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Three-dimensional dynamics of turbulence in the edge of fusion plasmas

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Introduction

Different turbulence simulations show that the drift wave is a possible candidate to explain the turbulence in the edge of fusion plasmas. The important properties of drift-wave turbulence are a cross phase between density and potential fluctuations smaller than $\pi/4$ and a finite parallel wavenumber $k_{\|}$. Furthermore, the key element of the drift wave is the parallel electron dynamics. It can couple the drift wave to the shear-Alfvén wave and determines the degree of instability and the level of transport. On the other hand, the turbulence dynamics parallel to the magnetic field is strongly coupled to the perpendicular dynamics. Therefore, a detailed understanding of drift waves requires fully three-dimensional investigations, i.e. of the dynamics perpendicular and parallel to the magnetic field.

The toroidal low-temperature plasma in the torsatron TJ-K is dimensionally similar to the one in the edge of fusion plasmas [1]. In contrast to fusion plasmas, the whole plasma volume in TJ-K is accessible to Langmuir probes. This allows the use of probe arrays with a large number of tips and high temporal and spatial resolution. A further advantage of the device is that its plasma can be simulated by turbulence codes such as GEM3 [2].

In this paper, the perpendicular dynamics of turbulence is studied with the focus on the poloidal wavenumber spectra and the turbulent transport. For the first time, the parallel dynamics of turbulence has been investigated in the core of a toroidally confined plasma. The results of the parallel wavenumber and the parallel propagation velocity are compared with results from the simulation code GEM3.

Experimental setup

The experiments have been carried out in the torsatron TJ-K, which has a major and minor radius of 0.6 and of 0.1 m, respectively [3]. The rotational transform is about 1/3. TJ-K is operated at an electron temperature in the range $T_e \approx 4-12$ eV and a line-average density $\bar{n}$ in the range $2-6\times 10^{17}\mathrm{m}^{-3}$. The ions are cold ($\leq$1 eV). Due to plasma generation by microwaves at 2.45 and 8.25 GHz, the nominal magnetic field is in the range 70–300 mT. However, the di-

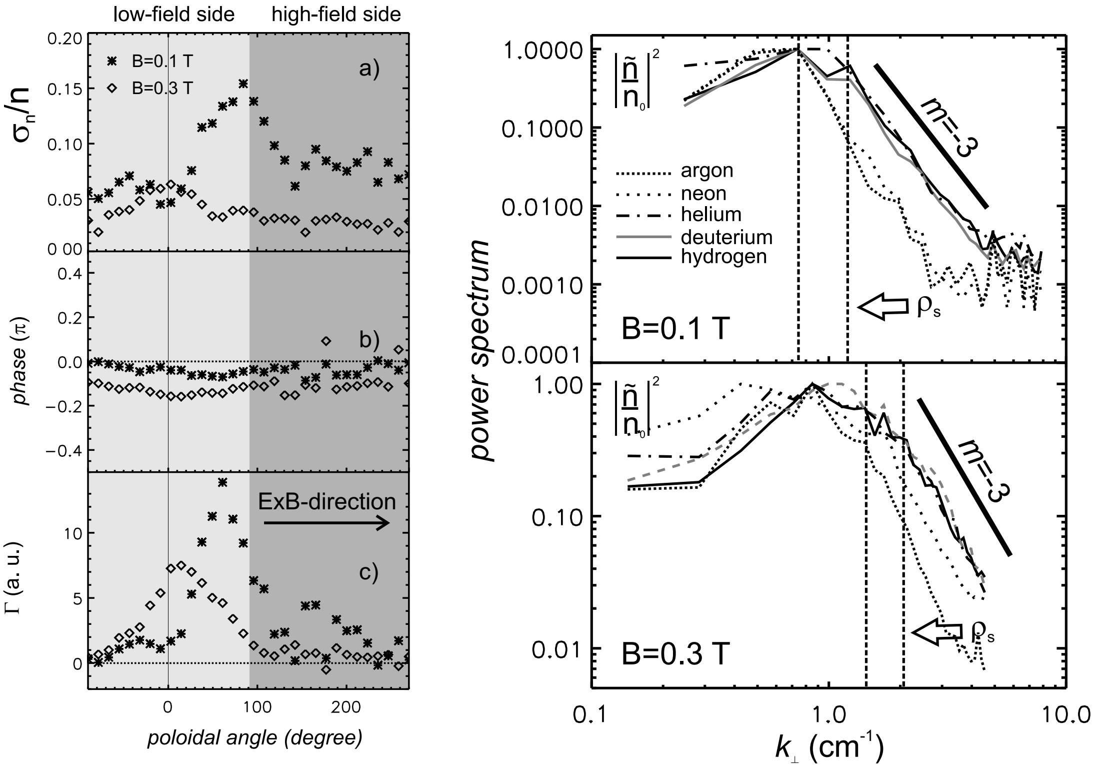

Figure 1: Left: Poloidally resolved relative fluctuation amplitudes in density (a), cross phase between density and floating potential fluctuations (b) and mean transport (c) for the helium discharges at $B = 0.1$ (asterisk $*$) and $B = 0.3$ T (diamond $\diamond$). The bright gray area denotes the low-field side region, whereas the dark gray marks the high-field side. Right: wavenumber spectra of the normalised density fluctuations as a function of k for different gases at $B = 0.1$ T (top) and at $B = 0.3$ T (bottom). The dashed lines mark the shift of the inertial region when changing the gas from argon to hydrogen

mensionless parameters (dimensionless collisionality $\hat{\nu}$, plasma pressure $\hat{\beta}$ and the normalised mass ratio $\hat{\mu}$) resulting from this setup are similar to those in the edge of fusion plasmas [1].

Dynamics perpendicular to the magnetic field

The dynamics of turbulent structures perpendicular to the magnetic field is investigated by using a poloidal probe array, which consists of 64 Langmuir probe tips aligned on a flux surface in the region of the maximum density gradient. This allows simultaneous measurements of the fluctuations in the ion-saturation current $\tilde{I}_{isat}$ and in the floating potential $\tilde{\phi}_{fl}$ over a flux surface. In Fig. 1 (left) from top to bottom, the relative fluctuation levels in density, the cross phase between density and floating potential and at last, the mean radial transport are plotted versus the poloidal angle for a helium discharge. The turbulent transport has a maximum on the low-field side, which is most likely related to the magnetic field curvature effect. In comparison to the low-field side, the mean transport on the high-field side is clearly small. This asymmetry points to an influence of interchange drive on the drift-wave turbulence. Noteworthy is that maximum transport at $B = 0.1$ T is not observed at $\theta = 0^\circ$ (on the low filed side) but rather at $\theta = 60^\circ$, which is the position shifted to the direction of the $E \times B$ drift. By increasing the magnetic filed, i.e, decreasing the $E \times B$ drift resulting from the background plasma potential, the maximum transport is shifted to $\theta = 0^\circ$. Of further interest for analysing fluctuations is at which scales the fluctuations have their maximum. The poloidal wavenumber spectrum contains this information. In Fig. 1 (right), the wavenumber spectra of the normalised density fluctuations are plotted versus the perpendicular wavenumber for the various working gases. For all discharges, the wavenumber spectra decay with an spectral index of $m \approx -3$. This finding is consistent with the Kolmogorov hypothesis, which predicts an universal form of the inertial range, independent of the changes of the magnetic field and gases. Due to the ρ_s scaling, the wavenumber spectrum is shifted to large scales, at increasing ρ_s. The characteristic feature of the ρ_s scaling is apparent, when one compares the argon with the hydrogen discharges at both $B = 0.1$ and 0.3 T. According to the ρ_s scaling, the wavenumber spectrum of the density fluctuations in argon discharges is shifted to large scales in comparison to those in hydrogen discharge. This is also consistent with dedicated studies on the scaling carried out earlier in TJ-K [4].

Dynamics parallel to the magnetic field

In contrast to measurements with only two probes in previous experiments, an array of 8×8 probe tips and a 2D probe system have been used to get simultaneous spatial and temporal information on the parallel dynamics of turbulence [5, 6]. A finite parallel wavenumber of turbulent structures has been measured. As required for drift-wave turbulence, the parallel extension, which is about 15 m, is much larger than the perpendicular one of typically only 2-7 cm. The measured parallel velocity is larger than expected from a simple perpendicular propagation of the structures with the diamagnetic velocity. It was found to be in-between the ion-sound and the Alfvén velocity. The experimental propagation velocity of turbulent structures of $u_\parallel = (3.44 \pm 1.9) \times 10^5$ m/s is somewhat higher than the one found in the simulation, which amounts to $u_\parallel = (1.9 \pm 0.2) \times 10^5$ m/s. Taking into account the difference between the actual magnetic configuration of TJ-K and the slab geometry used in GEM3, this is a quite good result. Fig. 2 shows this significant dependence of the parallel group velocity $u_\parallel$ on $k_\perp \rho_s$. As a general trend, the ratio of the parallel group velocity to the Alfvén velocity $u_\parallel / u_a$ increases with $k_\perp \rho_s$.

Summary

For the first time, the three-dimensional nature of drift waves has been verified experimentally inside the confinement region of a toroidal plasma. It was shown that the propagation in the direction parallel to the magnetic field is affected by Alfvén dynamics. The cross phase between density and potential fluctuations is small, which is consistent with the drift-wave model. These results strongly confirm previous investigations, which have demonstrated the importance of drift-wave turbulence in TJ-K and therefore also in fusion edge plasmas.

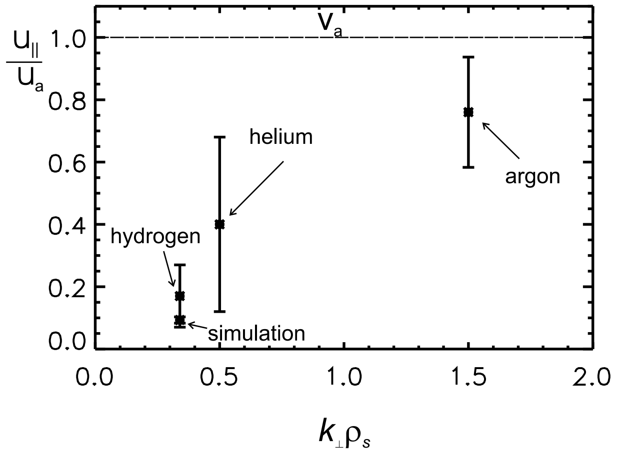

Figure 2: The ratio of the parallel group velocity to the Alfvén velocity $u_{\|}/u_a$ versus $k_\perp\rho_s$ for experimental and simulated data.

The measurements show that turbulent fluctuations on the low-field side are responsible for a major fraction of turbulent transport. This asymmetry of the turbulent transport could be related to magnetic field curvature effects, which becomes important on the low-field side.

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