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Recent studies on turbulent transport in the torsatron TJ-K

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Introduction

A better understanding of turbulent transport remains one of the major challenges in fusion plasma research. In recent years there has considerable progress been made in identifying the dominant instabilities in the tokamak core plasma, which are trapped-electron and ion-temperature-gradient modes. Due to critical gradients, which have to be overcome to destabilise the modes, models are able to produce the stiff temperature gradients which are observed since many years in tokamak plasmas. For a quantitative comparison with experimental profiles, however, these models have to include a certain level of subcritical transport and to rely on the experimental temperature at the edge as a boundary condition. This boundary condition is the result of turbulent transport in the edge and the scrape-off layer, which is not yet well understood.

The present work is dedicated to the investigation of turbulent transport in the plasma edge or, more precisely, under dimensionally similar conditions. The experiments are carried out on the torsatron TJ-K with minor and major plasma radii of 0.1 and 0.6 m, respectively, which is operated at reduced plasma parameters ($B = 80$ mT, $\bar{n} \leq 5 \times 10^{17}$ m^{-3}, $T_e \approx 5$ eV, cold ions)[1]. Parameters relevant for plasma turbulence, as the dimensionless collisionality ν^* and plasma pressure β^*, are, however, similar to those in the edge of fusion plasmas [1].

In order to identify the turbulence on a microscopic level, close comparisons with the simulation codes DALF3 and the improved version GEM3 [2] are carried out. In previous studies, the drift wave had been identified to be the leading instability in these low-beta plasmas, with the key characteristic of a small cross-phase between density and potential fluctuations on all spatial scales. The present paper presents results which elaborate on the three-dimensional nature of drift-wave turbulence and their consequences.

[1]Parameters are magnetic field strength, density and electron temperature

Drift-wave characteristics

Previously on TJ-K, poloidal probe arrays have been used to measure the wave number spectra of turbulent density and potential fluctuations as well as the cross-phase between them [1]. Broad spatial spectra indicated fully developed turbulence. Special interest was attributed to the distribution of the cross phase at different spatial scales. The phases were distributed around zero as it was predicted by simulations carried out with the drift-Alfvén-wave code DALF3. In addition, a propagation in the electron diamagnetic direction was observed, further substantiating that the turbulence in TJ-K was due to drift waves.

The investigations have now been extended to smaller scales [3] by reducing the probe separation and by reducing the scaling parameter ρ_s by a factor of 3. This became possible due to a new heating system at 8.2 GHz and a heating power of 1 kW. The drift scale $\rho_s = \sqrt{m_i T_e}/eB$ is expected to determine the characteristic spatial scale of the turbulent structures. Previously, ρ_s could only be modified substantially by changing the ion mass m_i due to the use of H, D, He, Ne and Ar as working gases. A scaling of the perpendicular correlation length as $\sim \sqrt{\rho_s}$ was found [4]. Now the magnetic field is increased by a factor of 3 to about 0.3 T which reduces ρ_s to 1 mm. In this case, the density gradient in hydrogen discharges has a width of about $40\rho_S$, while for simulating turbulence we esteem about $16\rho_s$ as sufficient.

The measured k spectra confirmed the previous results. The spectra are again broad and they shift to smaller wave numbers, when B is increased. By comparing the turbulent transport on low- and high-field sides, it was found that the major fraction appears on the former. The average value of the cross phases stays small also at the smallest scales, but as previously observed in both experiment and simulation, their distribution broadens at large wave numbers.

Parallel turbulent structure

The small cross-phase between density and potential fluctuations is due to the almost adiabatic parallel response of the electrons to the parallel pressure gradient of the fluctuations and hence due to the 3D structure of drift-wave turbulence. In order to further substantiate the drift-wave nature of the fluctuations, a direct measurement of the parallel wave length has been undertaken using correlation techniques [3]. They are applied to data from a probe matrix and a reference probe, separated by about 1 m in parallel direction from the latter. In order to interpret the data, a detailed knowledge of the path of the magnetic field line from the reference probe to the matrix is mandatory. It has been calculated by field-line tracing and also measured using a small plasma created by a filament that was placed at the position of the reference probe.

Fig. 1 shows a typical example. Maximum correlation is found on the matrix at a time delay of typically 10 μs in a distance of a few cm in perpendicular direction from the field line. The same behaviour is observed in the GEM3 simulations, which have been carried out at the same dimensionless parameters. The deviation from the field line is used to estimate the parallel wave number of the fluctuations. It turns out to be small but finite with a ratio to the perpendicular one of about 0.008. The parallel phase velocity has values in-between the ion-sound and the Alfvén velocity.

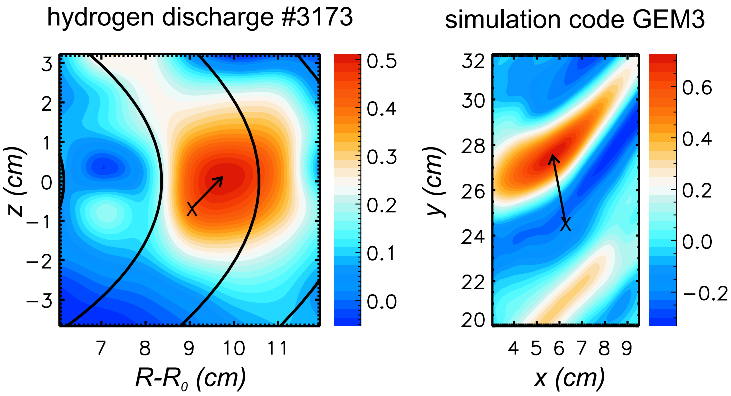

Figure 1: Spatial cross correlation for hydrogen discharge. The structure at time delay of maximum correlation is shown for the experimental(left) and simulated (right) data at maximum correlation. The black cross marks the intersection point of the magnetic field line.

Magnetic component of drift-wave turbulence

The parallel electric current driven by the parallel electron response leads to a coupling of the turbulence to shear Alfvén waves and hence to magnetic fluctuations. These fluctuations were measured with excellent resolution using magnetic probes [5]. Although the technique to measure the magnetic fluctuations with B-dot probes is straight forward, to obtain a reliable signal of a fluctuating quantity which is more than 5 orders of magnitude smaller than the ambient field is rather tedious.

Fig. 2 shows the result of this effort. A turbulent spectrum was measured which decays over 6 decades down to the nano-Tesla range. In order to compare the data with theory, the response in an induction loop to vector-potential fluctuations in GEM3 was simulated and scaled to physical coordinates. The results is also plotted in Fig. 2 and shows an excellent quantitative agreement with experiment [5].

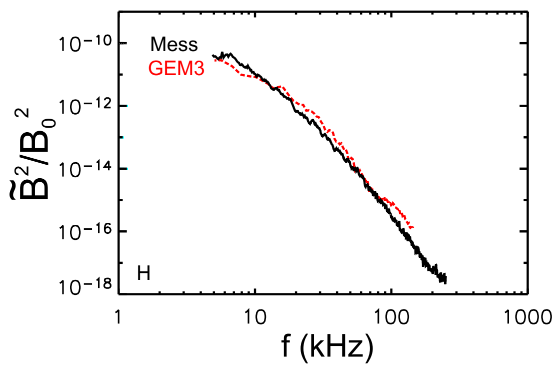

Figure 2: Spectrum of magnetic fluctuations from experiment and GEM3 simulations.

Transition from core to SOL

As a new elements of the investigations, the turbulent characteristics are studied at the transition from closed to open field lines [6]. To this end, the scrape-off layer (SOL) in TJ-K has been homogenised and extended by introduction of a toroidal limiter. This way the minor plasma radius was reduced to less then 5 cm and a large SOL with constant connection lengths of 1 toroidal turn has been obtained. The profiles in the reduced core were still peaked and the turbulence stayed drift-wave like.

Conditional averaging was used to investigate the dynamics of turbulent structures at the transition to open field lines. The dynamics in SOL and core are observed to stay coupled, since even with the reference probe inside the SOL, a drift-wave like dynamics was found for the core plasma. With the reference probe in the core it was shown, that a significant number of SOL structures originates from the core plasma. In the SOL, the structures in density start to separate from those in potential and the character gradually changes from drift-wave to curvature-driven dynamics.

The turbulent cascade

Furthermore, a first study of the dual turbulent cascade was carried out on 2D experimental data from the 8×8 Langmuir-probe matrix and on simulated data [7]. A d dual turbulent cascade is expected to be active in drift-wave turbulence. The data was analysed with bispectral techniques. The newly developed code was successfully tested on simulation data from a Hasegawa-Wakatani turbulence code. Then the technique was applied to the measured 2-dimensional density and potential fluctuation data. The dispersion relation and growth rates of the turbulence were found to be similar to the Hasegawa-Wakatani results. This confirms the turbulence to be drift-wave like. The energy transfer from the density fluctuations, which propagate with the vorticity, showed a direct cascade. For potential fluctuations, on the other hand, an inverse cascade is found. Hence, this work showed first experimental evidence for the dual cascade in drift-wave turbulence.

References

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