Overview of Edge Turbulence and Zonal Flow Studies on TEXTOR

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In the TEXTOR tokamak, the edge turbulence properties and turbulence-associated zonal flows have been systematically investigated both experimentally and theoretically. The experimental results include the investigation of self-organized criticality (SOC) behavior, the intermittent blob transport and the geodesic acoustic mode (GAM) zonal flows. During the Dynamic Ergodic Divertor (DED) operation in TEXTOR, the impact of an ergodized plasma boundary on edge turbulence, turbulent transport and the fluctuation propagation has also been studied in detail. The results show substantial influence by the DED on edge turbulence. The theoretical simulations for TEXTOR parameters show characteristic features of the GAM flows and strong reduction of the blob transport by the DED at the plasma periphery. Moreover, the modelling reveals the importance of the Reynolds stress in driving mean (or zonal) flows at the plasma edge in the ohmic discharge phase in TEXTOR.

Keywords: Tokamak, edge turbulence, self-organized criticality, blob transport, zonal flows, Dynamic Ergodic Divertor, Reynolds stress.

1. Inroduction

In the TEXTOR tokamak, the edge turbulence properties and turbulence-associated zonal flows have been systematically investigated experimentally by fast reciprocating Langmuir probe and correlation reflectometry measurements, and theoretically by three-dimensional (3D) non-linear electromagnetic drift-turbulence simulations. The role of the Reynolds-stress in driving mean plasma flows has also been studied by fluid modelling. In this paper, an overview of the recent work is given.

2. Experimental results

First, we report on some fundamental features of the edge turbulence observed on TEXTOR. These include: (i) the self-organized criticality (SOC) behavior and self-similar characters in the fluctuation data [1]; (ii) the turbulence intermittency and blob transport in the plasma boundary [2]; (iii) identification of geodesic acoustic mode (GAM) zonal flows in density and velocity fluctuations by poloidal correlation reflectometry [3].

(i) For the SOC studies, we have measured both the potential and density fluctuations by the Langmuir probes and analyzed the data using various methods [1]. The results show a lot of characteristics associated with the SOC dynamics, including similar frequency spectra to the "running sandpile" modelling and f^{-1} dependence in the spectrum as an indication of avalanche overlapping, a slowly decaying long tail in the autocorrelation function, a long-range radial propagation of avalanche-like events in the edge plasma region, and values of Hurst parameters larger than 0.5 at all detected radial locations, as shown in Fig. 1(a).

(ii) The intermittent convective transport has also been investigated by Langmuir probes in the plasma edge and in the scrape-off layer (SOL) [2]. It has been observed that the probability distribution function (PDF) of the density fluctuations are positively skewed, while a Gaussian shape is recorded for the negative values [see Fig. 1(b)]. The deviation of the signals from Gaussian statistics increases from the plasma edge to the SOL. Conditional averaging reveals that in the SOL the wave form of blobs is asymmetric in time and the blobs move radially outwards at velocities of 0.5~1 km/s. The large bursts (≥ 2.5×rms) account for ~ 40% of the total transport. Statistics of the waiting-time indicate that the PDF of the time interval follows a Poisson-distribution for small duration events and changes into a power-law form for larger ones. Moreover, the turbulence intermittency shows self-similar characters in the fluctuation data.

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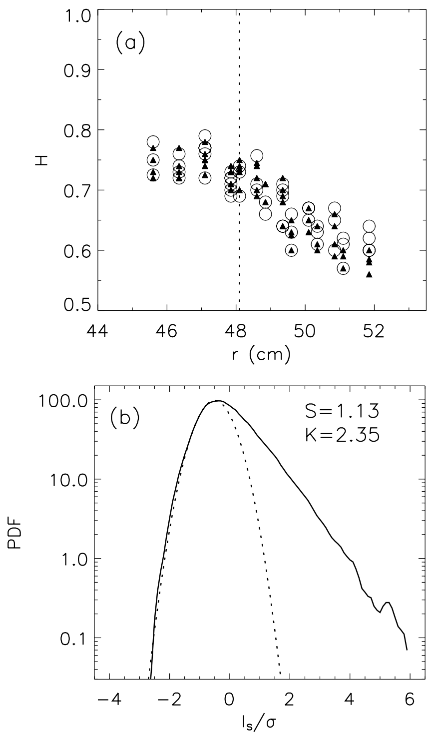

Fig. 1 (a) The radial dependence of Hurst exponent (H) estimated by rescaled range (open circles) and structure function (solid triangles) analysis of potential fluctuations. The dotted line marks the limiter position [1]. (b) Semi-log plot of the PDF of the density ($\propto I_s$) fluctuations normalized by the standard deviation, measured in the SOL. The S and K denote skewness and kurtosis. The dotted line is the best Gaussian fit [2].

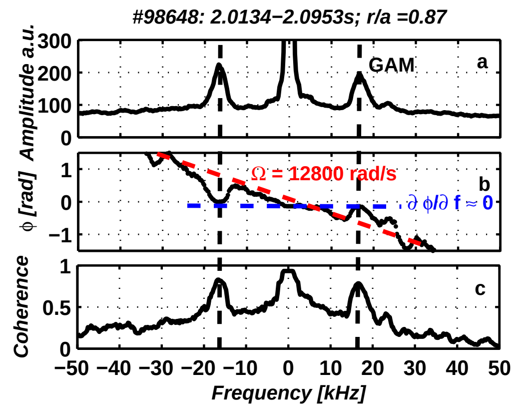

Fig. 2 Spectra of (a) amplitude, (b) cross-phase and (c) coherence of density fluctuations measured by the top antenna array of a correlation reflectometer [3].

(iii) In TEXTOR, the GAMs have been measured by an *O*-mode correlation reflectometer system [3]. Figure 2 shows the amplitude, cross phase ϕ, and coherence spectrum of density fluctuations measured by the top antenna array. The GAMs appears around 17 kHz for the reflection layer detected. The $\partial\phi/\partial f \cong 0$ at the GAM frequency implies a poloidal homogenous structure of the GAM zonal flows. The frequency dependence of the GAMs on the acoustic speed has been verified under different discharge conditions. The poloidal asymmetric (m=1) feature of density fluctuations of GAMs has also been identified by the cross-correlation of the top and midplane antennas. The influence of the GAMs on the ambient turbulence level has been observed from the modulation of the GAM flows on the fluctuation amplitudes of ambient turbulence. More recently, the direct evidence of the GAMs on the poloidal velocity fluctuations has been observed.

Secondly, we investigated the influence of DED (Dynamic Ergodic Divertor) on edge turbulence. During the DED operation in TEXTOR, the magnetic perturbation creates a chaotic behavior of the field lines at the plasma boundary, including an ergodic zone with long and a laminar zone with short connection lengths, respectively [4]. The impact of the static DED (dc DED current) on edge equilibrium profiles, turbulence properties, turbulent transport, plasma rotations, Reynolds stress profiles and the blob transport has been investigated in detail [5]. Common features have been found among different DED configurations (m/n =12/4, 6/2 and 3/1). At the plasma edge, the density and temperature profiles are steepened *or* flattened by the DED, depending on discharge conditions [5, 6]. During the DED, a typical behavior is the increase of the floating potential in the perturbation area, leading to a reversal of the radial electric filed E_r from the negative to positive in most of the laminar and the ergodic zone, as can be seen in Fig. 3(a). A possible interpretation is that during DED the electrons mover faster than massive ions along the field line to the wall so that a positive E_r must be brought about to restore the ambipolarity [7]. The influence of the DED on turbulence mainly occurs in the ergodic region. With DED, the fluctuation amplitudes in potential and poloidal electric field fluctuations are largely reduced, whereas for density fluctuations the modification is small. In the DED phase, it has been generally observed that the local turbulent flux reverses direction from radially outwards to inwards in the ergodic area, as illustrated in Fig. 3(b). Meanwhile, the turbulence itself is profoundly modified by energy re-distribution in frequency spectra, suppression of large-scale structures and reduction of the radial and poloidal correlation lengths at all frequencies [7]. With DED, the poloidal propagation of fluctuations changes direction from the electron diamagnetic drift to ion drift direction in the perturbation region, consistent with the observed reversal of the $E_r \times B$ flow [5, 8]. Moreover, in the plasma boundary the size of the blobs and the blob transport are significantly reduced by the DED [9]. In the ohmic discharge phase before the DED the Reynolds stress displays a radial gradient at the plasma edge while during DED the profile is suppressed, suggesting a rearrangement by the DED on the flow momentum profile [7, 10].

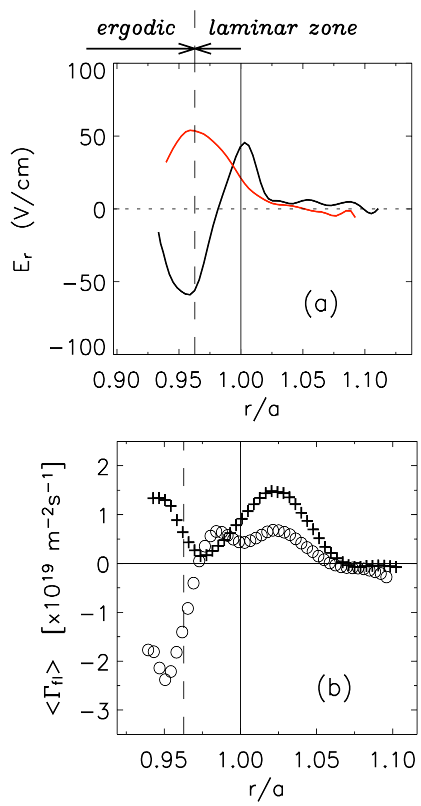

Fig. 3 (a) The radial dependence of radial electric field E_r measured by fast reciprocating probes before (black curve) and during (red curve) a static 6/2 DED [5]. (b) The radial dependence of fluctuation-induced flux, $<\Gamma_{fl}>$, measured by fast reciprocating probes before (crosses) and during (circles) a static 6/2 DED [5]. The vertical solid line denotes the limiter position. The dashed line separates the ergodic (left side) and laminar (right side) zones.

3. Theoretical modelling and simulations

For the study of the impact of the resonant magnetic perturbation fields on turbulence, three-dimensional numerical simulations of drift fluid turbulence for 4 fields (potential, density, magnetic potential and parallel ion velocity) have been performed [11, 12]. The simulations show a lot of results consistent with the experimental observations in TEXTOR-DED, for instance, the suppression of blob amplitudes by magnetic perturbation at the plasma boundary, as shown in Fig. 4. The simulations also show characteristic features of the GAM flows before the DED and the suppression of GAMs at the resonances during the DED.

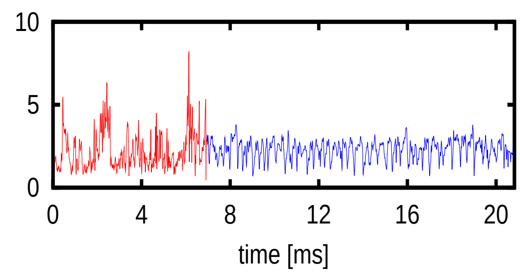

Fig. 4 Time trace of density fluctuations simulated before (red color) and during (blue color) the magnetic perturbation in the SOL. The blob amplitudes are suppressed by the magnetic perturbation.

In addition, starting from renewed 2D Hasegawa-Wakatani equations to explore the poloidally geometrical dependence of the Reynolds stress (*RS*), another fluid modeling (with flux-surface averaging in toroidal geometry) reveals the importance of the Reynolds stress in driving mean (or zonal) flows at the plasma edge in the absence of magnetic perturbation [13, 14]. To illustrate the role of *RS* in driving the mean poloidal flow and therefore the development of edge radial electric field E_r, the modeled E_r without *RS* (dotted blue line) and with *RS*

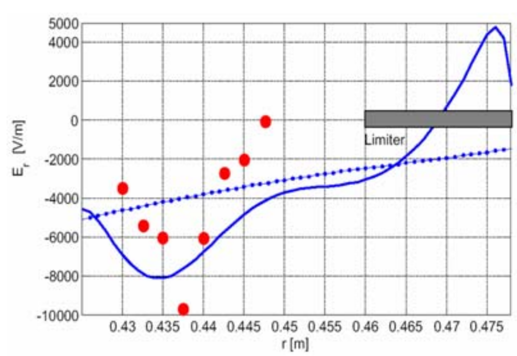

Fig. 5 Comparison of the simulated E_r (dotted blue curve without RS contribution and solid curve with RS contribution) and the experimentally measured one (red points).

(solid blue line) are depicted in Fig. 5 in comparison with the experimentally measured one (red points). It can be seen that with the contribution of *RS*, the solid blue curve is much closer to the measured E_r in the plasma edge.

4. Conclusions

In this paper, the recent experimental and theoretical work on the study of the edge turbulence and zonal flows on TEXTOR tokamak has been briefly summarized. The experimental observation of the basic features of edge turbulence, like SOC behavior, blob transport and GAM zonal flows, and the influence of the DED on turbulence properties have been presented. The simulation results show a lot of characteristics of turbulence, in agreement with the experimental observations.

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