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Perpendicular Plasma Velocity and Radial Electric Field Profiles measured by Doppler Reflectometry in the Stellarator TJ-II

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Abstract

Doppler Reflectometry (X-mode, $f = 33-50$ GHz) is used to investigate the perpendicular velocity of plasma density fluctuations $u_\perp$ and their wavenumber spectra $S(k_\perp)$ in the stellarator TJ-II. Plasma velocity profiles are presented for different plasma regimes. It is shown experimentally that the intrinsic phase velocity of the plasma turbulence is small compared to the $E \times B$–velocity allowing for the measurement of radial electric field profiles. Measurements of small scale turbulence (intermediate to high $k_\perp$) show fingerprints of TEM and ETG type instabilities.

Introduction

Doppler reflectometry is based on the backscattering of a microwave beam launched obliquely into the plasma. The power spectrum of the received signal shows a Doppler shifted peak at $\omega_D = \mathbf{u} \cdot \mathbf{k} \approx u_\perp k_\perp$, where $\mathbf{k} \perp \mathbf{B}$ and a symmetric k_r-spectrum have been assumed [1, 2]. The value of the Doppler shift ω_D and its amplitude give information on the perpendicular plasma velocity and the density turbulence level. The perpendicular velocity measured by Doppler reflectometry is a composition of the plasma background $E \times B$–velocity and the intrinsic phase velocity of the density fluctuations: $u_\perp = v_{E\times B} + v_{\text{ph}}$. If $v_{\text{ph}} \ll v_{E\times B}$, the radial electric field E_r can be deduced from the measurement of the perpendicular velocity through $E_r = u_\perp B$, where B is the absolute value of the magnetic field.

Experimental Setup

The recently installed Doppler Reflectometer System [3] in TJ-II works in the Q-band ($f = 33-50$ GHz) and is adapted to the three-dimensional geometry of the experiment. Typical radial measurement ranges are $\rho = 0.6-0.9$, where $\rho \approx r/a$ is the effective radius of the plasma. A sketch of the system is shown in fig. 1. Due to the high curvature of the plasma, special attention had to be paid to the design and fabrication of the antenna and

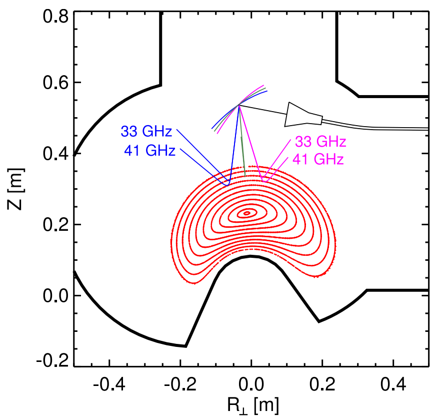

Figure 1: Sketch of the Doppler reflectometer system installed in TJ-II.

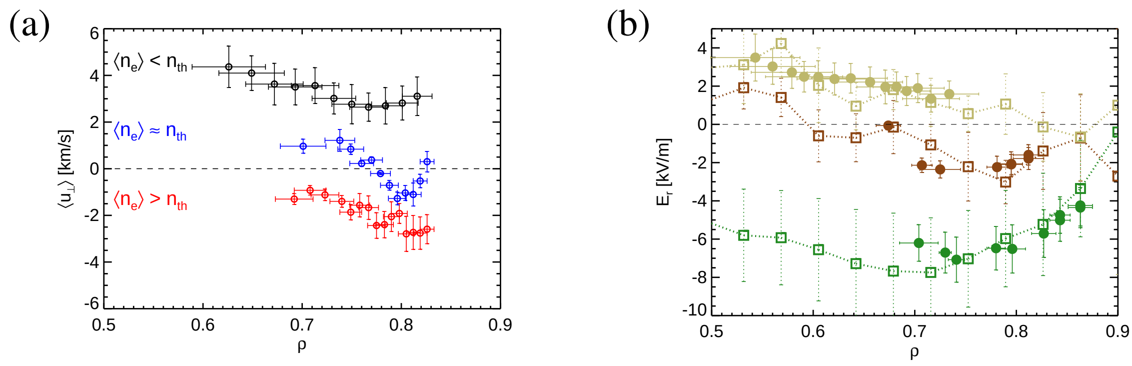

Figure 2: (a) (#20281, #20285, #20294) Radial profiles of the perpendicular velocity of plasma density fluctuations. Close to the threshold density $n_{\rm th}$, a well in the velocity profile develops. (b) (#21872, #21909) Radial electric field measured by the DRS assuming $v_{\rm ph} \ll v_{E\times B}$ (solid circles) and the HIBP system (open squares) for different plasma scenarios. The agreement between the two diagnostics is good.

the focusing mirror. The mirror is steerable, giving the possibility to change the launch angle θ_l of the beam by $\pm 20^\circ$ with respect to perpendicular incidence. This launch angle variation enables the measurement of perpendicular wavenumbers in the range of 3 – 15 cm^{-1}. The value of $k_\perp$ is calculated after each discharge using the 3D ray/beam-tracing code TRUBA [4] with input density profiles measured by AM reflectometry or Thomson scattering.

Radial Profiles of the Perpendicular Velocity / Radial Electric Field

Fig. 2 (a) shows typical perpendicular velocity profiles for ECRH discharges at different line-averaged densities $\langle n_e \rangle$. Velocities range from about -3 to +5 km/s. A well in the perpendicular velocity profile is formed close to a threshold density, confirming results obtained with the conventional reflectometer [5]. Fig. 2 (b) shows measurements of the radial electric field obtained by Doppler reflectometry assuming $v_{\rm ph} \ll v_{E\times B}$ (solid circles) and the Heavy Ion Beam Probe (HIBP, cf Ref. [6]) diagnostic (open squares). Three different plasma scenarios are covered: ECRH heated plasmas with low (yellow) and medium (brown) densities and an NBI discharge with high density (green). The agreement between the two diagnostics is good in all regimes and justifies *a posteriori* that $v_{\rm ph} \ll v_{E\times B}$ is valid for the radial range $\rho = 0.5$ to 0.9 in TJ-II.

In NBI discharges, perpendicular velocities are negative with higher values up to -8 km/s in L-mode, while in H-mode velocities of up to -18 km/s have been measured. A strong shear in the radial electric field can be observed in H-mode. For more information on NBI L- and H-Mode discharges, the reader is referred to Ref. [7].

Turbulence at intermediate/small scales (TEM/ETG fingerprints)

Going from large to small turbulence scales, different types of instabilities can be destabilized. They include the Ion Temperature Gradient modes at large scales (ITG, $k_\perp \rho_s \lesssim 0.5$), Trapped Electron Modes at intermediate scales (TEM, $k_\perp \rho_s \lesssim 2$) and Electron Temperature Gradient modes at small scales (ETG, $k_\perp \rho_s > 2$) [8]. Here $\rho_s = \sqrt{m_i T_e}/eB$ is the ion Larmor radius at electron temperature. TEMs are expected to be dominant in the hot electron regime ($T_e > T_i$) and when electron temperature gradients are strong in comparison with ion temperature gradients, i.e. $L_{T_i} > L_{T_e}$, with $L_{T_{i,e}}$ the ion and electron temperature gradient scale lengths, respectively. ETGs, however, are destabilized when $T_e \lesssim T_i$ and $\eta_e = L_n/L_{T_e} \gg 1$.

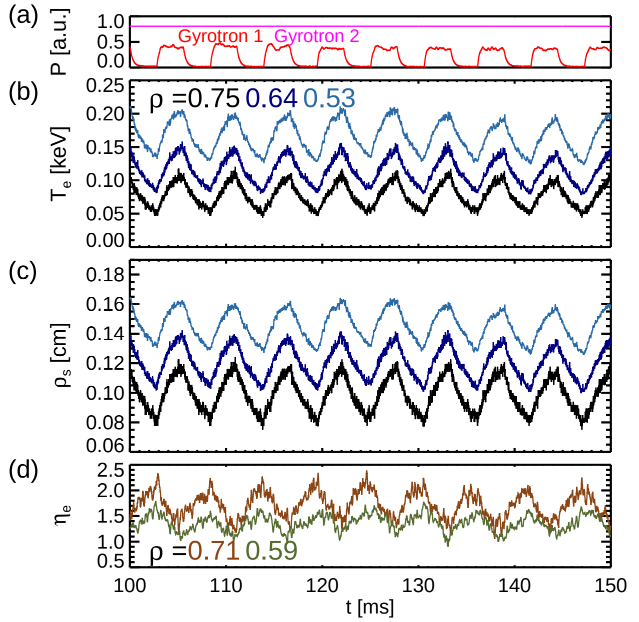

Figure 3: (#22351) Gyrotron power and electron temperature time traces. The ion Larmor radius at electron temperature (c) is modulated and out of phase with the modulation in η_e (d).

Experiments were conducted with one gyrotron heating on-axis with 210 kW while the other one working at 100 kW was heating off-axis ($\rho = 0.64$), depositing the ECRH power close to the measurement region of the Doppler reflectometer ($\rho = 0.6 - 0.8$ in these experiments). In addition the off-axis gyrotron was modulated at 180 Hz, so one on-off cycle took about 5.6 ms. This modulation alters T_e and ∇T_e (i.e. L_{T_e}), while density profile and ion temperature ($T_i \approx 70$ eV) changes are negligible. Fig. 3 shows the temporal evolution of the gyrotron power (a) and electron temperature (b) at three ECE channels ($\rho = 0.53 - 0.75$) during 50 ms of the discharge. When the Gyrotron is switched on, the temperature rises, and it falls again when the Gyrotron is switched off. The evolution of ρ_s is shown in (c) and due to its defintion is in phase with the T_e trace. However, the evolution of η_e (Fig. 3 (d)) is out of phase with T_e. This effect is due to the fact that during the on-cycle of the gyrotron, T_e rises significantly, but its gradient only changes slightly. The density scale length L_n shows no alteration caused by the ECRH power modulation.

Fig. 4 (a) shows two $k_\perp$-spectra measured with the Doppler reflectometer in comparable discharges when the modulated gyrotron was off (black line) and when it was switched on (red line). Fluctuations decrease in the whole wavenumber range when the gyrotron is switched on, while relative changes are stronger at high wavenumbers. Comparing with Fig. 3 (d), high η_e – attained when the gyrotron is off – correspond to strong fluctuations, pointing to ETG type instabilities. This interpretation is also supported by the higher relative changes at higher wavenumbers. However, from Fig. 3 (c) it can be seen that the values of ρ_s change between

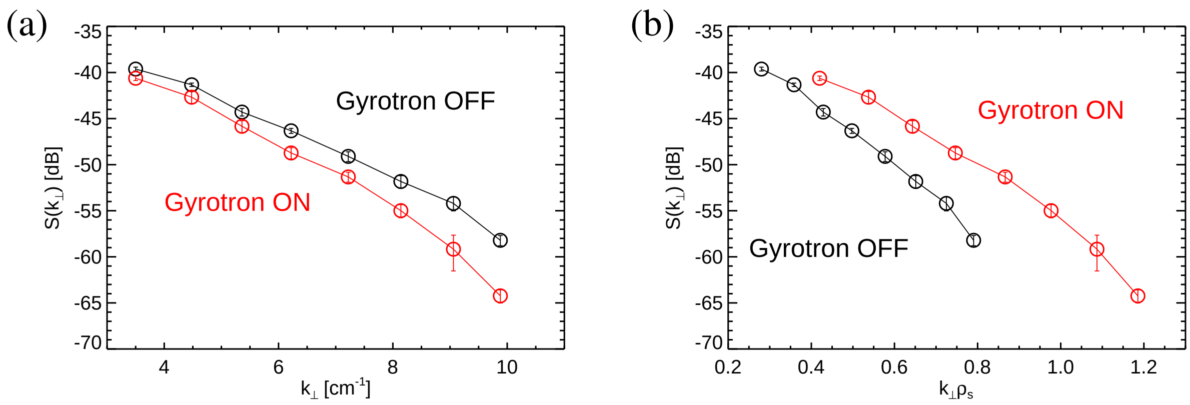

Figure 4: (a) Perpendicular wavenumber spectra versus wavenumber during off- (black) and on-cycles (red) of the gyrotron. (b) The same but plotted versus normalized wavenumber $k_\perp \rho_s$.

0.08 and 0.12 cm at $\rho = 0.75$ during one on/off-cycle of the gyrotron. Applying these values to the respective spectra of Fig. 4 (a) yields the perpendicular wavenumber spectrum dependence on $k_\perp \rho_s$ (b). In this case, fluctuations at fixed normalized wavenumber $k_\perp \rho_s$ increase when the gyrotron is switched on. This is in conflict with the η_e evolution of Fig. 3 (d) and points to TEM as the responsible microinstability, since during the on-cycle $T_e > T_i$ is fulfilled and structure sizes correspond to theoretical TEM scales ($k_\perp \rho_s \lesssim 2$). The trend that wavenumber spectrum changes are more pronounced at higher wavenumbers persists, so from Fig. 4 it becomes clear that ECRH modulation has more effect on small-scale turbulence. To be able to clarify exactly which is the dominant instability, gyrokinetic simulations are necessary, which are planned for the near future.

Summary

In conclusion it has been shown that the recently installed Doppler reflectometer in TJ-II is a diagnostic suited to investigate the perpendicular velocity of density fluctuations and radial electric fields. Going further, the diagnostic was employed to investigate small-scale turbulence and fingerprints of TEMs as well as ETGs were detected, although no clear conclusions on the nature of the microinstabilities can be drawn. More experiments and simulations are planned for the future to obtain a clearer picture.

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