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U.S. Department of Energy Office of Science
Fusion Energy Sciences

Suppression of Alfvénic modes through modification of the fast ion distribution

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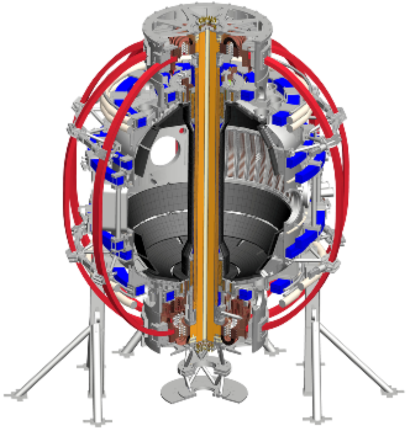
E Belova, N N Gorelenkov and NSTX-U Team

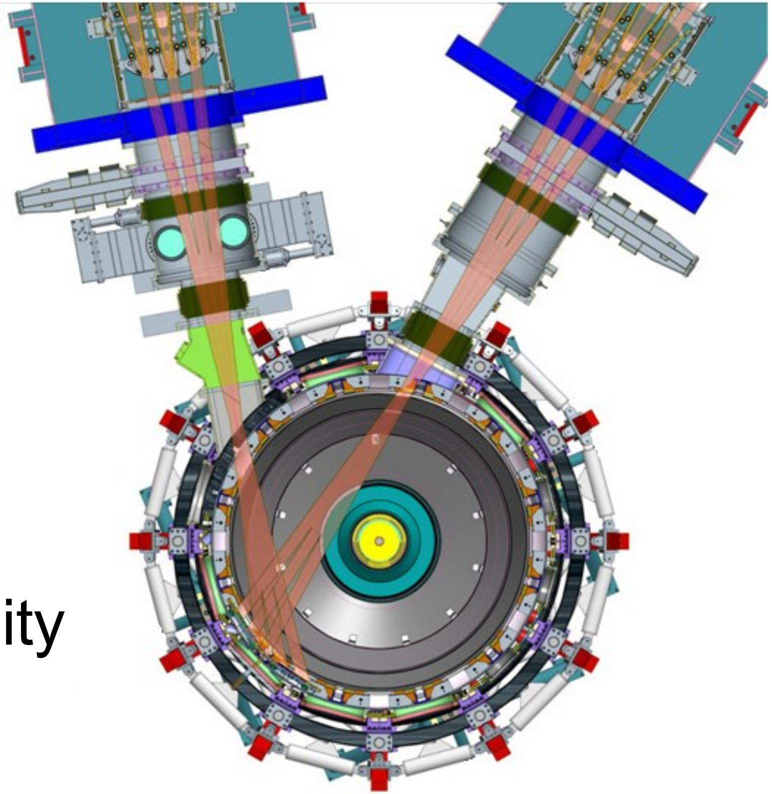
59th APS-DPP Meeting
Milwaukee, Wisconsin
Oct. 23 – 27, 2017



NSTX upgrade added a 2nd neutral beam and increased the toroidal field

Motivation:

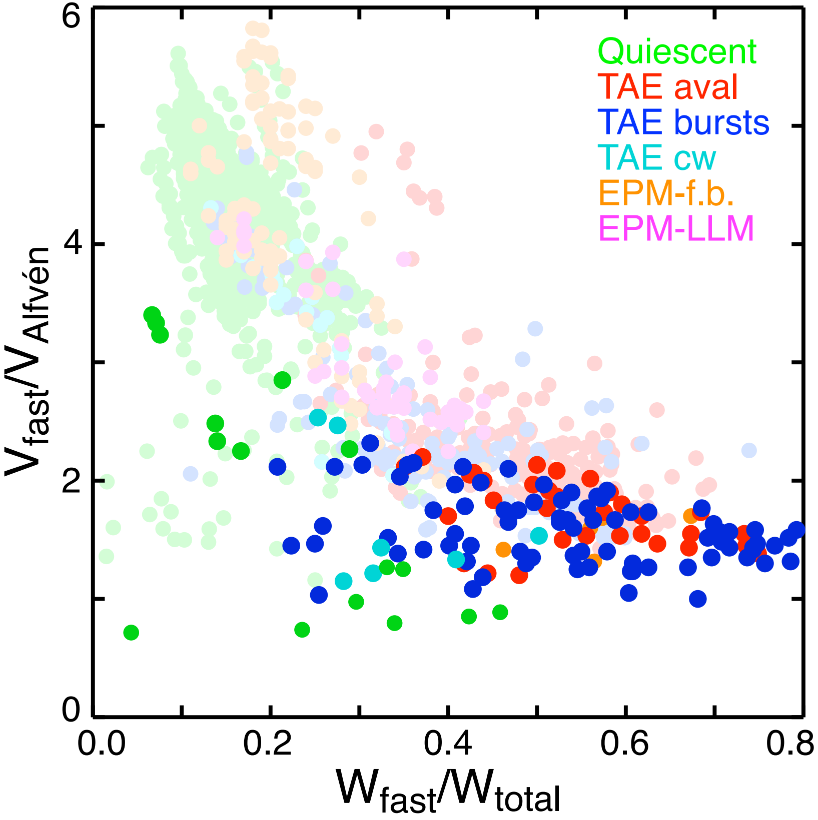
- Current profile control
  - off-axis beam to broaden current profile
- Non-inductive current drive
  - Tangential NBI → 2× current drive efficiency
- Higher field, higher plasma current
  - support increased heating power
- Transport, power handling and stability studies…



New capabilities also impact mission to study energetic particle driven instabilities

- Higher field
  - extends $V_{fast}/V_{Alfvén}$ range to sub-Alfvénic (conventional tokamak space).
- New beams allow control of fast-ion distribution function
  - hollow fast ion density profiles (TAE*)
  - control of fast-ion pitch distribution.

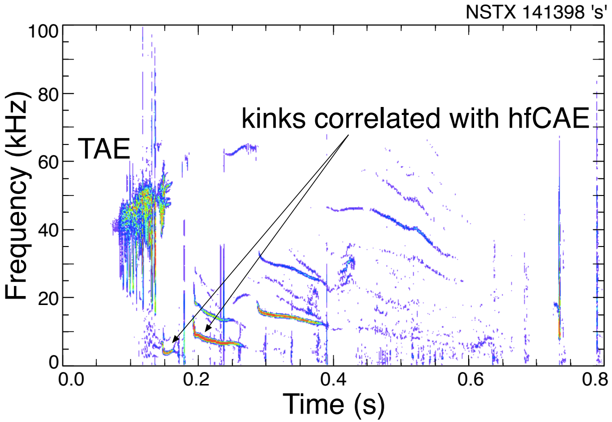
M Podestà – PP11 50, Wed. afternoon



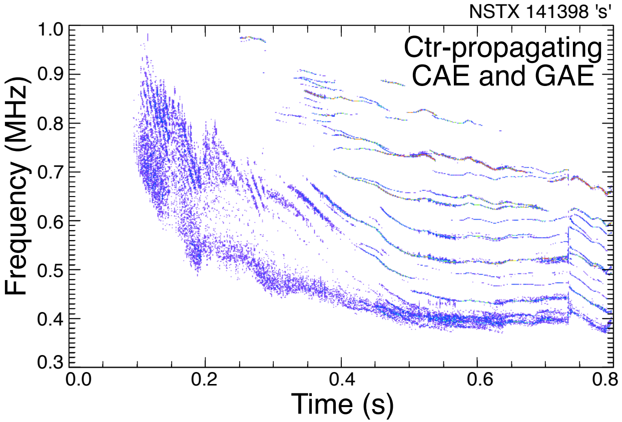
ITER, fusion reactors will operate with super-Alfvénic fast ions => fast-ion driven instabilities

- Spherical Tokamaks routinely operate in this regime

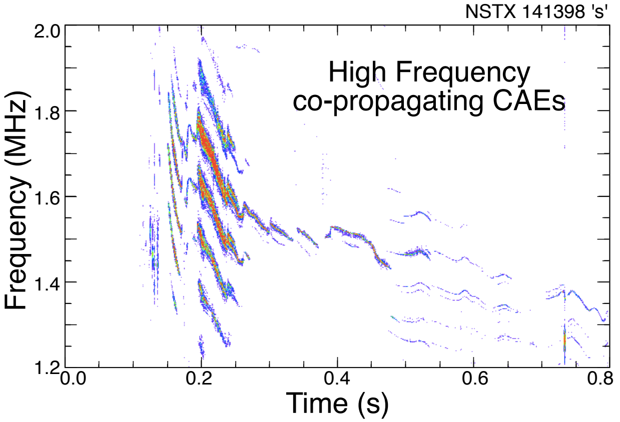
- Lower frequency -
  - Fishbones (EPM)
  - BAAE
  - BAE
  - Toroidal Alfvén eigenmodes



- Intermediate frequency are ctr-propagating:
  - Global Alfvén eigenmodes
  - Compressional Alfvén eigenmodes

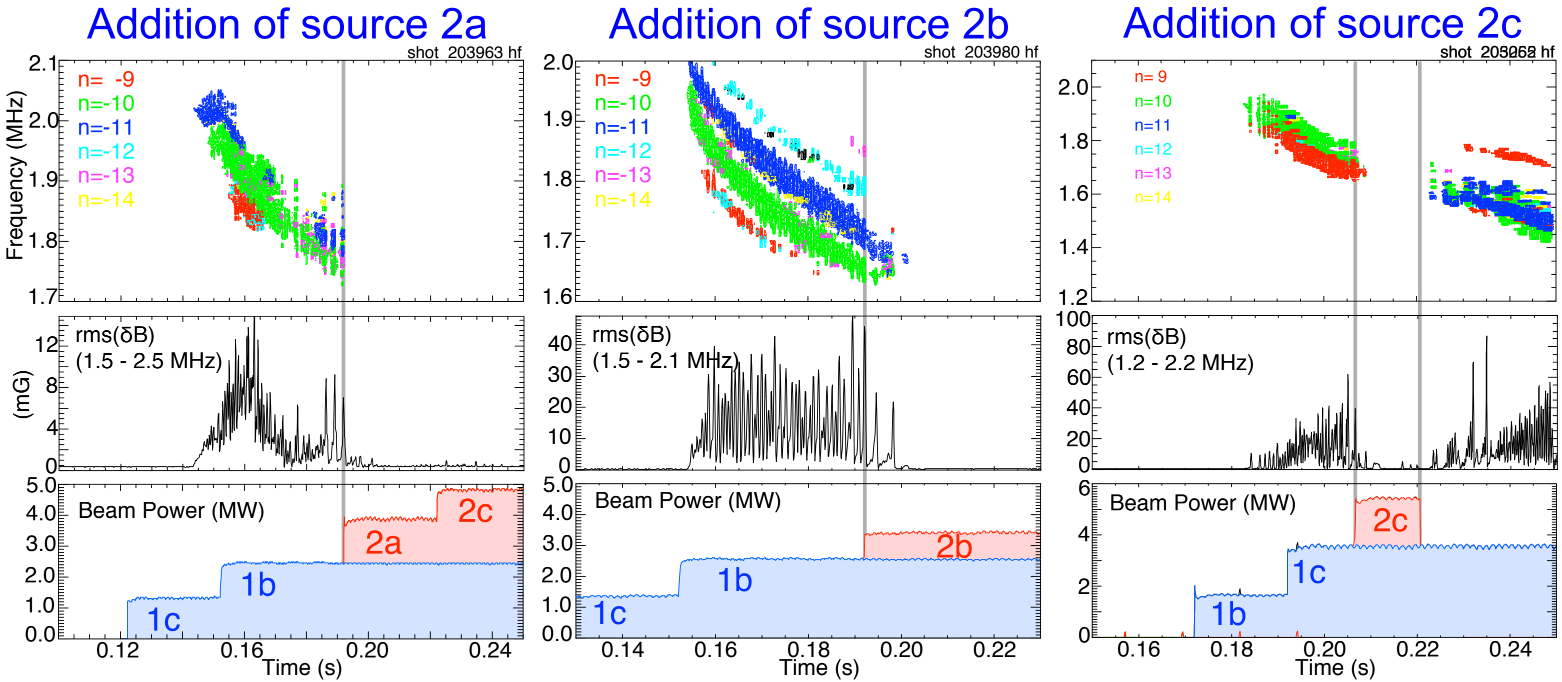


- Near the ion cyclotron frequency are:
  - co-Compressional Alfvén eigenmodes (CAE)
  - Ion Cycl. emission (ICE)



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

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

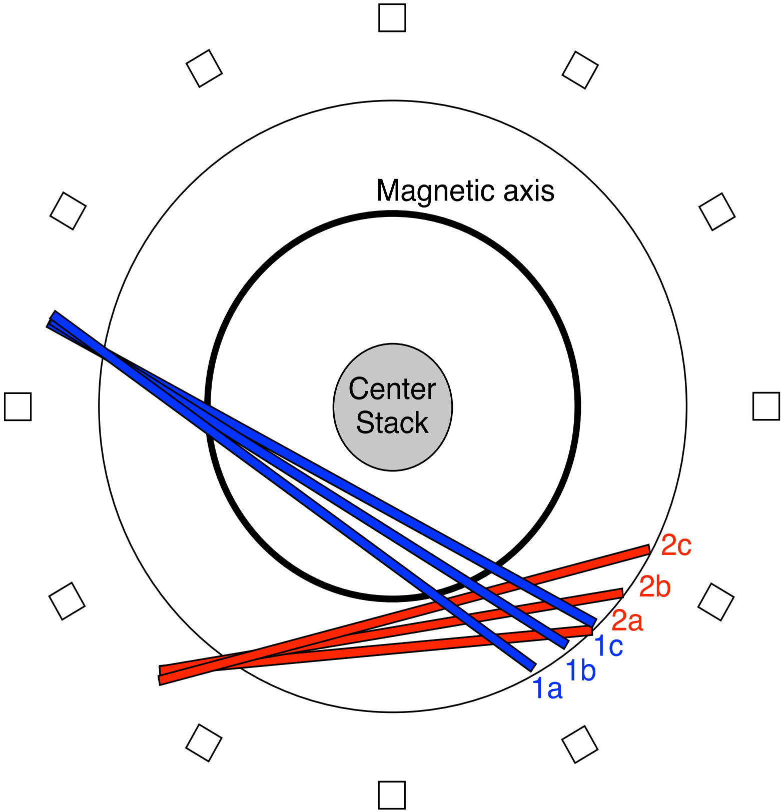


Strong anti-correlation between GAE activity and heating with BL-2 sources

- Transition 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 transition events;
  - BL-2 source turning on or off, during a plasma heated by BL-1.
- In most cases, complete suppression is seen with BL-2,
  - however, particularly with the on axis source, GAE may persist.
- Observations are qualitatively consistent with an analytic model of Doppler-shifted ion-cyclotron-resonance drive of GAE.
- HYM-code simulations, with more complete physics model, also predict new, off-axis, beams can suppress GAE.

New sources added to provide more power and current profile control are aimed off-axis

- Tangency radii of new beams for current profile control outside magnetic axis.
- 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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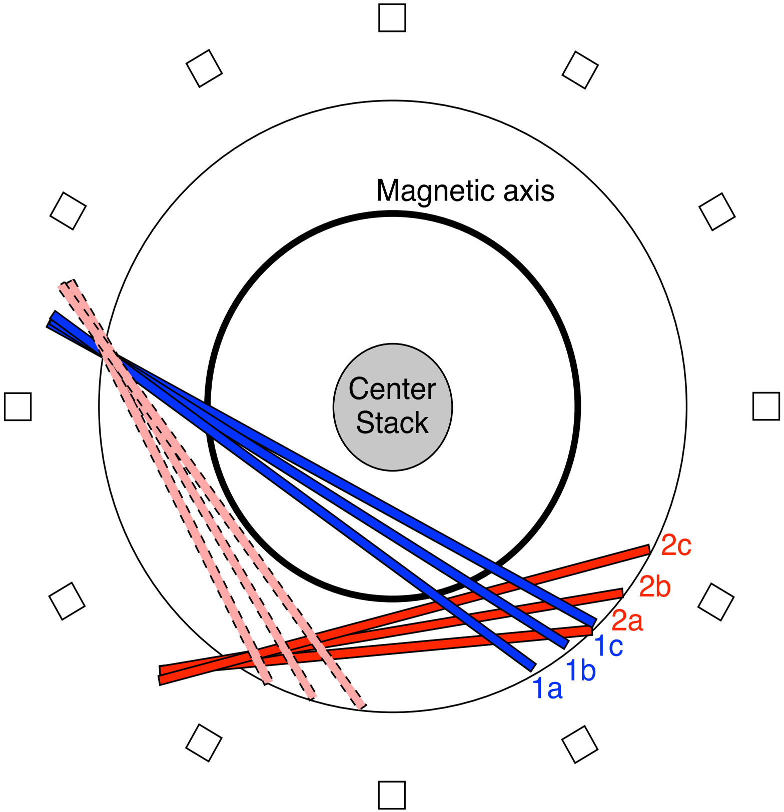
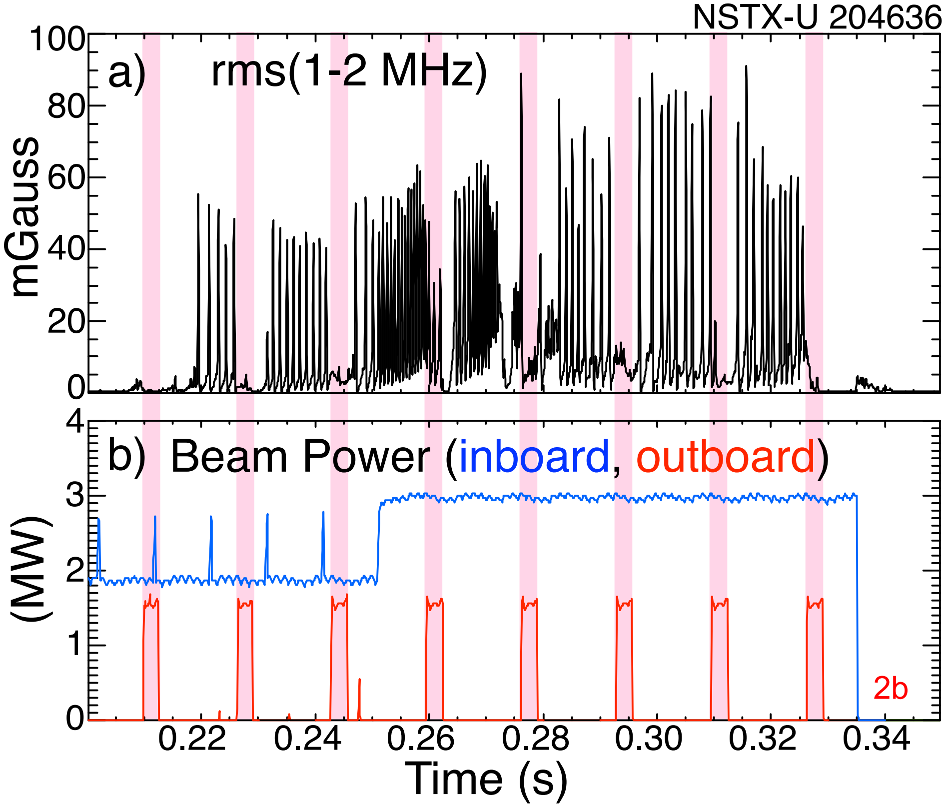


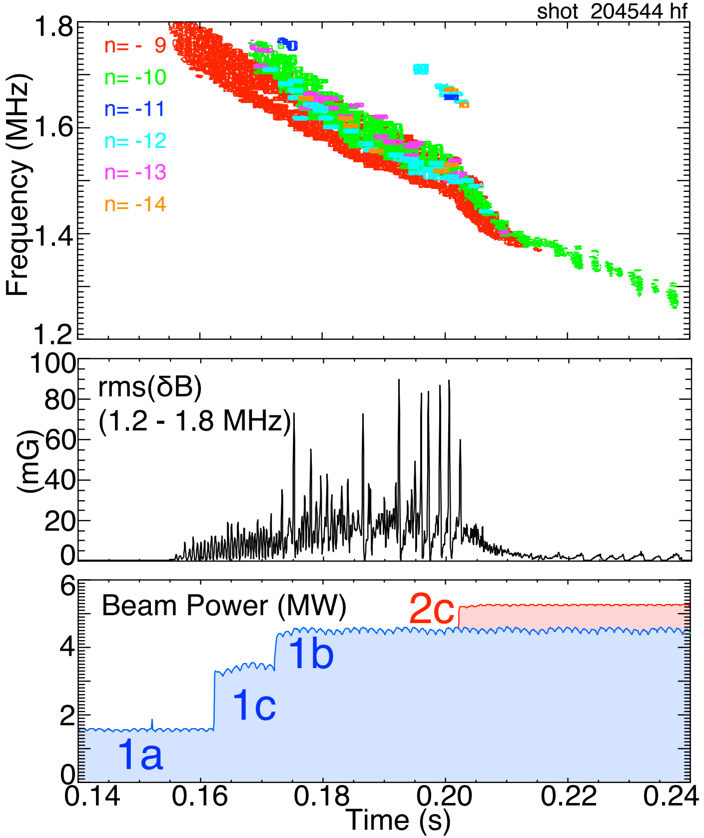
Suppression can occur in msec; fast ion distribution, not equilibrium changes, responsible

- Suppression occurs in msecs,
  - only a 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?
- Blue curve is total BL-1 source power, red curve is BL-2.



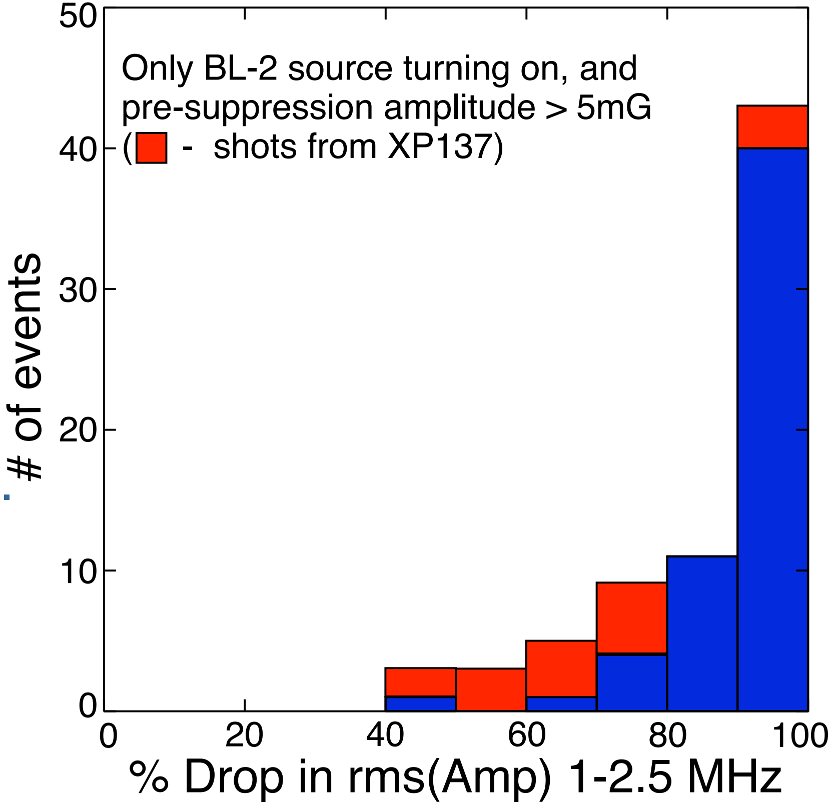
Even if suppression isn't complete, there is a strong reduction in mode amplitude

- 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 NSTX-U shots shows BL-2 is very effective for suppressing GAE

- Database constructed from 2016 shots where BL-2 source injected during strong GAE activity.
- Histogram of 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.
- Counts in red all from 2-day XP focused on H-mode access;
  - unique characteristic of these shots hasn't been identified.

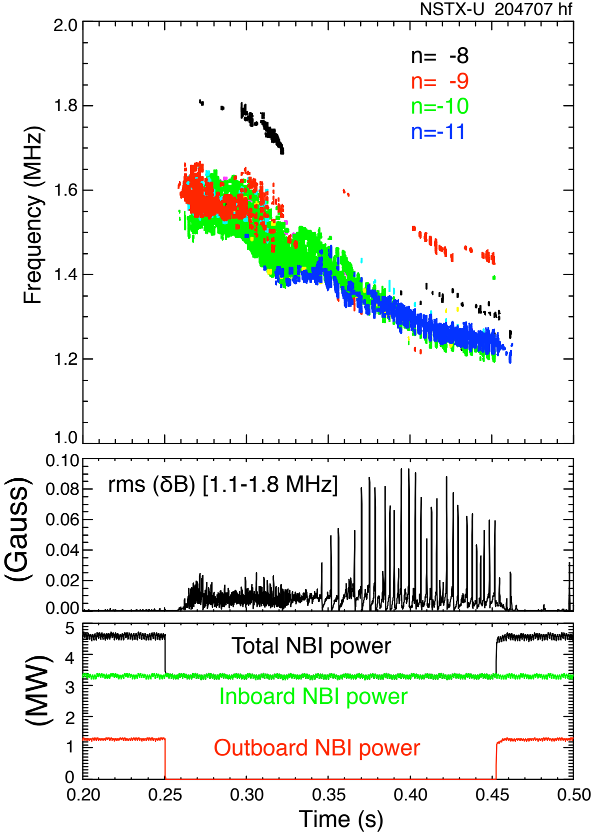


Strong anti-correlation between GAE activity and heating with BL-2

- 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 transient events; BL2 source turning on or off, during a plasma heated by BL1.
- In most cases, complete suppression is seen with BL-2 on,
  - however, particularly with the most inboard source, GAE may persist.
- Observations are qualitatively consistent with analytic model of cyclotron-resonance drive of GAE.
- HYM-code simulations, with more complete physics model, also predict new, off-axis, beams can suppress GAE.

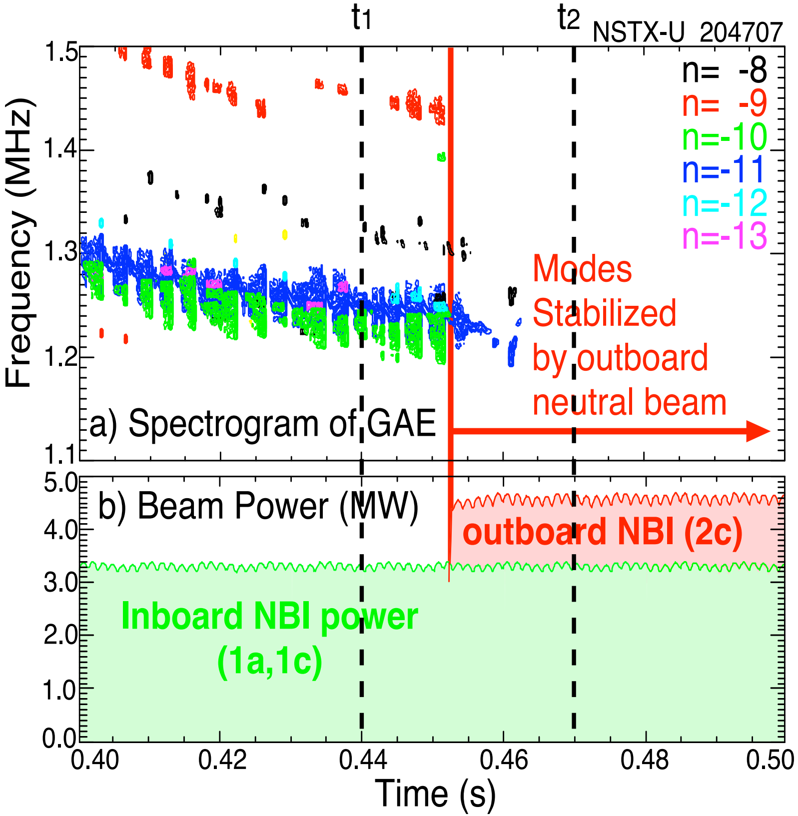
An example with strong GAE activity before suppression is chosen for analysis

- GAE appear after BL-2 source turns off.
- 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.
- Plasma is in L-mode, but suppression is also seen for H-mode plasmas.



Analytic model evaluated and HYM simulations done before and after BL-2 turns on.

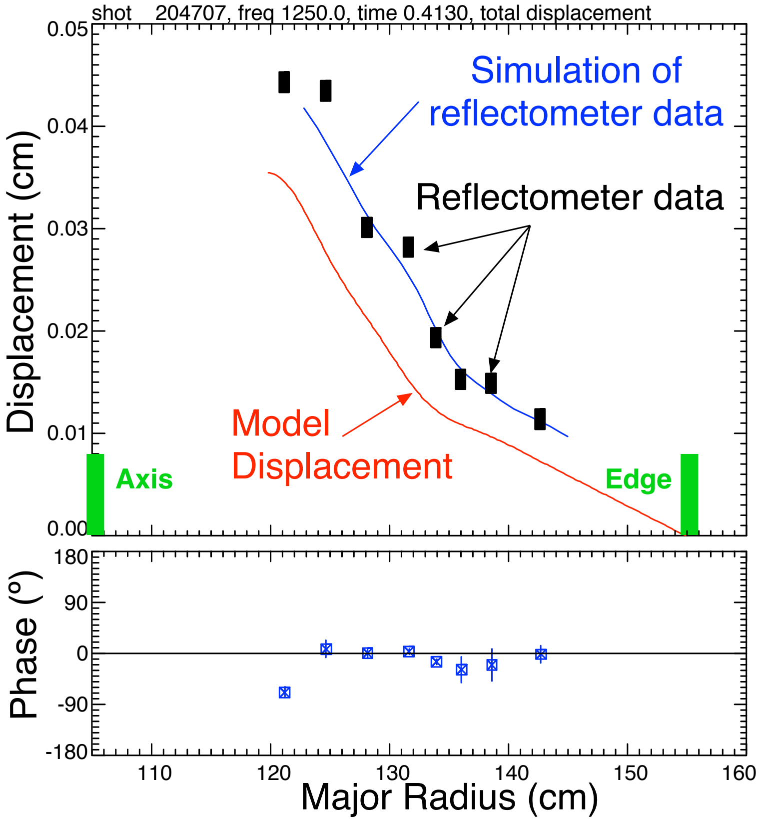
- GAE bursting before modes are suppressed.
- Analysis done at two times:
  - 0.44s,during GAE activity (w/o 2c),
  - 0.47s, after 2c on.
- GAE suppression noticeable within milliseconds.
- BL-2 (source 2c) only adds ≈1.2MW out of 4.6MW, ≈26%.



Reflectometer array* shows mode structure as expected for global Alfvén eigenmodes

- Reflectometer response combines “interferometer” response and cut-off layer displacement,
- Reflectometer data inverted with iterative model,
  - trial function
- Structure peaks near minimum in q, as expected for GAE.
  - nearly constant phase over radius.

*N A Crocker, S Kubota, UCLA



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

- Fast ions can be stabilizing/ destabilizing depending on their $k_\perp \rho_L$:

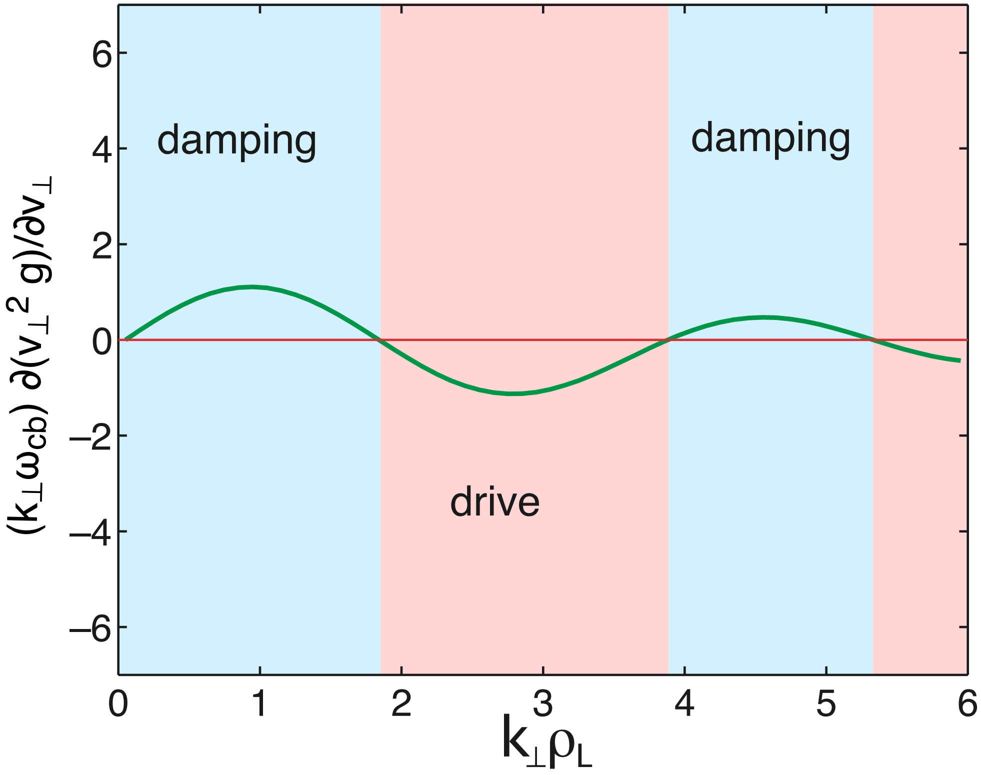
  Stable $: 0 \le k_\perp \rho_L \le 1.9$

  Unstable$: 1.9 \le k_\perp \rho_L \le 3.9$

- Resonant outboard beam ions 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



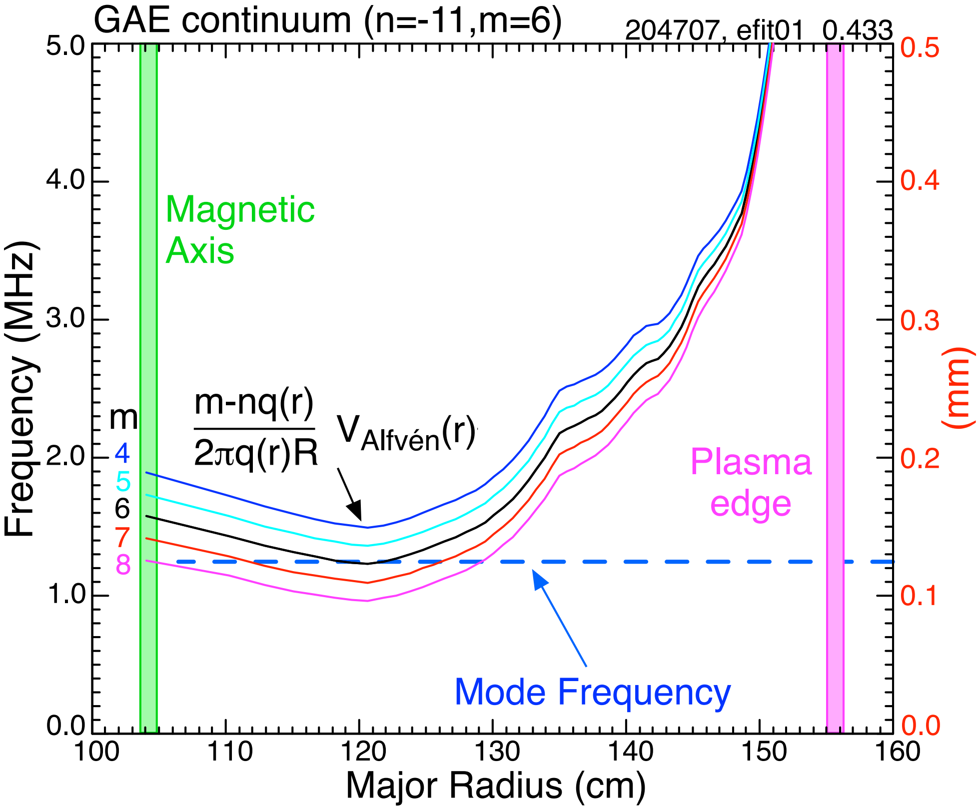
Local dispersion relation and experimental parameters are used to deduce $k_{||}$ and $k_{\perp}$

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

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

$$k_{||} \approx \frac{m-nq}{qR}$$

- Experimental inputs are q, density, rotation profiles and mode frequency, toroidal mode number.



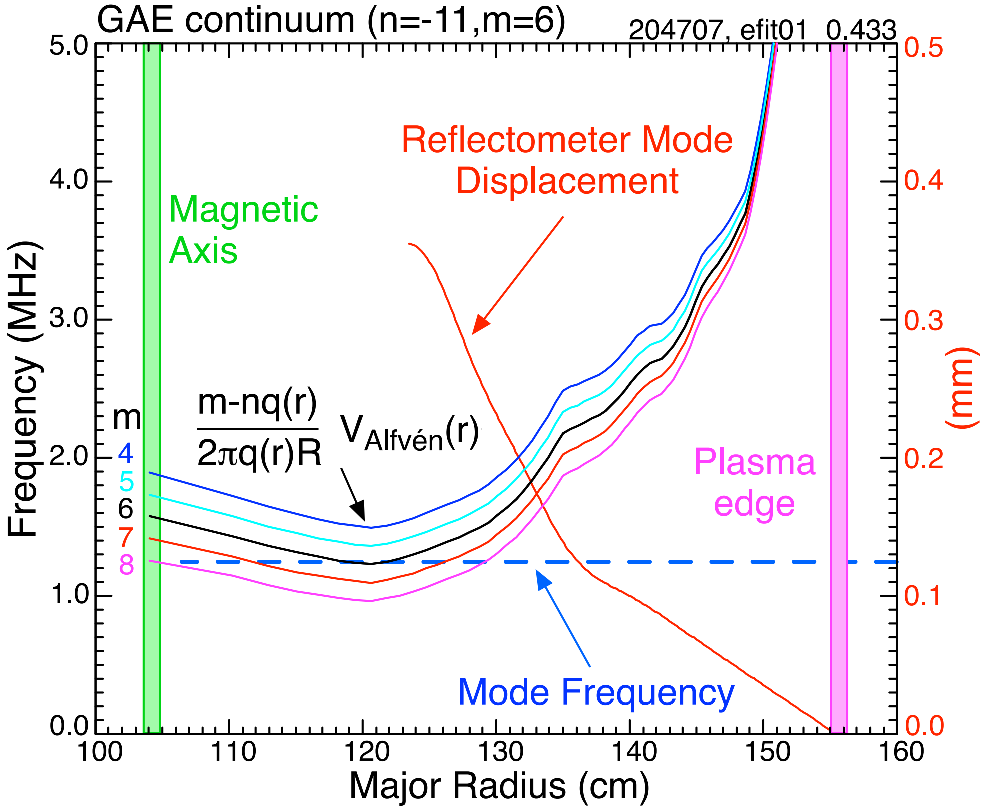
Analytic theory predicts GAE amplitude to peak near minimum in continuum

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

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

$$k_{\|} \approx \frac{m - nq}{qR}$$

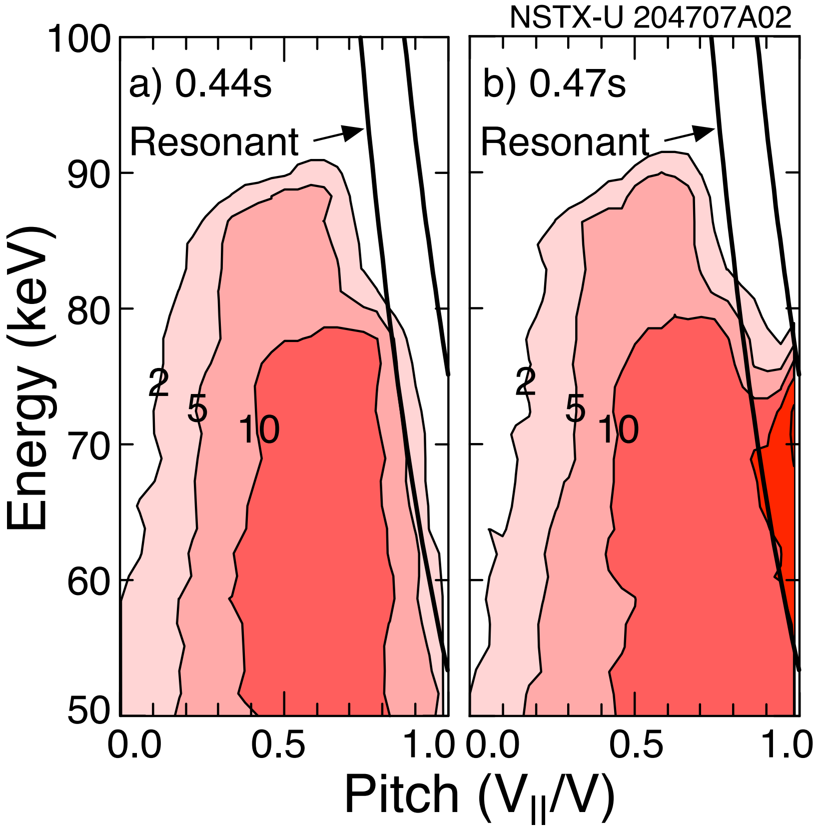
- Experimental inputs are q, density, rotation profiles and mode frequency, toroidal mode number.



TRANSP modeling predicts that beam fast ions are resonant with the GAE

- The parallel beam ion velocity for resonant fast ions is estimated from the resonance condition:
  - $\omega_{GAE} + \left| k_{\parallel} \pm 1/qR \right| V_{b\parallel} = \omega_{ci}$
  - the sidebands arise from particle drifts

- Two side-band fast ion resonances are indicated by black lines in the 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

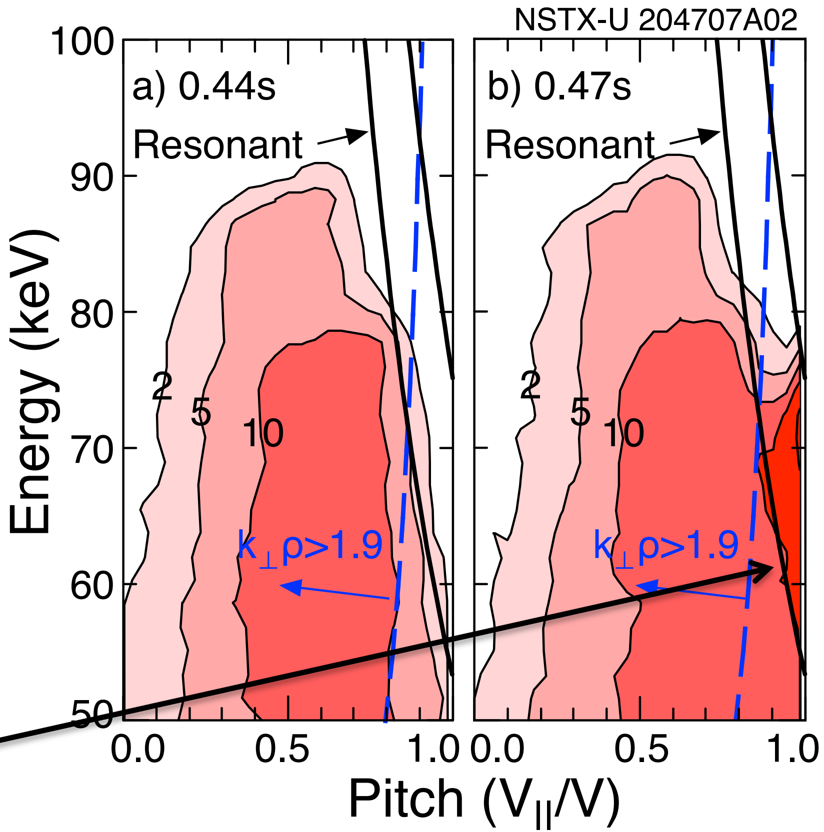
- $k_{||}$ estimated above is used to calculate $k_\perp$:

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

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

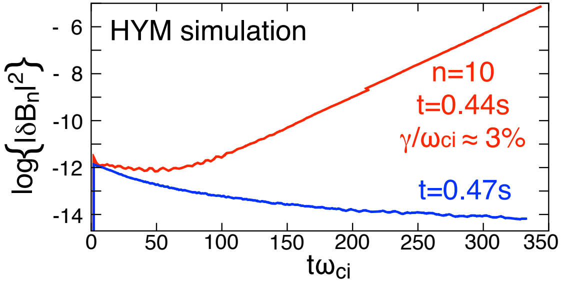
$$\text{Drive: } k_\perp \rho_L > 1.9, \text{ Damping: } k_\perp \rho_L < 1.9$$

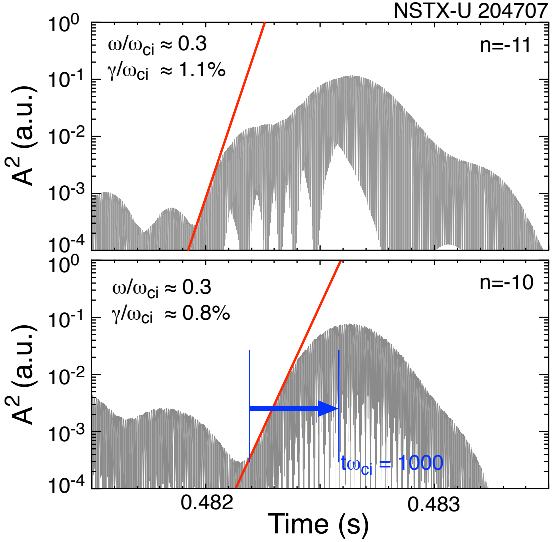
- …where ρ_L is calculated from the perpendicular fast ion energy.
  - The boundary between damping and drive is shown by the dashed blue lines.
- The BL2 sources add primarily fast ions with high pitch (Fig. b).



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

- HYM is an initial value, hybrid code in toroidal geometry
  - beam ions treated with full-orbit, δf scheme
  - thermal plasma is one-fluid MHD
- Code can run non-linear, but only linear results shown here.
- Growth rate positive at 0.44s, negative at 0.47s with added source 2c.
- Simulated growth rates sensitive to fast ion distribution.

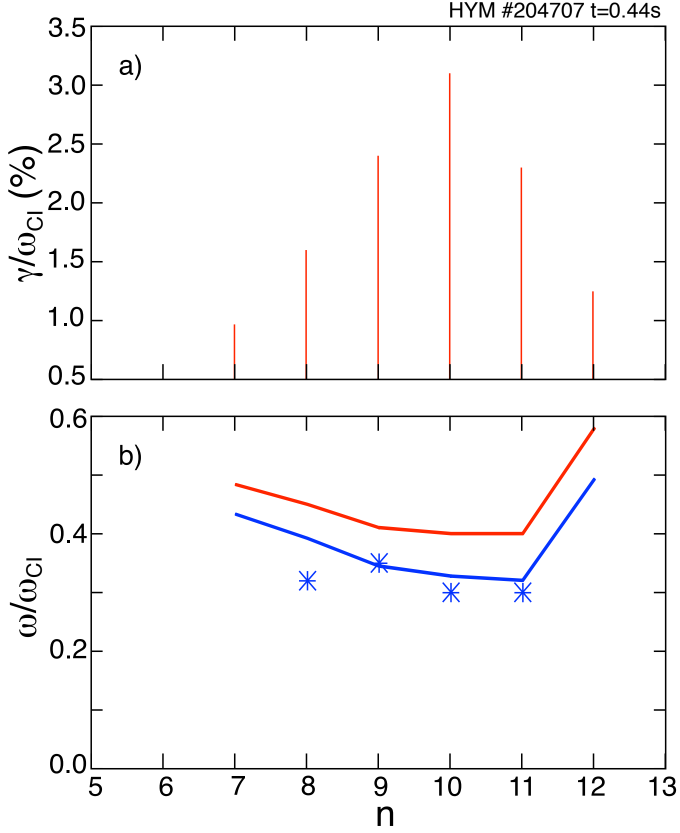




*Belova, PoP **10** (2003) 3240

HYM predicts frequencies of observed modes

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



GAE suppression with increased NBI power is robustly observed

- 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.
- A qualitative explanation is found in an analytic model for GAE drive through the Doppler-shifted cyclotron resonance.
- Quantitative simulations with the hybrid MHD code, HYM, find excellent agreement with the experimental observations.
- Extension of similar techniques to other instabilities may provide an efficient method of improving fusion reactor efficiency.

Related posters

- For more information on HYM-code simulations, please see at the NSTX-U poster session this afternoon:
  - Numerical simulations of GAE stabilization in NSTX- U

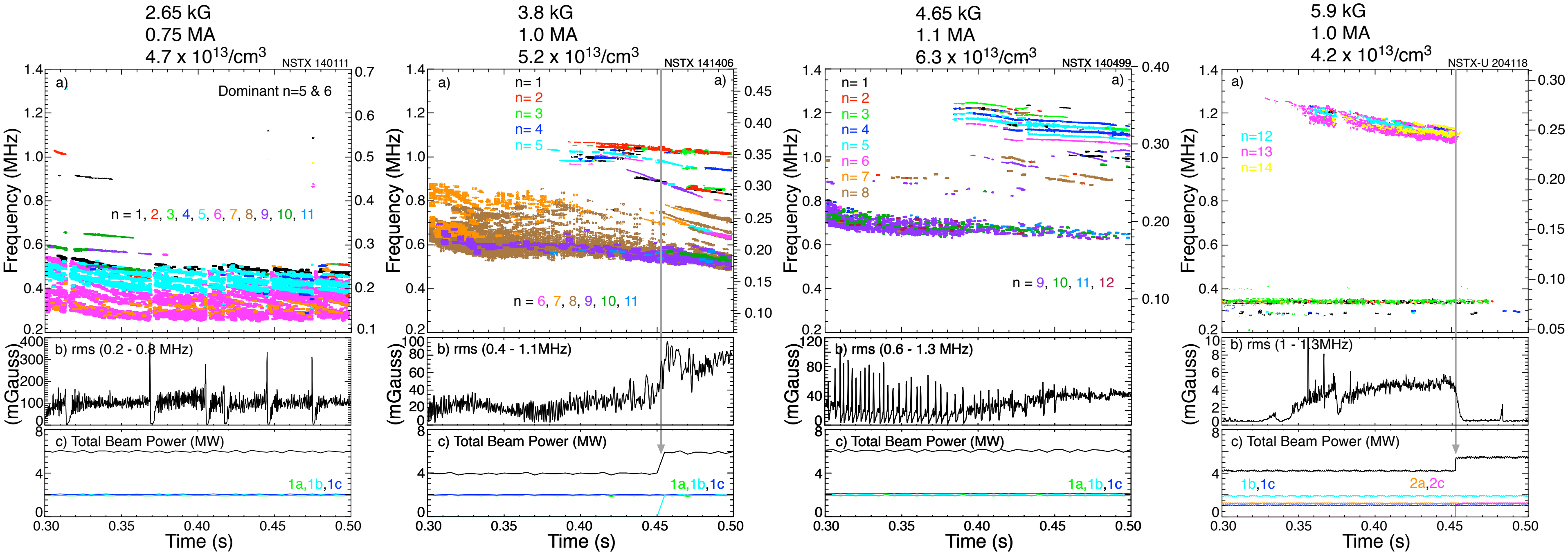
    E. Belova PP11-45
  - Energetic-particle-modified global Alfvén Eigenmodes

    J. Lestz PP11-46
  - Destabilization of counter-propagating TAEs by off- axis, co-current Neutral Beam Injection

    M Podestà PP11 50

GAE frequency and toroidal mode number increase with toroidal field

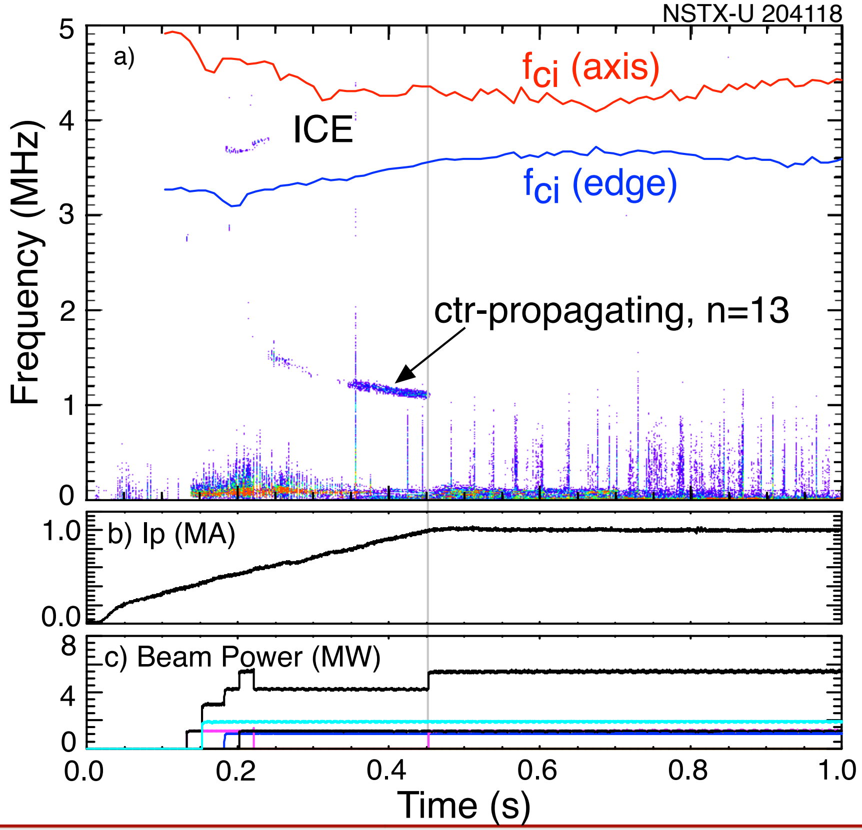
- Frequencies of GAE on NSTX-U consistent with this scaling.



‘Similar’ 1MA, 6MW NSTX-U H-mode

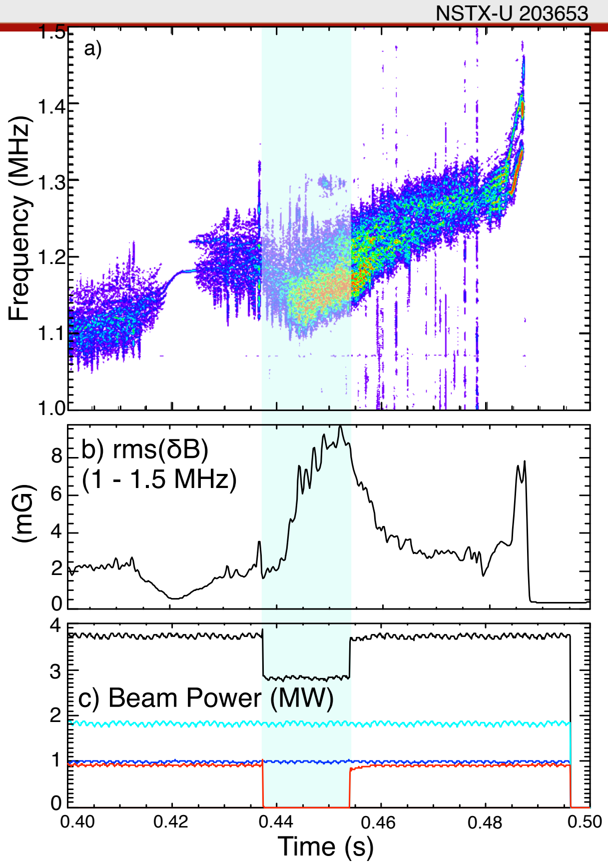
- 6.5 kG toroidal field.
- One 90 kV beam, 3 - 70 kV beams
- Two outboard sources.
- Density similar

- Note minimal hfAE activity



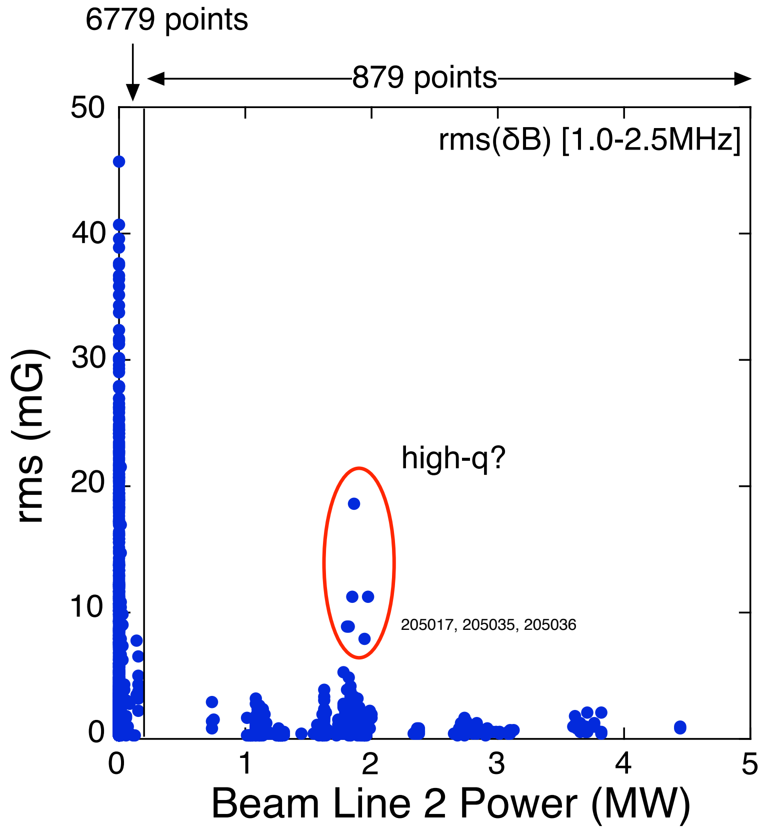
GAE grows during 2a beam block

- 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.