Beta-induced Alfvén-acoustic Eigenmode instability observations in NSTX (XP741-1/2day = 1invited EPS talk, PPCF paper)

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NSTX results and theory review, 2007

What is the importance of low-f instabilities?

- New class of instabilities called here Beta-induced Alfvén Acoustic Eigenmode (BAAE) helps to study two fundamental MHD waves: Alfvén and acoustic.
- Energetic particle driven low-f MHD instabilities mostly result in radial particle transport:
  - On NSTX, bursting low-f modes can lead to a significant loss of injected beam ions (Fredrickson'06).
- MHD spectroscopy application for q-profile diagnostic:
  - BAAE can complement MHD spectroscopy in low-, medium-β plasma
  - BAAE maybe the only MHD spectroscopy tool in high-β plasma, such as in STs when RSAEs are suppressed.
- Due to coupling to acoustic branch strong interaction with thermal ions is expected:
  - $\Rightarrow$ strong drive due to fast ions and strong damping due to thermal ions,
  - $\Rightarrow$ potential for energy channeling from beam ions directly to thermal ions (α-channeling, Fisch'93, hot-ion mode, LiWall).

Theory of Alfvén/acoustic continuum

Simplified shear Alfvén and acoustic coupled equations capture main effects in low-β, large aspect ratio plasma, low ω_*, (Cheng, Chance '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 $\Omega \equiv \omega R_0/v_A$, $y \equiv \xi_s \varepsilon/q$, $\xi_s \equiv \vec{\xi} \cdot \frac{[\mathbf{B}\times\nabla\psi]}{|\nabla\psi|^2}$ and $z \equiv \nabla\cdot\vec{\xi}$, $\hat{k}_\parallel \equiv i\partial_\parallel$.

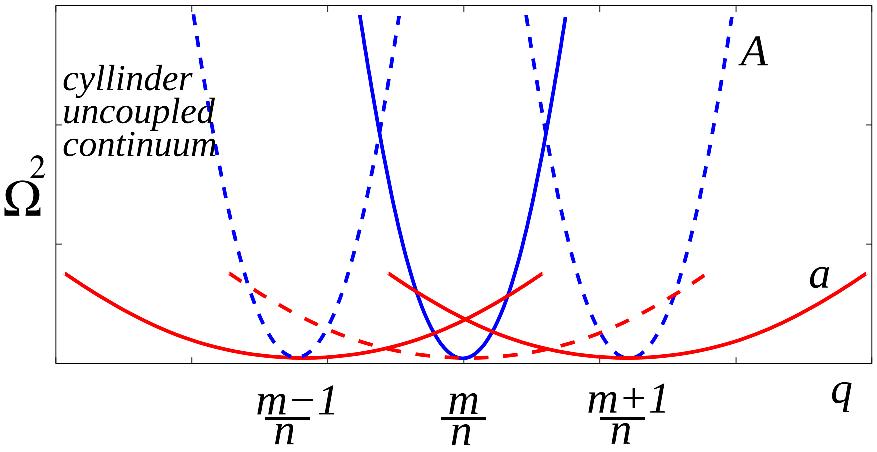
Coupling is due to geodesic curvature: m Alfvénic and $m \pm 1$ acoustic harmonics.

Various solutions follows (Winsor'68, Goedbloed'75, Mikhailovski'75,'98, Chu'92, Turnbull '92, Zonca'96, van der Holst'00, Breizman'05, Berk'06):

- Pure acoustic modes (AMs) $\Omega^2 = \frac{1}{2}\gamma\beta k_\parallel^2$.
- Pure Alfvénic branch $\Omega^2 = k_\parallel^2 + \gamma\beta\left(1 + 1/2q^2\right)$.
- GAMs: $\Omega^2 = \gamma\beta\left(1 + 1/2q^2\right)$ in the assumption of $\Omega^2 \geq \gamma\beta$.
- Modified shear Alfvén branch $\Omega^2 = k_0^2/\left(1 + 2q^2\right)$ exists for $\Omega^2 \ll \gamma\beta$.

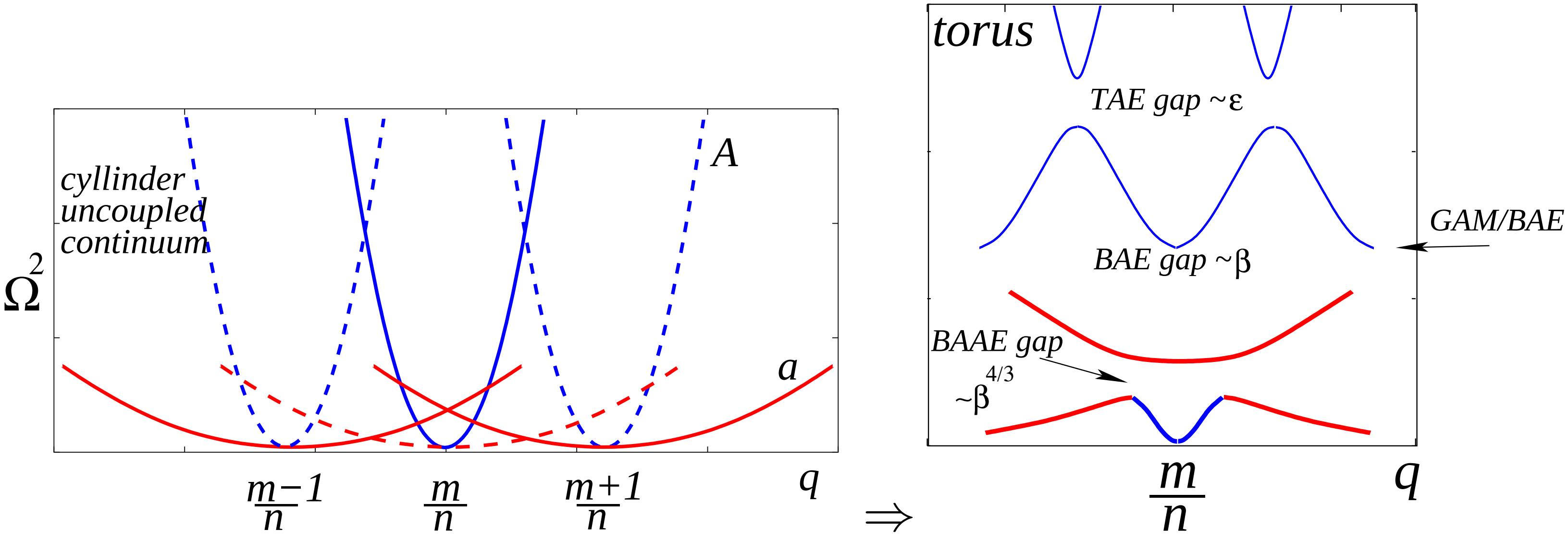
Alfvén/acoustic coupling in toroidal equilibrium (schematic)

- Alfvén (A) continuum at low frequency: $\Omega^2 = k_{0,\pm1}^2$
- Acoustic (a) branch $\Omega^2 = \gamma\beta k_{0,\pm1}^2/2\,(1+\delta)$



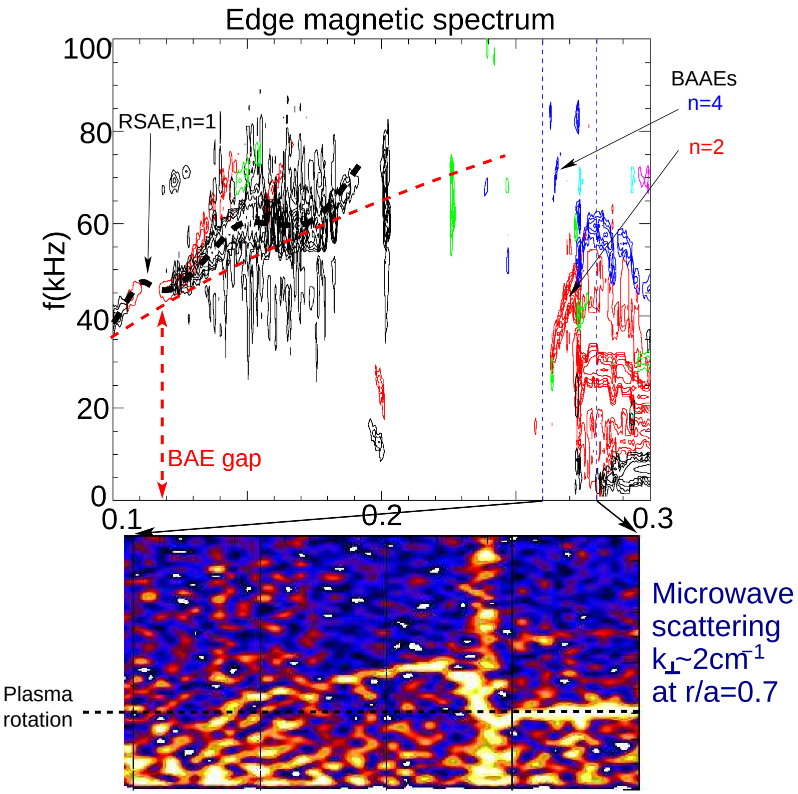
Alfvén/acoustic coupling in toroidal equilibrium (schematic)

- Alfvén (A) continuum at low frequency: $\Omega^2 = k^2_{0,\pm1} \,/\, \left(1+2q^2\right)$ (modified)
- Acoustic (a) branch $\Omega^2 = \gamma\beta k^2_{0,\pm1}/2\,(1+\delta)$ is coupled via $m \pm 1$ sidebands with modified Alfvén continuum (m harmonic) due to geodesic curvature and pressure.



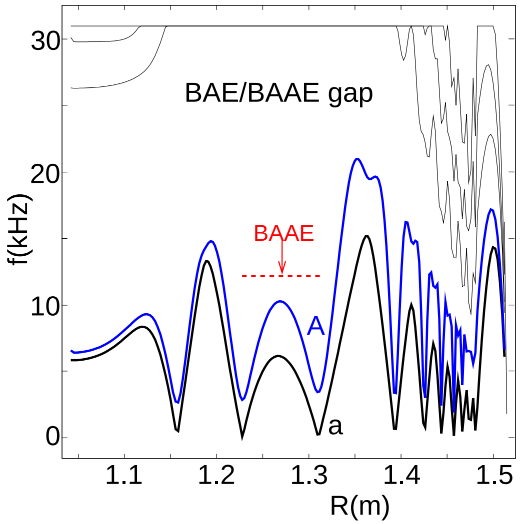
NSTX experiments with MSE address theory/experiment frequency mismatch observed on JET

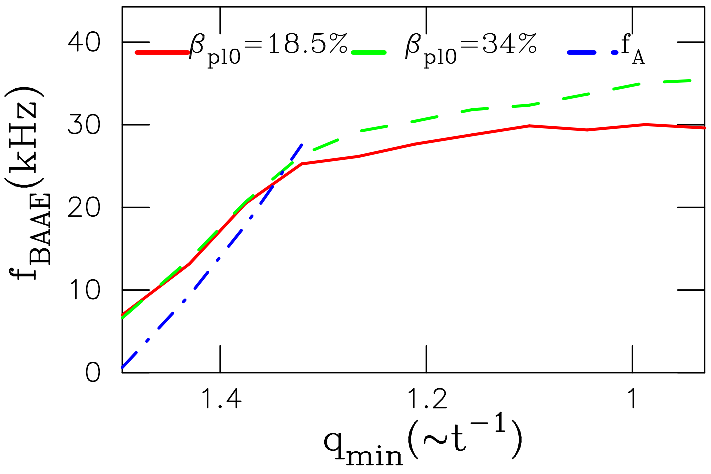
- Low density $n_e \simeq 3 \times 10^{19} m^{-3}$, $P_{NBI} = 2MW$, $E_{NBI} = 90keV$ shot #123816.
- 12 channel MSE measures q profile (reversed shear).
- Need to test the theory.
- Low frequency oscillations (BAAEs) are seen unstable:
  - upshift frequency evolution from zero (plasma frame).
  - BAAEs reside in wider BAE gap $f \sim \sqrt{\beta_{pl}}$.
- High-k component of BAAE at $r/a = 0.7 \Rightarrow$ conversion to KAW (H.Park, EPS07,P2.045).



TAE/RSAEs are suppressed (E. Fredrickson, EPS07) and BAAEs are excited by beams in high-β NSTX plasmas (typically $\beta_{pl} >\sim 15\%$).

Numerically global BAAE modes are found at q_{min} surface in NSTX

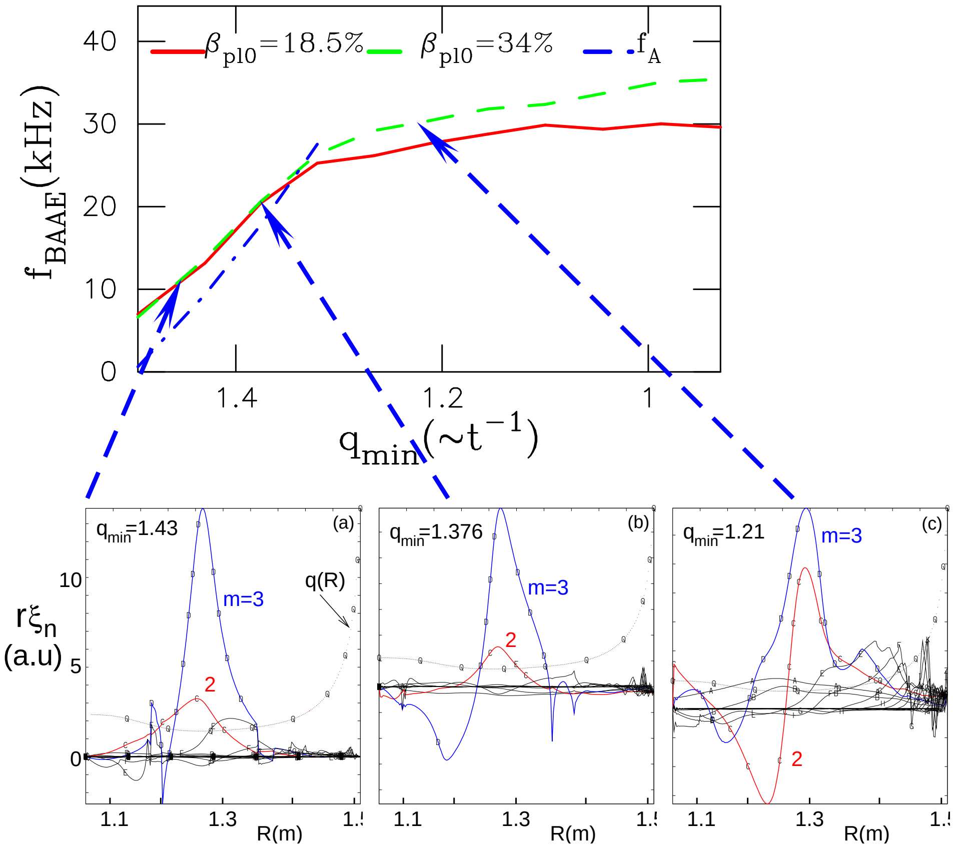




MSE measured inversed q-profile is used in NOVA modeling.

- At high-$\beta_0 = 34\%$, BAE is wide, up to TAE frequency.
- Two Alfvén/acoustic (A/a) continuum branches are found with $\Omega^2 < \gamma\beta$, $n = 2$
- Low shear BAAE frequency
  - does not depend on β for q close to rational
  - continuously transporms to gap mode (due to higher β, strong coupling)
  - f_{BAAE} is close to modified Alfvén branch $f_A = v_A k_\parallel / \sqrt{1+2q_{min}^2}|_{r=0}$.

NOVA: BAAE broadens radially as q_{min} decreases

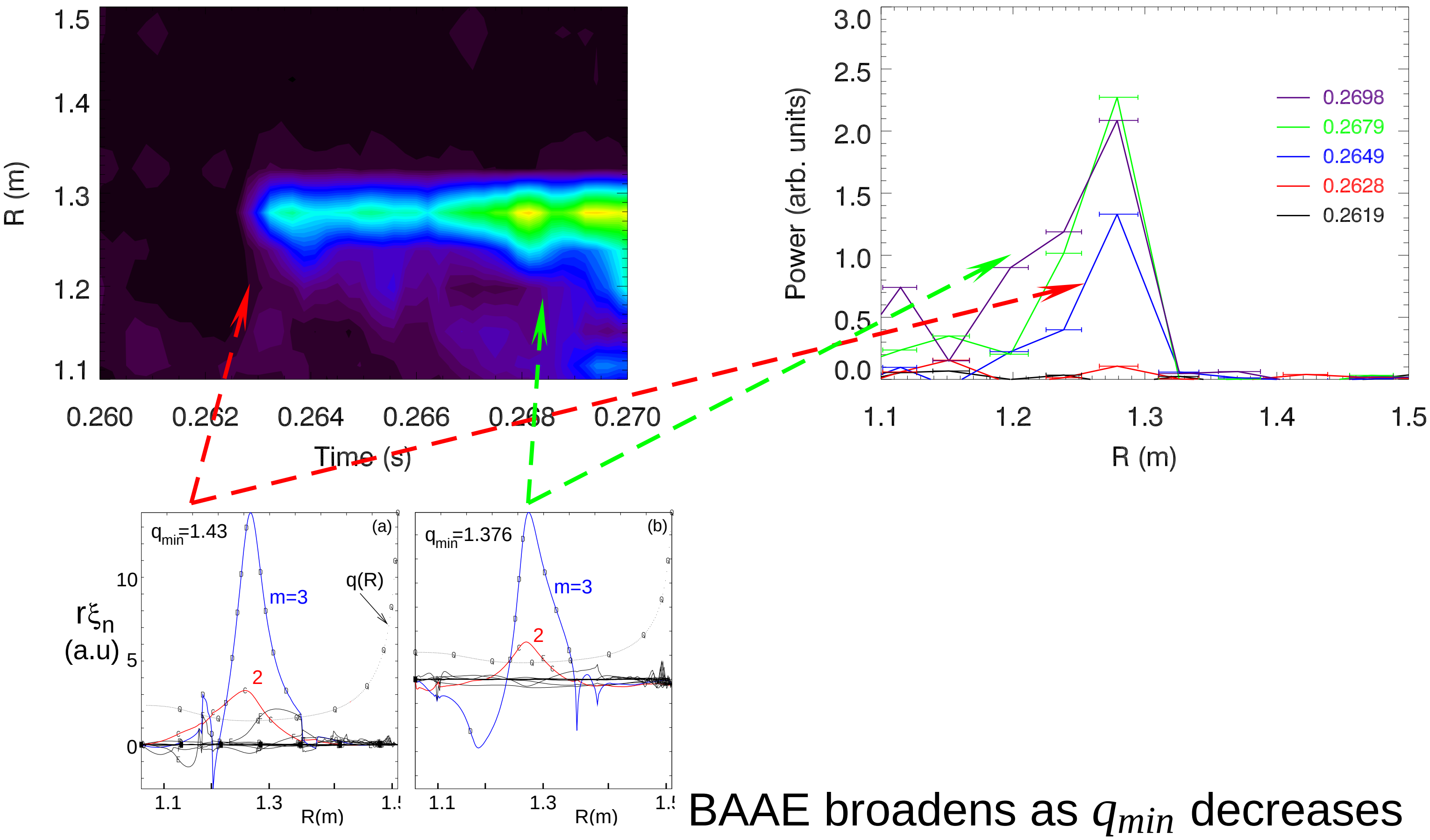


- BAAE frequency sweeps as q-profile relaxes.
- One dominant harmonic $m = nq_{min} = 3$.
- BAAEs interact with the continuum.

Ultra SXR measures the same radial structure broadening

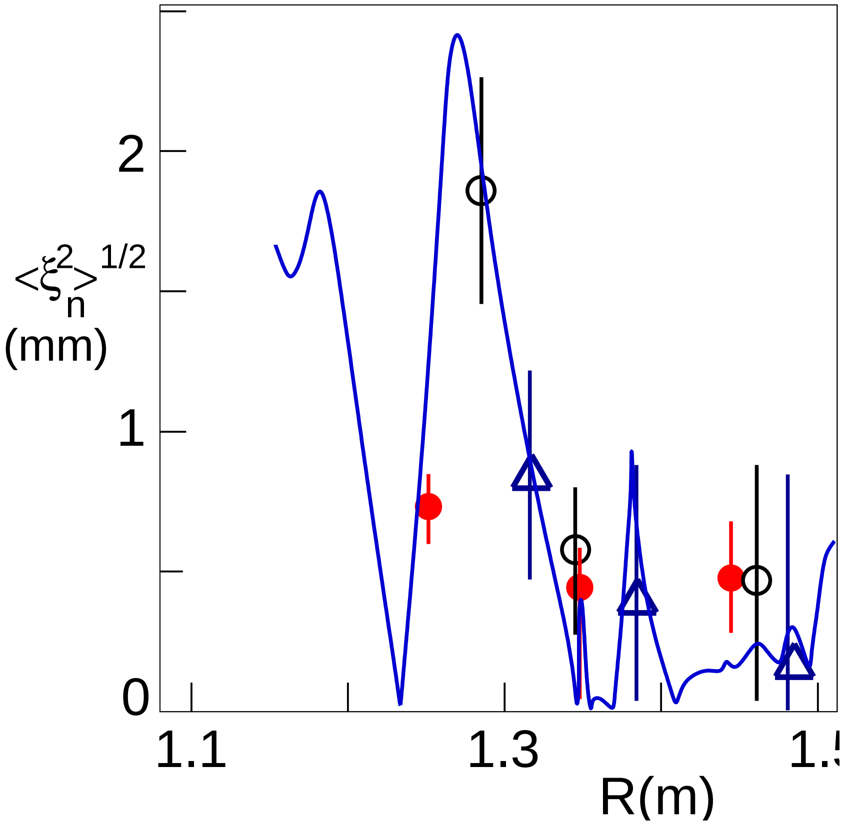
Raw USXR signal (∼BAAE structure)

Radial profile evolution



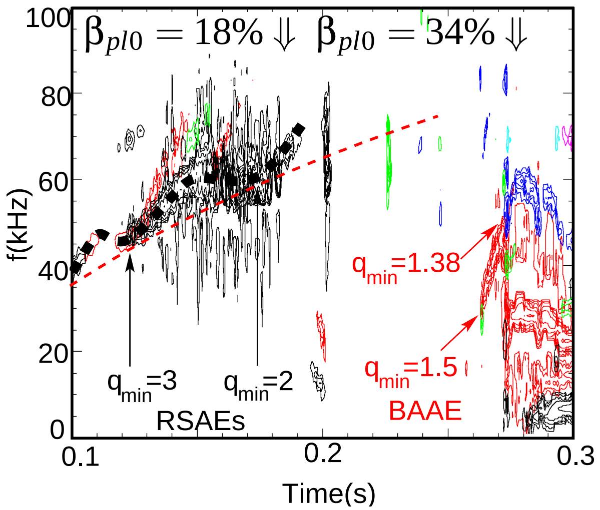
BAAE broadens as q_{min} decreases

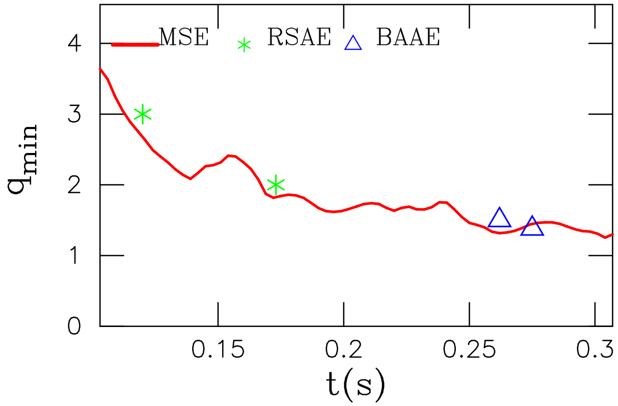
Reflectometer confirms localized BAAE structure



- Three plasmas, 3 points each:
  ● $n_e = 3.3 \times 10^{19} m^{-3}$
  O $n_e = 3.6 \times 10^{19} m^{-3}$
  Δ $n_e = 3.8 \times 10^{19} m^{-3}$
- Vertical axis refers to points ● - #123816.
- Measurements are taken at signal maximum.
- Internal fluctuations level $\delta n/n \sim 2 \times 10^{-3}$.

In high-β plasma BAAEs may be the only MHD spectroscopy tool for determining q-profile





- RSAE/TAEs can be used to infer q_{min} in low-, medium-β plasma
- Zero BAAE frequency point (plasma frame) indicates rational q_{min}.
- BAAE activity is terminated at $t = 0.275s$.

  Potential interplay of beam driven instabilities with internal $m = 3/n = 2$ kink-like instability - similar to TAE/sawtooth nonlinear interplay (Bernabei'01, Sharapov'06).
- RSAE/TAE and BAAE inferred q_{min} values are in agreement with MSE measurement.

Discussion and Summary

- Theory and numerical analysis show:
  - the existence of geodesic curvature induced gaps in the Alfvén/acoustic continuum below GAM frequency (van der Holst'00),
  - low-n global beta-induced Alfvén/acoustic eigenmodes - BAAE are found,
  - BAAEs exist in finite beta plasma within wider BAE gap.
- BAAEs are different from BAEs (Heidbrink-Turnbull-Chu-Huysmans) interpretation as BAAEs require compressibility effect, i.e. sound wave coupling:
  - frequency can sweep up from almost zero in reversed shear.
  - frequency is lower $0 < \Omega < \sqrt{\gamma\beta/2}/q_{min}$ vs. $\Omega = \sqrt{\gamma\beta\left(1+1/2q_{min}^2\right)}$ for BAE/GAM.
  - both low shear and gap BAAEs can coexist (similar to RSAE/TAEs)
- Kinetic modification of MHD theory is required for new global modes (Zonca'96, Mikhailovski'98):
  - damping is expected to be strong due to phase velocity of acoustic component close to thermal ion velocity.
  - dominant electron plasma is expected to be favorable for BAAE existence.

Summary (continued)

- NOVA shows existence of BAAEs in ICRH JET and NBI NSTX plasmas.
- Qualitatively NOVA predicts BAAE frequency evolution in agreement with observations on both tokamaks.
- In NSTX $n = 2$ low shear BAAE internal structure, frequency and their evolution are in agreemnt with NOVA.
  - MSE measurements on NSTX seem to validate theory and MHD (q_{min}) spectroscopy via BAAEs.
  - Maybe useful for burning plasmas, ITER.
- For pure electron plasma (lowest f) gap (sound wave effect) BAAE frequency is above the measured value in JET by factor ~ 1.77 (if $T_i \ll T_e$).
- Need to reconcile theory and experiment via kinetic theory and/or:
  - may imply local reversed shear with $q_{min} = 1.5$ but strong indications exist for $q_0 = 1$,
  - possible redistribution of the current drive due to:
    - MHD activity H-minority transport,
    - ICRH current drive,
    - runaway electrons in low density JET plasma.
- BAAEs are expected in plasmas with $T_e > T_i$ and strong drive from fast ions and/or η_i (ITG-like drive)