p. 469.
[20] P.H. Diamond, Y.M. Liang, B.A. Carreras, and P.W. Terry, Phys. Rev. Lett. **72**, 2565 (1994).
[21] G.R. Tynan, in *Transport Chaos and Plasma Physics 2*, Advanced Series in Nonlinear Dynamics Vol. 9 (World Scientific, Singapore, 1996), p. 254.
[22] M. Tendler, Plasma Phys. Controlled Fusion **39**, B371 (1997).
[23] C.V. Varandas *et al.*, Fusion Technol. **29**, 105 (1996).
[24] M.A. Pedrosa *et al.*, in *Proceedings of the 23rd European Conference on Controlled Fusion and Plasma Physics, Kiev* (European Physical Society, Geneva, 1996), Vol. 1, 20C, Part II, p. 827.
[25] Ch.P. Ritz *et al.*, Rev. Sci. Instrum. **59**, 1739 (1988).
[26] S.P. Hirshman, Nucl. Fusion **18**, 917 (1978).
[27] R. Balbín, L. Giannone, C. Hidalgo, H. Niedermeyer, and the W7-AS Team, in *Proceedings of the 10th International Conference on Stellarators, Madrid, 1995* (EUR-CIEMAT, City, 1995), p. 90.
[28] L. Giannone *et al.*, Phys. Plasmas **1**, 3614 (1994).