Validation studies of ion-scale GENE simulations in L-mode plasmas at ASDEX Upgrade

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For the prediction of the performance of future fusion machines, it is essential to have a fundamental understanding of the physics mechanisms which drive the heat, particle and momentum transport. This can be achieved by a combination of detailed measurements of the properties of the turbulent fluctuations and the quantitative comparison of those measurements with the most accurate available theoretical models [1]. Recently, the development of the fidelity of gyro-kinetic (GK) simulations and advanced synthetic diagnostics, means that GK models can be tested more thoroughly than ever. There only exist a handful of examples [2, 3, 4, 5] where turbulent electron temperature fluctuations (δT_e) have been quantitatively compared to GK simulations, with varying results. The physical reasons underlying the observed discrepancies is still an outstanding problem.

We present a quantitative comparison of experimental and GK δT_e using GENE [6]. Measured $\delta T_e/T_e = (0.75 \pm 0.02)\%$, whereas simulated $\delta T_e/T_e = (1.2 \pm 0.2)\%$, showing a disagreement outside the uncertainties.

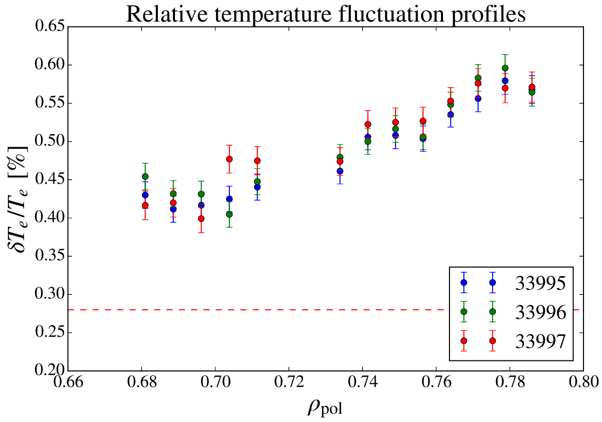

Figure 1: *$\delta T_e/T_e$ profiles for three repeat discharges showing the low statistical error and high radial resolution of the upgraded ASDEX Upgrade CECE*

ASDEX Upgrade (AUG) has a large set of turbulence diagnostics. Recently, to compliment these diagnostics, a Correlation ECE (CECE) radiometer for the study of electron temperature fluctuations has been installed [7]. This has since been significantly upgraded [8, 9] to allow more detailed radial profiles and correlation lengths to be measured. CECE works on the principle that the cross-correlation of two radiometer channels spaced radially much less a turbulent correlation length can overcome the fundamental noise limitations imposed on a single radiometer channel [10, 11], allowing the typically broadband, low amplitude fluctuations to be detected. Figure 1 shows a fine radial resolution (~ 4 mm spacing) fluctuation amplitude profile for 3 consecutive low density, electron heated L-mode discharges. The data has been averaged over 3 seconds of steady state plasma, producing low statistical error as confirmed by the comparison of the profiles. The dashed red line at the bottom of the plot indicates the sensitivity limit of the diagnostic under these conditions.

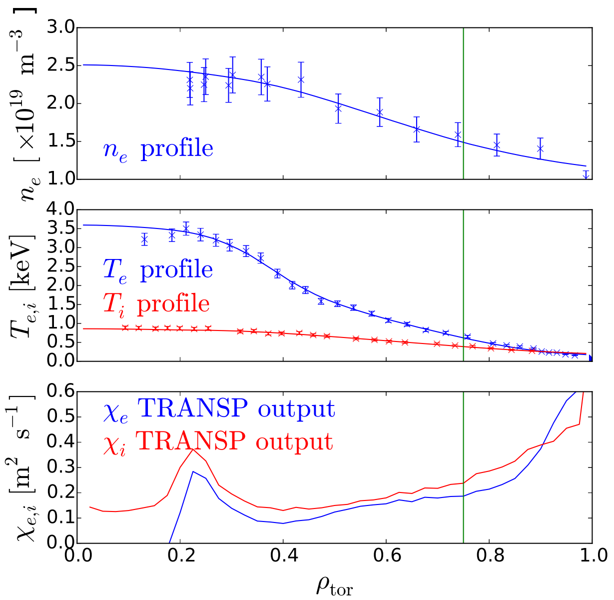

Figure 2: *Showing fitted profiles of electron and ion temperature and density as well as ion and electron thermal diffusivities derived using TRANSP for AUG 33585. GENE simulations are performed at* $\rho_{\rm tor} = 0.75$ *(green line).*

CECE measurements of fluctuation frequency spectra have been quantitatively compared to physically realistic turbulence simulations using the GENE GK code [6]. The profiles for the chosen L-mode plasma, AUG 33585, are shown in Figure 2. For this discharge at the simulation radius ($\rho_{\rm tor} = 0.75$), the normalised profile gradients are: $a/L_{Ti} = -2.56$, $a/L_{Te} = -5.11$, $a/L_{ne} = -1.46$ and $E \times B$ shearing rate = 0.0168. The reults of the GENE linear eigenvalue solver, shown in Figure 3, shows this plasma to be a mix of ITG and hybrid TEM-ETG modes. a/L_{Ti} is scanned from 0.9 to 1.2 times the nominal value, with the dominant linear mode changing from hybrid TEM-ETG for lower values to ITG at higher values. The comparable growth rates for both unstable modes makes this discharge an excellent test case for the non-linear model. The ratio $\gamma_{\rm high\,k}/\gamma_{\rm low\,k} = 35$ suggesting that the electron scales contribute in only a minor way to the experimental heat flux and that an ion scale simulation should be sufficiently accurate [12].

A set of non-linear ion-scale simulations were performed with GENE, with kinetic electrons, using a realistic mass ratio for ions and electrons, including electromagnetic effects and using a linearised Landau-Boltzmann collision operator. Experimental heat fluxes were inferred from TRANSP simulations and the GENE simulations were able to match both the ion and electron heat flux simultaneously within the experimental errors for the heat fluxes and ion temperature gradient. There is thus no ion or electron "shortfall" seen by GENE for this plasma. Non-linearly, the electron heat flux is shown to be relatively insensitive to 20 % variations in

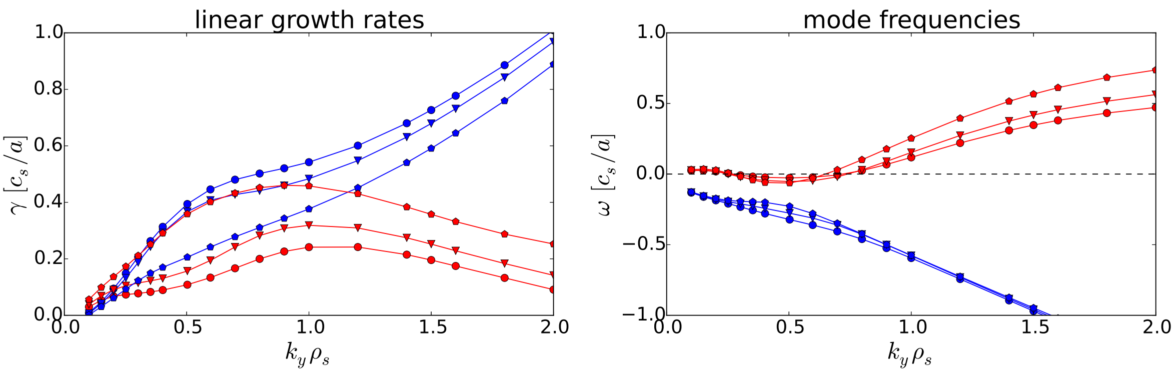

Figure 3: *The growth rate (Left) and mode frequency (Right) of the unstable Eigenmodes present in the plasma for 90%, 100% and 120% a/L_{Ti}. Electron modes are coloured blue and ion modes are coloured red.*

a/L_{Ti} suggesting that the hybrid TEM-ETG mode is mostly responsible for the electron heat flux in the simulations.

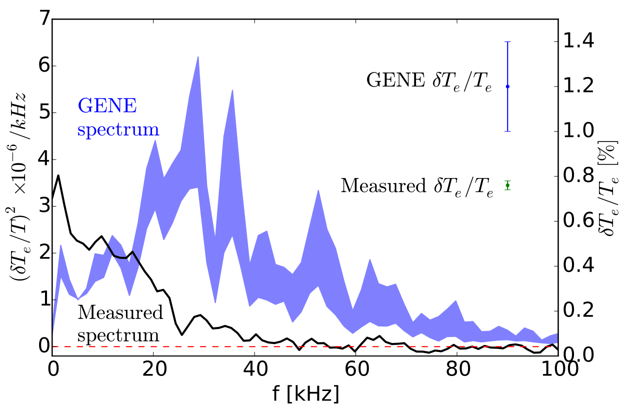

Figure 4: *Comparison of the measured low-k frequency spectrum with the synthetic diagnostic result from GENE.* $\delta T_e/T_{e,\text{measured}} = (0.76 \pm 0.02)\%$, $\delta T_e/T_{e,\text{GENE}} = (1.2 \pm 0.2)\%$

These simulations show a high degree of anisotropy in δT_e, with $\delta T_{e\perp}$, exceeding $\delta T_{e\parallel}$ by a factor of 5. Since the CECE, as has been reported before [2], is sensitive exclusively to the perpendicular temperature fluctuations it is especially important to account for this anisotropy in the synthetic diagnostic to allow a quantitative comparison. The GENE CECE synthetic diagnostic convolves $\delta T_\perp$ with Gaussians approximating the region each CECE channel is sensitive to. The radial width is calculated from the emissivity function [13] and the z extent comes from measurements of the CECE beam width made ex-vessel with a near field scanning probe [14]. The convolved fluctuations are then put through the same signal analysis as the measured data for direct comparison.

Figure 4 shows the comparison of the measured low-k frequency spectrum with that from the GENE synthetic diagnostic. The filled area of the synthetic diagnostic curve shows the effect of the uncertainty of the CECE beam width on the fluctuation spectra. As can be seen from the figure, GENE predicts a fluctuation amplitude $\delta T_{e,\perp}/T_e = (1.2 \pm 0.2)\%$ whereas the measured value is $\delta T_{e,\perp}/T_e = (0.76 \pm 0.02)\%$. Some diagnostic uncertainty in the experimental beam width due to the possible presence of higher order modes in the waveguides is included in the GENE error bar as the effects are modelled using the synthetic diagnostic. GENE over-predicts $\delta T_{e,\perp}/T_e$ outside the uncertainties, despite matching well the electron heat flux. The exact reason for the discrepancy is not yet known. In the simulation, both the electron heat flux and $\delta T_{e,\perp}/T_e$ are relatively insensitive to scans in a/L_{Ti}, suggesting that, non-linearly, the ITG is not significantly contributing to δT_e. Further sensitivity scans will be performed to assess the robustness of the result. Also, GK predictions can now be made for the turbulent correlation length for this discharge along with the phase angle between $\delta T_{e,\perp}$ and δn_e. Both of these quantities can be measured in upcoming AUG experiments with the upgraded CECE radiometer in a repeat discharge. Above all, the fact that the GK model is able to match high level quantities and not match measures of the turbulence provides a strong motivation for comparing more experimental quantities for a single discharge. Are the models able to match many turbulence quantities simultaneously, and if so, do they still match the experimental heat flux? Plans are currently underway to use several AUG turbulence diagnostics to simultaneously measure several fluctuation properties simultaneously, strongly constraining the GK model .

This work is supported in part by the US DOE under Grants DE-SC0006419 and DE-SC0017381

This work has also been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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