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Investigation of turbulent transport and shear flows in the edge of fusion plasmas

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Introduction: Turbulent transport is a key issue in magnetic confinement of fusion plasmas. Edge transport due to micro-instabilities sets the values of temperature and density at the edge pedestal top and significantly contributes to a global confinement degradation [1]. Transport in the scrape-off layer (SOL) is commonly observed to have an intermittent nature. A significant fraction of SOL energy and particle transport was found to be carried by intermittent bursts [2], so-called blobs. SOL transport ultimately determines the peak power load on the divertor plates and the first wall and, therefore, is a critical issue for ITER. Furthermore, shear flows as a trigger of transport barriers play a key role in confinement improvement [3].

The low-temperature plasmas in TJ-K provide a unique accessibility to the microscopic structure of plasma turbulence by Langmuir probes. In terms of dimensional similarity, results from TJ-K are relevant for fusion edge plasmas [4]. Current investigations involve the generation mechanism and dynamics of blobs. Comparative studies are also carried out on ASDEX Upgrade and HSX. The complexity of zonal-flow physics is approached with a sophisticated diagnostics, which measures the Reynolds-stress drive on a full poloidal turn of a flux surface. This paper gives a summary of recent results.

Basic turbulence characteristics in TJ-K: TJ-K [5] is a small-scale torsatron with a major and a minor plasma radius of $R_0 = 0.6\,\mathrm{m}$ and $a = 0.1\,\mathrm{m}$, respectively. With magnetic field strengths in the range $B = 70$–$280\,\mathrm{mT}$, low-temperature plasmas are toroidally confined with electron temperatures T_e around $10\,\mathrm{eV}$ ($T_i < 1\,\mathrm{eV}$) and densities 10^{17} to $10^{18}\,\mathrm{m}^{-3}$. The plasma is produced via microwaves at 2.45 and 8 GHz. Detailed information on turbulent fluctuations in density ($\widetilde{n}$) and potential ($\widetilde{\phi}$) in the core plasma are obtained from different types of multi-probe arrays.

Previously, turbulence inside the separatrix was shown to be drift-wave like: the spatial phase relation of $\widetilde{n}$ and $\widetilde{\phi}$ is close to zero [4], the size of turbulent structures shows a ρ_s dependence [6], the structures have a finite elongation parallel to the magnetic field [7], and perpendicularly they propagate into the direction of the electron-diamagnetic drift [8]. Due to the low β, magnetic field fluctuations were found to be small [9]. So far, multi-probe measurements have been carried out at a toroidal position, where the flux surfaces have a triangular symmetric shape. Here, fluctuation amplitudes and transport levels were found to vary poloidally with peak values on the low-field side (LFS) in a region of unfavorable curvature. The relation of magnetic field geometry and turbulent transport is an important issue for fusion devices and will be addressed in a separate work.

Edge/SOL transition: In magnetized plasmas, turbulent transport is commonly observed to have an intermittent nature. In Ref. [10], it has been shown that the bursty behavior of the fluctuations and transport is not necessarily due to avalanches caused by critical gradients. Fig. 1 a) shows the skewness of $\widetilde{n}$ in the vicinity of the separatrix of TJ-K.

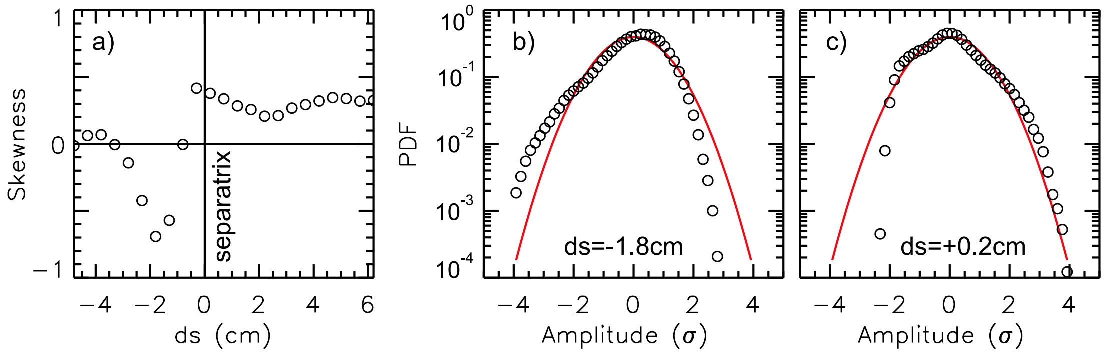

Fig. 1: *Radial profile of the skewness of $\widetilde{n}$ (a), PDF inside (b) and outside (c) the separatrix.*

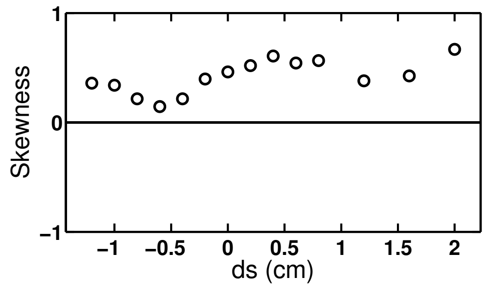

Fig. 2: *Skewness profile of fluctuations in the ion-saturation current from HSX (QHS, 1 T) discharges. No holes are observed.*

The skewness measures the asymmetry of the fluctuation amplitude distribution compared to a Gaussian (see Fig. 1 b), c)). Negative values indicate holes with the PDF being asymmetric towards negative amplitudes. Positive values indicate blobs. These results confirm observations on DIII-D [11], ASDEX Upgrade [12] and JET [13] tokamak. The observation of holes and blobs in- and outside the separatrix, respectively, indeed points to a local blob generation via an interchange mechanism rather than to transport through avalanches from deeper inside the plasma. While positive events appear to be a universal feature of edge fluctuations, holes are not. In, e.g., TEXTOR [14] and HSX (Fig. 2) no obvious signs of holes were found near the separatrix. A local minimum in the radial skewness profile as can be seen in Fig. 2 at $ds \approx -0.5\,\mathrm{cm}$ points to a local generation of blobs in the vicinity of the separatrix ($ds \approx 0\,\mathrm{cm}$).

The low-temperature plasma in TJ-K allowed to study this universal feature in more detail. Two-dimensionally resolved probe measurements in TJ-K showed that the blobs are generated on the transition from closed to open field lines [15]. They were found to be fed by drift-wave structures in the edge. After generation, the density blobs started to propagate into the $E \times B$-drift direction opposite to the electron-diamagnetic drift U_{dia} and to decouple from potential perturbations. The propagation reversal across the separatrix is reflected in an abrupt change in the measured phase velocity of the density structures (see Fig. 2 in Ref [15]). In hot fusion plasmas, a strong $E \times B$ shear layer has been observed at the transition from closed to open field lines, which could explain the propagation reversal. In TJ-K, however, the $E \times B$ flow velocity is small compared to U_{dia}, which dominates the propagation velocity of the drift-wave structures in the edge. The velocity reversal can be attributed to a change in turbulence characteristics from drift-wave inside to non drift-wave-like outside the separatrix, where the parallel dynamics of drift waves is suppressed due to the finite connection length of the field lines to the limiter.

Coupling of drift-wave turbulence and shear flows: The non-linear energy transfer in drift-wave turbulence is expected to be similar as in two-dimensional fluids. Experimental evidence for the dual cascade has been reported in TJ-K [16]. In the inverse cascade, in which the energy of turbulent fluctuations is transferred along the inverse cascade from small to large scales, non-local transfer, i.e. transfer between non-contiguous spectral ranges, has been found to play an important role. The non-local inverse energy transfer has the capability of driving large-scale flows. Direct experimental evidence for the kinetic energy transfer from drift-wave turbulence to zonal flows is provided in Ref. [17]. The non-local transfer can be understood in terms of small-scale vortices dispensing energy to the large-scale flow by being tilted and strained. This mechanism could be considered as the main cause of transport reduction instead of the conventionally assumed decorrelation of larger scale vortices.

Despite of the energy transfer, self-excited zonal flows are marginally developed in present operation regimes of TJ-K. Hence, plasma biasing is applied to study the influence of strong shear flows on turbulence. The influence on density fluctuations was analyzed in Ref. [18]. Except for distinct modes, broad-band fluctuations were reduced. The dominant poloidal mode structure changed from $m = 4$ to $m = 3$ during biasing (see Fig. 3, a)). Density-potential cross-phase changes related the $m = 3$ mode to inward

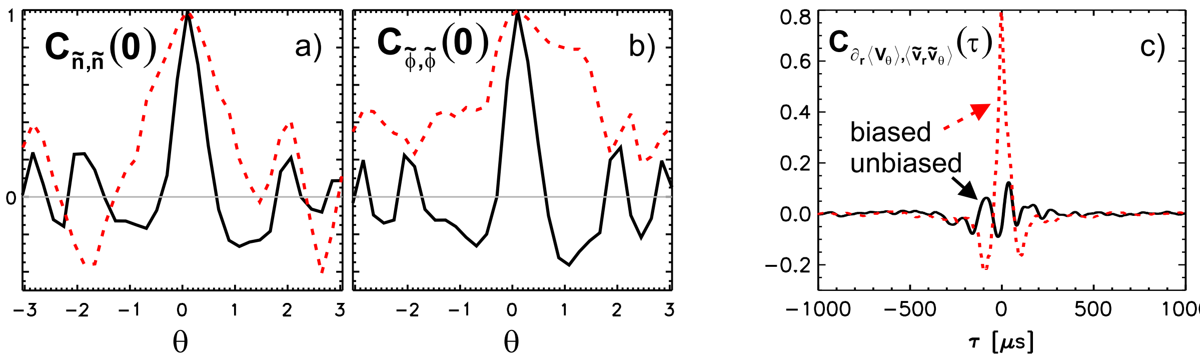

Fig. 3: Poloidal mode structure from correlation analyses in $\tilde{n}$ (a) and $\tilde{\phi}$ (b) with (solid) and without biasing (dashed) (adapted from Ref. [20]). c) Correlation function of poloidally averaged $E \times B$ flow shear and poloidally averaged Reynolds stress (c).

transport, which demonstrated another path to the reduction of net transport. A significant change also in the structure of potential fluctuations was reported from TJ-II [19], where an enhancement of long-distance correlations during biasing was observed. This enhancement has been confirmed in TJ-K [20]. In the unbiased case, $\tilde{n}$ and $\tilde{\phi}$ as measured with the poloidal probe array have the same poloidal mode structure, which can be seen from Fig. 3 a) and b). In the biased case, $\tilde{\phi}$ is dominated by an $m = 0$ structure (Fig. 3, b)): At a time lag of $\tau = 0$, the correlation with respect to the reference signal on the LFS ($\theta = 0$) is positive everywhere in the poloidal cross section and, thus, shows high correlations over long connection lengths. The zonally averaged flow shear and the zonally averaged Reynolds stress as measured with a 128-tip Reynolds-stress probe array show a strong increase in correlation during biasing (see Fig.3, c)), which indicates zonal-flow amplification due to the Reynolds stress [21].

Summary: The generation mechanism of blobs in the scrape-off layer of TJ-K has been studied in detail. The statistical properties of density fluctuations across the separatrix indicated holes inside and blobs outside the separatrix and showed strong similarities to those measured in ASDEX Upgrade tokamak, which supports the scalability of the dynamics in small-size devices to fusion edge plasmas. Blobs are observed universally. The absence of holes in some devices, however, motivates further investigations. Furthermore, the quantification of heat and particle transport through blobs is an important issue for fusion devices.

Furthermore, the interaction of shear flows and turbulence has been investigated intensively with multi-probe arrays. The energy transfer from small-scale fluctuations to zonal flows has been observed in wavenumber space. The results suggest that turbulence and transport reduction is rather due to the vortex thinning mechanism than to turbulent structures being torn apart in a shear layer. While the observation of long-range correlations complies with results from TJ-II [19], the fluctuation spectra in the presence of strong shear flows in TJ-K feature additional modes, whose origin remains be clarified. These modes might be related to the magnetic field geometry, whose role for plasma turbulence is planned to be investigated in the future.

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