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On the energy transfer between flows and turbulence in the plasma boundary of fusion devices

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Abstract

The energy transfer between perpendicular flows and turbulence has been investigated in the JET plasma boundary region. The energy transfer from DC flows to turbulence, directly related with the momentum flux (e.g. $\langle \tilde{v}_\theta \tilde{v}_r \rangle$) and the radial gradient in the flow, can be both positive and negative in the proximity of sheared flows. The direct computation of the turbulent viscosity gives values comparable to the anomalous particle diffusivitiy (in the order of $1\,\mathrm{m^2/s}$). Furthermore, this energy transfer rate is comparable with the mean flow kinetic energy normalized to the correlation time of turbulence, implying that this energy transfer is significant. These results show, for the first time, the dual role of turbulence as a damping (eddy viscosity) and driving of flows in fusion plasmas emphasizing the important role of turbulence to understand perpendicular dynamics in the plasma boundary region of fusion plasmas.

PACS: Plasma confinement; Electric fields; Plasma turbulence, momentum transport
Keywords: Radial electric fields; Turbulence; Fluctuations; Langmuir probe; JET

1. Introduction

It is well known that, in a turbulent flow, energy can be interchanged between the mean flows (large scales) and the turbulence (small scales). Reynolds first studied this energy interchange by introducing into the fluid equations what have after been known as Reynolds decomposition [1].

From the theoretical point of view, several works have pointed out the importance of Reynolds stress as a way to interchange energy between the different scales present in plasmas [2,3]. These works have suggested not only the possibility of a energy (or momentum) transference from the macroscopic flows to the turbulent scales, but also the possibility of an energy flux going from the small scales to the macroscopic flows driving plasma rotation. More recent works have been focused on the study of the formation of the so-called zonal flows in plasmas [4].

From the experimental point of view, pioneer works were focused in a direct measure of the radial-poloidal

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component of the Reynolds stress in the plasma boundary region of fusion plasmas [5–8]. Several other works focused in a frequency domain analysis have studied the formation or evolution of zonal flows in fusion plasmas and the spectral energy transfer [4,9,10]. In these works an energy transfer between different scales has been identified but the amount of energy transferred has not been estimated.

In the present work we have investigated the energy transfer between perpendicular flows and turbulence in the JET plasma boundary region. We compute the turbulence production term following classical works [11,12].

2. Experimental set-up

The experimental set-up consists of multi-arrays of Langmuir probes [13] which allow to measure the plasma potential in several positions simultaneously and thus to estimate poloidal and radial components of electric field, related to radial and poloidal components of $E \times B$ fluctuating velocity, respectively (Fig. 1). Probe enters by the upper side of the plasma and signals are digitized at a rate of 0.5 MHz. Plasmas studied in this paper were produced in ohmic plasmas in both limiter and X-point plasma configuration with toroidal magnetic fields $B = 2$–2.4 T, and plasma currents $I_p = 2$–2.2 MA.

Four pins (B, A, J and H in the picture), aligned perpendicular to the magnetic field and poloidally separated ($\Delta\theta \approx 5$ mm), were used to measure fluctuations of the poloidal electric field, as deduced from the floating potential signals (ϕ_f) and neglecting electron temperature fluctuation effects. J and A pins, radially separated ($\Delta r \approx 8$ mm in limiter plasmas and $\Delta r \approx 5$ mm in divertor plasmas), were used to measure radial component of fluctuating electric field (Fig. 1). From potential measurements at B and A positions an estimation of the poloidal component of electric field ($E_{\theta 1}$) can be obtained. Another estimate ($E_{\theta 2}$) can be obtained from J and H measurements. Finally, the poloidal component of electric field is computed as the mean value of these two estimations ($E_\theta = (E_{\theta 1} + E_{\theta 2})/2$). In this way the radial and poloidal components of electric field are both estimated at the same position. Electrostatic radial-poloidal component of Reynolds Stress, $\langle \tilde{v}_\theta \tilde{v}_r \rangle$, where $\langle\rangle$ means cross-correlation, is computed from electric field estimates, taking into account the $E\times B$ drift fluctuating velocities ($\tilde{v}_\theta = \widetilde{E}_r \times \overline{B}/B^2$; $\tilde{v}_r = \widetilde{E}_\theta \times \overline{B}/B^2$).

The mean perpendicular velocity of fluctuations can be estimated at two radial positions by the two points correlation technique [14] using probes poloidally separated, A–B, $V_{\theta 1}$ (outer) and J–H, $V_{\theta 2}$ (inner) and thus the radial component of velocity gradient ($\partial V_\theta/\partial r$) can be estimated. From the radial component of the mean poloidal velocity gradient and the radial-poloidal component of Reynolds stress, the turbulence production (P) is computed (see Eq. (5)–(133) in Ref. [11] p. 125) as

$$P = -\langle \tilde{v}_r \tilde{v}_\theta \rangle \frac{\partial V_\theta}{\partial r}. \tag{1}$$

This term (P) combines the velocities cross-correlation $\langle \tilde{v}_r \tilde{v}_\theta \rangle$ (momentum flux) with the mean velocity gradient ($\partial V_\theta/\partial r$) and gives a measure of the amount of energy per unit mass and unit time that is transferred between mean flow and fluctuations. The measurement of the energy transfer term is a real challenge for experimentalists, involving significant error sources that we will discuss later in this paper.

Typical profiles of potential as measured by floating Langmuir probes (A, B, J and H) in limiter configuration are shown in Fig. 2. From these measurements radial profiles of the averaged quantities (V_θ, $\langle \tilde{v}_r \tilde{v}_\theta \rangle$ and the production term P) can be obtained. In this paper the averaged quantities, cross-correlations and perpendicular mean velocities were calculated using 2500 signal points (5 ms). Within this time the probe, and also the measured signals, can be considered stationary.

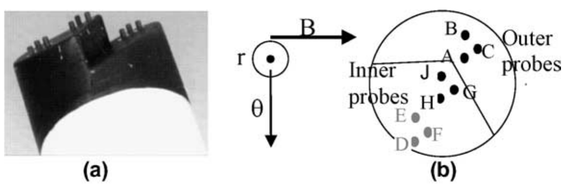

Fig. 1. (a) Multiple Langmuir probe used for measurements in JET tokamak. (b) Schematic view of probes in the array and orientation with respect to magnetic field.

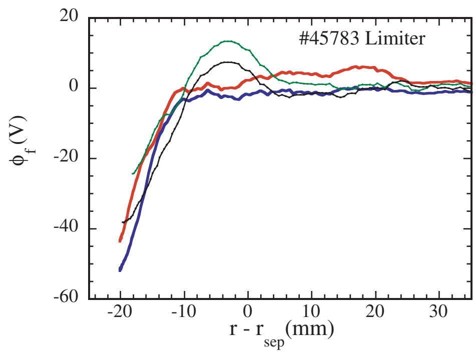

Fig. 2. Profile of floating potential measured by the Langmuir probe in a limiter discharge (#45783).

3. Results

3.1. Limiter configuration

Results presented in this section were obtained in ohmic heating regime under limiter configuration, with a magnetic field $B = 2.4\,\mathrm{T}$. In this case the angle between radial ($\phi_J - \phi_A$) and poloidal estimates ($\phi_A - \phi_B$, $\phi_J - \phi_H$) of electric field components is very close to 90°. Fig. 3 shows the radial profile of the calculated production term (P) and the mean poloidal velocity of fluctuations computed by using the two-point technique [14]. The velocity has been computed as the mean value of inner and outer estimations of velocity. Error bars take into account the statistical errors in cross-correlation calculation (Reynolds stress) and also in mean velocity estimates.

Given the signs used in these calculations, positive sign in P means energy going from the mean flow to the fluctuations, and negative the opposite situation. As shown in Fig. 3, two different signs are found in P, thus implying that turbulence acts as an energy sink for the mean flow (viscosity) at the velocity shear location (where the poloidal velocity reverses sign) and as a energy source (pumping) in the scrape-off layer (SOL) side of the reversal in the phase velocity. Fig. 4 shows the coherence between floating potential signals, which turns out to be high (>0.6) in the interest region ($r - r_{sep} < 30\,\mathrm{mm}$). This shows that measurements are within the fluctuations correlation volume. Similar results were observed in other ohmic plasma discharges.

3.2. Divertor configuration

Most of measurements in experiments carried out in divertor plasmas ($B = 2$ T) were taken with probes radially separated 5mm, and, as a consequence, the angle between estimates of radial ($\phi_J - \phi_A$) and poloidal ($\phi_A - \phi_B$ and $\phi_J - \phi_H$) components of electric field is not exactly 90°, but close to 60°. A correction can be

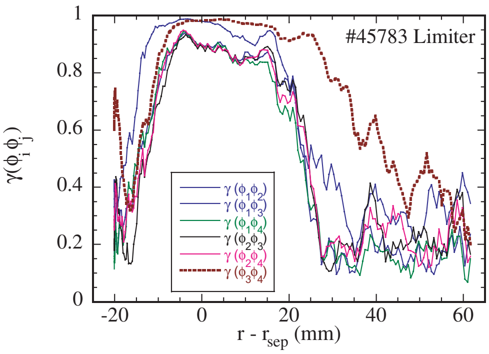

Fig. 4. Coherence between potential signals measured in JET plasma discharge 45783 under limiter configuration, ohmic heating.

applied in order to obtain an estimate of E_r in an orthogonal frame of reference. From a simple algebra it follows that radial component of the electric field in the orthogonal frame of reference (E_r) can be obtained from measurements in a non-orthogonal frame as

$$E_r = -\frac{\cos\alpha}{\sin\alpha}E'_\theta + \frac{1}{\sin\alpha}E'_r, \qquad (2)$$

where α is the angle between the poloidal and pseudo-radial directions of measurement and E'_r, E'_θ variables are measures in the non-orthogonal frame (see Fig. 5).

Fig. 6 shows the radial profile of the production term obtained in divertor configuration (JET discharge #54278) taking into account the axis correction. Results

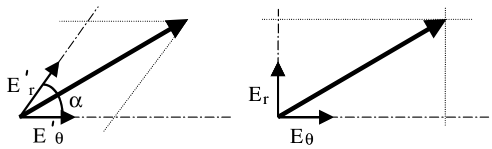

Fig. 5. Schematic view of the electric field measurement in a orthogonal and nonorthogonal axis frame of reference ($\alpha \approx 60°$).

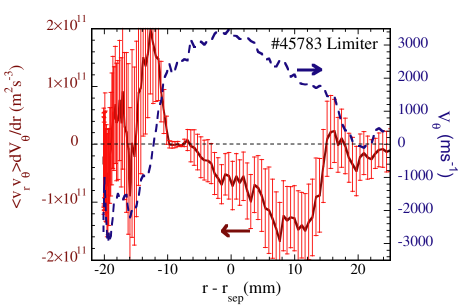

Fig. 3. Poloidal velocity of fluctuations and turbulence production term measured in JET plasma discharge 45783 under limiter configuration, ohmic heating.

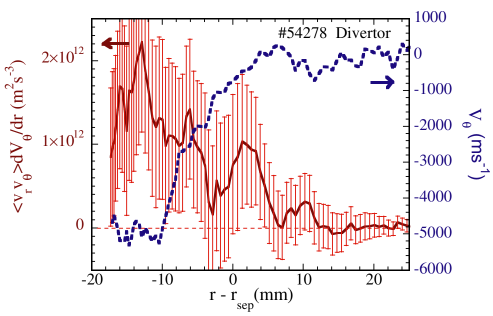

Fig. 6. Turbulence production term and poloidal velocity of fluctuations measured in JET plasma discharge 54278 under divertor configuration.

in this case show also a region where production term is positive near the region with strong sheared flows but no evidence of negative production region is seen in this case.

4. Discussion

Firstly we would like to point out the qualitatively different point of view applied in this analysis with respect to previous ones [5–8]. In those works a flux surface averaging was implicit in the momentum balance equation relating radial gradient in Reynolds stress and perpendicular plasma rotation, while in the energy approach discussed in this paper all averaged quantities are time-averaged and flux surface-averaging is not supposed. Therefore, present measurements should be considered as local estimates of the energy production term. Care should be taken if trying to extrapolate from these local measurements the influence in the whole plasma.

Results obtained in limiter configuration clearly show two different regions in the radial profile (Fig. 3). In the plasma region with strong gradients in the perpendicular velocity, the production term is positive, thus meaning that turbulent fluctuations are generated by the mean flow shear thus acting as a viscous term for the mean flow. In the SOL side of the reversal in the phase velocity, the production term is negative, implying that in this region fluctuations contribute to pump the mean flow. So far, no pumping region (P negative) has been observed in divertor configurations.

While results qualitatively show two interesting effects (damping and pumping of mean flow by turbulence), an important question is how relevant is the contribution of turbulence in DC plasma momentum (kinetic energy). For this purpose we will focus on limiter measurements, using shot #45783 as reference.

From standard definitions, the turbulent viscosity (υ_T) is given by $\upsilon_T = \langle v_i v_j \rangle / \partial V_i / \partial x_j$, resulting that in the flow shear region

$$\upsilon_T = \frac{\langle v_\theta v_r \rangle}{\partial V_\theta / \partial r} = \frac{(3.6 \pm 0.2) \times 10^5}{(4.3 \pm 2) \times 10^5} \approx (0.8 \pm 0.4) \mathrm{m}^2/\mathrm{s}. \tag{3}$$

This result turns out to be comparable to the particle diffusivity ($D \approx 1\,\mathrm{m}^2/\mathrm{s}$), in consistency with previous measurements [13,15]. As far as the authors know this is the first direct measurement of turbulent viscosity in fusion plasmas.

Looking at the region were the production term is negative (flow pumping) it makes sense to compare the magnitude of the production (P) to the energy involved in plasma rotation. From Fig. 3 it follows:

$$P = -\langle v_\theta v_r \rangle \frac{\partial V_\theta}{\partial r} \approx (-1.2 \pm 0.5) \times 10^{11}\,\mathrm{W/kg}. \tag{4}$$

The power per unit mass necessary to pump the flow up to the velocity value experimentally measured in a turbulence characteristic time (τ_t) is given by

$$W = \frac{E}{\tau_t} = \frac{V_\theta^2}{2\tau_t} = \frac{(1.25 \pm 0.8) \times 10^6\,\mathrm{m}^2/\mathrm{s}^2}{(2.25 \pm 0.7) \times 10^{-5}\,\mathrm{s}} = (5 \pm 4.6) \times 10^{10}\,\mathrm{W/kg}, \tag{5}$$

which is close to the value of the production term in this region. This result suggests that the magnitude of mean flow generated by turbulence is relevant for plasma rotation.

Attention should be paid to the errors in the production term estimations. We have taken into account statistical errors associated to the cross-correlation calculation in Reynolds stress estimation and also to the mean velocity estimation. Errors in velocity components cross-correlation have been estimated as [16]

$$\varepsilon(\langle v_r v_\theta \rangle) = \frac{1}{\sqrt{N}} \sigma(v_r) \sigma(v_\theta), \tag{6}$$

where N is the number of samples used to calculate the cross correlation and $\sigma(v_r)$, $\sigma(v_\theta)$ are the standard deviations of radial and poloidal components of the fluctuating velocity. The statistical error in the mean poloidal velocity calculation is estimated based on the two point technique used. The imprecision in wave number and frequency and also the statistical dispersion in instant velocity estimates are all taken into account. From the two basic error sources (mean velocity and cross-correlation), errors in derived quantities (Figs. 3 and 6) can be estimated by applying standard error propagation analysis techniques.

It should be noted that with the present experimental set-up a non-zero cross-correlation can be obtained due to the presence of common pins in measurements of poloidal and radial components of electric field (pin J). It is difficult to quantify this error source but clearly it will be more important when measurements are taken outside the fluctuation correlation volume. When all measurements are well inside a correlation volume, as it is the case in present experiment (see Fig. 4), no important error is expected from this source.

5. Conclusions

In conclusion, the investigation of energy transfer between perpendicular flows and turbulence in the plasma boundary region of the JET tokamak has shown that:

- The energy transfer from mean flows to turbulence (P), directly related with the momentum flux (e.g. $\langle \tilde{v}_\theta \tilde{v}_r \rangle$) and the radial gradient in the flow, can be both positive (energy transfer from DC flows to turbulence) and negative (turbulence driven flows) in the proximity of the shear layer in ohmic plasmas. So far, no evidence of pumping region (P negative) has been observed in divertor configurations.

- The direct computation of the turbulent viscosity gives values comparable to the anomalous particle diffusivities (in the order of $1\,m^2/s$).
- The estimated energy transferred from turbulence to the mean flow in the pumping region (P negative) in limiter configuration measurements is close to the power per unit mass needed to pump the flow up to the experimentally measured values in a turbulent characteristic time (tens of microseconds).

These results show, for the first time, the dual role of turbulence as a damping (eddy viscosity) and driving of flows in fusion plasmas emphasizing the important role of turbulence to understand perpendicular dynamics in the plasma boundary region of fusion plasmas.

Finally, it must be noted that the evolution of poloidal flows involves many contributions not considered in the present work. A quantitative estimate of the role of the production term (P) would need to consider all terms contributing to the equation for the energy of the poloidal flow. In particular, attention should be paid to the influence of magnetic topology in the proximity of the last closed fluxes. This issue will be addressed in ongoing publications.

References

[1] O. Reynolds, Philos. Trans. R. Soc. London Ser. A 186 (1895) 123.
[2] B. Carreras, V.E. Lynch, L. García, Phys. Fluids B 3 (1991) 1438.
[3] P.H. Diamond, Y.B. Kim, Phys. Fluids B 3 (7) (1991) 1626.
[4] P.H. Diamond, M.N. Rosenbluth, E. Sanchez, et al., Phys. Rev. Lett. 84 (2000) 4842.
[5] P.G. Matthews et al., Phys. Fluids 5 (1993) 4061.
[6] E. Sánchez et al., Contrib. Plas. Phys. 38 (1998) S93.
[7] C. Hidalgo et al., Phys. Rev. Lett. 83 (11) (1999) 2203.
[8] Y.H. Xu et al., Phys. Rev. Lett. 84 (17) (2000) 3867.
[9] H. Xia, M. Shats, Phys. Plasmas 11 (2004) 561.
[10] M.G. Shats, W.M. Solomon, New J. Phys. 4 (2002) 30.1–30.14.
[11] Stephen B. Pope, Turbulent flows, Cambridge University, Cambridge, 2001.
[12] W.D. McComb, The physics of fluid turbulence, Oxford University, 1990.
[13] I. García-Cortés et al., Plasma Phys. Control. Fus. 42 (2000) 389.
[14] J.M. Beall, Y.C. Kim, E.J. Powers, J. Appl. Phys. 53 (6) (1982) 3933.
[15] S.D. Scott et al., Phys. Rev. Lett. 64 (1990) 531.
[16] J.S. Bendatt, A.G. Piersol, Random Data, John Wiley, 1986.