Turbulence measurements and gyrokinetic validation at ASDEX Upgrade

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Understanding the turbulent driven heat flux in a tokamak remains one of the key goals of fusion research. Anomalous transport up to two orders of magnitude above what one would expect from neoclassical theory is observed and this is now understood to be caused by turbulent fluctuations in the plasma density, temperature and potential, originating from drift-wave like instabilities which grow and non-linearly saturate [1, 2]. In order to study in detail the turbulence giving rise to electron heat transport on ASDEX Upgrade (AUG), a correlation ECE (CECE) diagnostic [3] was significantly upgraded [4], introducing a channel comb arrangement. This new diagnostic can now measure high radial resolution fluctuation amplitude, $\delta T_{e\perp}/T_e$ profiles, profiles of the radial correlation length $L_r(T_{e\perp})$ and, with the addition of one V-band and two W-band reflectometers on the same line of sight, the cross-phase angle between temperature and density fluctuations α_{nT} [5].

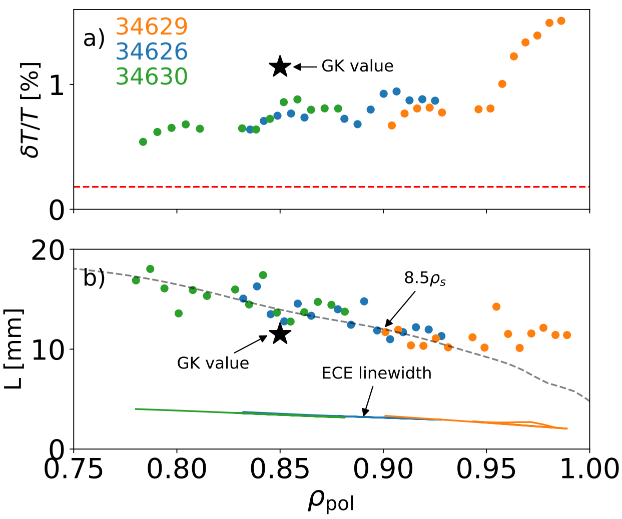

Figure 1: *a) radial profile of the temperature fluctuation amplitude, composed of 3 AUG L-mode discharges. b) radial profile of the correlation length of the temperature fluctuations*

Figure 1 a) shows a fluctuation amplitude profile for a combination of three repeat L-mode discharges with dominant electron heating and $T_e > T_i$. The CECE channels were moved radially by slightly adjusting the magnetic field (<4%) between shots. Non-linear gyrokinetic simulations were performed with GENE [?] at a normalised toroidal flux radius of $\rho_{\text{tor}} = 0.75$ where it was found that $\delta T_{e\perp}/T_e$ is overestimated [5]. Figure 1 (b) shows the corresponding profile of radial correlation length of the $\delta T_{e\perp}$ calculated from the same data. The measured correlation length is well above the ECE linewidth in this case and is in good agreement with the non-linear gyrokinetic simulations. For the first time, the proportionality of $L_r(T_e)$ with the ion sound speed gyro-radius ρ_s has been demonstrated.

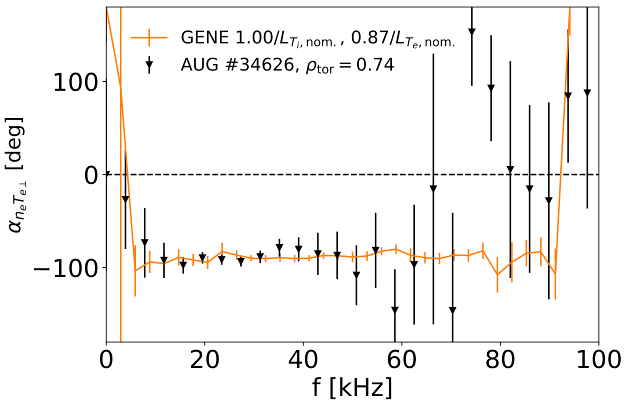

Figure 2: *The frequency spectrum of the density-temperature cross-phase angle from experiential and gyrokinetic modelling. Reproduced with permission from [5].*

The cross-phase angle α_{nT} also shows excellent agreement to the gyrokinetic model, as shown in Figure 2, where the frequency spectrum from experiment and simulation are compared. Agreement is found between 10 and 50 kHz, where the ECE and reflectometer fluctuations show a high coherence. The gyrokinetic results are chosen from a simulation with a 12% reduced electron temperature gradient, which is within the experimental uncertainty. While the gyrokinetic simulations are very sensitive to the experimentally measured profile gradients in terms of heat flux, in cases such as this, where ITG and TEM modes have very similar growth rates, α_{nT} may be effectively used to distinguish simulations, acting as a measure of the balance of ITG and TEM turbulent structure in the experiment.

Figure 3 shows the synthetic diagnostic output for α_{nT} for simulations where the normalised temperature profile gradients $(1/L_X = d/d\rho_{\text{tor}}(\ln X))$ were varied within their uncertainties. On this graph a pure ITG mode has $\alpha_{nT} = -137^o$ and for pure TEM $\alpha_{nT} = -18^o$. It can be seen that the average α_{nT} moves towards the pure ITG (TEM) case when $1/L_{T_i}$ is increased (decreased) and vice versa with $1/L_{T_e}$. When compared to the experimental measurement, a combination of gradients can be identified which pro-

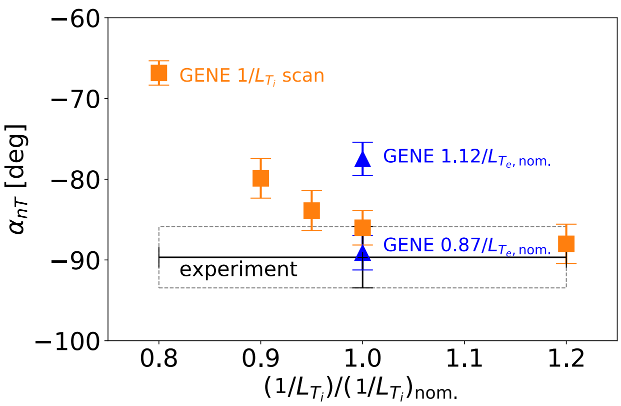

Figure 3: *Synthetic diagnostic results for the average α_{nT} after scanning the gradient drives for ITG and TEM modes. α_{nT} is shown to vary continuously between ideal ITG (-137^o) and TEM (-18^o) values, rather than jumping from one to the other. Reproduced with permission from [5].*

duces a quantitative match and this is
achieved for a simulation which also matches the experimental heat fluxes,Q_i and Q_e. These observations are also in agreement with previous experimental observations, where α_{nT} has been found to vary continuously depending on the normalised electron temperature gradient [6, 7, 8] and T_e [9] suggesting that a transition from dominant ITG to TEM turbulence (and vice versa) is not a sharp transition, but rather the mode structures co-exist with comparable amplitudes over a range of parameters.

If we consider the plasma state to be quasi-linear and the final α_{nT} to be given by the argument of the linear sum of two complex amplitudes, then the the ratio of the magnitude of the ITG and TEM amplitudes is given by:

$$\frac{|A_{\text{ITG}}|}{|A_{\text{TEM}}|} = \frac{\sin(\alpha_{\text{expt}} - \alpha_{\text{TEM}})}{\sin(\alpha_{\text{ITG}} - \alpha_{\text{expt}})}, \tag{1}$$

where α_{expt} is the measured cross-phase angle, α_{TEM} is the simulated cross-phase angle determined by artificially setting the ITG mode drive to zero, and α_{ITG} is the cross-phase angle obtained by setting the TEM drive to zero. The ratio $|A_{\text{ITG}}|/|A_{\text{TEM}}|$ may be taken as a measure of the relative contribution of ITG and TEM to the final turbulent state (not necessarily the heat flux), within the measured range of wavenumbers. This expression evaluates to 1.3 for the case described above, meaning that, quasi-linearly, there is 30% more ITG structure than TEM structure in this plasma at $\rho_{\text{tor}} = 0.74$, with $k\rho_s < 0.28$.

In conclusion, a significantly upgraded CECE diagnostic now measures high radial resolution $\delta T_{e\perp}/T_e$ and $L_r(T_{e\perp})$ profiles and has confirmed for the first time that $L_r(T_{e\perp})$ is proportional to ρ_s. The measurement of α_{nT} is made possible with the addition of a reflectometer along the same line of sight. These quantities were measured simultaneously at the same radial location to constrain a set of non-linear, ion-scale, flux tube simulations of an ECH heated L-mode plasma with $T_e > T_i$. These simulations matched ion and electron heat fluxes, $L_r(T_{e\perp})$ and α_{nT}. $\delta T_{e\perp}/T_e$ was over-predicted by 60%. Simulations show that the average α_{nT} varies continuously between the ideal ITG and TEM values, suggesting that the measurement can be used as a practical proxy for the ratio of ITG and TEM contributions to the final turbulent state.

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