NSTX-U

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Suppression of Alfvénic modes through modification of the fast ion distribution

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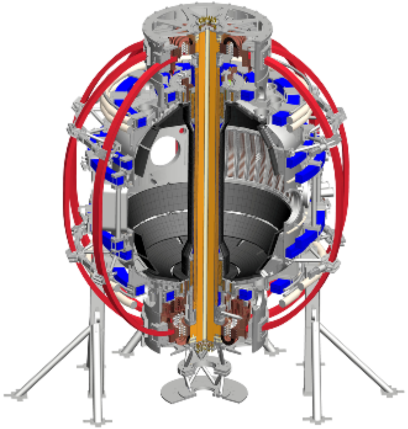
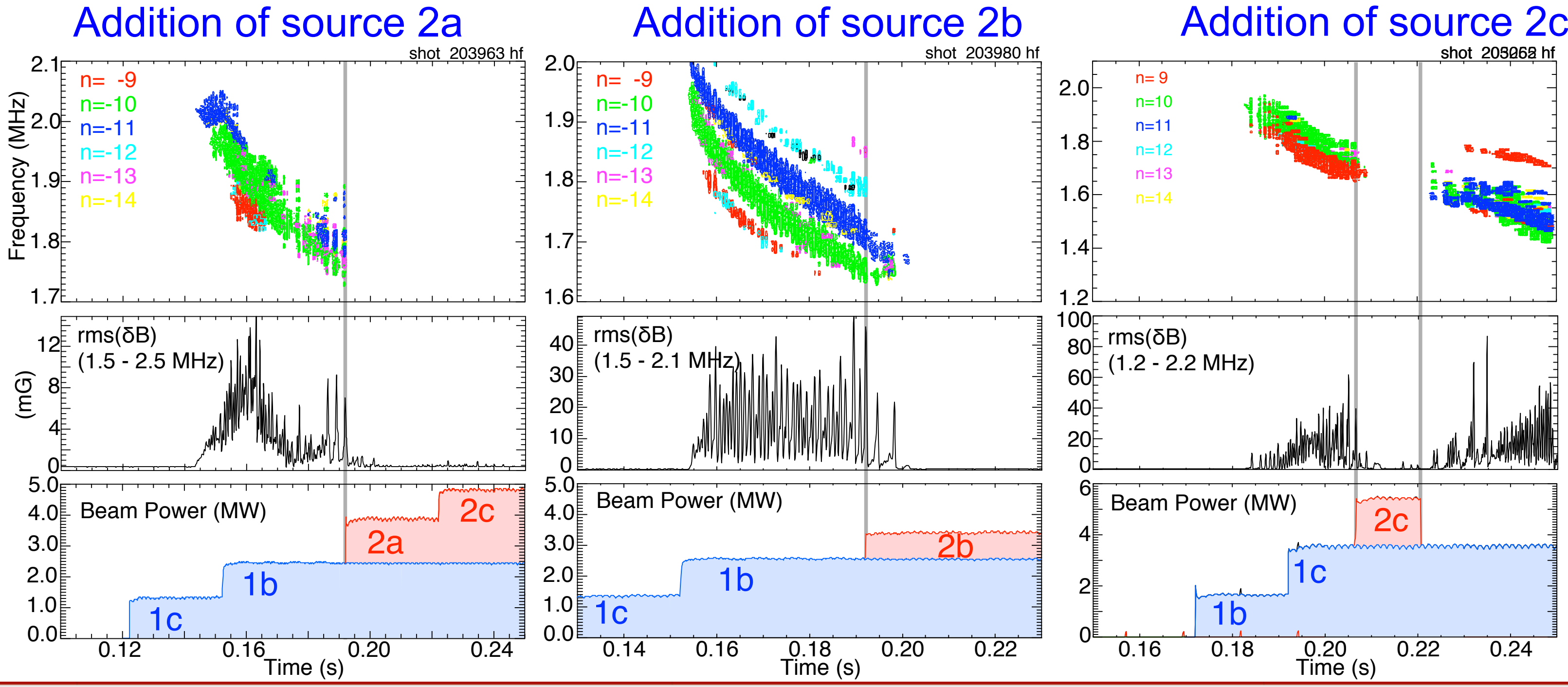
PPPL



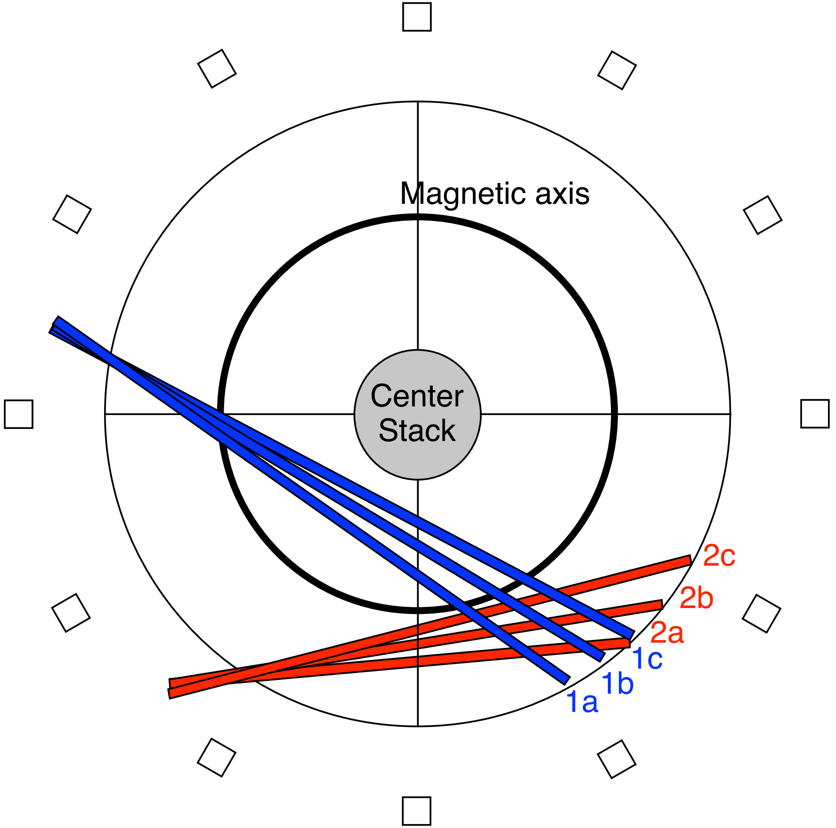
Early in NSTX-U operation it was seen that *adding* beam power could suppress GAE

- Each of the new sources can suppress Global Alfvén eigenmodes (GAE).
- Suppression occurs within milliseconds, *e.g.*, it's the ions.



New sources added to provide more power and current profile control

- Tangency radii of new beams outside magnetic axis for current profile control.
- Fast ions deposited with high pitch ($V_{||}/V$), velocity nearly parallel to magnetic field.
- Suppression of GAE discovered on NSTX-U with injection of new neutral beams.



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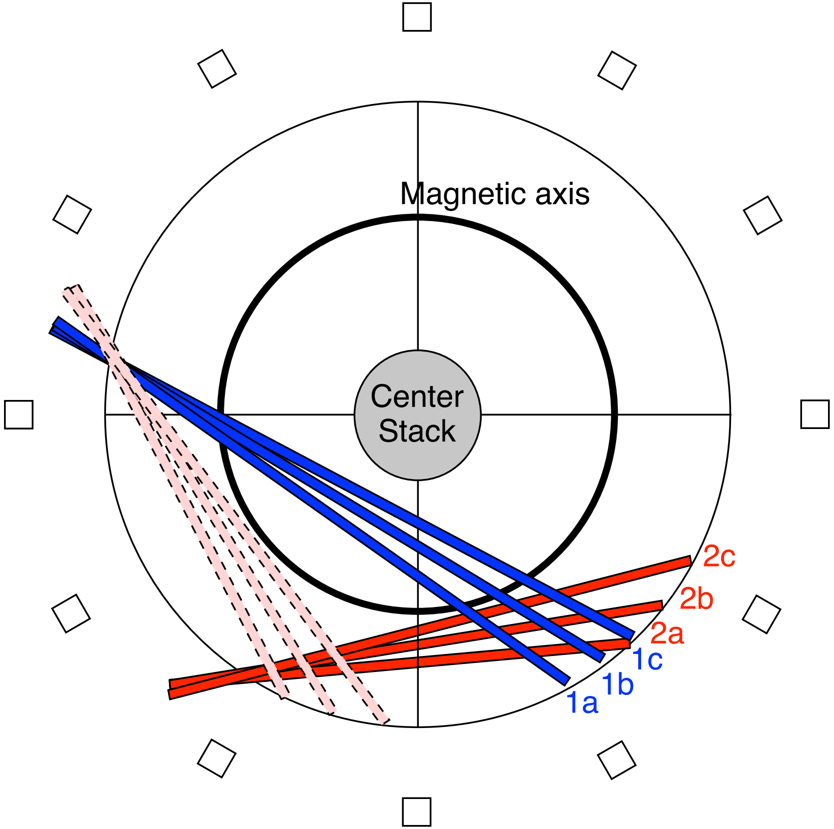
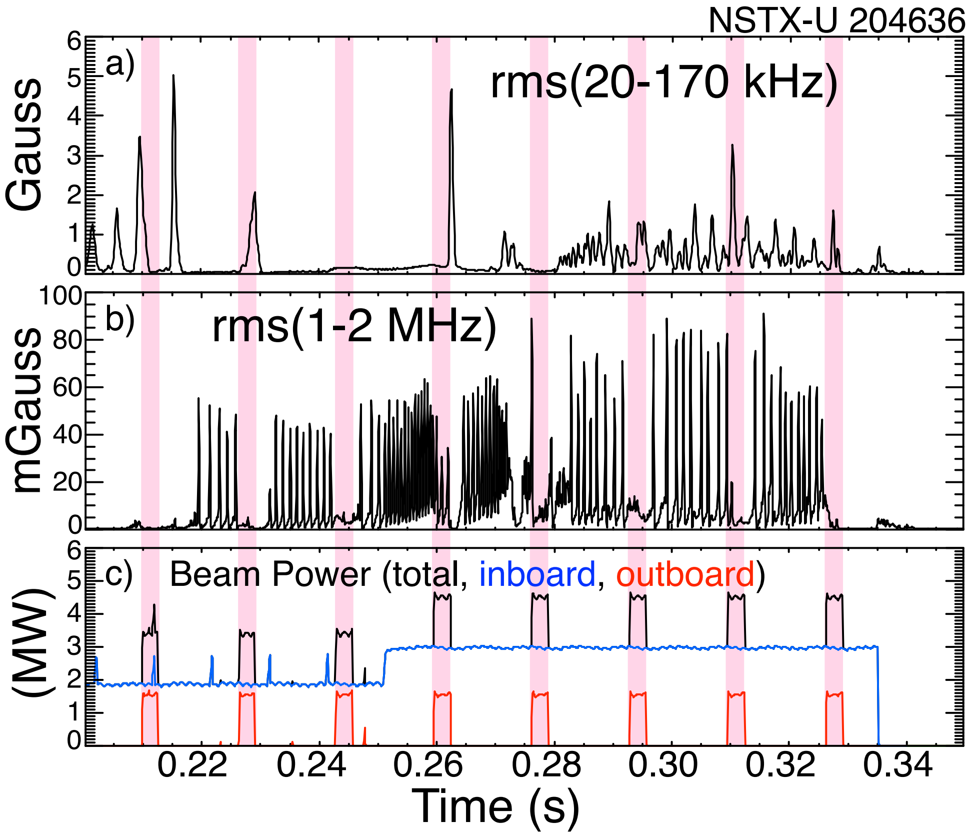


Many examples where no Global Alfvén eigenmodes detected in plasmas heated by BL-2

- Transient events show clearest demonstration of suppression,
  - reduction of ctr-GAE amplitude with turn-on of outboard source
  - or, growth of ctr-GAE amplitude with turn-off of outboard source.
- More than 120 examples of BL2 source turning on or off during a plasma heated by BL1.
- In most cases, complete suppression is seen,
  - however, particularly with the most inboard source, GAE may persist.
- Observations are qualitatively consistent with analytic model of cyclotron-resonance drive of GAE; $k_\perp \rho < 1.9$ is stabilizing.
- Analytic interpretation supported by HYM-code simulations.

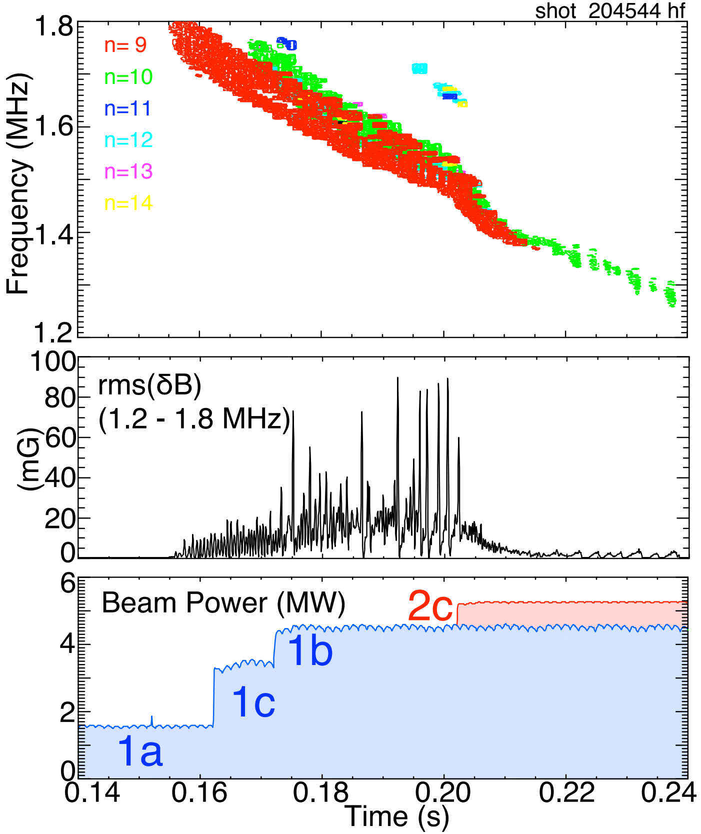
Suppression can occur in msec; fast ion distribution, not equilibrium changes

- Blue curve is total BL-1 source power, red curve is BL-2.
- During BL-2 blips, GAE bursts are suppressed.
- Fast suppression in msecs,
  - few BL-2 fast ions added.
- Typical fast-ion slowing down time is of order 25 ms
  - full-energy BL-2 fast ions responsible for suppression?



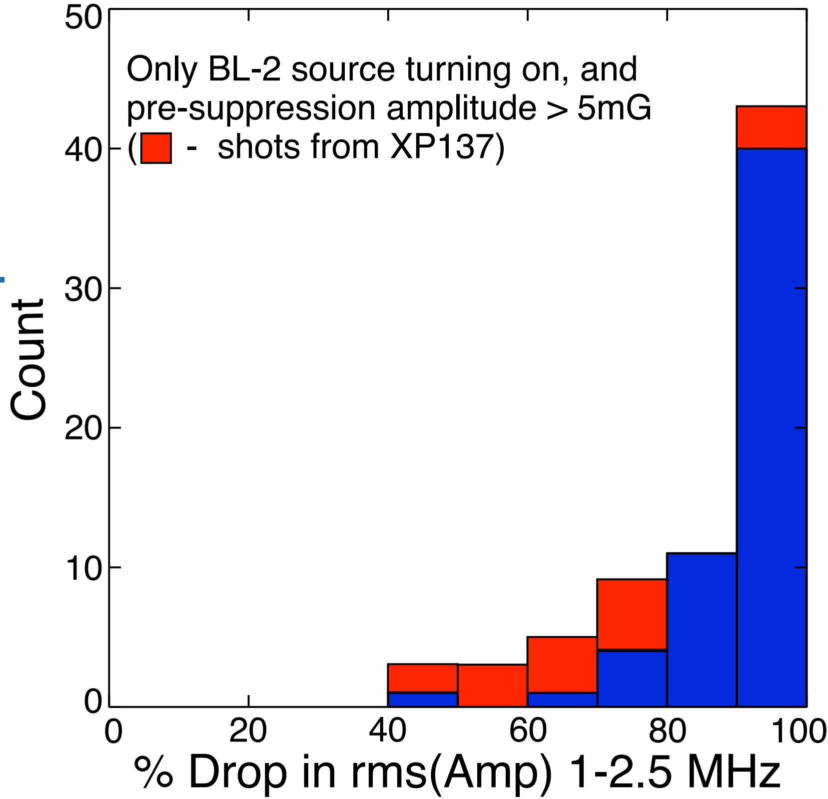
Even if suppression isn't complete, there is a strong reduction in mode amplitude

- Happens most commonly early in the plasma, probably when q is still high, density is low.
- Incomplete suppression is also more common the deepest of the new sources (closest to BL-1 sources).
- This is a fairly extreme example with only ≈15% of the total power coming from a BL-2 source.



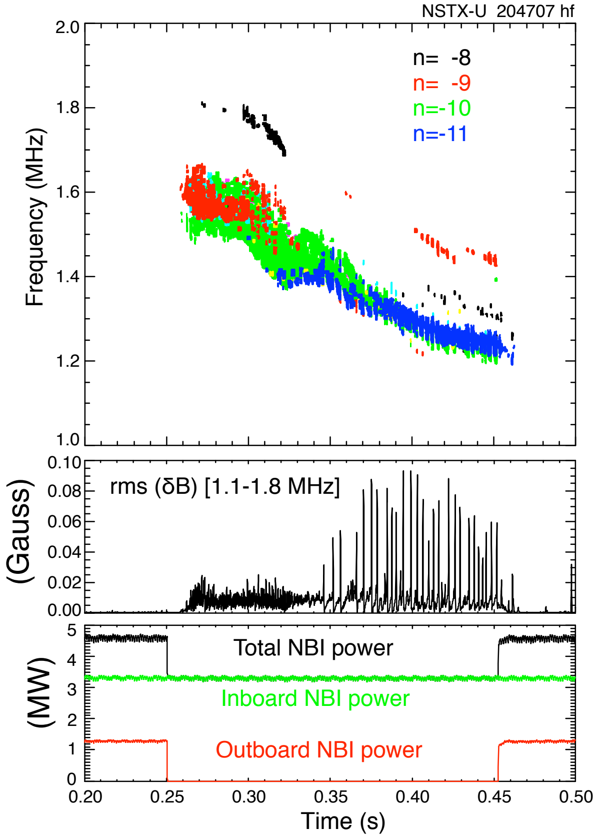
Database constructed from all shots shows BL-2 is very effective for suppressing GAE

- Fractional drop in mode amplitude 25ms after injection of a BL-2 source,
  - comparison of amplitude averaged over 10 ms before, to 20-30 ms after injection.
- Database constructed from all 2016 shots where BL-2 source injected during BL-1 heating phase.
- Counts in red all from 2-day XP focused on H-mode access,
  - unique characteristic of these shots hasn't been identified.



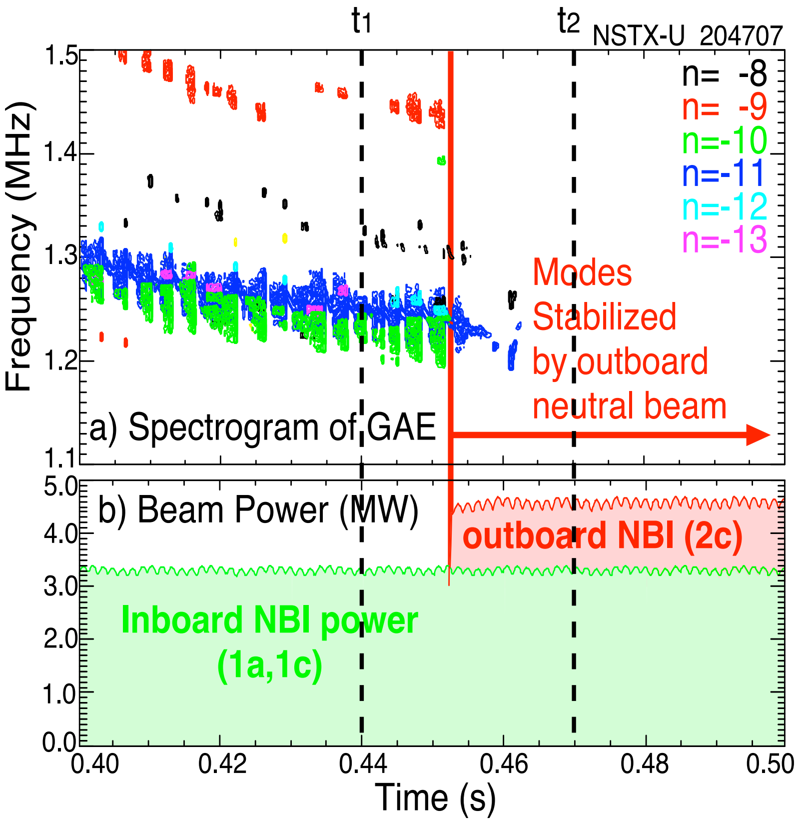
An example with strong GAE activity before suppression is chosen for analysis

- GAE appear after BL-2 source turns off.
- Plasma is in L-mode, but suppression is also seen for H-mode plasmas.
- Modes evolve from dominantly n=-9 to dominantly n=-11.
- GAE suppressed again, late in discharge, when BL-2 comes back on.
- BL-2 provides roughly 25% of total power.



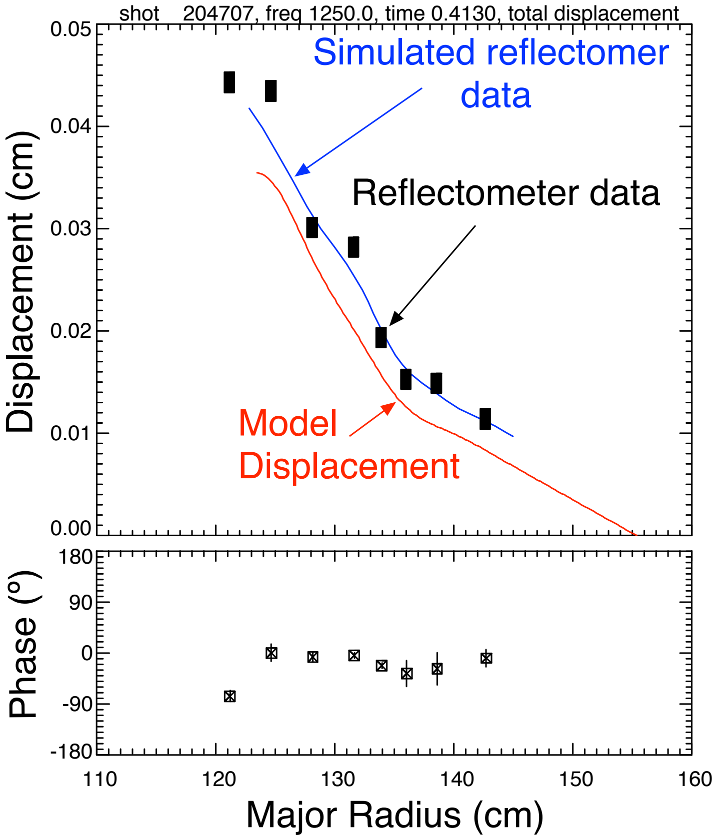
Analytic model and HYM simulations find unstable GAE before, stable after BL-2 turns off.

- GAE bursting before modes are suppressed.
- Analysis done at two times:
  - 0.44s,during GAE activity (w/o 2c),
  - 0.47s, after 2c on.
- GAE suppression noticeable within milliseconds.
- BL-2 (source 2c) only adds ≈1.2MW out of 4.6MW, ≈26%.



Reflectometer shows mode structure consistent expected global Alfvén eigenmode structure

- Amplitude of GAE expected to peak near minimum in q.
- Mode structure found by 'inverting' reflectometer data.
- Model displacement profile iterated until simulated reflectometer data matches raw data.
- Phase is nearly constant.
- Structure peaks near core, as expected for GAE.

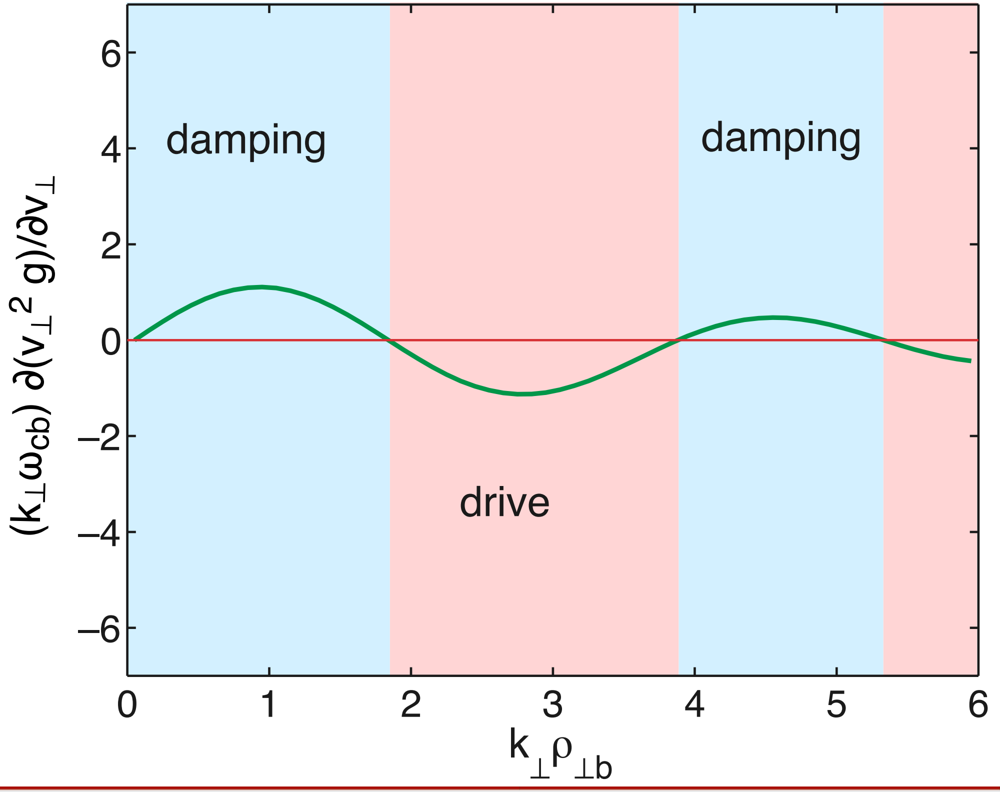


Analytic model* qualitatively predicts low $k_\perp\rho$ (high pitch) fast ions will stabilize GAE

- Fast ions can be stabilizing/destabilizing depending:
  - Stable : $0 \le k_\perp\rho_\perp \le 2$
  - Unstable: $2 \le k_\perp\rho_\perp \le 4$
- Resonant outboard beams with pitch > 0.9 have small ρ_L, are stabilizing by this theory.

Gorelenkov, NF **43** (2003) 228.

Fig. 3, Gorelenkov, Nucl. Fusion 43 (2003) 228

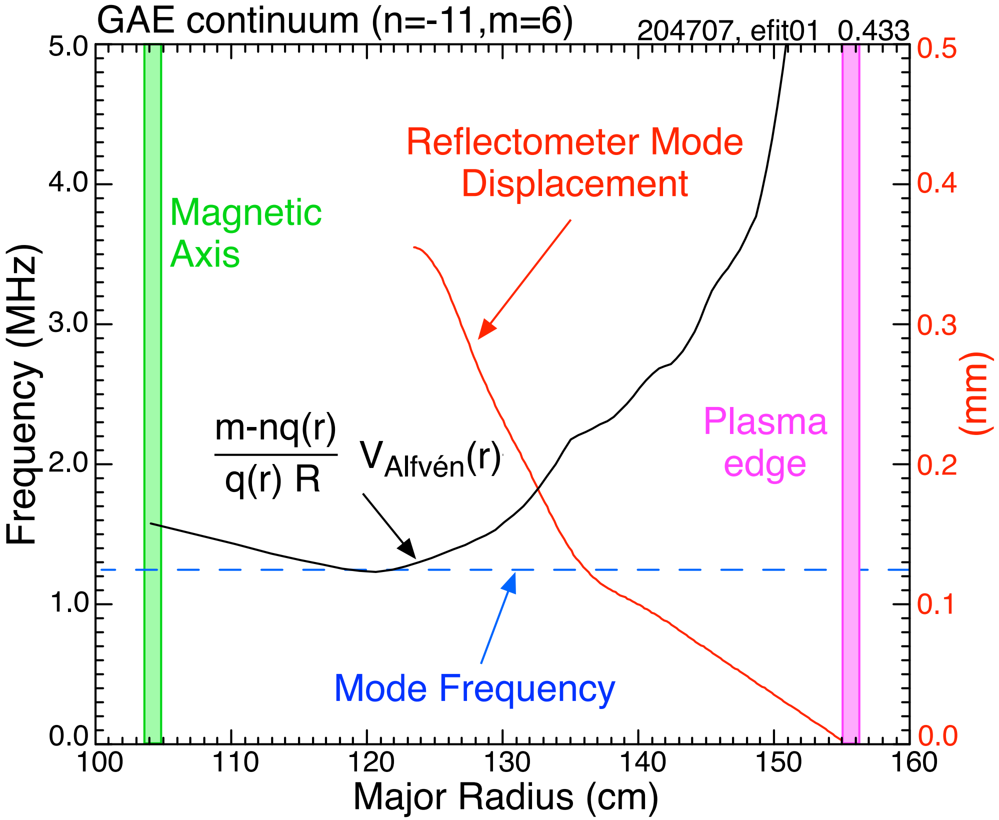


Local analytic dispersion relation predicts GAE amplitude to peak near axis

- Experimental mode frequency used to estimate $k_{\|}$ from dispersion relation

$$\omega_{GAE} \approx \min\left| k_{\|} V_{Alfvén}(r) + n\omega_{rot}(r) \right|$$

- Experimental inputs are q, density and rotation profiles.



TRANSP modeling predicts beam fast ions are resonant with GAE

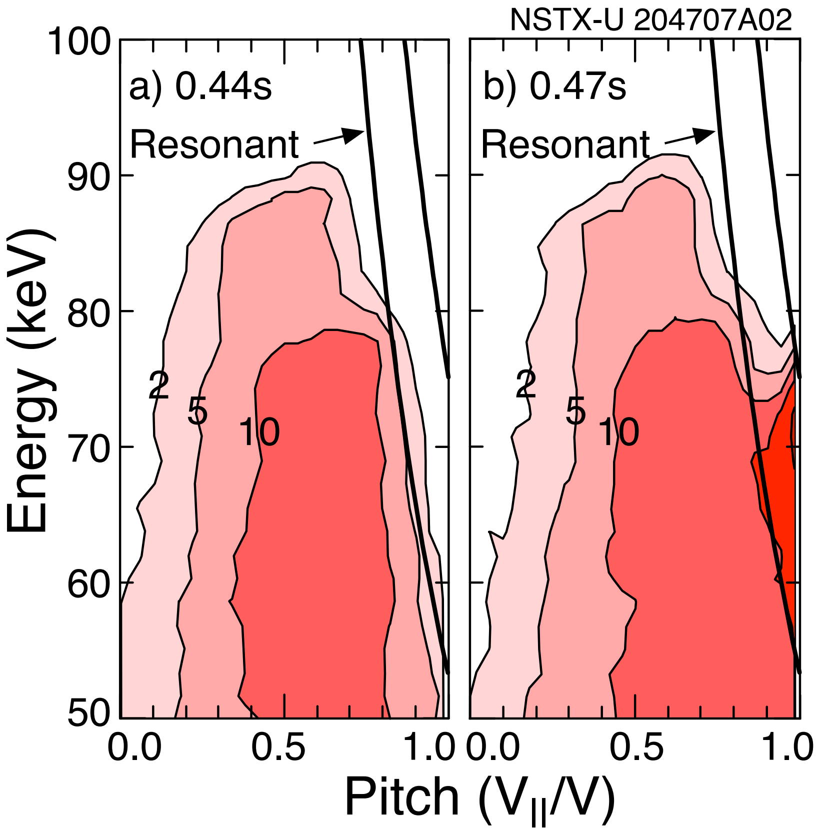
- Measured mode frequency, dispersion relation are used to estimate $k_{\parallel}$ from:

$$\omega_{GAE} \approx \min\left|k_{\parallel} V_{Alfvén}(r) + n\omega_{rot}(r)\right|$$

- The parallel beam ion velocity is estimated from the resonance condition:

$$\omega_{GAE} + \left|k_{\parallel} \pm s / qR\right| V_{b\parallel} = \omega_{ci}, \quad s = 0,1$$

- Two side-band fast ion resonances indicated by black lines in figures.
  - lines show fast ions at constant parallel velocity.
  - gaining/losing perpendicular energy moves fast ions along black resonance lines.



Addition of BL-2 (2c) deposits resonant fast ions that are predicted to damp the GAE

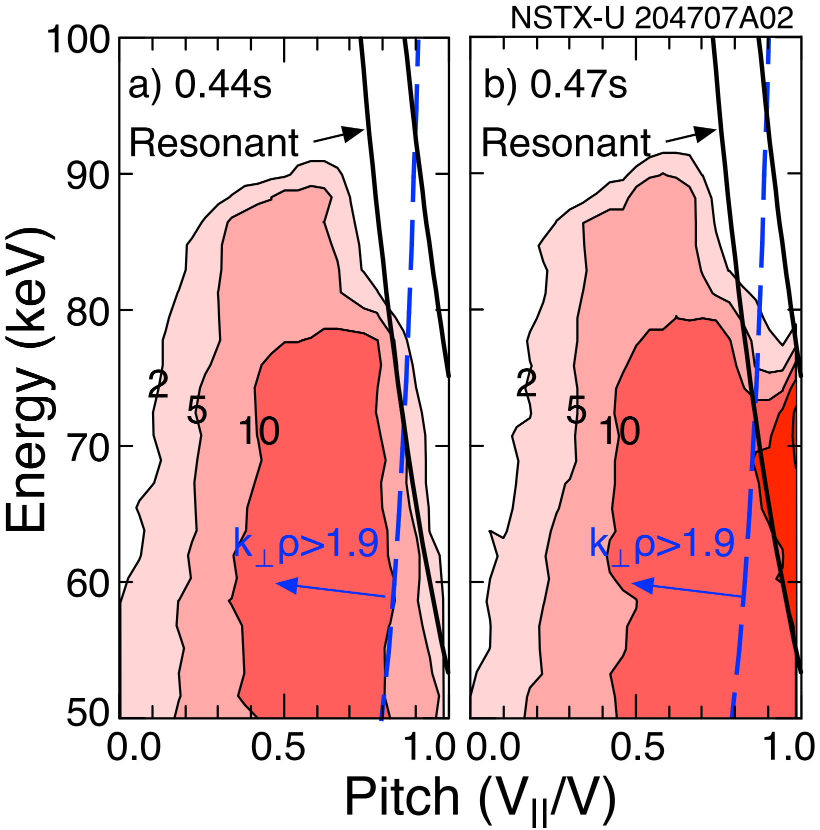
- $k_{||}$ estimated above is used to calculate $k_\perp$:

$$k_{||} \approx \frac{m - nq(r)}{q(r)R}, \quad k_\perp \approx \frac{m}{r}$$

  - The boundary between fast ions that drive *vs* damp the mode is:

$$\text{Drive: } k_\perp \rho < 1.9, \text{ Damping: } k_\perp \rho > 1.9$$

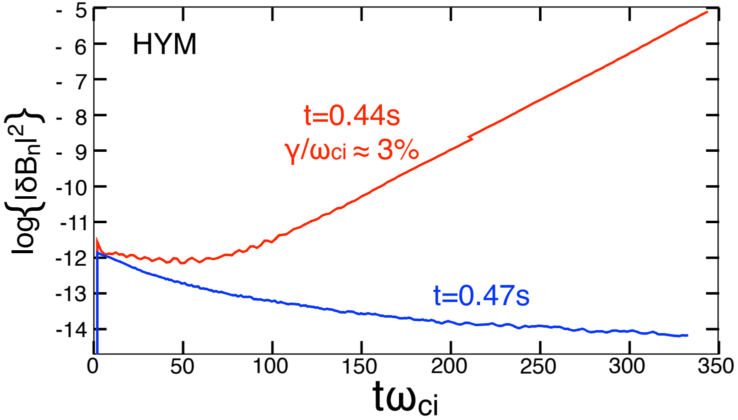
- …where ρ is calculated from the perpendicular fast ion energy.
  - The boundary between damping and drive is shown by the dashed blue lines.
- The BL2 sources add primarily fast ions with high pitch (Fig. b).

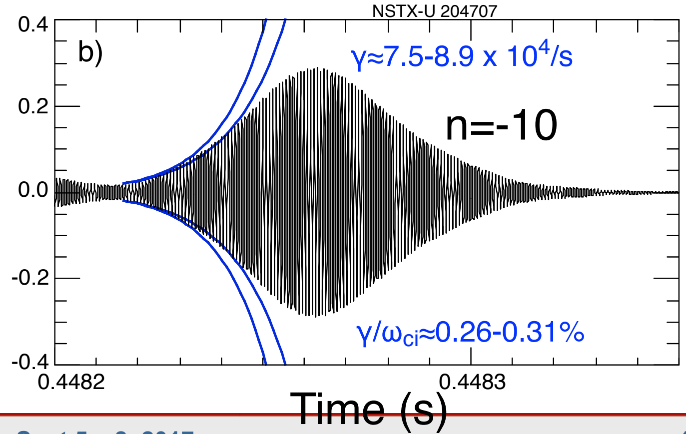


HYM* code predicts mode instability at 0.44s, stable at 0.47s

- HYM is an initial value, hybrid code in toroidal geometry
  - beam ion treated with full-orbit, δf scheme
  - thermal plasma is one-fluid MHD
- Code can be non-linear, but only linear runs done here.
- Growth rate positive at 0.44s, negative at 0.47s with source 2c.

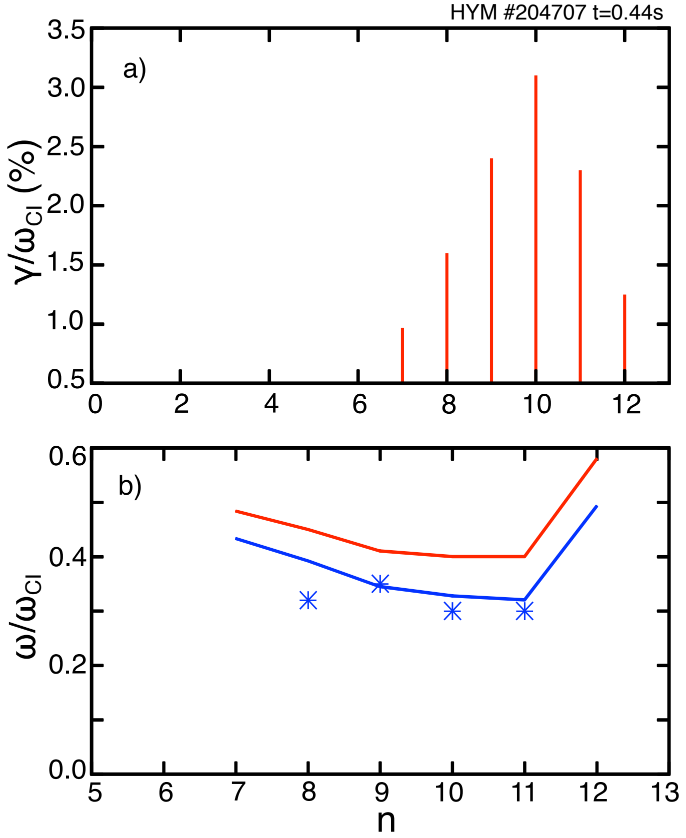
*Belova, PoP **10** (2003) 3240





HYM predicts frequencies of observed modes

- Top figure shows positive growth rates for n = 7 – 12
  - strong n = 8 – 11 shown above
  - weak n = 7 and 12 are also seen.
- Agreement with the experimentally observed frequencies is also good
  - simple correction for Doppler shift added.

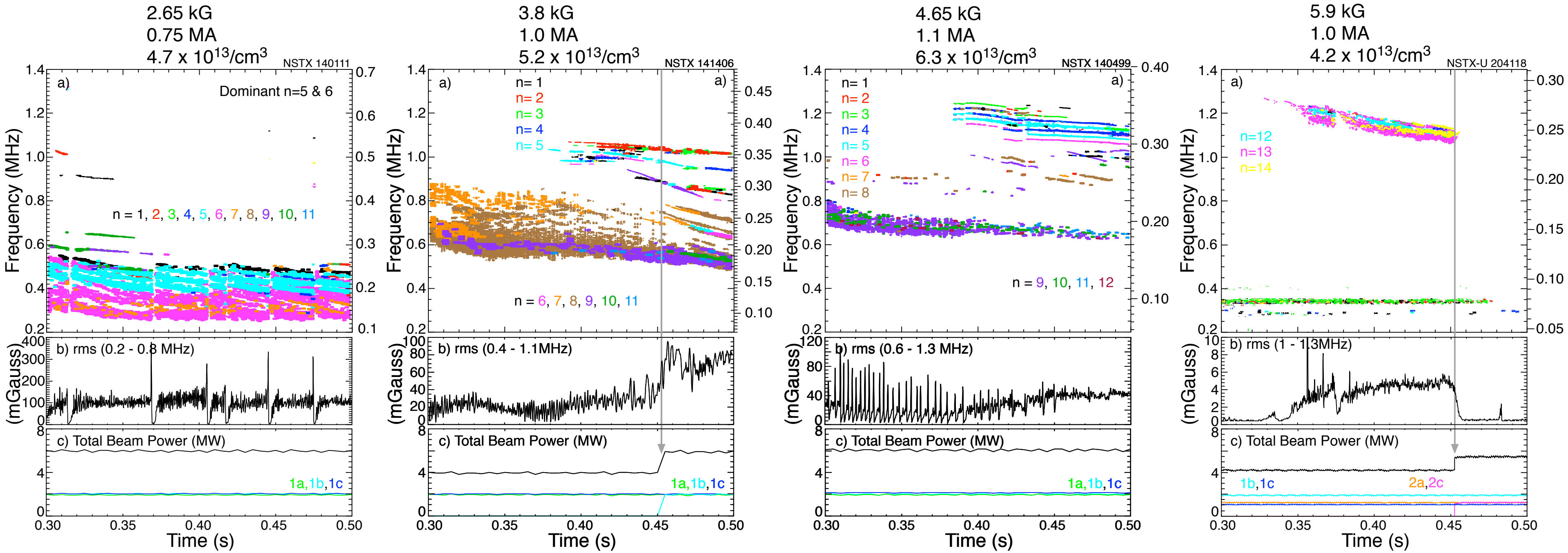


The GAE suppression seen with increased NBI power is reproduced with HYM simulations

- ctr-propagating GAE have been correlated with flattening of the core electron temperature profile, possibly through enhanced electron thermal transport, or through some form of energy channeling.
- Experiments on NSTX-U with new neutral beam sources have found that the GAE can be completely suppressed with ≈25% of the beam power supplied by one of the new beam sources.
- Future experiments will explore GAE effect on electron heat transport.
- Hopefully, similar techniques can be extended to other instabilities.

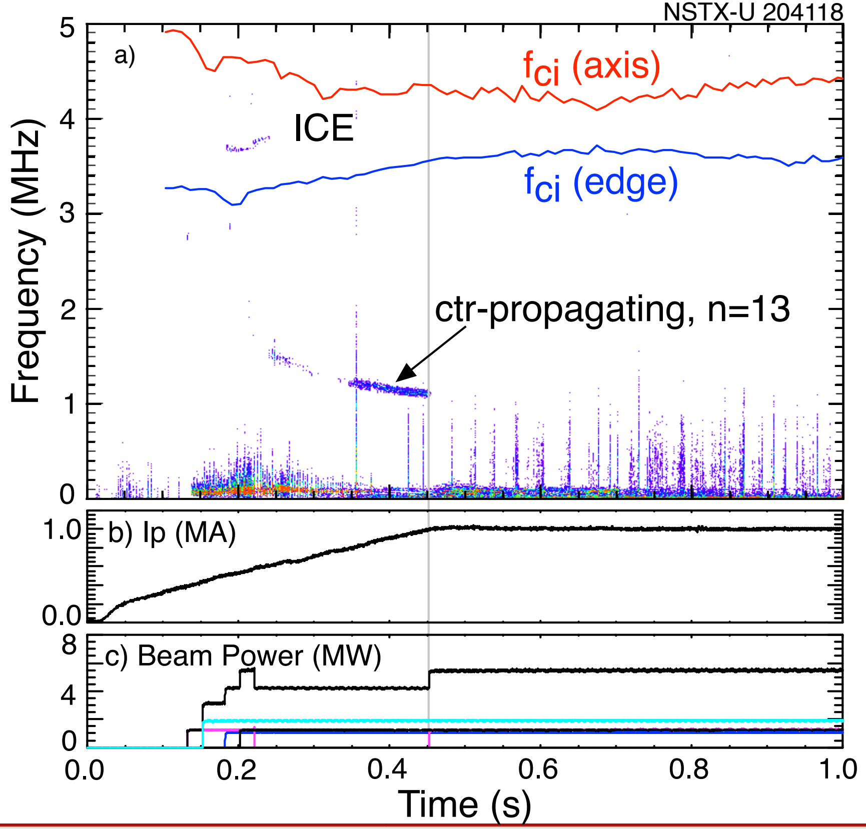
GAE frequency and toroidal mode number increase with toroidal field

- Frequencies of GAE on NSTX-U consistent with this scaling.



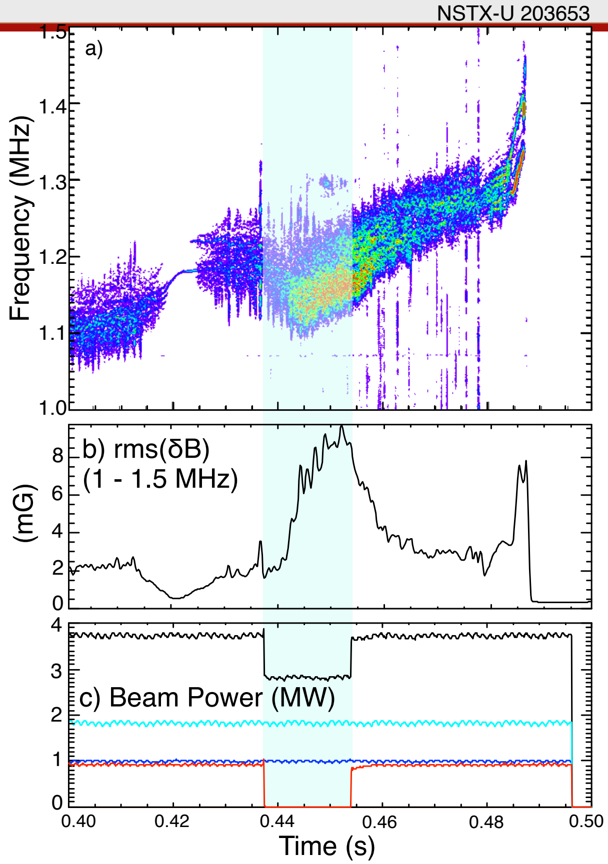
'Similar' 1MA, 6MW NSTX-U H-mode

- 6.5 kG toroidal field.
- One 90 kV beam, 3 - 70 kV beams
- Two outboard sources.
- Density similar
- Note minimal hfAE activity



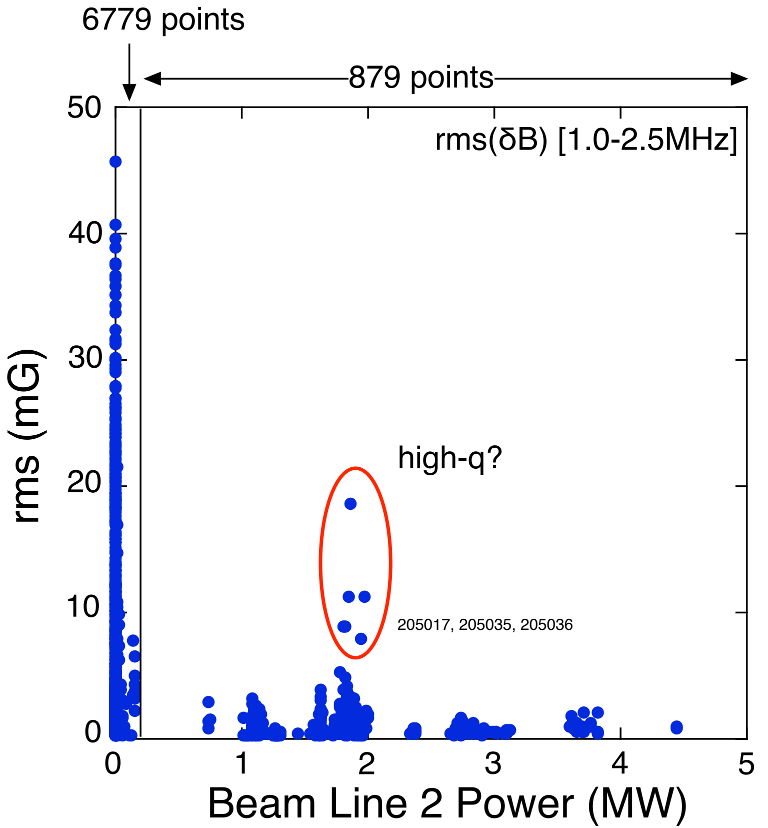
GAE grows during 2a beam block

- Top panel shows GAE excited by inboard sources 1b and 1c (blue and cyan, lower panel).
- Outboard source 2a has block from 0.437s to 0.454s.
- GAE amplitude grows during 2a off-time, suppressed after.



Database supports anecdotal evidence

- Significant amplitude in GAE frequency range only with no Beam Line 2 power.
- A few exceptions are mostly from early GAE when q was probably high (no MSE data yet).
  - High q means high m_{eff}, means large $k_{\perp}$, and Beam Line 2 could be destabilizing.



Global Alfvén eigenmodes on NSTX are an example of (possibly) deleterious EP modes

- GAE resonant with trapped electrons:
  - direct electron heat transport…
- …or, GAE 'channel' energy through GAE away from core:
  - less core electron heating.
- Control of GAE could help answer open questions about electron heat transport in STs.