Recent GAM studies in ASDEX Upgrade

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- GAM parameter dependences – freq. & amp. scaling
- GAM structure & propagation
- Magnetic signature
- Impact of non-axisymmetric (resonant) magnetic perturbations MP
- GAM envelope detection – turb. interaction

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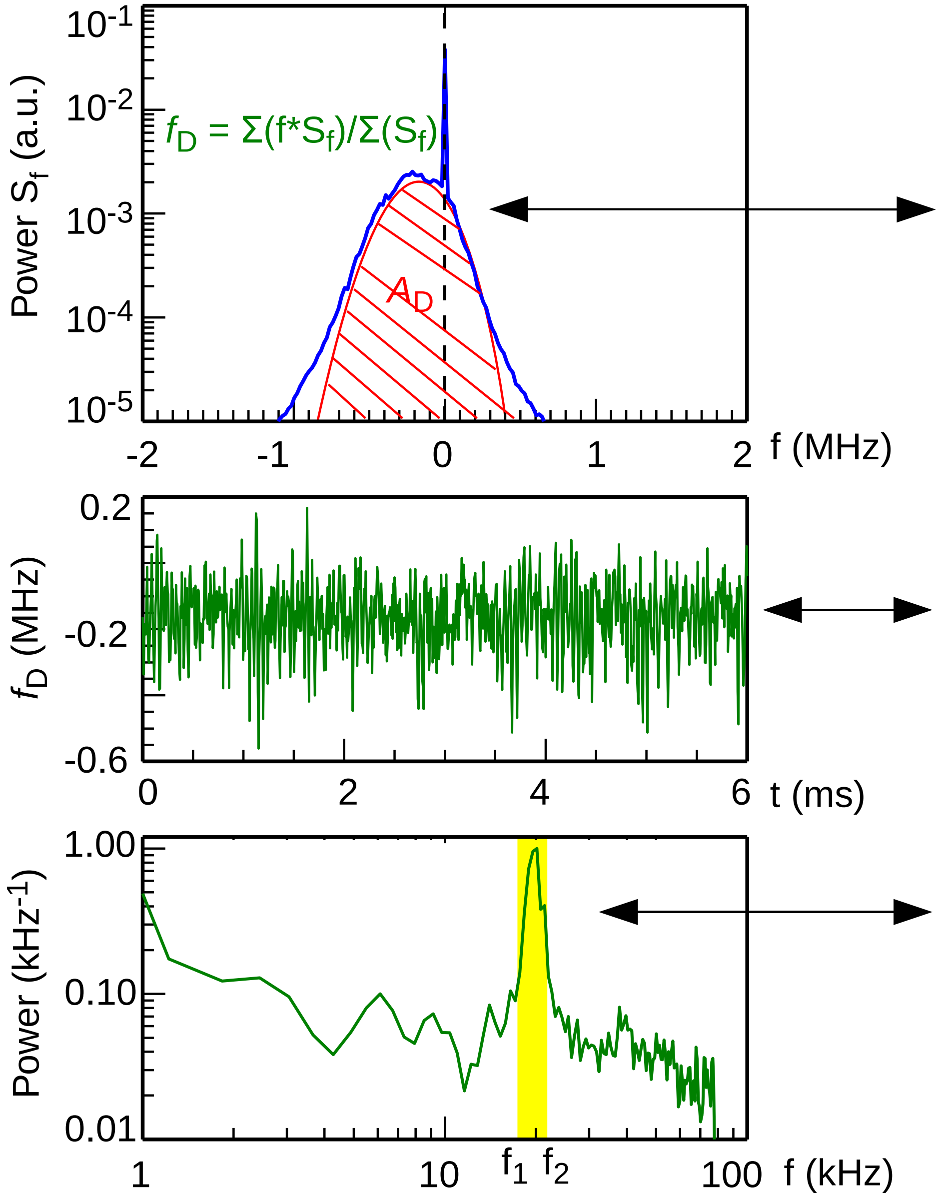
GAM measurements from Doppler reflectometry on AUG



- Complex spectra from I/Q signal and determine Doppler peak f_D & A_D (using weighted average CoG or Gaussian fit)

$f_D = k_\perp u_\perp / 2\pi$ $A_D \sim (\delta n)^2$

- Repeat process on sliding window to obtain $f_D(t)$ and $A_D(t)$ time series

- Power spectrum of $f_D(t)$ to find peak at f_{GAM}

- Calculate GAM strength

$$A_{[kHz]} = 2\sqrt{\Sigma_{f_1}^{f_2} S(f_D) 4/1.5}$$

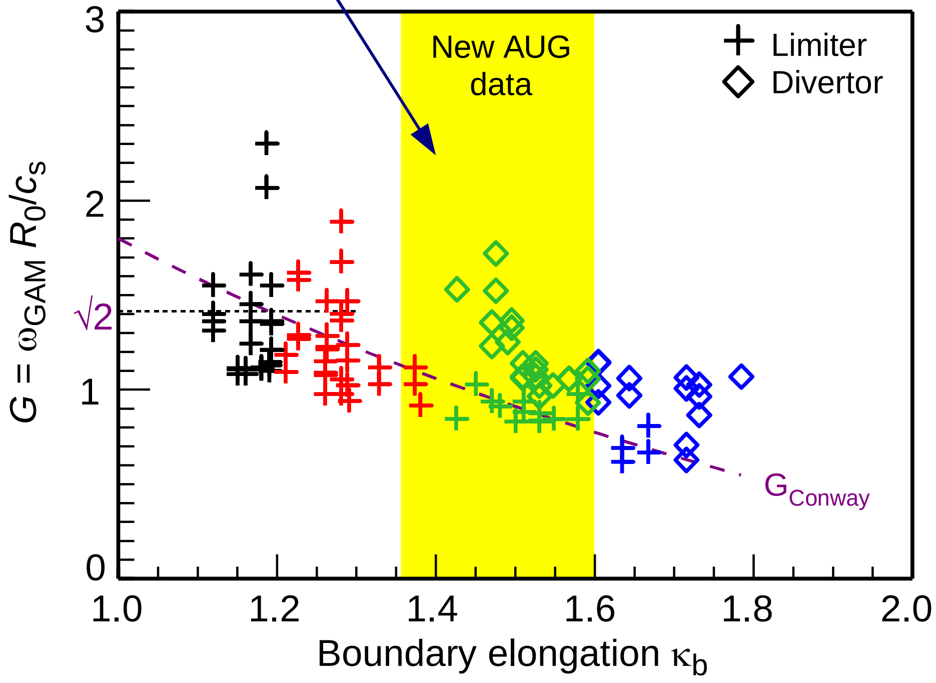
$$\boxed{A_{GAM} = 2\pi A_{[kHz]}/k_\perp}$$

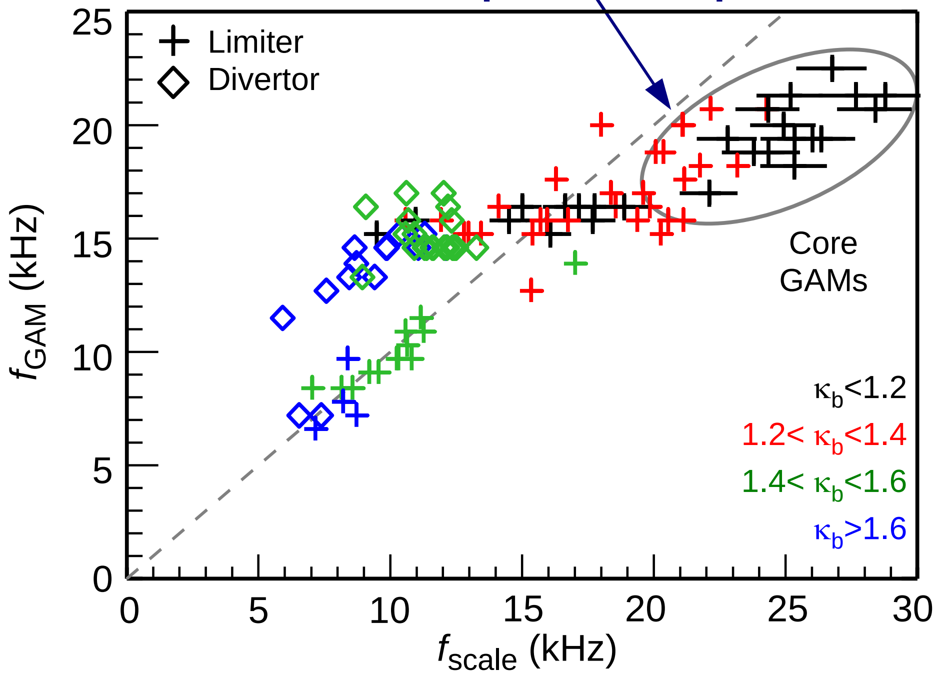
GAM Frequency Scaling: κ_b Dependence

- Freq. scale factor $G = \omega_{GAM} R_o / c_s$: $G \sim \sqrt{2}$ for "core" (inside ped. circular $\kappa_b \rightarrow 1$) [Windsor, PF 1968]
- Edge GAMs ($\rho_{pol} > 0.95$) show strong dependence on boundary elongation κ_b
- Conway *empirical* scaling → good overall prediction of edge GAMs (especially limiter config.)
- Divertor data deviate more than limiter → role of X-point?

[Conway, PPCF 2008]

$$f_{scale} = \frac{c_s}{2\pi R_o} 4\pi \left[\frac{1}{1+\kappa_b} - \epsilon_o \right]$$



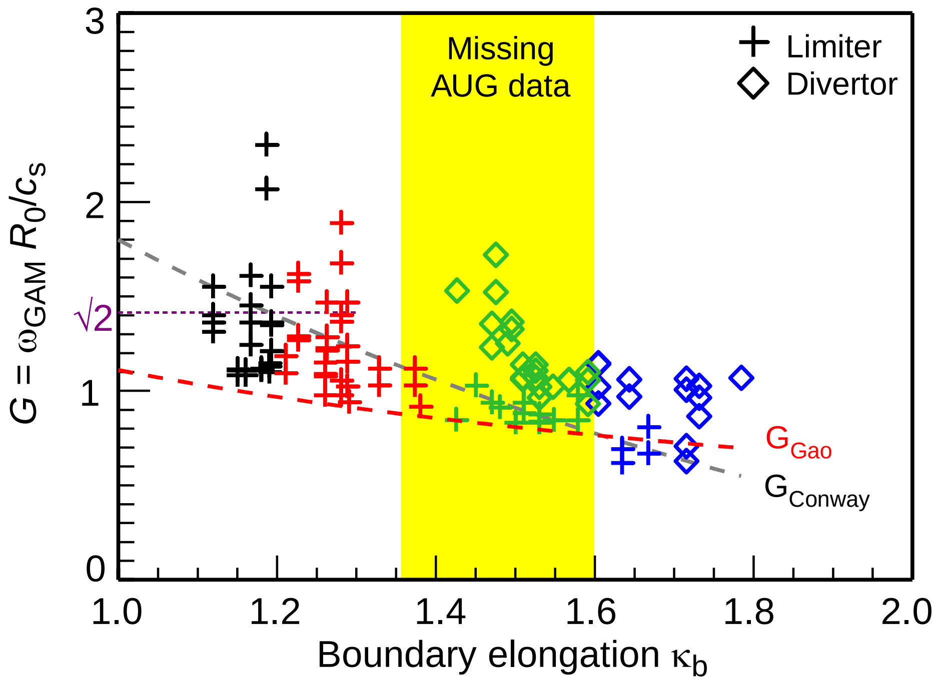


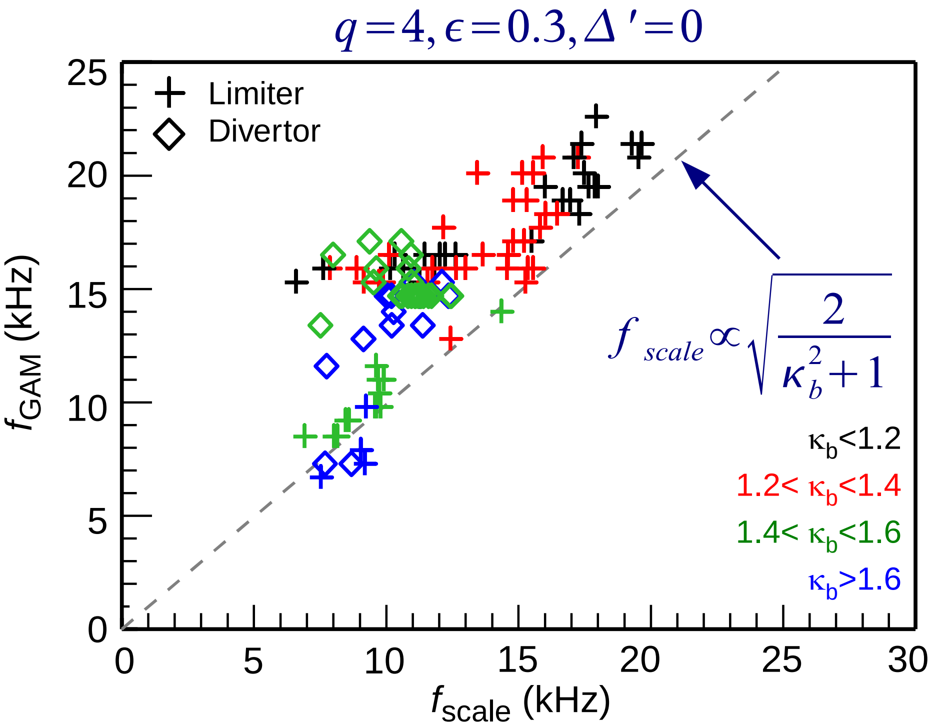
GAM Frequency Scaling: Gao-scaling

- Analytic Gao scaling: Influence of κ less strong than Conway scaling
- All experimental data lie above Gao
- Gao (linear) gives min. ω_{GAM} – non-linearity & X-point etc. may raise GAM frequency

$$\frac{\omega}{v_{ti}/R_0} = \sqrt{\left(\frac{7}{4}+\tau\right)\boxed{\left(\frac{2}{\kappa^2+1}\right)}\left(1-\frac{s_\kappa}{2}\frac{7+2\tau}{7+4\tau}\right)}$$
$$\times\left[1-\varepsilon^2\frac{9\kappa^2+3}{8\kappa^2+8}-\Delta'^2\frac{\kappa^2}{4\kappa^2+4}+\varepsilon\Delta'\frac{4\kappa^2+1}{4\kappa^2+4}\right.$$
$$\left.+\frac{(23+16\tau+4\tau^2)(\kappa^2+1)}{2(7+4\tau)^2q^2}\right]$$

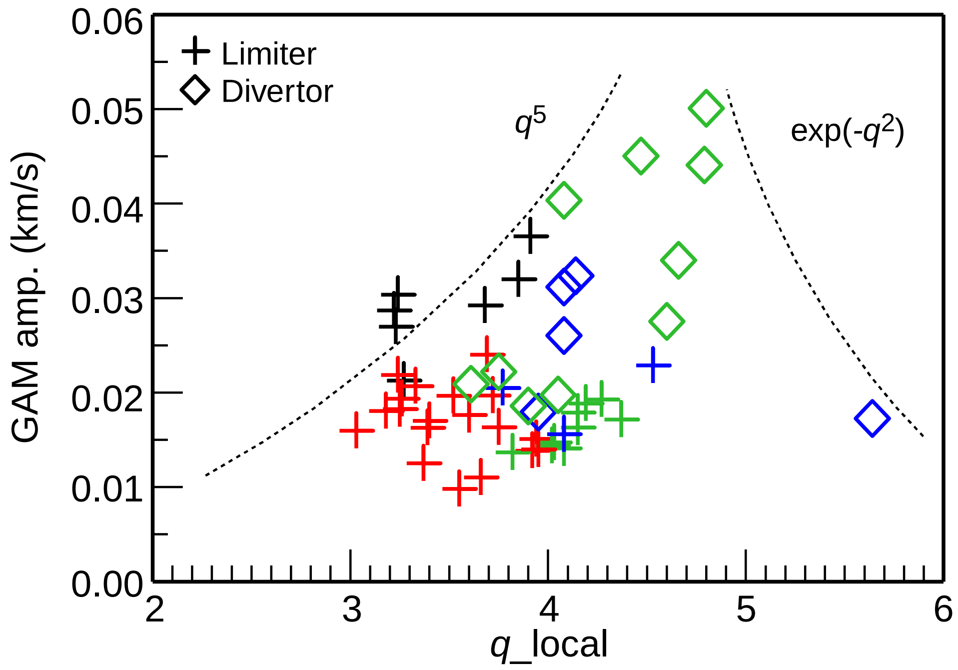
[Gao, PST 2011]

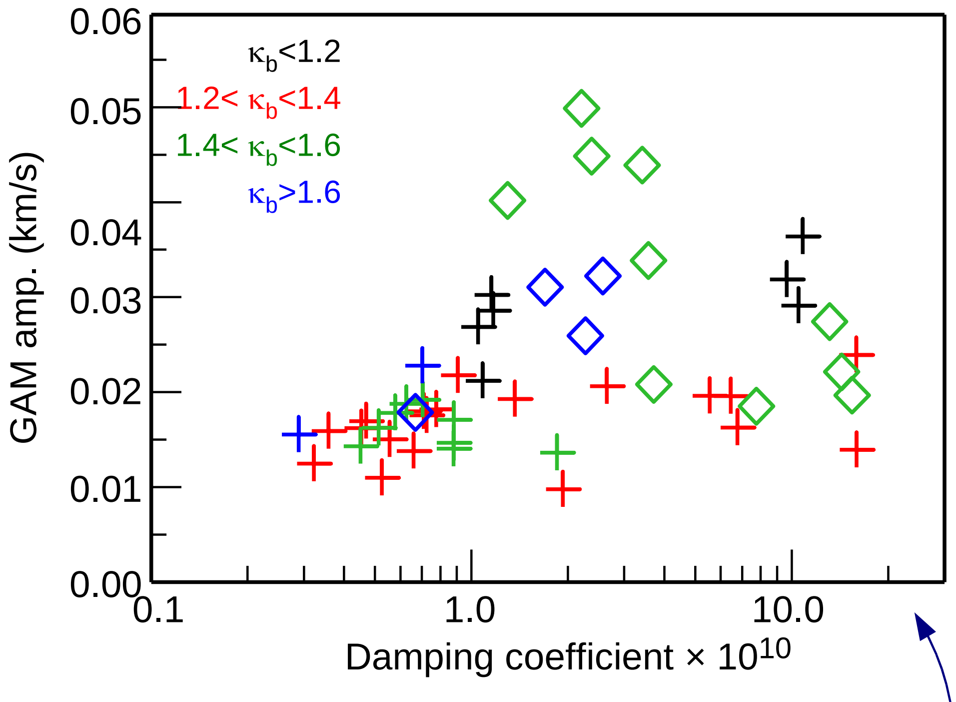




[Simon, IRW 2015]

GAM Amplitude: Damping dependence on κ & *q*





- GAM amp. generally increases with *q*, but falls at high *q*
- Shape / κ_b dependence also present
- Stronger variation for divertor configuration
- NEMORB simulations in progress

- Collisionless damping – w/o $k_r\rho_i$ (Finite Orbit Width) corrections [Gao, PoP 2008]:

$$\gamma_{\rm GAM} = -i\frac{\pi^{1/2}}{2}\frac{v_{ti}}{R}\frac{(R\boxed{\omega_{\rm GAM}}/v_{ti})^6}{(7/4+\tau)}\boxed{q^5}\boxed{\exp\left[-\left(\frac{qR\omega_{\rm GAM}}{v_{ti}}\right)^2\right]}$$

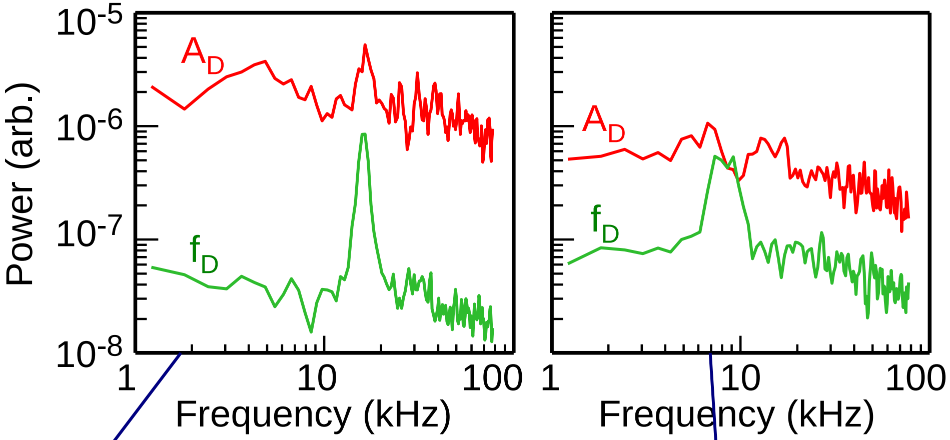
Strong freq. dependence

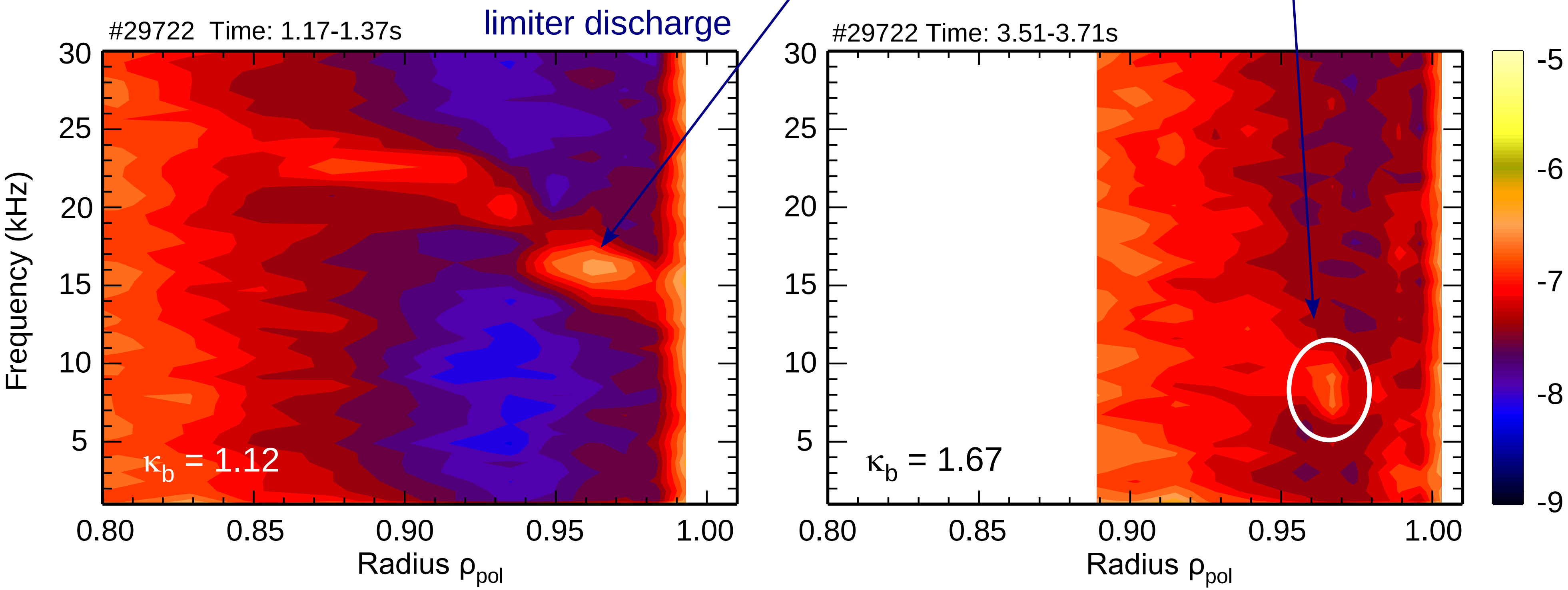
Dominant at low *q*

Dominant at high *q*

GAM Radial structure

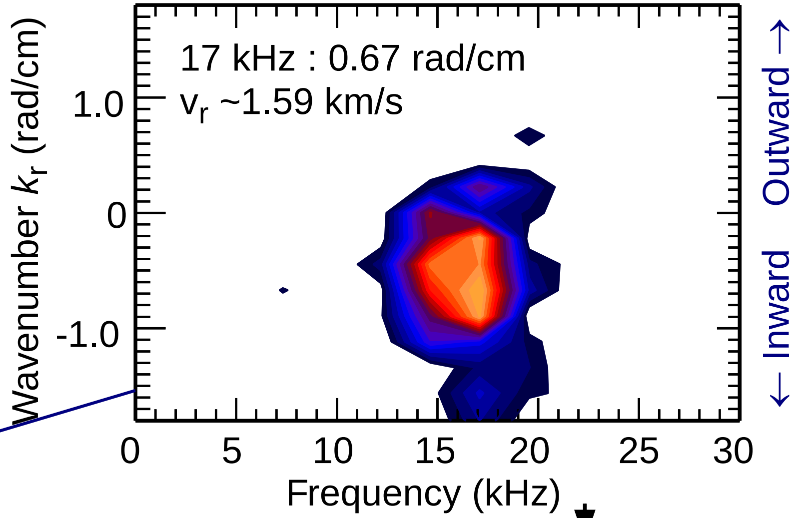
- 2 forms of GAM radial structure:
  - low κ_b: freq. continuum
  - high κ_b: freq. eigenmode
- Stronger GAM at low elongation κ_b (lim.)
- Collisionality & other dependences under investigation

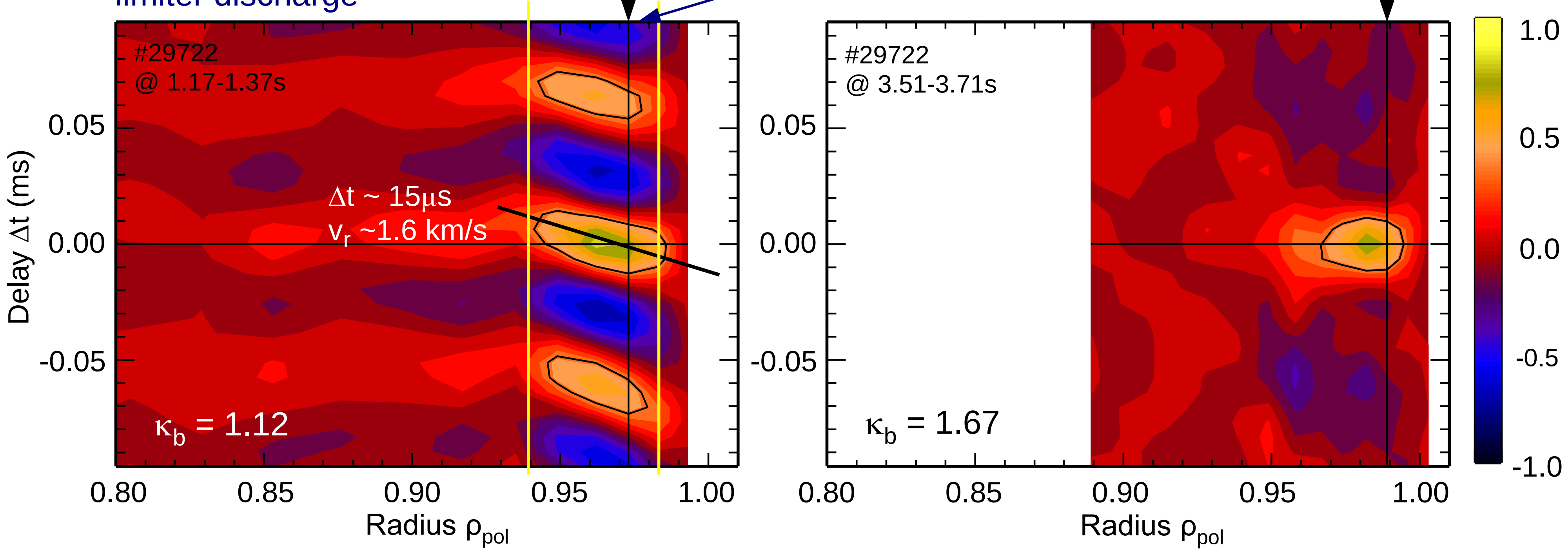




GAM Propagation

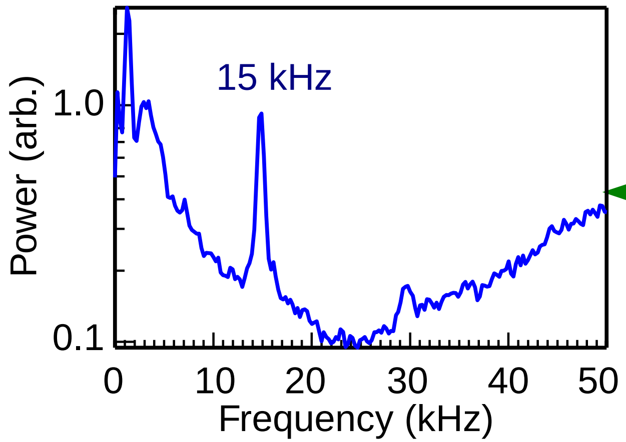
- 2 chn. radial corr. f_D filtered around f_{GAM} (5 – 25kHz)
- Corr. pattern inclined → inward GAM radial prop. (outward prop. also seen: towards GAM peak)
- Inclination falls at high κ_b, eigenmode vs continuum?
- Local $S_l(\omega, k_r)$ spectra → inward k_r ~ 0.67 rad/cm^{-1}

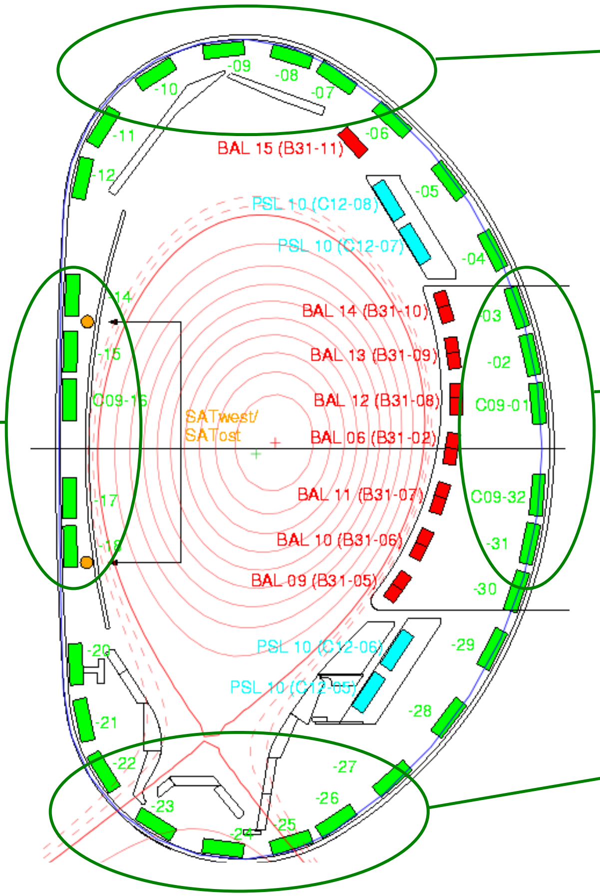




GAM magnetic signature: Divertor discharge

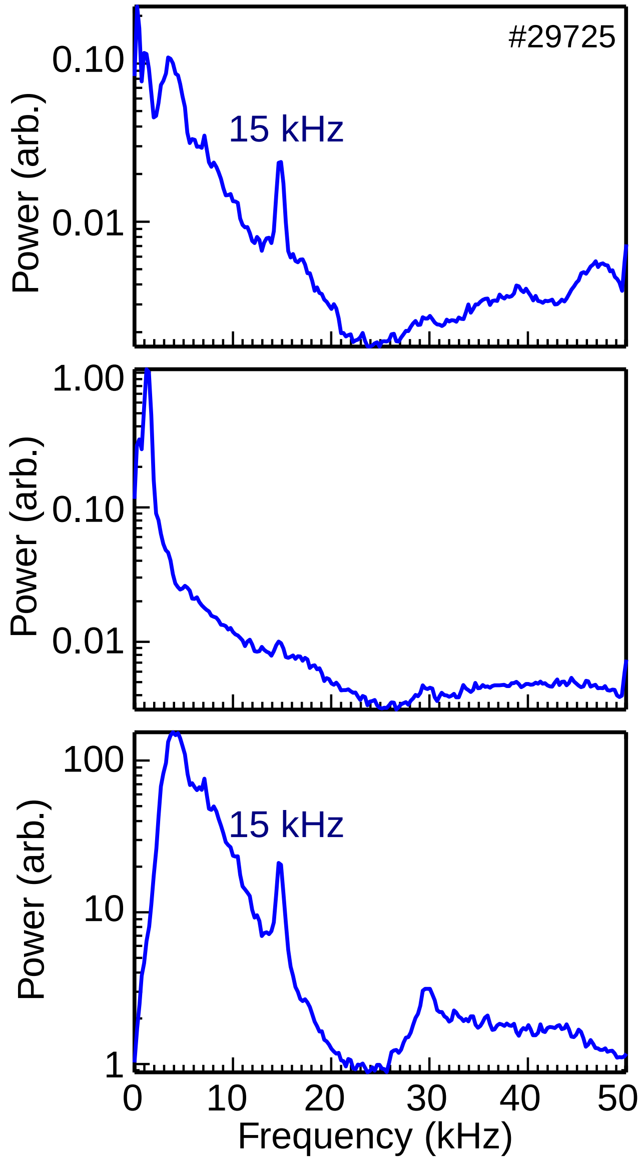
- Theory indicates $m = \pm 2$ magnetic component [Wahlberg, PPCF 2009]
- Doppler: strong eigenmode GAM at 15 kHz





B_r coils (LFS, midplane)

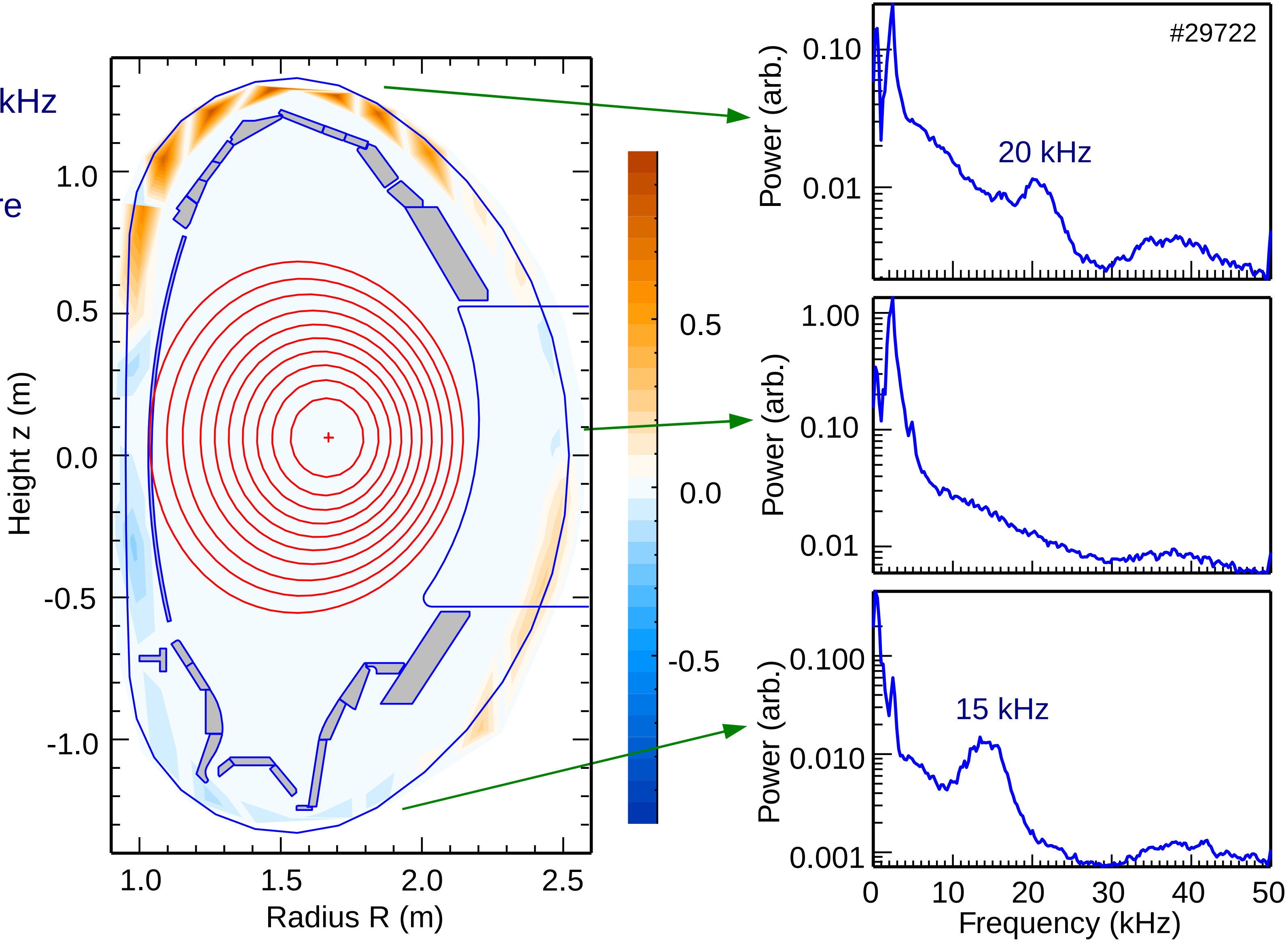
B_{pol} coils (poloidal coverage)



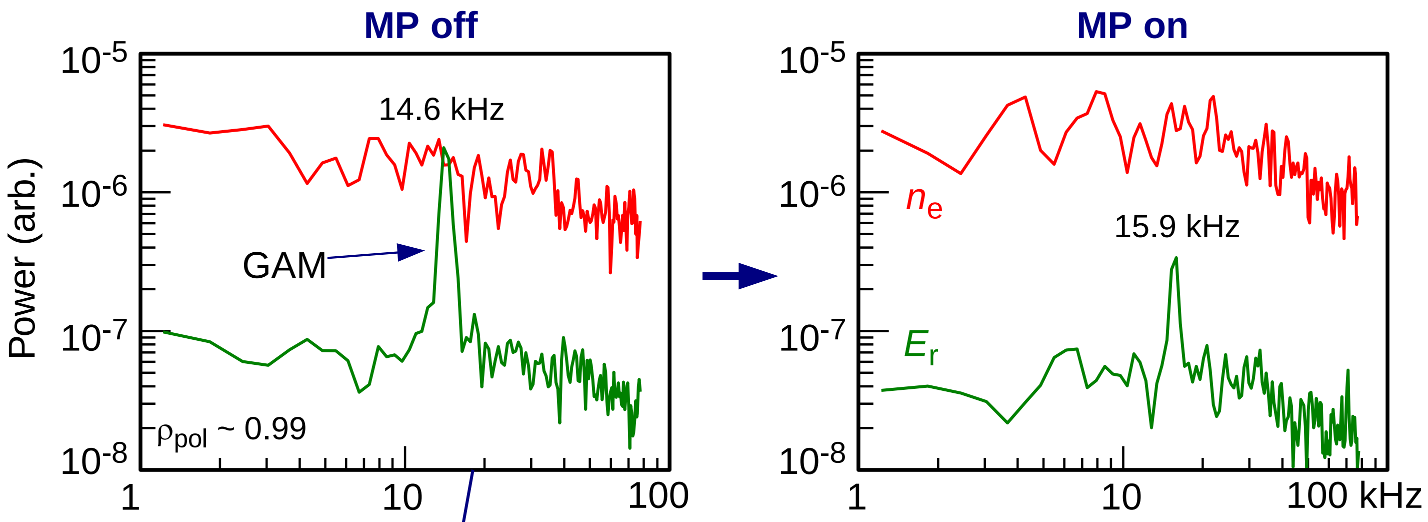
- No B_r signal near outer mid-plane, but weak at top
- For GAM expect: $B_{pol} > B_r$
- Mode analysis: $m \sim 2$ structure

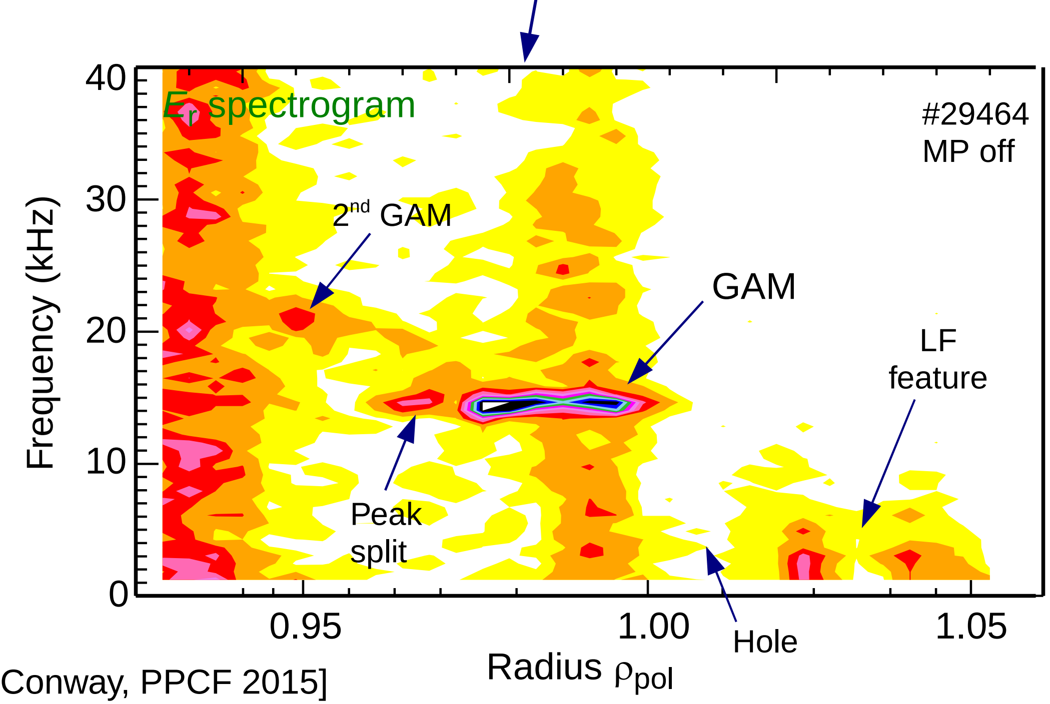
GAM magnetic signature: Limiter discharge at low κ

- Doppler: GAM freq. continuum: 15 – 20 kHz
- Magnetics: approx. *m* = 2 mode structure
- Tilt due to choice of reference probe
- Why different f_{GAM} at top & bottom?



Impact of RMPs on GAM





[Conway, PPCF 2015]

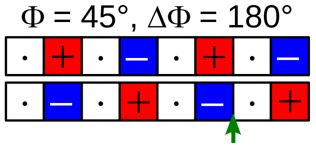
Axisymmetric GAMs

Flow: $n = 0$, $m = 0$

Pres: $n = 0$, $m = \pm1$

Mag: $n = 0$, $m = \pm2$ ...

- Without MP: Strong GAM (flow peak) inside separatrix
- With MP: Flow peak weakens & freq. increases (nb. no T_e change)
- Radial max. moves closer to E_r min.
- $\langle \delta n_e \rangle$ increases, $\langle \delta E_r \rangle$ decreases



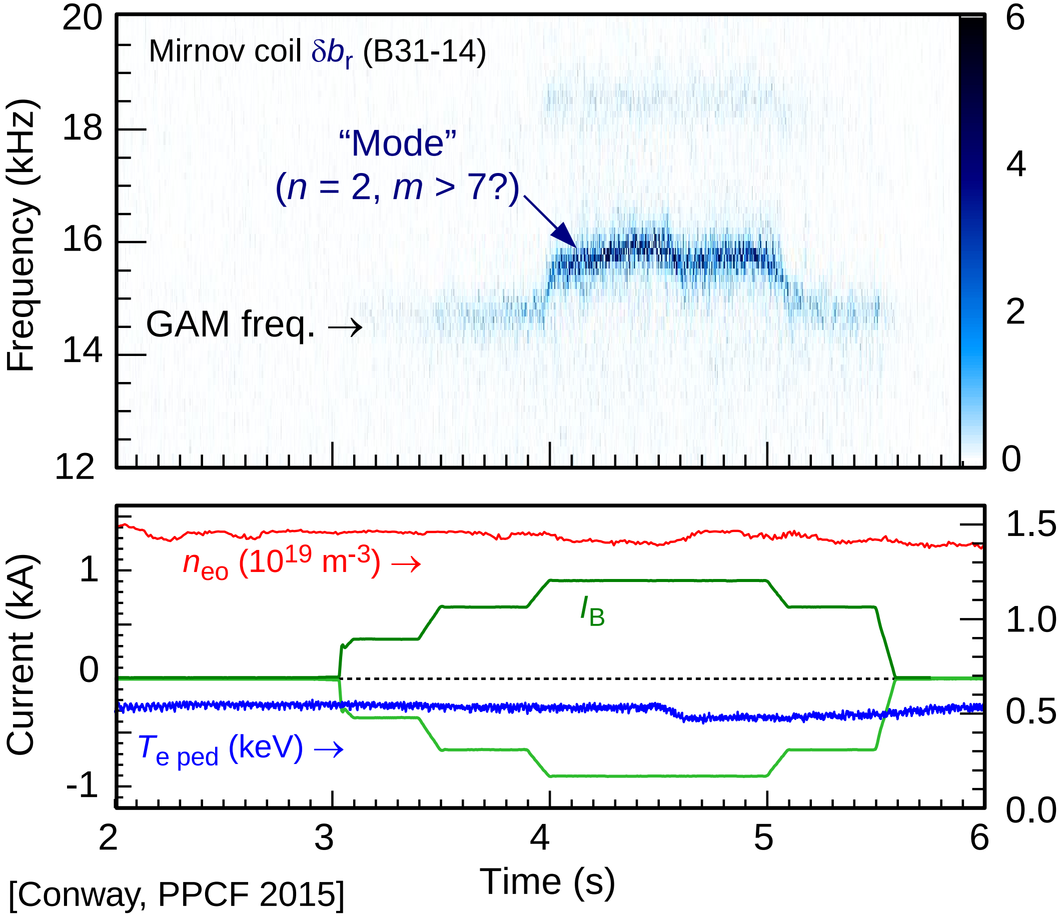
$n = 2$, sig. resonant

$B_T = -2.5$ T, $I_p = 0.8$ MA

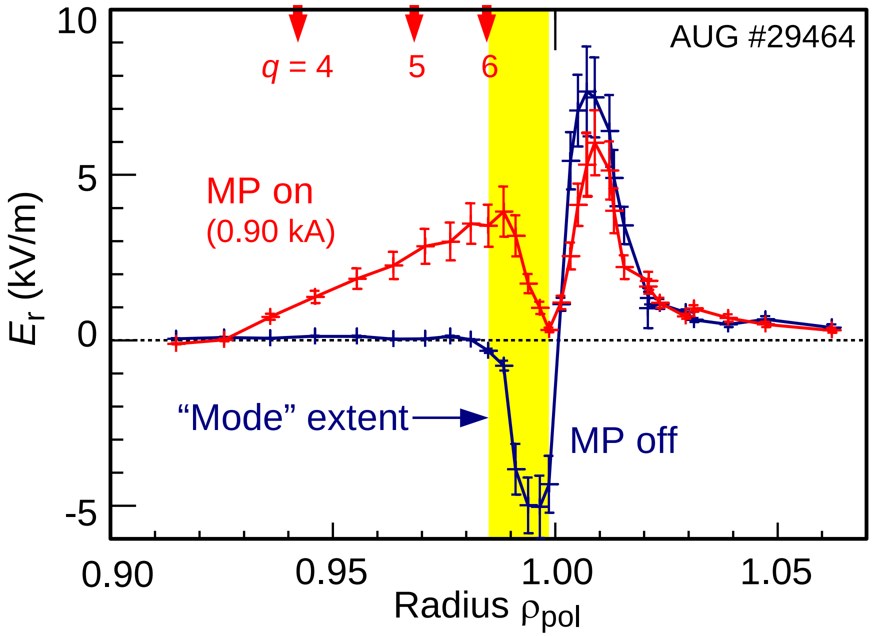
$q_{95} \sim 5.2$, $n_o = 1.5\times10^{19}$ m^{-3}

Impact of RMPs on GAM

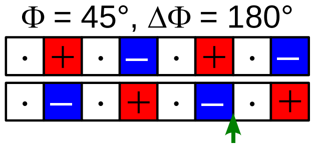
- Enhanced edge magnetic “signature” above MP threshold (in both δb_r & δb_θ)
- Non-MP GAM *normally* only δb_θ signature



[Conway, PPCF 2015]



- δb_r & δb_θ : Complex toroidal structure
- GAM interacts with MP field → non axisymmetric ($n \neq 0$) GAM
- GAM reduced in stochastic regions

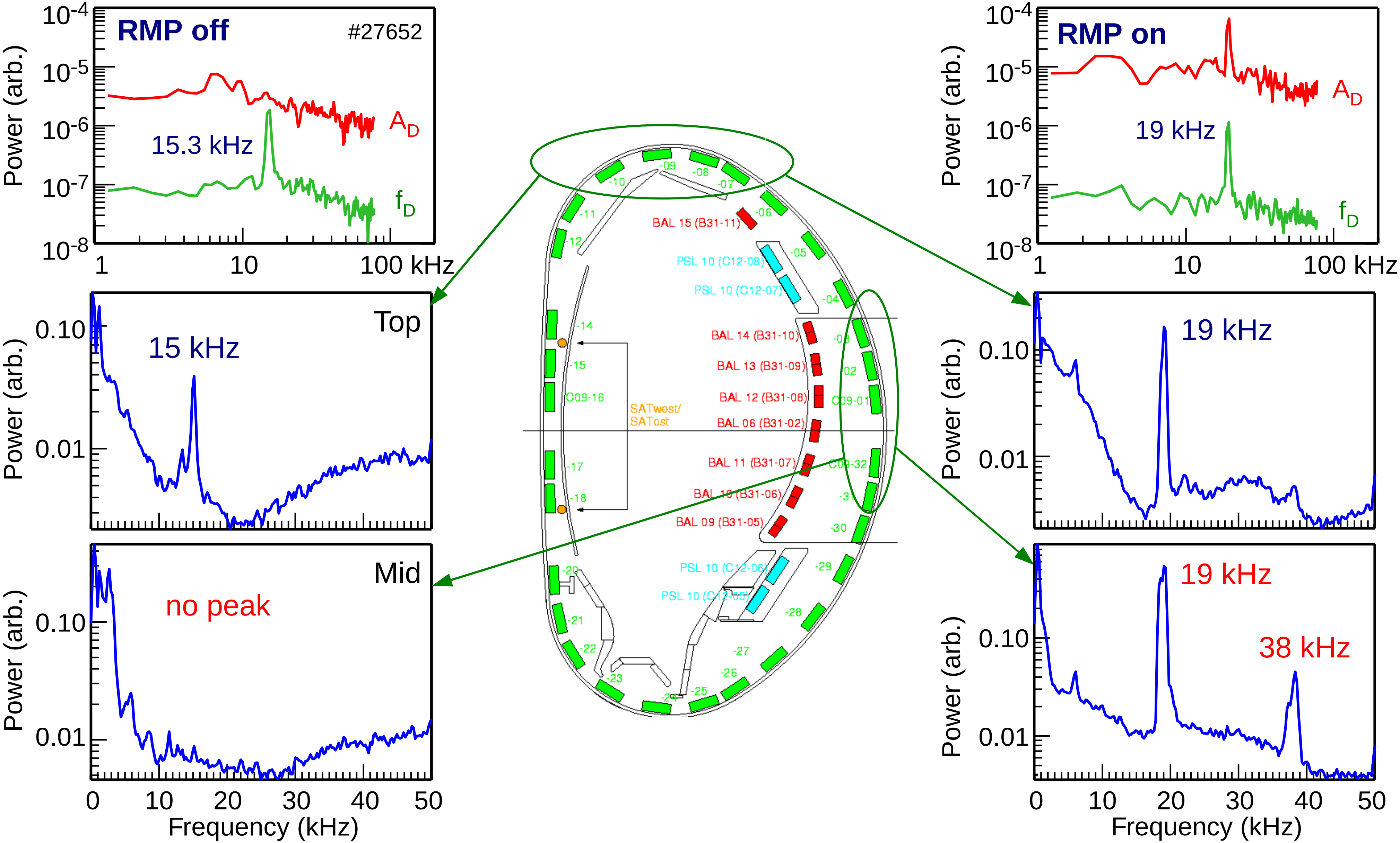


$n = 2$ MP sig. resonant

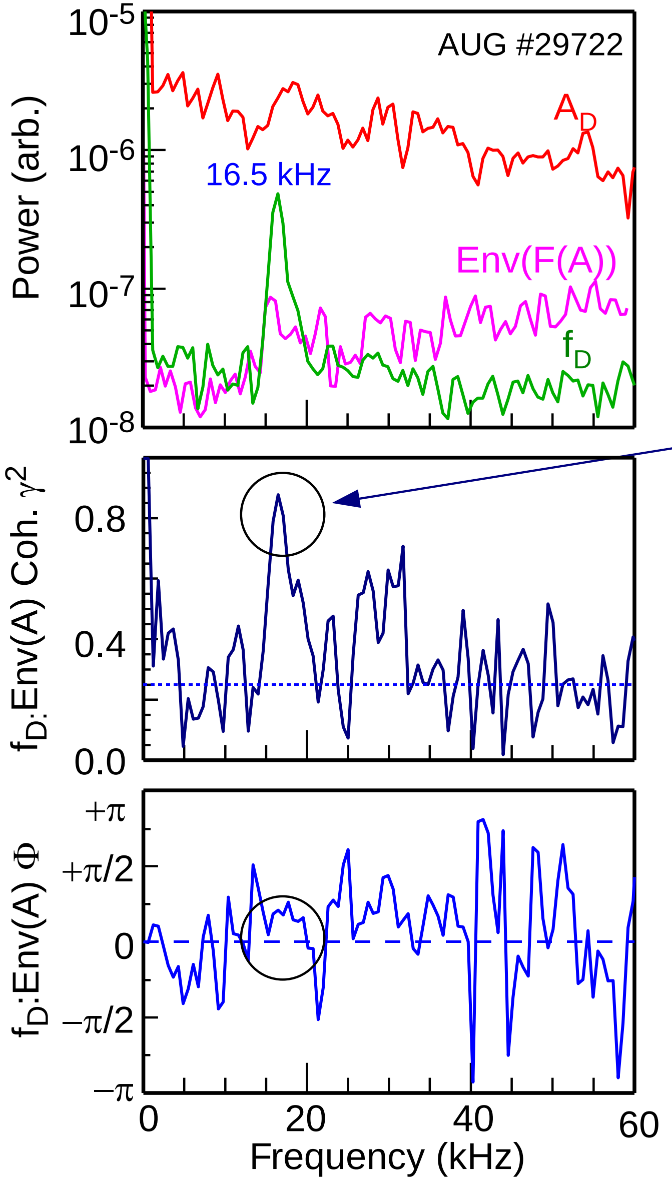
$B_T = -2.5$ T, $I_p = 0.8$ MA

$q_{95} \sim 5.2$, $n_o = 1.5\times10^{19}$ m^{-3}

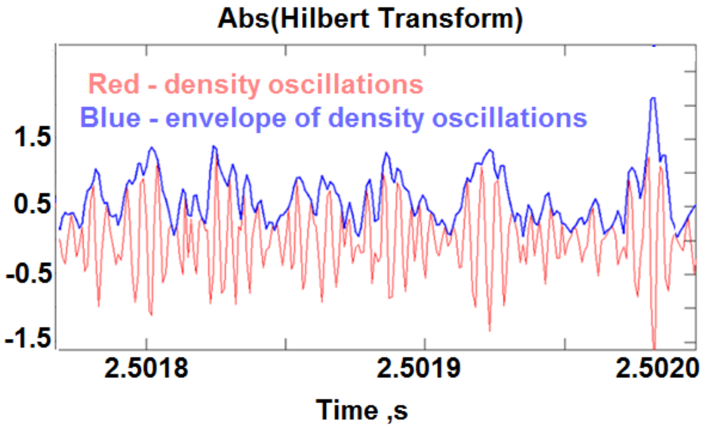
Impact of RMPs on GAM: Magnetic signature



GAM / turbulence interaction

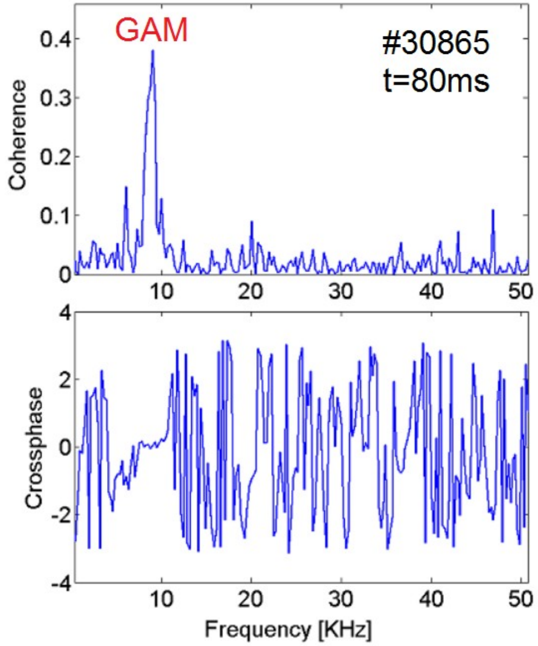


- Theory → GAM modulates the HF density fluctuations
- Extract flow from *envelope* of *high-pass filtered* δn_e using Env(n) = $\sqrt{\{nn^* + \mathfrak{H}(n)\mathfrak{H}^*(n)\}}$ [Nagashima, PPCF 2007]
- Correlate Env(δn_e) $_{\{PCR\}}$ & $f_{D\ \{DR\}}$ → $\Phi \sim 0$ cross-phase at tok. mid-plane (different tor. sectors)
- Env(A)$_{\{DR\}}$ & $f_{D\ \{DR\}}$ → $\Phi \sim 0.0$ Expect $\Phi = \pi/2$ at top?



Coh. γ between Env(δn) $_{(PCR)}$ & flow $_{(DR)}$

[Prisiazhniuk, IRW 2015]



Conclusions

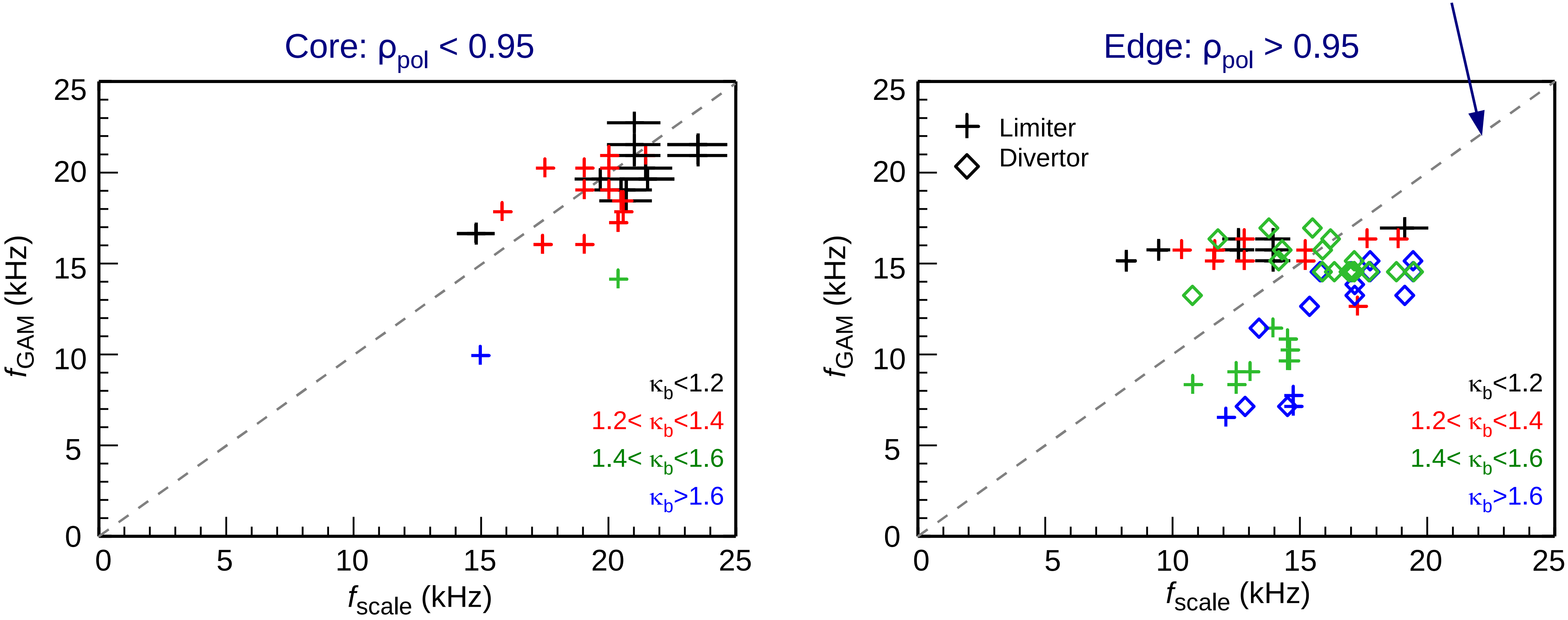
- GAM frequency > Gao formular (gives min. freq.)
  - f_{GAM} raised by non-linear effects and possibly higher shaping orders (X-point)
  - Still to include Z_{eff} in scaling
- GAM amplitude
  - Scales roughly inversely with damping (drive effects under investigation)
  - Different behaviour for divertor config.
  - Numerical simulations progressing
- GAM structure & propagation
  - Either radial continuum or eigenmode (κ dependence – collisionality under investigation)
  - Propagates mostly inward: $k_r \sim 0.7$ rad/cm & $v_r \sim 1.6$ km/s (radial acceleration under invest.)
  - Roughly $m = 2$ magnetic structure (eigenmode vs continuum)
- External MPs – strong impact
  - non-axisymmetric GAM structure?
  - Stochastization weakens & ev. suppresses GAM despite turb. rise
- GAM – turbulence interaction evident

GAM Frequency Scaling: Core vs. Edge

- GAMs contribute to effective shearing rate & reduce turb. correlation length if $f_{GAM} < \tau_d^{-1}$
- Analysis of new limiter and divertor with varying κ_b line-up with previous results
- Core GAMs (limiter only) follow classic scaling (even with κ_b scan)
- Edge GAMs deviate from core scaling

[Winsor *et al.*, PF 1968]

$$f_{scale} = \sqrt{2}\, c_s / (2\pi R_0)$$



GAM Amplitude: Dependence on κ & *q*