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Observations on core turbulence and radial electric field transitions in ASDEX Upgrade using Doppler reflectometry

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1. Introduction

In contrast to normal fluctuation reflectometry, which is sensitive to a broad turbulence wavenumber spectra centred on $k_\perp = 0$, the poloidally tilted antenna in Doppler reflectometry selects (via Bragg) a specific non-zero $k_\perp = 2k_o \sin\theta$. If the turbulence is moving then a Doppler frequency shift appears in the reflected signal, $f_D = u_\perp k_\perp / 2\pi$, which is directly proportional to the perpendicular (to B) velocity of the turbulence moving in the plasma, $u_\perp = v_{E\times B} + v_{\rm ph}$. For typical probed $k_\perp > 8$ cm^{-1} the phase velocity, $v_{\rm ph}$, of electron drift-wave turbulence is small compared to the $E \times B$ velocity, $v_{\rm ph} \ll v_{E\times B}$, which allows a straightforward extraction of the edge radial electric field E_r from $u_\perp$. However, for ion temperature gradient (ITG) or trapped electron mode (TEM) turbulence $v_{\rm ph}$ may not be negligible. While this may complicate the extraction of core E_r it opens the possibility of studying turbulence phenomena via $v_{\rm ph}$.

2. Rotation profile

Fig. 1 shows a typical $u_\perp$ radial profile for a 4.5MW co-NBI H-mode shot [1]. In the SOL $u_\perp$ always flows in the ion diamagnetic drift direction (i.e. $E_r > 0$) but reverses across the separatrix ($E_r < 0$) due to the pedestal pressure gradient. However, in the core the direction and magnitude of $u_\perp$ depends on the plasma scenario. For example, with neutral beam injection the momentum driven toroidal rotation dominates - as indicated by the match with toroidal impurity velocities from CXRS mapped into the poloidal plane $v_\phi B_\theta / B$ - typically tens of km s^{-1}. In the absence of dominant toroidal rotation, e.g. balanced NBI, ICRF, ECH or ohmic plasmas, the core $u_\perp$ is only a few km s^{-1}, which is comparable to expected turbulence phase velocities and poloidal fluid velocities.

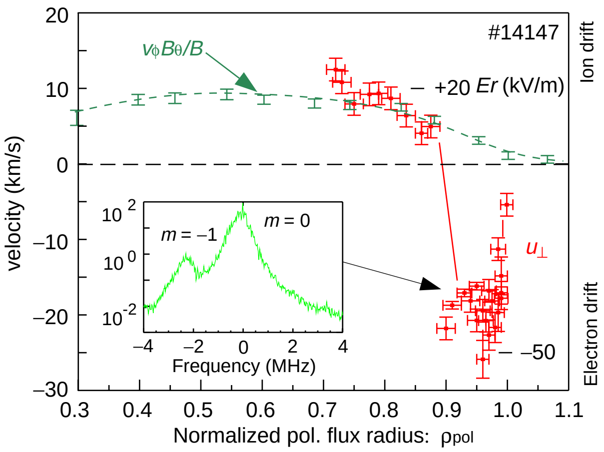

Figure 1: $u_\perp$ vs normalised radius ρ_{pol} for NBI H-mode shot #14147 c.f. [1].

3. Collisionality dependence

Fig. 2 shows $u_\perp$ radial profiles for a series of ohmic shots with varying density and plasma current. The edge shows the usual positive and negative peak structure associated with the separatrix and pedestal ∇P shear regions - which remains remarkably robust for all shots. However, the core rotation (inside the n_e pedestal) can be in either the ion or electron diamagnetic drift direction depending on core density and temperature.

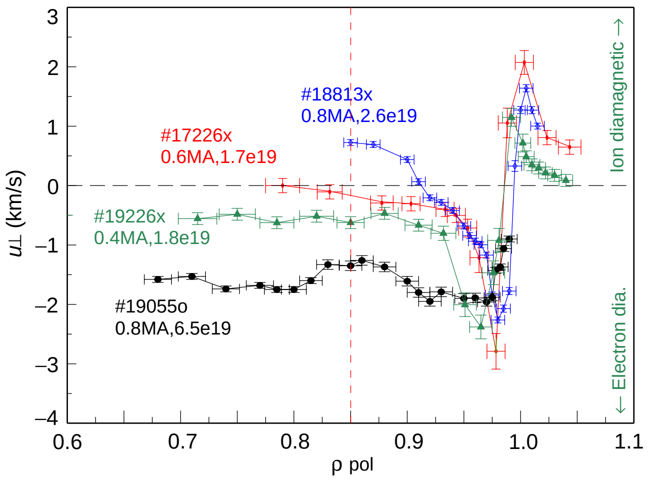

Figure 2: $u_\perp$ vs normalised radius ρ_{pol} for various ohmic discharges.

In fact the relevant parameter is the local collisionality - as shown in Fig. 3, which is a slice through the rotation profiles at $\rho_{\mathrm{pol}} = 0.85$ with $u_\perp$ plotted vs the local effective collisionality, defined as $\nu_{\mathrm{eff}} = \nu_{ei}/\omega_{De} \approx 0.1\ R\ Z_{\mathrm{eff}}\ n_e/T_e^2$, with $k_\perp\rho_s = 0.3$, $R = 1.65$ m and $Z_{\mathrm{eff}} = 2$. At low collisionality $u_\perp$ is in the ion drift direction but reverses smoothly to the electron drift direction with increasing ν_{eff}.

These measurements show similarities to edge E_r reversals observed using CXRS on the LHD stellarator during density ramps [2]. The LHD transitions are thought to be explained by neoclassical theory for helical plasmas. For tokamaks, neoclassical formulas also indicate possible reversals in the poloidal rotation velocity (hence E_r) with collisionality [3].

Initial calculations for the discharges in fig. 2 indeed show the poloidal fluid velocity for deuterium reversing from a few km/s in the ion direction to a few km/s in the electron direction as collisionality increases across the range shown in fig. 3. Fuller, more detailed neoclassical simulations are currently in progress.

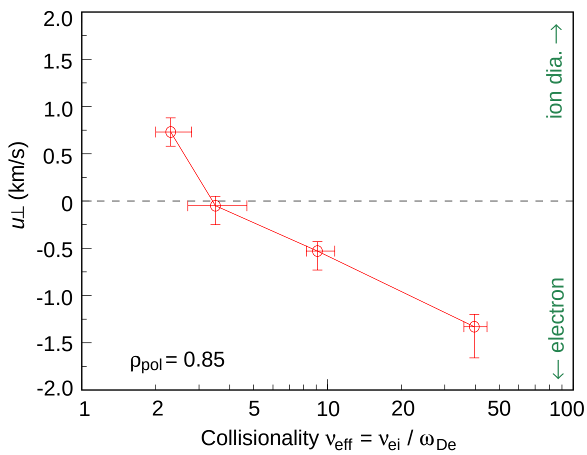

Figure 3: $u_\perp$ vs effective collisionality ν_{eff} at $\rho_{\mathrm{pol}} = 0.85$ for ohmic conditions.

4. TEM to ITG transition

However, gyro-kinetic calculations predict that TEM turbulence should become linearly stable at high densities/collisionalities while ITG turbulence remains unstable [4]. There are experimental observations, e.g. on density peaking and heat flux, which appear to confirm this transition hypothesis [4,5]. A transition in the dominant turbulence with increasing ν_{eff} would lead to a reversal in the measured v_{ph} direction from the electron to the ion drift direction. This is shown in fig. 4 where the dominant turbulence phase velocity $v_{\mathrm{ph}} = \omega_r/k_\theta$ (i.e. at the maximum growth rate) is plotted vs effective collisionality from GS2 calculations at $\rho_{pol} = 0.6 - 0.7$ using experimental input data. The clear transition from TEM to ITG dominance occurs at a similar ν_{eff} value as the $u_\perp$ transition in fig. 3 - but in the opposite direction! The resolution of this apparent contradiction depends of course on the relative magnitudes of $v_{E\times B}$ and v_{ph}. The relative sensitivity of the phase and $E \times B$ velocities to collisionality can be tested using density or temperature perturbations.

5. ECRH perturbation experiments

As $\nu_{\rm eff} \propto n_e/T_e^2$ there are two possible experimental approaches to induce a transition: density ramping or temperature perturbation using central electron cyclotron resonance heating (ECRH). A density ramp produces a monotonic change in $\nu_{\rm eff}$ and a corresponding variation in f_D as shown in fig. 3. A temperature perturbation is more subtle and its effect depends on the density and its proximity to the transition threshold. For example, fig. 5 shows a frequency vs time spectrogram of complex amplitude, $A\exp(i\phi)$, fluctuations from a 52 GHz O-mode Doppler reflectometer during the L-mode shot #18725 at $I_p = 0.8$ MA and a (medium) line averaged density of $\sim 4\times10^{19}$ m^{-3} (close to critical transition where TEM and ITG may co-exist) as shown by the time traces beneath.

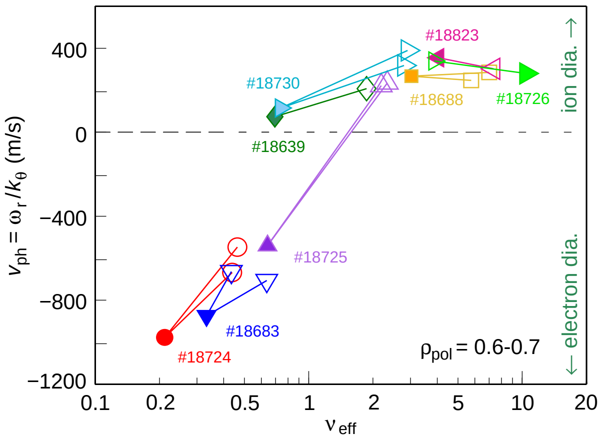

Figure 4: Computed $v_{\rm ph}$ vs effective collisionality $\nu_{\rm eff}$ at $\rho_{pol} = 0.6-0.7$ from GS2. Open symbols = ohmic, solid = ECRH.

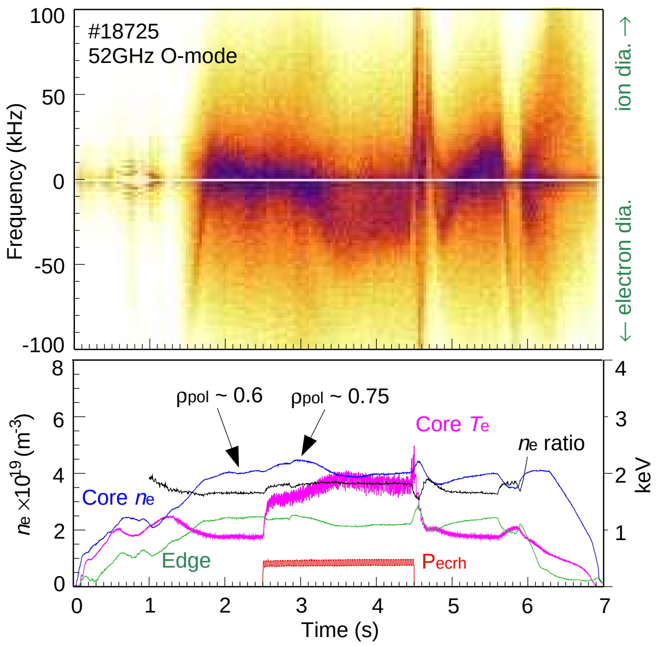

Figure 5: Spectrogram of Doppler reflectometer.

During the initial ohmic phase the core $u_\perp$ is in the ion direction but reverses to the electron direction with the application of 0.8 MW of on-axis ECRH. The ECRH raises the core T_e and gradient which lowers $\nu_{\rm eff}$. The movement in the electron direction is therefore inconsistent with the $u_\perp$ dependence in fig. 3, but is consistent with the $v_{\rm ph}$ dependence in fig. 4. (Note the gradual f_D change at the start of the ECRH phase is the result of the density rise and fall which moves the cutoff layer out from $\rho_{pol} \approx$ 0.6 to 0.75 and back. Other shots display a more abrupt change. The rapid change in f_D at the end of the ECRH phase is due to an NBI beam-blip.) On the other hand, fig. 6 shows Doppler refl. spectra at $\rho_{pol} = 0.6-0.7$ for three different line average densities with same plasma current $I_p = 0.8$ MA. The blue spectra are during the ohmic phase of the discharges while the red spectra are during the ECRH phase. With increasing density the Doppler shift moves from the ion to the electron direction in the ohmic phase consistent with increasing collisionality as shown in fig. 3. At low density (well below threshold - TEM only) the f_D shift with ECRH moves in the ion direction. This suggests that the $\Delta v_{E\times B}$ change associated with neoclassical effects dominate over the $\Delta v_{\rm ph}$ associated with the turbulence. In fig. 4 there is only a small $\Delta v_{\rm ph}$ at low $\nu_{\rm eff}$ - shown by the lines from open to closed symbols. At medium density (close to threshold - TEM & ITG present) f_D moves in the electron direction, which is consistent with $\Delta v_{\rm ph} \gg \Delta v_{E\times B}$ as indicated in fig. 4 at medium $\nu_{\rm eff}$. At high density (well above threshold - ITG only) f_D moves very slightly back in the ion direction. Again consistent with the roughly constant $v_{\rm ph}$ at high $\nu_{\rm eff}$ indicating $\Delta v_{\rm ph} \ll \Delta v_{E\times B}$. Note at high density the turbulence frequency spectra is also excessively broadened (beyond that due to rotational broadening alone) which suggests a change in the underlying turbulence k-spectrum and hence a change in turbulence. Finally, it should be mentioned that the effect of ECRH varies with the deposition point, e.g. on/off-axis, with additional effects observed inside the deposition radius.

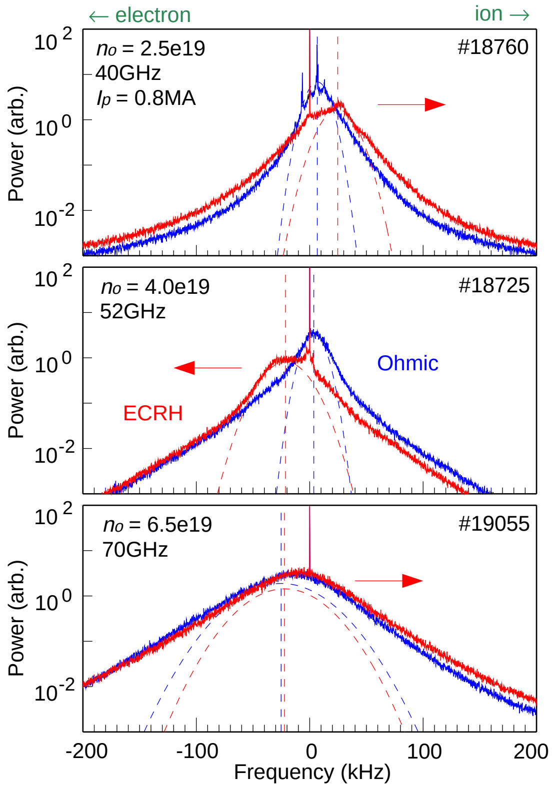

Figure 6: Doppler spectra for ohmic (blue) and ECRH (red) phases at low, medium and high line average densities, $\rho_{\rm pol} = 0.6 - 0.7$.

6. Discussion

It was noted that the $u_\perp$ profiles in the edge (fig. 2) are particularly robust, this is most likely because the edge plasmas of AUG are always highly collisional - certainly well above any critical collisionality - and the turbulence is predominantly drift-wave type. Hence, turbulence transition effects will only be observed in the core, where of course the impurity ($Z_{\rm eff}$) profile will also be important. The strongest changes in the $u_\perp$ were observed for conditions where TEM and ITG are predicted to co-exist. Co-existence suggests that two Doppler peaks might be observable in the reflectometer spectra. This is reminiscent of the FIR laser scattering measurements on TEXT which showed ion and electron peaks during the transition from linear to saturated ohmic confinement conditions [6]. However, Doppler reflectometry has the additional advantage of radial localisation with high $k_\perp$ (which is desirable as $v_{\rm ph}$ scales with $k_\perp$). Initial attempts with optimal conditions for TEM/ITG co-existence and ECRH modulation to switch on/off the TEM have not yet revealed convincing double Doppler peaks, or a modulation of $u_\perp$ about a mean $v_{E\times B}$ - possibly due to too small $\pm v_{\rm ph}$, or insufficient diagnostic spectral resolution, or peaks of incomparable amplitude.

7. References

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