Investigation of plasma turbulence and geodesic acoustic modes using tangential phase-contrast imaging in the TCV tokamak

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Introduction

The anomalous transport caused by the plasma turbulence is one of the outstanding physics issues in magnetic-confinement fusion research, due to the attendant degradation of energy confinement and ultimately fusion reactivity. Experimental measurements of plasma microturbulence, i.e. , fine-scale, broadband fluctuations have thus become an essential need. A tangential phase-contrast imaging (TPCI) diagnostic [1, 2] has been designed and installed on the Tokamak à Configuration Variable (TCV) [3] to measure localized plasma density fluctuations across the plasma cross section, by employing a spatial filtering technique. Experiments were performed to investigate the dependence of density fluctuations on plasma shape (in particular edge triangularity), radial position and collisionality with the aim of understanding the improved energy confinement at negative triangularity. In addition, we have extended our studies of geodesic acoustic modes (GAM) [4], in particular by identifying for the first time an experimental scenario featuring a multimode to eigenmode transition, and by studying the GAM-turbulence interaction through bispectral analysis.

The tangential phase-contrast imaging diagnostic on TCV

Phase-contrast imaging is an established technique for measuring line-integrated plasma density fluctuations, particularly in magnetic confinement fusion devices [5, 6]. Because only wavenumbers perpendicular to both the magnetic field and the beam direction can contribute to the signal, a spatial filtering technique can then be employed to select a wavenumber direction and thus localize the measurement [1]. The localization is greatly enhanced at the point where the beam is tangential to the magnetic field, where the diagnostic measures mainly k_r. On TCV, taking advantage of its flexibility of plasma shaping and position, localized measurement can be achieved over the full radial extent of the plasma by shifting the plasma vertically within the highly elongated vacuum vessel.

Dependence of plasma turbulence on the triangularity

A significant energy confinement improvement is obtained at negative edge triangularity relative to positive δ on the TCV tokamak [7]. With negative δ, only half the central electron-cyclotron heating (ECH) power was required to obtain the same electron temperature and density profiles as in positive δ cases [8]. Recent studies indicate that at equal power the core gradients are very similar for $\delta > 0$ and < 0 and that the global confinement change is governed by the plasma edge [9]. Nonlinear local flux-tube gyrokinetic simulations have also shown that turbulence is suppressed for negative δ, but only at the plasma edge [10], consistent with the poor penetration of triangularity to the core.

The TPCI diagnostic was used to measure localized density fluctuations in order to investigate the effect of plasma triangularity on microturbulence from the core region to the edge for a wide range of plasma collisionalities. Experiments were performed both at constant triangularity for each shot but varying the vertical position to allow the TPCI diagnostic to access different radial locations, and varying the triangularity at constant vertical position for each shot. The radial range in terms of ρ_{vol} (the normalized square root of the plasma volume) is different for different δ because of different geometries: for the vertical scan it yields from the last closed flux surface (LCFS) to $\rho_{\text{vol}} = 0.47$ to 0.54, and for the δ scan the radial range is $0.33 < \rho_{\text{vol}} < 0.43$. The plasmas have similar elongation ($\kappa \approx 1.4$) with a plasma current of 250 kA; 0.45 MW ECH was applied in the center of the plasma. The density fluctuation $\tilde{n}/n$ was calculated as the root mean square (rms) value of TPCI signal normalized by the effective integration length and by the local electron density measured by the Thomson scattering diagnostic. Because the TPCI diagnostic is currently in a preliminary configuration without absolute calibration, the absolute value of $\tilde{n}/n$ is not known.

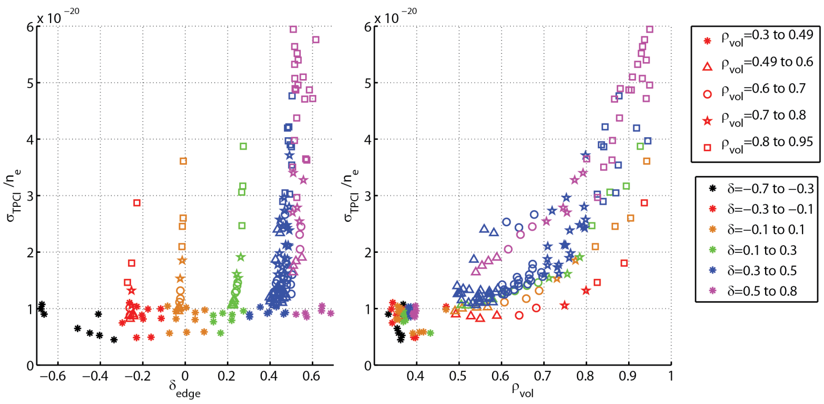

Figure 1: Measured density fluctuation $\tilde{n}/n$ as a function of edge triangularity δ (a), and radial position in terms of ρ_{vol} (b).

Figure 1 shows that the turbulence level increases with ρ_{vol} from core plasma to the edge, and increases with δ from negative to positive at a fixed radial position. The effect of triangularity is more significant at the edge in comparison to the core plasma. In the case of the δ scan where $\rho_{\text{vol}} < 0.5$, the density fluctuation level doesn't change with the triangularity. However, the electron temperature in the core increases with decreasing δ due to improved confinement. This leads to lower effective collisionality ($\nu_{\text{eff}} = 0.1 n_e Z_{\text{eff}}/T_e^2$) which tends to increase the transport [8]. Hence an investigation of the dependence of turbulence on collisionality is required to complete the study. This was done by varying both density and ECRH power and combining all data in a multi-parameter database.

The dependence on collisionality is illustrated by Fig. 2, using only data at $\rho_{\mathrm{vol}} < 0.6$ where the dependence of turbulence on radial position is relatively weak, to separate the effect of ν_{eff} and ρ_{vol}, which are otherwise highly correlated. Figures 2 (a-b) show that the turbulence level increases with decreasing collisionality, at constant triangularity and radial position. Figure 2 (c) shows the data in the vertical scans at different values of delta, illustrating the positive correlation between ν_{eff} and δ due to the changes in confinement.

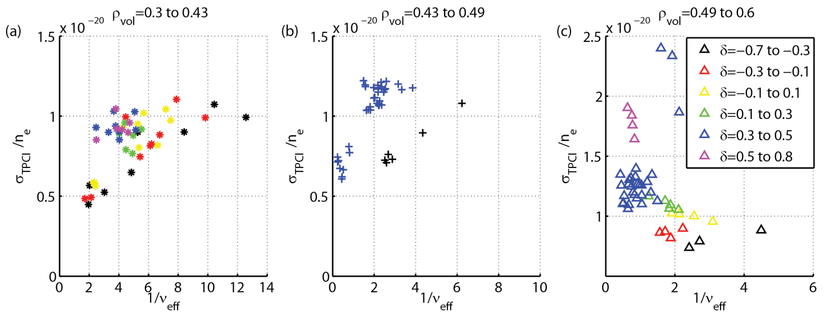

Figure 2: Measured density fluctuation $\tilde{n}/n$ as a function of the reciprocal of the plasma effective collisionality ν_{eff} in δ scan at $0.3 < \rho_{\mathrm{vol}} < 0.43$ (a), collisionality scan at $0.43 < \rho_{\mathrm{vol}} < 0.49$ (b), vertical scan at $0.49 < \rho_{\mathrm{vol}} < 0.6$ (c).

The results that the turbulence level increases with decreasing collisionality and increasing triangularity are consistent with former studies of the dependence of the electron heat diffusivity χ_e on ν_{eff} and δ [8].

GAM characterization

The geodesic acoustic mode has been studied experimentally in the TCV tokamak with multiple diagnostics, including TPCI, magnetic probes, Doppler backscattering and correlation ECE [2, 11]. It was observed simultaneously as a coherent mode by all these systems. Measurement of the magnetic component by a complete, multi-point toroidal array permitted the first unambiguous determination of the axisymmetry of the mode. In parallel, gyrokinetic simulations have been performed with the global particle-in-cell code ORB5 and directly compared with experimental measurements, with good semi-quantitative agreement [11].

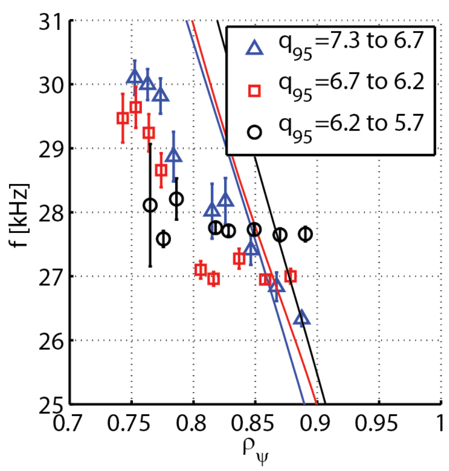

Figure 3: GAM frequency at different radial location during a q scan.

The GAM was also identified by the fact its frequency roughly follows the expected c_s/R scaling law, c_s being the ion sound speed. In the literature, different radial structures have been reported for the GAM, such as dispersive continuum [12], eigenmode frequency plateaus [13] and single-frequency eigenmode [11, 14]. A transition from GAM eigenmode to continuum was observed on the DIII-D tokamak after the plasma transitioned from an L-mode to the Ohmic regime [13]. On TCV, we recently observed a GAM eigenmode-continuum transition by varying the safety factor q, as shown in figure 3. The calculated GAM frequency $f = c_s/2\pi R$ assuming $T_e = T_i$ is also plotted. It can be seen that the GAM frequency scales with local temperature at high q, whereas this dependence is lost at low q.

The GAM drive and damping were investigated in a density ramp-up. The broadband density fluctuations increase with density whereas the density component of the GAM remains roughly constant, as shown in figure 4. The increased collisional damping thus appears to compensate the increased drive that is expected from the rise in background turbulence. To investigate the drive itself we applied a bispectral analysis. We find that the bicoherence between the GAM and the broadband turbulence vanishes during the ramp-up *before* the GAM peak on the power spectrum becomes hidden by the background, suggesting a more complex picture in which the drive does not simply increase with turbulence.

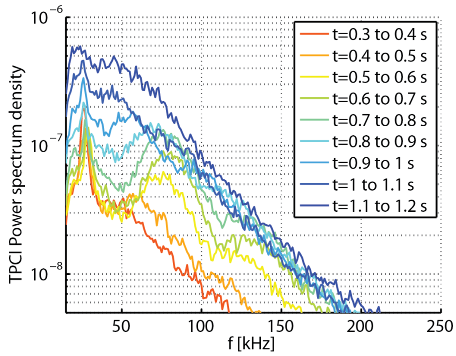

Figure 4: Power spectrum of TPCI signal during density ramp-up. The GAM peak is at about 30 kHz.

Acknowledgment

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