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Fluctuations, turbulence and related transport in the TORPEX simple magnetized toroidal plasma

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1. Introduction

Progress in understanding fluctuations, turbulence and related transport in magnetized plasmas is achieved in the basic plasma experiment TORPEX [1] via high-resolution measurements of plasma parameters and wave fields throughout the plasma cross-section. Plasmas are confined by a toroidal magnetic field up to B_T=0.1T, and a vertical field, B_z<50mT, corresponding to a simple magnetic configuration with open field lines terminating on the vessel. The main ingredients for drift wave instabilities and turbulence, pressure gradients and magnetic field line curvature are thus present. Highly reproducible plasma discharges with $n_e \sim 10^{16}$-$10^{17}m^{-3}$ and T_e~5-10eV are driven for more than 3s by microwaves (f=2.45GHz, P<50kW), in the electron cyclotron frequency range, and are diagnosed primarily using a large set (>200) of Langmuir probes, sampled at 250kHz.

2. Investigation of the nature of electrostatic fluctuations

The transition from a regime dominated by drift instabilities to one dominated by interchange instabilities is observed [2]. Drift modes are observed on the high field side with respect to the peak of the density profile. For a limited range of B_z values they coexist with interchange modes in the unfavorable curvature region, i.e. on the low field side. With increasing B_z, a gradual transition between the two regimes is observed, controlled by the value of the field line connection length and consistent with predictions of a two-fluid linear model.

3. Generation of plasma blobs from interchange modes

In the interchange-dominated regime, we have identified a scenario in which blobs with properties similar to those observed in tokamaks originate from coherent interchange modes [3]. To investigate the blob generation mechanism, time-resolved 2D profiles of n_e, T_e, V_{pl} and velocity fields are obtained by performing a conditional sampling (CS) over many blob events of the I-V characteristic of probes in a time window centered on the blob [4]. Figure 1(a) shows the n_e time evolution in the mode region and in the source free region . Figure 1(b-e) shows 2D profiles of n_e at four different times during the blob ejection, together with the total **ExB** velocity field. The dynamics of blob formation and ejection from the interchange wave is captured by frames (c-e). A radially elongated density structure forms from the positive cell of the wave, and a relative displacement between them is obtained, Fig. 1(d). The original density structure is then sheared off by the **ExB** flow, forming a new structure on the low field side that is a plasma blob (Fig. 1(e)).

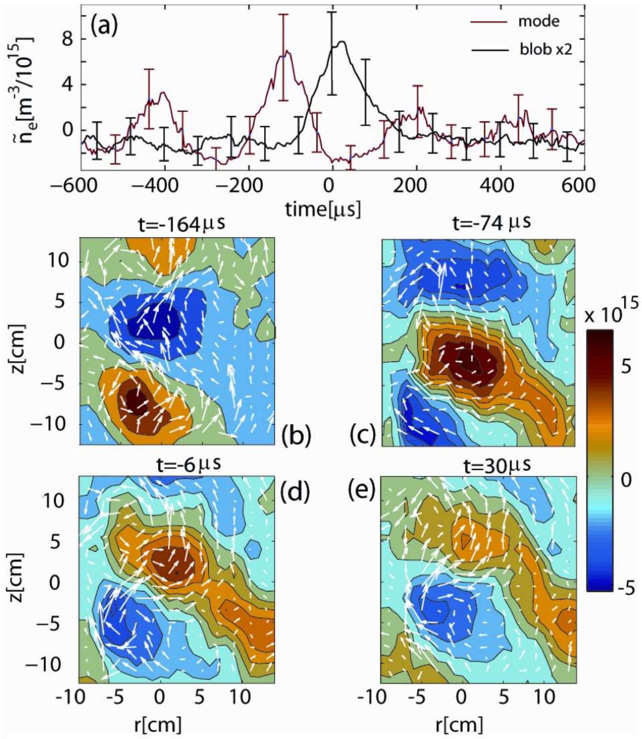

Fig. 1 *Plasma dynamics from the CS technique: (a) time history of ne in the mode region (red) at r = 1cm, z = 5cm and in the source free region (black) at r = 13cm, z = 5cm. (b-e) 2D profiles ofne at different times during blob ejection. Arrows show the instantaneous v_{ExB} profile.*

The measured fluctuating v_{ExB} pattern demonstrates the interchange mechanism, exchanging a high pressure zone with a low pressure zone (Fig. 2). The interchange drive is maximum where the pressure negative wave crest is localized (Fig. 2(a)). The elongation of the density cell is observed to follow a sudden increase of the drive (Fig. 2(b)). CS analyses over different classes of blob amplitudes provide information on the link between blob amplitude and pressure scale length. This shows that a steepening of

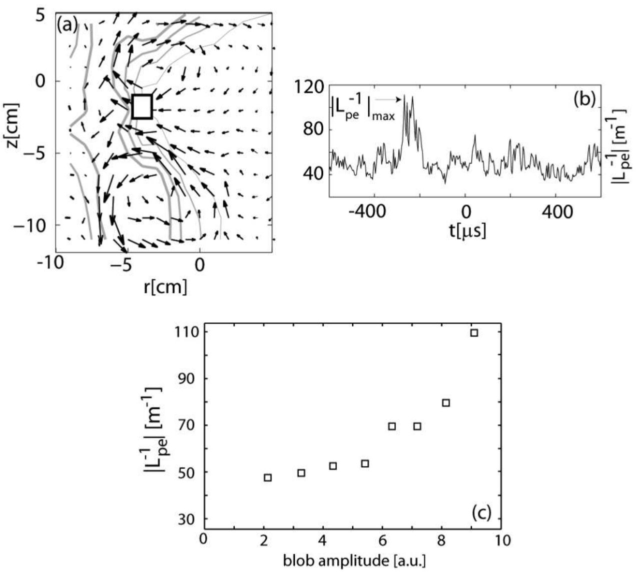

Fig. 2 *A zoomed view of the instantaneous fluctuating v_{ExB} velocity field at t=-184μs shows the convective cells interchanging zones of high and low plasma pressure. (b) Time evolution of the interchange drive. (c) Dependence of blob amplitude upon the interchange drive.*

the pressure profile is at the origin of intermittent transport events and blobs, and that blobs with larger amplitude correspond to a larger interchange drive (Fig. 2(c)) [5].

4. Plasma blobs and momentum generation and transport

The question of whether or not blobs carry momentum is addressed through measurements of 2D toroidal velocity (v_ϕ) profiles (Fig. 3). Negative $v_\phi$values of indicate that the plasma flows clockwise (seen from above). The CS technique provides the time evolution of the profile of v_ϕ correlated with a blob detected at the plasma edge (Fig. 3 center). A positive perturbation of v_ϕ is expelled and moves radially with the density blob (Fig. 3 right), suggesting conservation of angular momentum.

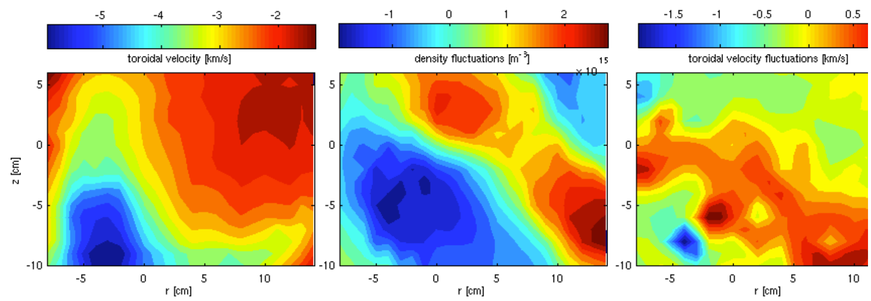

Fig. 3 (left) 2D time averaged profile of v_φ, Density fluctuations (center) and toroidal velocity fluctuations (right) at the time when the blob is detected.

5. Nonlinear fluid modeling and prediction of low and high confinement regimes

The first theoretical nonlinear investigations of the TORPEX plasma focused on the interchange-dominated regime, i.e. high B_z configurations. Owing to the flute character of the interchange mode, the plasma can be described by evolving 2D, three-field fluid equations. The simulations show the presence of two turbulent regimes, akin to tokamak L and H modes [6]. Snapshots from a simulation in the L-mode regime are shown in the upper panels of Fig. 4. In this case background shear flow effects are negligible, and the interchange instability has an intermittent character. Plasma blobs transfer plasma from the source region to the low field side region. The time-averaged profiles of T_e

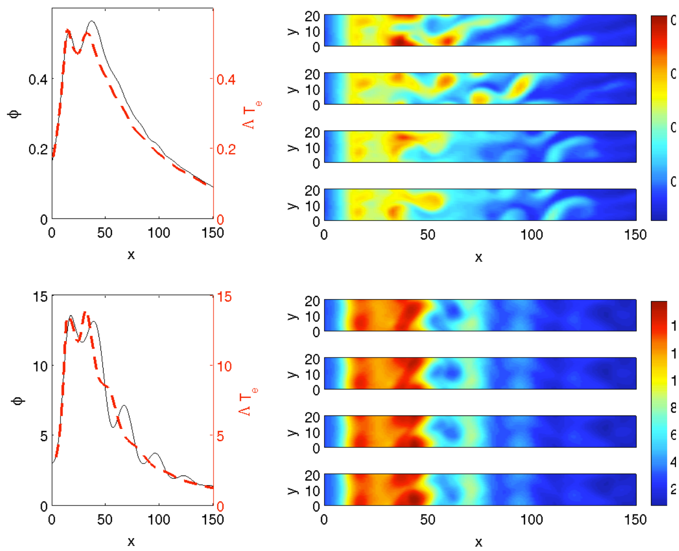

Fig. 4 Simulated time-averaged profiles of potential and temperature, with typical potential snapshots, for L-mode (upper panels) and H-mode (lower panels).

and n_e show an exponential decay on the low field side where the interchange dynamics is active. By increasing the plasma source strength or reducing B_z, the character of turbulence changes, reaching a new regime (denoted as the H-mode) in which a strong **E**x**B** shear flow appears. This flow limits the perpendicular diffusion, causing the peak density and temperature to increase and the plasma profiles to steepen. The lower panels in Fig. 4 show typical snapshots and profiles in the H-mode regime. The measured intermittency suggests that TORPEX turbulence is generally in the L-mode regime. The theory provides guidelines to identify the transition to H-mode in dedicated experimental campaigns.

To explore turbulence in the drift-wave dominated regime, a 3D parallel code was developed, evolving the drift-reduced Braginskii equations. In the linear regime, the growth rates of the unstable modes agree with those found in an independent eigenvalue code. First simulations based on the fully nonlinear equations show that in the interchange dominated regime the blob detachment dynamics is qualitatively similar to that observed in the 2D simulations.

6. Summary and outlook

A combination of local measurements of plasma parameters and wave fields with high spatial and temporal resolution and nonlinear 2D and 3D numerical simulations of turbulence in the open field line geometry of a simple magnetized plasma provides insight into the generation of turbulent structures carrying particles, energy and momentum across the magnetic field. The nature of the instabilities from which blobs are generated, the exact generation mechanisms, and details of the blob dynamics and induced transport are unambiguously identified. These investigations will be complemented in the near future by non-perturbative imaging using a fast framing visible camera [7], and by measurements of the phase space transport of supra-thermal fast ions interacting with drift-interchange turbulence, addressing basic aspects of interest for burning plasma physics.

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