Characteristics of micro-turbulence in LHD from 2d CO2 phase contrast imaging

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It is well known that particle and energy transport are strongly influenced by fluctuation-driven processes. To gain an accurate description of how this is important, we need to understand the interplay between (a) plasma and magnetic parameter profiles, (b) fluctuation profiles and (c) resulting particle and energy transport. Here we focus on the first link (a-b), i.e. looking at the relationship between parameter profiles and fluctuation profiles. The purpose of such an investigation is twofold, since fluctuation profiles have ramifications for the transport and may regulate the profiles, and also to provide evidence for particular theoretical descriptions of the turbulence behavior.

Drift-wave like fluctuations are driven by gradients in density and ion/electron temperature profiles, and are affected by magnetic properties. The key parameters often used to describe these are the normalized temperature and density gradients, $L_T^{-1} = \nabla T/T$, $L_n^{-1} = \nabla n/n$, and the ratio, $\eta = L_T^{-1}/L_n^{-1}$. Ion temperature gradient (ITG) turbulence is driven by the temperature gradient and can be stabilized by density gradient, so the η parameter is crucial in determining its stability. On the other hand, trapped electron mode (TEM) turbulence can be driven in the absence of a temperature gradient. In general, these modes couple to each other and both can exist simultaneously. In simplified geometries, analytic instability criteria can be derived. In complicated geometries, numerical simulations are required to calculate linear growth rates. Such calculations have been performed in LHD [1].

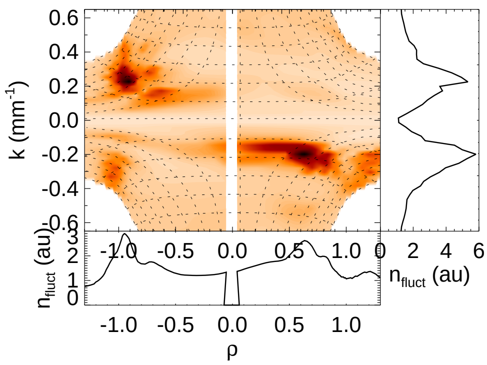

Figure 1: Spatial and k resolved profiles of fluctuation amplitude. The dashed lines indicate the characteristic resolution. The sign of ρ indicates the direction about the midplane.

Phase contrast imaging fluctuation profile measurements

Fluctuation measurements presented here were made using a novel 2-d CO_2 laser phase contrast imaging (PCI) system [2]. This diagnostic has the capability to simultaneously resolve line integrated fluctuations both along the line of sight, which we label by flux coordinate ρ, and in k, as shown in Fig. (1). With PCI, small angle scattering implies that no resolution along the line of sight can obtained. However, since fluctuations generally have $k_{||} << k_{\perp}$, the position along the line can be inferred from the propagation direction which is perpendicular to the local magnetic field. The system uses a (6x8) 2d detector array to measure the propagation direction and obtain a spatial/k map as shown in Fig. (1). The characteristic resolution $\Delta\rho \sim 0.1$ depends on the value of k of the fluctuations.

Analysis of phase velocity

The phase velocity of the fluctuations conveys information about the underlying nature of the instability, depending on whether it is in the ion or electron diamagnetic direction.

To accurately perform the comparison, it is necessary to compute the ion/electron drift velocities in the plasma frame of reference: $v_{\text{drift lab}} = V_{E\times B} \pm \frac{T}{B}(L_n^{-1} + L_T^{-1})$.

In this comparison, the $E \times B$ rotation is measured directly with a measurement of the Doppler shift of C VI CX radiation driven by perpendicularly injected positive NBI, and was recently installed in the last experimental campaign [3]. The new system provides much more detailed information near the edge of the plasma. Density profiles are taken from the FIR interferometer and electron temperature profiles from Thomson scattering. The drift velocities are projected perpendicular to the PCI line of sight $\hat{l}$ by the factor $\hat{l}.\hat{\theta}$. The ion and electron diamagnetic velocities can only be distinguished in regions where the pressure gradient is large and the $l.\theta$ is significant. This is true for the edge regions though not the core and not at the edge where the pressure is close to zero. Classification is possible around $0.6 < \rho < 0.9$, depending on plasma profiles.

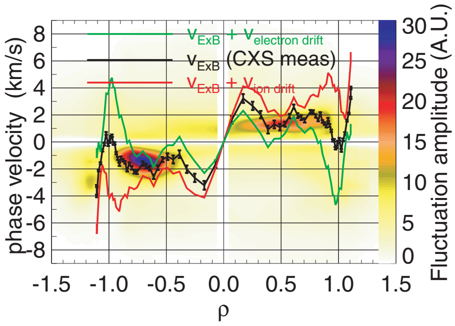

Figure 2: Space and phase-velocity resolved Fluctuation amplitude $S(\rho, v)$, compared with measured ExB and drift velocities. This discharge corresponds to Fig. (3b).

The phase velocity of fluctuations is calculated based on ω and k. A two dimensional "image" of the fluctuation amplitude as a function of ρ and v is calculated from
$S(\rho, v) = \int S(\rho, vk, k)(dv/d\omega)dk$, where $S(\rho, \omega, k)$ is the frequency resolved image shown in Fig. (1).

A comparison of PCI phase velocity and diamagnetic velocities is shown in Fig. (2). The measurements are consistent in that the shape of the ExB profile closely corresponds with with the fluctuation velocity. In the edge, there is a significant ExB shear. This may play a role in regulating the transport in certain scenarios. The fluctuation velocities are approximately offset from the $E \times B$ velocity by the electron drift velocity. This is evidence for TEM like modes, which should only occur when the temperature gradient is small. However, in this scenario, the temperature gradient is appreciable, as shown in Fig. (3b).

Fluctuation driving forces

We present results for 2 discharges showing different driving terms. We choose to analyze fluctuations away from the edge, since normalized gradients are difficult to evaluate accurately in this region, and edge processes can have an influence. However, the edge peaks are generally the strongest.

In the first example, we consider the change of the profile from peaked to hollow, after pellet injection, to elucidate the role of density gradient. The fluctuation profiles are shown in Fig. (3a,b). In the peaked density profile, fluctuations are strongest in the edge, while when the profile hollows, a new branch is excited towards the core, in the hollow part of the profile. The temporal dynamics are shown explicitly in Fig. (3c). After pellet ablation, the density profile is transiently hollow. When the profile switches to peaked, fluctuations are reduced. At around $t = 1.8$s, the heating power is increased and the profile returns to hollow. Again, when and the sign of η changes, fluctuations increase again.

Because the temperature gradient is nonzero, and density gradient is a regulating parameter, this is evidence of an "ITG like" mode. However, ITG dominated modes propagate in the ion-diamagnetic direction, contrary to the observed phase velocity described in the previous section. (However, since the the drift velocity in the $E \times B$ frame is small in the hollow region at $\rho = 0.7$, one cannot deny that it

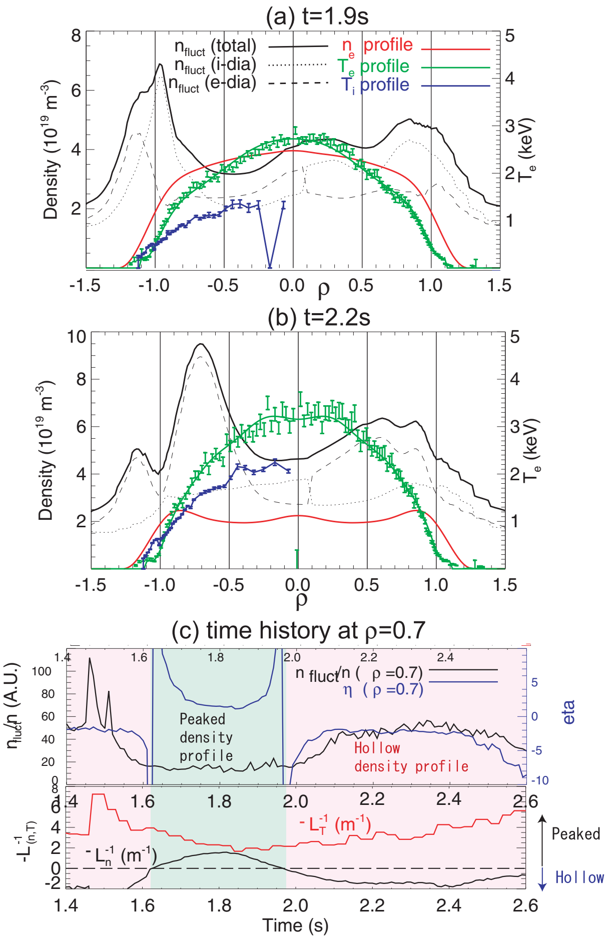

Figure 3: Spatial profiles of fluctuation amplitude compared with density, temperature profiles in (a) peaked density profile,t=1.9s and (b) hollow density profile, t=2.2s. (c) Comparison of time evolution of fluctuation amplitude and η at $\rho = 0.7$.

could be in the ion diamagnetic direction.) This feature is also inconsistent with the expectations of the calculations in [1], which show that fluctuations are stabilized under hollow density profile and peaked temperature profile. The presence of a fluctuation peak in the hollow region of the density profile is universal in that it occurs in a variety of discharges, though exceptions can be found with no peak in the hollow region. In the commonly used configurations of LHD ($R_{ax} = 3.6\text{m}, 3.75\text{m}$), hollow density profiles are common in steady-state. The direction and magnitude of the fluctuation-induced flux may have ramifications for the causality of the hollow density profile.

In the second example, we present fluctuations in the core region of a super dense core (SDC) discharge [4] in Fig. (4a). In this case, rapid pellet injection forces a highly peaked dense core, with a strong gradient. A peak in the fluctuation amplitude is observed in this density gradient region. The temperature profile in the core is flat. This is an example of density gradient driving instabilities (since $\nabla T \sim 0$). To show this role clearly the fluctuation amplitude at $\rho = 0.4$ is compared with the normalized density gradient L_n^{-1} in Fig. (4b). It is clear that as the gradient steepens, the fluctuation level increases. A comparison of the fluctuation velocity with $E \times B$ and diamagnetic velocities shows that this branch appears to propagate at around the electron drift velocity. This evidence suggests that the mode is TEM like, since it is driven by the strong density gradient at zero temperature gradient, and since it propagates in the electron drift direction.

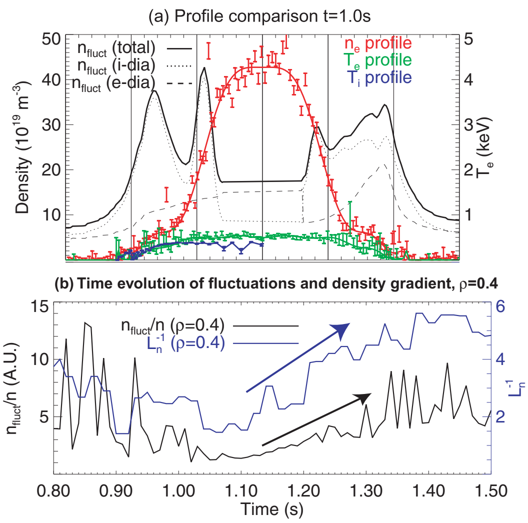

Figure 4: (a) Fluctuation and plasma parameter profiles in a super-dense core discharge, (b) Time evolution of fluctuation amplitude and normalized density gradient at $\rho = 0.4$.

Referenes

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