Link between turbulent eddies and shear flows and the characteristics of limit-cycle oscillation in the edge plasma of HL-2A tokamak

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Conditional sampling analysis using turbulent vorticity as the trigger reference was applied to Langmiur probe data from strongly heated L-mode plasmas. Here eddies with turbulent vorticity exceeding one standard deviation of vorticity fluctuation were selected and regarded as large vortices. This approach is complementary to the more standard spectral studies and can present a complementary picture which identifies the average dynamics of individual structures. The results show that large turbulent eddies (or blobs [1]) mediate significant particle, momentum and vorticity transport at the edge of a tokamak plasmas, with over 90% of the turbulent momentum and vorticity fluxes contributed by the motion of large amplitude vorticies that act to amplify the ExB shear layer at the last closed flux surface (LCFS). The experiment was carried out in the HL-2A tokamak which has a major radius R=1.65 m, a minor radius a=0.4 m, and a toroidal field and plasma current up to 2.7 T and 450 kA respectively. Details about this machine and relevant experimental results can be found in the literature [2].

The analysis shows that eddies with relative positive vorticity (blue lines in figures 1(a)-(f)) are associated with a transient reduction in particle density (figure 1(b)) and electron temperature (figure 1(c)), i.e. positive vorticity is associated with the generation of a cold density hole in this region. These events have $v_r<0$ (figure 1(d)) and thus propagate inward towards the core. An analysis of the average fluctuating poloidal velocity of these events (figure 1(e)) indicates that they have a deficit of poloidal momentum relative to the mean flow at this position. Negative vorticity events (red lines in figure 1(a)-(f)) are associated with hot, high density structures (i.e. "blobs" [2]). These structures have $v_r>0$ and thus propagate outward towards the LCFS and carry an excess of positive poloidal momentum (i.e. in the electron-diamagnetic direction) relative to the poloidal mean flow velocity. As a result of the correlations between radial motion, poloidal motion and vorticity, both types of events in this region contribute to a positive Reynolds stress and negative vorticity flux at the position ~2 cm inside the LCFS. The same conditional average analysis has been carried out on data taken in the SOL region at $r-r_{LCFS}=1\,cm$. Due to space restrictions the figures are not shown here. Here we find that although there is a phase shift between eddies' radial velocity fluctuation and the fluctuations of vorticity, density, electron temperature and poloidal velocity, eddies with positive vorticity in the SOL are associated with higher density and lower temperature perturbations, and propagate outward towards the wall. Conversely, negative vorticity eddies propagate from the SOL inward towards the LCFS and are correlated with lower density and higher temperature perturbations.

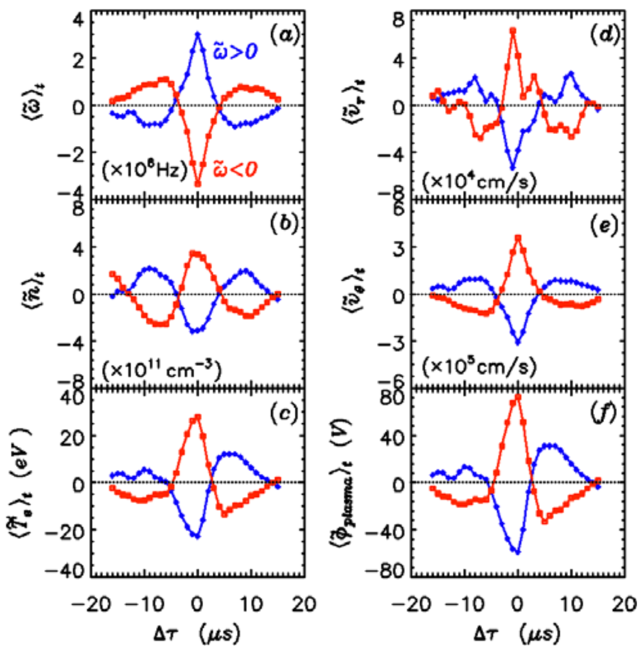

Figure 1 Conditionally averaged quantities inferred by using the vorticity as the reference. All the figures (a)-(f) are measured at $r-r_{LCFS}=-2cm$. Notice that the negative vortices (red) with relatively higher density, temperature, and excessive positive poloidal momentum propagate outward towards the LCFS.

This immediately means that prograde structures (i.e. eddies with a negative vorticity parallel to the shear layer negative vorticity) have an excess of positive azimuthal momentum (defined as the electron-diamagnetic drift direction) and are drawn from both sides of and move towards the ExB shear layer located about 1 cm inside the LCFS; retrograde eddies (i.e. those with positive vorticity) have a deficit of azimuthal momentum and are ejected away from the shear layer, moving towards the core and scrape-off layer (SOL) plasma regions. These interactions pile up turbulent momentum at one specific radial location which should naturally lead to the formation of a mesoscale shear flow at this location. Full discussions of vorticity transport or mixing and zonal flow formation can be found in Diamond et al [3, 4].

In order to determine the detailed spatial distribution of these phenomena, we have repeated the conditional averaging process described above for data taken across the edge and SOL regions, and then compute the radial profile of the conditionally averaged effective radial propagation velocity, v_r^{eff} , of positive and negative density, vorticity, and electron temperature fluctuations events. Note that this approach by definition selects either inward going or outward going events and then finds the average radial propagation speed of those events. The results are shown in figure 2, where the blue (red) curve corresponds to the positive (negative) fluctuation events. From figure 2(b), we find that negative vorticity events move towards the region located about 1cm inside the LCFS, while positive vorticity events move away from this region.

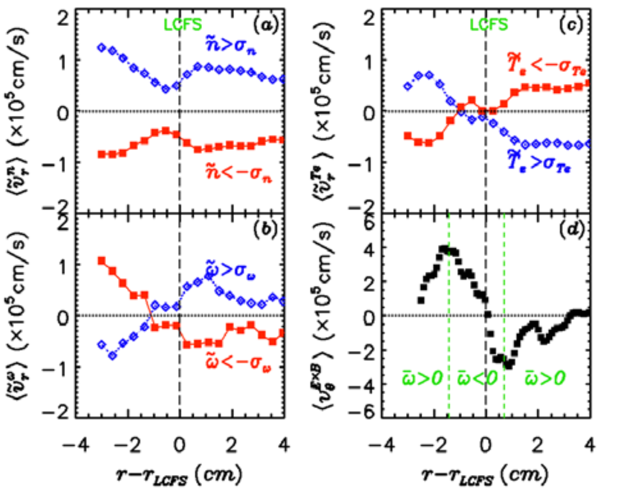

Figure 2 Radial velocity profiles for positive and negative eddies/blobs estimated by using conditional average with different trigger references. (a) density fluctuation as the reference (b) vorticity fluctuation as the reference (c) electron temperature as the reference. (d) Mean ExB flow velocity and its associated mean vorticity.

The data also suggest that the poloidal velocity can even change sign from the positive (electron diamagnetic) direction into the negative (ion diamagnetic) direction across the region $r\text{-}r_{LCFS}$<-2.0cm to $r\text{-}r_{LCFS}$<-3 to -4cm. The same prograde vortex-shear layer merging process should occur at this location, where now it is understood that the inward going positive vortices which have a deficit of poloidal momentum would be prograde with respect to the local ExB shear. As a result, there will be an accumulation of negative momentum at this location which would act to modify the shear layer locally as well. If repeated at a sufficient rate, this process could then lead to the formation of a mesoscale "ExB staircase" structure that has been recently reported in full-f gyrokinetic simulations [5] which could then act to regulate turbulent transport across the No-Man's Land region [6].

We also found that when the heating power is increased the vortices concentrate turbulent momentum in the shear region more rapidly, resulting in an increasing amplification of the shear flow. With sufficient heating power (NBI~ 0.8-1.0MW), the shear flow becomes strong enough to bring the plasma into an intermediate phase (I-phase) characterized by 2-3 kHz limit-cycle oscillations in potential, density and radial electric field, during which electron pressure gradient and the Reynolds stress, etc. are simultaneously modulated by the 2-3 kHz oscillation which disappears when plasma enters H-mode.

Fig. 3 (a)-(b) shows the time evolution of D_α and inverse scale lengths of electron pressure gradients (L_{pe}^{-1}) during the L-mode to I-phase, then to H-mode process. It is found that L_{pe}^{-1} first rises rapidly at L-I transition, then gradually increases during the I-phase. In order to clarify the link between turbulence and $\partial P_e/\partial r$ fluctuation, we show the time evolutions of them during L, I and H mode in Fig. 3 (c)-(e). In L-mode, the $\partial P_e/\partial r$ fluctuation is weakly correlated with turbulence amplitude. During the I-phase, the turbulence amplitude is modulated by $\partial P_e/\partial r$ fluctuation. At the end of I-phase, $\partial P_e/\partial r$ has the second abrupt rise, which is prior to I-H transition about 1-2 ms. After this $\partial P_e/\partial r$ jump the plasma enters H mode. In cases without this $\partial P_e/\partial r$ jump or continuous increase, plasma drops out of I-phase and returns to L-mode. Thus, this indicates that mean flow associated with pressure gradient plays a critical role on I-H transition.

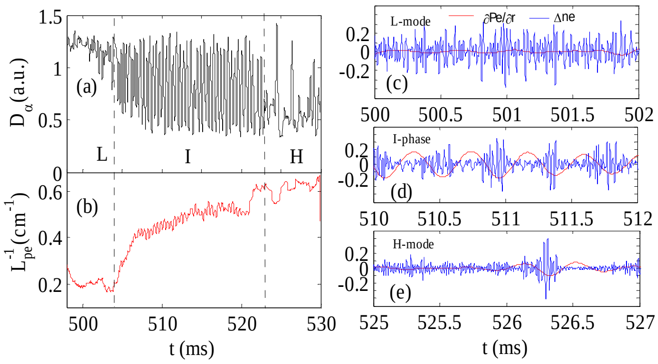

Fig.3 Time evolution of D_α (a), L_{pe}^{-1} (b) and zoomed time windows show time evolution of $\partial Pe/\partial r$ and density fluctuations in L mode (c), I-phase (d) and H mode (e), respectively.

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