

Turbulent energy transfer in the RFX-Mod device

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Understanding turbulence represents an outstanding critical issue in the physics of magnetically confined plasmas for thermonuclear fusion research. Indeed plasma turbulence has been recognized since the beginning as the cause of the so-called *anomalous* particle and energy transport [1]. Since the discovery of improved confinement regimes, associated with turbulent reduction and highly sheared plasma flows, a great effort has been devoted to investigating shear flow generation mechanism, and particularly the turbulence-induced plasma flows via Reynolds Stress [2]. The simplest model implying this mechanism may be inferred from an ensemble average of the momentum balance equation [3]:

$$\partial_t \bar{V}_\phi + \partial_r \left[\langle \tilde{v}_r \tilde{v}_\phi \rangle - \frac{\langle \tilde{b}_r \tilde{b}_\phi \rangle}{\bar{\rho} \mu_0} \right] = \partial_r \left(\frac{\bar{B}_r \bar{B}_\phi}{\bar{\rho} \mu_0} - \bar{V}_r \bar{V}_\phi \right) + \nu \nabla^2 \bar{V}_\phi \quad (1)$$

where each field has been divided into its average and fluctuating part ($\mathbf{V} = \bar{\mathbf{V}} + \tilde{\mathbf{v}}$, $\mathbf{B} = \bar{\mathbf{B}} + \tilde{\mathbf{b}}$) and ν is the kinematic viscosity [3]. In equation (1) we have considered the fact that in the edge region of reversed field pinch experiment (RFP) the magnetic field is mainly poloidal so that the mean $\mathbf{E} \times \mathbf{B}$ drift is mainly toroidal and perpendicular velocity fluctuations are in radial and toroidal directions. The term $R_{r\phi} = (\langle \tilde{v}_r \tilde{v}_\phi \rangle - \frac{\langle \tilde{b}_r \tilde{b}_\phi \rangle}{\bar{\rho} \mu_0})$ is the *generalized Reynolds Stress*, whereas its velocity and magnetic components are referred also as *Electrostatic Reynolds Stress (ERS)* and *Maxwell Stress (MS)*. The generation of perpendicular flows by turbulent Reynolds stress mechanism has been experimentally observed in fusion and linear devices [4, 5, 6], and these observations are also supported by numerical simulations [7].

Recently in RFX-mod RFP device a new probe has been installed to investigate the edge region during low-current discharge [8]. The system consists of two Boron Nitride cases, 5 cm toroidally spaced. Each case contains 40 electrostatic pins, combined in

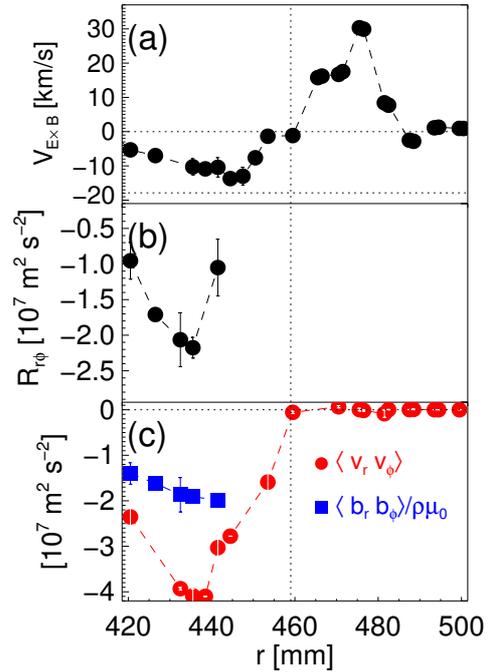


Figure 1: (a) $\mathbf{E} \times \mathbf{B}$ velocity profile (b) Total Reynolds Stress (c) Reynolds and Maxwell stress profiles. The vertical dotted line indicates wall position

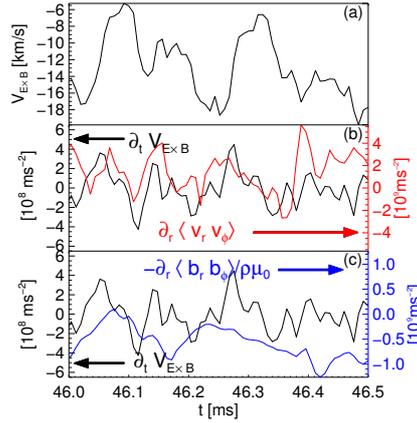


Figure 2: (a) Mean toroidal $\mathbf{E} \times \mathbf{B}$ drift (b) $\partial_t \bar{V}_\phi$ (black line) $\partial_r \langle \tilde{v}_r \tilde{v}_\phi \rangle$ (red line) (c) $\partial_t \bar{V}_\phi$ (black line) $-\partial_r \frac{\langle \tilde{b}_r \tilde{b}_\phi \rangle}{\rho \mu_0}$

eight 5-pins balanced triple probes, 6 mm radially spaced. Together with electrostatic pins a radial array of 7 three-axial magnetic coils is located in each case in order to measure the time derivative of the three components of the magnetic field. With the chosen configuration the probe allows the determination of Reynolds and Maxwell stress with high frequency bandwidth (~ 700 kHz for electrostatic measurements and ~ 1 MHz for the magnetic ones), and in 6 radial position simultaneously. Moving the probe on a shot to shot basis the profiles of the Reynolds and Maxwell stresses have been measured for the first time in RFX-mod. In figure 1 these profiles are shown together with the $\mathbf{E} \times \mathbf{B}$ velocity profile obtained from floating potential and temperature measurements. The velocity profile exhibits a double shear layer which has been observed also in other RFP's [9]. The first region closer to the wall (located at $r = 459$ mm) has been already discussed in terms of Finite Larmor Radius effects [9], whereas the innermost shear has been recently claimed to be caused by Electrostatic Reynolds Stress mechanism [4]. As previously observed in other experiments [5, 4] also in RFX-mod it is fairly evident that the coupling between perpendicular velocities becomes important inside the plasma, beyond the nominal position of the graphite-tiles. It is worth to note that this is also the region where a strong density gradient occurs [8]. Specifically we are interested in the innermost shear region ($r \lesssim 440$ mm), where ERS exhibits a strong gradient whereas MS is lower with an almost flat profile. The high spatial and temporal resolution of the experimental equipment allows also the estimate of the temporal evolution of the various terms entering the momentum balance equation (1). In particular the temporal evolution of ERS and of MS has been estimated through the Continuous Wavelet Transform (CWT) technique following the procedure described in [10]. In figure 2 a sample from a single shot of the time traces of \bar{V}_ϕ and of the radial derivatives of ERS and MS are shown. In particular in panel (b) the comparison between $\partial_t \bar{V}_\phi$ and $\partial_r \langle \tilde{v}_r \tilde{v}_\phi \rangle$

shows the clear correlation between plasma acceleration and the variation of ERS gradient.

Sheared flow generation mechanism suggests the existence of an energy exchange process between turbulent and macroscopic flow scales. In particular the energy transfer is regulated by the term $P = \left[\langle \tilde{v}_r \tilde{v}_\phi \rangle - \frac{\langle \tilde{b}_r \tilde{b}_\phi \rangle}{\rho \mu_0} \right] \partial_r \bar{V}_\phi$ which represents the energy exchange per unit time and unit mass from the turbulent to the mean kinetic content of the plasma [3]. The radial profile of P and of its electrostatic and magnetic contributions is shown in figure 3. It is observed that in the region of the innermost shear electrostatic fluctuations produce a net energy transfer from fluctuations to mean flow whereas the magnetic contribution to P is lower by a factor up to 5 and represents a small energy sink. This confirms numerical observation in the low β regime [7].

Apart from stationary profiles, strong interest arises from the analysis of the temporal evolution of energy exchange processes. By applying the same technique adopted in [10] the time evolution of $\bar{K} = \frac{\bar{V}_\phi^2}{2}$ and of the production term P have been calculated. A sample of the obtained results is shown in figure

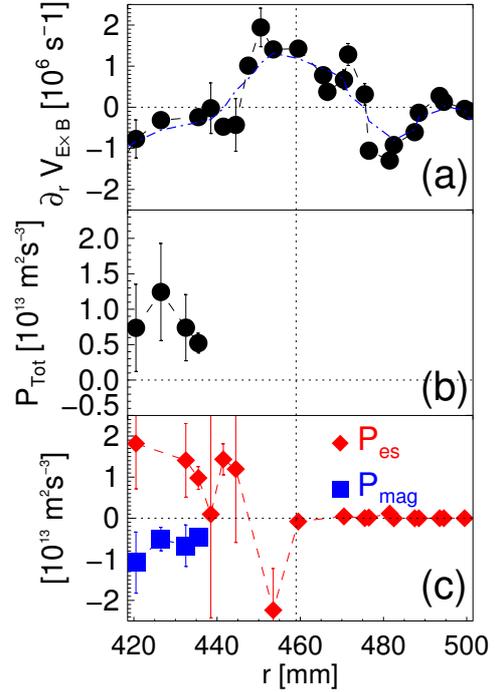


Figure 3: (a) $\mathbf{E} \times \mathbf{B}$ velocity shear (b) Total Energy Production term (b) Electrostatic and Magnetic energy production terms. The vertical dotted line indicates wall position

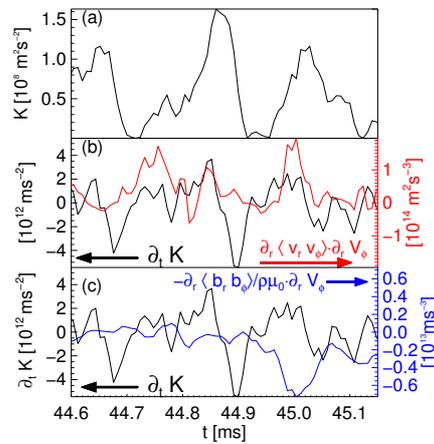


Figure 4: (a) Mean kinetic energy $\bar{K} = \frac{\bar{V}_\phi^2}{2}$ (b) $\partial_t \bar{K}$ (black line) $P_{es} = \langle \tilde{v}_r \tilde{v}_\phi \rangle \partial_r \bar{V}_\phi$ (red line) (c) $\partial_t \bar{K}$ (black line) $P_{mag} = -\frac{\langle \tilde{b}_r \tilde{b}_\phi \rangle}{\rho \mu_0} \partial_r \bar{V}_\phi$ (blue line)

4. Strong oscillations in \bar{K} may be recognized as observed also in Extrap-T2R [10]. By comparing the time evolution of $\partial_t \bar{K}$ and P (fig 4 (b)) the role of electrostatic fluctuations in driving the mean flow is evidenced, whereas magnetic contributions do not exhibit any clear relationship with $\partial_t \bar{K}$. In order to increase the statistical reliability of these experimental observations which pertain to a single shot, a conditional average has been applied to the various quantities (\bar{K} and P). Suitable time windows have been chosen around the strongest oscillations of mean kinetic energy \bar{K} . In each time window signals have been normalized by subtracting their average in the same time window and by dividing by their standard deviation. After averaging the resulting waveforms are subsequently brought back to their physical values by multiplying for the average of their standard deviation. The results are shown in figure 5. In panel (a) the oscillations around the average of $\partial_t \bar{K}$ are shown whereas electrostatic and magnetic contribution to P are shown in panel (b). It is fairly evident that the increase of \bar{K} are well correlated with the time traces of P_{es} thus confirming on a statistical basis what is observed during a single shot.

To summarize we have provide the first measurements of Reynolds and Maxwell stress on RFX-Mod RFP device, proving the role of ERS in the generation mechanism of sheared flows. We also proved that this mechanism is accompanied by an energy transfer from electrostatic fluctuations to mean flow scales.

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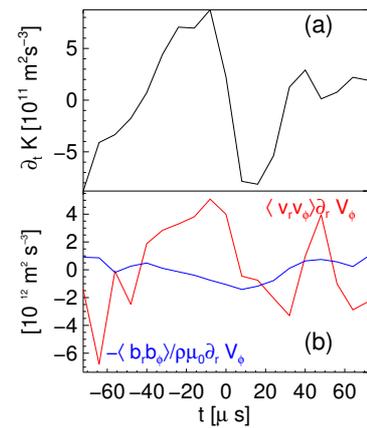


Figure 5: Conditional average procedure: (a) Oscillation of $\partial_t \bar{K}$ (b) oscillation of P_{es} and of P_{mag}