Measurement of the turbulent phase velocity in the L-mode edge of ASDEX Upgrade and comparison with GEMR simulations

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1. Introduction

The measurement and understanding of the turbulent dispersion relation $\omega(k_\perp)$ is an important task for identification of the underlying instability. Knowledge of the underlying instability is particularly important in the L-mode edge region ($0.95 < \rho_{pol} < 1$) where the density fluctuation level is high and a transport barrier can be formed under high shear velocities (i.e. transition to H-mode). In several theoretical works e.g. [1] electron drift waves (EDW) are predicted to govern the turbulence in the plasma edge driven by a density gradient. Resistive balloning (RB) and ion temperature gradient (ITG) modes can also be excited in a similar parameter range [2].

Here we report on measurements of the turbulent phase velocity $v_{ph}(k_\perp)$ of an underlying instability in the edge region of the ASDEX Upgrade (AUG) tokamak within the normalized wavenumber range $k_\perp \rho_s = 0$–1.3 ($\rho_s = \sqrt{m_i T_e}/eB$ is the drift wave scale) using poloidal correlation reflectometry (PCR) [3] ($k_\perp = 0$–3 cm^{-1}) and Doppler reflectometry (DR) with a steerable mirror [4] (up to $k_\perp = 15$ cm^{-1}). We compare the obtained phase velocity and dispersion relation with linear estimations and with nonlinear turbulence simulations from the GEMR gyrofluid code [5].

2. Phase velocity measurement

Both PCR and DR measure the density fluctuations in tokamaks propagating perpendicular to the magnetic field with the velocity $v_\perp(k_\perp) = v_{E\times B} + v_{ph}(k_\perp)$, consisting of the background $E\times B$ drift and the intrinsic phase velocity of the turbulent structures. Therefore, to obtain the phase velocity, the $v_{E\times B}$ velocity needs to be substracted.

Figure 1a shows the measured dispersion relation from PCR at the $\rho_{pol} = 0.985$ (E_r well position). This dispersion relation was obtained using $k_\perp(f) = \Delta\phi(f)/\varepsilon_\perp$, where $\Delta\phi(f)$ is the cross-phase spectrum between two poloidally separated measurements of density fluctuations and $\varepsilon_\perp$ the perpendicular separation between reflection points of receiving antennas (for de-

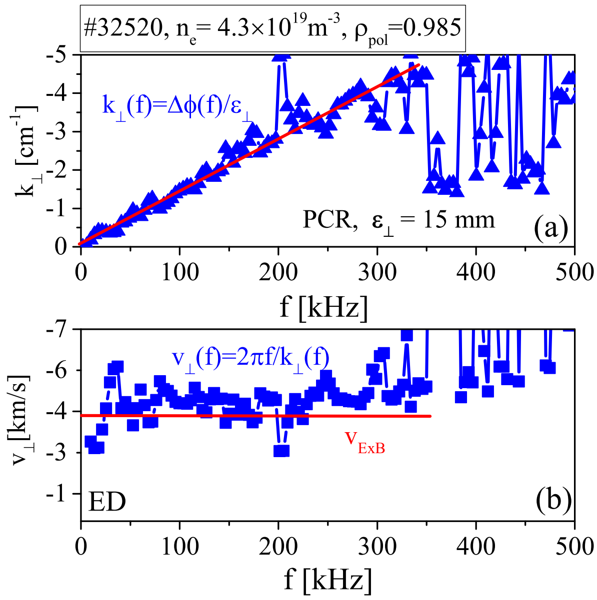

Figure 1: Dispersion relation (a) and perpendicular velocity (b) from PCR.

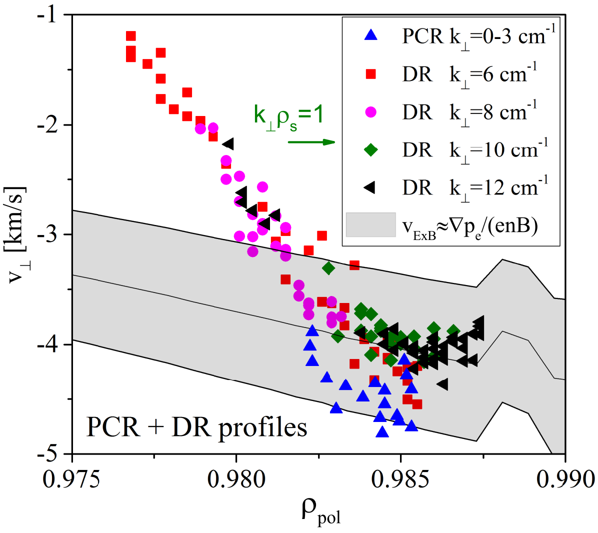

Figure 2: Comparison of radial profiles of measured velocities at different $k_\perp$ using PCR ($k_\perp$=0–3 cm^{-1}) and DR ($k_\perp$=6, 8, 10, 12 cm^{-1}).

tails on the method see [6, 7]). The antenna combination used for this case has a perpendicular separation of $\varepsilon_\perp = 15\,\text{mm}$. The PCR diagnostic at AUG has antenna cluster with different $\varepsilon_\perp$ and all combinations give a similar dispersion relation [7]. The correlation for $f > 350\,\text{kHz}$ drops which causes the fluctuation in the cross phase measurements and limits the maximum $k_\perp$ approximately to 3–4 cm^{-1}. The slope of the dispersion relation (fitted red line) is approximately linear which implies a constant propagation velocity $v_\perp = v_{E\times B} + v_{ph}(k_\perp)$ within the wavenumber range of $k_\perp = 0$–3 cm^{-1}. Figure 1b shows the velocity as a function of frequency $v_\perp(f) = 2\pi f/k_\perp(f)$. Since $v_{E\times B}$ is independent of $k_\perp$ we can conclude that $v_{ph}(k_\perp)$ does not depend on $k_\perp$ within $k_\perp = 0$–3 cm^{-1}.

To extent the measured wavenumber region, the DR diagnostic was used to measure profiles of $v_\perp(k_\perp)$ at $k_\perp$ = 6, 8, 10 and 12 cm^{-1} as shown in figure 2. The measurements obtained by the PCR are also plotted in the same figure. The data cover the region $k_\perp\rho_s = 0$–1.3. The results suggest that the dependence of $v_{ph}(k_\perp)$ is weak ($\Delta v_{ph} \lesssim 0.5$ km/s).

The magnitude of the turbulent phase velocity v_{ph} in the edge can be estimated from the difference of the measured $v_\perp$ and the neoclassical estimate of the $E\times B$ velocity $v_{E\times B}$. Here, the simple approximation $v_{E\times B} \approx \nabla p_i/enB \approx \nabla p_e/enB$ has been used, which is shown to be valid at the E_r well position ($\rho_{pol} \approx 0.985$) [8, 9]. It is assumed that $T_e \approx T_i$, which is in agreement in the plasma edge for line average density around 4.0×10^{19} m^{-3} due to high electron-ion collisional energy exchange as shown in [10]. Note that according to [8] $v_{E\times B}$ can have an additional contribution of toroidal velocity for $\rho_{pol} < 0.98$. The neoclassical $E \times B$ velocity in the edge (gray shadow in figure 2) is close to the DR values at high $k_\perp = 12$ cm^{-1}, however, slightly smaller (≈ 0.5 km/s) compared to the lower PCR values of $k_\perp = 0$–3 cm^{-1}. This suggests that v_{ph} at the position of the E_r well is small ($\lesssim 0.5$ km/s in electron diamagnetic (ED) direction). The difference in shapes of the $\nabla p_e / enB$ and measured $v_\perp$ profiles could be a result of the toroidal rotation contribution to $v_{E\times B}$ which increases towards the plasma core [8].

3. Comparison to linear predictions and GEMR simulations

The measured turbulent phase velocity of $v_{ph} \lesssim 0.5$ km/s in the edge region has been compared with theoretical expectations of electron drift waves modes (see figure 3). According to linear EDW theory [1] $v_{ph}(k_\perp) = v_{de} / \left(1 + k_\perp^2 \rho_s^2\right)$ corresponds to 4 km/s at $k_\perp = 1$ cm^{-1} in the ED direction, which is clearly too large. Moreover, a strong $k_\perp$ dependence is expected, which is not observed experimentally. One approach to investigate the difference is to cross-check with nonlinear turbulence simulations.

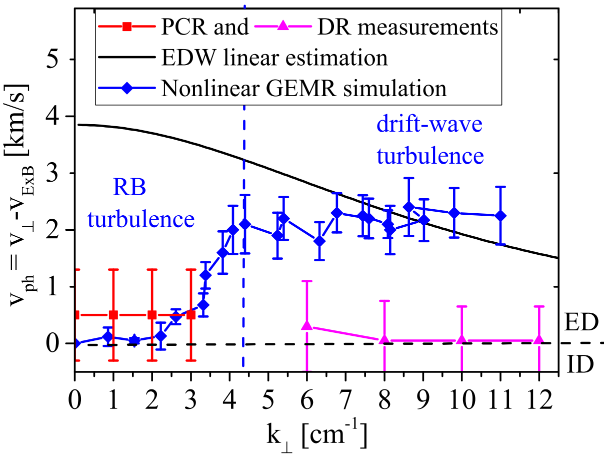

Figure 3: Comparison of v_{ph} from the PCR (red) and DR (magenta) with linear EDW estimation (black) and GEMR simulation (blue).

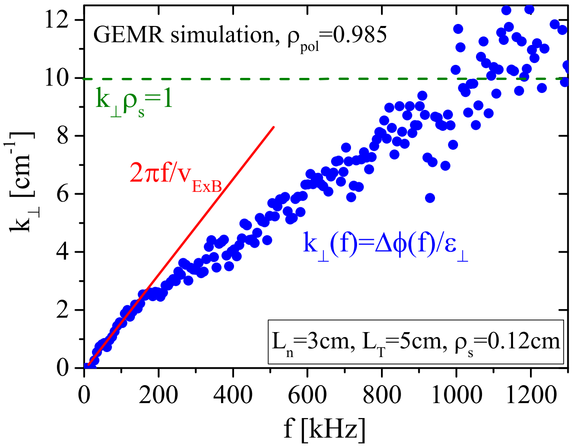

Figure 4: Dispersion relation from nonlinear GEMR simulations.

Turbulent fluctuations in the tokamak edge can be simulated with the GEMR gyrofluid code. GEMR solves the gyrofluid equations in three dimensional space (r, $\perp$, $\|$) simultaneously for electrons and ions [5, 11] and is capable of simulating EDW, ITG and RB turbulence. The code does not include trapped particles and therefore trapped electron mode (TEM) turbulence cannot be simulated, however, TEMs are expected to be damped due to high collisionality in the edge region. The field-aligned approach of GEMR does not allow simulations in X-point geometry, thus all simulations are performed with a circular plasma cross-section, however with similar parameters as in AUG. Gradients of temperature and density were set close to experimentally measured values (see box at the bottom of figure 4).

Similar to the procedure used for the experimental data the dispersion relation has been obtained from the cross-phase $\Delta\phi(f)$ of simulated density fluctuations between two separated points. Figure 4 shows such a dispersion relation at the E_r well position ($\rho_{pol} = 0.985$). The density fluctuations are found to rotate with the $v_{E\times B}$ velocity at low $k_\perp = 0$–$3\,\mathrm{cm}^{-1}$ (red line) however, include an additional phase velocity for $k_\perp > 4\,\mathrm{cm}^{-1}$. Here, $v_{E\times B}$ has been calculated from the derivative of the background electrostatic potential at the same radial position. In figure 3 the GEMR phase velocity is calculated as the difference of the measured $v_\perp$ and the $v_{E\times B}$ velocities. The analyses of fluctuations from the GEMR code suggest that at low wavenumbers resistive balloning turbulence is dominant which may explain the small phase velocity. Comparison at the higher wavenumber region shows a difference of 2 km/s in ED direction between measurements and GEMR simulation coinciding with the EDW dispersion relation. The difference in phase velocities at high $k_\perp$ is still unclear and more studies are needed to understand this difference.

4. Conclusion

Analyses of the perpendicular velocity in the edge region of AUG L-mode plasma have been performed showing that $v_\perp$, and hence $v_{ph}(k_\perp)$, is nearly constant between $k_\perp = 0$ and $12\ \mathrm{cm}^{-1}$ ($k_\perp\rho_s = 0$–1.3). The extracted phase velocity from the difference of $v_\perp$ and $v_{E\times B}$ is significantly smaller than EDW predictions. Comparison with nonlinear simulations from the GEMR code for tokamak L-mode parameters suggest that turbulence at low wavenumbers is dominated by resistive balloning exhibiting a small phase velocity. However, at high wavenumbers ($k_\perp > 4\,\mathrm{cm}^{-1}$) a difference of 2 km/s in ED direction between measurements and GEMR simulations is still observed.

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