Turbulent Eddy-Mediated Particle, Momentum, and Vorticity Transport in the Edge of HL-2A Tokamak Plasma

M. Xu[1,2], G.R. Tynan[1], P.H. Diamond[1,3,4], K.J. Zhao[2], J.Q. Dong[2], J. Cheng[2], C. Holland[1], P. Manz[1], N. Fedorczak[1], S.Chakraborty Thakur[1], J.H. Yu[1], W.Y. Hong[2], L.W. Yan[2], Q.W. Yang[2], Y. Huang[2], X. M. Song[2], L.Z. Cai[2], W.L. Zhong[2], Z.B. Shi[2], X.T. Ding[2], X.R. Duan[2], Y. Liu[2], and HL-2A team

[1]Southwestern Institute of Physics, P. O. Box 432, Chengdu, China
[2]CMTFO & CER & MAE Department, UCSD, La Jolla, CA, USA
[3]WCI Center for Fusion Theory, NFRI, Gwahangno 113, Yusung-gu, Daejeon 305-333, Korea
[4]CASS & Department of Physics, UCSD, La Jolla, CA, USA

E-mail contact of the main author: minxu.min@gmail.com

Abstract. We report the first experimental evidence that turbulent eddies mediate the particle, momentum and vorticity transport at the edge of a tokamak plasma so as to amplify the shear layer at the last closed flux surface (LCFS). We find that turbulent eddies with relative negative vorticity (opposite to B field) and positive azimuthal momentum (electron-diamagnetic drift direction) are drawn from both sides of and move towards the location about 1 cm inside separatrix; while eddies with relative positive vorticity (i.e. parallel to the B field) and negative azimuthal momentum (ion-diamagnetic drift direction) propagate away from this location towards to the core and scrape-off layer (SOL) plasma regions. Thus negative vortices act to concentrate positive momentum into the region just inside the LCFS, and plasma in this region acquires an ExB drift in the electron drift direction while plasma deeper within and out in the SOL has an ExB drift in the ion diamagnetic direction. This physical picture links the macroscopic confinement to the microscopic transport dynamics. Also since the vortcity drive gets stronger as the heating power is increased, it should naturally lead to a very strong shear flow that can suppress the turbulent transport and ultimately can lead to H-mode with sufficient heating. The results also show that turbulence/shear layer interactions not only lead to an amplification of the shear layer, but they also generate inward going population of cold holes which impose a non-trivial boundary condition on the particle and heat flux escaping from the core region of L-mode discharges.

1. Introduction

The last closed flux surface region of toroidally confined magnetic fusion plasmas plays a critical role in achieving the conditions necessary for net energy gain, and in governing the location and intensity of particle and thermal loads imposed on the material surfaces facing the plasma. Thus the physics of particle, momentum and heat transport in this region is of fundamental importance for magnetic fusion. The region is characterized by the presence of large amplitude turbulent fluctuations that play a dominant role in determining the rate of cross-field transport via correlated cross-field velocity, density and temperature fluctuations and by the existence of a sheared ExB drift velocity which can interact with and regulate the rate of turbulent mixing in this region [1]. Recent work [2] has demonstrated that as the input heating power is increased in the so-called low confinement mode (L-mode), the rate of turbulent transport and the strength of this ExB shear layer both increase. Furthermore, it was shown that the turbulent Reynolds stress acts to reinforce, or amplify, this shear layer, and that this amplification process becomes stronger as the heating power into the plasma was increased. Using a spectral approach, this process was found to occur via a transfer of kinetic energy from small-scaled (typically with the radial correlation length < 1cm and the poloidal correlation length ~ 1-3 cm in the edge velocity shear region in HL-2A) turbulence into the large-scaled shear flow. This result demonstrates that the edge turbulence acts to amplify the shear layer at the expense of the turbulence, and that this process becomes more intense as the heat flux through the edge is increased. Actually this shear flow generation from turbulence is clearly demonstrated by Diamond et al. [3], where it has been shown that the potential vorticity or polarization charge transport is of fundamental importance in driving shear flows. Theory indicates [4, 5] that such positive feedback processes can lead to a bifurcation in which the system moves to a state of high rate of ExB shear flow and reduced turbulent transport. Recent results from several other tokamak experiments suggest that such a process may be responsible for the transition into the high confinement mode (H-mode) regime [6-9]. Furthermore, studies of this nonlinear turbulence/sheared ExB flow interaction in laboratory plasma devices have shown that this feedback mechanism can be understood in terms of the interaction of small-scaled turbulent vortices and the large scale shear flow [10, 11]. These experiments also showed that vortices mediate turbulent momentum transport and the vorticity flux and wave stress are responsible for the shear flow amplification [10].

In this work, we use a conditional averaging approach to analyze spatiotemporal fluctuation data obtained from a two-dimensional probe array that is inserted into the region just inside the LCFS of the HL-2A tokamak during strongly heated L-mode discharges. The analysis permits the identification of turbulent structure vorticity and facilities the study of the structure motion. The results demonstrate that the ExB shear layer amplification is due to a vortex merging process that is occurring at the plasma boundary region. The ExB shear layer has a specific sign of vorticity. Turbulent structures with the same sign of vorticity (i.e. prograde vortices) are attracted towards the shear layer where they are absorbed. Structures with opposite vorticity (i.e. retrograde vortices) are ejected away from the ExB shear layer. As a result the shear layer is amplified or reinforced by the turbulence. In addition, we find that the turbulent vorticity has a clear correlation with density and electron temperature fluctuations. These results show that the interaction of prograde and retrograde turbulent vortices with the ExB shear layer results in the ejection of hot, high density turbulent plasma structures (known in the literature as blobs [12], avaloids [13], or Intermittent plasma objects (IPOs) [14] into the scrape-off layer (SOL). These observations are consistent with a very recent theoretical work [15] that offered the generation mechanism of drift holes and their role to excite zonal flows through dynamical interactions. In addition, the results also show that the interaction of retrograde vorticies with the ExB shear layer leads to the injection of *inward going cold holes* – that is structures with a reduced plasma density and temperature – that are launched from the edge shear layer into the core plasma region. The results show that these cold holes propagate 2-3 cm inside the LCFS, a distance approximately 2-3 times the radial scale size of the vortices themselves. These inward going cold density holes result in an effective outward going particle and heat flux at the interface between the plasma edge and the plasma core. This flux is a significant fraction of the estimated total flux escaping the core region, and thus plays an important role in the overall power balance and confinement of the system. Thus these results clearly show that turbulence/shear layer interactions not only lead to an amplification of the shear layer, but they also generate inward going population of cold holes which impose a non-trivial boundary condition on the particle and heat flux escaping from the core region of L-mode discharges. Similar phenomenon of density blobs and holes propagation was also reported in JET [16].

2. Experiment

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. The device can apply up to 3.0MW of electron cyclotron resonance heating (ECRH) power and 1.5MW of neutral beam injection (NBI) heating power. For these experiments reported here, B=1.35 T, ECH heating power is up to ~ 700 kW, and Ip~150 kA; no NBI heating was used in this work. The chord averaged density measured by HCN interferometer is ~ 1-2x10^{19} /m^3 and the plasma was operated with a circular cross-section plasma limited on the inner high-field side wall. Details about this machine and relevant experimental results can be found in the literature [17-19].

3. Experimental Results

The results reported in this paper were obtained using a 3x4 electrostatic Langmiur probe array installed on the midplane. Profiles of the time-averaged plasma density, electron temperature and space potential are shown in Figure 1(a)-(c). In this plasma, a strong mean sheared ExB flow develops at the edge, as we can see from figure 1(d). This ExB mean flow is estimated from the ExB drifts computed from the measured equilibrium plasma potential (Figure 1(c)), which is estimated as $\phi_{plasma} \approx \phi_{float} + 2.8T_e$ using the triple probe measurements of floating potential and T_e. For 730kW ECR heating the decorrelation rate due to this ExB shear flow reaches a maximum at roughly 1 cm inside the LCFS, and is estimated as $|\omega_{shear}| \approx |\partial \langle v_\theta \rangle / \partial r| \sim 3\times10^5 Hz$, which is larger than the typical eddy turnover rate $\tau_{eddy}^{-1} \approx 0.4 - 1.2\times10^5 Hz$ estimated from potential fluctuation amplitude and radial and poloidal correlation length measurements.

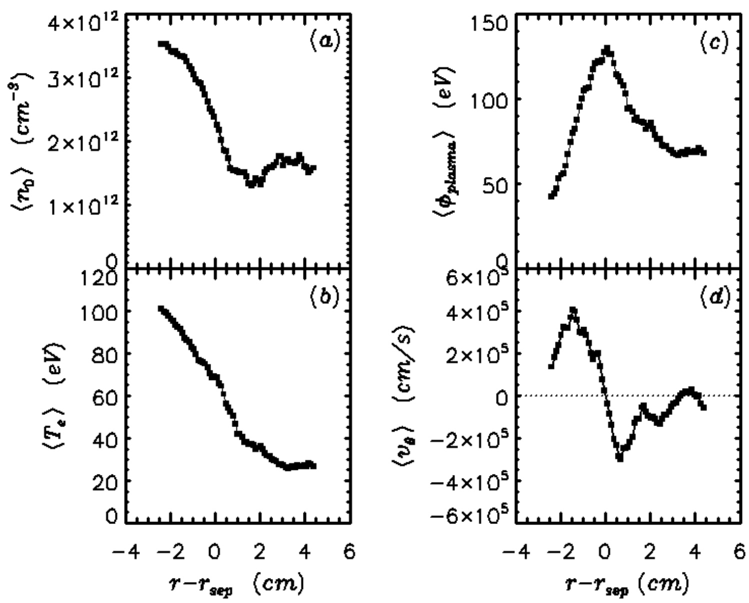

Figure 1 Profiles of time-averaged statistics for discharges at 730 kW ECR heating. (a) Time-averaged density (b) electron temperature (c) plasma space potential (d) Poloidal flow velocity estimated by mean radial electric field.

The total turbulent Reynolds stress $\langle \tilde{v}_r \tilde{v}_\theta \rangle$, shown as the red curve in figure 2(a) has a negative gradient (in the region -2cm < r < 0cm) indicating an accumulation of positive turbulent momentum (corresponding to flow in the electron diamagnetic direction with E_r<0) in this region. Noting that the vorticity flux is related to Reynolds stress through the Taylor identity for a two-dimensional incompressible flow with a direction of symmetry (e.g. here the direction within the flux surface), we can write the Reynolds force arising from the transport of momentum and vorticity as $F_\theta^{rs} = -\partial \langle \tilde{v}_r \tilde{v}_\theta \rangle / \partial r = -\langle \tilde{v}_r \tilde{\omega} \rangle$ [2, 20, 21]. The total Reynolds force arising from all turbulent fluctuations is shown as the red curve in figure 2(b). Whether viewed from the perspective of momentum transport (a.k.a. the Reynolds stress) or vorticity transport (i.e. the vorticity flux), the net result shows that the turbulence acts to reinforce or amplify the ExB shear flow that exists at the plasma boundary. The more commonly measured turbulent particle flux and electron heat fluxes are also shown as the red curves in figure 1(c-d), and when integrated over the last-closed flux surface yield total particle and heat loss rates that are roughly (factor of ~2) consistent with globally observed confinement. .

As pointed out earlier, laboratory plasma studies indicate that shear layer amplification by turbulence occurs largely via the merger of small scaled turbulent vortex structures with the large scale ExB shear layer [10], and the turbulent stress profiles were also shown to be related to the tilting of anisotropic turbulent structures in the background sheared ExB flow [22]. The similarity of the results shown here suggests that a similar eddy merging process is occurring at the tokamak boundary. We address this question by performing a conditional average analysis of the turbulent eddy events. When the vorticity goes above one standard deviation at time t, an event with positive vorticity is considered to be passing by the probe. Thus an event is considered to have been triggered and a time window with length of Δt is selected around t, i.e. a slice of data such as density and temperature, etc., from $t-\Delta t/2$ to $t+\Delta t/2$ is selected and is associated with the passage of the positive vorticity event. Δt is arbitrarily selected and it should be larger the typical turbulence fluctuation time scale. In a data record of 4 milliseconds roughly a total of 120 such events were selected and averaged to obtain an average event with an average lifetime (as measured by the autocorrelation time of the averaged event) of ~ 20-30 microseconds. The same technique was performed for the negative vorticity events with a trigger of one negative standard deviation. In this way a statistically averaged picture of the dynamics of vortex behavior along with associated fluctuations in density and electron temperature, etc., can be constructed. Note that the positive and negative vorticity mentioned in this paper are relative quantities, with the average background vorticity having been subtracted during the process of isolating fluctuating quantities from time-averaged quantities. Figure 3 shows the cross-correlation between conditionally averaged vorticity and the conditionally averaged density,

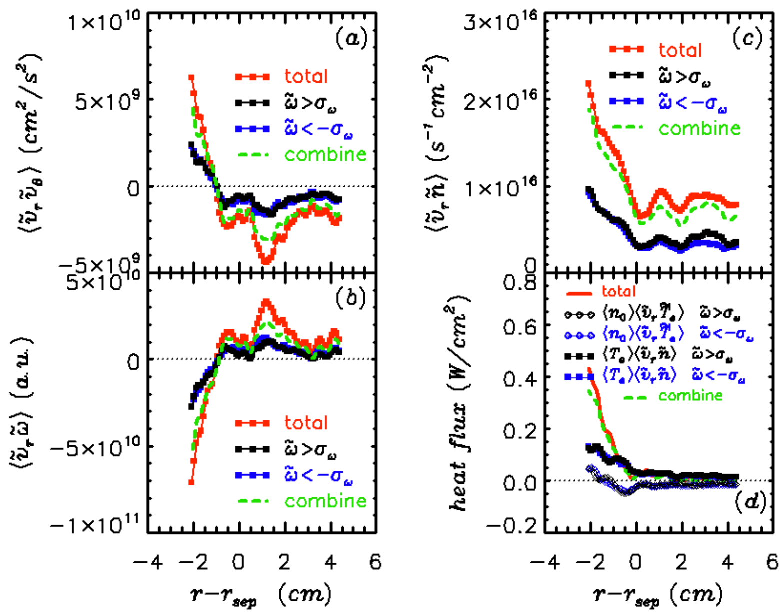

Figure 2 Statistically averaged radial profiles for 730 kW ECH power discharges showing (a) Reynolds stress (b) vorticity flux (c) particle flux (d) electron heat flux. Red curves in (a-d) indicate the total turbulent fluxes irrespective of vorticity sign and magnitude. The contribution of positive vortices (i.e. those with vorticity parallel to B_0) and negative vortices (i.e. those with vorticity anti-parallel to B_0) with amplitudes larger than one standard deviation are isolated using conditional sampling and their contribution to the fluxes is also shown. Black and blue solid squares correspond to contribution from positive and negative vortices respectively . The green lines in (a-d) are the sum of contribution from positive and negative vortices with amplitudes larger than one standard deviation, and the red is the total contribution to fluxes from turbulence with all different amplitudes.

electron temperature, radial and poloidal velocities, all of which are obtained by using the fluctuating vorticity as the reference for the event trigger.

Figure 3(a)-(d) show the conditionally averaged quantities obtained via this process for data taken at radial position $r - r_{LCFS} = -2cm$ inside the LCFS. Results show that eddies with relative positive vorticity (blue lines in Figures 3(a)-(d)) are associated with a transient reduction in particle density and electron temperature (not shown here due to limit space) (i.e. positive vorticity is associated with the generation of a hole in plasma density and electron temperature in this region). These events have $v_r<0$ and thus propagate inward towards to the core. An analysis of the average fluctuating poloidal velocity of these events (Figure 3(d)) indicates that they have a deficit of poloidal momentum relative to the mean flow. Triggering an event on a negative vorticty event allows the behavior of eddies with relative negative vorticity to be examined (red lines in figure 3(a)-(d)). These negative vorticity events are associated with higher density and higher electron temperature with respect to the average background. They have $v_r>0$ and thus propagate outward towards the LCFS and carry an excess of positive poloidal momentum (i.e. they have a positive fluctuating poloidal momentum (electron-diamagnetic) relative to the mean flow). 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.

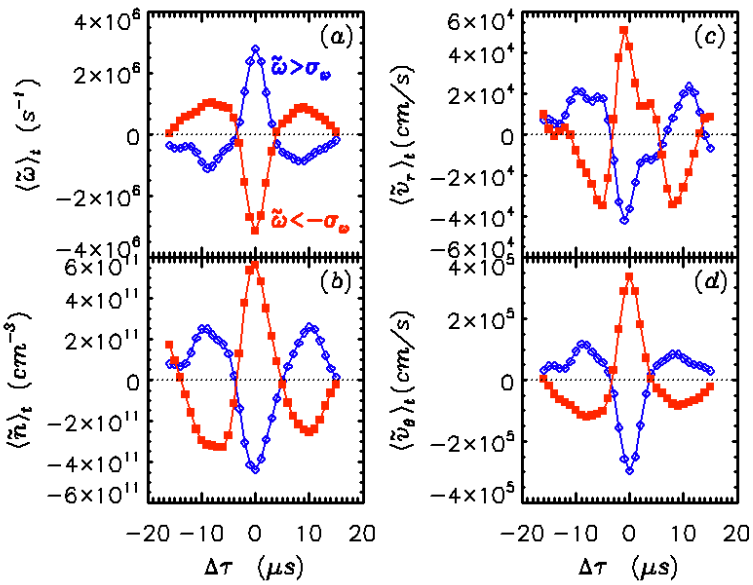

Figure 3 Conditionally averaged quantities inferred by using the vorticity as the trigger reference. Results in (a)-(d) were obtained at $r - r_{LCFS} = -2cm$ inside the LCFS. Notice that the negative vortices (red) with relatively higher density, temperature, and excessive positive poloidal momentum propagate outward towards the wall at $r - r_{LCFS} = -2cm$, which indicates that the negative vortices mediate and concentrate particles and positive momentum in the region round 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 plots are not shown here. In the SOL region we find that eddies with positive vorticity in the SOL are associated with higher density perturbations, and propagate outward towards the wall. Thus both blobs and holes contribute an outward flux of particles and heat in the SOL as expected. Eddies with negative vorticity from both inside the LCFS and out in the SOL mediate the transport of positive poloidal momentum and concentrate it just inside the LCFS where it can amplify the shear flow located at this region. And eddies with positive vorticity inside the LCFS are associated with cold density holes and move into the core region

In order to determine the detailed spatial dependence of these phenomena, we have repeated the conditional averaging process described above for data taken across the edge and SOL region, 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 fluctuation events. Here $v_r^{eff}\Big|_{\tilde{\xi}>\sigma_\xi} \equiv \left\langle \tilde{v}_r \right\rangle\Big|_{\tilde{\xi}>\sigma_\xi}$ and $v_r^{eff}\Big|_{\tilde{\xi}<-\sigma_\xi} \equiv \left\langle \tilde{v}_r \right\rangle\Big|_{\tilde{\xi}<-\sigma_\xi}$ defines the effective radial velocity associated with the transport of the field quantity $\tilde{\xi}$ (which denotes either $\tilde{n}, \tilde{T}_e, \tilde{\varpi}$) for conditionally averaged events selected with either the $\tilde{\xi} > \sigma_\xi$ or $\tilde{\xi} < -\sigma_\xi$ criteria described earlier, where $\tilde{v}_r$ is the ExB velocity and σ_ξ is the rms of $\tilde{\xi}$. 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 which does not vanish; if no conditional averaging was done then this velocity would vanish as expected for zero-mean fluctuations. The results are shown in figure 4, where the blue (red) curve corresponds to the positive (negative) fluctuation events. Figure 4(a) shows that positive density fluctuation events propagate outwards and negative density events propagate inwards across the whole edge plasma region (at least in the region r-r_LCFS > -3.0 cm). From figure 4(b), we find that negative vorticity events are being attracted towards or are moving towards the region located about 1cm inside the LCFS, while positive vorticity events are moving away from this region. Examining the mean shear flow profile in detail (Figure 5d), we observe that the mean sheared ExB flow has a mean shear (which can also be seen as a mean vorticity $\bar{\varpi} = \frac{\partial \bar{V}_E}{\partial r}$) with $\bar{\varpi} > 0$ for r-r_{LCFS} < *-1.5cm* and r-r_{LCFS} >*+0.5* cm, and $\bar{\varpi} < 0$ for *-1.5cm* < r-r_{LCFS} < *+0.5 cm.* Thus is appears that the turbulent vortices with $\tilde{\varpi} < 0$ are attracted towards the $\bar{\varpi} < 0$ mean shear flow region while vortices with $\tilde{\varpi} > 0$ are repelled away from this region.

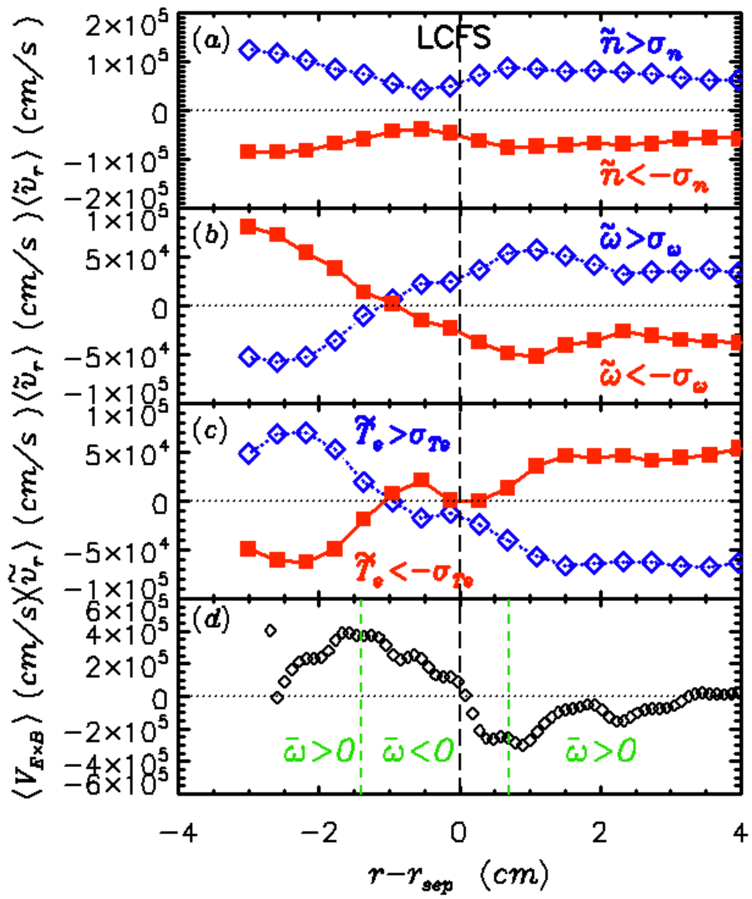

Figure 4 Radial velocity profiles for positive and negative eddies/blobs estimated by using conditional average with different trigger references. (a) density fluctuation as the reference (b) vorticity fluctuation as the reference (c) electron temperature as the reference. (d) Mean ExB flow velocity and its associated mean vorticity.

Clearly the conditionally averaged vortex events are associated with fluctuations in density, azimuthal momentum and electron temperature. As a result, the radial motion of the vortices will lead to radial fluxes of density (i.e. particle flux and a convective electron heat flux), azimuthal momentum (i.e. Reynolds stress) and electron temperature (i.e. conducted electron heat flux). To determine if these fluxes are material in comparison to the total fluxes discussed earlier, we have computed the radial profiles of the relevant flux carried by the conditionally averaged events. The results are also shown as the black and the blue solid squares in Figure 2(a-c). We see that ~80% of the turbulent stress, vorticity flux and particle flux is associated with the motion of large amplitude ($|\tilde{\omega}| > 1\sigma_{\omega}$) events. Furthermore, examining the results for the region well inside the LCFS, we find that the inward going density holes lead to a net outward particle flux that is quite significant. These holes are also cooler than the surrounding plasma (i.e. we have inward going cold holes). Due to the combination of both convective and conducted heat fluxes, the plot in Figure 2(d) is a bit more complex, but again the result is the same: a significant fraction (~80%) of the outward going heat flux is dominantly carried by large amplitude ($|\tilde{\omega}| > 1\sigma_{\omega}$) events and approximately half of this flux (i.e. 40% of the total flux) is carried by inward going cold holes that propagate into the region $r\text{-}r_{LCFS} < -3\ cm$, i.e. inside of a normalized minor radius r/a~0.92.

4. Discussion and Conclusions

Based on the above discussions, the following physics picture of edge transport/shear layer interactions can be proposed. Positive and negative vortices are born within the immediate vicinity of the LCFS as a repeating dipole vortex chain distributed along the poloidal direction. Due to radial force which holds on the closed field lines this region immediately inside the LCFS has $E_r<0$, while out in the SOL the rapid parallel loss of electron heat causes a steep gradient in electron temperature which, due to the sheath which exists at the limiter or divertor surface, causes a $E_r>0$ to develop in this region. Thus at the vicinity of the LCFS, a sheared E_r region naturally exists due to the plasma equilibrium. This equilibrium shear flow has a negative vorticity just inside the LCFS, and thus can be thought of as a large-scale negative vortex, which will interact with the vortex chain that is generated in the same region. This shear layer will act to tilt the eddies in the vortex chain, causing them to have a finite turbulent stress and vorticity flux. As a result of the turbulent vortex-shear layer interactions, negative vorticity will accumulate at the shear layer and amplify it, while positive vortices will be ejected towards the core and into the SOL. Parallel electron dynamics set the cross-phase between the electrostatic potential fluctuations and the density fluctuations. As a result, cold density holes are advected inwards towards the core, while hot high density blobs are ejected into the SOL. The turbulence stress and vorticity flux acts to amplify the equilibrium shear flow, and increases in heating power effectively increase both the strength of the equilibrium shear layer and the strength of this positive feedback mechanism. The shear layer then acts to extract kinetic energy and momentum out of the turbulence and thus plays an important role in regulating the saturation amplitude of the turbulence. As the energy transfer/shear layer amplification process gets stronger as the heating power is increased, it seems clear that a very strong shear flow could then emerge. The result would then be consistent with a birfurcation into a strong shear flow/small turbulence amplitude state.

Another rather interesting phenomenon is that there exists another shear layer deeper inside plasma ($r\text{-}r_{LCFS}<2.0$cm) as shown by the poloidal velocity profile in figure 1 (d). And the poloidal velocity can even change sign from the positive (electron diamagnetic) direction into the negative (ion diamagnetic) direction across the region from $r-r_{LCFS}<0$cm to $r-r_{LCFS}<3$-4cm. This is consistent with the observation that positive vortices carry negative momentum (in the ion diamagnetic direction) and propagate inward towards the core. As a result, there will be a piling up negative momentum deeper inside plasma and will naturally lead to the "ExB staircase" phenomenon as reported by theorists recently [23].

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