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Intermittent radial transport in the linear VINETA device

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Motivated by the observation of particle and energy losses perpendicular to the magnetic field in fusion devices, the fluctuation induced cross-field plasma flow into the far scrape-off layer (SOL) has been subject of intense investigation in the last two decades [1, 2]. As a result of this transport, the formation of a pronounced shoulder in the radial density profile and enhanced recycling of plasma particles at the first wall is observed [3], which has a strong impact on the divertor efficiency. A characteristic feature of this convective particle flux in the SOL are intermittent density bursts, characterized by a non-Gaussian amplitude probability distribution function (PDF), which are ascribed to large-amplitude turbulent structures, called blobs, propagating radially outwards with a velocity of typically $v \sim 10\,\%$ of the ion sound speed [2]. It was shown that blobs contribute considerably to the radial transport in the SOL [4]. Common models addressing the radial blob propagation in the SOL rely mainly on curvature of the magnetic field, which causes either polarization of the blobs [5] or gives rise to electrostatic interchange dynamics [6]. However, intermittent density fluctuations in the plasma edge and the formation and radial propagation of spatiotemporal structures have recently also been observed in linear devices with homogeneous magnetic field geometry [7]. In this paper we characterize the formation and propagation of turbulent structures in drift wave turbulence in the linearly magnetized VINETA device [8]. As a general feature of helicon sources a rather dense plasma ($n_{\text{peak}} \leq 2\cdot 10^{19}\,\text{m}^{-3}$) at low electron temperatures ($T_e \sim 3\,\text{eV}$) is produced. The results presented in the present paper were obtained in an Argon helicon plasma with a neutral gas pressure of $p = 0.1\,\text{Pa}$, a magnetic field of $B = 60\,\text{mT}$ induction, and a $RF-$power of $P_{rf} = 1.8\,\text{kW}$. Typical values for the drift scale ρ_s and for the peak plasma-β_{peak} are $\rho_s = 18\,\text{mm}$ and $\beta_{\text{peak}} = 1\,\%$, respectively. Time averaged radial profiles of the plasma density density and the plasma potential as measured with rf-compensated Langmuir probes are shown in Fig. 1. Both, the

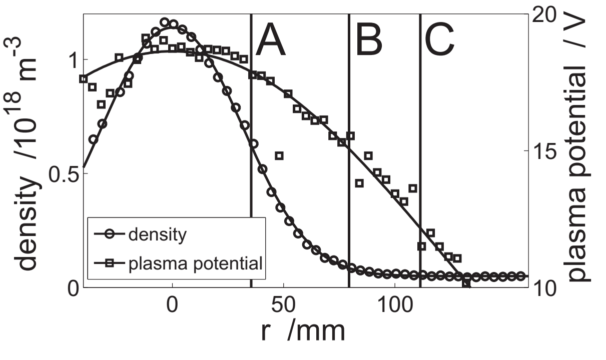

Figure 1: Time averaged plasma density and plasma potential profiles.

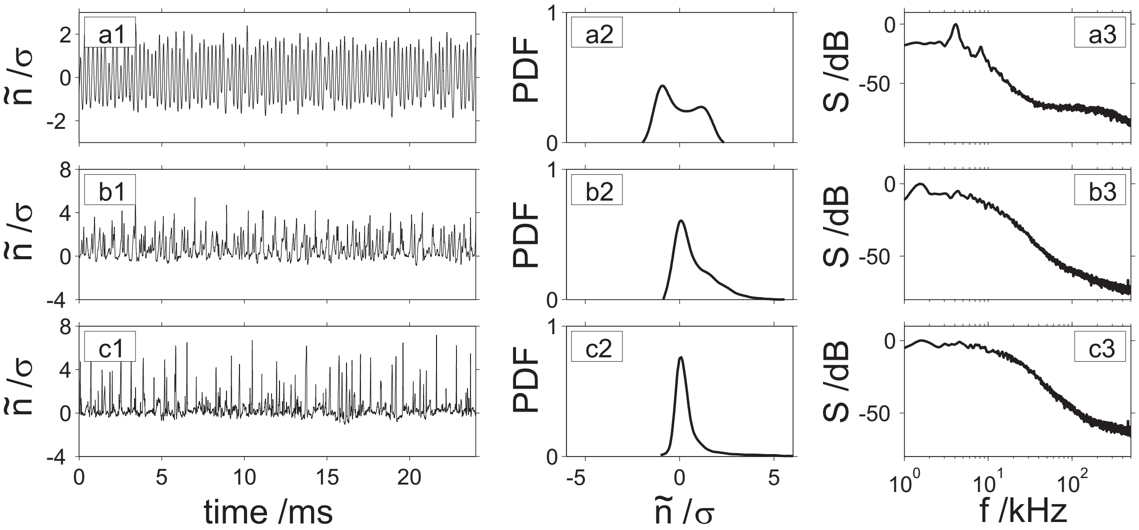

Figure 2: Plasma density fluctuations normalized to standard deviation, respective probability distribution function (PDF) and frequency power spectrum at radial positions A (a.1-a.3), B (b.1-b.3) and C (c.1-c.3) (cf. Fig. 1).

plasma density and the plasma potential profile are characterized by an exponential shape with different $1/e$–folding lengths (46 mm for plasma density and and 169 mm for plasma potential profile). Plasma density fluctuations are measured with uncompensated Langmuir probes. The probes are operated in the ion saturation regime at a probe bias of $U = -100$ V with respect to the plasma vessel and fluctuations of the ion saturation current are taken as directly proportional to plasma density fluctuations (electron temperature fluctuations are assumed to be negligible). To characterize the evolution of plasma density fluctuations across the radial plasma density profile single-point measurements at three different radial positions were done. The positions are indicated in Fig. 1 and in the following are referred to as positions A, B and C. Position A is at the position of the maximum radial density gradient, position B is in the plasma edge, where the density decreases to 7% of the peak density, and in the far plasma edge at position C, the density decreased to 4% of the peak plasma density. In Fig. 2 measurements of time series of density fluctuations normalized to standard deviation σ, the respective probability distribution function (PDF), and the frequency power spectrum at those three positions A, B, and C are shown. In the radial density gradient region (pos. A) coherent density fluctuations of a $m = 1$ drift wave mode with relatively small maximum amplitudes ($< 2\sigma$) dominate the time series (Fig. 2.a1). This is supported by the peak in the frequency power spectrum (Fig. 2.a3) at a frequency of $4.1\,$kHz. For higher frequencies above $8\,$kHz a power law decay is observed in the spectrum. The PDF is symmetric and double-humped. In the plasma edge at (pos. B) the density fluctuations display positive density bursts with maximum amplitudes of 4σ (Fig. 2.b1),

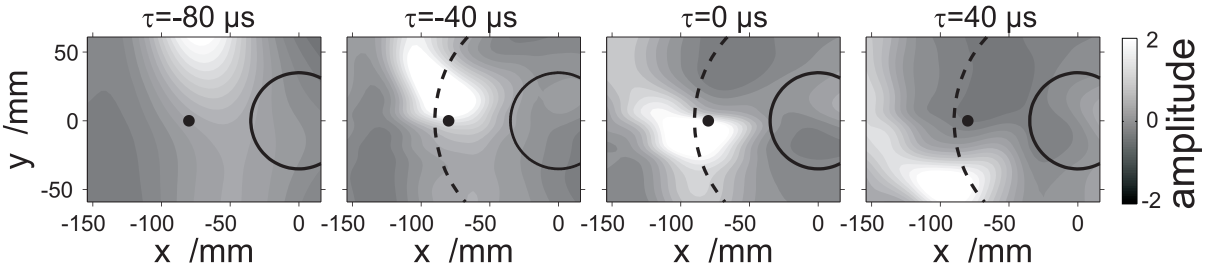

Figure 3: Conditional average (CA) of density fluctuations for four different time lags τ in the azimuthal plane. The amplitude condition applied to the reference probe, which is located in the plasma edge ($r = -80\,\mathrm{mm}$) was chosen to p=3σ. The CA amplitude is normalized to standard deviation. The black dashed line indicates the azimuthal direction, the black solid line indicates the position of the maximum radial density gradient.

which result in a skewed PDF having a pronounced positive tail. The occurrence of positive density bursts is not completely random in time but has a characteristic frequency, which leads to a broadened peak in the frequency power spectrum at a frequency of $\sim 1.5\,\mathrm{kHz}$ (Fig. 2.b3). The intermittent character of density fluctuations is even more pronounced the far plasma edge (pos. C, Fig. 2.c), where the normalized maximum amplitude of the positive density bursts is $7\,\sigma$. The corresponding PDF is strongly skewed and peaked with values of the higher order moments skewness S and kurtosis K of $S = 2.9$ and $K = 11$. The amplitude of the positive density bursts is comparable to the density fluctuations in the maximum radial gradient region, which indicates that the the large fluctuations in the far plasma edge originate in the density gradient region.

To gain insight into the spatiotemporal dynamics in the azimuthal plane we arranged 16 single probes as a vertical array with a spacing of $d = \rho_s/2 = 9\,\mathrm{mm}$. The array scans in consecutive measurements the azimuthal cross sections. The spatiotemporal evolution of the large-amplitude plasma density fluctuations in the azimuthal plane is reconstructed by use of the conditional average (CA) technique [9]. The reference probe for this technique is located in the plasma edge at position B and also measures density fluctuations. The condition for the CA analysis is an amplitude threshold condition of $p = 3\,\sigma \pm 5\,\%$ at falling slope to extract the coherent part of the positive large-amplitude fluctuations. The results of the CA procedure is shown in Fig. 3 for four different time lags τ. A coherent turbulent structure can be observed, which propagates mainly azimuthally in the direction of the background E×B-drift (counter-clockwise in this representation). The turbulent structure is slightly distorted with an azimuthal correlation length of $l_\theta^{corr} \approx 70\,\mathrm{mm} = 3.8\,\rho_s$ and a radial correlation length of $l_r^{corr} \approx 50\,\mathrm{mm} = 3.2\,\rho_s$. However, the propagation of the coherent structure is not purely in azimuthal direction (indicated by the dashed lines in Fig. 3) but has also a radial component. To quantify the structure's propagation behavior the trajectory of the center-of-mass of the coherent structure was tracked in time from $\tau = -40\,\mu\text{s}$ to $\tau = 40\mu\text{s}$, which yields a constant azimuthal velocity of $v_\theta = 760\,\text{ms}^{-1}$. This velocity results in an azimuthal turn-over time of the structure, which corresponds to a frequency of 1.3 kHz and agrees with the burst frequency of the single-point measurement (cf. Fig. 2.c1). The obtained radial velocity is $v_r = 230\,\text{ms}^{-1} \approx 10\%\,c_s$, which is much smaller than the azimuthal velocity.

In conclusion the radial propagation of turbulent structures is not intrinsically tight to a curvature of the magnetic field but is also observed in linear magnetic field geometry. In azimuthal direction the propagation speed of turbulent structures is determined by the background $E \times B$ drift. In radial direction structures propagate self-consistently with velocities, which are much smaller than in azimuthal direction. Thus, the picture emerges that turbulent structures spiral radially outwards, thereby considerably contributing to radial fluctuation induced transport. The details of the underlying mechanisms leading to radial propagation is subject of further investigations. As was suggested by Krasheninnikov and co-workers [10] vertical polarization of density fluctuation structures in linear magnetic geometry can be caused by a gradient in the velocity of the neutrals, the so-called neutral wind. For the present plasma conditions a radial velocity caused by neutral wind of $v_r^{nw} = 270\,\text{ms}^{-1}$ is obtained, which is comparable with our experimental findings.

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