Radial structure of vorticity in the plasma boundary of tokamak plasmas

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The energy and moment transfer between flows and turbulence in fusion plasmas is a topic that has been increasing in importance [1-**4**]. The simultaneous existence of multiple scales in turbulence and fluctuations was observed [**5**,**6**] and vortex formation, in regard to structure formation, transport phenomena and turbulent flows in plasmas have been given much attention. Vorticity is a primary physical quantity in fluid equations and known to play a key role in the physics of transport of energy and particles in plasmas and fluids. In spite of the strong scientific interest, experiments dealing with the dynamics of vorticity are rare [7-10]. Experiments were carried out in ISTTOK which supports AC operation (plasma current inverted periodically, in a time scale of typically 30 ms with a total duration up to 1s). The Deuterium plasma main parameters, for the set of discharges under consideration, were I_P~4kA flat top and n_e~3.5-4 x $10^{18}m^{-3}$. The use of AC discharges allows for a bigger set of experimental results for each radial position and in this work three comparable cycles were obtained per discharge. Edge parameters were digitized at 2 Mega Samples Per Second (MSPS) from a 3-5 ms time window during each semi-cycle discharge flat top (~20 ms). Plasma profiles and turbulence have been investigated using the probe head, located on the equatorial plane of the device. It consists of an array of Langmuir probes, with two parallel arrays of Langmuir probes separated radially by Δr~3 mm (Fig. 1) allowing the simultaneous investigation of the radial structure of fluctuations on vorticity, Reynolds stress and turbulence. Measurements were taken at different radial positions, both in the edge ($r < a_{limiter}$) and in the scrape-off layer (SOL) ($r > a_{limiter}$) on a shot by shot basis. The vorticity probe uses Langmuir probes as a discrete

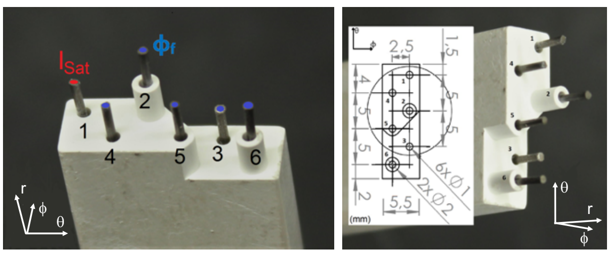

Fig. 1: (left) Tips of the vorticity probe: ion saturation current (I_{Sat}) in red, and floating potential (ϕ_f) in blue; and (right) probe dimensions (axis: r radial, θ poloidal and ϕ toroidal).

approximation of the Laplacian used in numerical computations. The five probe tips are aligned perpendicular to the magnetic field in approximately Diamond pattern, separated radially and poloidally. The vorticity fluctuations were computed from the fluctuations in the ExB velocities measured by the probe following the equation

$$\tilde{\omega} = \frac{1}{B}\left(\frac{\tilde{V}_{f2} - 2\times\tilde{V}_{f5} + \tilde{V}_{f3}}{\Delta r^2} + \frac{\tilde{V}_{f6} - 2\times\tilde{V}_{f5} + \tilde{V}_{f4}}{\Delta\theta^2}\right)$$

The flux of vorticity can also be estimated as $\langle\tilde{v}_r\tilde{\omega}\rangle \propto \langle\tilde{E}_\theta\tilde{\omega}\rangle/B$. The electrostatic Reynolds stress term (Re) can be determined by $\mathrm{Re} = \langle\tilde{v}_r\tilde{v}_\theta\rangle$ and can be related to the ExB 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. Figure 2 (top) shows the $\langle\tilde{v}_r\tilde{v}_\theta\rangle$ radial profile, which exhibits a radial gradient in the proximity of the velocity shear layer location. It was shown on ISTTOK that this mechanism can drive significant poloidal flows in the plasma boundary region [11]. Figures 2 (middle) and 2 (bottom) show the radial profile of the vorticity and of the vorticity flux respectively. It was observed that the vorticity is constant in the SOL and limiter region but in the plasma edge, where the ExB shear flow is higher, a larger dispersion is observed in the vorticity measurements. The observed dispersion is not unexpected as theoretical models have predicted that the magnitude of the shear layer leads to selectivity of the vorticity [12]. The vorticity has a maximum in the plasma edge and seems to change to negative further inside the plasma. The vorticity flux is positive in the plasma edge and decays to close to zero (or even negative) towards the limiter region. In [13] it is shown that for ExB-dominated turbulent flows which have azimuthally invariant fluctuation statistics, the Taylor identity holds and shows that the vorticity flux is related to the turbulent Reynolds stress and Reynolds force F_θ^R exerted by the fluctuations upon the background plasma by the relation $F_\theta^R = -\nabla_r\langle\tilde{v}_r\tilde{v}_\theta\rangle = -\langle\tilde{v}_r\tilde{\omega}\rangle$ [14,15]. A good fit between the gradient calculated the radial profile of the Reynolds stress the vorticity flux can be obtained. Both the Reynolds stress and the vorticity flux exhibit a strong gradient in the region inside the limiter. The order of magnitude of the gradient is within the expected values, meaning that the Reynolds force F_θ^R

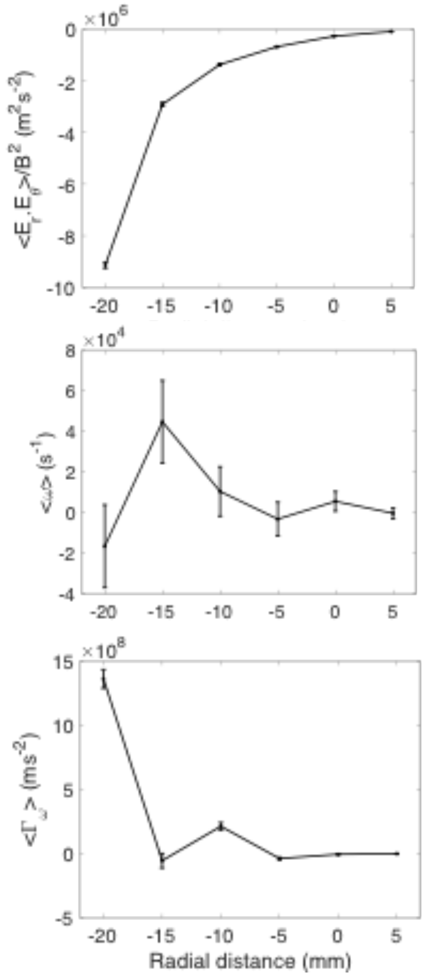

Fig. 2: Radial profiles of (top) Reynolds stress; (middle) vorticity; and (bottom) Vorticity flux

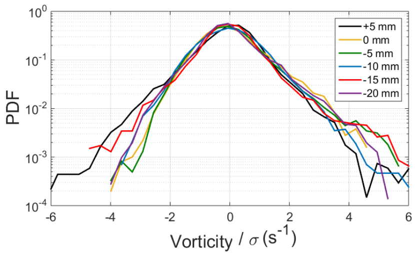

Fig 3: Probability Distribution Function (PDF) normalized to the standard deviation of the signal fluctuations, at different radial locations, of vorticity.

resulting from the vorticity flux amplifies the shear flow in the tokamak plasma edge region. This result shows that the vorticity flux may strongly contribute to the shear flow amplification in the plasma edge region of tokamaks and that the particle flux and vorticity flux are closely related, as also observed in linear plasma devices [10]. The Probability Density Function distribution (PDF) of vorticity for different radial positions. becomes broader as the probes are moved into the plasma, with larger events being clearly visible in the tails of the PDF which in both cases is slightly asymmetric and dominated by positive events. Figure 3 shows the PDF of the vorticity normalized to its RMS for the different radial locations. The PDFs show some degree of self-similarity although in these cases the tales of the distribution show some scattering due to a reduced number of events larger than several RMS. The self-similarity observed in ISTTOK indicates that there is no morphological change in the coherent structure in the plasma boundary region and that the fluctuation in these quantities can be described by a PDF that tends to a universal shape. The vorticity PDF shows a fat tail typical of strongly correlated systems, implying the existence of large intermittent coherent structures. Among various non-Gaussian distributions that emerge from consistent thermodynamical and statistical frameworks, q-Gaussians, based on the so-called non-extensive statistical mechanics introduced by Tsallis [16], are appealing for their simplicity. The q-Gaussian distribution is specified by the PDF

$$p_{qg}(x) = p_0 \left[1 - (1-q)\left(\frac{x}{x_0}\right)^2\right]^{1/(1-q)}$$

For $1-(1-q)(x/x_0)^2 \geq 0$ and $p_{qg}(x)=0$ otherwise. Figure 4 shows the overlap of the probability distribution function of vorticity obtained from the experimental measurements obtained at a fixed radial position and the result of a least squares fitting of the experimental distribution to a q-Gaussian distribution from which we obtain q=1.494. The PDF of the vorticity exhibit fat tails with a q-Gaussian shape typical of a non-equilibrium process. The q-Gaussian fit holds over several orders of magnitudes of the distribution with amplitudes of fluctuations up to 4σ and for different radial positions. For q=1 we would be reduced to a Gaussian distribution valid in equilibrium. Figure 4 shows the radial variation of the q parameter resulting from the fit performed to the PDFs of vorticity at different radial positions. A dip is observed in the radial profile, close to the limiter position with a q closer to that of a Gaussian distribution. In the limiter region, as expected due to the decorrelation resulting from the higher velocity shear layer, the fitting factor q shows a minimum closer to a Gaussian distribution. These are very

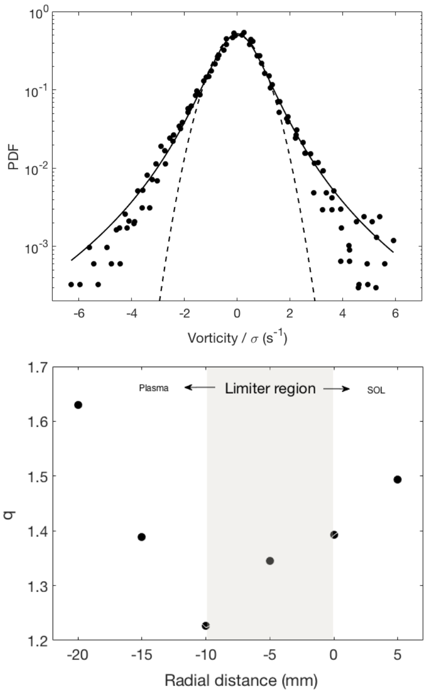

Fig 4: (top) Probability distribution function of the vorticity obtained from the experimental data (scattered points) at the radial position r=5 mm located in the SOL. The line indicates the q-Gaussian fit to the experimental data with a q=1.494 while the dashed line shows a Gaussian fit to the data; (bottom) Radial profile of the q parameter resulting from the fit of a q-Gaussian to the probability distribution function of the vorticity

positive and exciting results because it paves the way to identify the underlying turbulent mechanisms. In this paper we have presented the first measurement of vorticity and vorticity flux for different radial positions on a fusion relevant plasma. The experimental results presented show that the vorticity flux divergence amplifies the shear flow in the tokamak plasma edge region. Self-similarity in the PDF of vorticity is observed indicating that there is no morphological change in the coherent structures in the plasma boundary region and that momentum flux is regulated by blobs. Further work may be necessary to explore possible relations between the results and the theoretical models. Future work will also focus on performing edge biasing experiments on ISTTOK to study the effects of the ExB shear in the vorticity, the comparison of the result with numerical simulations, e.g., HESEL [17] and GBS code [18, 19] and on performing similar measurements in larger devices.

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