New beam driven modes below the GAM frequency in NSTX

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in collaboration with
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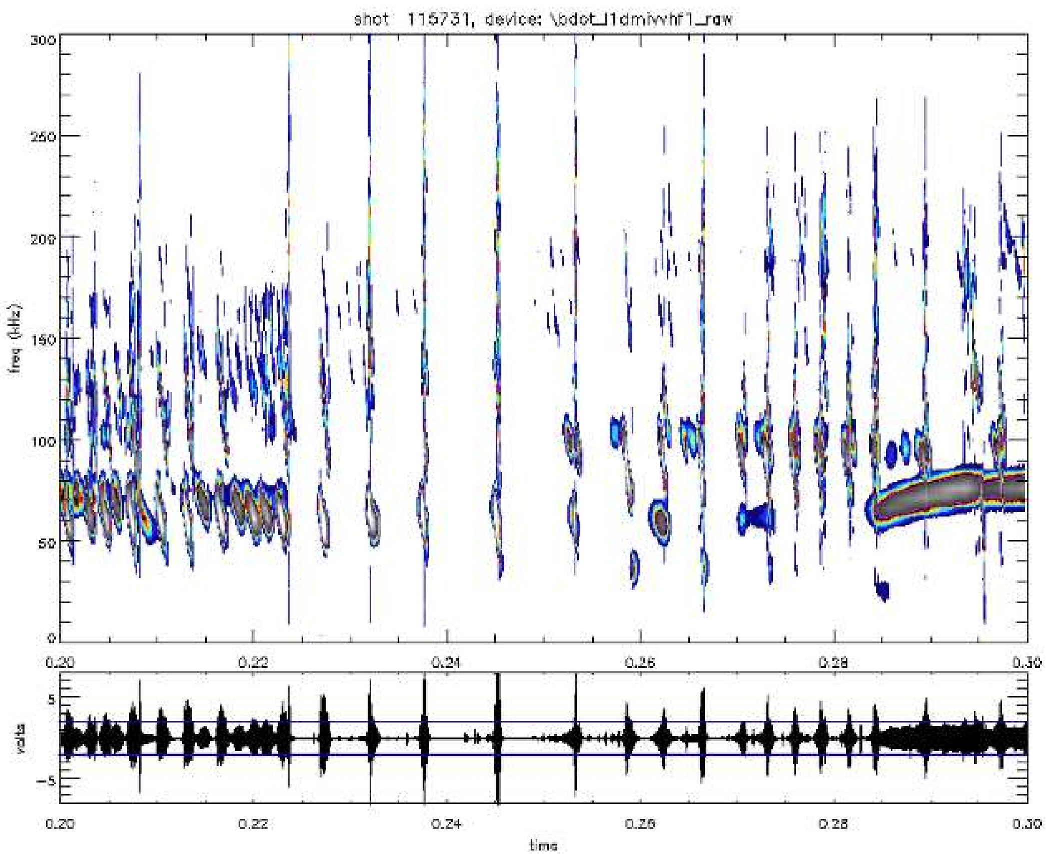
Multiple MHD instabilities are routinely observed in NSTX

Mirnov activity @ reversed shear #115731 ($f_{TAE} = v_A/2qR \simeq 90kHz$)



At $t = 0.262 sec$, $n = 2$ mode frequency $f_{lab} \simeq 103\, kHz$,
$f_{pl} \simeq f_{lab} - n \times 25 = 63\, kHz$, $\Rightarrow$ too low for TAE for all observed modes.

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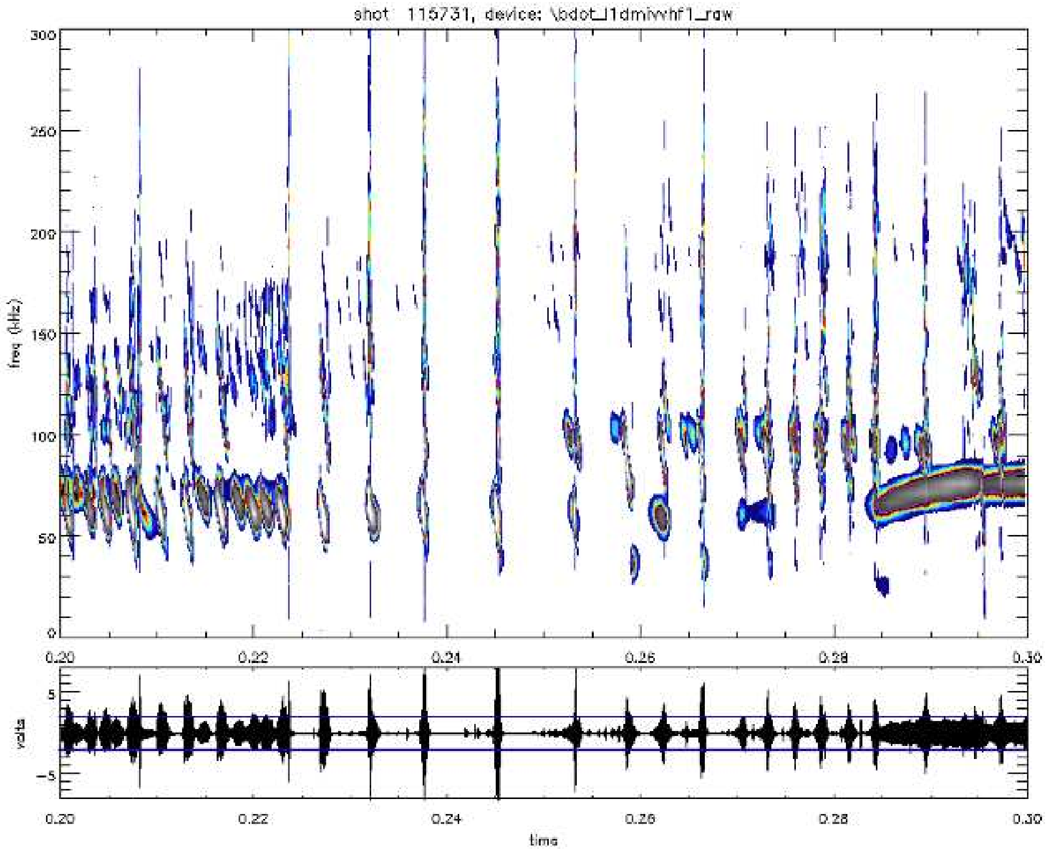

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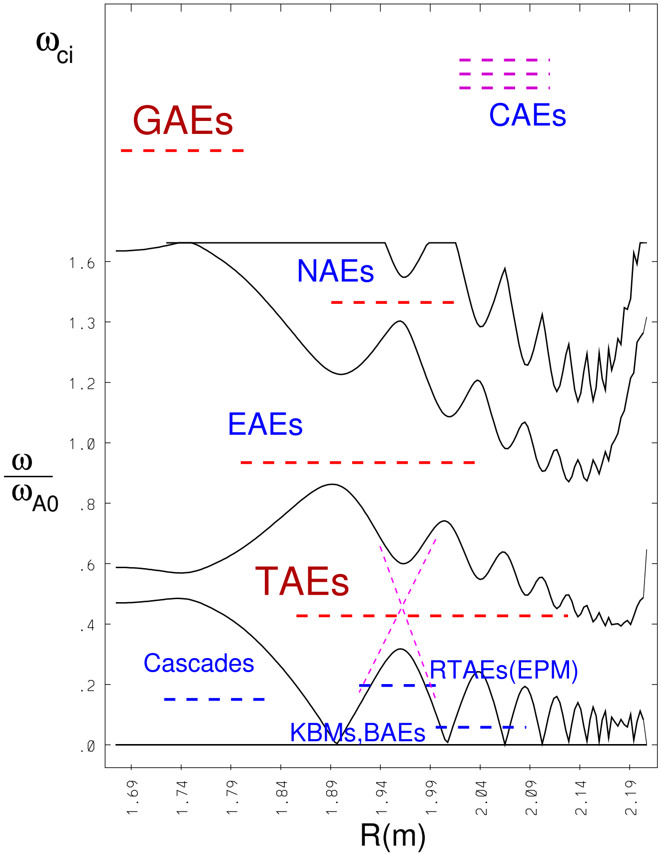
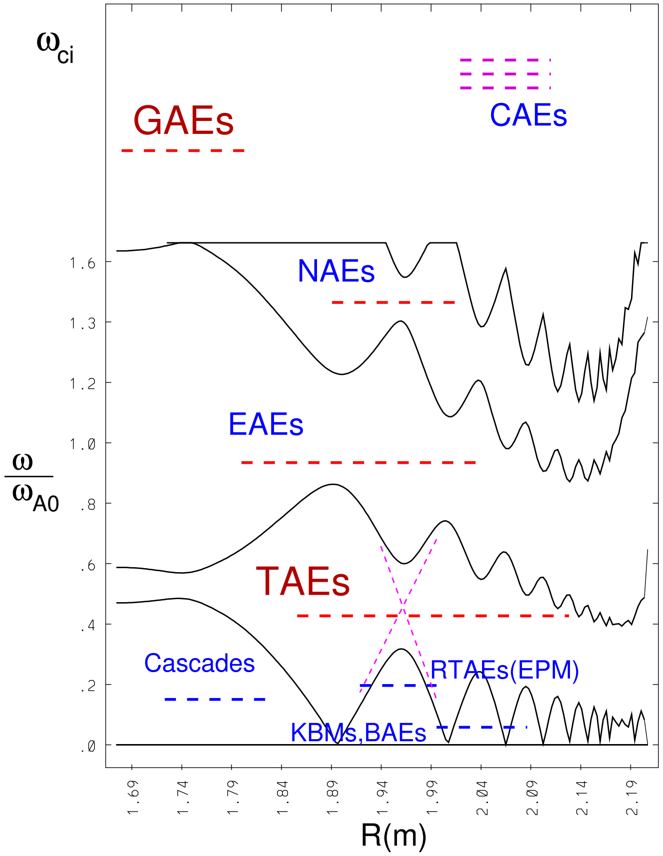
What are these modes: EPMs, fishbones, KBM, TAEs?

Typical AE spectrum





- Simple, commonly used estimate

$$\omega_{TAE} = \frac{v_A}{2qR} \Leftarrow k_{\|m} = -k_{\|m+1}$$

- For NSTX #115731 with reversed q-profile, $q_{min} = 1.3$, we find

$$\omega_{TAE} \simeq 90kHz.$$

- Rotation is important factor in mode identification in NSTX

$$f_{pl} = f_{lab} - nf_{rot}$$

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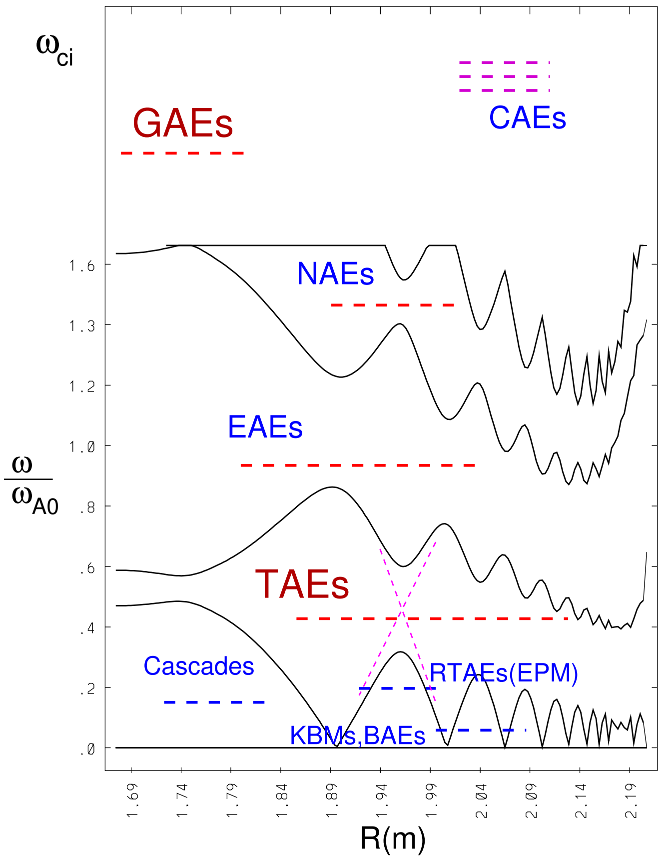

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- In general low frequency modes are more effective in radial EP transport.

Theory for Alfven/acoustic continuum in low-β large aspect ratio equilibrium

Simplified shear Alfvén and acoustic equations (from Cheng, Chance '86):

$$\begin{aligned} \Omega^2 y + \partial_\parallel^2 y \quad & + \gamma\beta \sin\theta\, z & = 0 \\ \Omega^2 \left(1 + \frac{\gamma\beta}{2}\right) z + \frac{\gamma\beta}{2}\partial_\parallel^2 z \quad & + 2\Omega^2 \sin\theta\, y & = 0, \end{aligned} \qquad (1)$$

where $\Omega \equiv \omega R_0 / v_A$, $y \equiv \xi_s \varepsilon / q$, $\xi_s \equiv \vec{\xi} \cdot \frac{[\mathbf{B}\times\nabla\psi]}{|\nabla\psi|^2}$ and $z \equiv \nabla \cdot \vec{\xi}$, $\hat{k}_\parallel \equiv i\partial_\parallel$.

- Pure Alfvénic branch $\Omega^2 = k_\parallel^2 + \gamma\beta\left(1 + 1/2q^2\right)$ (Chu'92, Breizman'05, Berk'06, Turnbull '92).
- Pure acoustic modes (AMs) $\Omega^2 = \frac{1}{2}\gamma\beta k_\parallel^2$.
- GAMs: $\Omega^2 = \gamma\beta\left(1 + 1/2q^2\right)$ (Winsor'68, Breizman'05, Berk'06) in the assumption of $\Omega^2 \geq \gamma\beta$.
- Toroidal AMs (is it a good name?) exist for $\Omega^2 \ll \gamma\beta$ and is new theoretically.

Alfven/acoustic continuum contains gaps due to geodesic curvature coupling.

- New Alfvenic-like branch emerges at low frequency: $\Omega^2 = k_0^2/\left(1+2q^2\right)$.
- It couples with acoustic sideband modes $\Omega^2 = \gamma\beta k_{\pm 1}^2/2\left(1+\delta\right)$ and creates a gap.

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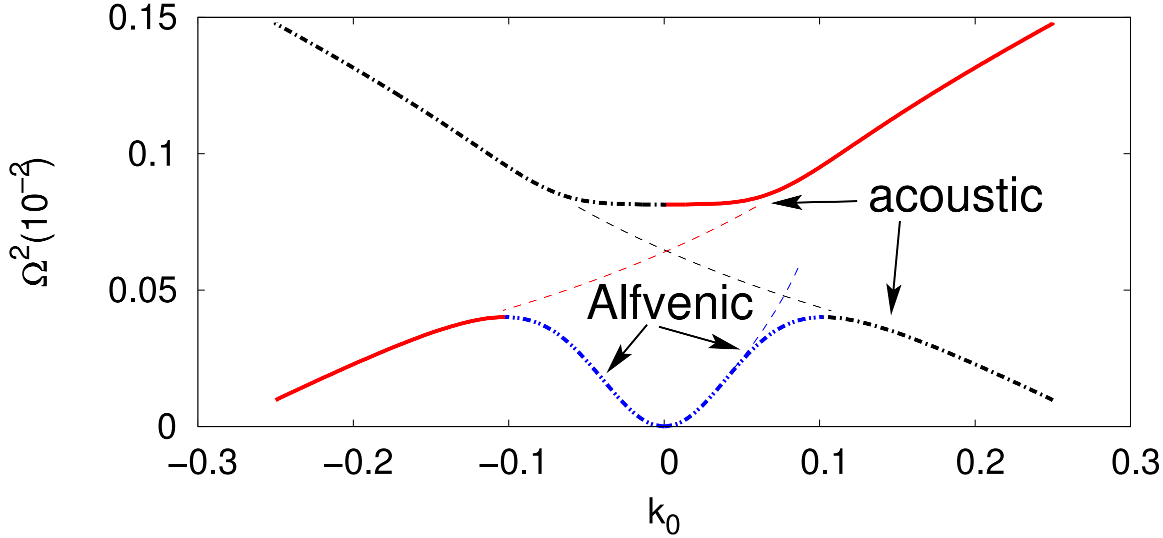

Figure 1: Local dispersion relation (solid lines) in high-m limit at $q = 1.75$, $\beta = 0.3\%$.

Consider high aspect ratio low-β tokamak

$R_0 = 0.806m$, but with the aspect ratio $A = 10$, $a = 0.081m$,
$\beta \equiv 2p/B_0^2 = 0.3\%$, $q_a = 11.3$, $q(0) = 2.16$, $q_{min} = 1.3$,
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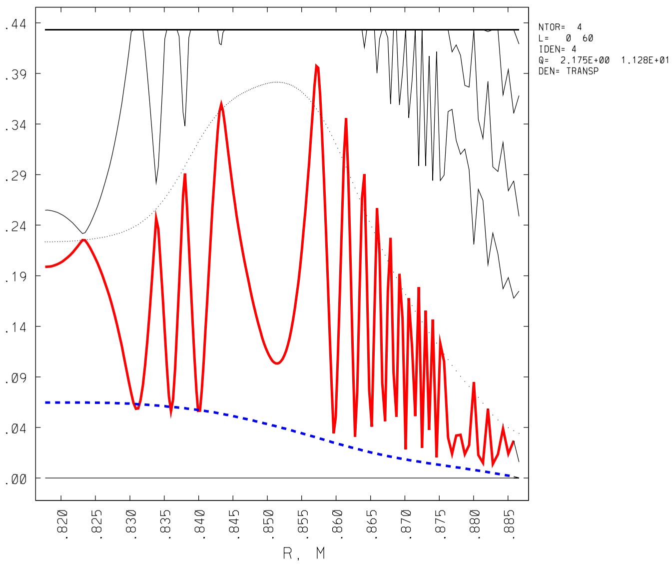
Acoustic filtered continuum (Chu'92) vs



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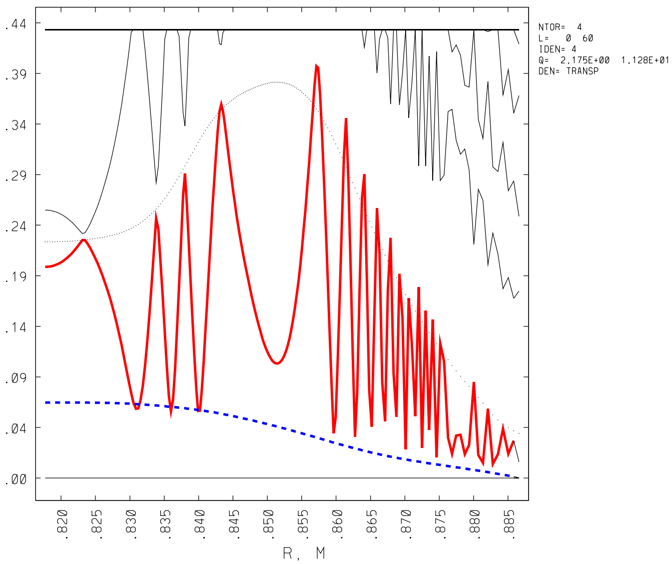
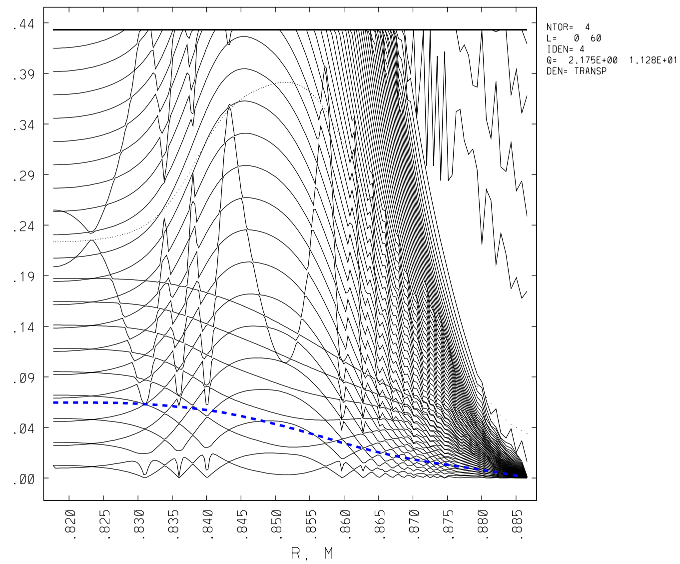
Acoustic filtered continuum (Chu'92) vs Full MHD continuum

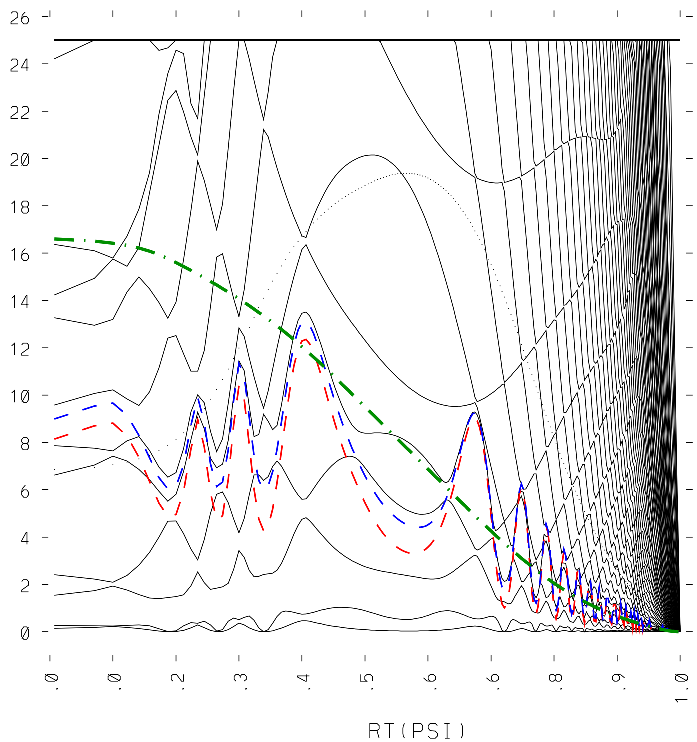




Numerical analysis is very much simplified with filtering (singularities are avoided).

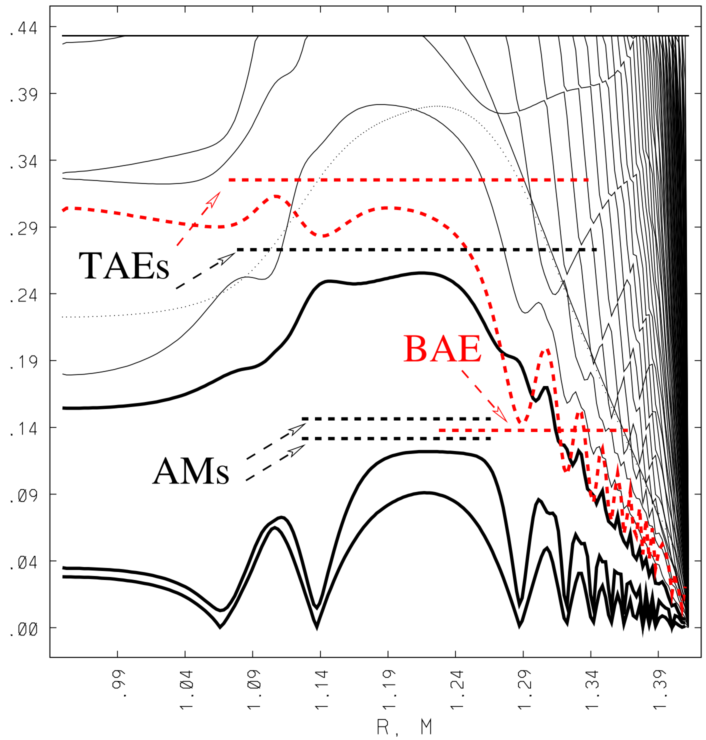
BAE and TAE gaps are well reproduced with the filtering technique.

NSTX medium $\beta = 5\%$ equilibrium from TRANSP @q (MSE)



- Overlaid red is for acoustic mode filtering scheme (Chu'92)
- Overlaid blue continuum includes q correction $\left(1+1/2q^2\right)$.
- Black is for full ideal MHD NOVA continuum. Influence on gaps from the acoustic modes.
- Global AMs are more likely at high β since frequency spacing for the acoustic continuum is $\Delta\Omega \sim \sqrt{\gamma\beta/2}$.
- Harder to find the mode at lower beta due to stronger interaction with the continuum.

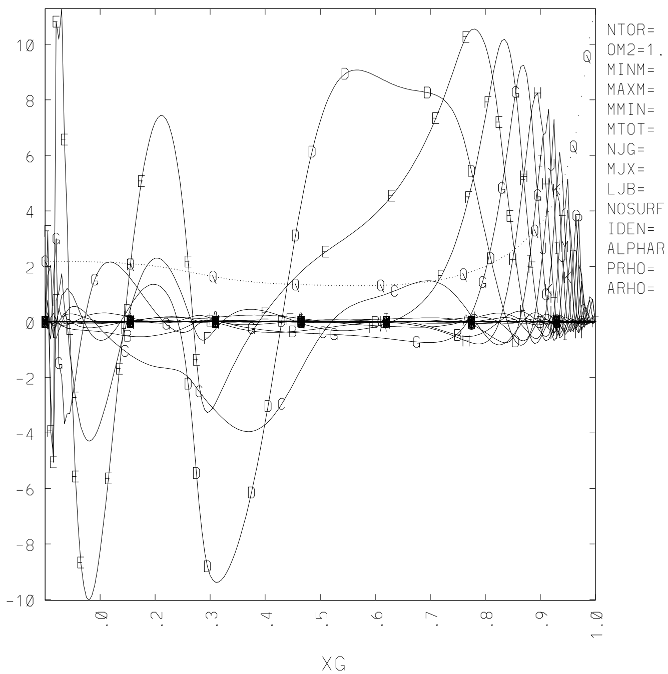
TRANSP high $\beta = 21\%$ *equilibrium case*



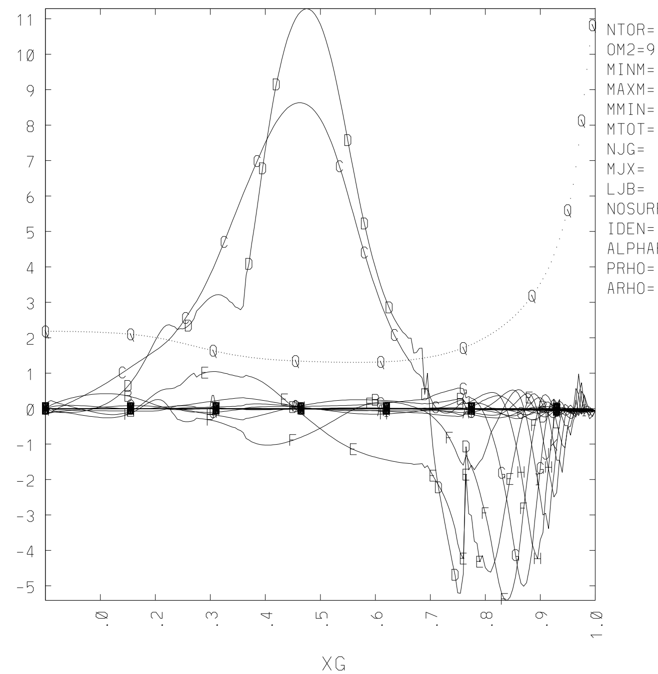
- Red is for acoustic mode filtering scheme (Chu'92): TAE and BAE (Turnbull '93) modes are recovered but frequencies are shifted.
- Black is for full ideal MHD NOVA continuum.
- Global AMs are more likely to exist at high β since frequency spacing for the acoustic continuum is $\Delta\Omega \sim (\gamma\beta)^{3/4}/q$.
- Two AM branches are found. GAM interacts strongly with the Alfvén-like branch.
- TAM forms global eigenmodes above acoustic continuum.

TAE structure with and without filtering

Filtered continuum opens the gap



Full continuum limits TAE localization

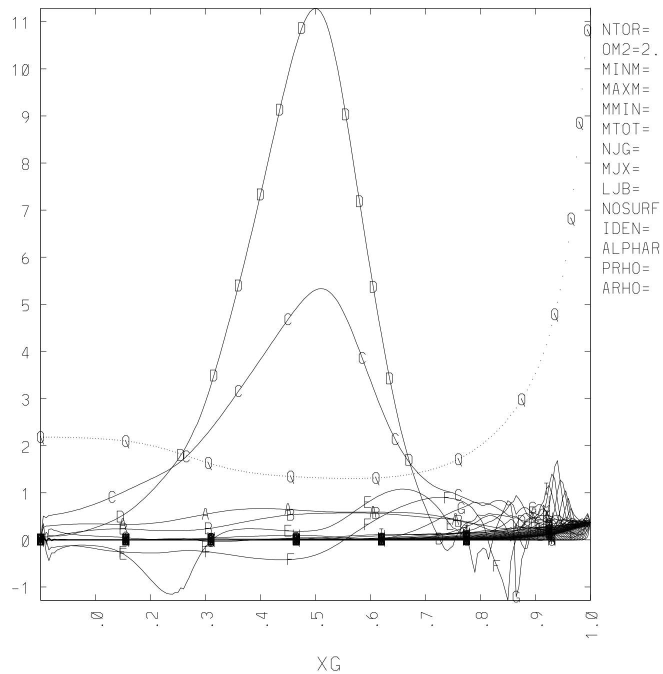


Mode structures are notably different in two models

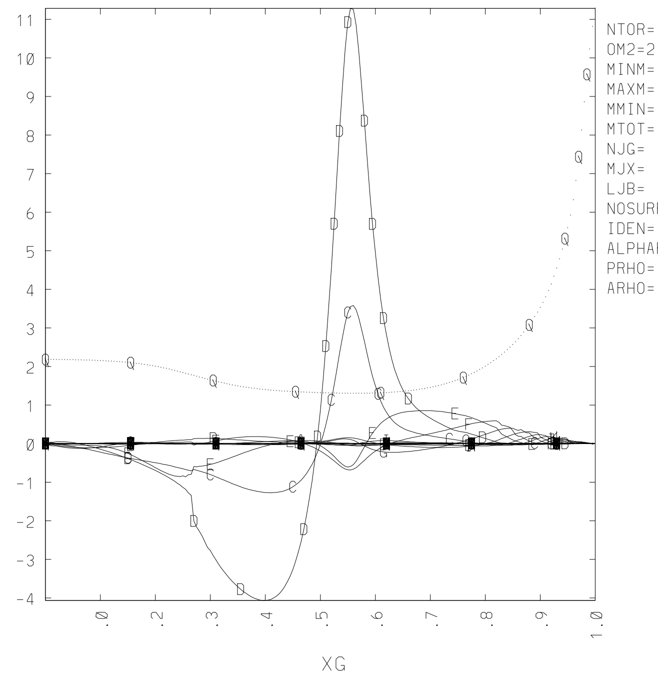
Interaction with the continuum is stronger without filtering. Is continuum damping proportional to β (MAST results)?

Toroidicity-induced global Acoustic mode (TAM) structure and frequency

First radial TAM (higher $f = 35kHz$)

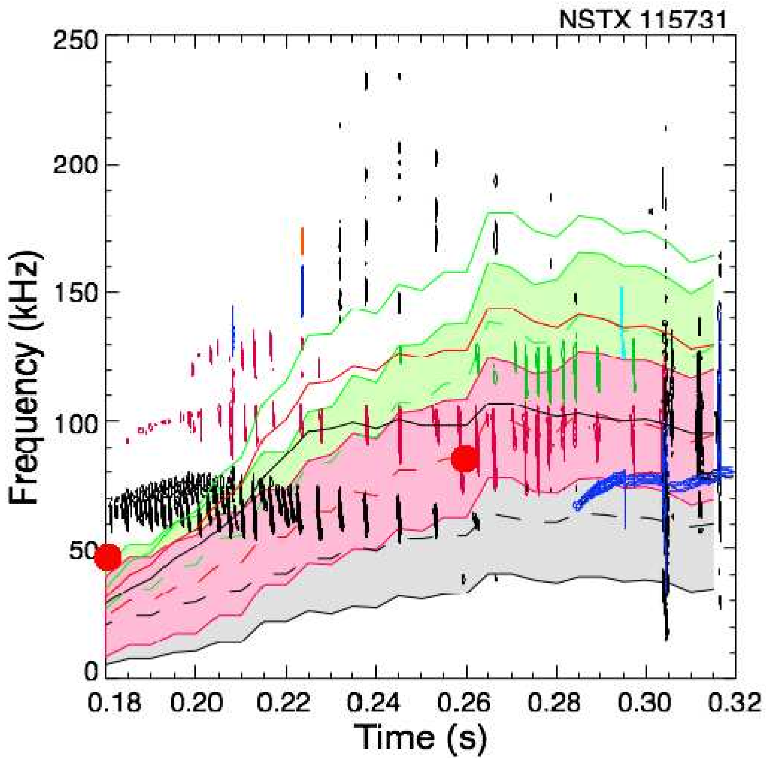


Second radial TAM $f = 33.8kHz$



Two dominant harmonics, $m = 2, 3$, are present due to $nq_{min} = 2.6$.

How TAM frequency compares with NSTX data?



- Black, red, green shaded areas are for theoretical scaling of TAM with rotation and $n = 1, 2, 3$.
- Black is for full ideal MHD NOVA continuum.
- Upper black, red and green are core n=1,2 and 3 TAE frequencies.
- Red dots are predictions by NOVA for $n = 2$.
- Discrepancy is due to strong rotation $f_{rot} = 24kHz$ at $t = 0.26sec$ (local).
- Possible causes of the discrepancy:
  - toroidal rotation is strongly sheared and may affect the mode localization
  - EPM effects push TAE frequency down to merge into TAM solution. r-TAE to r-KBM transition like effect (Cheng '95, Gorelenkov '03).

SUMMARY

- Theoretical analysis shows the existence of low-n global Toroidicity-induced Acoustic eigenModes (TAM) in NSTX.
- TAMs can exist in high beta plasma with wider BAE gap.
- TAEs are pushed higher in frequency due to beta effect.
- The $n = 2$ TAM frequency computed by NOVA, $35kHz$, is very close to the observed frequency $43kHz$ after deducting the toroidal rotation Doppler shift for $\#115731$ shot.
- Kinetic modification of MHD theory may be important issue for new class of modes (parallel phase velocity is between the Alfven and sound speed).