Study of Turbulence and Radial Electric field Transitions in ASDEX Upgrade using Doppler Reflectometry

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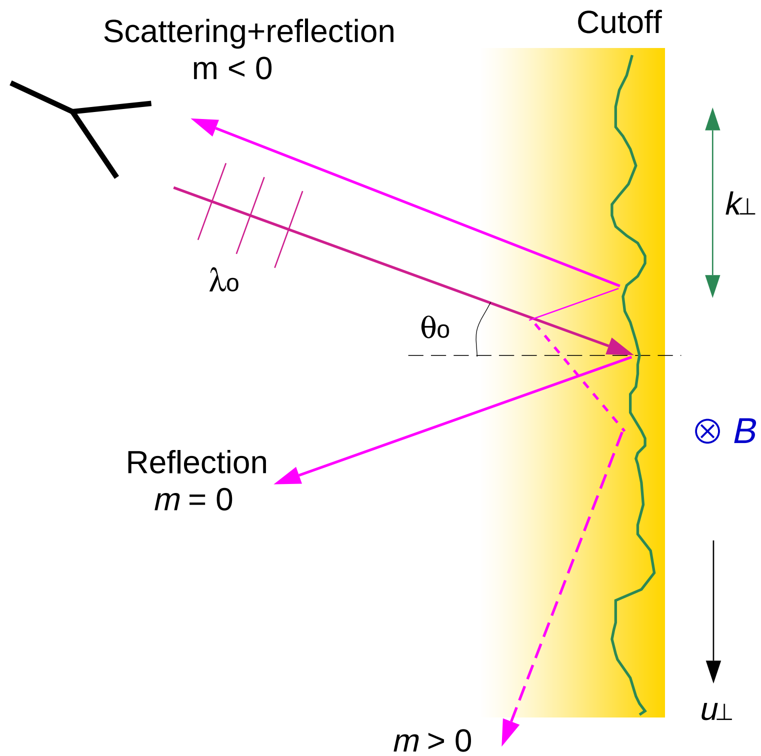
- Doppler reflectometry basics
- E_r and E_r shear profiles
- Core ITG ↔ TEM turbulence transitions
- Flow perturbations (GAM / zonal flow studies)
- Summary and outlook

Introduction - Why Doppler Reflectometry ?

- Hybrid diagnostic = localization of reflectometry
  + k selectivity of scattering
- Microwave beam oblique to plasma cutoff
- Density fluctuations → Forward scattering + Reflection
- Fluctuations move → Doppler shift f_D



$$2\pi f_D = \mathbf{u} \cdot \mathbf{k} \approx u_\perp k_\perp + \cancel{u_{||} k_{||}}$$

when $k_{||} << k_\perp$

$$u_\perp = v_{E\times B} + v_{ph} \qquad k_\perp = 2 N k_o \approx 2k_o \sin \theta_o \quad \text{(slab)}$$

$$E_r = -v_{E\times B} B$$

Theory / modelling ~ few 100m/s

Case 1: When $v_{E\times B} >> v_{ph}$ → E_r

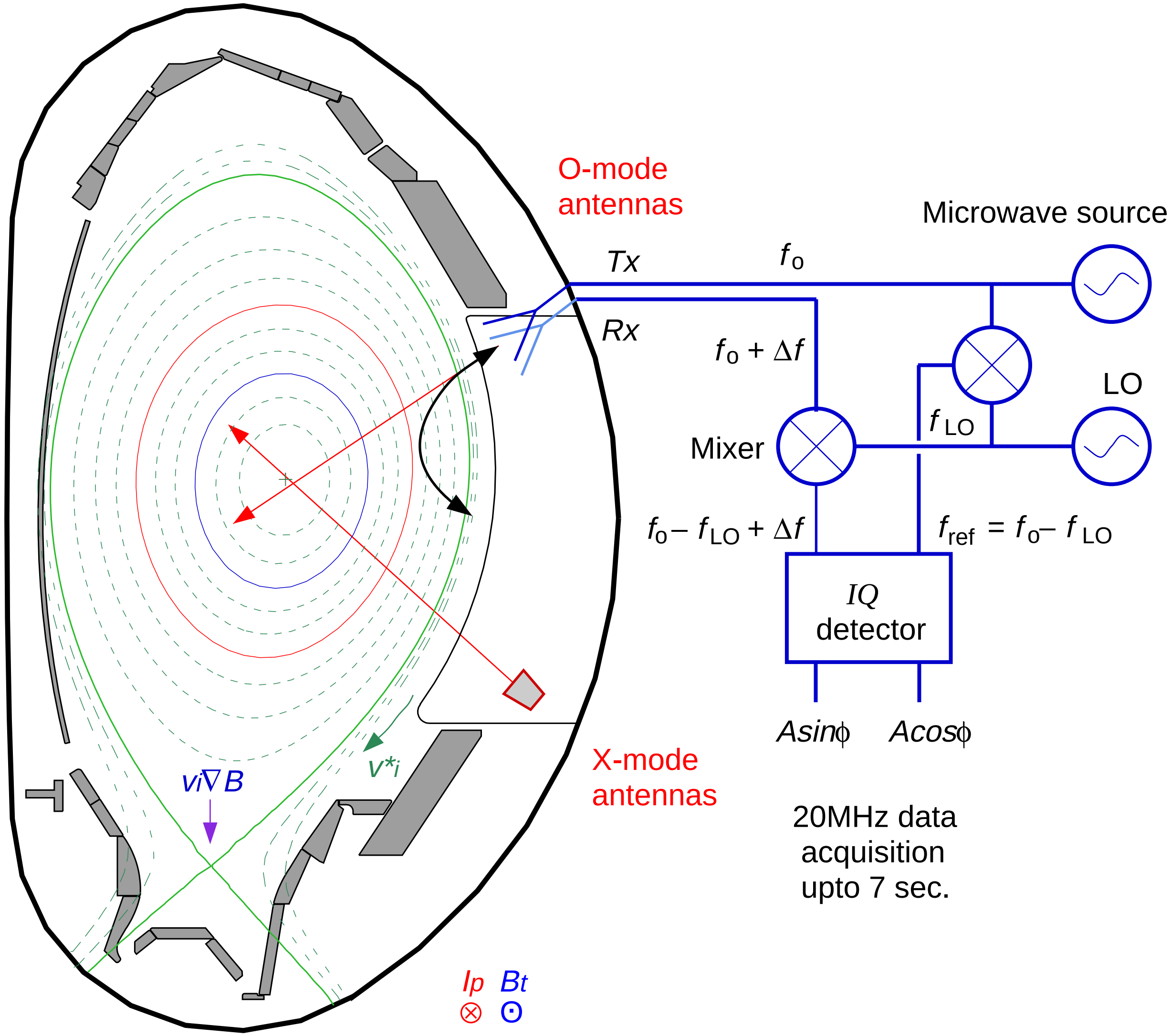
Case 2: When $v_{E\times B} \sim v_{ph}$ → identify turb.

Case 3: $\tilde{E}_r \Rightarrow \tilde{f}_D$ → GAMs & zonal flows

Case 4: Vary θ_o → probe turb. $k_\perp$ spectrum

⇒ Important parameters for plasma confinement

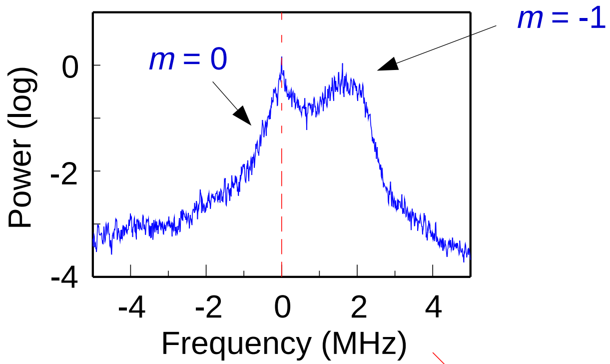
AUG Doppler Reflectometer systems



- 2 channels: V-band 50 – 75 GHz stepped
- Standard heterodyne detection with I & Q
- Fixed tilt O & X-mode antennas: $\theta \approx 12° - 20°$
- Doppler shift from Gaussian fit to complex amplitude spectra: $f_D \leq 4$ MHz
- Cutoff position & $k_\perp = 2N\, k_o$ from TORBEAM ray-trace $k_\perp \approx 6 - 15$ cm^{-1}
- Fitted n_e profile using DCN interf. TS, Li-beam, FM refl.
- CLISTE equilibrium reconstruction

*G.D.Conway etal. PPCF **46** (2004) 951*

Case 1: $v_{E\times B} \gg v_{ph}$ - H-mode *Er* radial profile

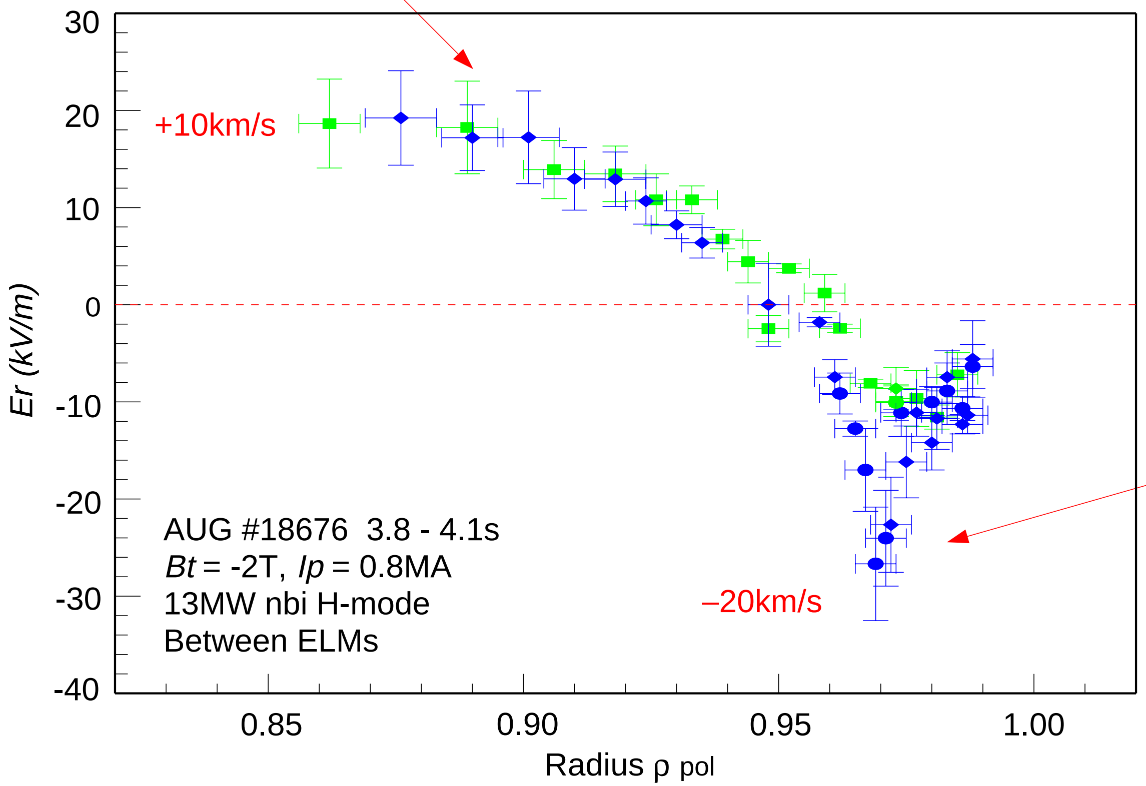


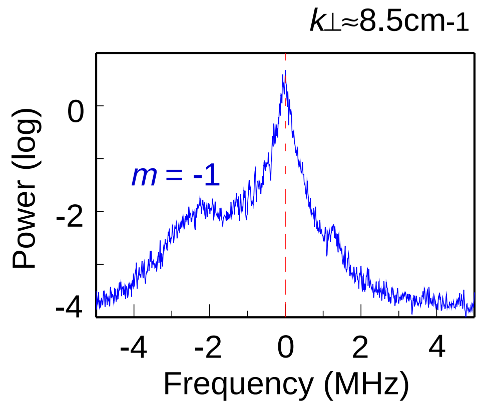
NBI momentum drive dominates H-mode core: $u_\perp$ follows toroidal fluid component in radial force balance eqn.

$$v_{E\times B} = u_\perp - v_{ph} = v_\phi B_\theta / B - v_\theta B_\phi / B - \nabla P / qnB$$

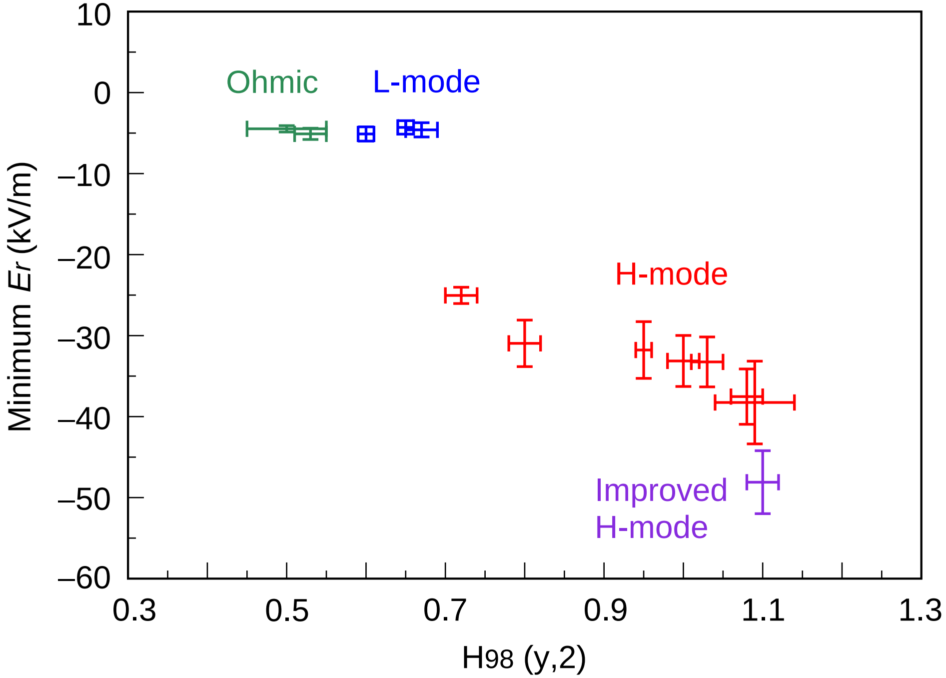
But ∇P dominant in edge barrier $\rightarrow$ negative radial electric field well

$$E_r = -v_{E\times B} B$$

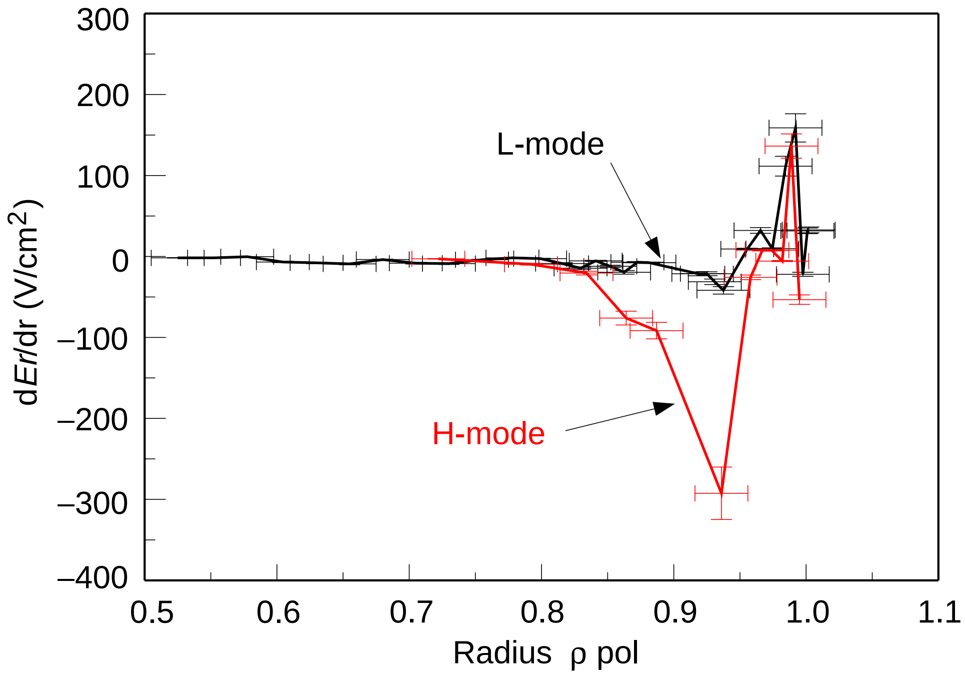




Doppler reflectometry - Edge *Er* well



- 2 channel Doppler - fixed Δf ~ 2GHz, scan radially → instantaneous *Er* shear profile
- Positive shear (SOL), Negative shear (Ped)
- Negative shear increases with confinement
- Shear width ≤ 5cm



- *Er* well increases with confinement

Ohmic & L-mode:	–5 kV/m
Bifurcates in H-mode:	–30 to –35 kV/m
Rises in Imp. H-mode:	–50 kV/m
Deeper in QH-mode:	–60 kV/m or more

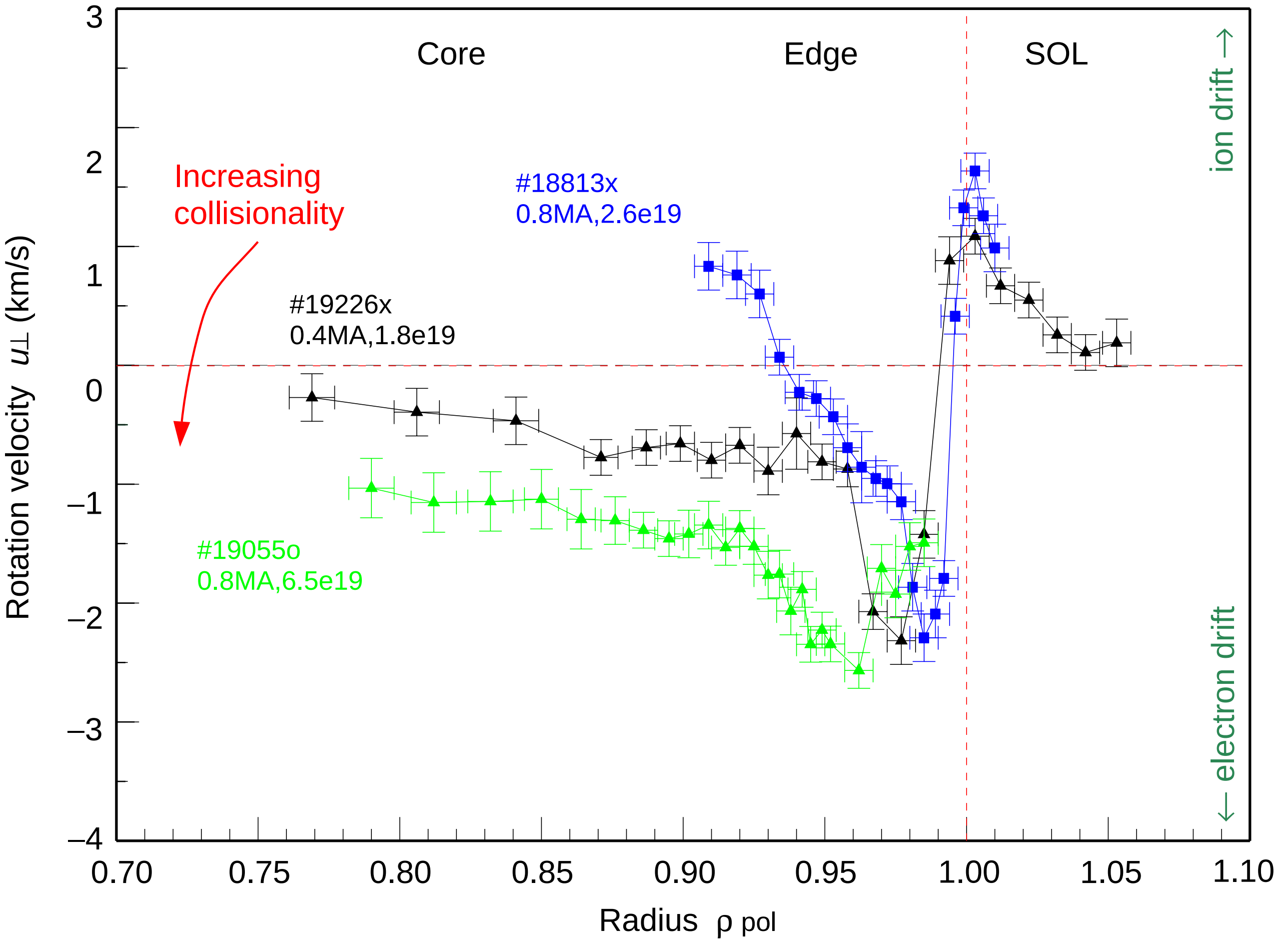
J.Schirmer etal Nucl.Fus. ***46*** *(2006) S780*

J.Schirmer etal. EPS (2006) P2-136

Case 2: $v_{E\times B} \sim v_{ph}$ - ohmic core $u_\perp$ profile

- Without NBI, no strong fluid rotation: core $u_\perp$ ~ few km/s
  → $u_\perp \sim v_{E\times B} \sim v_{ph}$
  → See turbulence effect
- Edge → Robust positive & negative peak structure: High ν* + EDW turb.
- Core → $u_\perp$ varies with collisionality
- Due to $v_{E\times B}$ or v_{ph} ?

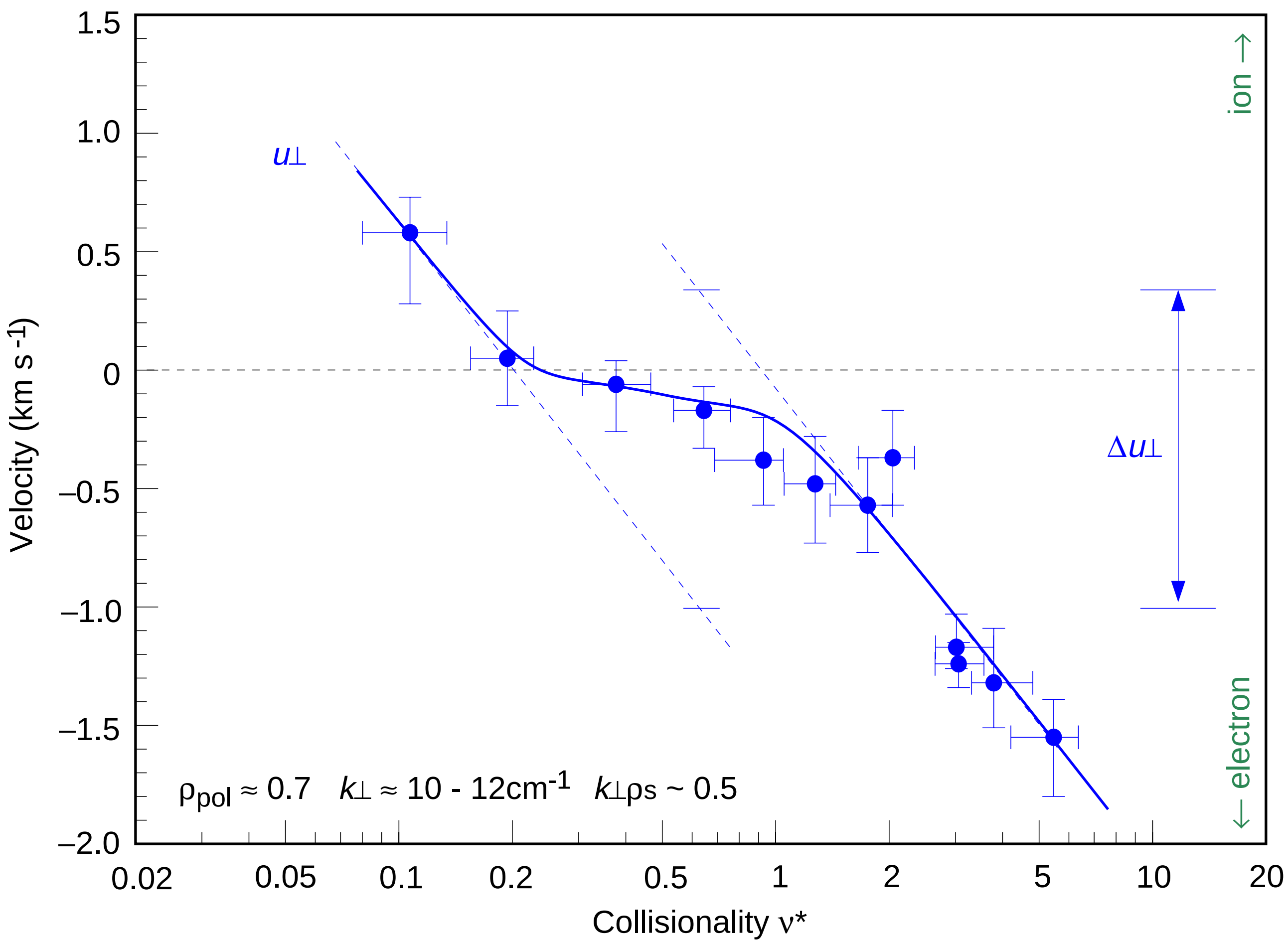
Ohmic shots with various I_p / n_e



Conway etal. Nucl.Fus. ***46*** *(2006) S799*

Core $u_\perp$ velocity vs collisionality

- Core $u_\perp$ rotation at $\rho_{pol} \approx 0.7$ vs local collisionality ν^* from various I_p & n_e ohmic shots
- $u_\perp$ reverses direction with $\nu^* \to$ two branches $\Delta u_\perp$

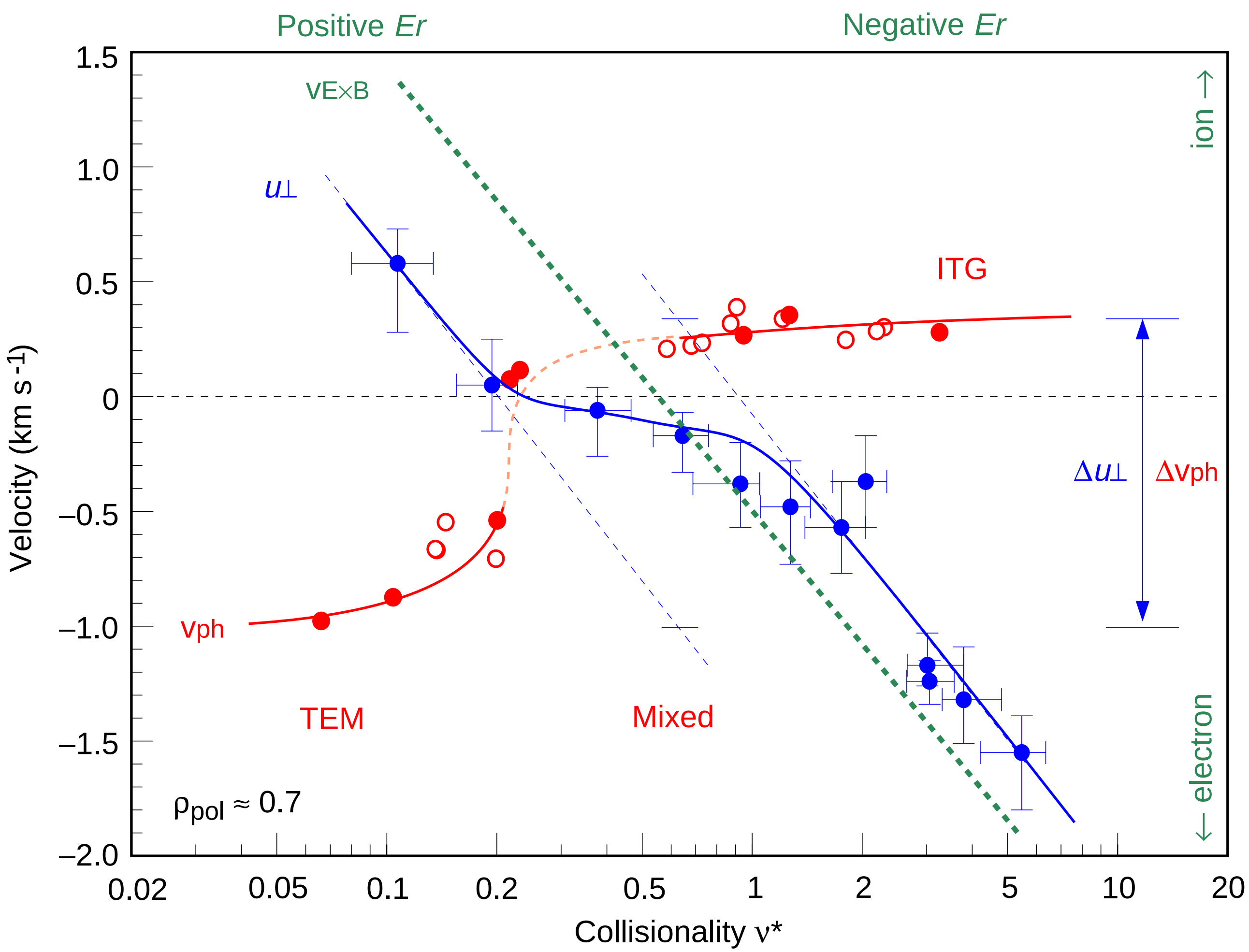


$$\nu^* = \nu_{ei}/(\varepsilon\omega_{be}) \approx 6.9 \times 10^{-18} q \ \ln\Lambda \ R_o \ Z_{eff} \ n_e \ T_e^{-2} \varepsilon^{-3/2}$$

Bounce freq. — 1.68m — 2 — 0.07

Core $u_\perp$ velocity vs collisionality

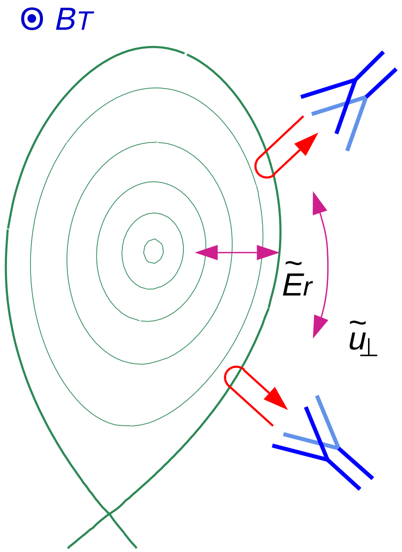
- Core $u_\perp$ rotation at $\rho_{pol} \approx 0.7$ vs local collisionality ν^* from various I_p & n_e ohmic shots
- $u_\perp$ reverses direction with $\nu^* \rightarrow$ two branches $\Delta u_\perp$
- Simulate shots with GS2 linear gyrokinetic code $\rightarrow v_{ph} = \omega_r/k_\theta$ at max $\gamma/k_\perp^2$
- TEM suppressed at high ν^*
- $\Delta u_\perp \approx \Delta v_{ph} \rightarrow$ validates code
- $v_{E\times B} = u_\perp - v_{ph}$ uniform
- No douple peak (line-splitting) in mixed turb. region
- Similar results with ECRH to perturb ν^* via T_e



$$\nu^* = \nu_{ei}/(\varepsilon\omega_{be}) \approx 6.9\times10^{-18} q\ \ln\Lambda\ R_o\ Z_{eff}\, n_e T_e^{-2}\varepsilon^{-3/2}$$

Bounce freq. (ω_{be}), 1.68m (R_o), 2 (Z_{eff}), 0.07 (ε)

Case 3: $\tilde{v}_{E\times B}$ - Plasma flow perturbations



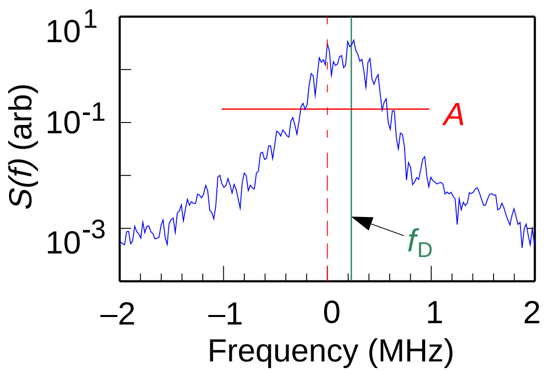
$f_D = 2\,(v_{E\times B} + v_{ph})\,\sin\theta_t\,/\,\lambda_o$

$\tilde{v}_{ph} = 0$ $\tilde{\theta}_t$ & $\tilde{B}$ small (no MHD)

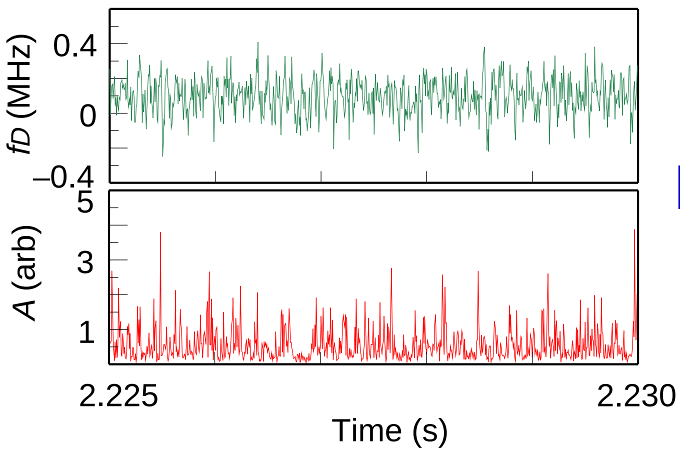
- $\tilde{E}_r \rightarrow \tilde{u}_\perp \rightarrow \tilde{f}_D$ while $\tilde{n}/n \rightarrow \tilde{A}$ at selected $k_\perp$
- MHD appears in both $\tilde{f}_D$ and $\tilde{A}$
- Coherent oscillations $\rightarrow$ Geodesic Acoustic Mode (Zonal flow)
- Important : Turbulence drives ZF $\rightarrow$ regulate turb. (saturation mechanism) $\rightarrow$ transport

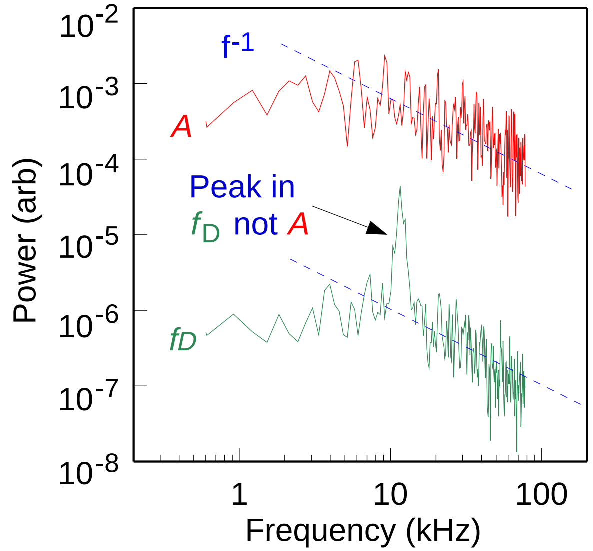
Complex spectra $A\exp(i\phi)$
sliding FFT

$f_D = \Sigma\, f.S(f)\,/\,\Sigma\, S(f)$, $A = \Sigma\, S(f)$



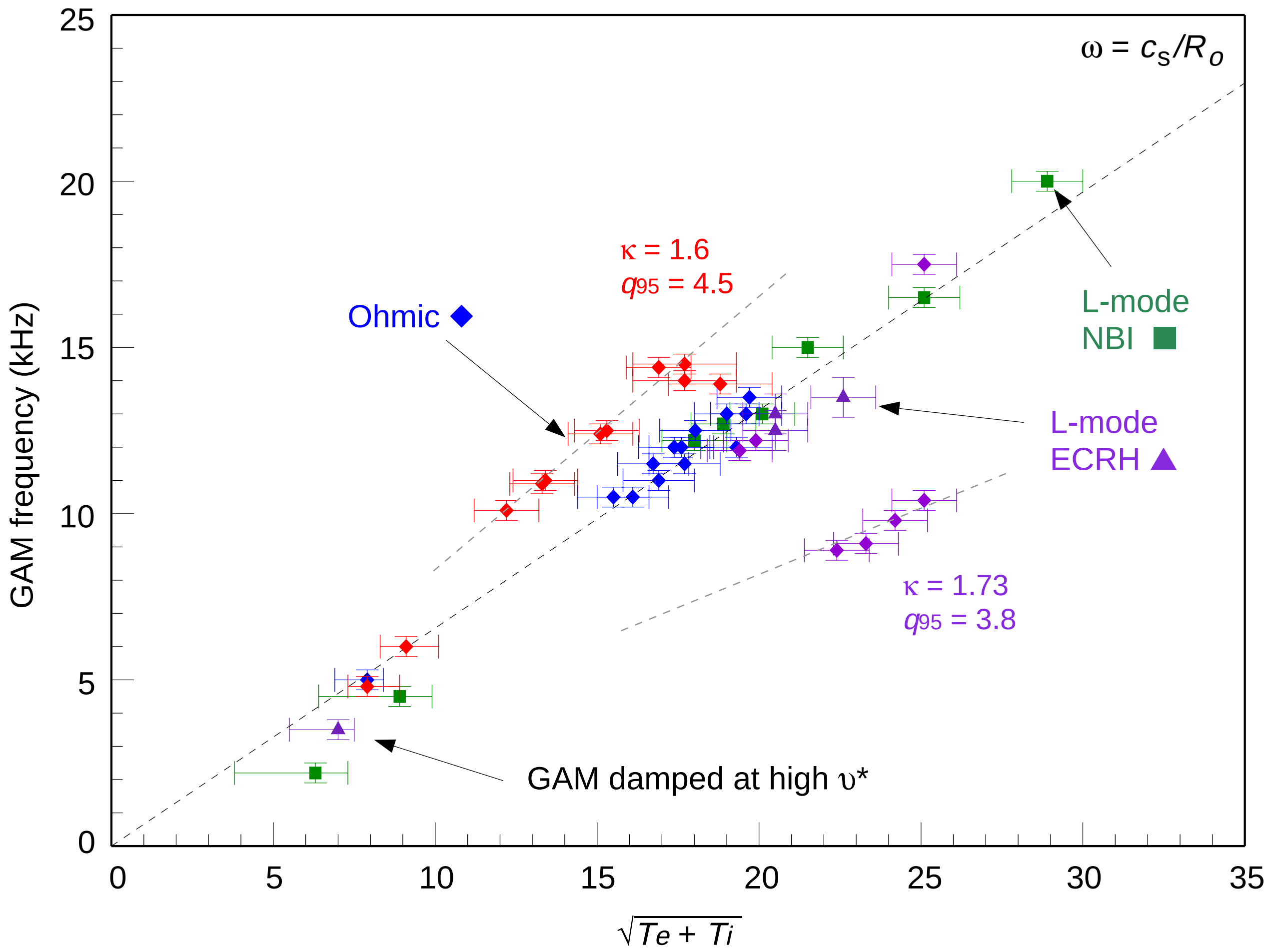
Generate time series of $\tilde{f}_D$ and $\tilde{A}$





Geodesic Acoustic Modes

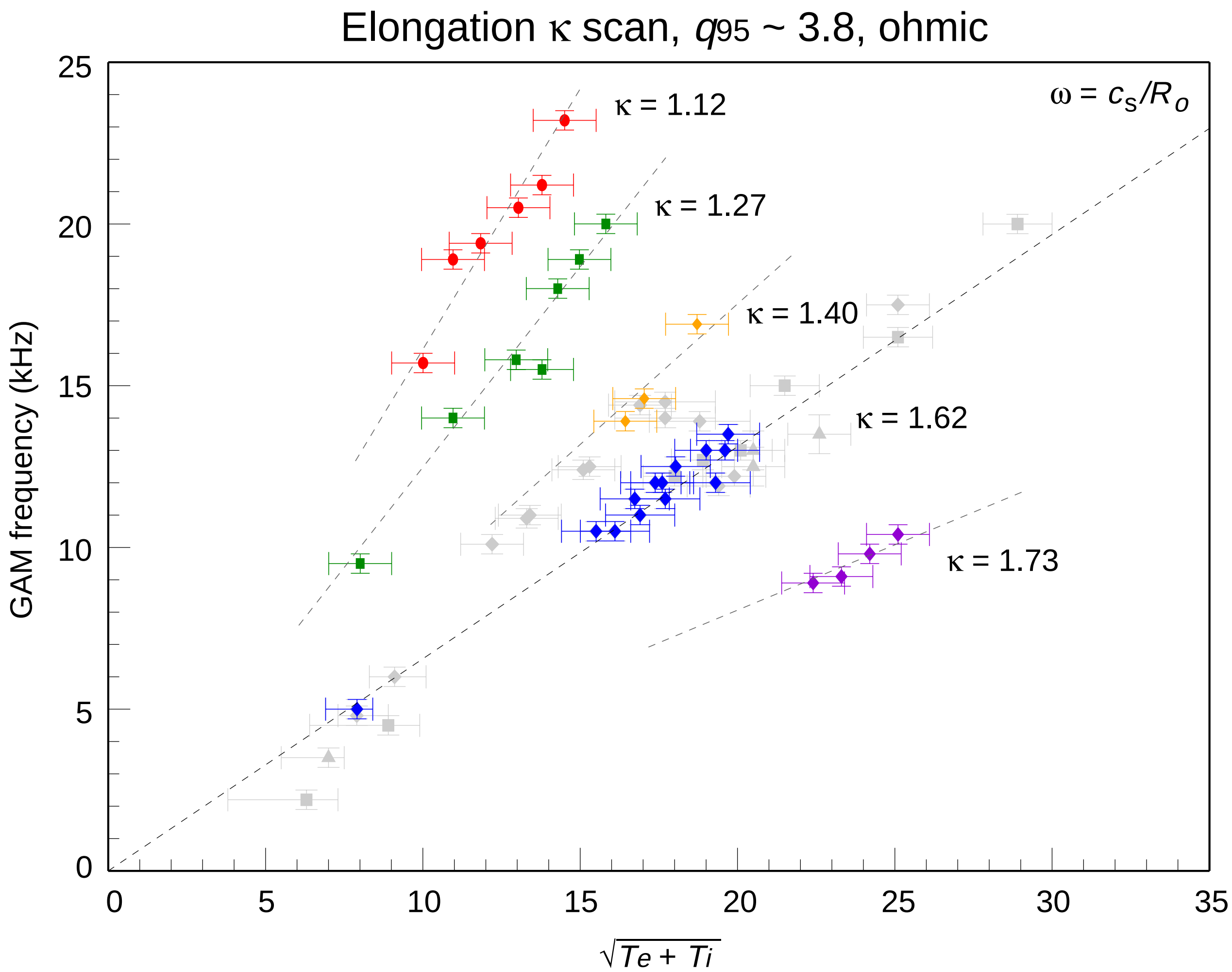
- No magnetic signature
  Weak density signature
- Frequency scales linear
  with $T_{e/i}^{0.5}$, B^0, n_e^0 → Acoustic
- Rigid poloidal flow oscillation:
  $m = n = 0$, $k_r \neq 0$
- Seen in ohmic & L-mode
  edge. No GAM in H-mode
- $\omega = G\, c_s/R_o$ *(theory)*
  sound speed / maj. radius
- Scale factor G depends
  on geometry: κ and q



*G.D.Conway etal. PPCF **47** (2005) 1165*

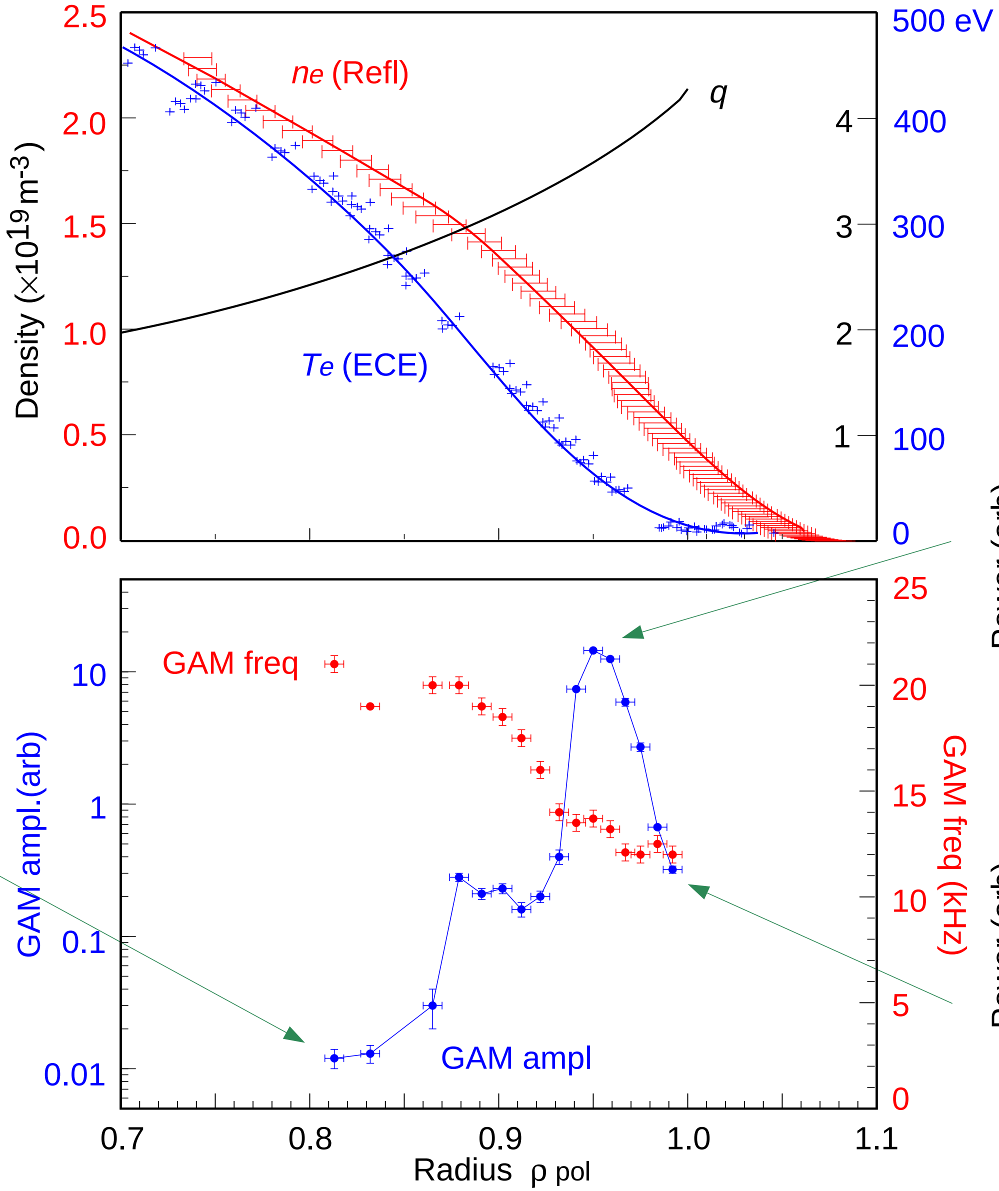
GAM parameter dependence

- No magnetic signature
  Weak density signature
- Frequency scales linear
  with $T_{e/i}^{0.5}$, B^0, n_e^0 → Acoustic
- Rigid poloidal flow oscillation:
  $m = n = 0$, $k_r \neq 0$
- Seen in ohmic & L-mode
  edge. No GAM in H-mode
- $\omega \approx \frac{c_s S}{R_0} \left[\frac{1}{1+\kappa} - \frac{1}{q} \right]$
- $S \approx 4\pi$, varies with radius
- Min. q threshold:
  falling q profile pushes
  GAM outward
- GAM damped at high
  collisionality ν^*
- GAM intensity intermittent

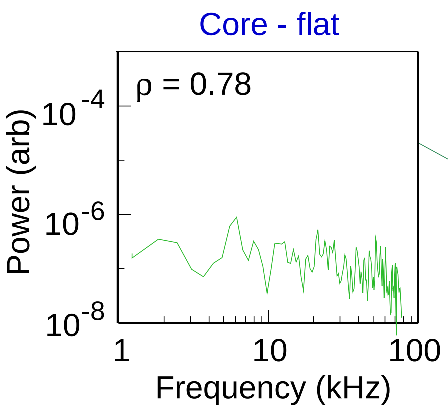


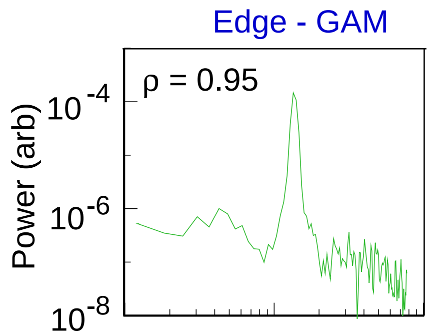
GAM radial localization

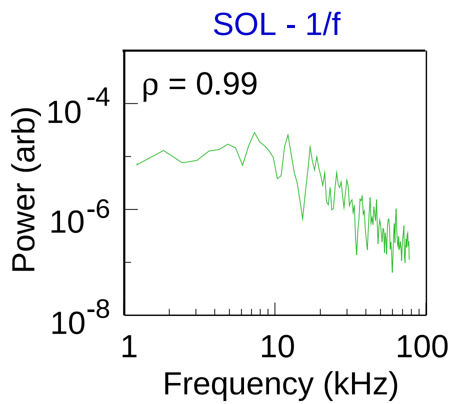
- GAM seen only in plasma edge
- GAM radially bounded by *q*-profile and ∇n_e
  - $\rightarrow$ large $\partial^2/\partial r^2$
  - $\rightarrow$ E_r shear / vorticity
- GAM frequency locks across intensity peaks $\rightarrow$ zones



#20787 Ohmic
κ = 1.12 q_{95} = 3.5



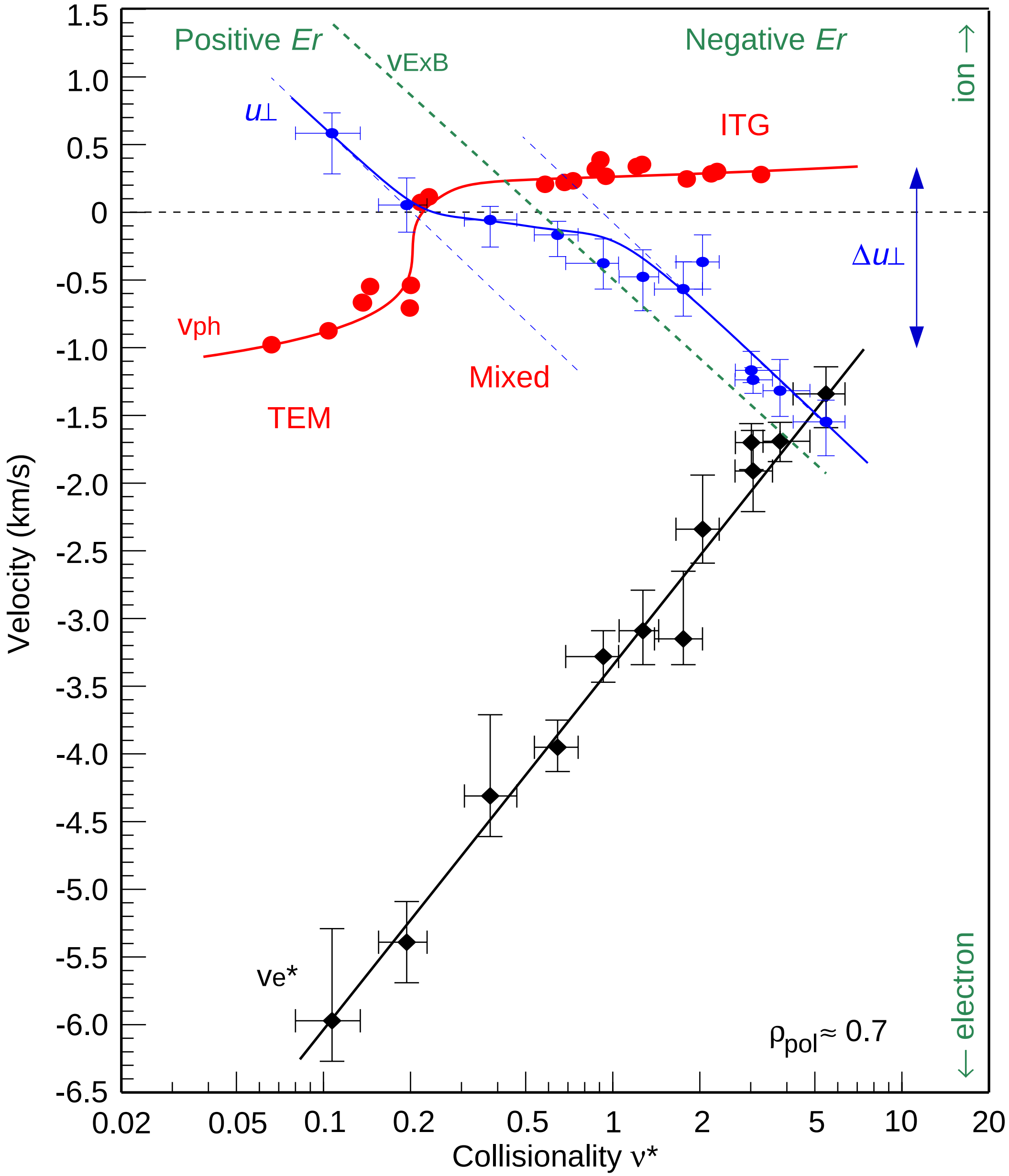




Summary and Outlook

- High resolution E_r and E_r shear profiles
  - ♦ Edge E_r well scales with confinement
  - ♦ Negative shear appears to be dominant parameter
  - ♦ Doppler correlation refl. $\rightarrow$ Simultaneous turbulence L_r reduced with inc. E_r shear
- Core turbulence
  - ♦ Observations consistent with ITG $\leftrightarrow$ TEM transition - depends on collisionality & gradients
  - ♦ Measured v_{ph} jump matches linear gyrokinetic simulations
  - ♦ No double peak seen in mixed turb. region $\rightarrow$ Investigate different $k_\perp$ regions
- Zonal flows & GAMs
  - ♦ Strong evidence of edge localized ($k_r \neq 0$) GAMs $\rightarrow$ Radially bounded by ∇n_e and q
  - ♦ Frequency scaling with κ and q $\rightarrow$ Other parametric dependence suspected $\rightarrow$ Theory
  - ♦ Intermittent $\rightarrow$ Turbulence modulation. Mode structure + pressure sideband indications
- Outlook & upgrades
  - ♦ New channels in W-band (75 - 110GHz) $\rightarrow$ Wider coverage + multi-point radial correlation
  - ♦ Remote steerable antenna $\rightarrow$ Investigate turb. $k_\perp$ spectrum **(Case 4)**
  - ♦ Investigate high $k_\perp$ $\rightarrow$ ETG signature
  - ♦ Search for core low frequency zonal flows

E×B velocity and turbulence transitions



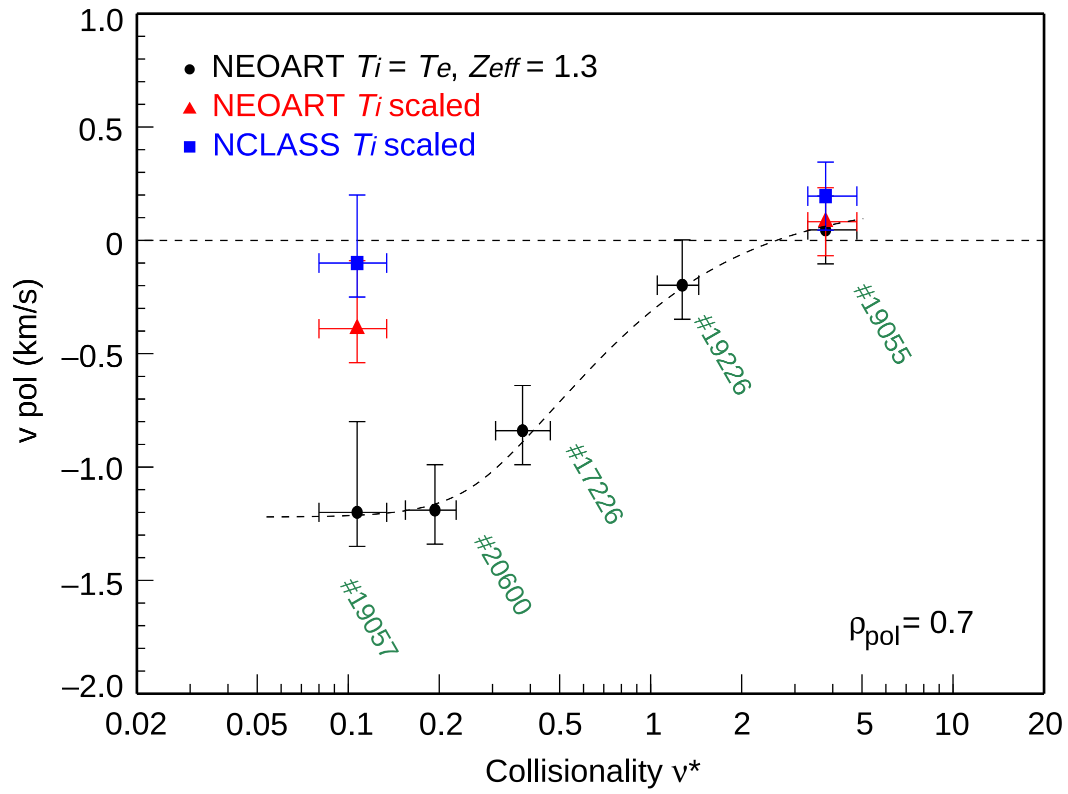
- $v_{E\times B} = u_\perp - v_{ph}$
  - measure ($u_\perp$), code (v_{ph})
- $\Delta u_\perp = \Delta v_{ph}$ → validates GS2 code
- E_r reverses with turbulence
- Radial force balance eqn.

  $v_{E\times B} = v_\perp - v^*$
  - perp fluid ($v_\perp$), diamag. (measure) (v^*)
- $v_\perp = v_\phi B_\theta/B - v_\theta B_\phi/B$
  - O (0.16), O (0.98)
- $v_i^* < v_e^*$
- $v_{i\perp} \approx$ +4.8km/s (ion) low ν^*

  −0.7km/s (elec) high ν^*
- If $v_\phi \rightarrow 0$ then require $v_{i\theta} \approx -v_{i\perp}$

Poloidal fluid velocity: NCLASS & NEOART

Deuterium ion poloidal fluid velocity



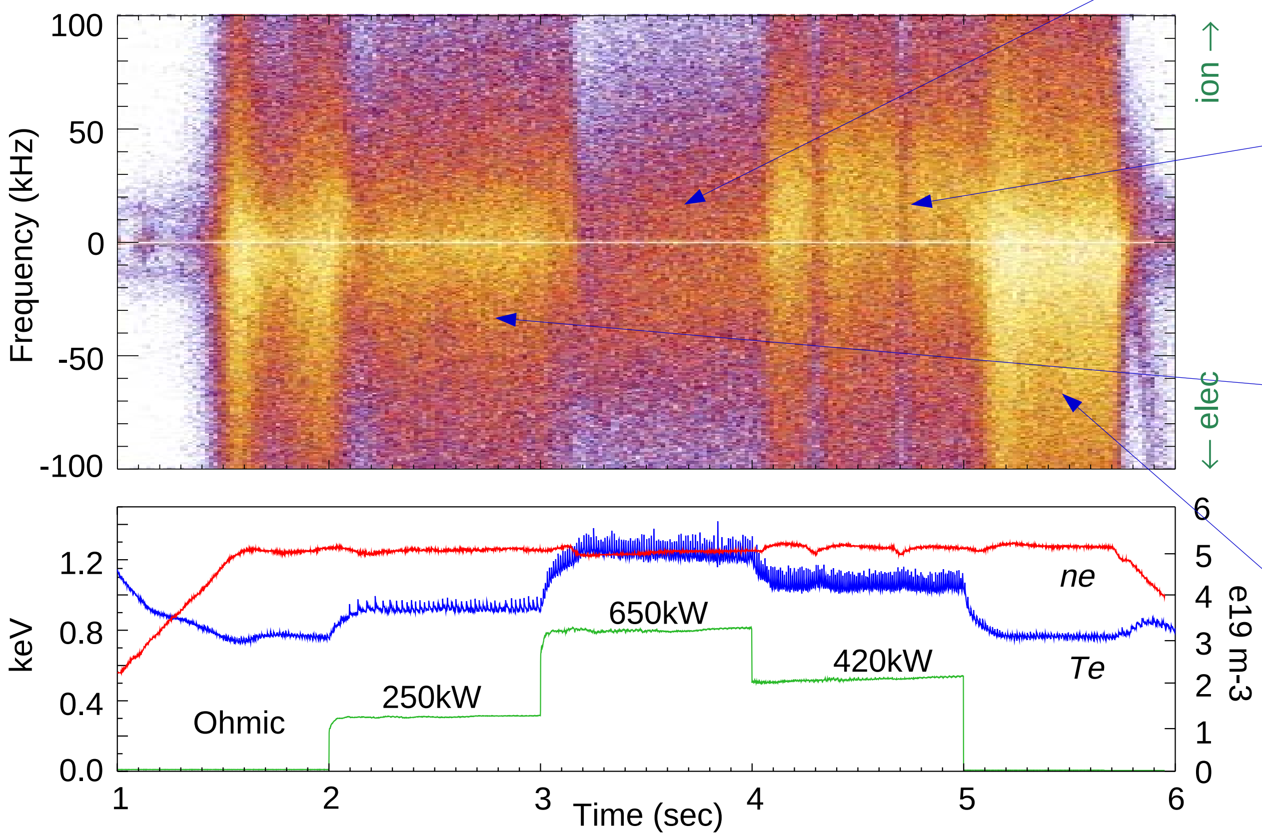
#19057 T_i = 0.55 T_e Z_{eff} = 2.5

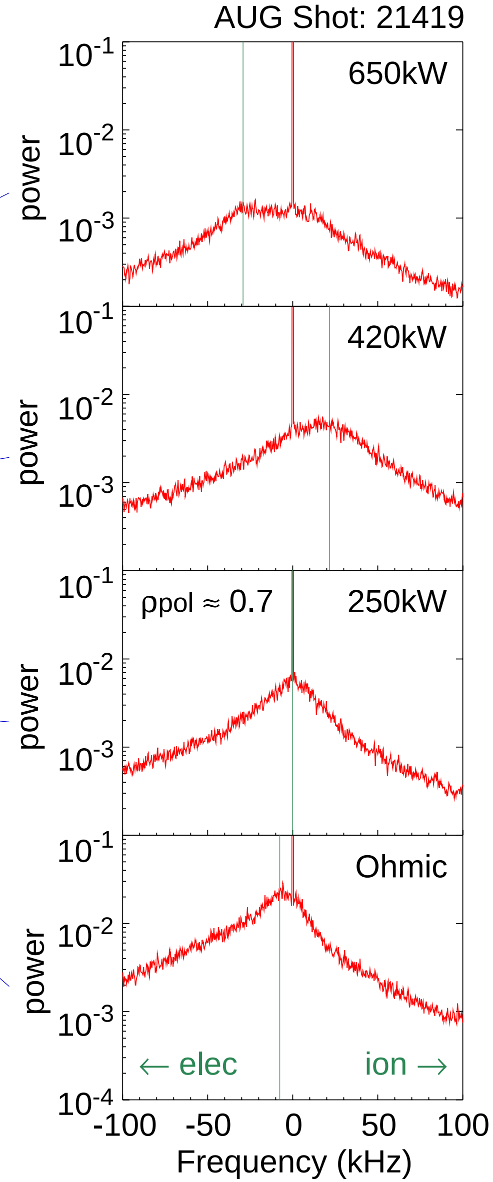
#19055 T_i = 0.85 T_e Z_{eff} = 1.3

- Neoclassical predictions using NEOART and NCLASS codes
- Full collisionality scan using $T_i = T_e$ and $Z_{eff} = 1.3$
  - → v_θ monotonic with ν^*
  - → saturates at low ν^*
  - → reverses sign at high ν^*
- Reducing $T_i \rightarrow v_\theta$ more positive
  Increasing $Z_{eff} \rightarrow v_\theta$ smaller
- NCLASS results similar to NEOART but (electron) $v_{e\theta}$ too large
- $v_{i\theta}$ factor of 10 too small compared to measured $v_{i\perp}$ (ion)
  - → v_θ is not neoclassical, or
  - → $v_\phi \neq 0$ (but need $v_\phi \approx 30$ km/s !)

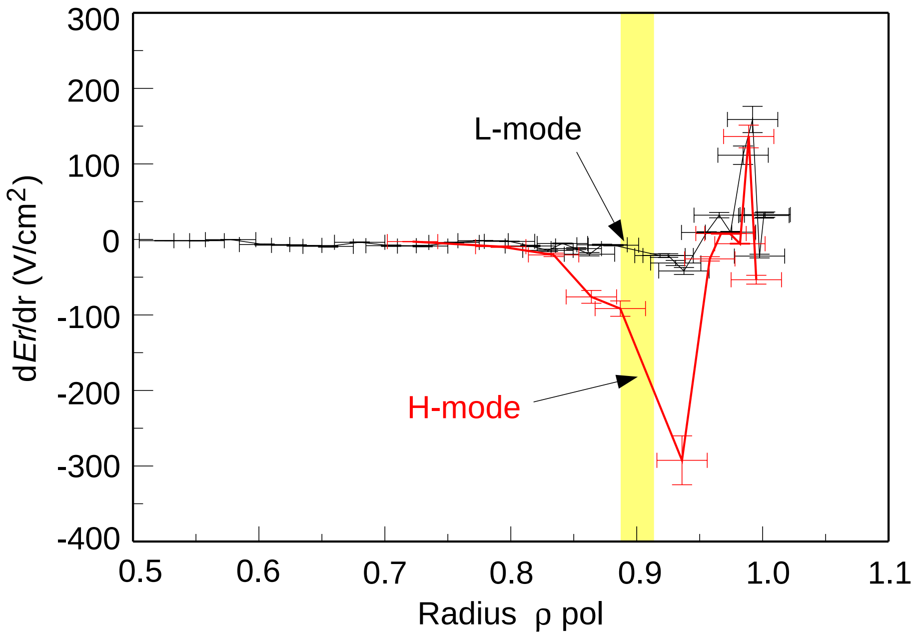
ITG - TEM core turbulence transition with ECRH

- Collisionality $\nu^* \propto n_e/T_e^2 \rightarrow n_e$ ramp or T_e pertubation
- ECRH power steps at $n_e \approx 5 \times 10^{19} m^{-3}$ (ITG dominant)
- Low power $u_\perp \rightarrow$ ion drift (as per ohmic), TEM transition >600kW
- P_{ECRH} threshold rises with $n_e \rightarrow$ critical ν^* or T_i/T_e



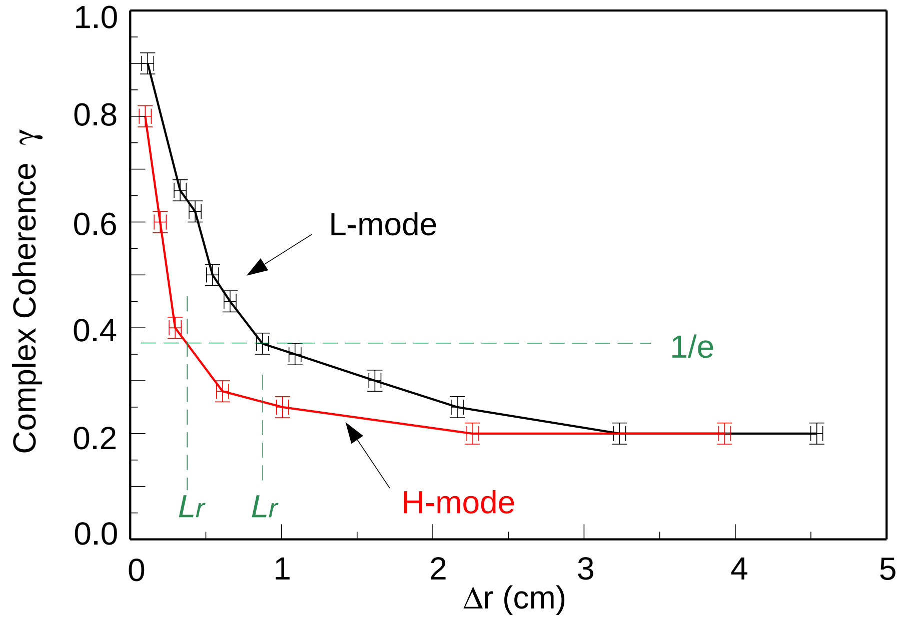


Doppler correlation reflectometry



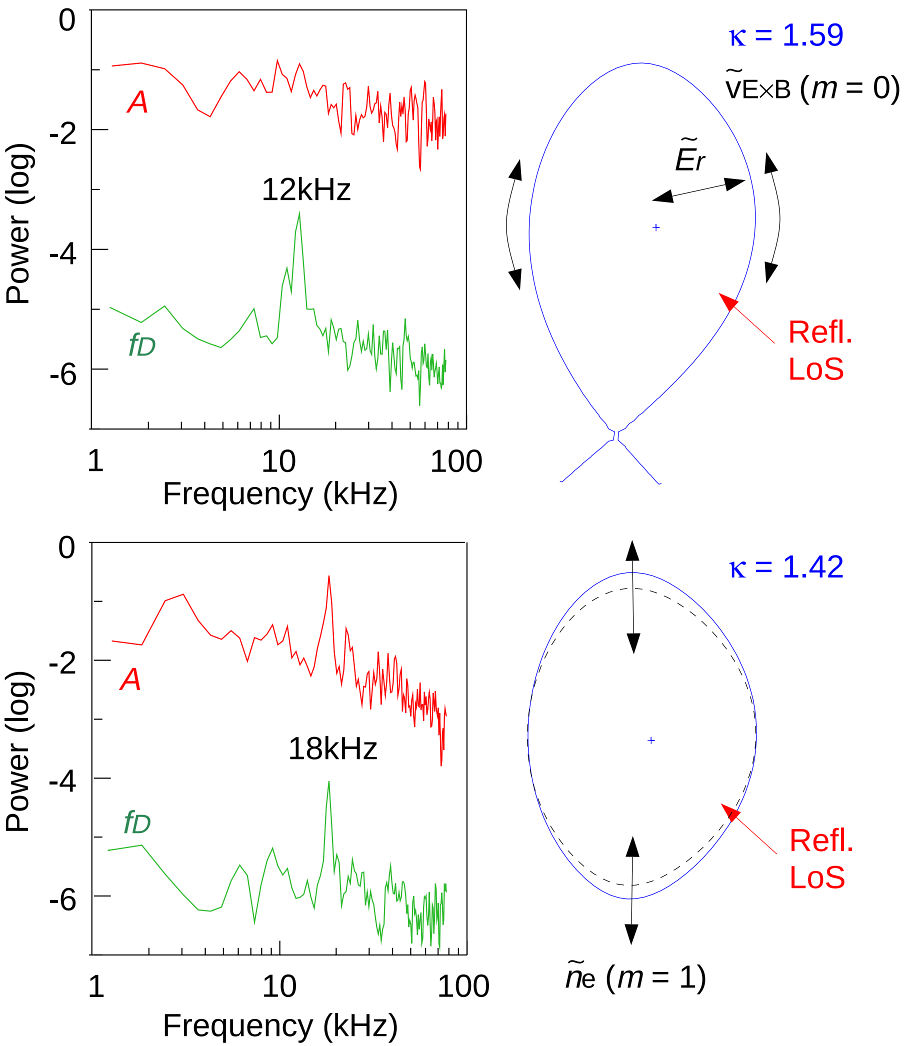
- 2 channel Doppler - fixed $\Delta f \sim$ 2GHz, scan radially $\rightarrow$ instantaneous E_r shear profile
- Positive peak (SOL) + negative peak (Ped) zero elsewhere
- Negative shear increases with confinement while positive peak constant
- Shear width $\leq$ 5cm

- 2 channel Doppler - step Δf logarithmic (Δr) fix f_1 radially, cross correlate complex ampl. signals $\rightarrow$ radial correlation length L_r
- L_r decreases in H-mode (by half) in concert with increasing E_r shear
- L_r increases in core
- L_r decreases with increasing triangularity together with improving confinement



J.Schirmer etal. EPS (2006) P2-136

GAM mode structure



- Doppler X-mode line-of-sight (LOS) = lower mid-plane on LFS
- For diverted (high κ) shape: reflectometer insensitive to *m* = 1 pressure side-band mode → no peak in *A* (*ne*) spectrum
- For non-diverted (mid to low κ : circular) refl. LOS closer to *m* = 1 mode maxima → peak appears in *A* (*ne*) spectra

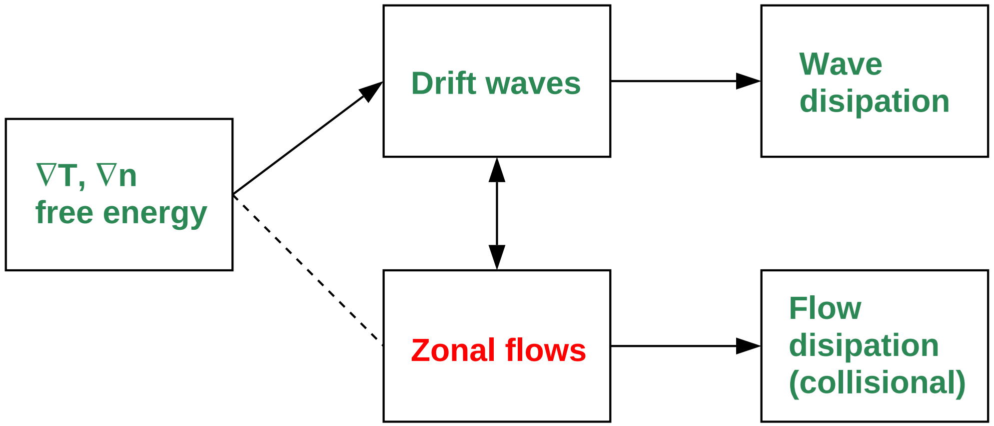
◊ c.f. TEXTOR results (Krämer-Flecken)

- Precise mode structure still to be measured with poloidally separated LOS
- GAM frequency vs radius shows plateaus, plus peaks in GAM intensity → zones ~ a few cm wide → $k_r \neq 0$

G.D.Conway etal. (2006) IAEA-CN-149/EX/2-1

Plasma flow perturbations

- Temperature & density gradients drive turbulence (e.g. Drift Wave)
- Non-linear turbulence interactions drive Zonal flows (ZF)
  - Electrostatic, potential/E_r fluctuations
  - Rigid poloidal plasma flows
  - Poloidally symmetric, $m = n = 0$, $k_r \neq 0$
  - $0 \leq \omega \leq \omega_{turb}$
  - ZF regulate DW turbulence & transport



Diamond *etal. PPCF*, **47**, R35 (2005)

- ZF couple to $m = \pm 1$ pressure sideband modes
  $\rightarrow$ generate Geodesic Acoustic Oscillations (GAM)
  - Driven at all frequencies but resonant at $\omega_{GAM} \approx c_s / R_o$
- Sideband also couples to Parallel ion Sound Waves (SW)
  - $\omega_{SW} = c_s / qR_o$

GAM intermittency

- GAM generally continuous but --
- Intensity modulated:
  - Ampl. ~50%
  - Length few ms
  - Repetition ~200Hz

  $\rightarrow$ looks like bursts
- Peak intensity behaves inversely to background f_D and *A* fluctuations
- Suggests GAM envelope time-modulated by low frequency zonal flow
  - as predicted by simulations