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DIRECT MEASUREMENT OF ZONAL FLOWS AND GEODESIC ACOUSTIC MODE (GAM) OSCILLATIONS IN ASDEX UPGRADE USING DOPPLER REFLECTOMETRY

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1. Introduction

Zonal flows (ZF) and associated geodesic (GAM) oscillations are turbulence-generated time varying $E_r \times B_T$ rigid poloidal plasma flows with finite radial extent. They are of major interest for tokamak confinement since they are predicted to moderate drift-wave turbulence [1], and hence edge transport. However, detection of ZFs and GAMs is challenging since they appear predominantly as low frequency (few kHz) potential or radial electric field E_r fluctuations. ZFs (believed to be driven by Reynolds Stress) have been inferred from bicoherence analysis of Langmuir probe data [2] while BES measurements have recently revealed the GAM (driven by poloidal pressure asymmetries) directly [3]. Presented here are new measurements of GAM/ZF properties in Ohmic, L-mode and H-mode ASDEX Upgrade tokamak discharges using a new Doppler reflectometry technique to measure E_r fluctuations directly.

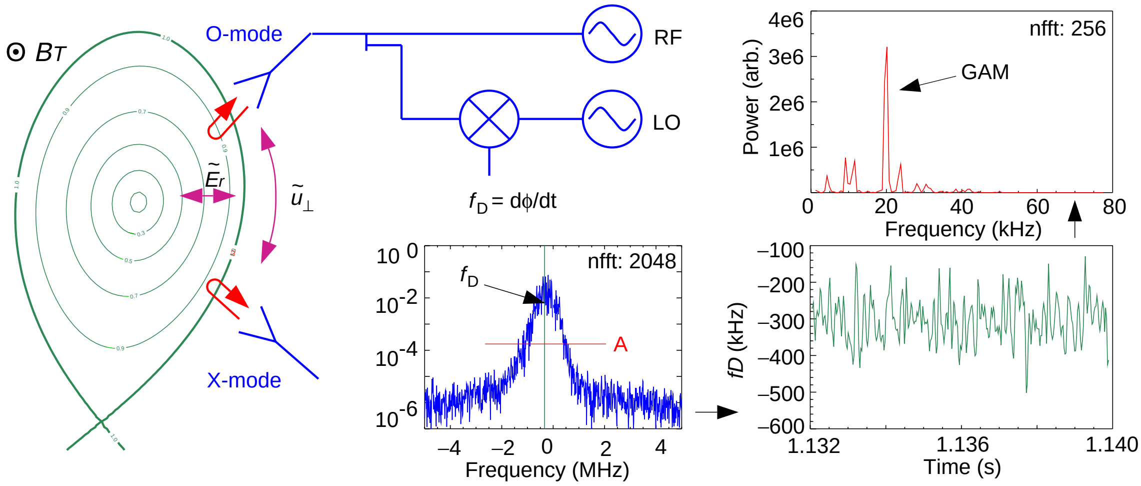

Figure 1: Schematic of measurement technique. Data from Ohmic shot #16179 in X-mode at 56 GHz, $\rho_{pol} \approx 0.98$ *with* $T_e \sim 240$ *eV.*

2. Technique

By poloidally tilting the antenna of a microwave reflectometer a Doppler frequency shift $f_D = u_\perp 2 \sin\theta / \lambda_o$ is induced in the reflected signal, which is proportional to the tilt angle θ and the perpendicular rotation velocity $u_\perp = v_{E\times B} + v_{ph}$ of the turbulence moving in the plasma [4]. For edge drift-wave turbulence the $E \times B$ velocity dominates, hence E_r fluctuations translate directly to f_D. That is, the diagnostic can give a direct measure of $\tilde{E}_r$ with high spatial and temporal resolution (n.b. small $\tilde{\theta}$). Figure 1 illustrates the measurement procedure. Applying a sliding FFT to 20 MHz sampled in-phase and quadrature signals from a dual channel V-band reflectometer [4] produces time sequences of complex amplitude spectra. A weighted spectral mean gives the

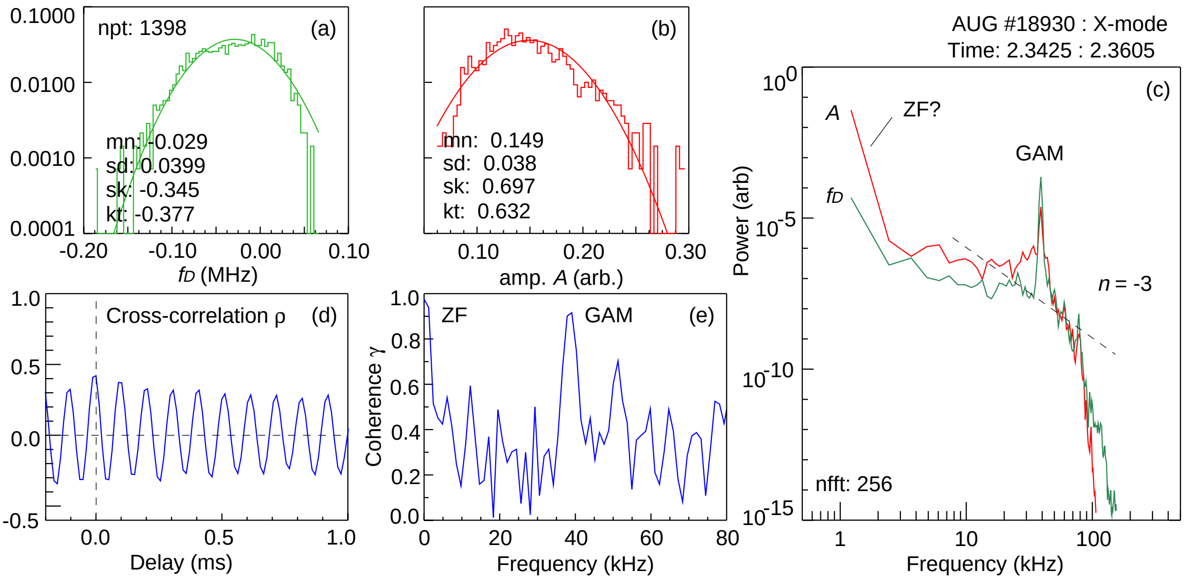

Figure 2: (a) $\tilde{f}_D$ pdf and (b) $\tilde{A}$ pdf plus (c) frequency spectra, (d) cross-correlation and (e) coherence spectrum for AUG QH-mode #18930 at the GAM radial peak position.

Doppler frequency $f_D = \sum f.S(f)/\sum S(f)$ (for small shifts) while the integrated spectra $A = \sum S(f)$ is a measure of the density fluctuation amplitude. The FFT of $f_D(t)$ gives the $\tilde{E}_r$ spectrum. Different cutoff layers are probed by stepping the microwave launch frequency. Although the reflectometer has a radial resolution of a few mm, the finite reflectometer beam diameter (~cms) limits the poloidal resolution to long wavelength E_r fluctuations. This is nevertheless ideal for studying $k_\theta = k_\parallel = 0$, $k_r \neq 0$ Zonal flows.

3. Results

In the absence of a GAM both $\tilde{f}_D$ and $\tilde{A}$ tend to Gaussian distributions. Their spectra are generally flat below $\sim$ 10 kHz then roll-off with a spectral index $n \approx -2.8$ - which reflects the underlying broad-band incoherent $\tilde{E}_r$ background. Above 80 kHz or so the spectra are restricted by the long wavelength sensitivity dictated by the reflectometer spot size. A GAM oscillation when present appears as an exceptionally narrow dominant coherent peak around $5-40$ kHz - even in the absence of MHD activity (i.e. $\tilde{\theta} \sim 0$) - with an amplitude of 1 (Ohmic) to 4 orders of magnitude (QH-mode) above the background, c.f. figure 2(c). Strong GAMs also generate a significant corresponding modulation in the electron density (expected from theory [5]) as shown by the cross-correlation between $\tilde{f}_D$ and $\tilde{A}$ in figure 2(d). The coherence spectrum peaks at almost unity. At very low frequency the spectra and coherence peak again, suggestive of the zero frequency Zonal flow.

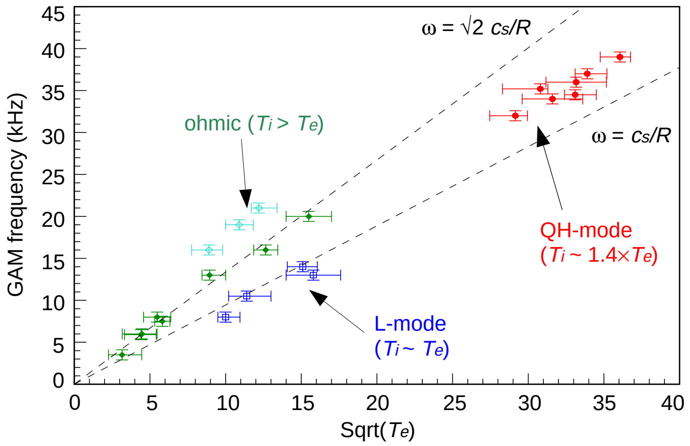

Figure 3: GAM frequency vs $\sqrt{T_e}$ for Ohmic, NBI L-mode and ELM-free Quiescent H-modes.

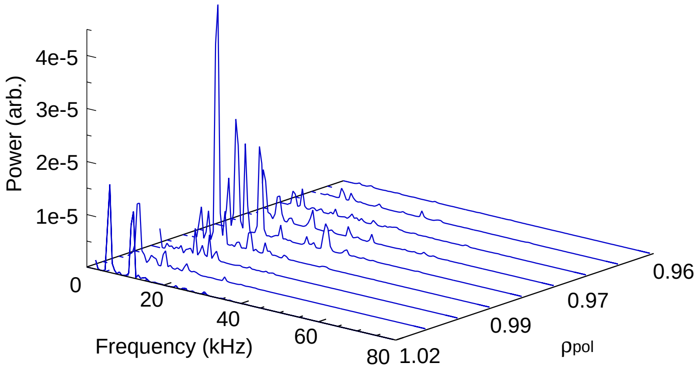

Figure 4: f_D spectral power vs frequency and radial position for Ohmic shot #18271.

Figure 3 shows the spectral peak frequency vs the square-root of the local T_e for a range of Ohmic, NBI L-mode and ELM-free Quiescent H-mode discharges. The peak frequency scales linearly with $\sqrt{T_e}$, and no obvious dependence on B_T or n_e - thus confirming the oscillation is a GAM. The dashed lines are predicted GAM frequency scalings $\omega \propto c_s/R$ where $c_s = \sqrt{kT_e/M}$ is the (cold) ion acoustic speed and R the major radius. Ion temperature measurements from Li-beam CXRS are available for some shots and indicate that, when included, part of the variation in the scaling constant can be accounted for. However, theory and modelling results suggest that the safety factor q and plasma shape (elongation and curvature) are also important parameters [5-7]. As the data-base of shots expands these issues can be addressed.

Figure 4 shows f_D spectra as a function of radius (normalised poloidal flux ρ_{pol}) for a typical Ohmic divertor shot. In this example the GAM peak is highly localised inside the separatrix (GAMs are not seen in the open field-line SOL). This is the same region of high radial shear in the $E \times B$ velocity, as shown in figure 5 for another Ohmic shot. The $u_\perp$ velocity flows in the ion diamagnetic direction in the SOL but reverses inside the separatrix to form an E_r well across the density pedestal. The well depth increases in H-modes as the edge transport barrier strengthens - see [4] for further details. Coinciding with the E_r well is an increase in the overall $\tilde{f}_D$ RMS fluctuation level (irrespective of whether a GAM peak is observed or not) together with an enhancement in the cross-correlation between $\tilde{f}_D$ and low amplitude density fluctuations $\tilde{A}$. Towards the top of the density pedestal the $\tilde{f}_D$ RMS fluctuation level rises again (in QH-mode shots the strongest GAM peaks are observed here), coinciding with gradients in $u_\perp$. Note also the sinusoidal pattern in the cross-correlation, which is highly suggestive of a radial structure in the GAM or E_r fluctuations.

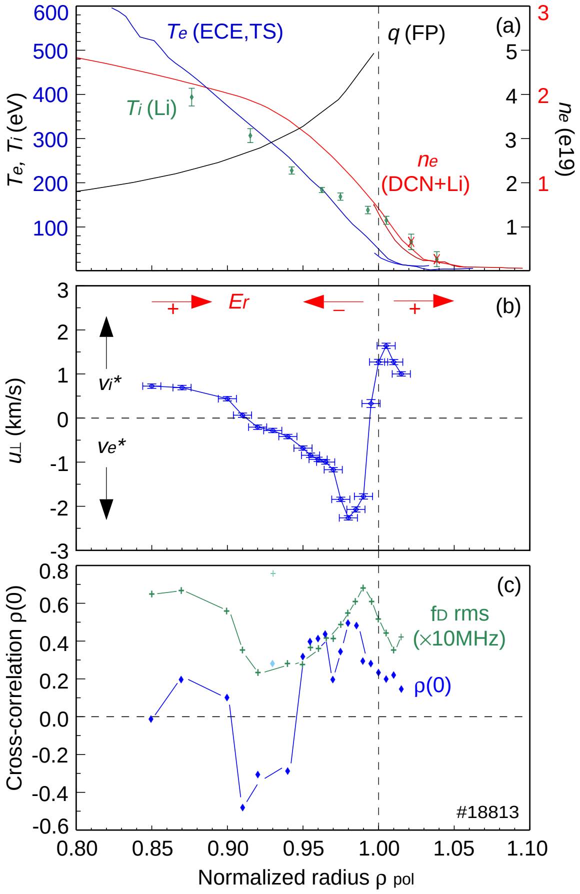

Figure 5: Radial profiles of (a) T_e, T_i, q and n_e, (b) $u_\perp$, (c) f_D rms and $f_D - A$ correlation for Ohmic #18813.

The GAM oscillation is not always detected. In the $\tilde{f}_D$ spectrogram of figure 6 (fixed launch frequency) the 10.5 kHz peak appears intermittent. Possible explanations might include: a density variation sweeping the reflectometer cutoff across the radially localised GAM (however, the displacement to GAM width would need to be substantial, which is not observed) or the GAM position may be jumping radially. Or, more plausibly, the GAM intensity envelope is time-modulated by the low frequency ZF, as is predicted by modelling results [8].

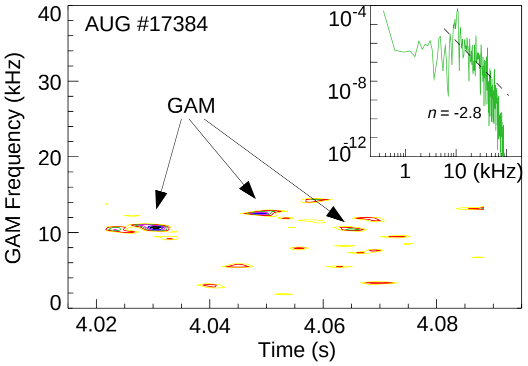

Figure 6: Time evolution of f_D spectrum for L-mode #17384.

4. Discussion and conclusions

The measurements presented here have concentrated on the plasma edge region where GAMs are most evident. The current diagnostic can, in some conditions, reach into the plasma mid-radius allowing a check for the existence of core ZFs and GAMs. The low frequency $\tilde{f}_D$ spectral peak (often independent of the GAM) appears to be the “zero frequency” Zonal flow. However, confirmation, such as by observing spectral broadening, will require longer time sequence data than presently available. The radial wave-like structure in the $\tilde{f}_D - \tilde{A}$ cross-correlation (i.e. correlating $\tilde{E}_r$ with $\tilde{n}_e$) is consistent with the expected finite k_r of the GAM. Confirmatory measurements are in progress using the second Doppler reflectometer channel to obtain the $\tilde{f}_D$ radial correlation length directly. Likewise the poloidally displaced O-mode and X-mode antennas can be used to check the $m = 0$ or $m = \pm 1$ mode structure. The low density ELM-free Quiescent H-mode measurements are the first observations of GAMs under H-mode conditions. Measurements of edge ZFs in standard ELMing H-modes have been precluded so far by restricted data lengths due to the high ELM frequency. The presence of an edge localised MHD oscillation in the QH-mode is not so problematic, it appears at an unrelated lower frequency than the GAM. Further, Ohmic and L-mode data show that the GAM is present even in the absence of MHD, c.f. [3]. The QH-mode GAMs also scale linearly with the square-root of the temperature, consistent with the Ohmic and L-mode data, however, their most notable feature is their larger relative amplitude. This may be expected considering the stronger E_r gradients and plasma vorticity present in H-modes and further, may indicate their greater role in moderating the edge turbulence.

5. References

[1] P.H.Diamond *et al*, 17th IAEA Fusion Energy Conf. (Yokahama), p1421 (1998)

[2] G.S.Xu *et al*, Phys. Rev. Lett. **91**, 125001-1 (2003). M.G.Shats *et al*, Phys. Rev. Lett. **91**, 125002-1 (2003)

[3] M.Jakubowski *et al*, Phys. Rev. Lett. **89**, 265003-1 (2002). G.R.McKee *et al*, Plasma Phys. Control. Fusion **45**, A477 (2003)

[4] G.D.Conway *et al*, Plasma Phys. Control. Fusion **46**, 951 (2004)

[5] N.Winsor *et al*, Phys. Fluids **11**, 2448 (1968)

[6] K.Hallatschek and D.Biskamp, Phys. Rev. Lett. **86**, 1223 (2001)

[7] B.Scott, Phys. Lett. A **320**, 53 (2003)

[8] M.Ramisch *et al*, New J. Phys. **5**, 12 (2003)