

Excitation of Beta-induced Alfvén-acoustic eigenmodes (BAAEs) and q-profile MHD spectroscopy in NSTX

N.N. Gorelenkov, E.D. Fredrickson

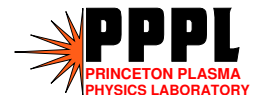
Princeton Plasma Physics Laboratory, Princeton

H. L. Berk

Institute for Fusion Studies, Austin, Texas

and the NSTX team

**49th Annual Meeting of the Division of Plasma Physics
Orlando, Florida, November 12-16, 2007**



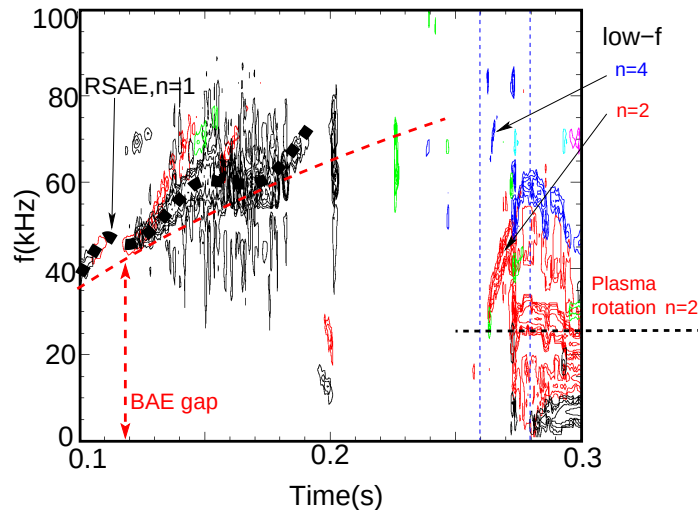
OUTLINE

1. Theory outline of Alfvén - acoustic continuum
2. NSTX analysis and data comparison
3. Application of BAAEs for MHD spectroscopy
4. Discussion and Summary

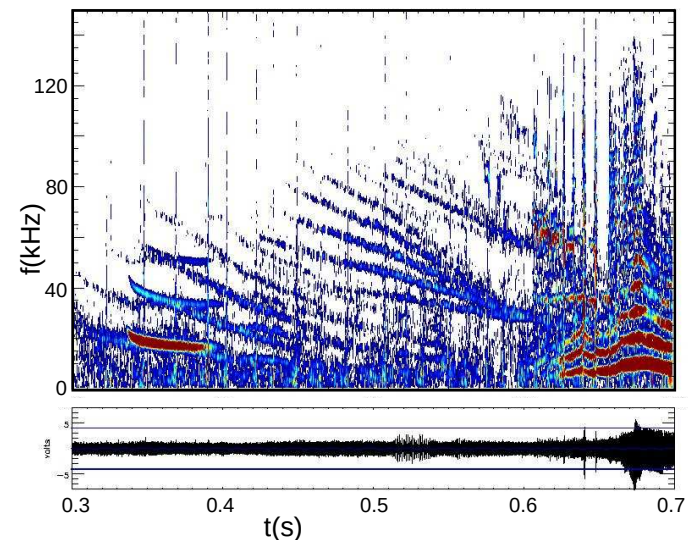
Sweeping frequency BAAEs observed and identified on NSTX

Typical parameters: $B = 0.45T$, $R/a(m) = 0.85/0.66$, $\beta_{0,pl}/\beta_{0,fast}(\%) = 34/15$, $P_{NBI} = 2MW$.

Initial phase of the discharge



Discharge flattop, evolving q



Frequencies sweep up (or down) from the rotation level, $f_{pl} = 0 - 40kHz$

q-profile: reversed in NSTX.

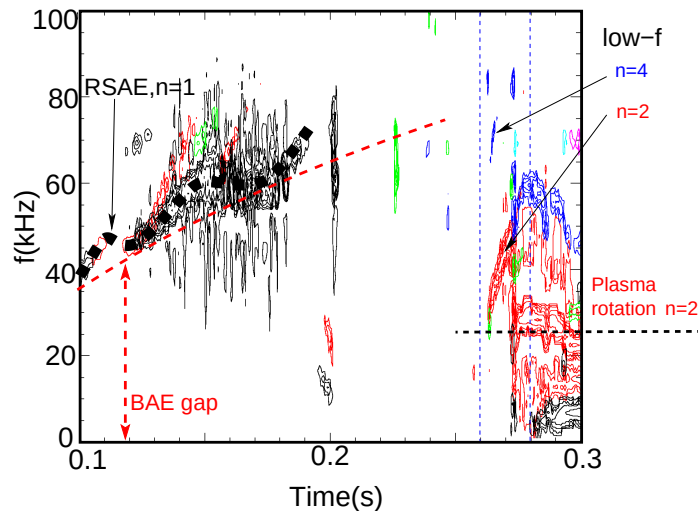
Frequency is much lower than RSAE/TAE frequency, $v_A/2qR$ and $\omega_* < 1kHz$

BAAEs in NSTX and JET were first reported in Gorelenkov, APS'06, EPS'07. May be similar to low-f cascades, Lauber, Varena'06.

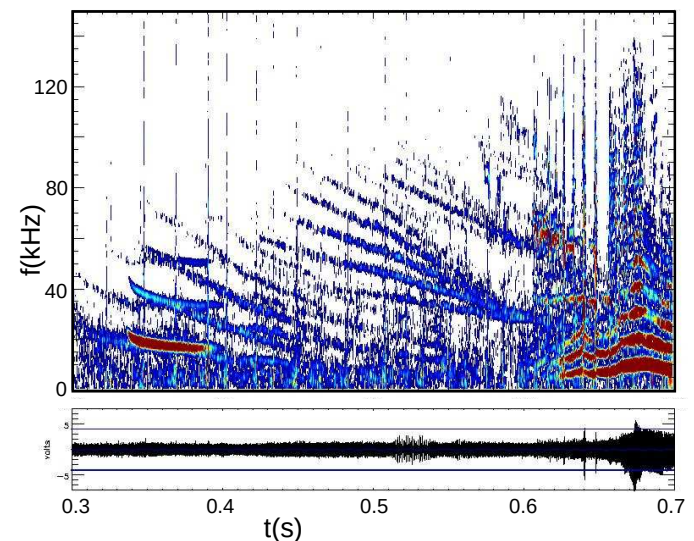
Sweeping frequency BAAEs observed and identified on NSTX

Typical parameters: $B = 0.45T$, $R/a(m) = 0.85/0.66$, $\beta_{0,pl}/\beta_{0,fast}(\%) = 34/15$, $P_{NBI} = 2MW$.

Initial phase of the discharge



Discharge flattop, evolving q



Frequencies sweep up (or down) from the rotation level, $f_{pl} = 0 - 40kHz$

q -profile: reversed in NSTX.

Frequency is much lower than RSAE/TAE frequency, $v_A/2qR$ and $\omega_* < 1kHz$

BAAEs in NSTX and JET were first reported in Gorelenkov, APS'06, EPS'07. May be similar to low-f cascades, Lauber, Varena'06.

BAAEs are ubiquitous in high- β NSTX plasma

What is the importance of low- f instabilities?

- Low- f instabilities called here **Beta-induced Alfvén Acoustic Eigenmode (BAAE)** helps to study two fundamental MHD waves: Alfvén and acoustic.

What is the importance of low- f instabilities?

- Low- f 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).

What is the importance of low- f instabilities?

- Low- f 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 plasmas
 - BAAE maybe the only MHD spectroscopy tool in **high- β plasma**, such as in STs when RSAEs are suppressed.

What is the importance of low- f instabilities?

- Low- f 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 plasmas
 - 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 outline of Alfvén/acoustic continuum

Simple shear Alfvén and acoustic coupled equations capture main effects in low- β , large aspect ratio plasma, low ω_* , (Cheng, Chance '86):

$$\Omega^2 y + \partial_{\parallel}^2 y + \gamma \beta \sin \theta z = 0 \text{ (Alfvénic)} \quad (1)$$

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

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 $z \equiv \nabla \cdot \vec{\xi}$, $\hat{k}_{\parallel} \equiv i \partial_{\parallel}$.

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

Theory outline of Alfvén/acoustic continuum

Simple shear Alfvén and acoustic coupled equations capture main effects in low- β , large aspect ratio plasma, low ω_* , (Cheng, Chance '86):

$$\Omega^2 y + \partial_{\parallel}^2 y + \gamma\beta \sin \theta z = 0 \text{ (Alfvénic)} \quad (1)$$

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

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 $z \equiv \nabla \cdot \vec{\xi}$, $\hat{k}_{\parallel} \equiv i \partial_{\parallel}$.

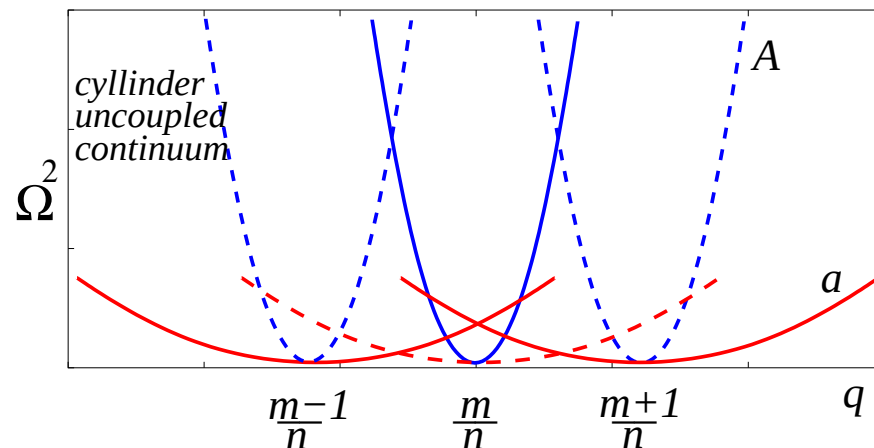
Geodesic curvature coupling: m Alfvénic and $m \pm 1$ acoustic harmonics.

Various solutions follow (WinsorPF'68, GoedbloedPF'75, MikhailovskiPIPhR'75,'98, ChuPF'92, TurnbullPF'92, ZoncaPPCF'96, van der Holst PoP'00, Breizman PoP '05, Berk NF'06)

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

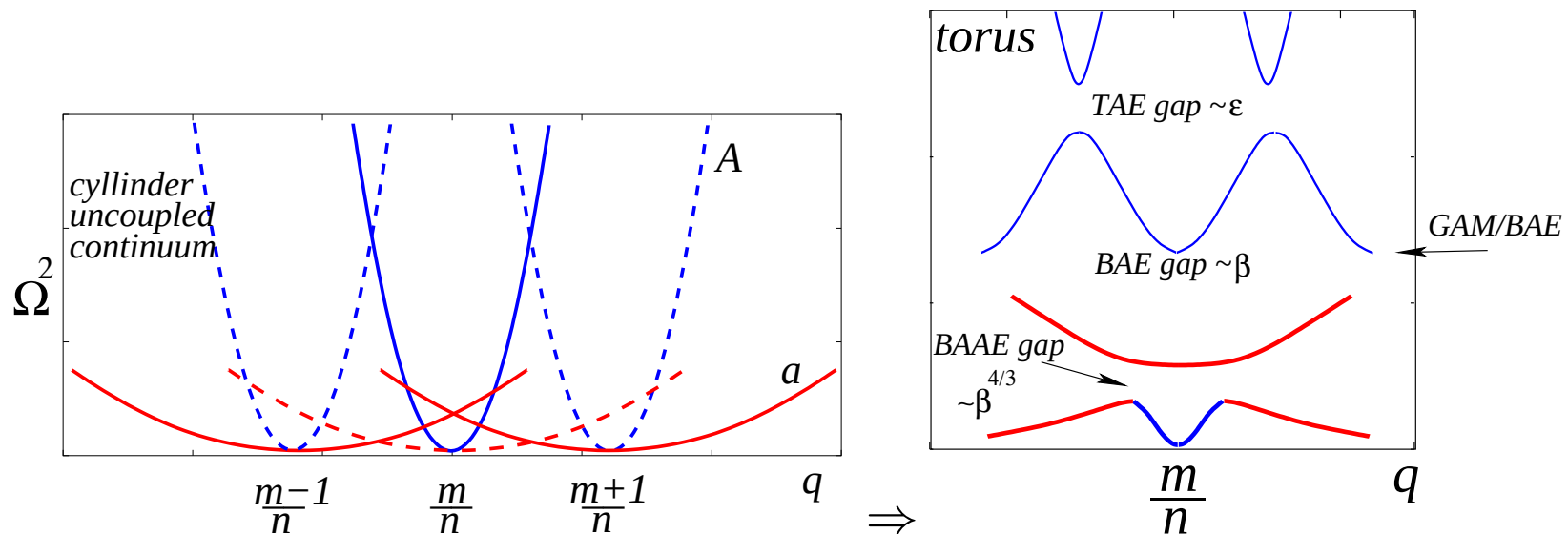
Alfvén/acoustic coupling in toroidal equilibrium (schematic)

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



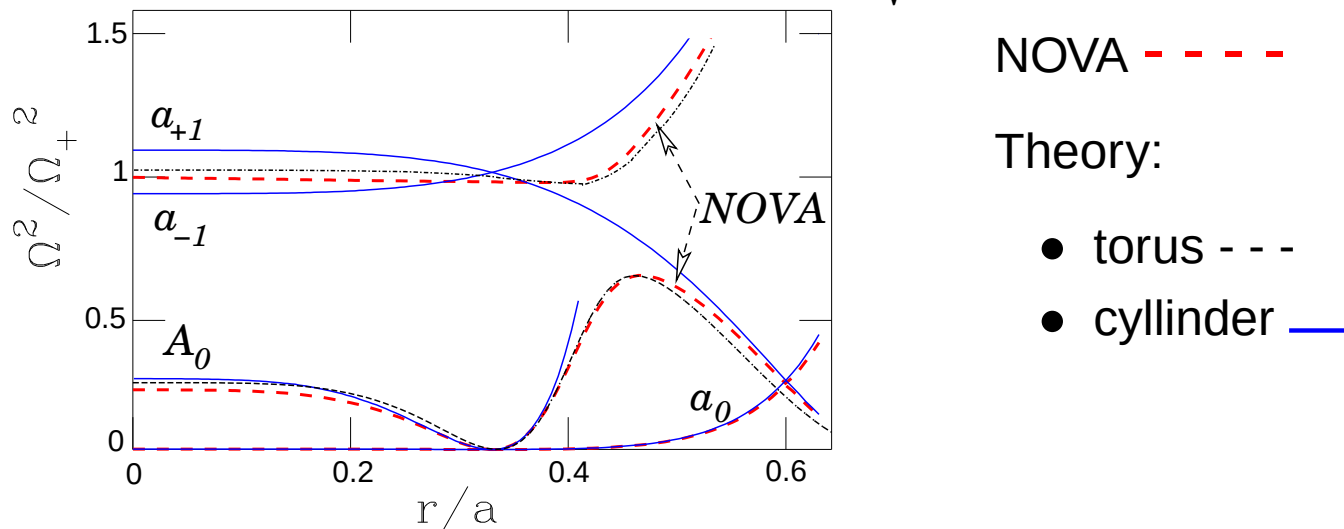
Alfvén/acoustic coupling in toroidal equilibrium (schematic)

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



Analytic dispersion for Alfvén/acoustic continuum gap is derived

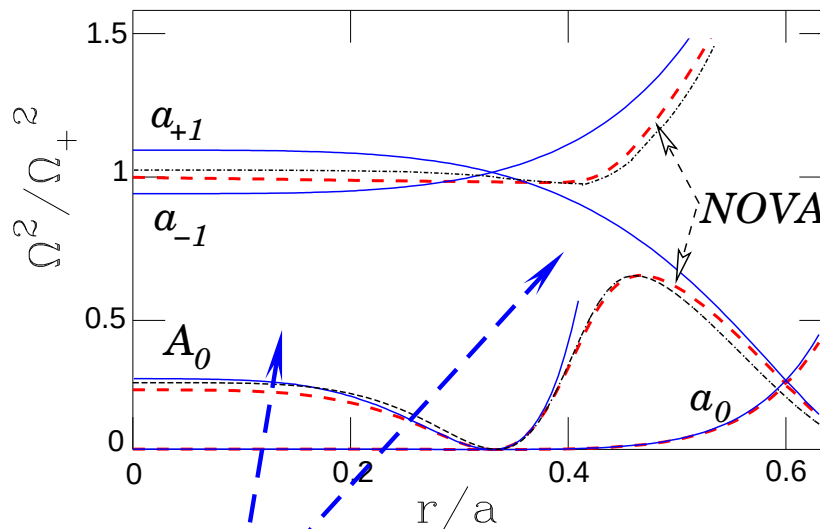
- Consider high aspect ratio, monotonic q-profile, A/10 of JET.
- $\Omega_+ = \sqrt{\gamma\beta/2}/q_r$ (compare with GAM $\Omega = \sqrt{\gamma\beta(1 + 1/2q^2)}$).



Exact MHD (NOVA) continuum is in good agreement with theory.

Analytic dispersion for Alfvén/acoustic continuum gap is derived

- Consider high aspect ratio, monotonic q-profile, A/10 of JET.
- $\Omega_+ = \sqrt{\gamma\beta/2}/q_r$ (compare with GAM $\Omega = \sqrt{\gamma\beta(1 + 1/2q^2)}$).



NOVA - - -

Theory:

- torus - - -
- cylinder —

Exact MHD (NOVA) continuum is in good agreement with theory.

Two global modes exist:

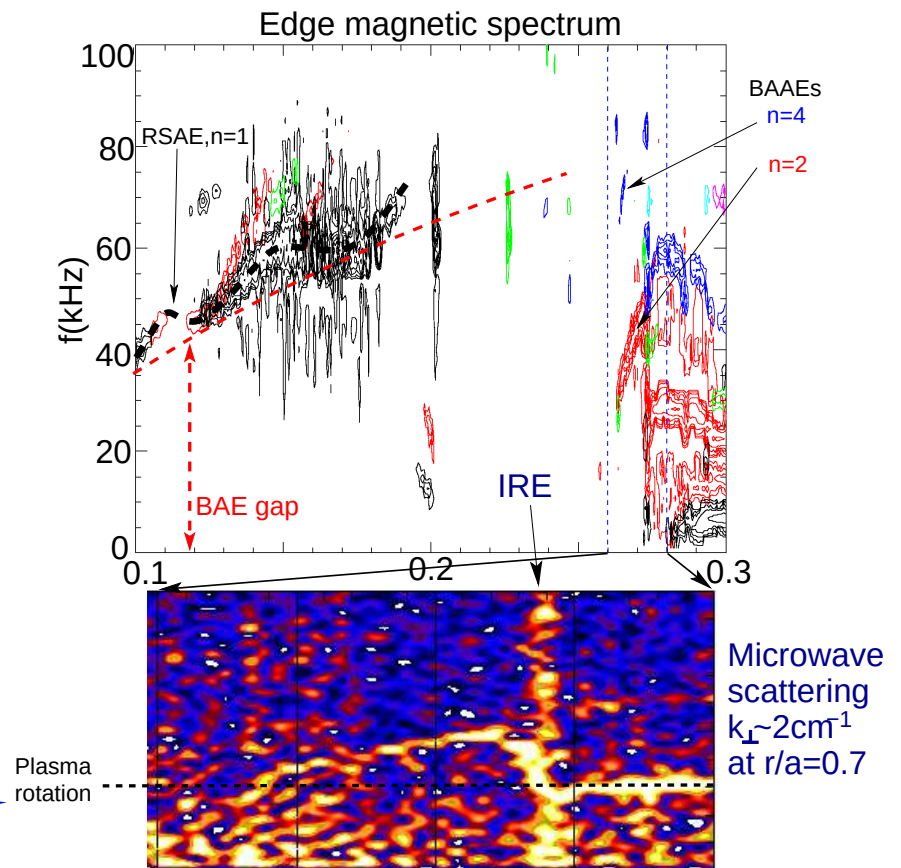
Core/low-shear localized BAAE (A): $\omega = v_A k_{\parallel} / \sqrt{1 + 2q_0^2}$ - sweeps in ω
 Gap BAAE (A-a): $\Omega_+ \simeq v_A \sqrt{\gamma\beta/2}/q_{min}R$ bounds frequency sweep,
 quantitatively frequency differs from measured at JET by 50%.

NSTX experiments aimed at detailed BAE studies

- Low density $n_e \simeq 3 \times 10^{19} m^{-3}$,
 $P_{NBI} = 2MW$, $E_{NBI} = 90keV$.
- 12 channel MSE measures $q(r)$
- Address JET experiment/theory frequency mismatch.

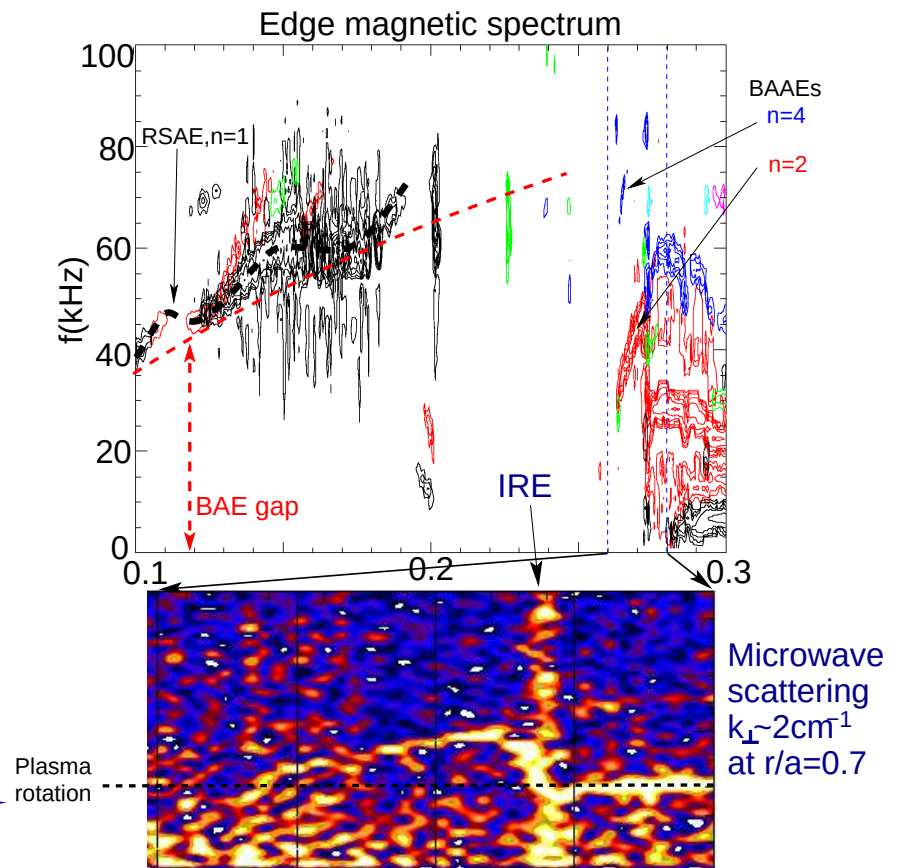
NSTX experiments aimed at detailed BAE studies

- Low density $n_e \simeq 3 \times 10^{19} m^{-3}$, $P_{NBI} = 2MW$, $E_{NBI} = 90keV$.
- 12 channel MSE measures $q(r)$
- Address JET experiment/theory frequency mismatch.
- Low frequency oscillations (BAAEs) are seen unstable:
 - Sweeping up 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, EPS'07, P2.045).



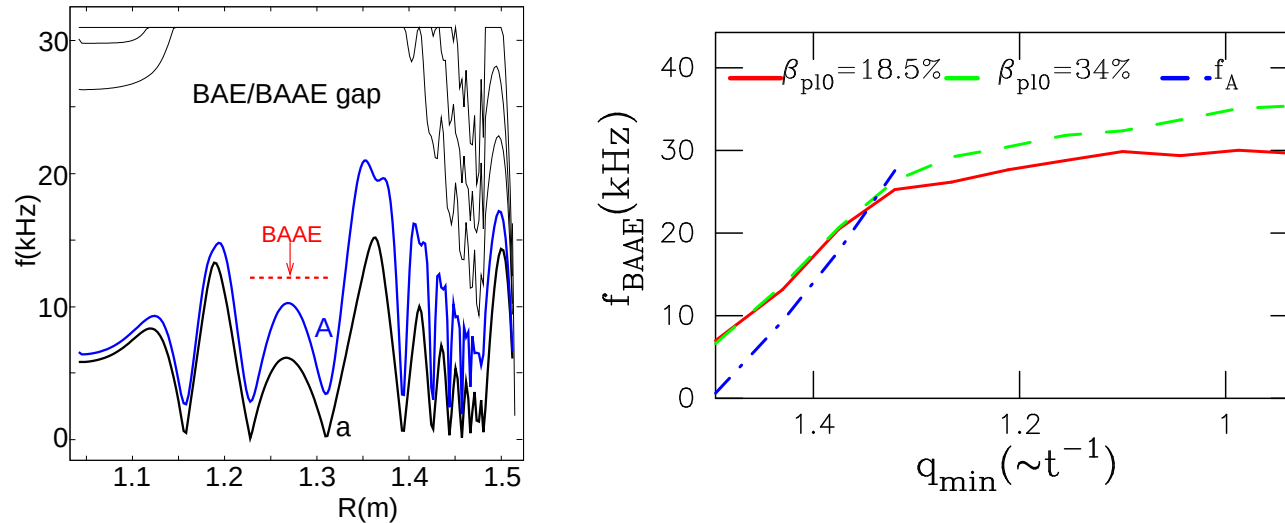
NSTX experiments aimed at detailed BAE studies

- Low density $n_e \simeq 3 \times 10^{19} m^{-3}$, $P_{NBI} = 2MW$, $E_{NBI} = 90keV$.
- 12 channel MSE measures $q(r)$
- Address JET experiment/theory frequency mismatch.
- Low frequency oscillations (BAAEs) are seen unstable:
 - Sweeping up 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, EPS'07, P2.045).



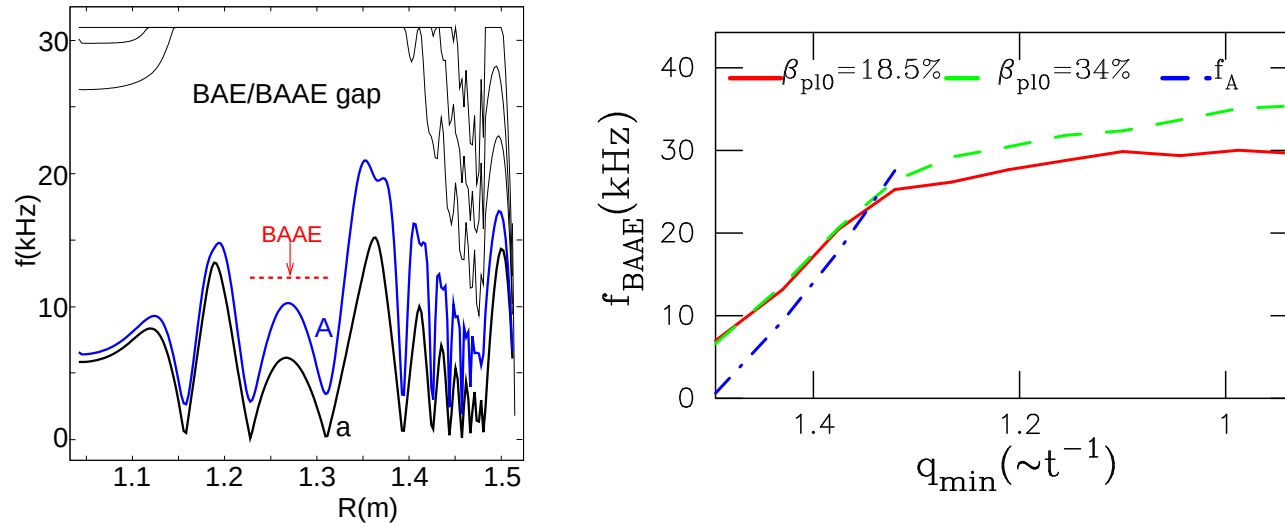
TAE/RSAEs are suppressed (E. Fredrickson EPS'07) and BAAEs are excited by beams in high- β NSTX plasmas (typically $\beta_{pl} > \sim 15\%$).

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



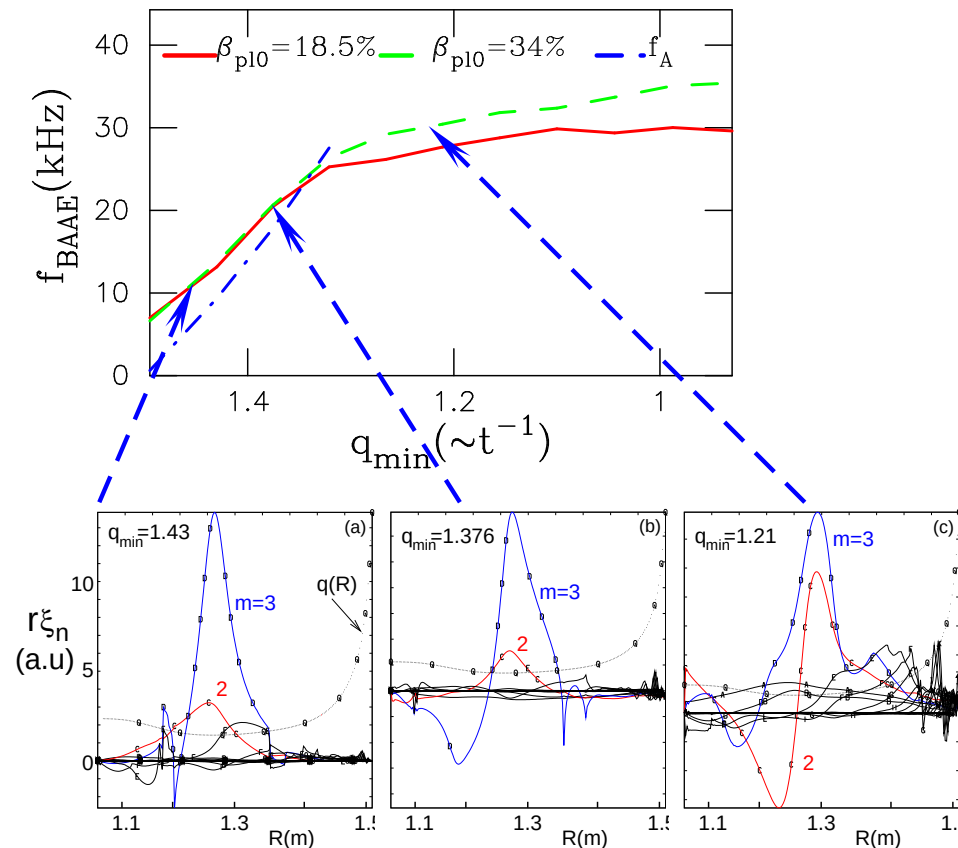
- MSE measured inversed q -profile is used in NOVA modeling.
- At high- $\beta_0 = 34\%$, BAE is wide, up to TAE frequency.
- Two Alfvén/acoustic (A/a) continuum branches are found with $\Omega^2 < \gamma\beta$, $n = 2$

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 (LS) BAAE frequency
 - does not depend on β for q close to rational
 - continuously transforms to gap mode (due to higher β , strong coupling)
 - LS f_{BAAE} is close to modified Alfvén branch $f_A = v_A k_{\parallel} / \sqrt{1 + 2q_{\min}^2}|_{r=0}$.

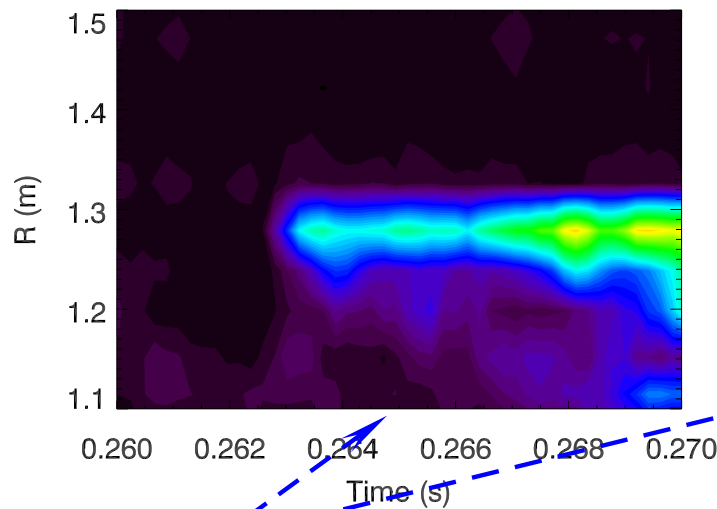
NOVA: BAAE broadens radially as $q_{\min}$ decreases



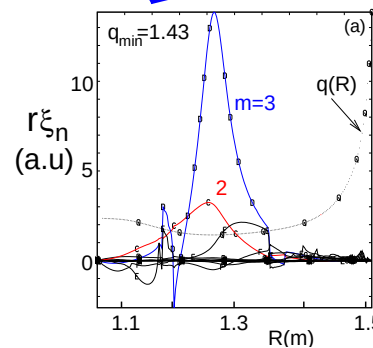
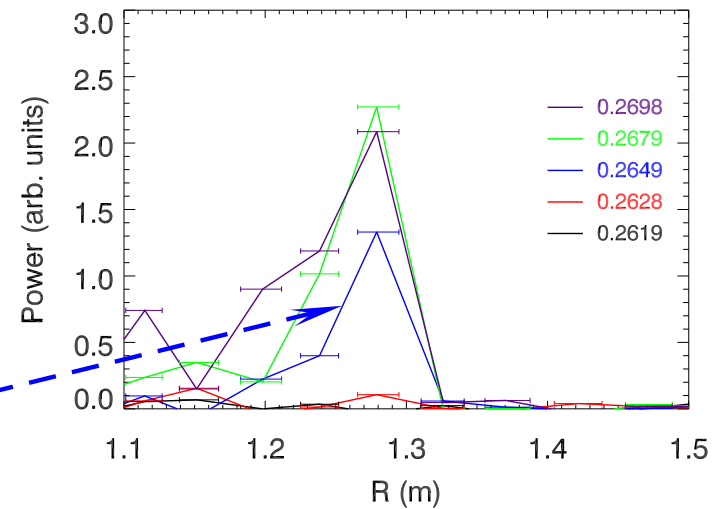
- BAAE frequency sweeps as q -profile relaxes.
- One dominant harmonic $m = nq_{\min} = 3$.
- Strong similarity to RSAE to TAE transition.
- BAAEs interact with the continuum.

Ultra SXR agrees with NOVA radial structure broadening

Raw USXR signal ($\sim$ BAAE structure)



Radial profile evolution

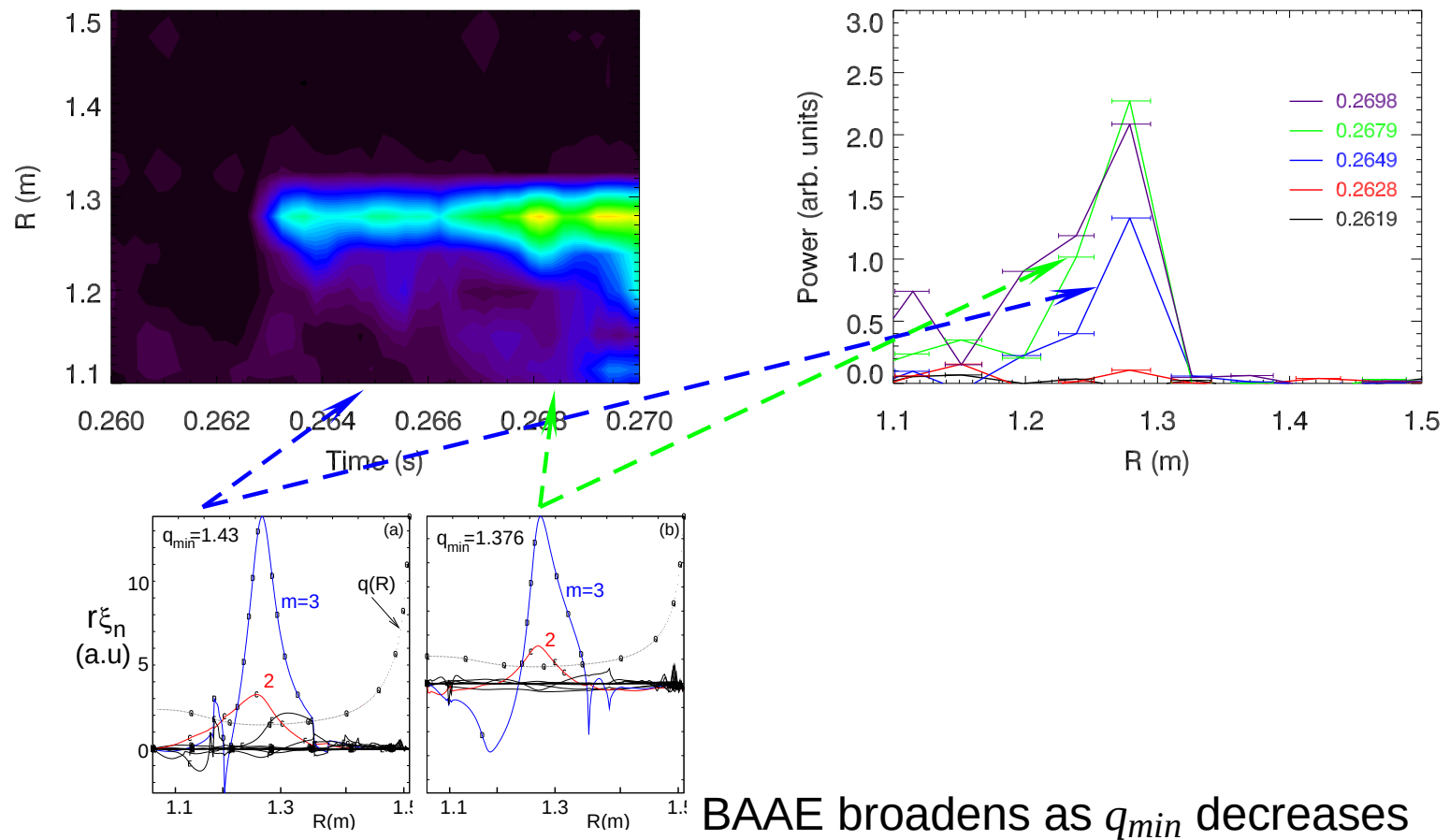


BAAE broadens as q_{min} decreases

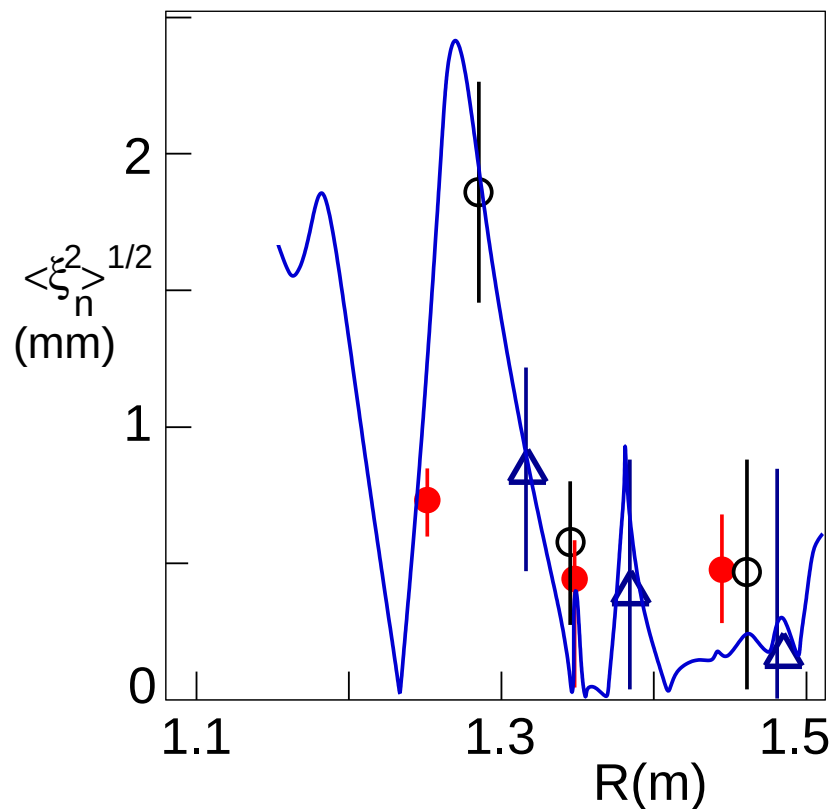
Ultra SXR agrees with NOVA radial structure broadening

Raw USXR signal ($\sim$ BAAE structure)

Radial profile evolution

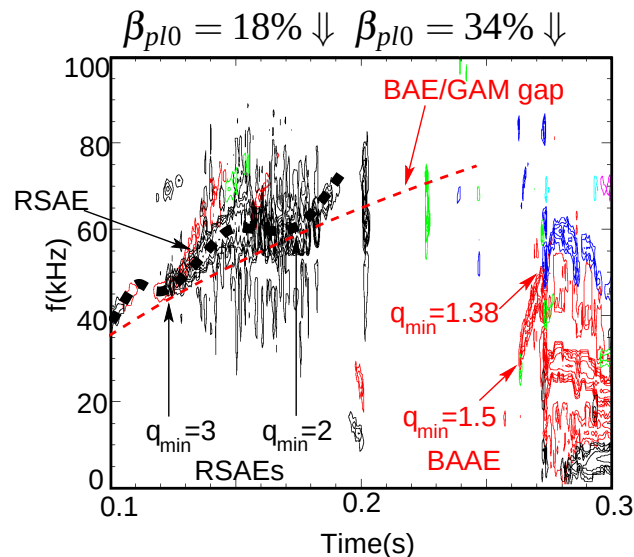


Reflectometer confirms localized radial displacement of BAEs



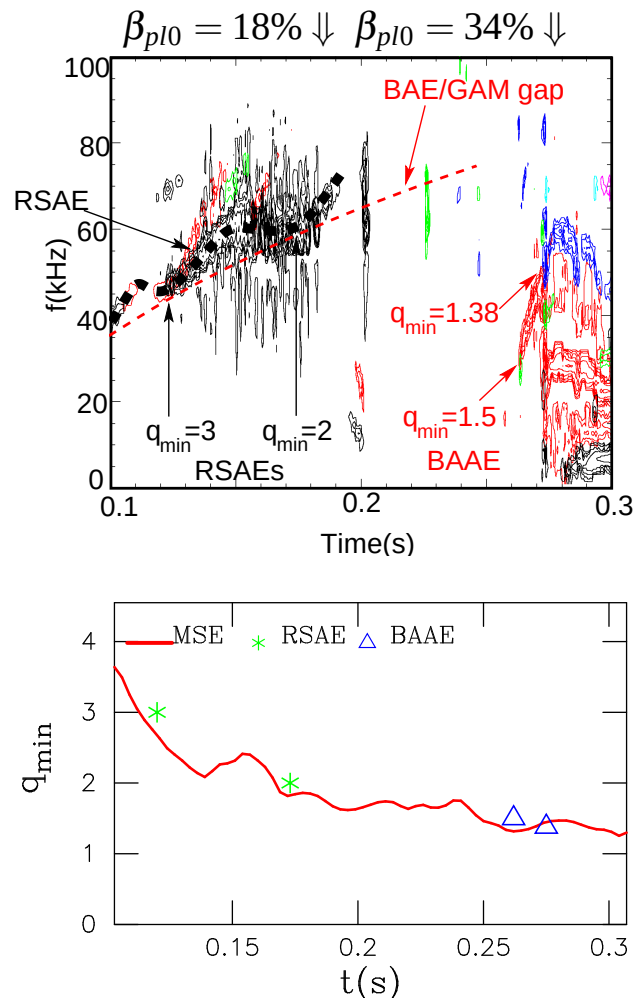
- Three plasmas, 3 points each:
 - $n_e = 3.3 \times 10^{19} \text{ m}^{-3}$
 - $n_e = 3.6 \times 10^{19} \text{ m}^{-3}$
 - △ $n_e = 3.8 \times 10^{19} \text{ m}^{-3}$
- Vertical axis refers to points
● - #123816.
- Measurements are taken at signal maximum.
- Internal fluctuations level $\delta n/n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

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



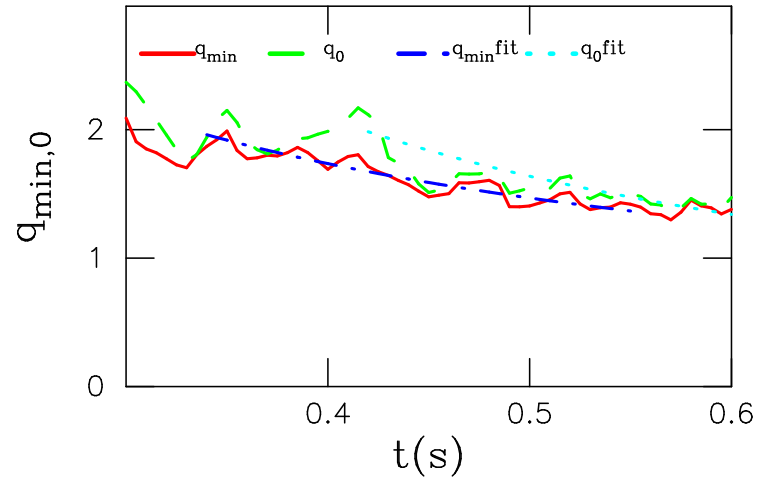
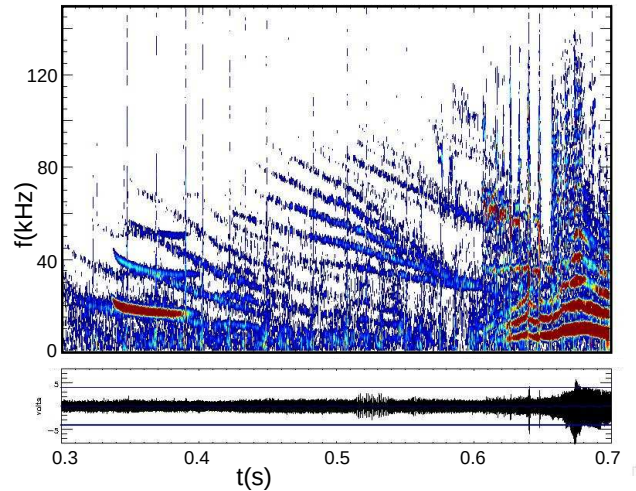
- RSAE/TAEs can be used to infer q_{min} in low-, medium- β plasma
- Zero BAAE frequency point (plasma frame) indicates rational q_{min} .
- BAAE activity is terminated at $t = 0.275s$.
Potential interplay of beam driven instabilities with internal $m = 3/n = 2$ kink-like instability - similar to TAE/sawtooth nonlinear interplay (Bernabei'01, Sharapov'06).
- RSAE/TAE and BAAE inferred q_{min} values are in agreement with MSE measurement.

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

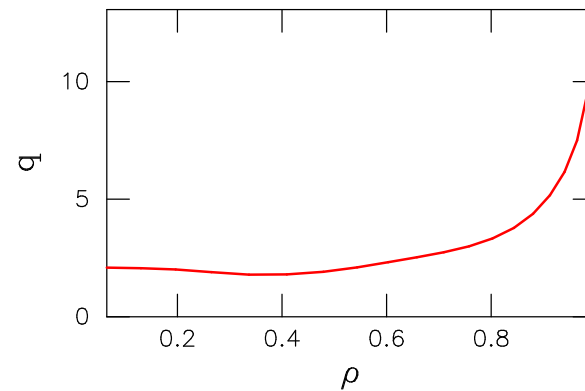


- RSAE/TAEs can be used to infer q_{min} in low-, medium- β plasma
- Zero BAAE frequency point (plasma frame) indicates rational q_{min} .
- BAAE activity is terminated at $t = 0.275s$.
Potential interplay of beam driven instabilities with internal $m = 3/n = 2$ kink-like instability - similar to TAE/sawtooth nonlinear interplay (Bernabei'01, Sharapov'06).
- RSAE/TAE and BAAE inferred q_{min} values are in agreement with MSE measurement.

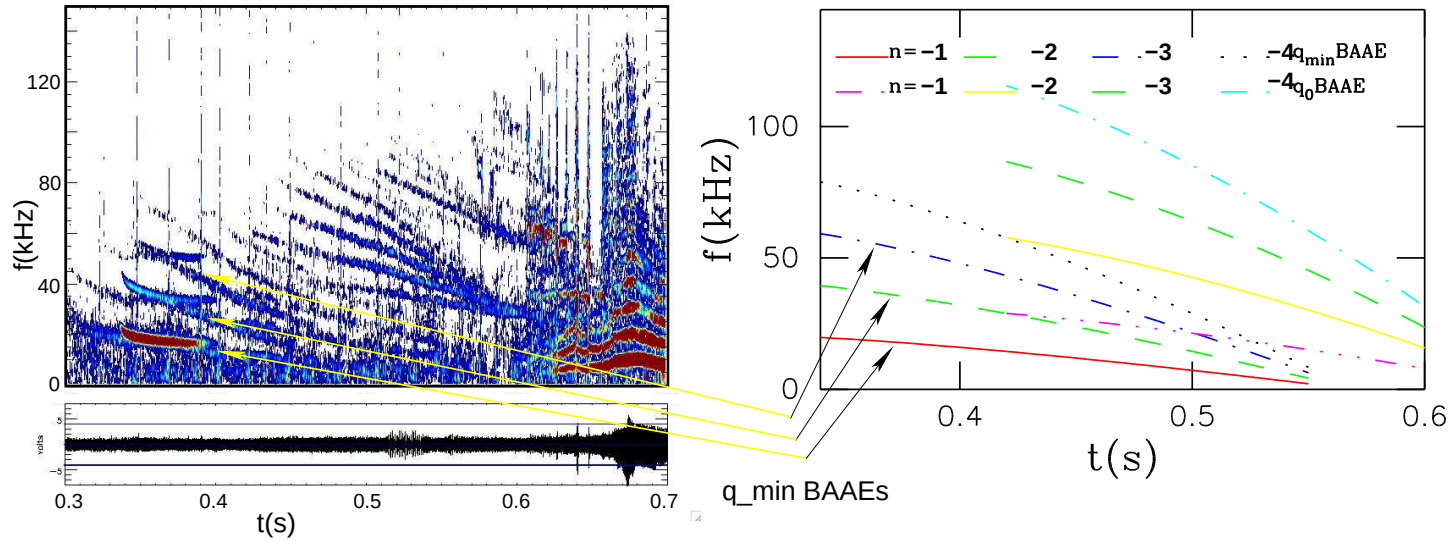
Multiple BAAE observations in NSTX



- Negative n , $|n| \leq 5$ BAAEs are excited, electron rotation direction.
- MSE measured reversed q -profile, high- $\beta_{0,tot} > 30\%$.
- Only LS-BAAEs were identified with modified Alfvénic wave dispersion - no gap modes.
- Low shear regions, $q_{0,min}$, are points of BAAE localization.
- Use to help to validate the theory.



Identified BAAE frequency evolution is consistent with theory predictions



Applied modified Alfvénic dispersion with rotation $f_{\text{rot}}(q_{\min}) = 19 - 23 \text{ kHz}$, $f_{\text{rot}}(q_0) = 26 - 30 \text{ kHz}$,

$q_{0,\min}$ is from MSE: $f = f_{\text{BAAE}} + n f_{\text{rot}}$, $n < 0$

Modified Alfvénic wave dispersion is essential: $f_{\text{BAAE}} = v_A k_{\parallel} / \sqrt{1 + 2q_{0,\min}^2}$

In addition to BAAE several other activities has to be identified.

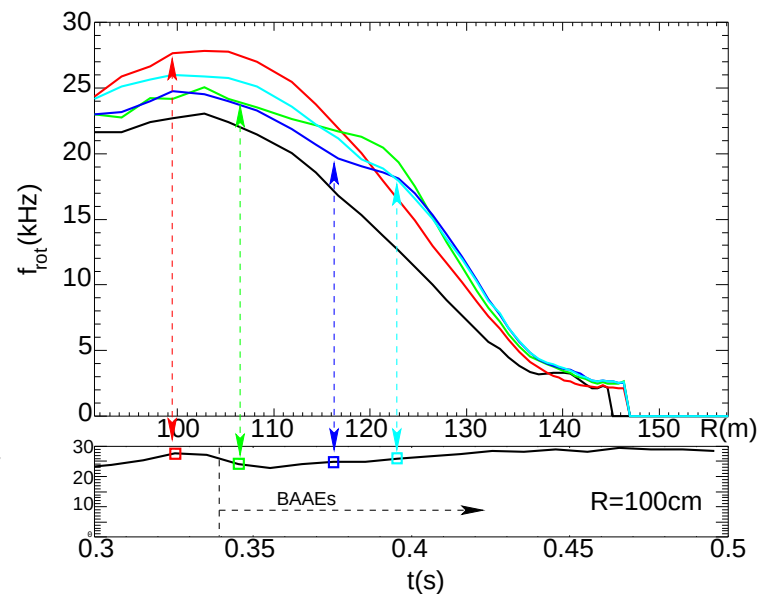
Possible other instabilities are TFAEs - toroidal Flow induced AEs (van der Holst, 2000, TMA?).

What are the effects of BAAEs on beam ion confinement?

- BAAE frequency range avalanch effect is reported in E.Fredrickson and D.Darrow talks;
Possibly “Sierpes” instabilites by Garcia-Munoz?

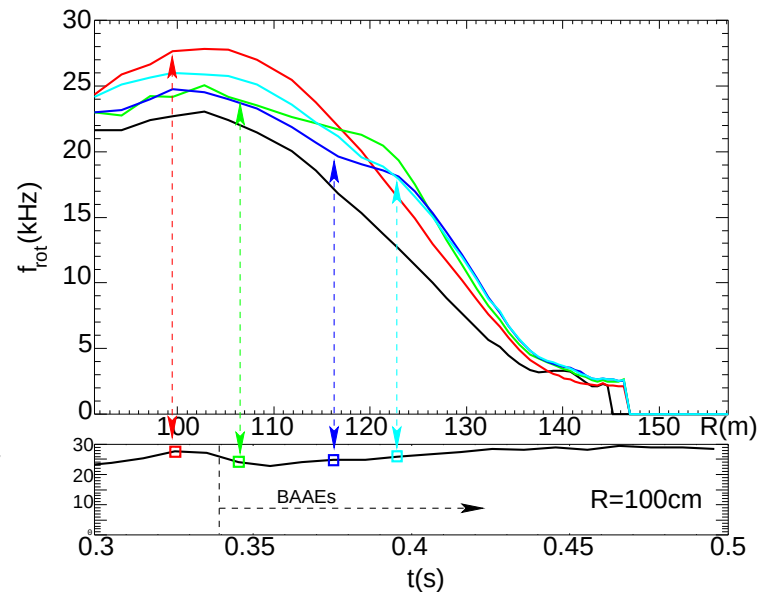
What are the effects of BAAEs on beam ion confinement?

- BAAE frequency range avalanche effect is reported in E.Fredrickson and D.Darrow talks; Possibly “Sierpes” instabilities by Garcia-Munoz?
- Low-f modes lead to the momentum transport — — — — —
- Both BAAEs and possibly kink/TFAEs are present at the time of momentum transport.



What are the effects of BAAEs on beam ion confinement?

- BAAE frequency range avalanche effect is reported in E.Fredrickson and D.Darrow talks; Possibly “Sierpes” instabilities by Garcia-Munoz?
- Low-f modes lead to the momentum transport — — — — —
- Both BAAEs and possibly kink/TFAEs are present at the time of momentum transport.



Model beam ion diffusion in TRANSP did not explained expected (from MSE) plasma current redistribution.

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 - BAAEs are found,
 - BAAEs exist in finite beta plasma within wider BAE gap.

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 - BAAEs 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 at low shear.
 - frequency is lower $0 < \Omega < \sqrt{\gamma\beta/2}/q_{min}$ vs. $\Omega = \sqrt{\gamma\beta (1 + 1/2q_{min}^2)}$ for BAE/GAM.
 - both low shear and gap BAAEs can coexist (similar to RSAE/TAEs)

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 - BAAEs 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 at low shear.
 - frequency is lower $0 < \Omega < \sqrt{\gamma\beta/2}/q_{min}$ vs. $\Omega = \sqrt{\gamma\beta (1 + 1/2q_{min}^2)}$ 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 NBI NSTX plasmas.
- Quantitatively NOVA predicts BAAE frequency evolution in agreement with observations on NSTX up to the BAAE gap.
 - MSE measurements on NSTX seem to validate theory and MHD (q_{min}) spectroscopy via BAAEs.
 - Maybe useful for burning plasmas, ITER.
- Need to reconcile theory and experiment via kinetic theory especially for the case of BAAE transforming into a gap mode
 - JET frequency mismatch has to be understood.
- BAAEs are expected in plasmas with $T_e > T_i$ and strong drive from fast ions and/or η_i (ITG-like drive)