Energetic Particle-Induced Geodesic Acoustic Modes on DIII-D

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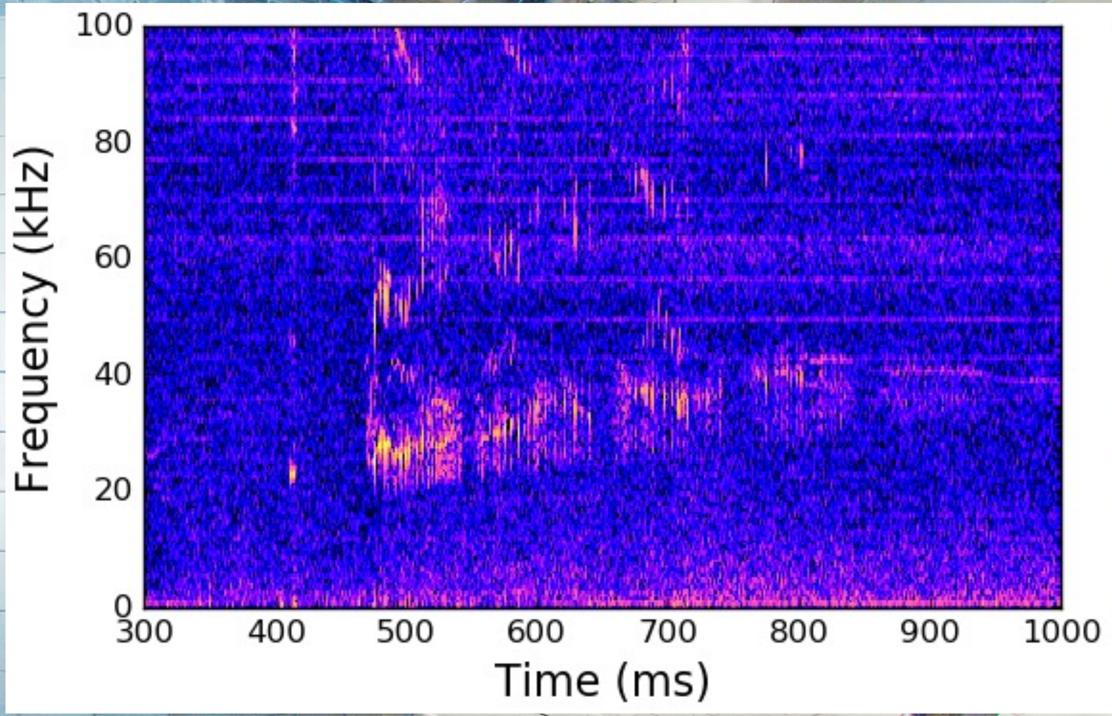

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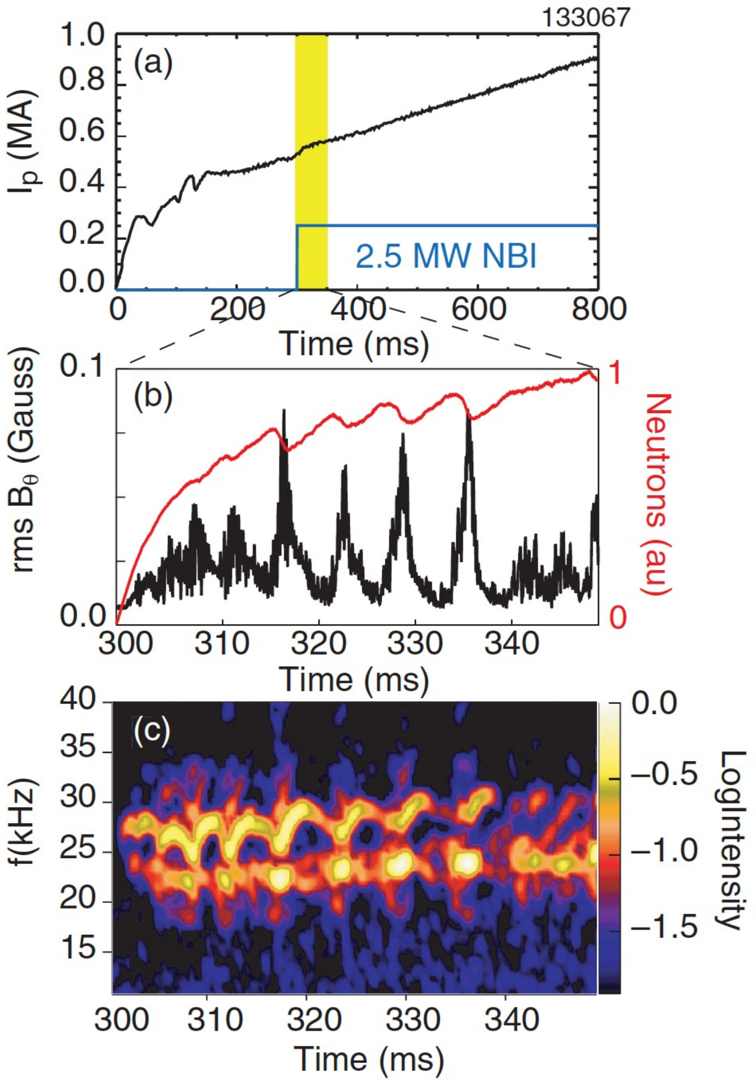
UCI

EGAMs typically appear in the early stages of the discharge on DIII-D

- **Low frequency toroidally symmetric (n=0) mode[1]**
  - Fundamental frequency between 20-40 kHz
- **Usually observed when counter-I_p beam is on**
- **Typically appears as amplitude bursts**
  - Also seen to be continuous, sweep in frequency, and oscillate in frequency and amplitude
- **Observed to cause losses of injected beam ions[1,2,3]**



Robustly characterize different EGAM properties using a large database

[1]R. Nazikian PRL 101 185001 (2008)
[2]G.J. Kramer et al PRL 109 035003 (2012)
[3]R.K. Fisher et al NF 52 123015 (2012)

Outline

- Background on EGAMs
- Example discharge with EGAMs
- Observed mode properties
- Summary

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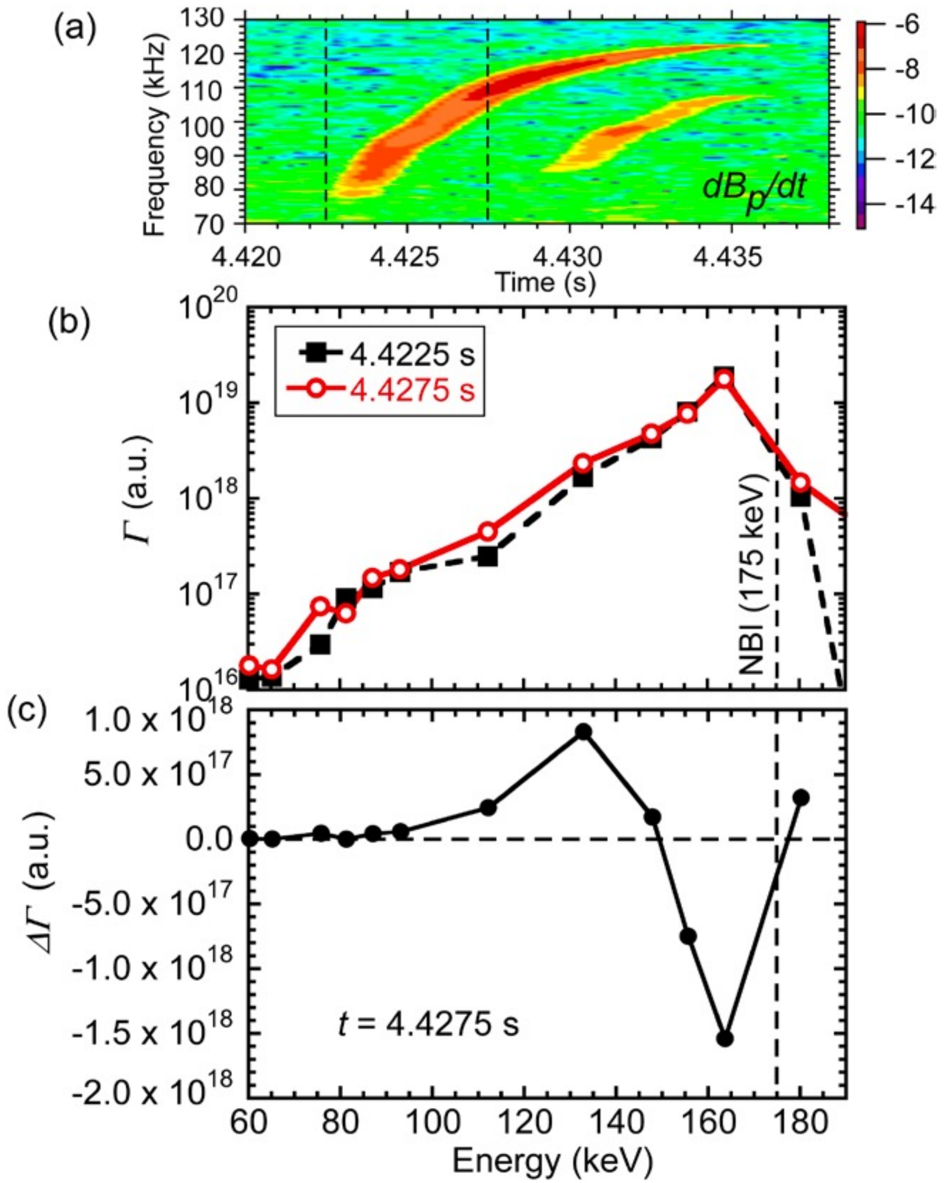
EGAMs are driven by wave particle interactions with the energetic particle distribution

- **Modes can originate from GAM branch or a distinct EGAM branch[1]**
  - Depends on ω_{b0}/ω_{GAM} and P_h/P_{th}
- **Existence of loss region suggested to produce necessary gradient to drive EGAMs[2]**
- **Energetic particle destabilization of GAMs first observed in JET using ICRH[3]**
- **Studies at LHD showed EGAM excitation by inverse Landau damping on a beam ion distribution[4]**



[1]G.Y. Fu PRL 101 185002 (2008)
[2]H.L. Berk and T. Zhou NF 50 035007 (2010)
[3]H.L. Berk et al NF 46 S888 (2006)
[4]T. Ido et al NF 55 083024 (2015)

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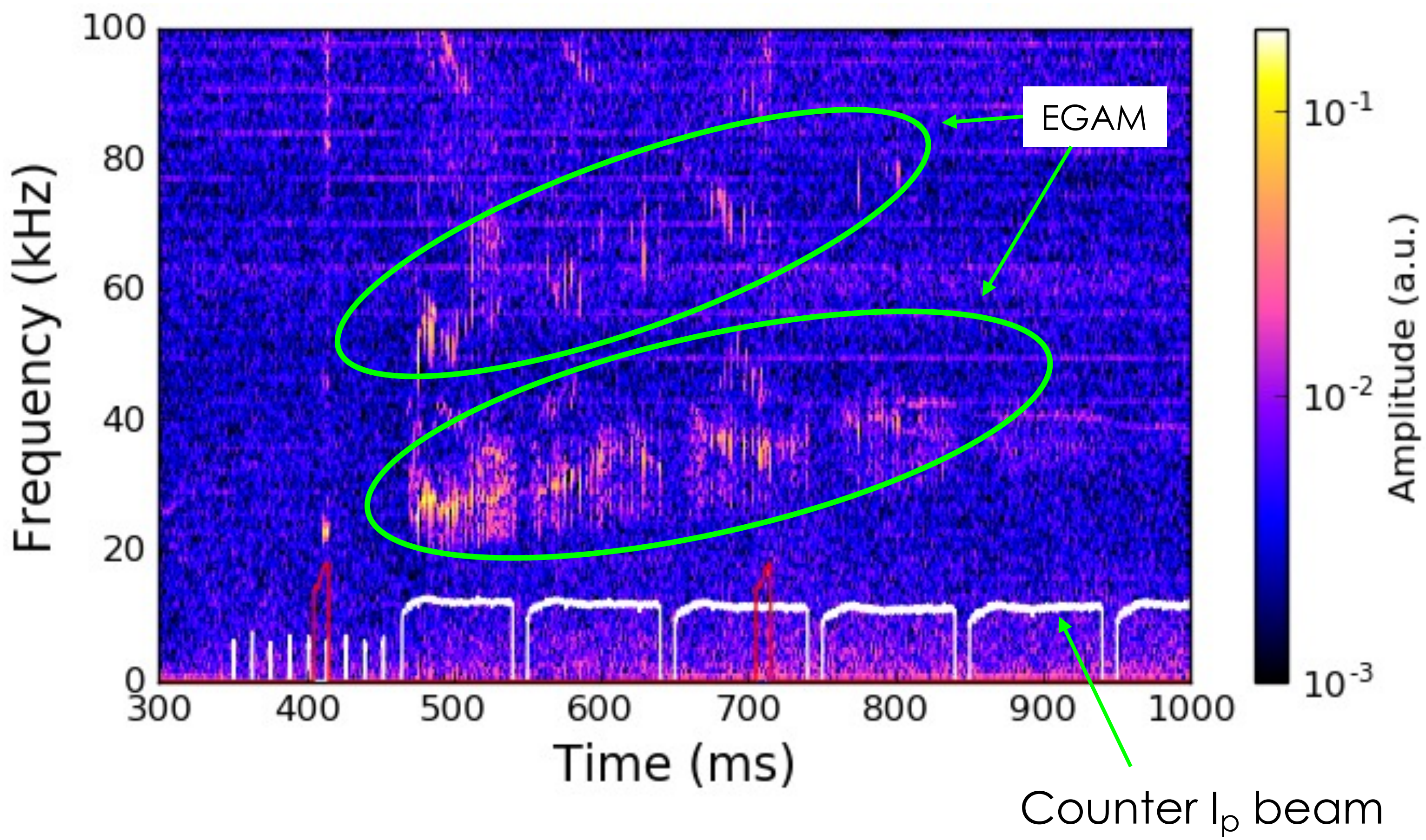
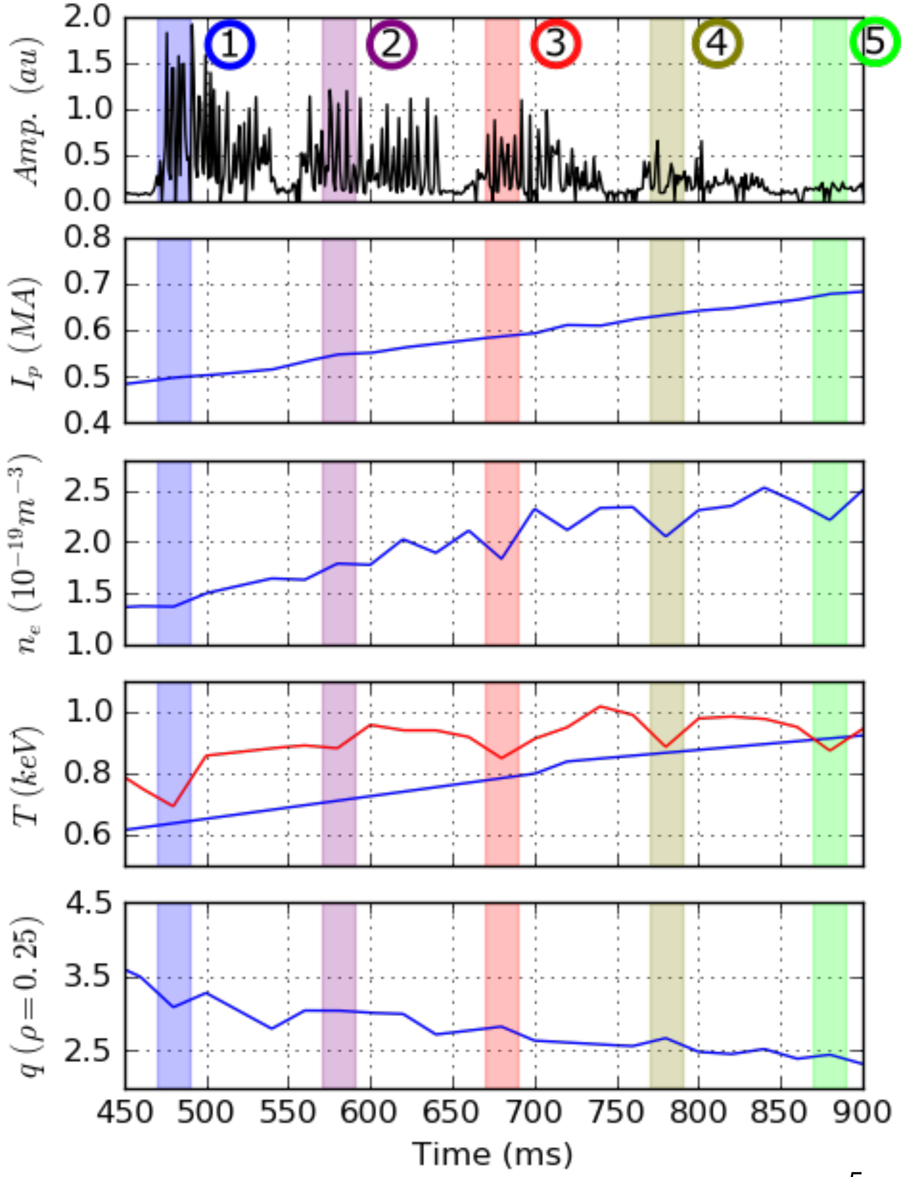
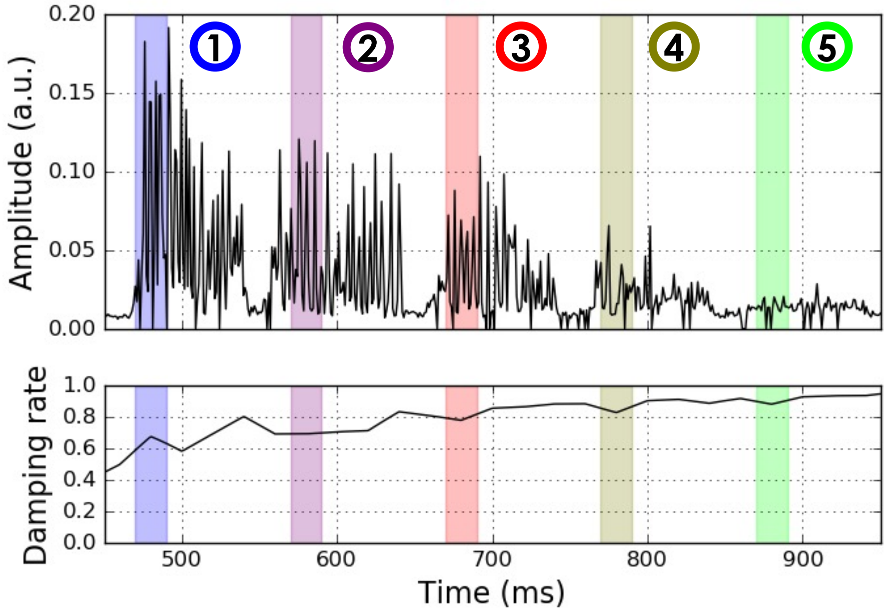
EGAMs appear in a discharge fueled by counter I_p beam on DIII-D

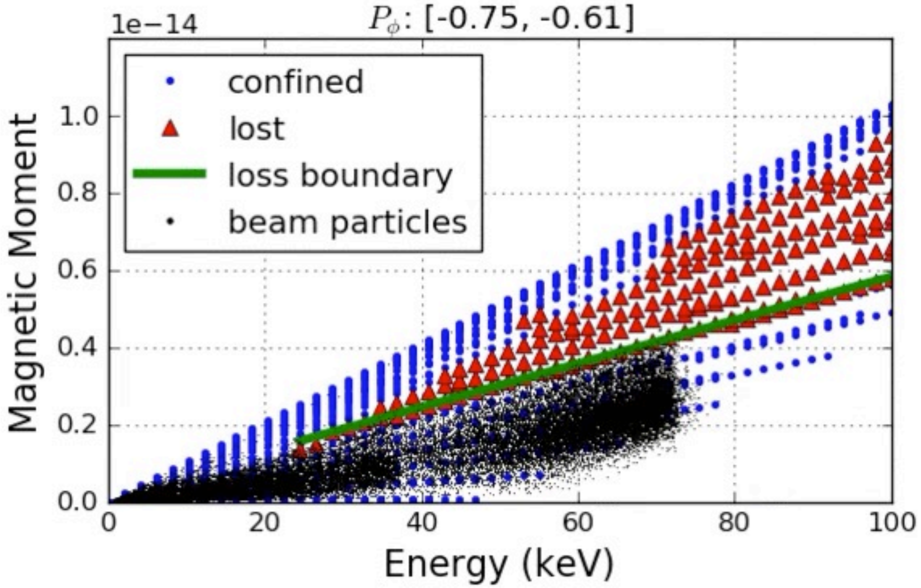


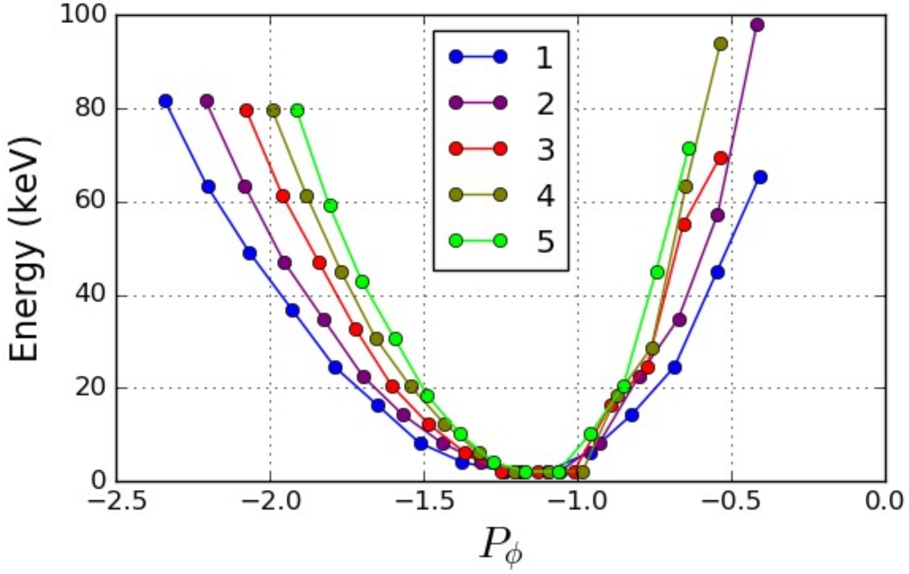


Loss region shrinks with mode amplitude

- **Scan of orbit topology reveals loss region in constants of motion space**
- **Loss boundary characterized by minimum energy for a given P_φ**
- **Loss region shrinks as time increases**







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Data from ~900 shots are compiled during the current ramp stage of the discharge

- **Nearly all shots selected from dedicated energetic particle experiments on DIII-D[1]**
  - Data taken between 300 – 1000 ms
- **Mode characteristics obtained through magnetic spectrograms**
  - Temporal resolution of ~1 ms w/ an FFT window of ~2 ms
  - Frequency resolution of ~0.5 kHz w/ ~0.3 kHz smoothing
- **Time points are determined to be stable or unstable based on how the amplitude compares to a manually set threshold**
  - Counter I_p must be on
  - ~28000 unstable points found
  - ~26000 stable points found

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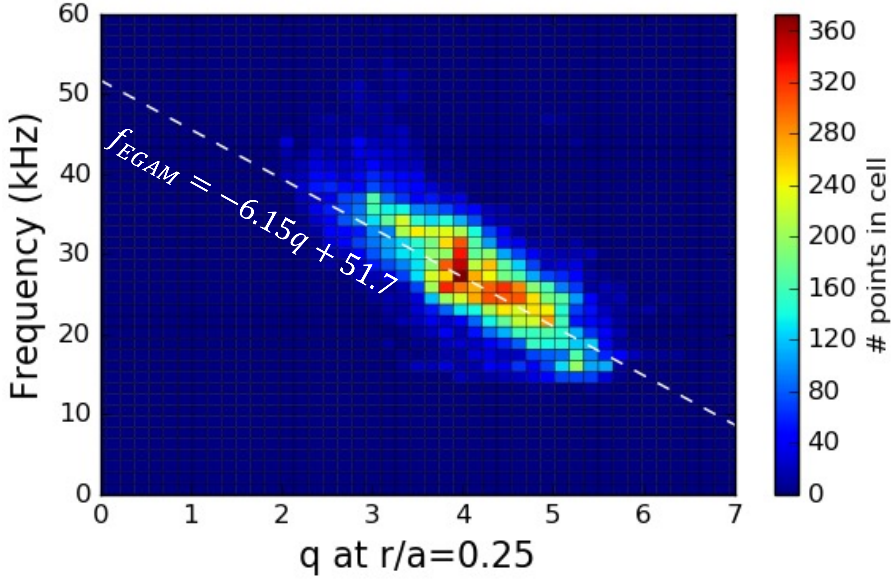
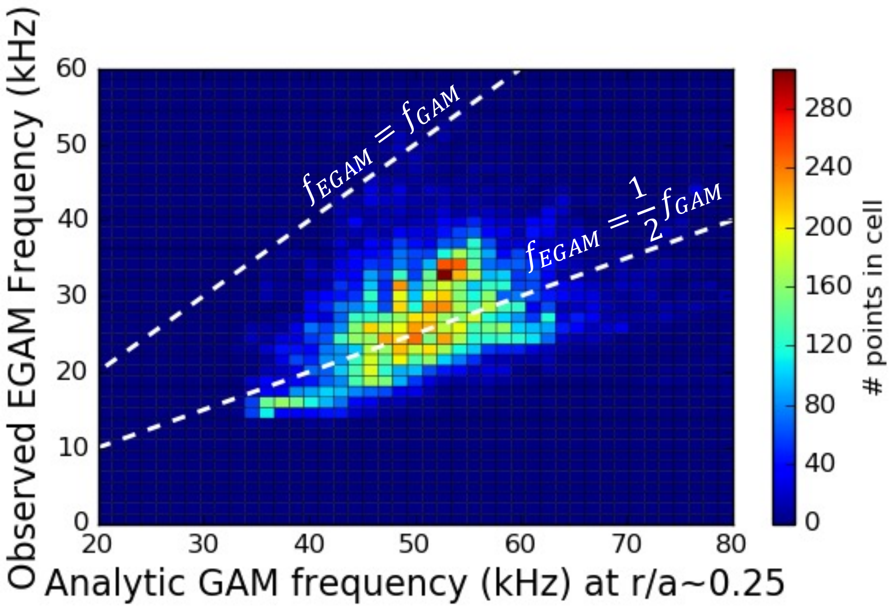
[1]W.W. Heidbrink NF 61 016029 (2021)

Mode frequency is strongly correlated with q



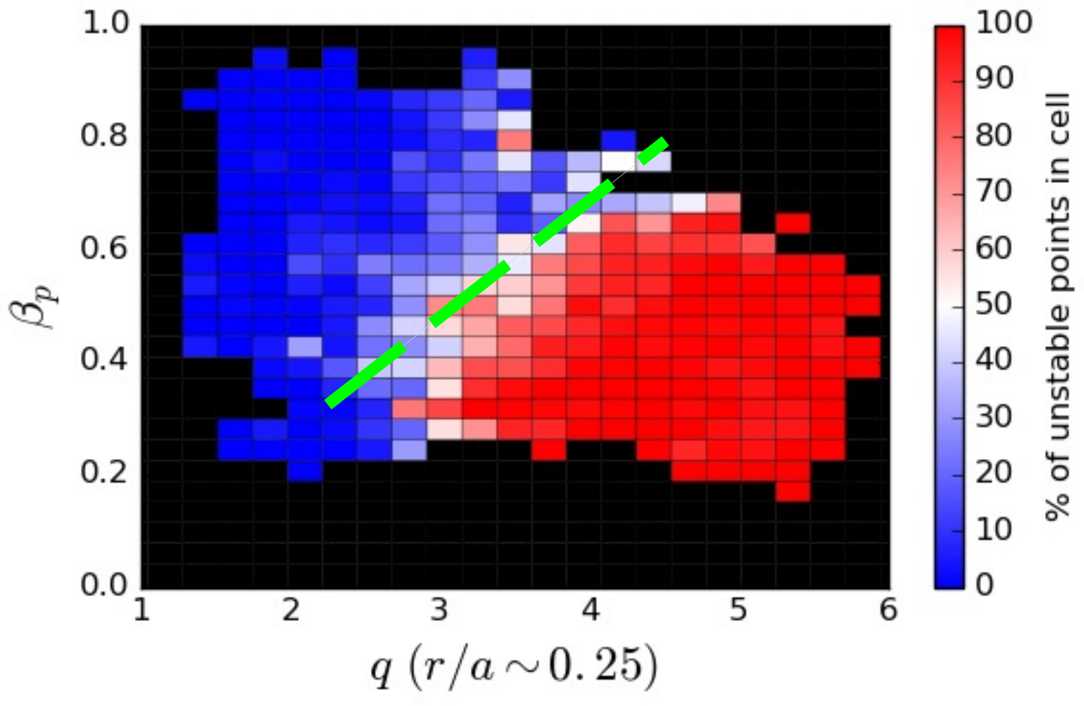


- **Correlation value of R=-0.712 found between mode frequency and the safety factor (q) at r/a~0.25**
  - Pearson correlation coefficient
- **Poloidal transit frequency affected by q for fixed particle energy**
- **Frequency ratio[1] expected to be around f_{EGAM}/f_{GAM}~0.5**
  - Mode does not originate from GAM branch

$$(\omega_{\mathrm{GAM}}^{\mathrm{WJD}})^2 = 2\frac{c_s^2}{R_0^2}\left(1+\frac{1}{2q^2}\right)$$

[1]G.Y. Fu PRL 101 185002 (2008)
[2]N. Winsor et al Phys. Fluids 11 2448 (1968)

EGAMs are most unstable at high q



More unstable
More stable

- **A stability boundary can be seen following an increase in β_p with q**
- **Modes at high q suggests that it is on distinct branch separate from GAM branch[1]**
- **Increase in β_p (ratio of plasma pressure to magnetic pressure) appears to stabilize the mode**
  - Previous study expected the opposite trend due to resonance condition[2]

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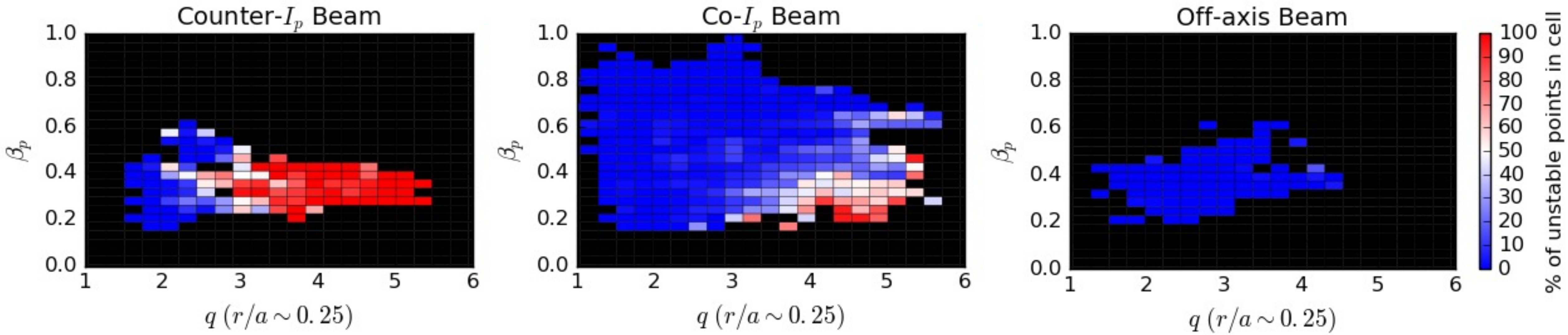
[1] J. Girardo et al Phys. Plasmas 21 092507 (2014)
[2] Ya.I. Kolesnichenko et al PPCF 55 125007 (2013)

EGAMs are most unstable during counter beam injection



Beam Geometry	Unstable points	Stable points	% Unstable points
Counter-I_p	3899	3900	50.0%
Co-I_p	4615	68014	6.35%
Off-axis	41	6073	0.67%

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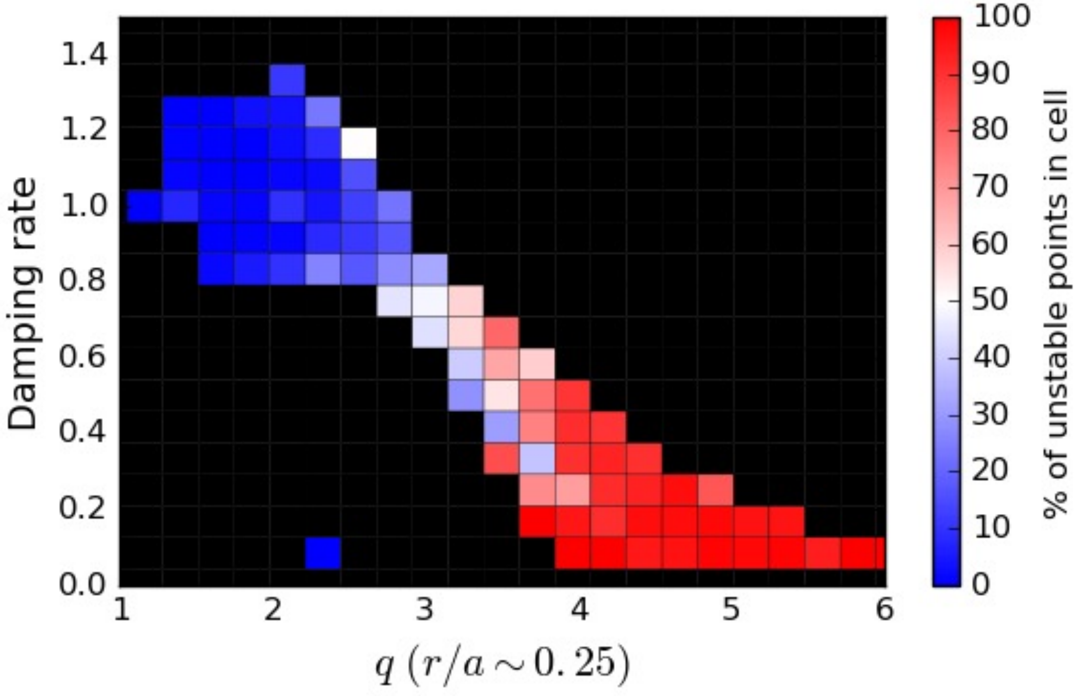
Mode stability appears to depend strongly on damping rate



$$\gamma_G \approx \frac{\omega_G\sqrt{\pi}}{2}\left[\sqrt{\pi}C_D\left[(5\lambda_0-2)(2-\lambda_0)-\frac{15\Delta\lambda_0^2}{4(1-\lambda_0)}\right]\right.$$

$$\boxed{\left.-\left[\frac{1}{2}\frac{\omega_G^3R_0^3q^3}{v_{Ti}^3}+(1+\tau_e)\frac{\omega_G R_0 q}{v_{Ti}}\right]e^{\left(-\frac{\omega_G^2R_0^2q^2}{v_{Ti}^2}\right)}\right]}$$

- **Landau damping rate contains a nonlinear dependence on q[1]**
  - Nearly linear within the database domain
- **Modes tend to be unstable when damping rate < 0.7**
- **Strong distinction suggests strong dependence on damping rate for mode stability**

[1]F. Camilo de Souza et al JPP (submitted)

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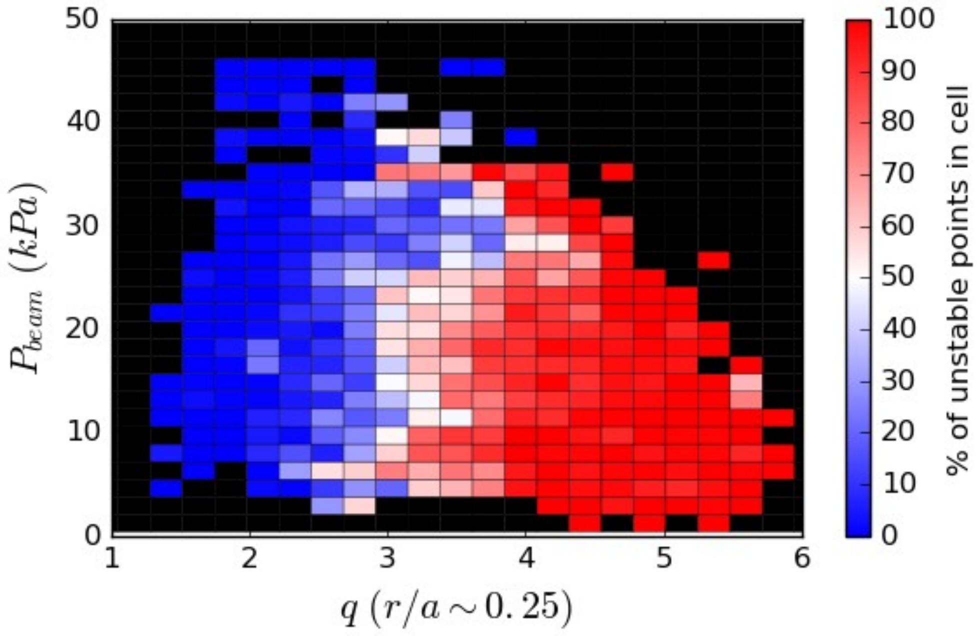
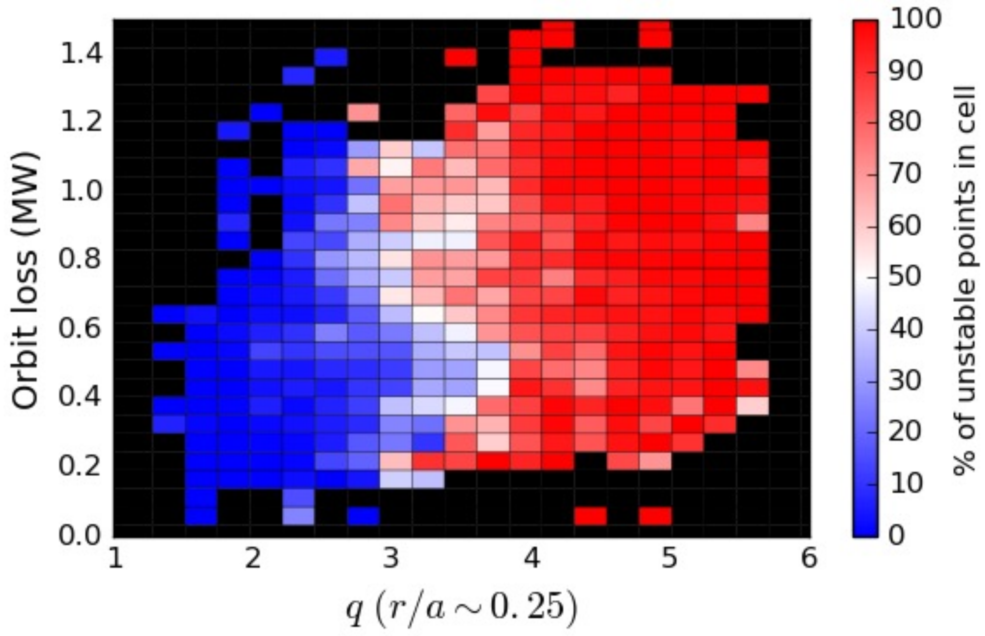
Mode stability does not appear to depend on quantities related to the drive

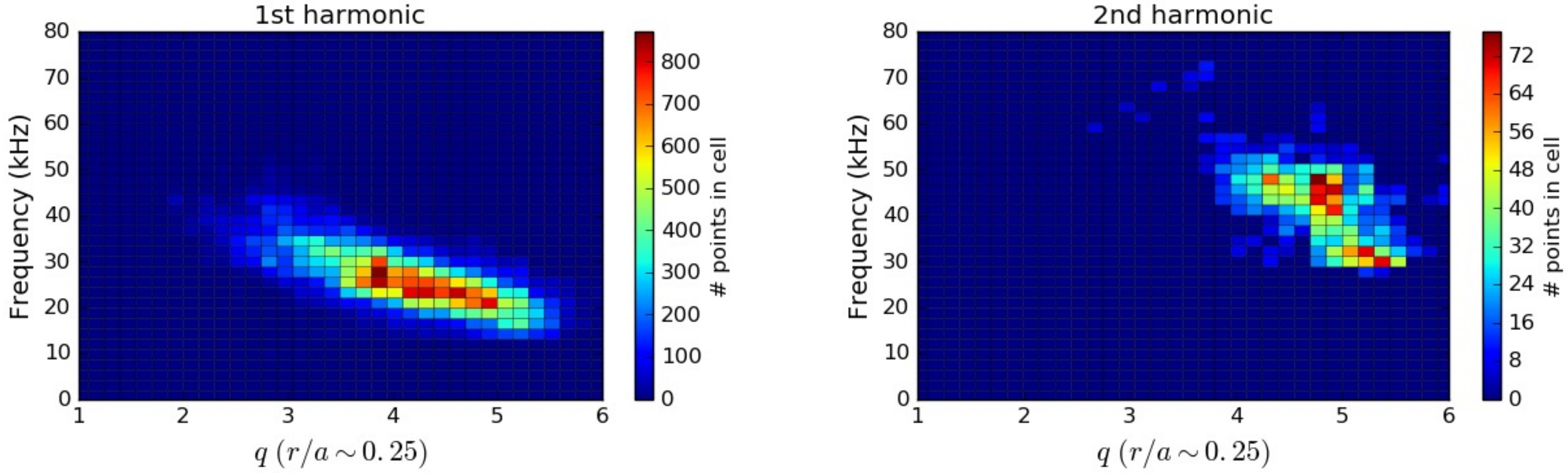




- **RABBIT[1] used to calculate beam pressure and power to loss orbits**
  - Classical calculations for beam ion distribution
- **No strong dependence on stability boundary for RABBIT quantities**
- **Variation in drive may be samll compared to damping rate**

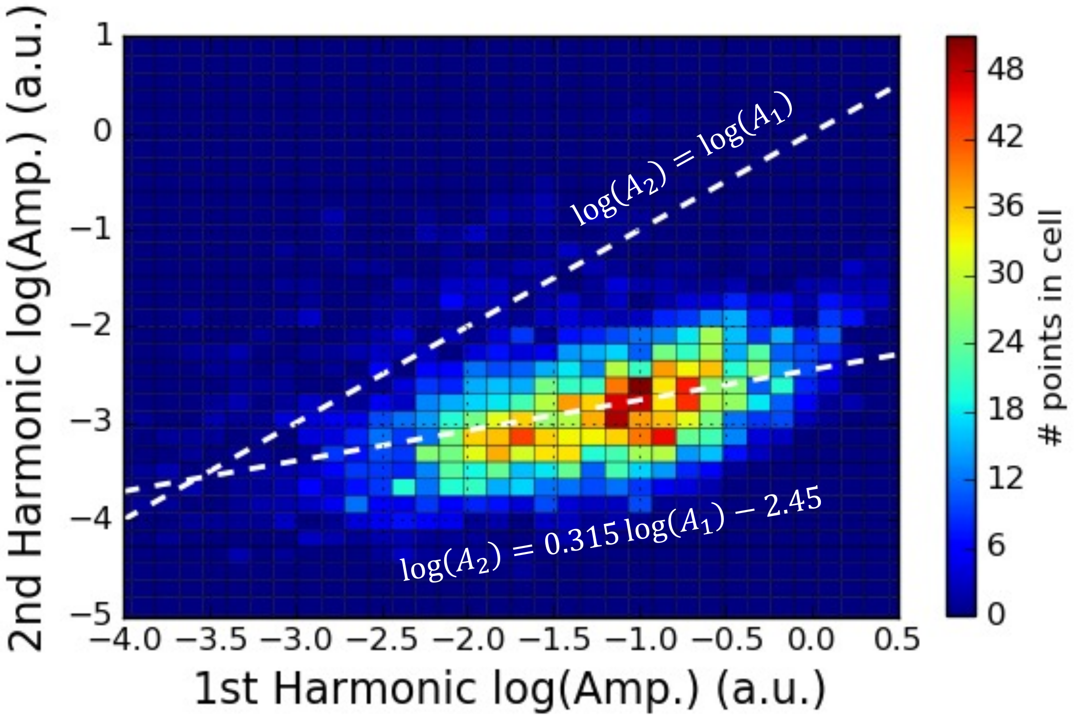
[1]M. Weiland et al NF 58 082032 (2018)

2^{nd} harmonic signals appear much less frequently



- 2^{nd} harmonic signals (~3000) occur ~15x less often than 1^{st} harmonic signals (~45000)
- 2^{nd} harmonic are present when q(r/a~0.25) > 3.5
- No significant amount of other higher harmonics are detected

2^{nd} harmonic amplitudes increase with 1^{st} harmonic amplitudes

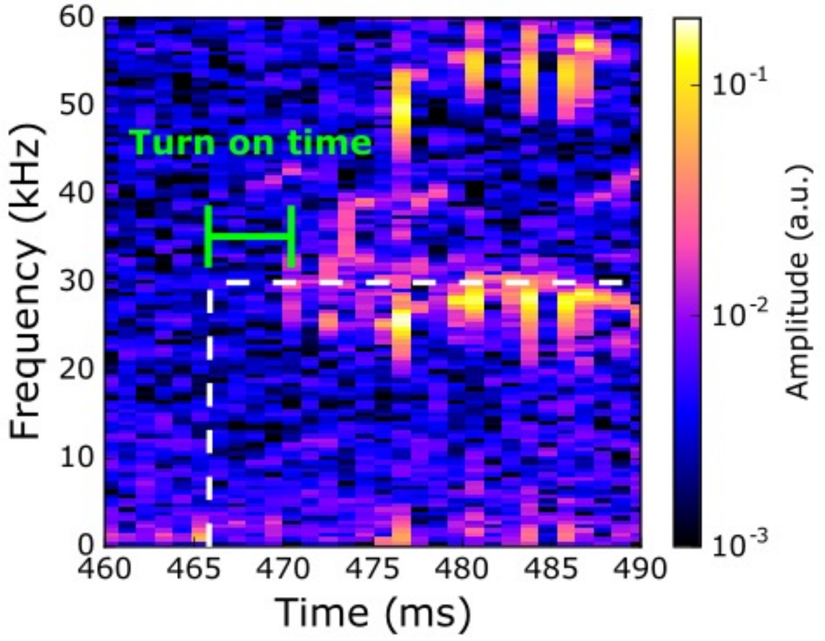


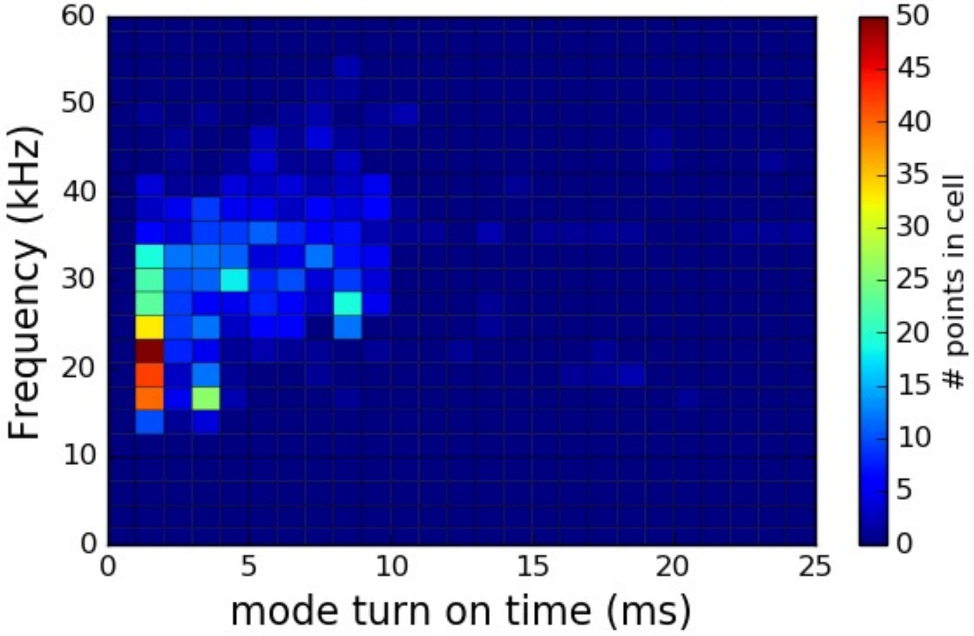
- **2^{nd} harmonic amplitude is lower than 1^{st} harmonic amplitude**

- **Visible trend where 2^{nd} harmonic amplitude scales with the 1^{st} harmonic amplitude**
  – Slope of log amplitude is ~0.315

EGAMs are quickly excited once the counter I_p beam turns on

- Mode turn on times are shorter than scattering times (~100 ms) and longer than resonant orbit transit times (~10 μs)
- Highest density of points clustered during 1 ms
- Faint relationship where modes take longer to appear when the frequency is higher





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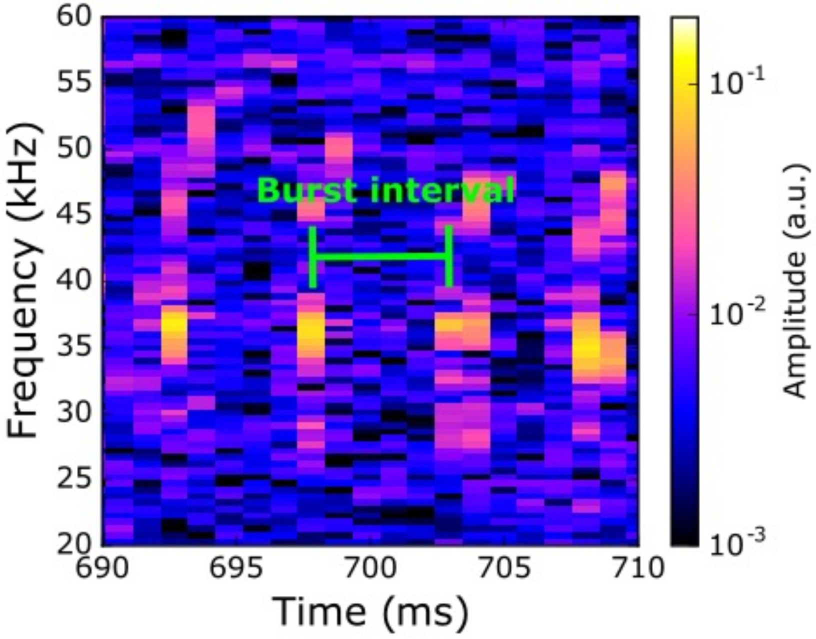
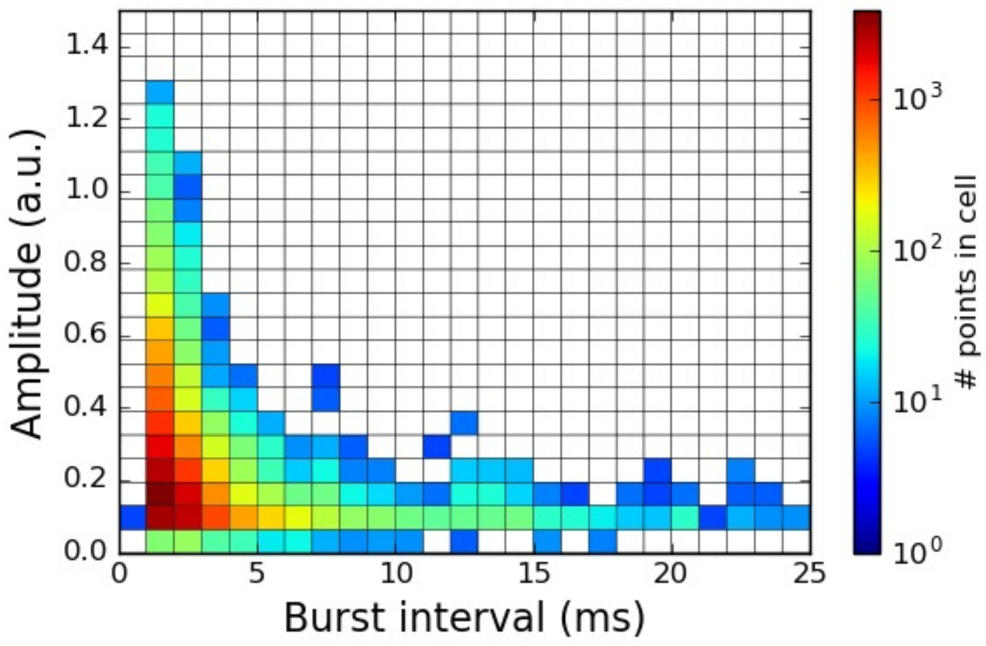
Mode amplitude decreases with increasing burst interval

- **Exponential-like decay of mode amplitude with the burst interval**
- **Behavior different from fishbones and TAE bursts where longer burst intervals have larger amplitudes[1]**
  - Larger amplitudes → larger flattening of gradient → longer gradient recovery
- **Larger amplitudes may somehow correlate to a faster gradient recovery**





[1]W.W. Heidbrink et al Phys. Fluids B 5 2176 (1993)

Summary

- Mode frequency strongly related to q
- Mode observed on DIII-D originates from a distinct EGAM branch separate from the GAM branch
- Mode is most easily destabilized by counter I_p beam
- Stability of the mode largely determined by damping rate for a given beam on DIII-D
- Mode amplitude exponentially decreases with increasing burst interval

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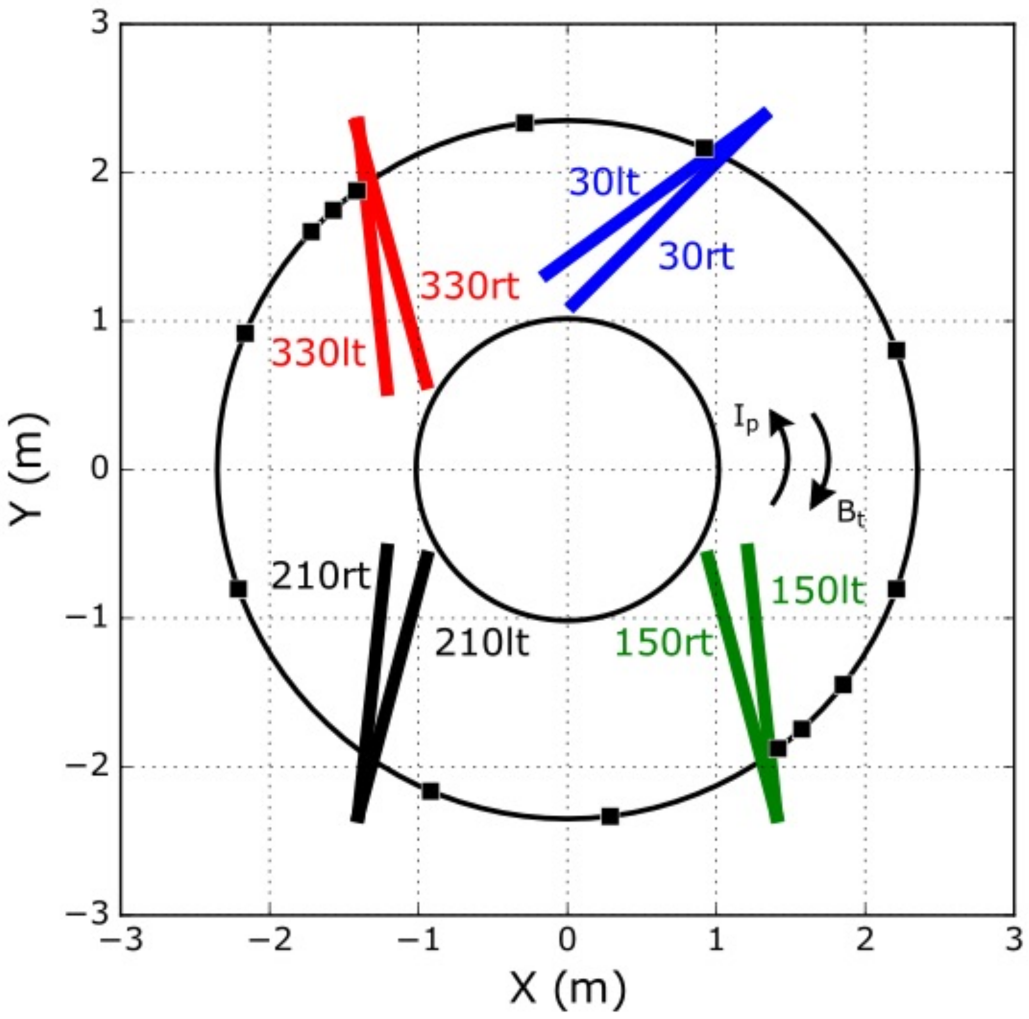
Backup

DIII-D utilizes different injection geometries from 8 neutral beams



- **On-axis co-current: 4-6 beams (30lt, 30rt, 150lt, 150rt, 330lt, 330rt)**
- **Off-axis co-current: 2 beams (150lt, 150rt)**
- **On-axis counter-current: 2 beams (210lt, 210rt)**
- **Black squares indicate location of magnetic probes**

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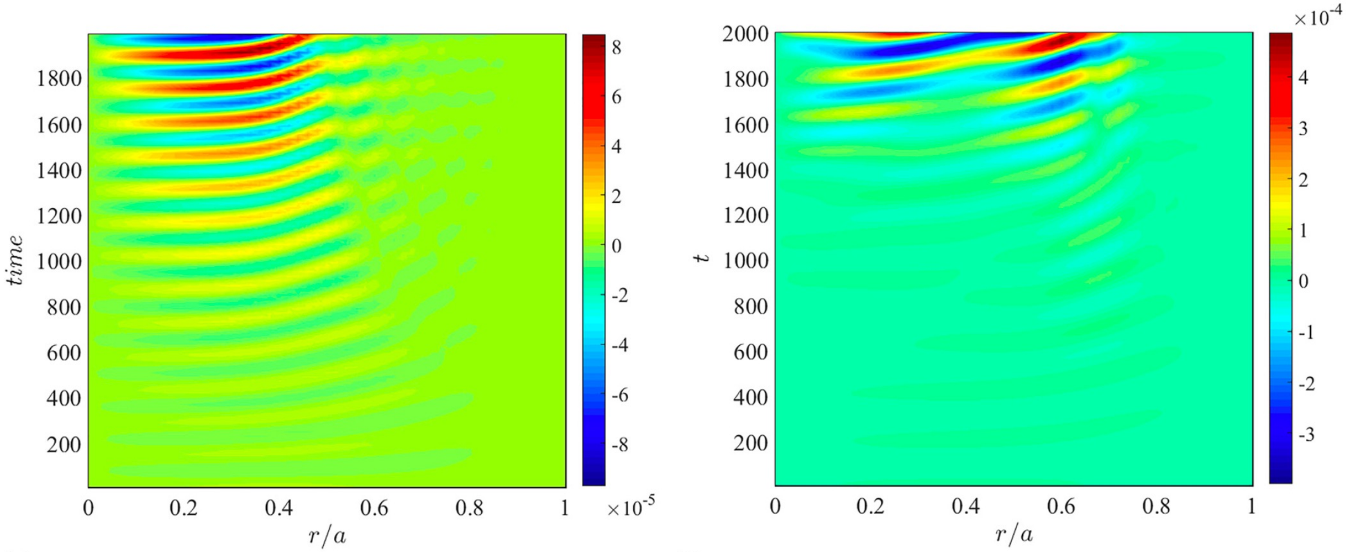
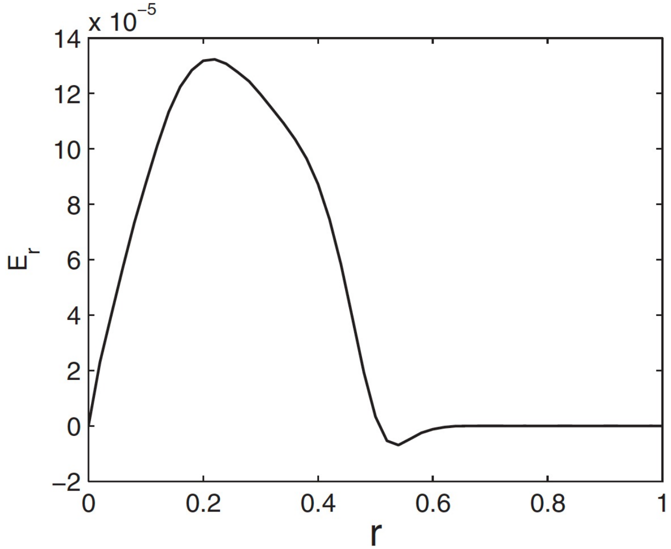
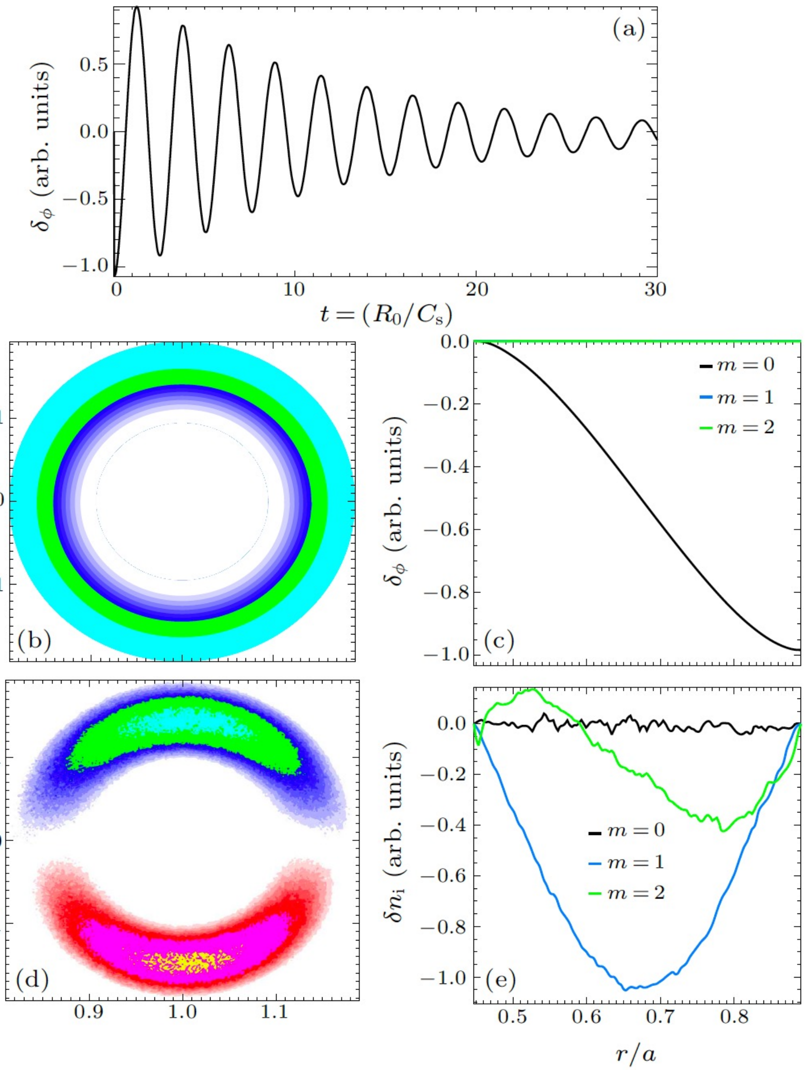
Mode structure



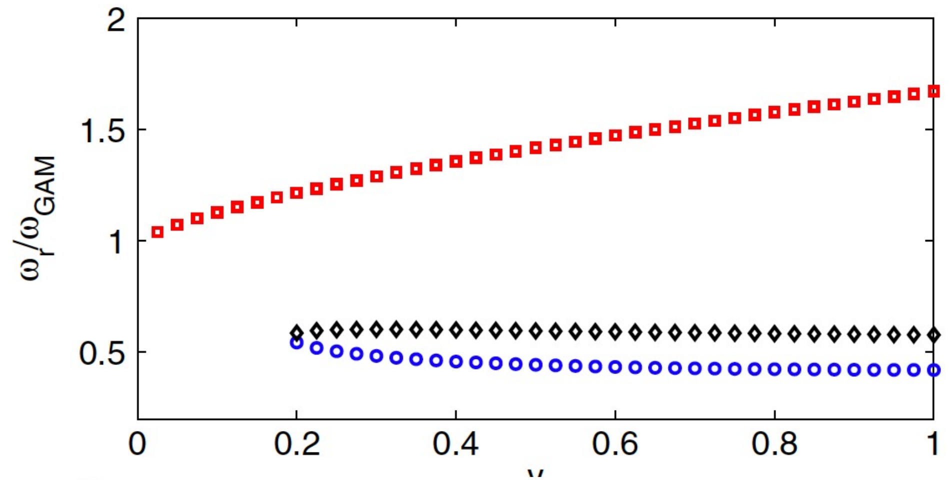
(a)

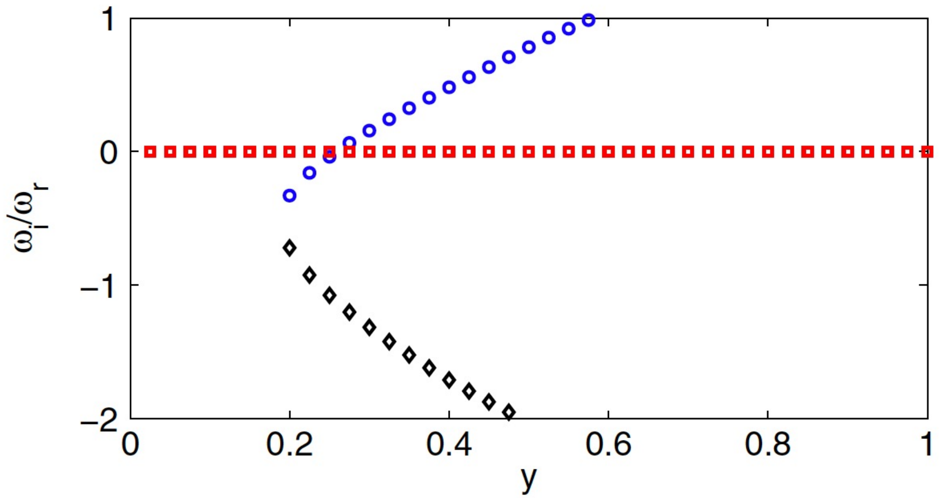


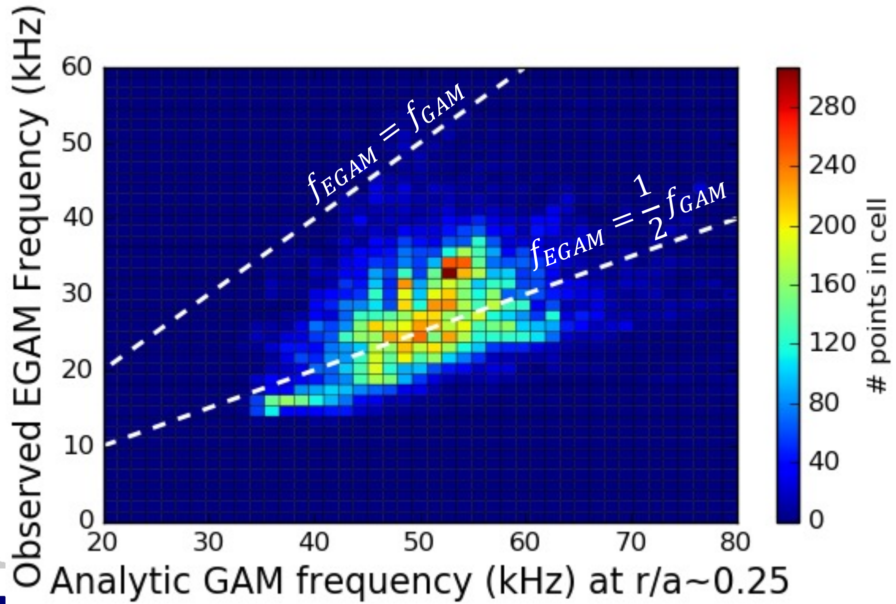


G.Y. Fu PRL 101 185002 (2008)
X. Xiang and G.Y.Fu Phys. Plasmas 26 032509 (2019)
Y. Chen et al CPL 37 095201 (2020)

EGAM mode distinct from GAM branch







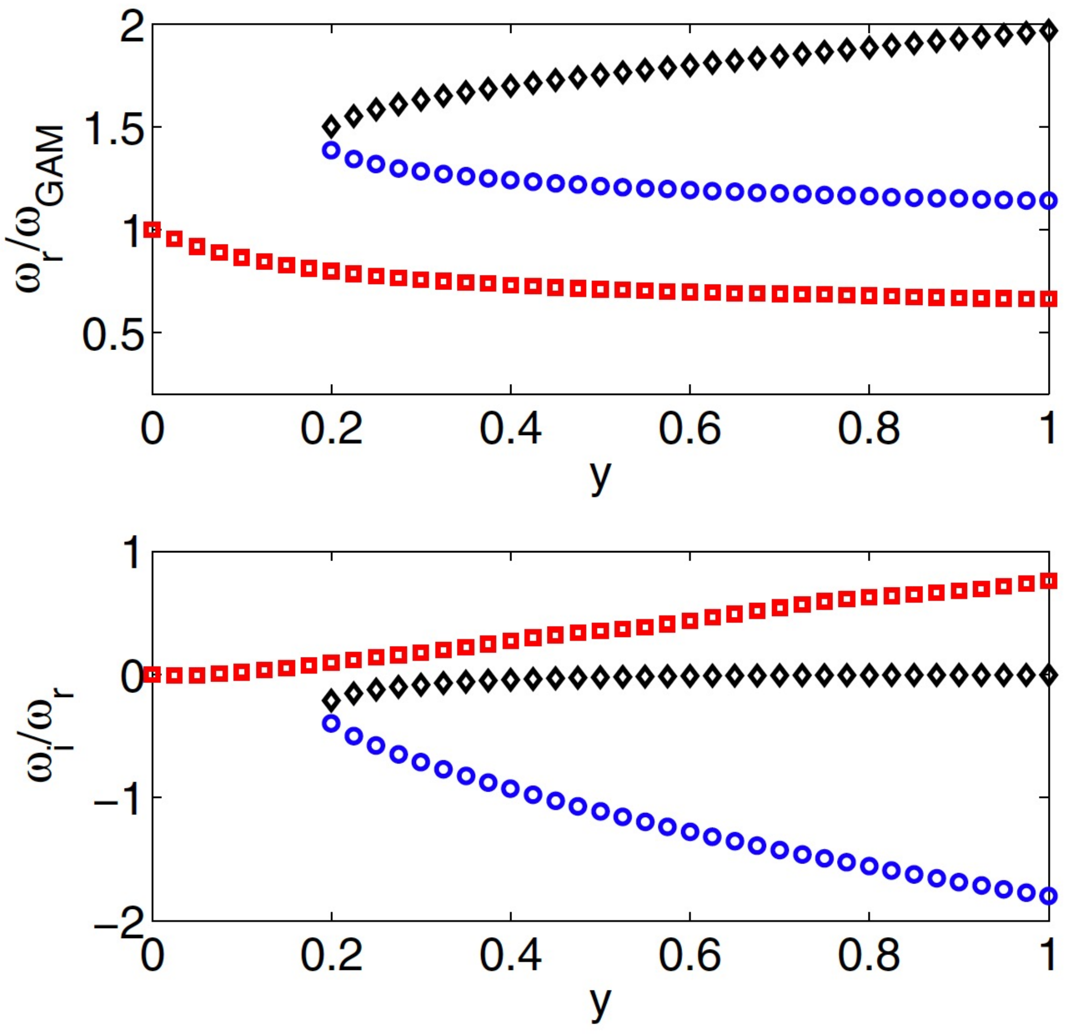
- f_{EGAM}/f_{GAM}~0.5
- Z = f_{b0}/f_{GAM}~1

$$Y = \langle P_{\|h} + P_{\perp h} \rangle / 2\gamma P_{\rm th}$$

$$(\omega_{\rm GAM}^{\rm WJD})^2 = 2\frac{c_s^2}{R_0^2}\left(1 + \frac{1}{2q^2}\right)$$

[1]G.Y. Fu PRL 101 185002 (2008)
[2]N. Winsor et al Phys. Fluids 11 2448 (1968)

Linear mode properties at Z=1.8



- **Z = f_{b0}/f_{GAM}~1.8**

$$Y = \langle P_{\parallel h} + P_{\perp h}\rangle / 2\gamma P_{\mathrm{th}}$$

$$\left(\omega_{\mathrm{GAM}}^{\mathrm{WJD}}\right)^2 = 2\frac{c_s^2}{R_0^2}\left(1+\frac{1}{2q^2}\right)$$

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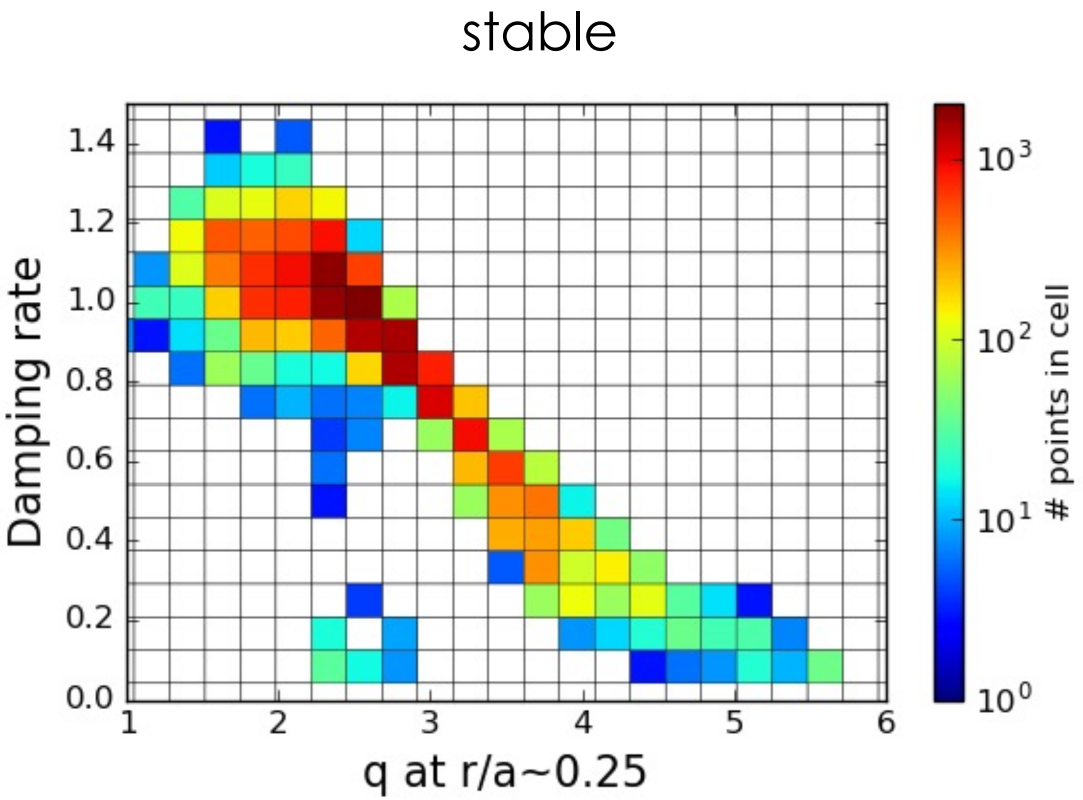
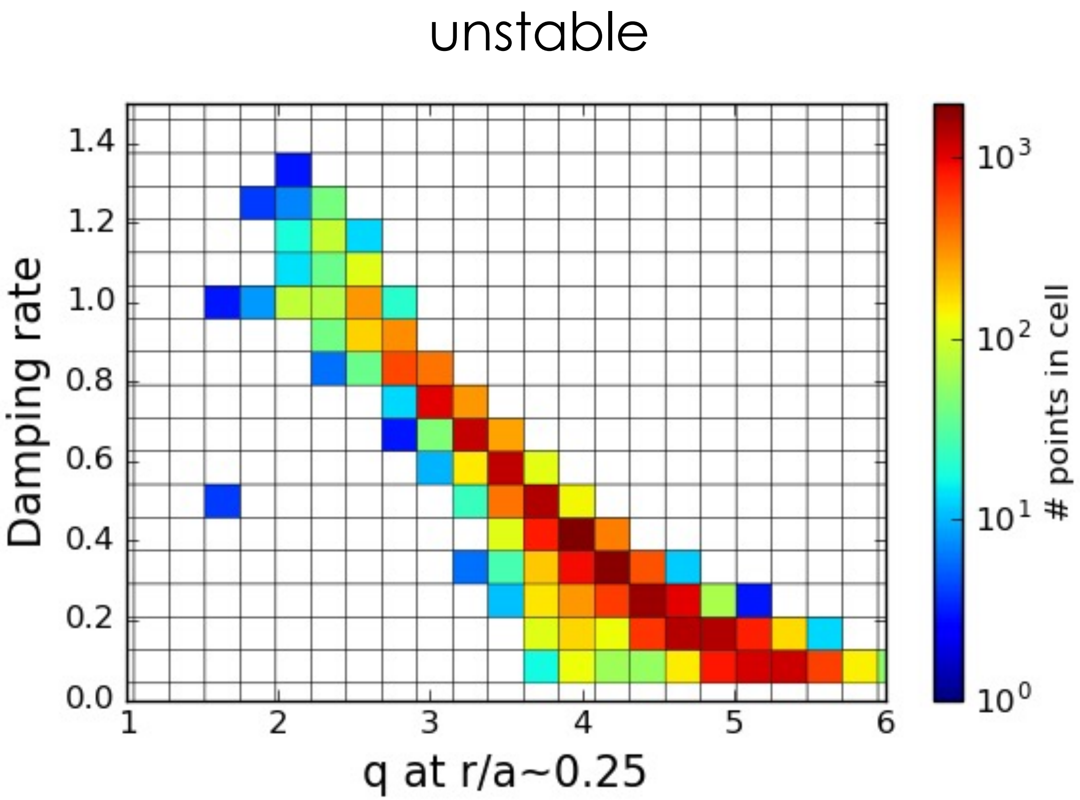
[1]G.Y. Fu PRL 101 185002 (2008)
[2]N. Winsor et al Phys. Fluids 11 2448 (1968)

Damping points in cell





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