# *Beta-induced Alfvén-Acoustic Eigenmodes in NSTX and DIII-D Driven by Beam Ions*

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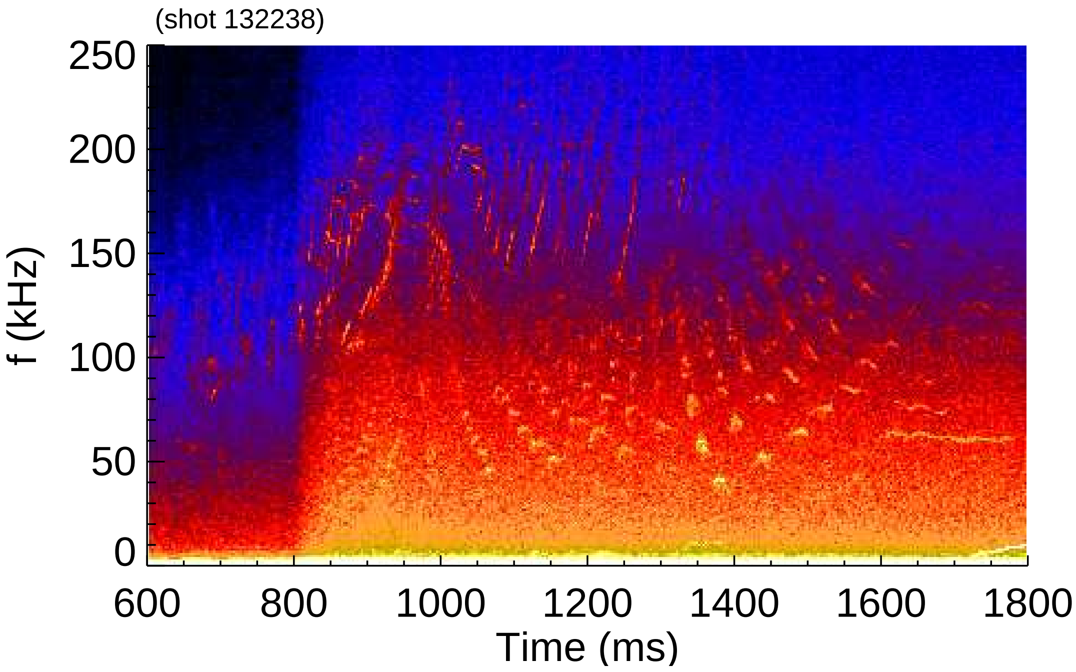
PPPL
PRINCETON PLASMA
PHYSICS LABORATORY

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

# *Interpretation of new experimental observations on tokamaks requires low frequency instability studies*

Strongly heated plasmas with energetic particles reveal complicated MHD spectra with multiple instabilities

**DIII-D ECE spectrum**



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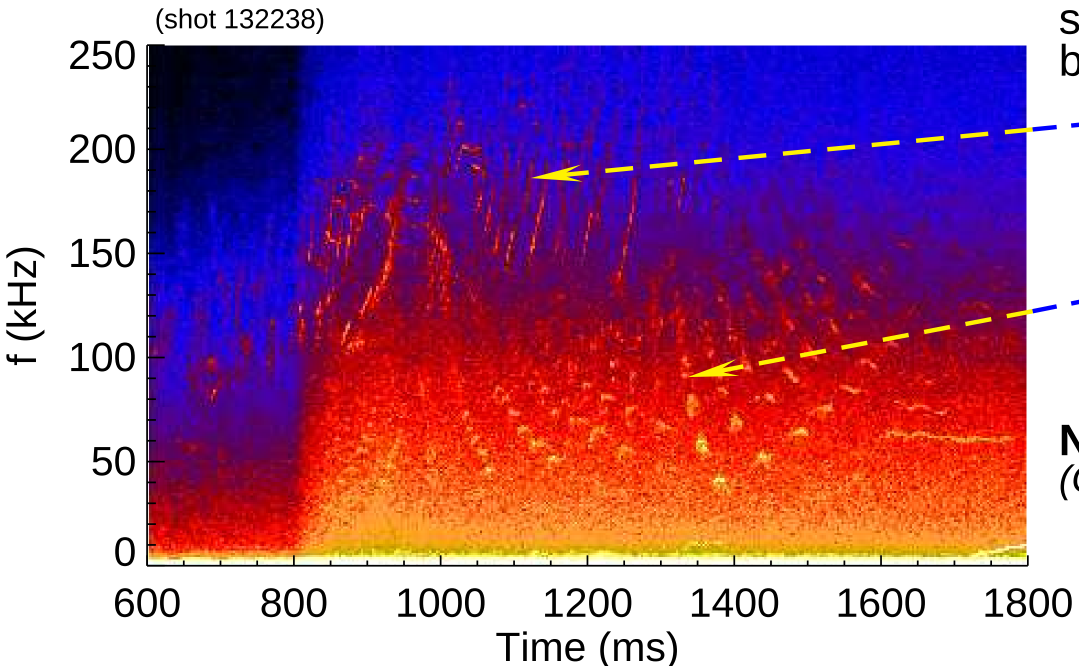

**DIII-D ECE spectrum** shows two sets of MHD instabilities:

- TAE/RSAEs and (toroidicity-induced/ reversed shear AEs - Alfvén Cascades)
- BAAEmodes (Beta-induced Alfvén-acoustic Eigenmodes)

**New BAAE modes** *(Gorelenkov,Phys.Lett.A.'07)*

- frequency below TAE/RSAE ($100-200kHz$)
- frequency sweep start correlates with rational $q(t)$
- indicates RS plasmas

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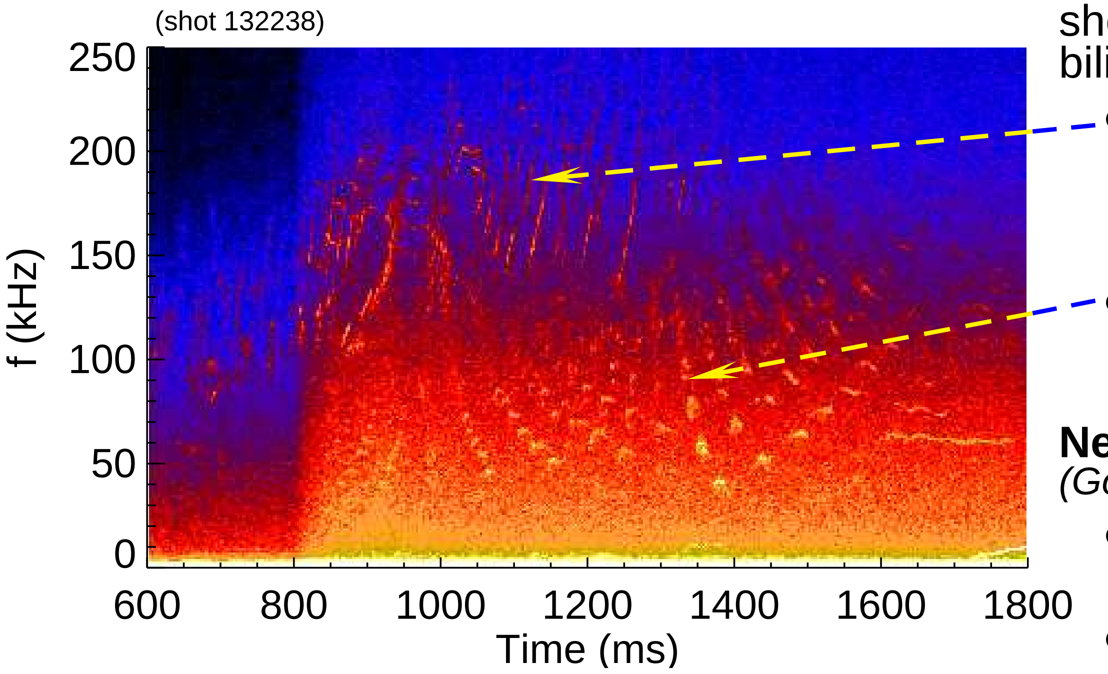

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**At low frequencies: 1) plasma $\beta$ and geodesic curvature are responsible for Alfvén-acoustic mode coupling 2) $\omega_{*i,e}$ effects become important $\Rightarrow$ need to be understood**

# *Motivation to study low-$f$ instabilities*

- Various *AE and a new class of instabilities called here Beta-induced Alfvén Acoustic Eigenmode (BAAE) help to study two fundamental MHD waves: Alfvén and acoustic *(Gorelenkov, APS'06, EPS'07)*.

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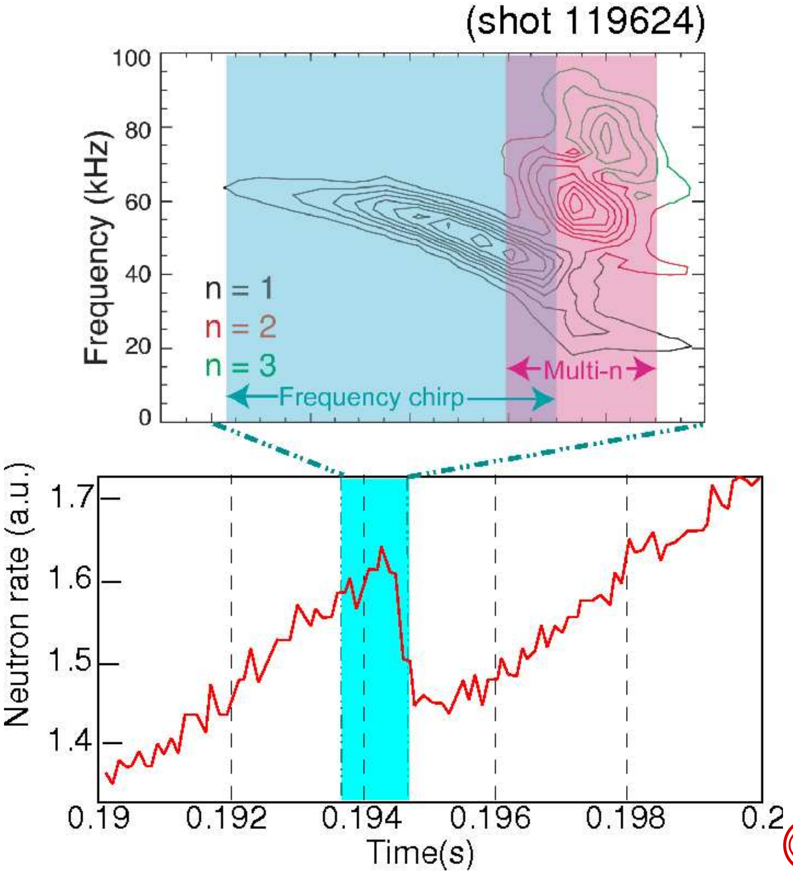


*(D. Darrow, NF'08)*

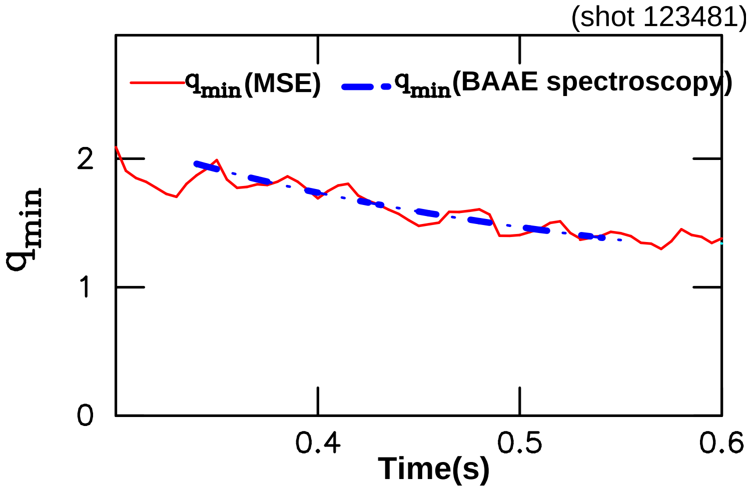
- Energetic Particle (EP) driven low-$f$ instabilities lead to radial EP transport

  On NSTX:
  - three modes form avalanches,
  - can be interpreted as BAAEs,
  - induce losses $\sim 13\%$ in this case as inferred from neutron signal.
  - SFLIP diagnostic observes complicated beam ion loss dynamic.

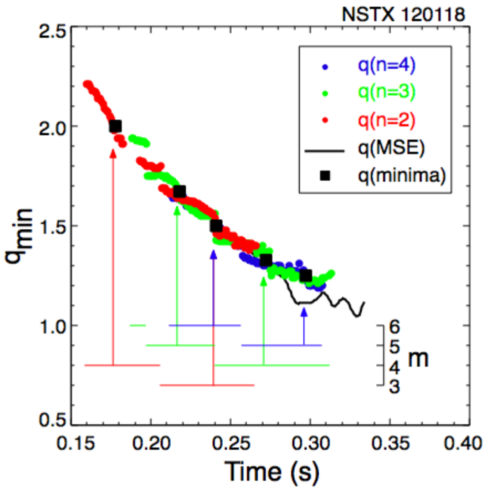
# *Motivation: BAAEs are useful as $q_{min}$ diagnostic*

- BAAEs MHD spectroscopy application is confirmed by MSE in NSTX

BAAEs



RSAEs



*(E.Fredrickson, PoP'07)*

$q_{min}$ from BAAEs (high $\beta$) complements $q_{min}$ from RSAEs (low to medium $\beta$)

- *AEs are expected in burning plasmas, ITER.

# *Talk outline*

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# *Shear Alfvén-acoustic continuum capture main effects*

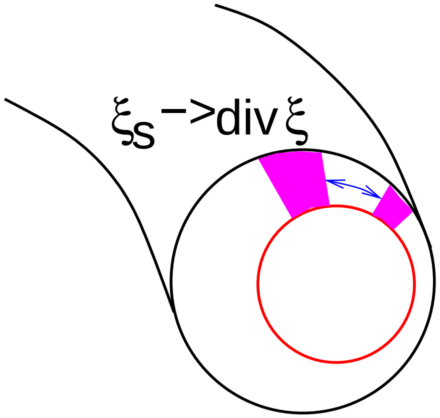
- Alfvén/acoustic continuum bounds global modes: $D(r)=0$, $(\partial_r D \partial_r - S)\,\phi = 0$
- In a low-$\beta$, large aspect ratio plasma, low $\omega_*$, *(Cheng, Chance, PFl '86):*

$$\Omega^2 y + \partial_\parallel^2 y \quad + \gamma\beta \sin\theta\, z \quad = 0 \; (Alfvenic) \tag{1}$$

$$\Omega^2 \left(1 + \frac{\gamma\beta}{2}\right) z + \frac{\gamma\beta}{2} \partial_\parallel^2 z \quad + 2\Omega^2 \sin\theta\, y \quad = 0 \; (acoustic)\,, \tag{2}$$

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

Geodesic curvature coupling: $m$ Alfvénic and $m \pm 1$ acoustic harmonics.



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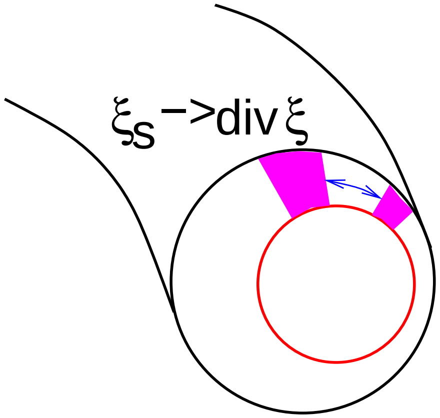
**Various solutions exist***

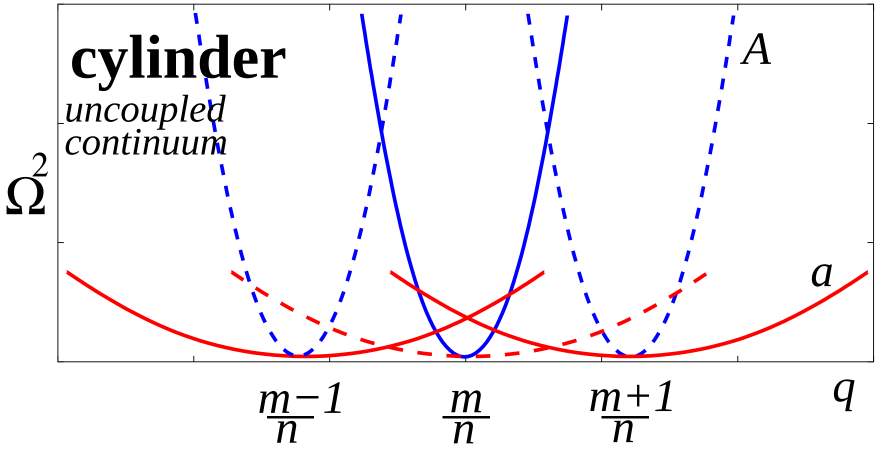
- uncoupled ***Alfvénic* (A)** $\Omega^2 = k_\parallel^2 R^2 + \Omega_{GAM}^2$
  and ***acoustic* (a)** $\Omega^2 = \frac{1}{2}\gamma\beta k_\parallel^2 R^2$ branches.
- ***GAM*s**: $\Omega_{GAM}^2 = \gamma\beta\left(1+1/2q^2\right)$
- ***modified shear Alfvén*** branch $\Omega^2 = k_\parallel^2 R^2/\left(1+2q^2\right)$



**Winsor'68, Mikhailovski'75,'98, Chu'92, Zonca'96, van der Holst'00, Smolyakov'08*

# *Alfvén/acoustic coupling in toroidal equilibrium (schematic)*

- *Alfvén* (A) continuum at low frequency: $\Omega^2 = k_{\|\pm1}^2 R^2$
- *Acoustic* (a) branch $\Omega^2 = \gamma\beta k_{\|\pm1}^2 R^2/2\,(1+\delta)$



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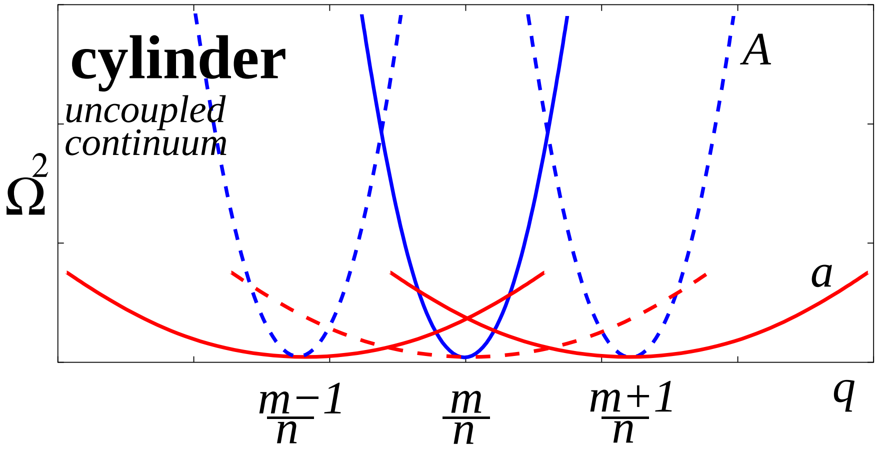
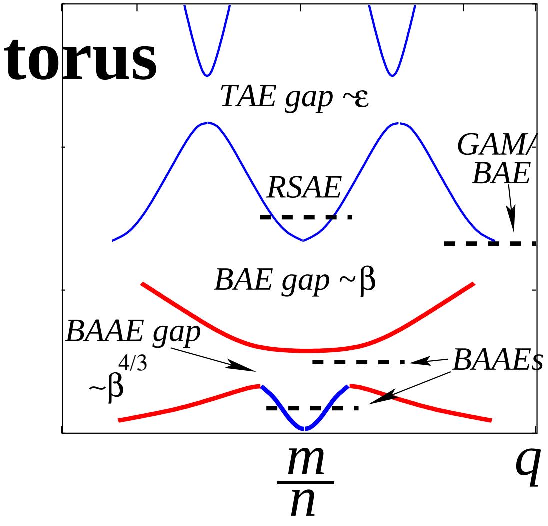
- *Acoustic* (a) branch $\Omega^2 = \gamma\beta k_{\parallel\pm1}^2 R^2/2\,(1+\delta)$ is coupled via $m\pm1$ sidebands with *modified Alfvén* continuum ($m$ harmonic)



$\Rightarrow$



Global modes exist in A-a continuum gaps

*(van der Holst'00)*

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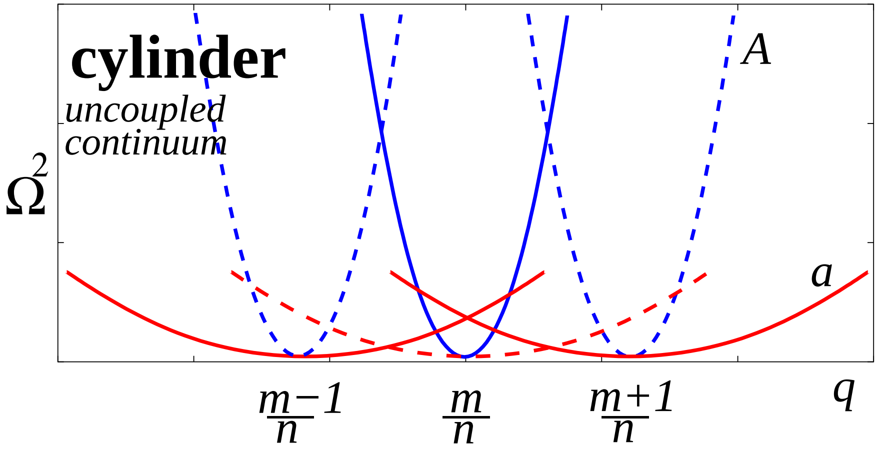

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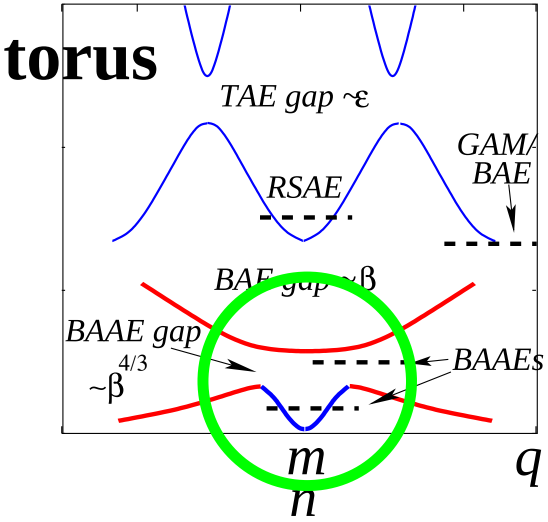

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*(van der Holst'00)*

**Lower (below TAE) gaps are due to $\beta$ and geodesic curvature effects**

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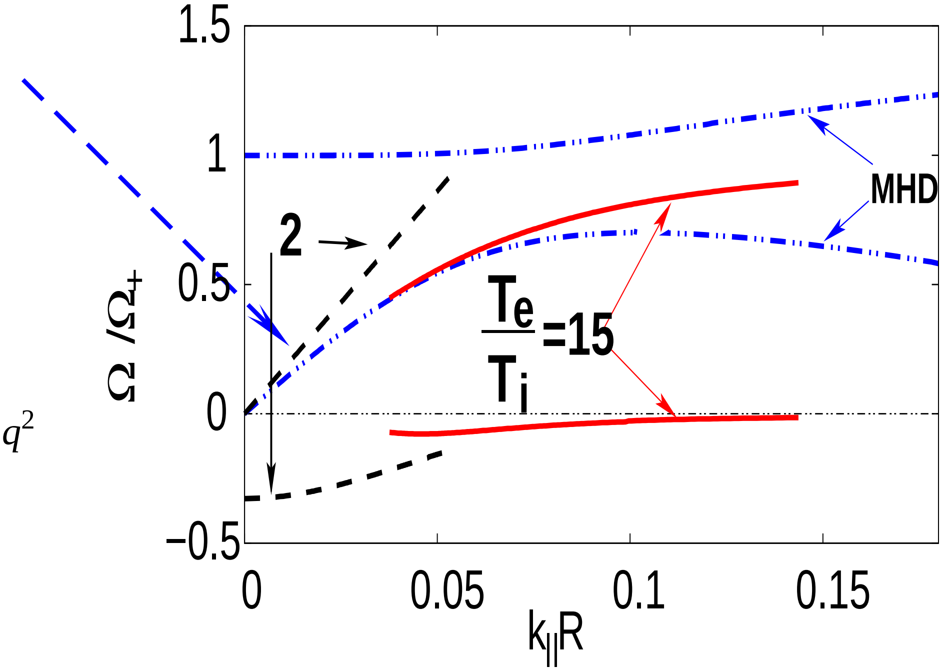
# *Two limit cases of the kinetic dispersion for BAAEs*

Basic assumptions $\beta \ll 1$ ($\delta B_\parallel$ is negligible), $\omega \leq v_s/qR \ll v_A/qR$.
General dispersion: *Zonca et.al. PPCF'96, Mikhailovskii et.al. Pl.Phys.Rep'99*

Two cases are of interest for the **modified Alfvén branch** (sweeping $f$ BAAEs) ($\tau\beta_i/2 = 0.25\%$, $\tau \simeq T_e/T_i$)



1. $\tau > 2\xi_i^2 \gg 1$, $\xi_i = \omega/k_{\parallel\pm1}v_{Ti}$
   results similar to MHD, $\tau = 15 \rightarrow$

$$\frac{k_\parallel^2 R^2}{\Omega^2} \simeq 1+2q^2\left(1+e^{-\xi_i^2}\frac{i\xi_i^3\sqrt{\pi}}{2}\right) \simeq 1+2q^2$$

2. $T_i \sim T_e$, $\xi_{\pm i} \ll 1$,

$$\frac{k_\parallel^2 R^2}{\Omega^2} \simeq 1+q^2\left(\frac{1}{2}+\frac{\pi}{8}\right)+\frac{iq^2\sqrt{\pi}}{\xi_s\sqrt{2}}$$

- phase velocity is different from Alfvénic, depends on $T_e/T_i$.

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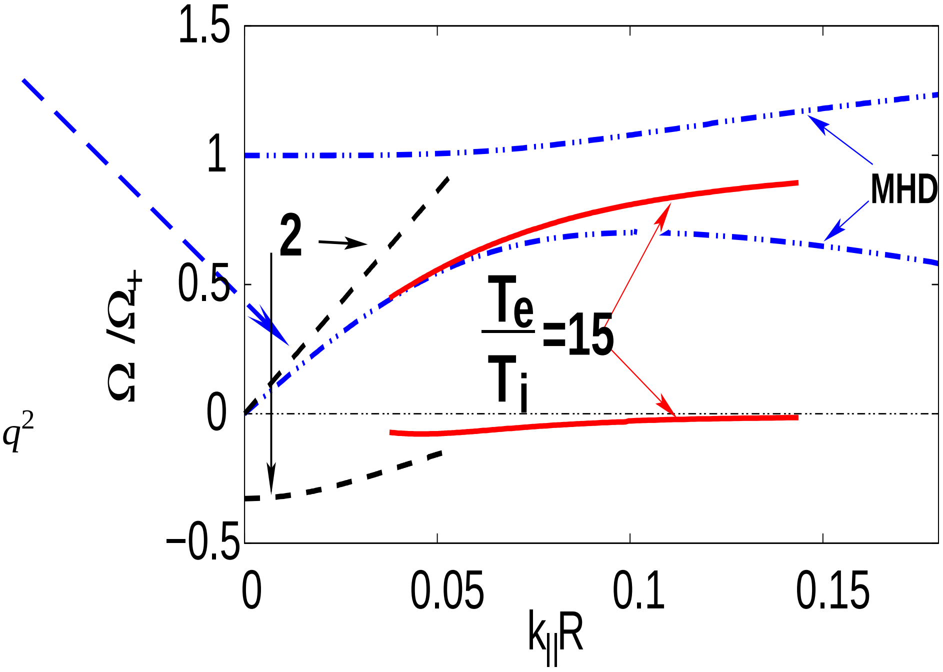
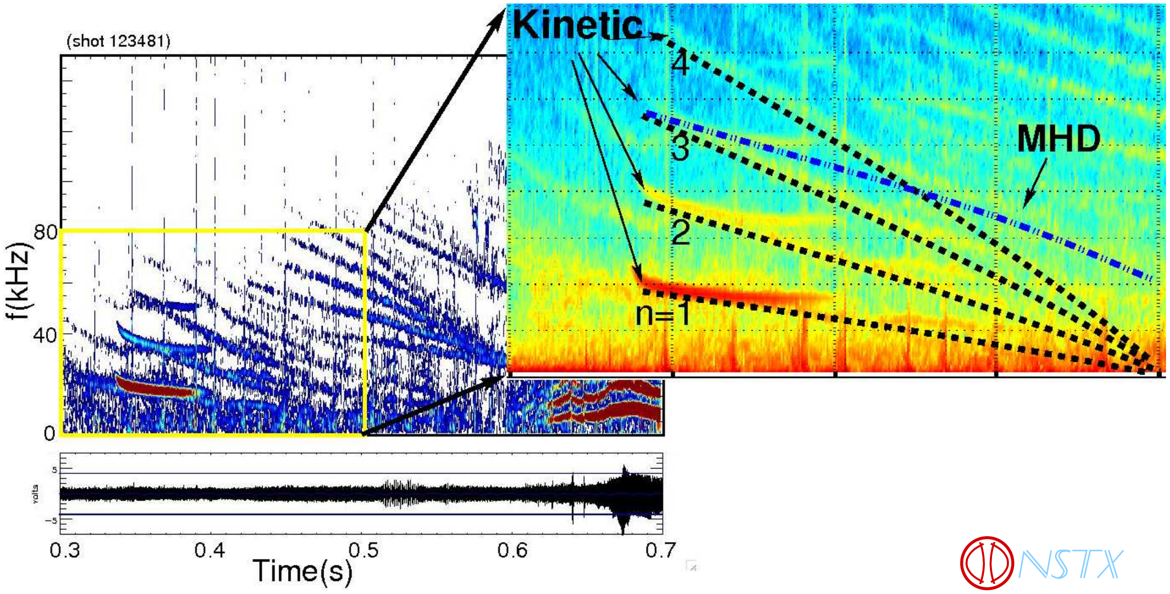


**$T_e \sim T_i$ is practical limit (departs from MHD)**
**NSTX - $T_e \simeq T_i$, DIII-D - $T_e \simeq 2T_i$**

# NSTX ($T_e \simeq T_i$) multiple BAAE frequency measurements confirm kinetic dispersion



$q_{min}$ is from MSE: $f = f_{BAAE} + n f_{rot}$, $n < 0$, $n = -1 \div -4$.

Applied modified Alfvénic dispersion with rotation $f_{rot}(q_{min}) = 19 - 23kHz$, $\omega_{*n=1} \simeq 2kHz \ll f_{BAAE}$

Modified Alfvénic wave dispersion agrees with the kinetic dispersion at $T_i = T_e$:

$f_{BAAE} = v_A k_\parallel / 2\pi \sqrt{1 + q_{min}^2 (1/2 + \pi/8)}$ vs MHD $v_A k_\parallel / 2\pi \sqrt{1 + 2q_{min}^2}$.

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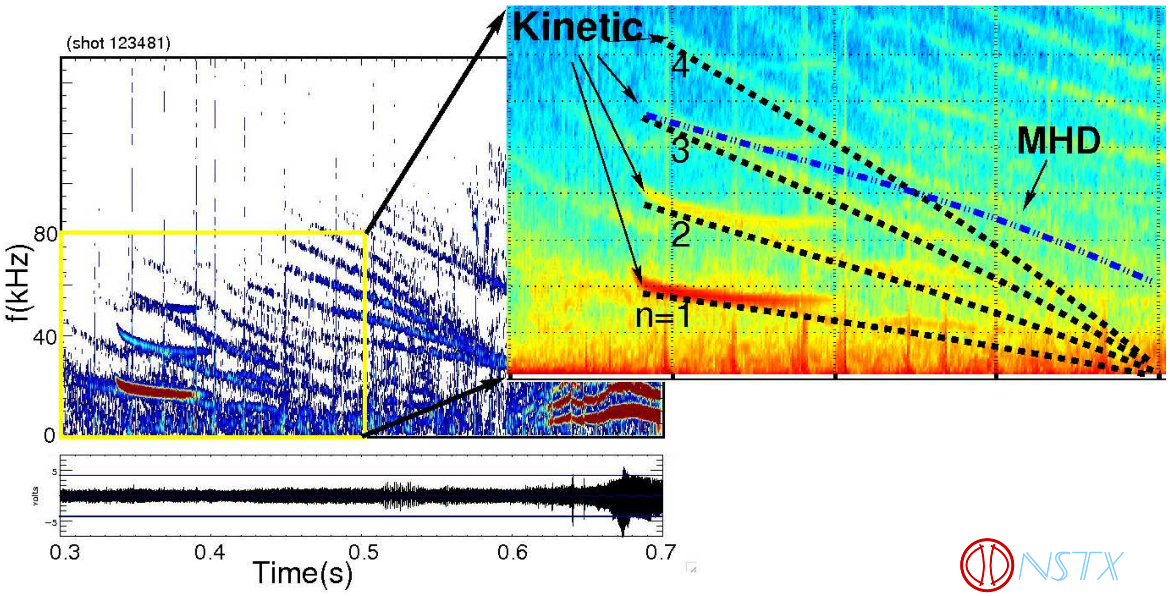

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**Kinetics improves and complements MHD framework for BAAE studies: i) proper acoustic wave dispersion, ii) ion Landau damping**

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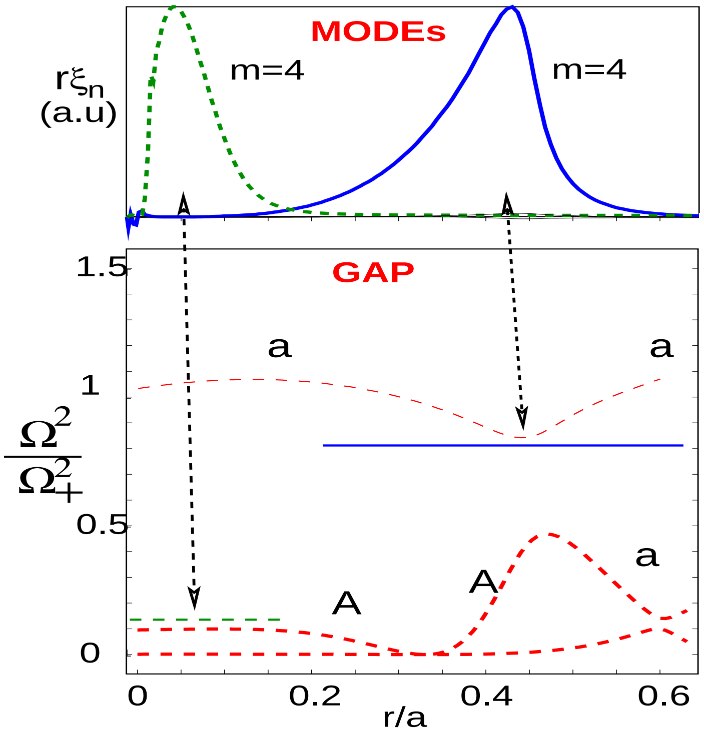
# *Global modes are localized to the extremum points of Alfvén - acoustic continuum*

Ideal MHD (NOVA) results computes localized BAAE modes



- Core localized and gap BAAEs are found with one dominant poloidal harmonic *(Gorelenkov,PLA'07):*
  - monotonic $q-$profile, $q_0 \sim 1$, $q_a = 4$.

  1. low shear sweeping BAAE (A): $\omega \simeq v_A k_\parallel / \sqrt{1+2q_{min}^2}|_{r=0}$
  2. gap BAAE: $\Omega_+ \simeq \sqrt{\gamma\beta/2}/q_{min}$, $\gamma = (T_e + 7T_i/4)/(T_e + T_i)$

- $\nabla\xi$, $m \pm 1$ sidebands are present ($\sim \xi_\theta / a$).

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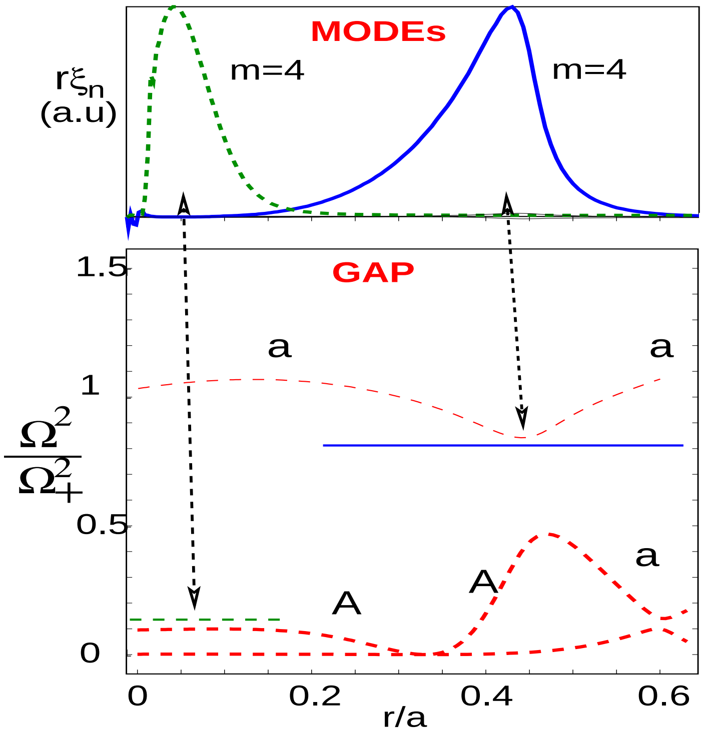

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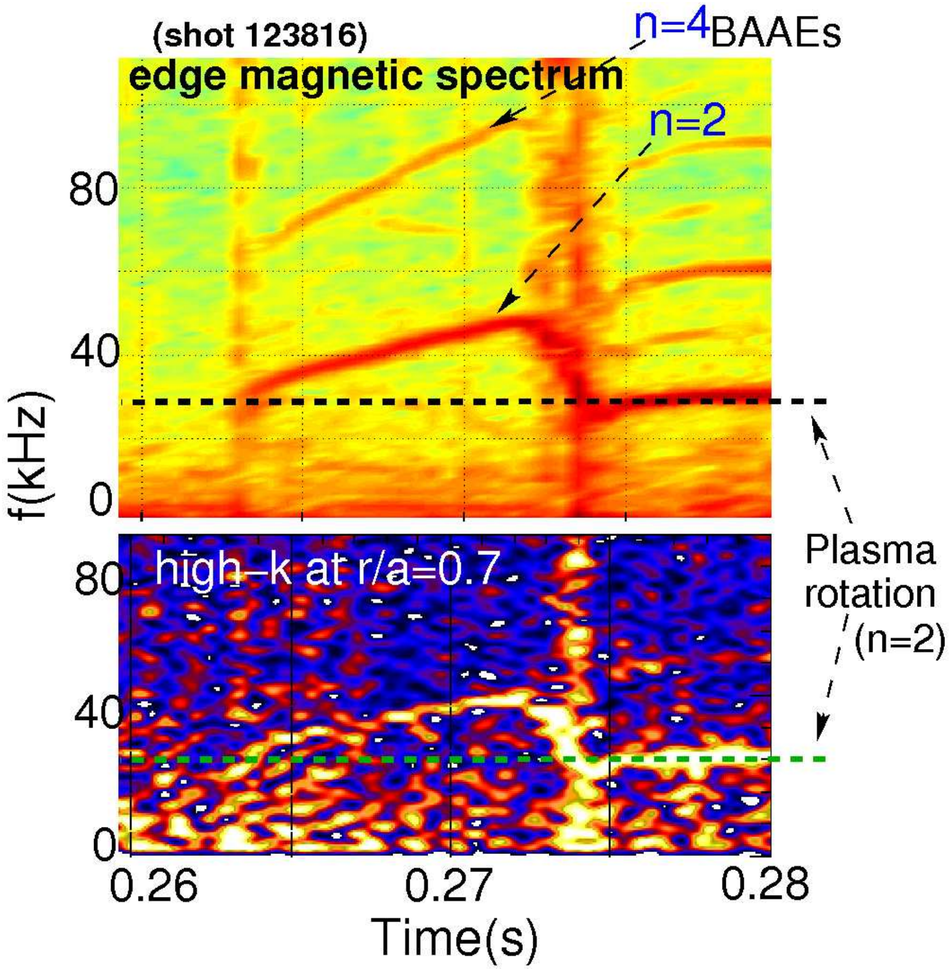
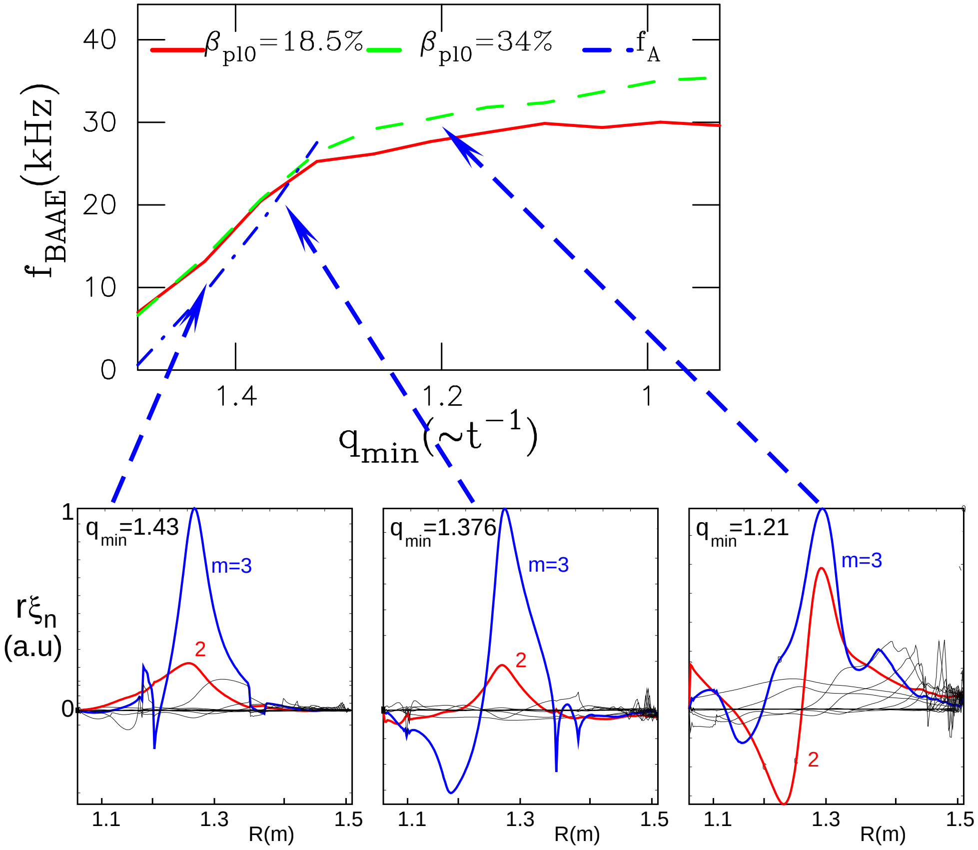
**How these global BAAE structures compare with experiments?**

# *NSTX experiments address BAAE dispersion*

- Low density $n_e \simeq 3 \times 10^{19} m^{-3}$, $P_{NBI} = 2MW$, $E_{NBI} = 90keV$.
- $12$ channel MSE measures $q$ profile (reversed shear).
  - helps to validate theory.
- Low frequency oscillations (BAAEs) are seen unstable:
  - Characteristic upshift frequency evolution from $\sim$zero (plasma frame).
  - Modes are localized to $q_{min}$ surface.
- High-k diagnostic sees BAAEs at $r/a = 0.7$ *(H.Park, APS'07)*.
- At $t = 0.263$ $q_{min} = 3/2 \Rightarrow$ even $n$ $(m = nq_{min})$



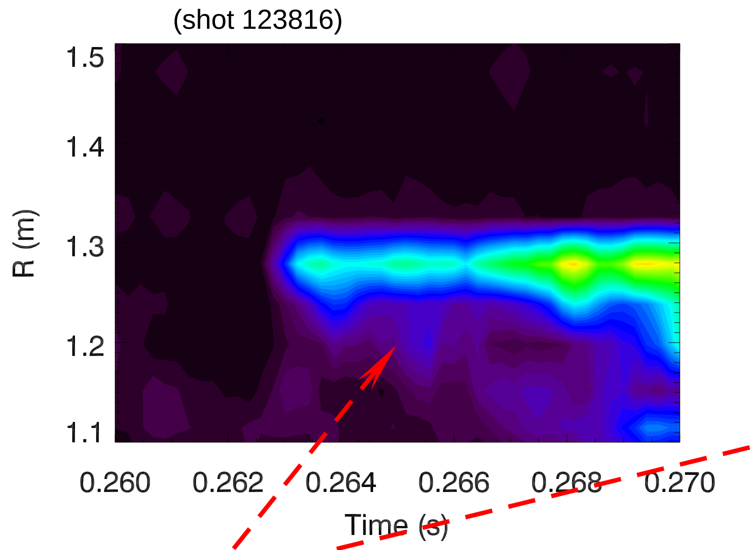
# *NOVA: BAAE broadens radially as $q_{min}$ decreases*



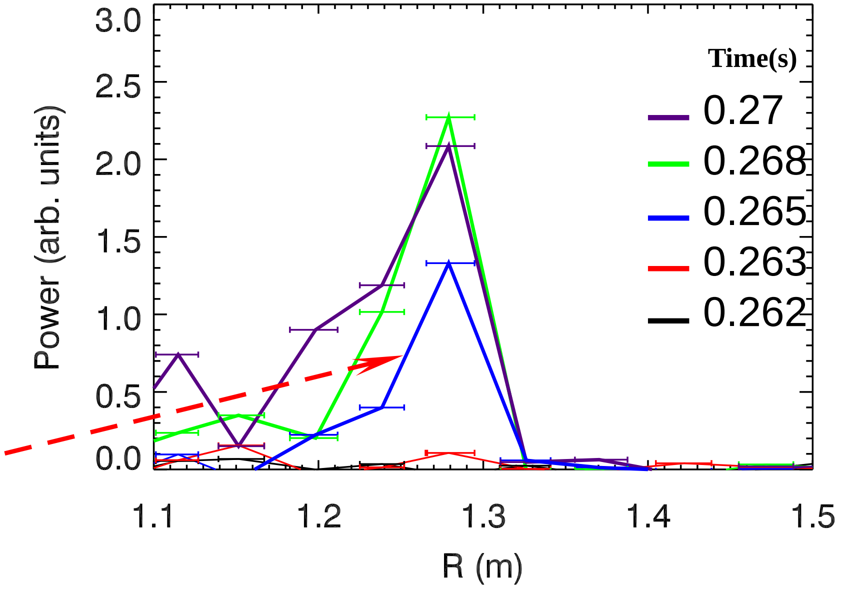
- BAAE frequency sweeps as $q$-profile relaxes.
  - $f$ does not depend on beta (as expected) near rational $q_{min}$ (=1.5).
  - $\xi_r$ has one dominant harmonic $m = nq_{min} = 3$.
- $f_{BAAE}$ is close to modified Alfvén branch $f_A = v_A k_{\|}/2\pi\sqrt{1+2q_{min}^2}$
- Continuously transforms to gap mode (second harmonic, $m = 2$)
- BAAEs interact with the continuum.

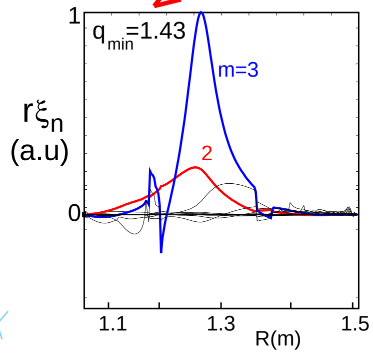
# *Ultra SXR measures the same radial BAAE broadening*

Raw USXR signal (∼BAAE structure, *Tritz, JHU*)



Radial profile evolution





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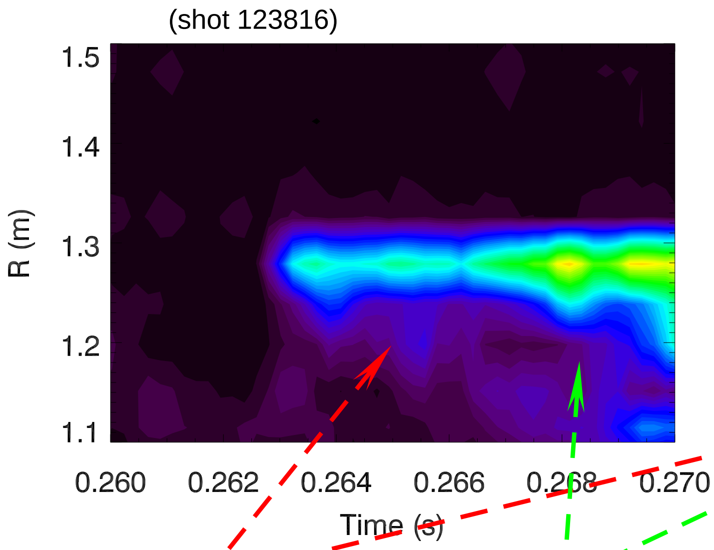

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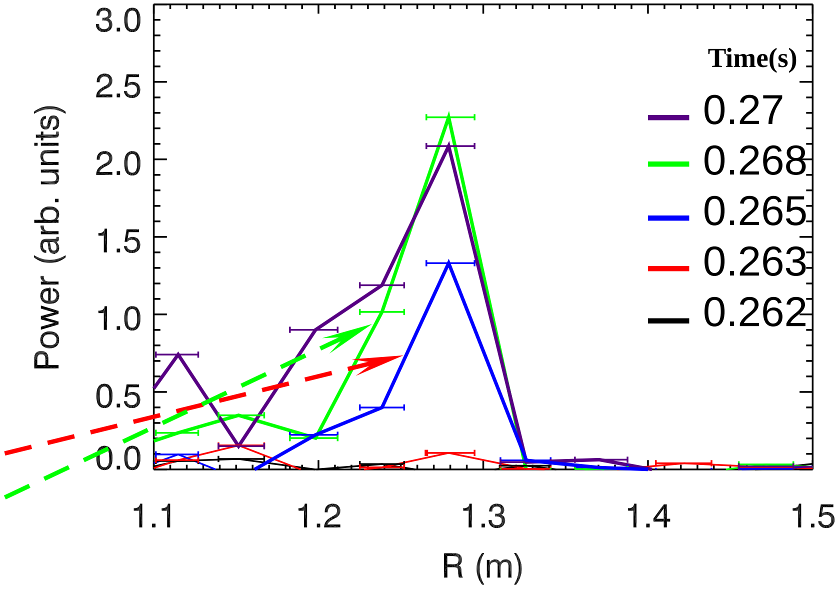
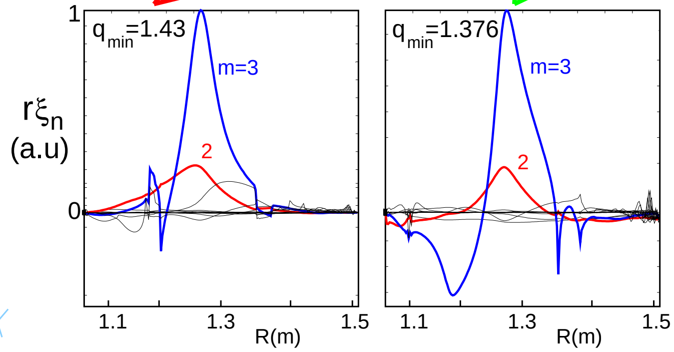
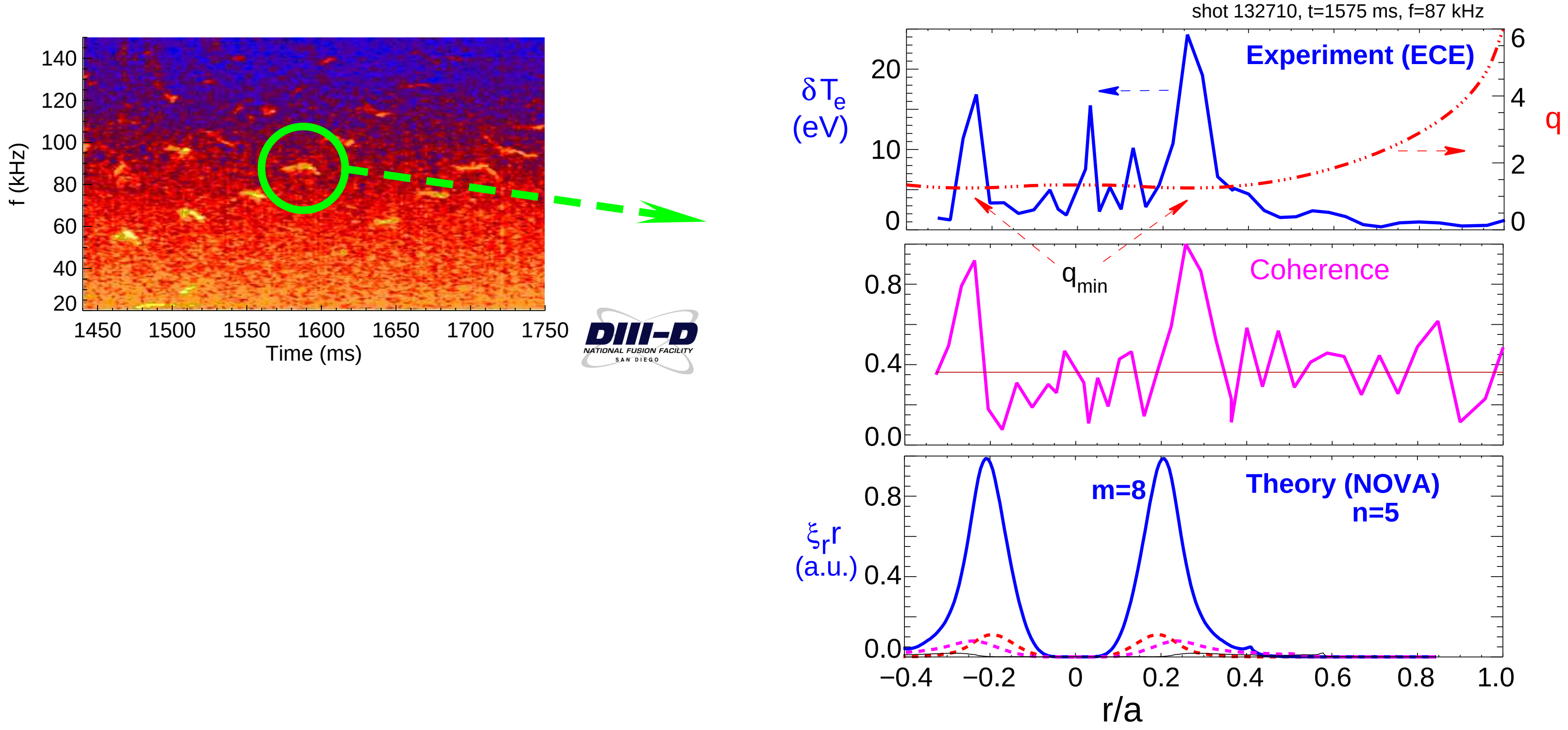




BAAE broadens as $q_{min}$ decreases.

Does not transform to gap mode.

# *ECE measures localized BAAE structure in DIII-D*



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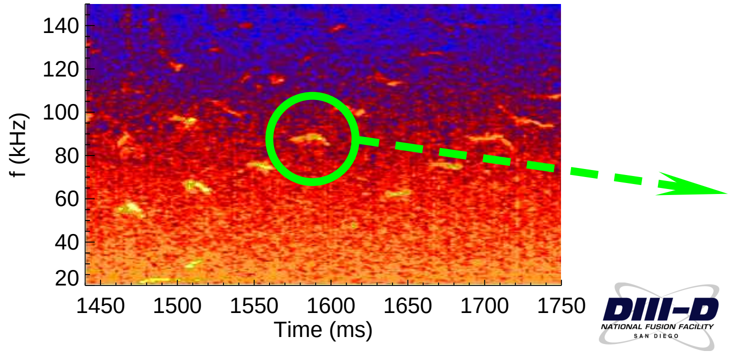

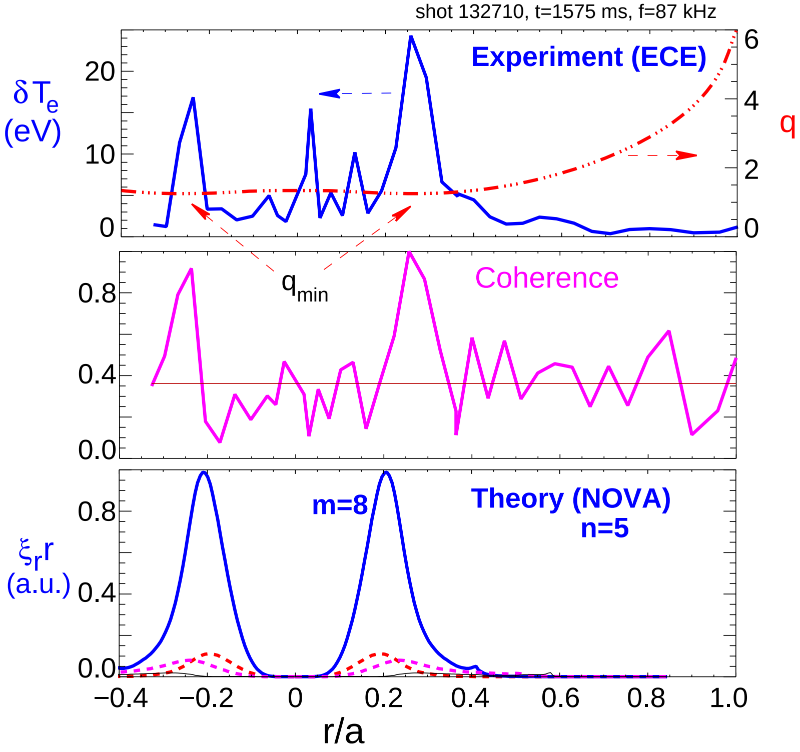

- Temperature perturbation:
  $\delta T_e = -\vec{\xi}\nabla T_e - (\gamma_e - 1)\, div\vec{\xi}$
- For low frequencies $\gamma_e = 1$
  $\Rightarrow \delta T_e$ is comparable on LFS and HFS.
- Oscillation amplitude
  $\xi_r/a \simeq 3\times 10^{-3}$.

- NOVA computes BAAE structure with symmetric amplitudes around $R_{axis}$.
- Small shift toward the center is due to the gap structure.

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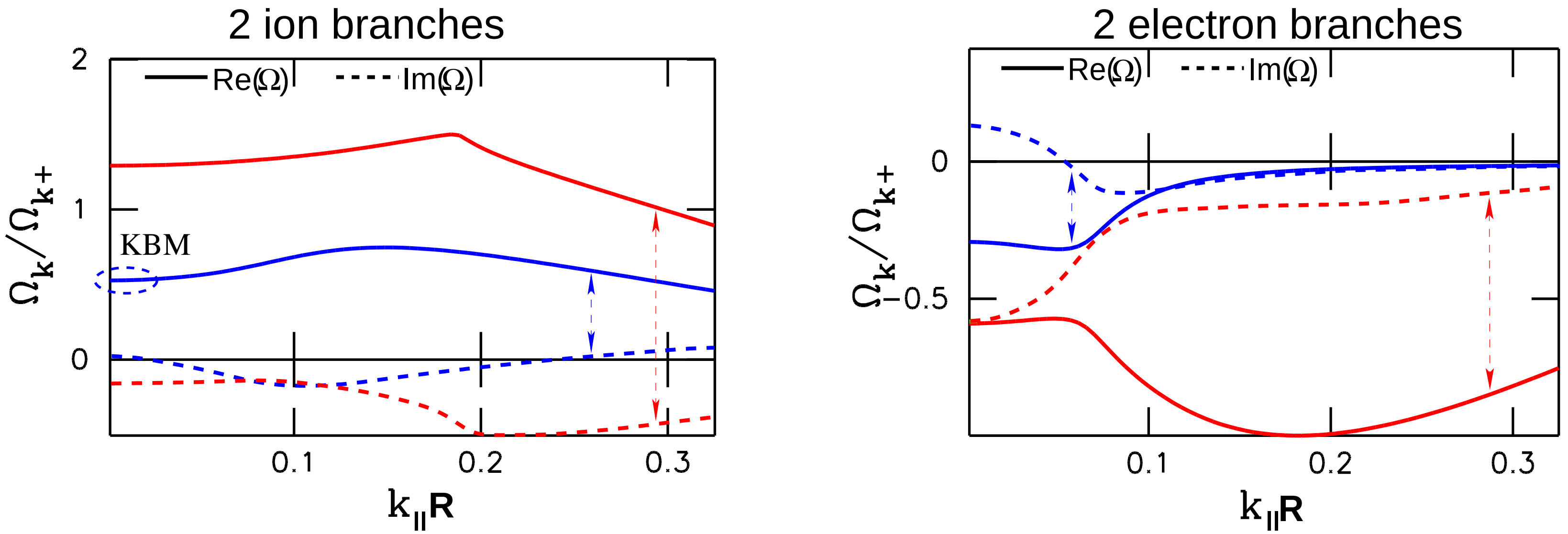
# Drift frequencies strongly modify BAAE dispersion

$$
\begin{aligned}
\frac{k_0^2\omega}{\Omega^2\delta\left(\omega-\omega_{*Ti}\right)} \quad &\simeq \quad 1+q^2\left[\frac{1}{2}+\frac{\pi\tau}{4}\frac{\left(\omega-\omega_{*Ti}/2\right)^2}{\omega\left(1+\tau\right)\left(\omega-\omega_{*Ti}\right)}\right] \\
&+ \quad \left[\omega-\frac{3\omega_{*Ti}}{2}-\tau\omega_{*Te}\frac{\omega-\omega_{*Ti}/2}{\omega\left(1+\tau\right)}\right]\frac{iq^2\sqrt{\pi}e^{-\xi_s^2\tau/2}}{\xi_s\sqrt{2\tau}\left(\omega-\omega_{*Ti}\right)}
\end{aligned}
$$

*Mikhailovskii,Pl.Phys.Rep.'99 (without $\omega_{*e}$), Kolesnichenko, IAEA'08 (2 fluid MHD), Lauber, ibid.*

- Ion branch at $k_\| = 0$: $\omega \simeq \omega_{*pi}$ - KBM
- Electron branch at $k_\| = 0$: $\omega \simeq \omega_{*pe}$.
- Drive is due to ITG *(at higher frequencies Afvénic ITG, Zonca,PoP'99)*
- BAAEs can be destabilized by $\omega_{*Ti}$ (ITG).

# *Ion and electron drift branches converge to BAAEs away from rational surface ($|k_{\|}|\uparrow$)*



- Both ion and electron branches are unstable at $k_{\|}=0$ but global mode structure and trapped electrons maybe stabilizing (most unstable solutions are shown)
- Inside BAAE gap damping rate is strongly reduced to $\gamma/\omega\sim-10\%$ from $\sim-25\%$ without $\omega_{*Ti,e}$ effects.
- NSTX $\omega_{*Ti}\ll\omega_{BAAE}$, DIII-D $\omega_{*Ti}=0.9\Omega_{+}$ for $n=8$.

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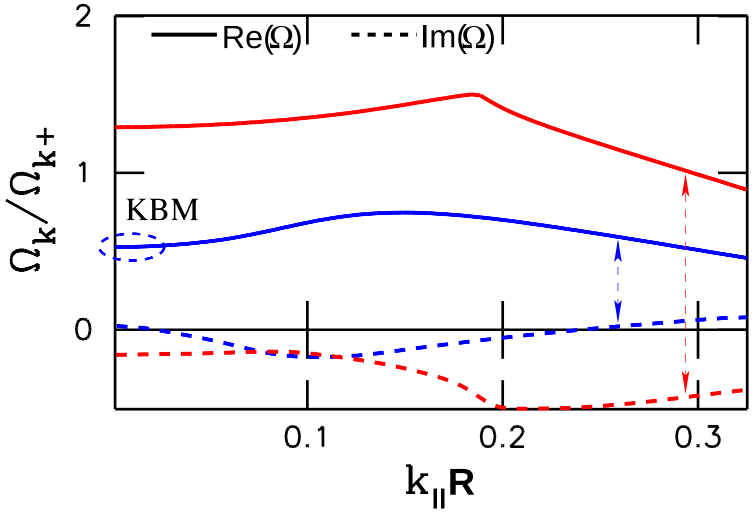
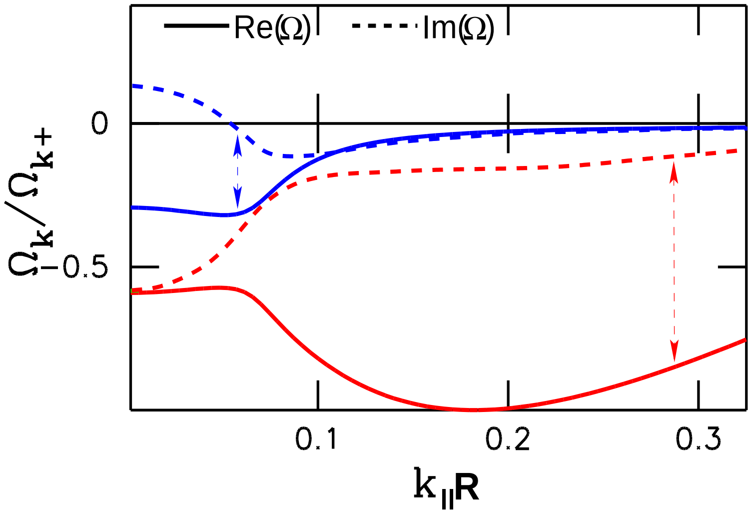
2 ion branches



2 electron branches



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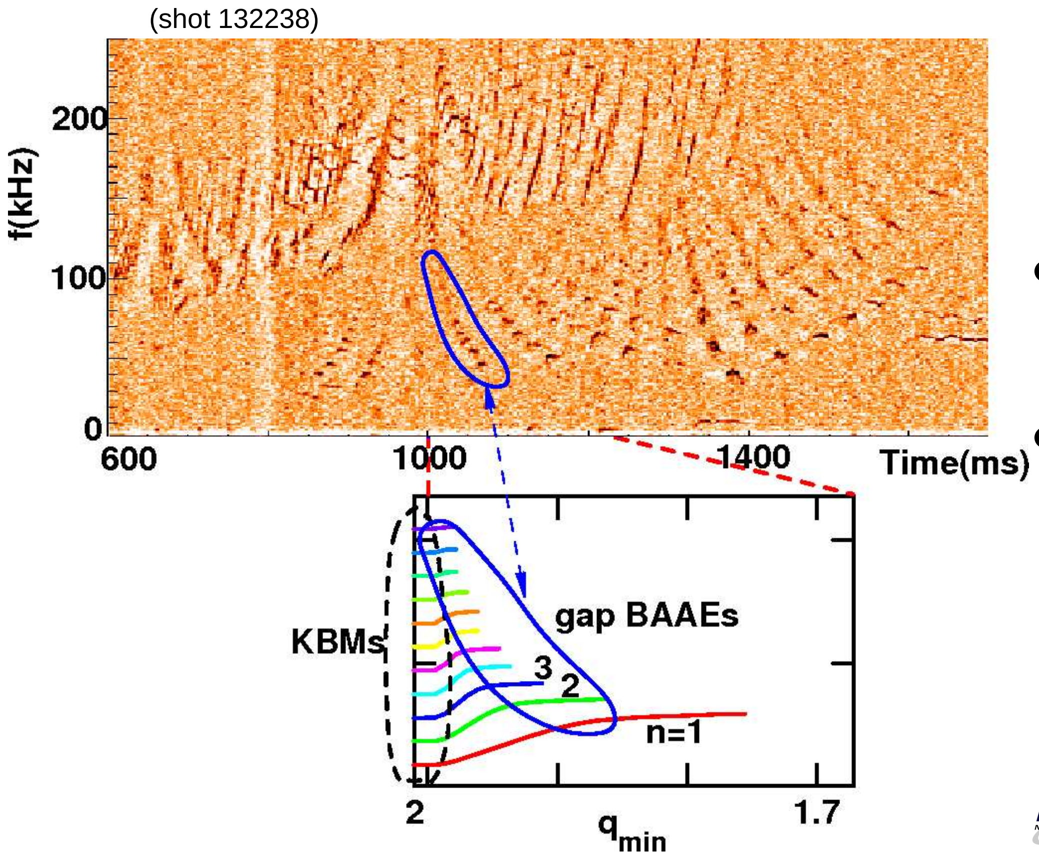
**KBM ($\omega_{*pi}$) can transform to gap BAAE if $q_{min}$ decreases**

# *DIIID observations are consistent with gap BAAE excitation*



- Only gap BAAE excitation is consistent with experimentally observed patterns.
- KBM-like instabilities would produce instability peaks aligned in time.

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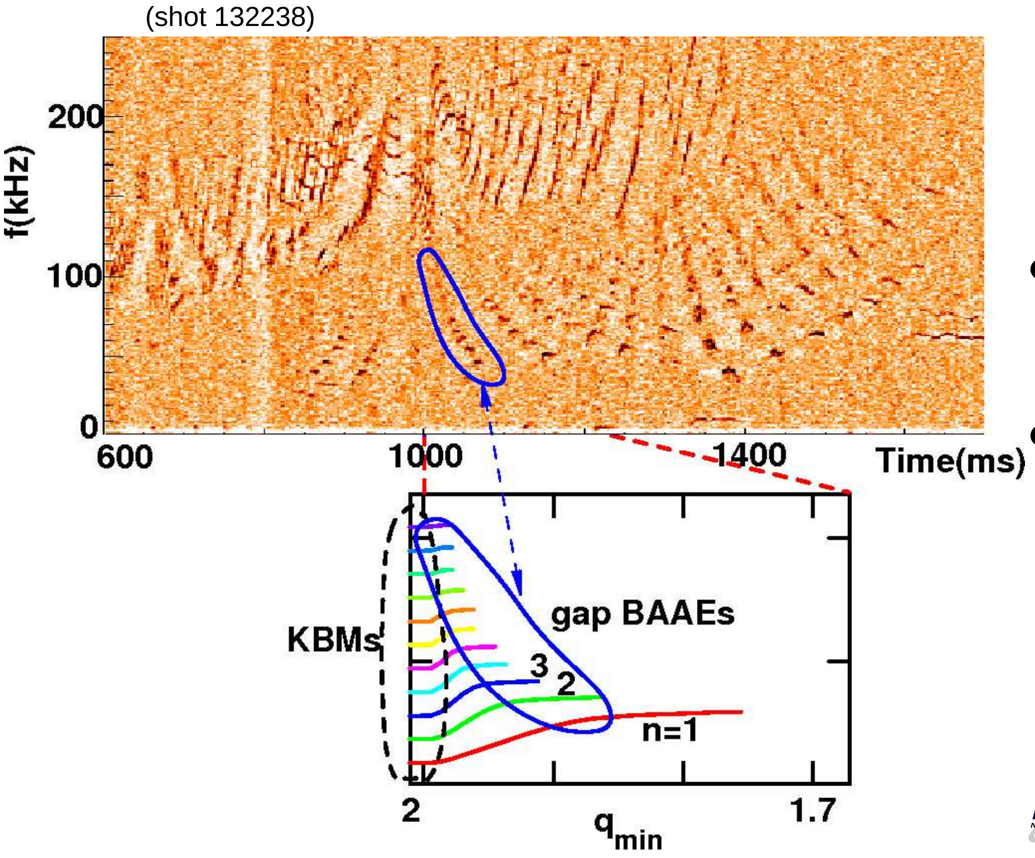

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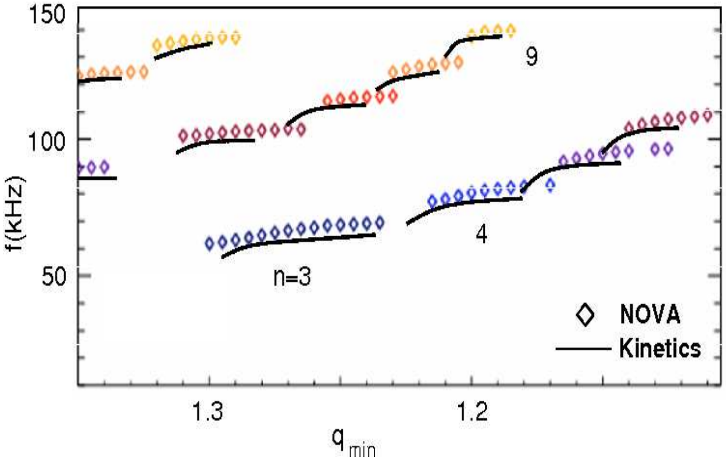
**For the global gap modes ideal MHD can be applied**

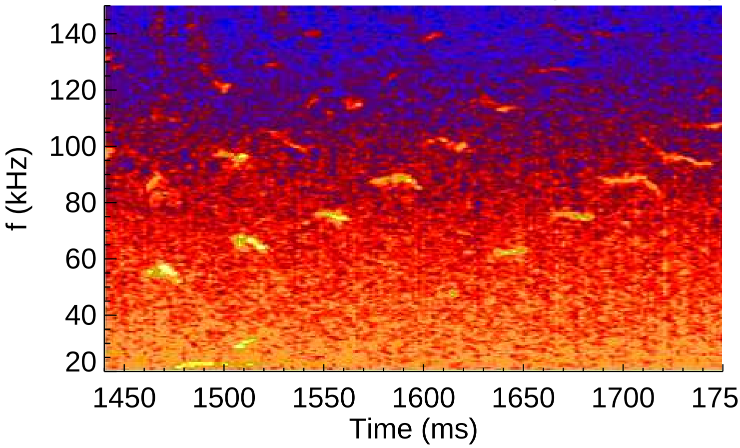
# *MHD and kinetics compute measured BAAE frequency patterns*

Theory



Experiment (DIII-D)

(shot 132710)



- Numerically (NOVA) global BAAEs are found inside Alfvén-acoustic continuum gaps - not as sweeping modes
  - maybe due to strong $\beta$ profile variation and shear effects
  - modes interacting with the continuum are not resolved (strong damping)
  - kinetic theory renormalization gives similar frequencies
  - $q_{min}$ comes from MSE, MHD spectroscopy (RSAE, sawtooth)
- There are uncertainties in $n$ numbers.

# *Talk outline*

1. Ideal MHD theory of Alfvén - acoustic continuum - BAAE gaps
2. Kinetic theory of Alfvén - acoustic continuum
3. Global BAAE structure measurements and simulations
4. Drift frequency effects on BAAE dispersion
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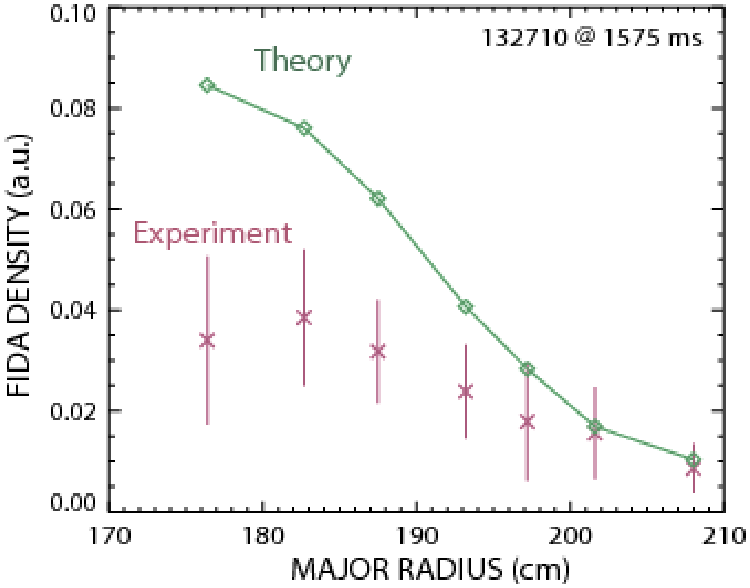
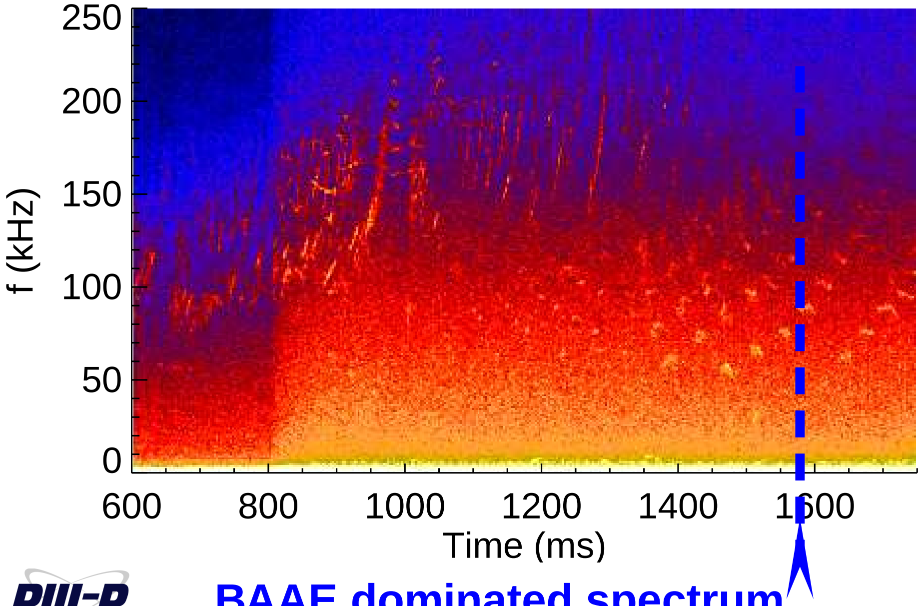
# *Flattening of beam ion profiles in DIIID when BAAEs are observed*

Classical (TRANSP) simulations and Fast Ion $D_\alpha$ spectroscopy diagnostic (FIDA) show beam ion depletion when BAAEs are excited.





**BAAE dominated spectrum**

*(for FIDA in NSTX see M.Podestà, GI1.00001)*

- BAAEs are excited to large amplitudes, $\xi_r/a = 3\times10^{-3}$.
- Just RSAE/TAEs can not explain beam ion depletion *(Heidbrink,PRL'07)* $\Rightarrow$ BAAEs may help to explain EP transport.

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# *Discussion*

Low frequency spectrum analysis in NSTX and DIII-D confirms previous results of BAAE observations in JET and NSTX *(Gorelenkov, Phys.Lett.A’07)*

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- Key elements of the analysis/comparison are:
  - frequency spectrum:
    trends (JET, NSTX, DIII-D), absolute values (NSTX),
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  - radial transport of beam ions on NSTX, DIII-D,
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  - energy channeling from beam ions directly to thermal ions ($\alpha$-channeling, Fisch, PRL'93; hot-ion mode, Zakharov, LiWall).

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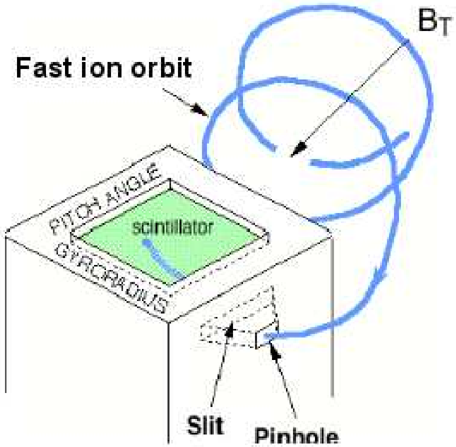
- Future work:
  - cross machine experiments/comparison,
  - numerical studies with kinetics and global mode structure,
  - stability with fast ions.

# *Summary*

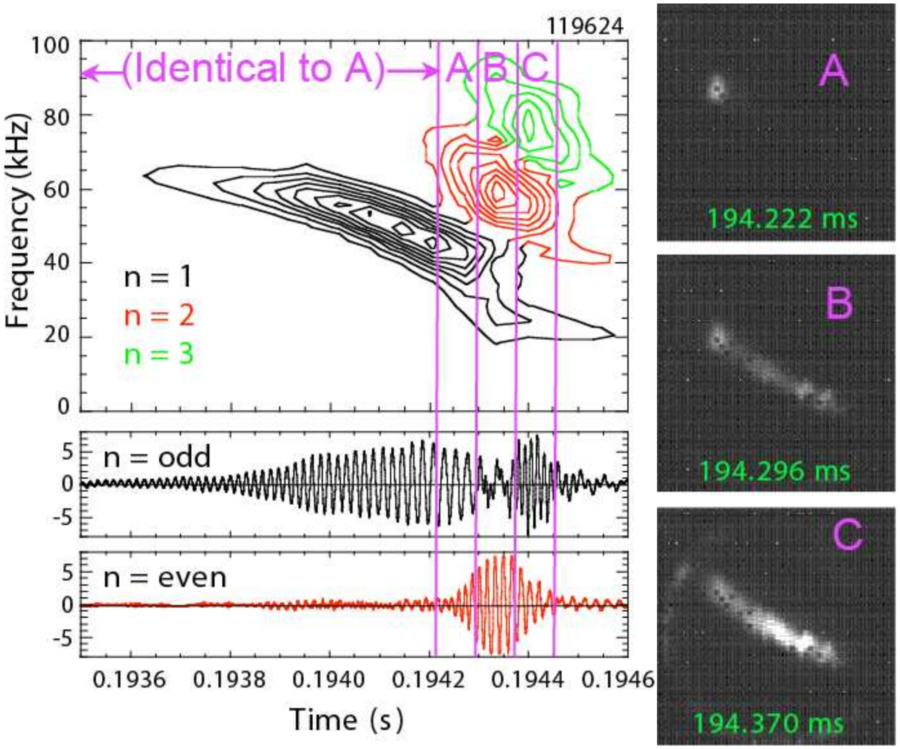
1. Low frequency Alfvén - Acoustic global Eigenmodes (BAAEs) are observed and studied **using MHD.**
2. BAAE dispersion is strongly modified in **kinetic theory.**
3. BAAEs induce beam ion transport in NSTX and DIII-D.
4. Both RSAEs and BAAEs can be used for $q_{min}$ diagnostic.

# *BAAEs can induce fast ion losses in NSTX*



SFLIP diagnostic on NSTX

*(D. Darrow et.al. NF'08)*



- Fast ions are lost in a broad pitch angle range - $v_{\parallel}/v$
- Multiple $n$ instabilities form avalanches
- Neutron flux is dropped by $13\%$