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Observations on Geodesic Acoustic Mode scaling and core localization in ASDEX Upgrade using Doppler reflectometry

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1. Introduction

Zonal flows and associated geodesic acoustic modes (GAM) are radially localized oscillating $E_r \times B$ flows in magnetic confinement devices with an $m = n = 0$ mode structure but finite radial extent $k_r \neq 0$. Theory indicates they are generated by non-linear plasma turbulence interactions and in-turn moderate the turbulence via shear de-correlation - hence they are of major importance to confinement [1]. Coherent fluctuations in the radial electric field E_r have been directly measured with high spatial and temporal resolution using Doppler reflectometry on the ASDEX Upgrade tokamak ($R_o/a \approx 1.68/0.5$ m) [2].

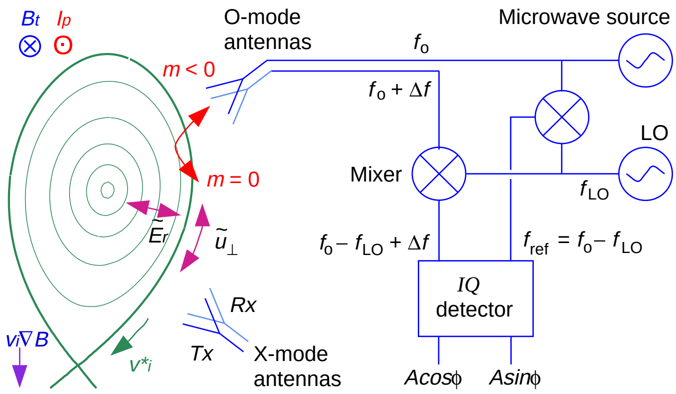

Figure 1: Schematic of Doppler reflectometer

2. Measurement Technique

Poloidally tilting a microwave reflectometer, shown schematically in fig. 1, selects, via Bragg scattering, a turbulence $k_\perp \approx 2k_o \sin\theta$ which generates a Doppler frequency shift in the backscattered signal, $f_D = u_\perp k_\perp / 2\pi$, due to the perpendicular movement of the turbulence in the plasma, $u_\perp = v_{E\times B} + v_{\rm ph}$ [3]. f_D is therefore directly sensitive to $\tilde{E}_r$. MHD fluctuations can also appear in f_D, but as they also modulate the backscattered signal amplitude A (a measure of $\tilde{n}_e$ at the selected $k_\perp$) they can be discriminated. Using a sliding FFT a time sequence of f_D and A fluctuations are generated from the weighted mean and the integral of the complex amplitude spectra $S(f)$ of the I and Q fluctuation signals.

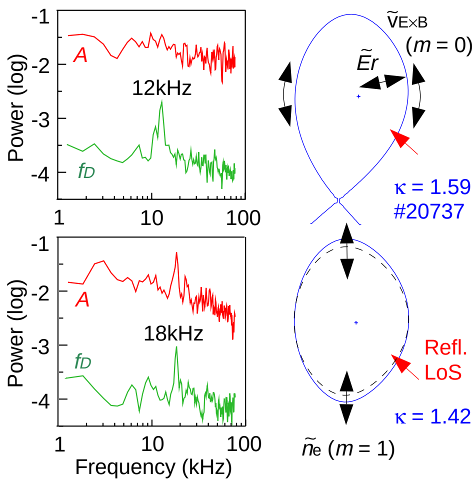

Figure 2: Edge GAM spectra for ohmic divertor and limiter geometry

3. GAM features

Strong coherent oscillations are observed in the f_D spectra between 5 – 25 kHz, even in the absence of MHD activity, with an intensity of 1 to 2 orders of magnitude above the background. The oscillations are generally seen in the edge density gradient region - where the turbulence vorticity and E_r shear are largest [2]. No coherent activity is seen in the open-field SOL region (f^{-1} spectra), nor deep inside the pedestal, i.e. mid-radius core region (flat spectra). The mode has the features expected of a GAM, its frequency scales linearly with the sound speed $c_s = \sqrt{(T_e + T_i)/M}$ (n.b. collisional edge) over a wide range of ohmic and L-mode conditions. So far GAMs have not been observed in H-modes. There is no dependence on B or n_e. There is no measurable magnetic perturbation, and only a weak density perturbation. Since the X-mode Doppler reflectometer antennas are positioned mid-way below the magnetic axis (shown in fig. 2 by red arrows) the diagnostic is usually insensitive to the GAM's $m = \pm 1$ pressure sideband mode structure for standard high elongation ($\kappa > 1.5$) diverted plasmas. However, for low elongation non-diverted configurations, when the reflectometer line-of-sight is closer to the $m = 1$ mode maxima, a corresponding amplitude A peak is often seen (fig. 2). The precise mode structure, however, is still to be confirmed with poloidal measurements.

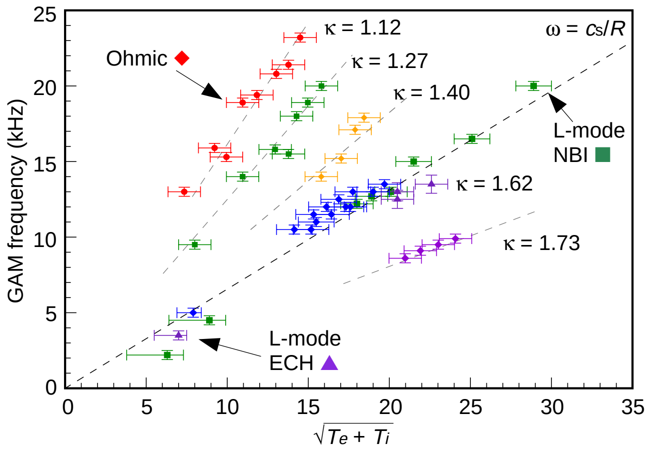

Figure 3: GAM frequency vs $(T_e + T_i)^{1/2}$ for various plasma elongation κ at fixed $q_{95} = 3.85$

4. GAM frequency dependence

As shown in fig. 3, the mode frequency scales as $\omega_{GAM} \propto c_s/R_o$ (sound speed over major radius) for ohmic and L-mode (NBI and ECRH) Deuterium discharges. The appropriate ion mass variation is also seen for Hydrogen and Helium plasmas. The frequency scaling factor is of the order of unity, but there is a strong inverse dependence on the plasma elongation κ and a weak direct dependence on the safety factor q. The variation in the scaling is shown in fig. 3 for a series of κ shape scans between 1.116 and 1.737 at a fixed $q_{95} \approx 3.8$ for ohmic plasmas. For single-null divertor configurations the GAM is only observed in the edge density gradient region. In fig. 4 the full database of GAMs for $\rho_{pol} > 0.95$ are plotted against the model frequency scaling:

$$\omega_{GAM} = \frac{c_s}{R_o} \frac{4\pi}{\kappa_b} \left(\frac{1}{1+\kappa_b} - \frac{1}{q_{95}} \right)$$

where κ_b is the elongation at the plasma boundary. The $(1+\kappa)^{-1}$ term arises from the poloidal circumference $C = \pi a(1+\kappa)$, the negative q^{-1} dependence - although not obvious in simple fluid theory [4] - may come from the shear, while the second κ^{-1} factor may contain any triangularity dependence - since δ tends to increase with elongation.

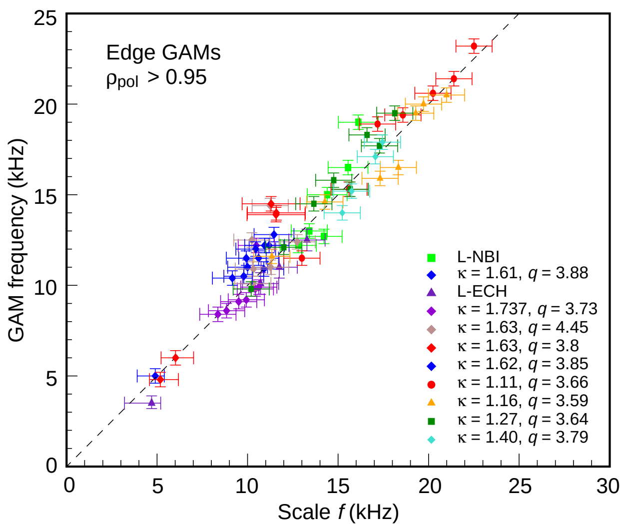

Figure 4: Edge f_{GAM} vs scale frequency $f = (c_s/2\pi R_o)(4\pi/\kappa_b)\left((1+\kappa_b)^{-1} - q_{95}^{-1}\right)$

5. GAM mode-locking

Experimentally the GAM frequency is not a smooth monotonic function of radius (unlike temperature) but shows a series of distinct steps and plateaus a few cm wide. The plateaus become progressively wider with decreasing radius. An example is shown in fig. 5 of f_{GAM} against normalized radius ρ_{pol} for the circular ($\kappa = 1.12$) inner limiter ohmic discharge #20787. The plateaus coincide with maxima in the GAM intensity (fig. 5 lower box) which suggests nested zonal flow layers where the mode phase locks across each zone. At the edge of each plateau the GAM intensity drops and the GAM frequency jumps, usually with splitting in the spectral peak. When the GAM intensity is weak between zones the mode unlocks and its frequency increases with c_s.

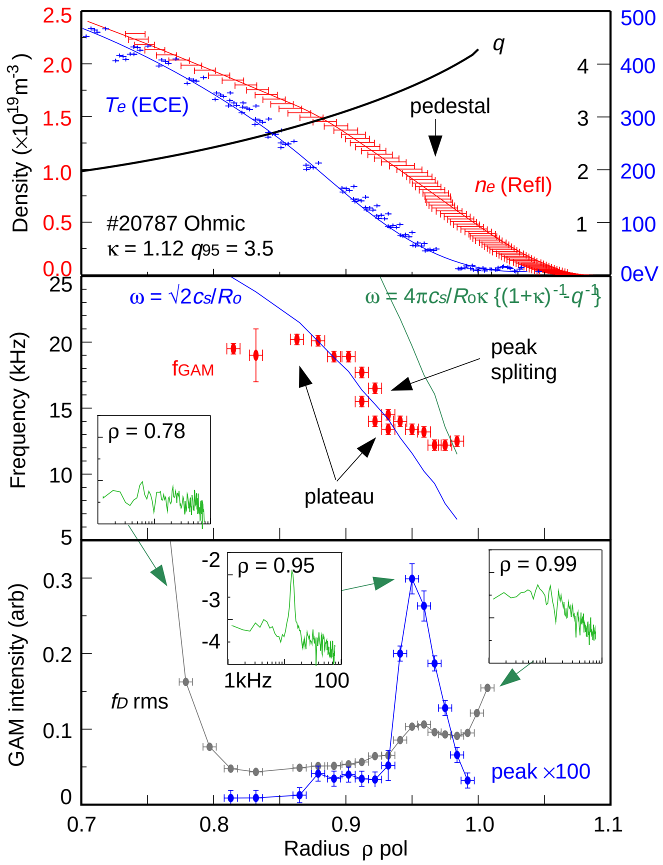

Figure 5: n_e, T_e, q plus f_{GAM} & amp. profiles

6. Core GAM behaviour

For inner limiter configurations the edge density pedestal can be weakened ($n_e \sim 1 \times 10^{19}$ compared to $> 2.5 \times 10^{19}$ m^{-3} for divertor configuration) allowing the GAM to reach further into the core, as far as $\rho_{\mathrm{pol}} \sim 0.75$ for low κ and high q_{95}. The mean frequency of these core GAMs, however, diverges from the edge GAM scaling in fig. 4 and now tends to follow more closely the classical circular plasma scaling $\omega_{GAM} = \sqrt{2}c_s/R_o$ as seen in fig. 5. The fit to the circular scaling is shown in fig. 6 for the GAM database with $\kappa_b < 1.16$ and a range of q_{95}. For GAM peaks outside $\rho_{pol} \approx 0.95$ the points are marked in lighter grey colour. These points do not fit the circular scaling but still follow the previous edge frequency scaling, indicating that (even at $\kappa = 1.1$) the physics is different in the density gradient region, where effects such as higher turbulence drive, higher collisionality, larger q and magnetic shear, larger vorticity and the stronger E_r shear are present.

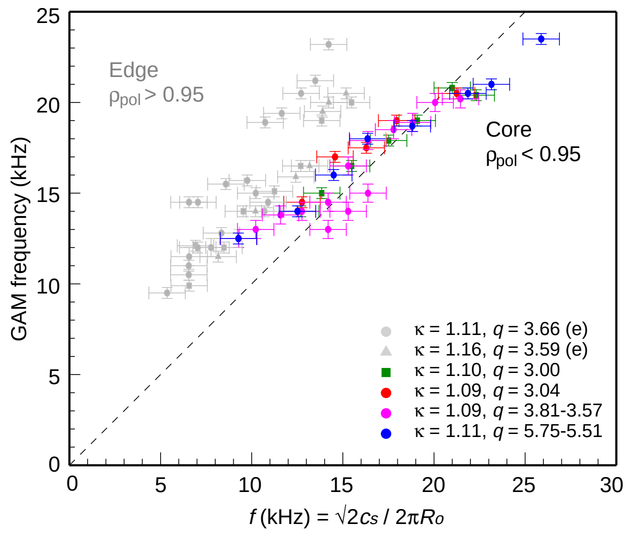

Figure 6: Core f_{GAM} vs $f = \sqrt{2}c_s/2\pi R_o$

7. GAM localization & damping

Fig. 7 shows the GAM spectral peak intensity vs radius ρ_{pol} for a range of discharges. The GAM is generally most intense in the edge density gradient region (excepting the ohmic low κ high q_{95} case). There is no clear preferred radial peak position and there is no alignment with rational q surfaces. The peaks become broader towards the core. The effect of increased turbulence drive with additional heating is also evident in the stronger L-mode peaks.

Fig. 7 also shows the GAM intensity and radial extent increase with q_{95}. Plotting the GAM intensity vs the fluid damping rate [5] $\gamma = \omega_{GAM} \exp(-q^2)$ in fig. 8 shows the suppression of the GAMs in the core as q local falls, as well as at very high q in the edge. The radial maxima points are marked with error bars. The GAMs also disappear at high collisionality.

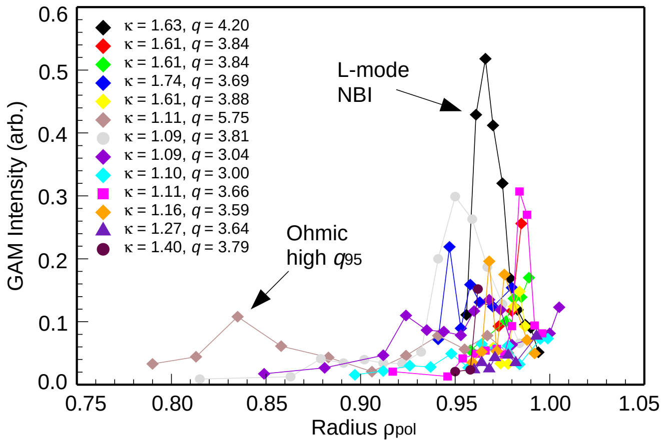

Figure 7: GAM spectral intensity vs radius ρ_{pol}

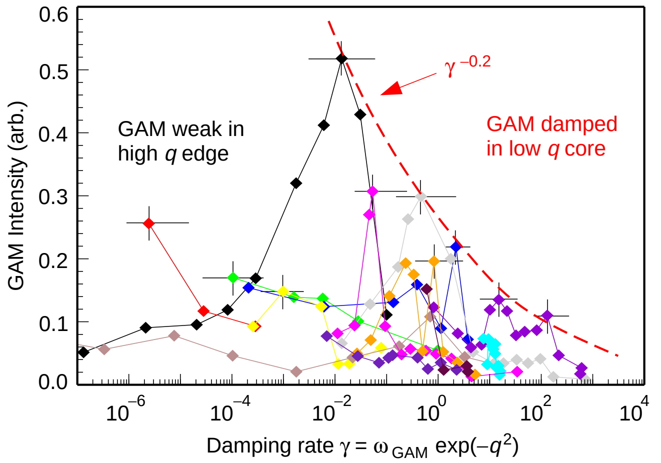

Figure 8: GAM intensity vs damping rate γ

8. Conclusions

Two distinct groups of GAMs separated by the density pedestal are observed. In the gradient region the GAM frequency universally scales inversely with κ_b and q_{95}. The shape dependence is expected from the $m = 0$ to $m = \pm 2$ mode coupling due to elongation. Reducing the pedestal influence via the limiter reveals a second GAM branch extending into the core. For circular plasmas these GAMs scale as $\omega \approx \sqrt{2} c_s / R_o$ (note $q > 1$ so its role is weak). Radial steps in f_{GAM} indicate mode-locking across zonal layers with frequency splitting at zone boundaries. The mode damping, intensity $\propto \exp(-q^2)$, is not inconsistent with either fluid or parallel (sound wave) losses etc. Studies are in-progress to check for shear and profile scale length (R/L_T etc.) sensitivity, as well as comparisons with various fluid and gyrokinetic predictions.

9. References

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