Doppler Reflectometry Simulations for ASDEX Upgrade

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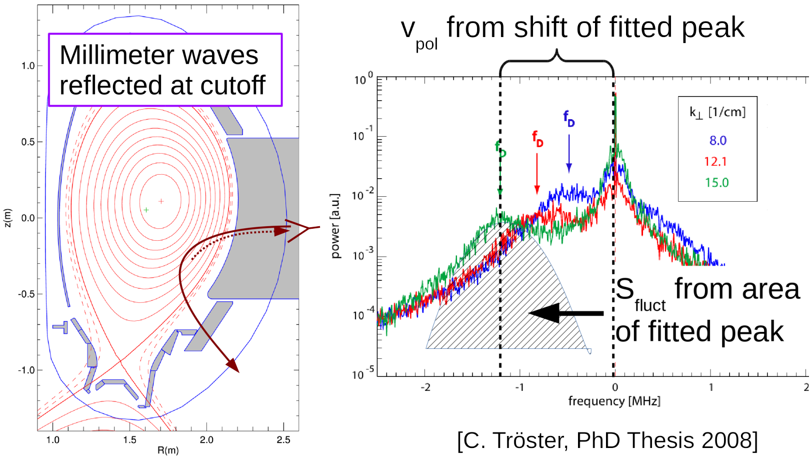
Introduction

In fusion plasmas, there usually exists a broad wavenumber spectrum $S(k_\perp)$ of density fluctuations that are responsible for radial transport and therefore losses. These range from low $k_\perp$ (ion gyroradius scales) ion temperature gradient driven (ITG) modes to high $k_\perp$ (electron gyroradius scales) electron temperature gradient driven (ETG) modes. Since material probes cannot be employed in the radial region of interest, microwave scattering techniques are employed. In Doppler reflectometry [1, 2, 3], the receiving antenna is tilted against the plasma density gradient. Fig. 1 shows a typical setup and scattered signal from ASDEX Upgrade. The non-normal beam incidence on the rotating plasma causes a Doppler shift of the moving scattered wave, allowing the determination of the perpendicular drift velocity $v_\perp$ of the cut-off layer perturbations. Doppler reflectometry is well established as a robust $v_\perp$ diagnostic (e. g. in ASDEX Upgrade [4]). However, the scattering sensitivity depends both on the plasma geometry (magnetic equilibrium, density profiles) and on the strength of the fluctutations themselves (nonlinearity [5, 6]). This is the reason for developing an integrated synthetic diagnostic that combines a plasma turbulence code with a wave propagation code for the reflectometer, and couples them to the experimental database.



[C. Tröster, PhD Thesis 2008]

Figure 1: *In Doppler reflectometry, only the the backscattered wave is received (left). It contains information about fluctuation strength and perpendicular velocity $v_\perp$ (right).*

The scattering condition for Doppler reflectometry is given by $k_{fluct} = -2k_i = -2Nk_o$ and the doppler shift by $\omega_D = -2k_i v_\perp \sin(\theta)$ where k_i is the wave vector at the turning point, k_o is the vacuum wave vector, N is the refractive index at the turning point (which can be determined by beam tracing techniques), k_{fluct} is the probed density fluctuation wavenumber (in the direction perpendicular to the background magnetic field), and θ is the tilt angle with respect to the density gradient. To measure the wavenumber spectrum of the density fluctuations, the tilt angle and frequency are varied to scan a range of wavenumbers.

The Synthetic Doppler Reflectometer

The synthetic diagnostic [7] takes the experimental equilibrium quantities of the plasma (magnetic equilibrium, profiles, heat fluxes) and uses the plasma turbulence code GENE[8, 9] to generate the plasma density fluctuations. GENE is a physically comprehensive, hyperscalable Vlasov code that supports both local (flux-tube) and global (full-torus) calculations. In this investigation, the local version was used, and the ion temperature profile was adjusted to match the experimental heat flux. Both experimental profiles and generated turbulence are then fed into the fullwave code IPF-FD3D [5], which simulates the wave propagation and scattering of the mm waves from sending to receiving antenna. The fullwave code is run separately on each time step of the turbulence, yielding a time series of about 1000 points with a sampling rate determined by the turbulent time scale. Any differences in the actual density flucatuation spectrum and the measured spectrum from reflectometry are subsumed in the *instrument function* which is modeled with the fullwave simulation.

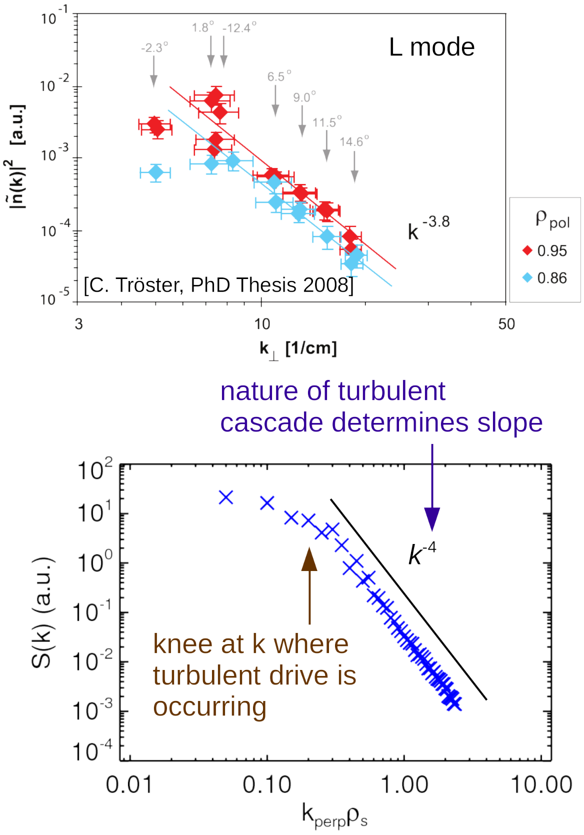


Figure 2: *Experimental (top) and* GENE *(bottom) spectra.* $k_\perp \rho_s = 1$ *corresponds to* $k_\perp = 10\,cm^{-1}$.

The signal is then analysed and yields the perpendicular wavenumber spectrum of the density fluctuations. It is only at this level that experiment and simulations can be compared, since neither instrument function nor the underlying fluctutation spectrum are known in the experiment. If the spectra agree, one can then conclude that the fluctuation spectrum from GENE (which may differ from the observed spectrum) is the one present in the experiment, therefore validating the turbulence code and enabling/encouraging future design optimization via the numerical tools.

Results

Fig. 2 shows the experimental spectrum from the X mode W-band reflectometer, and the simulated GENE spectrum. Turbulence spectra are characterised by 2 parameters: the knee between the mostly horizontal region of low wavenumbers k and the spectral index describing the roll-off at large k.

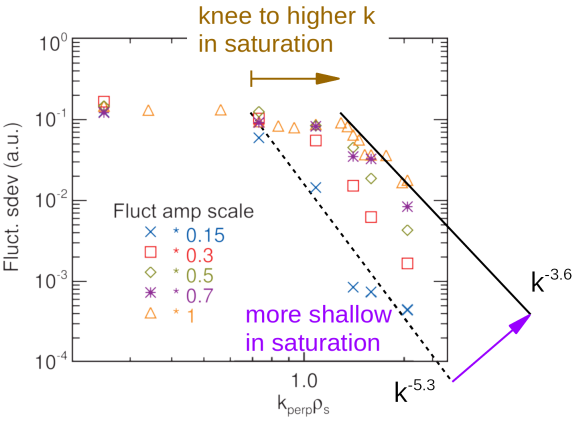


Figure 3: *Final spectra from the full synthetic diagnostic illustrating the non-linear saturation.*

While the spectral indices already seem to show agreement without the fullwave code, the knee position in the experimental data is at significantly larger k. Furthermore, from previous investigations [5], it was expected that the Doppler reflectometry result would have a steeper index (< -5) than the underlying turbulence, due to reduced sensitivity at large k.

In order to determine the influence of non-linear effects, the fullwave simulations were run not only with the full fluctuation level from the GENE data, but also at artificially reduced levels. As Fig. 3 shows, the shape of the spectrum depends strongly on the fluctuation level. Both knee position and spectral index are affected by the fluctuation level.

At the low fluctuation amplitude, the expected steeper spectral index does occur, and the knee moves toward the position seen in the GENE spectrum. As the amplitude is increased towards full strength, the scattered power goes into non-linear saturation, “squishing” the spectrum against the upper limit. This moves the knee to higher k, and also flattens the high k part of the spectrum.

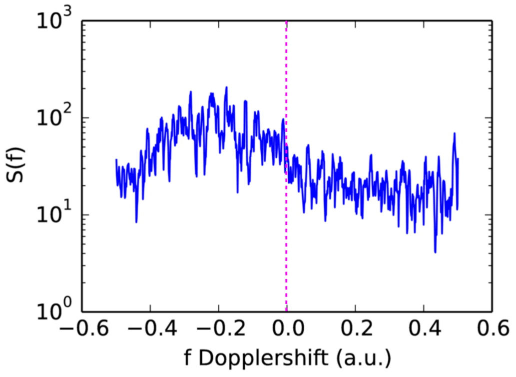


Figure 4: *Recovered Doppler spectrum at a single wavenumber, cf. Fig. 1*

In the final result, the spectral index at the unscaled turbulence level is -3.6, which agrees very well with the -3.8 observed in experiment. This means that in the instrument function, the steepening effect of the sensitivity curve is overwhelmed by the flattening effect of the non-linear saturation. The observed knee position is shifted significantly from its actual position in the ITG drive region. This also suggests that the actual spectral index of the turbulence in experiment is slightly steeper (-4) than in the observed spectrum.

To further refine the synthetic diagnostic, the fluctuation level at each wavenumber must be extracted from a fit to the Doppler peak in the frequency spectrum. In the previous analysis, the level was taken directly from the standard deviation of the received signal. As seen in Fig. 4, the reconstruction is possible, but may need more turbulent time steps for better statistics.

In conclusion, first promising results of a synthetic Doppler reflectometry diagnostic based on gyrokinetic turbulence and full wave code simulations for ASDEX Upgrade have been presented which may help to finally overcome alleged discrepancies in the spectral features between turbulence simulations and experimental measurements. Further refinements are currently investigated.

Acknowledgements

We would like to thank E. Blanco for fruitful discussions of the analysis of the synthetic receiver data. The computations were performed on the HPC-FF computer cluster in Jülich, Germany; on the BOB linux cluster at RZG; on the Hermit supercomputer at HLRS; and on the CUSS cluster at Uni Ulm.

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