Experimental Investigation of Turbulence at the Transition from Closed to Open Field Lines

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Abstract. Investigations of turbulent transport at the transition from closed to open field lines are summarised. The data are from dimensionally similar discharges of the torsatron TJ-K and the tokamak ASDEX Upgrade. Data from both devices indicate drift-wave turbulence in the plasma edge region. A flow-shear layer is observed in the vicinity of the separatrix incorporating pinch phenomena and the origin of SOL transport intermittency. Intermittent structures with negative (*holes*) and positive amplitudes (*blobs*) are observed in the core and the SOL, respectively. The blob generation mechanism can be understood in the frame of drift-wave turbulence.

1. Introduction

The understanding of turbulent transport at the plasma edge and the transition to the scrape-off layer (SOL) is of greatest importance for fusion plasmas. Edge transport sets the values of temperature and density at the pedestal top, parameters needed as input for core-turbulence simulations. SOL transport is responsible for the energy load on the first wall and defines the peak power density at the divertor plates. Furthermore, the natural flow-shear layer at the separatrix plays a key role for the H-mode transport barrier.

Since the early days of turbulent transport studies in magnetic fusion experiments, the intermittent nature of turbulent transport has been diagnosed and rare but large transport events, named *blobs*, have been identified to carry a large fraction of the radial energy and particle transport at the plasma edge [1–4]. More recent investigations aim at a better documentation of the statistical properties of blobs, an understanding of the location where they are generated and the responsible instability as well as at the origin of their high radial velocity. The observation made in the DIII-D tokamak of blobs outside the separatrix and negative density events called *holes* inside [5] points to a blob generation at the separatrix through an interchange-type of mechanism. But also in linear devices without magnetic-field curvature, the insertion of a limiter creates zones of holes inside the plasma column and blobs in the limiter shadow [6]. Blobs in the SOL have been observed in many devices [7–10]. A generation close to the separatrix is generally not disputed and a correlation between the fluctuations inside and outside the separatrix was also found in a linear device [11].

This work approaches edge transport from two directions: (1) Experiments on the ASDEX Upgrade tokamak are carried out to measure the blob dynamics in the SOL and across the separatrix of a high-temperature plasma. (2) The results are compared with data from the low-temperature stellarator experiment TJ-K, which has similar dimensionless plasma parameters as in the edge of fusion plasmas [12]. The comparison documents the level of similarity of the two experiments. Furthermore in TJ-K, Langmuir-probe arrays can be employed to investigate the blob generation in more detail than possible in a fusion plasma.

2. Experimental setup

The low-temperature plasma in the stellarator experiment TJ-K is generated by microwaves and has typical ion and electron temperatures of $T_i = 1$ and $T_e \approx 7$ eV, respectively, and densities of $n = 5 \times 10^{17}$ m^{-3}. The magnetic field strength is 70 mT and minor and major plasma radii are 0.1 and 0.6 m, respectively. Previous studies in the core plasma have shown, that turbulence is dominated by drift waves with density and potential fluctuations being almost in phase [12], finite structure sizes parallel to the magnetic field [13] and a small magnetic component in the fluctuations [14]. In all these studies, a high level of similarity with drift-Alfvén wave turbulence simulations from the DALF3 code [15] was observed.

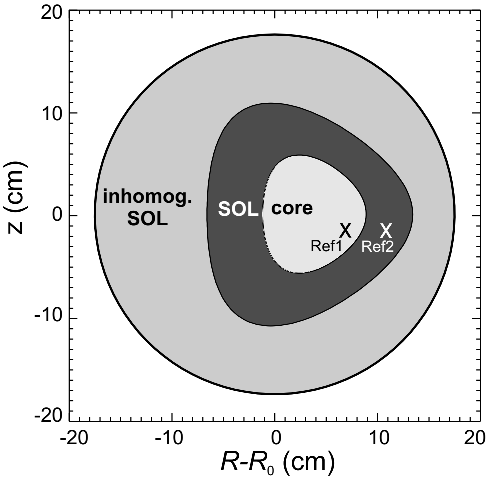

FIG. 1: Poloidal cross-section of TJ-K with limiter. The core region is reduced and a homogeneous and an inhomogeneous SOL are created. Reference probes are at Ref1 and Ref2.

For the investigation of the core-SOL transition, the experiment has been modified by introducing a massive toroidal limiter which was adjusted to an inner flux surface. As indicated in Fig. 1, in the shadow of the limiter a homogeneous SOL is created that extends to the original separatrix present when the limiter is removed. In this region, all field lines have the same connection length of one toroidal turn. The inhomogeneous SOL further out is characterised by changing connection lengths and will not be used for the analyses. Different Langmuir and emissive probes introduced from the low-field side (right side) can scan the entire plasma cross-section. For conditional averaging, two positions for a reference probe are indicated, one in the core and one in the SOL. Details of the experiments will be published elsewhere [16]. It was assured that in the reduced core turbulence remains drift-wave like.

The results are compared with data from Ohmic ASDEX Upgrade (AUG) [17] discharges. The reciprocating Langmuir probe penetrates the plasma horizontally at about 0.3 m above the outer midplane. The probe array used consists of 9 free-standing cylindrical carbon pins separated poloidally by about 3 mm. Experiments were conducted in deuterium L-mode discharges with a lower single-null magnetic configuration. The discharges were operated at a current of 800 kA at low density of about 2×10^{19} m^{-3} and a toroidal magnetic field of 2 T. Although the plasma parameters in AUG and TJ-K are quite different, key dimensionless parameters are similar: the dimensionless collisionalities are $\hat{\nu} \approx 0.28$ and 0.12 and the normalised $\hat{\beta}$ values are 0.56 and 0.1 – 0.25 in AUG and TJ-K, respectively.

3. Drift-wave character of turbulence in the plasma edge

The energy which drives turbulence in the SOL most likely comes from the plasma edge, where steep pressure gradients provide a strong source of energy. Hence, in order to investigate the coupling of core and SOL turbulence information on the character of the turbulent fluctuations in the edge is essential. In TJ-K, where the core plasma is accessible for Langmuir probes, turbulence has been studied in detail and the main characteristics of drift-wave turbulence have been identified [12,13,18], which are a dominant propagation into the electron-diamagnetic direction, a small cross-phase between density and potential fluctuations and a finite parallel length of the turbulent structures.

Figure 2 shows the cross-phase between measured ion-saturation-current and poloidal-electric-field fluctuations $\tilde{E}_\theta$ as measured in AUG plasmas. In 4 strokes the reciprocating probe array could penetrate the nominal separatrix position (shaded area) and enter a few millimetres into the plasma edge. All the way from the SOL to the edge, the measured cross-phase is close to $\pi/2$ which corresponds to a cross-phase between density and potential of close to zero. This important result is consistent with drift-wave turbulence being also the dominant mechanism at least in the edge of Ohmic fusion plasmas. It also supports the validity of the approach of dimensionless parameters [19] to extrapolate TJ-K results to fusion edge plasmas.

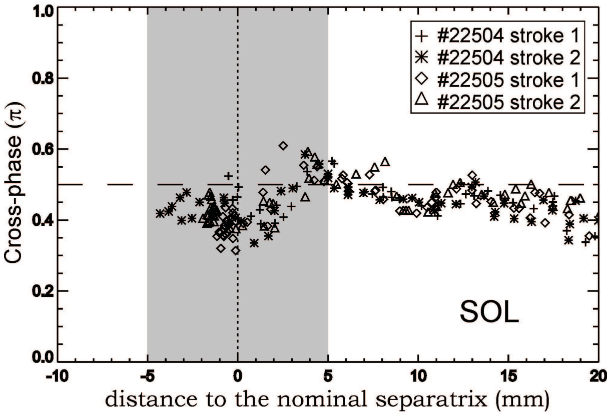

FIG. 2: Radial profile of the cross-phase between I_{sat} and E_θ fluctuations in AUG. The shaded area indicates the uncertainty range of the nominal separatrix position.

Since the propagation of drift-wave turbulence is primarily into the poloidal direction, the question arises, how it can contribute to the generation of blobs in the SOL. A radial flow component of the turbulent structures originates from (small) deviations of the cross-phase from zero. There are different sources for this deviation, but an obvious one magnetic field curvature.

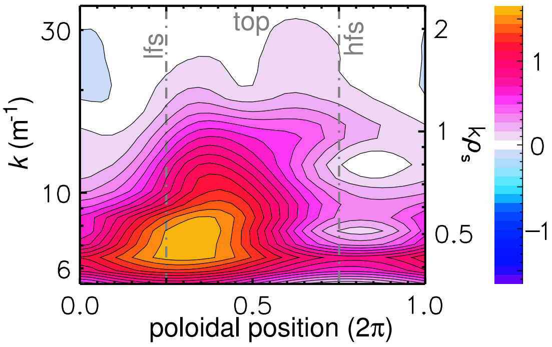

FIG. 3: Wavelet-wavenumber spectrum of turbulent transport as function of the poloidal position as deduced from the poloidal probe array in TJ-K. High and low-field sides are indicated.

To investigate the influence of magnetic curvature on turbulent transport in TJ-K, density and potential fluctuations have been measured with a poloidal ring of 64 Langmuir probes aligned to a flux surface [20]. Figure 3 shows the result of a spatial wavelet transform which has been applied to the data to obtain poloidal wavenumber spectra for each poloidal position. Maximum transport is found on the low-field side with a shift into the $E\times B$-drift direction. The dominant contribution to transport stems from wavenumbers $k_\perp\rho_s \approx 0.5$, with ρ_s the drift scale. The variation of transport with poloidal angle is related to changes in the cross-phase, which remains small but shows admixtures from interchange drive. Hence, although turbulence in the plasma edge is drift-wave like, curvature effects introduce a poloidal variation in the cross-phase and therefore also in the radial transport across the separatrix.

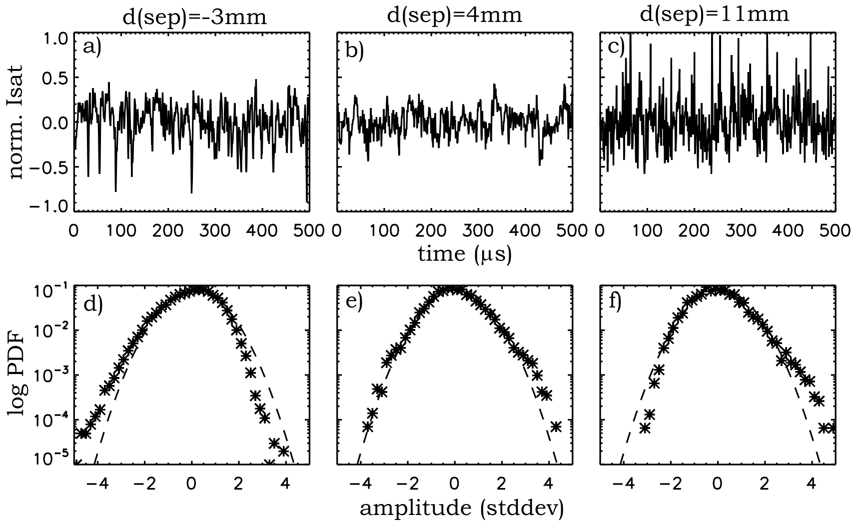

FIG. 4: Ion-saturation current measured at different radial locations in AUG (a-c) and corresponding PDFs (d-f) [21]. d *gives the distance from the nominal separatrix.*

4. Properties of turbulent fluctuations in the scrape-off layer

In Fig. 4, the raw signals from I_{sat} measurements from AUG are depicted at 3 radial positions. Inside ($d = -3$ mm) and outside ($d = 11$ mm) the nominal separatrix position, intermittent events can be identified by the prominent peaks in the signals. The amplitude of the events changes from negative at the inner to positive at the outer radial position. Hence, these data are consistent with the observation of holes in the core and blobs in the SOL of AUG and are consistent with findings on DIII-D [5]. Interestingly the intermittency is reduced in the vicinity of the separatrix. At $d = 4$ mm, the fluctuation amplitude distribution is nearly Gaussian. This can be seen at the bottom of Fig. 4 where the probability density functions (PDFs) of the fluctuation amplitudes are compared to a Gaussian (dashed line). At the outer and inner positions, the PDFs are clearly skewed. These data indicate that the positive intermittent events or blobs in the SOL do not originate from inside the confined plasma, they are rather generated close to the separatrix by interchanging low-density plasma from the SOL with high-density plasma from the edge.

Due to the lack of a reference probe in AUG, the radial velocity component of the intermittent events could not be assessed. But cross-correlation analysis of two adjacent probes were carried out to get information on the poloidal propagation velocity. The same kind of analysis has been applied to AUG and TJ-K data. In Fig. 5, the results are compared. In both devices, an abrupt change of the poloidal velocity v_θ can be seen in the vicinity of the nominal separatrix positions. The propagation switches from the electron-diamagnetic drift direction in the confined plasma to the ion-diamagnetic direction in the SOL. In both devices, a shear layer is observed close to the separatrix. Due to uncertainties in the determined separatrix and probe positions it cannot be decided whether the shear layer is right at or close to the separatrix. In AUG, v_θ changes from about $+3$ to less than -5 km/s within the radial resolution of the probes. This strong shear layer is observed for all pin combinations, while the absolute phase velocity and the exact radial position changes. The reason for these variations as well as for the abrupt change are subjects of present analyses and results will be published elsewhere [22]. A comparable shear layer close to the separatrix was also observed in other devices [23–25]. The poloidal correlation length of the structures increases inside the shear layer and radial inward transport is observed [21]. These findings agree with earlier results from biasing experiments on TJ-K [26].

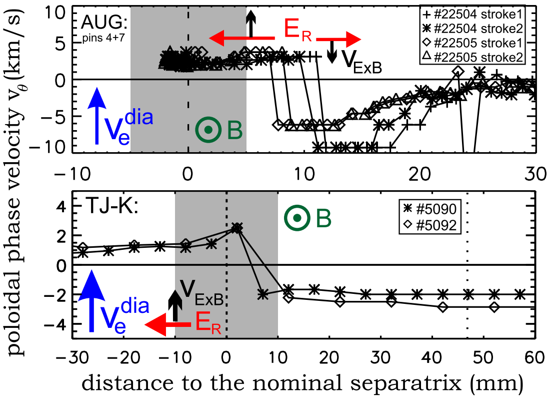

FIG. 5: Poloidal phase velocities of fluctuations from AUG (top) and TJ-K (bottom) [21]. The shaded areas indicate the nominal separatrix positions including uncertainties.

5. Transition from closed to open field lines

In order to investigate the generation of the coherent structures on a microscopic level, the ion-saturation current and the floating potential was measured in the poloidal plane of TJ-K. A conditional-averaging analysis was carried out with a reference probe measuring I_{sat} at position *Ref1* in Fig. 1. The analysis showed, that the fluctuations outside and inside the separatrix are correlated and similar results are obtained when the reference probe was moved to position *Ref2*. Details of this study will be published elsewhere [16].

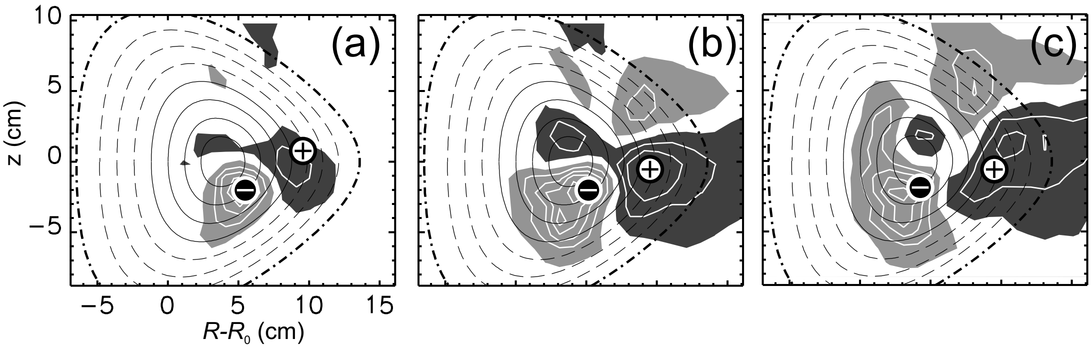

FIG. 6: Evolution of density structures in time steps of 10 μs. Dark and light grey indicate positive and negative density fluctuation amplitudes, respectively. The $+$ and $-$ signs indicate positions of potential maximum and minimum values.

Figure 6 depicts 3 snapshots of the temporal evolution of density perturbations. The temporal evolution was measured with μs resolution and the pictures in the figure were extracted every 10 μs. Dark areas indicate positive fluctuation amplitudes, grey areas negative ones. From the entire evolution (not shown in the figure) one can see that in the core the structures propagate mainly in poloidal direction. This is consistent with drift-waves and concordantly the potential fluctuations in the core plasma are found to be in phase with the density fluctuations. In Fig. 6 the positions of maximum and minimum potential fluctuation amplitudes are indicated by $+$ and $-$ signs, respectively. The left plot shows the instance when the positive density structure is cut by the separatrix and the fluctuating electric field extrudes high-density plasma from the core into the SOL. This process generates the large density structure visible in Fig. 6b. This structure can be identified with a blob. In the further evolution the blob propagates to the top, i. e. into the opposite direction as in the core and the potential decouples from the density perturbation.

The propagation in the SOL is mainly due to the background electric field. A similar procedure leads to the increase of the negative density structure in the core: low-density SOL plasma is advected into the core creating a hole that continues to propagate in the drift-wave direction.

6. Summary and conclusions

Turbulent transport at the transition from closed to open field lines has been investigated on dimensionally similar discharges from the toroidal low-temperature plasma of the torsatron TJ-K and the high-temperature plasma of ASDEX Upgrade. The structural similarity of the results support the approach of dimensionless parameters to compare discharges and the relevance of TJ-K results for the interpretation of fusion plasma phenomena as the intermittence of SOL transport. Data from both devices indicate drift-wave turbulence to be dominant in the plasma edge (Fig. 2). However, the observed small density-potential cross-phases, that are characteristic for drift wave turbulence, are modified due to magnetic-curvature effects (Fig. 3). This leads to a residual radial $E \times B$-drift component which advects turbulent structures across the separatrix (Fig. 6). Thus the fluctuating electric field can interchange core and SOL high and low-density plasma creating blobs and holes. A flow-shear layer is observed in the vicinity of the separatrices of both devices. However, due to the low ion temperature, the flows in TJ-K are small. Since intermittency is observed in both devices it is conjectured that it is not due to an instability related to the shear flow that is responsible for blob generation.

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