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NSTX

Alfvén Cascade modes at high β in NSTX*

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Neal Crocker for the NSTX Group

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49th Annual Meeting of the Division of Plasma Physics

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Rosen Centre Hotel
Orlando, Florida

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*Supported by U.S. DoE Grants DE-FG03-99ER54527 and DE-AC02-76CH03073

Recent NSTX results probe Alfvén Cascade mode physics at high β and high ε

- **Motivation is importance of Alfvén Cascade (AC) modes* in reverse-shear (RS) plasmas**
  - ACs transport fast-ions ($v_{ion}/v_A \gtrsim 1$) – impact plasma performance
  - RS is advanced scenario for ITER & Component Test Facility
  - AC modes diagnose $q_{min}(t)$ ("MHD spectroscopy")
  - high β and high ε (= a/R) are relatively unexplored regimes for AC modes

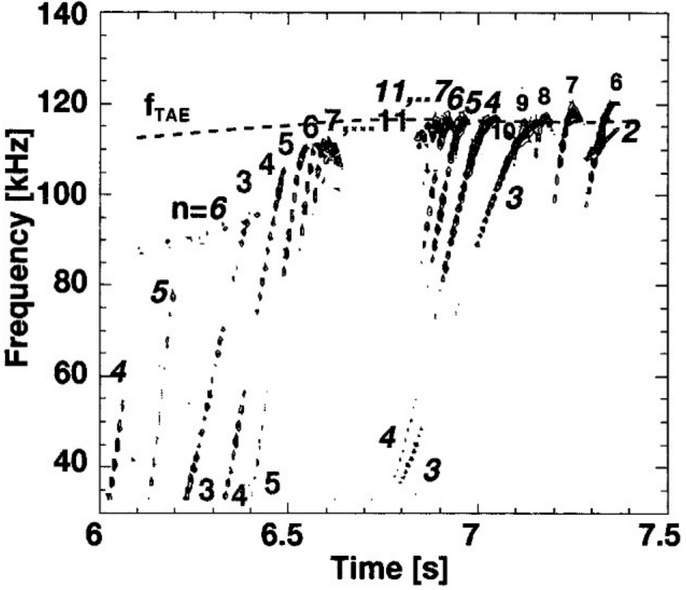
- **Experimental results include**
  - characterization of AC mode spectra and structure at low and high β at high ε
  - observation of fast-ion loss associated with AC modes

- **Experimental results are shown to be consistent with predictions of NOVA-K stability code**
  - comparison also extends understanding of experimental results

*a.k.a. reverse-shear Alfvén eigenmodes

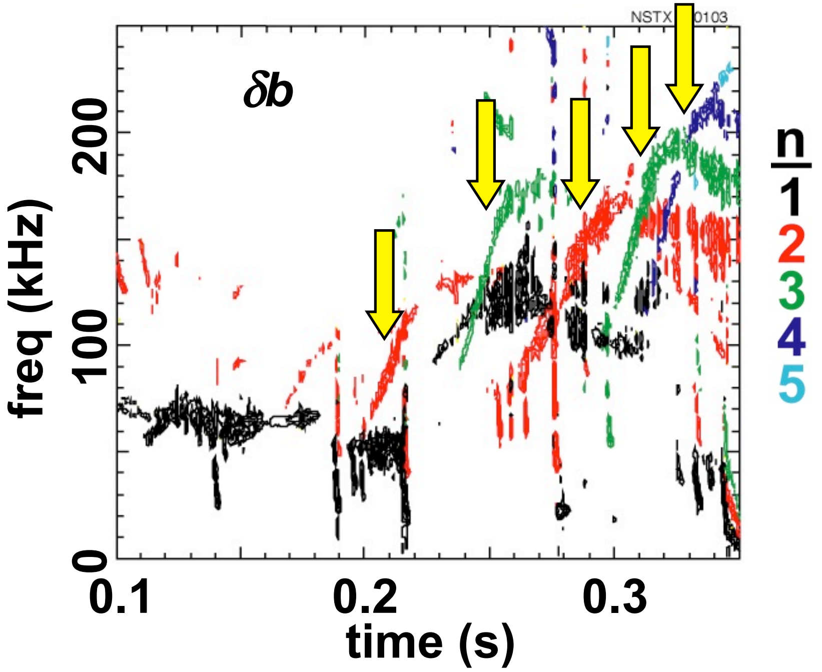
AC spectrum evolution at low β is distinctive and well-known

JT-60U



Y. KUSAMA et al., NUCLEAR FUSION **38**, 1215 (1998)

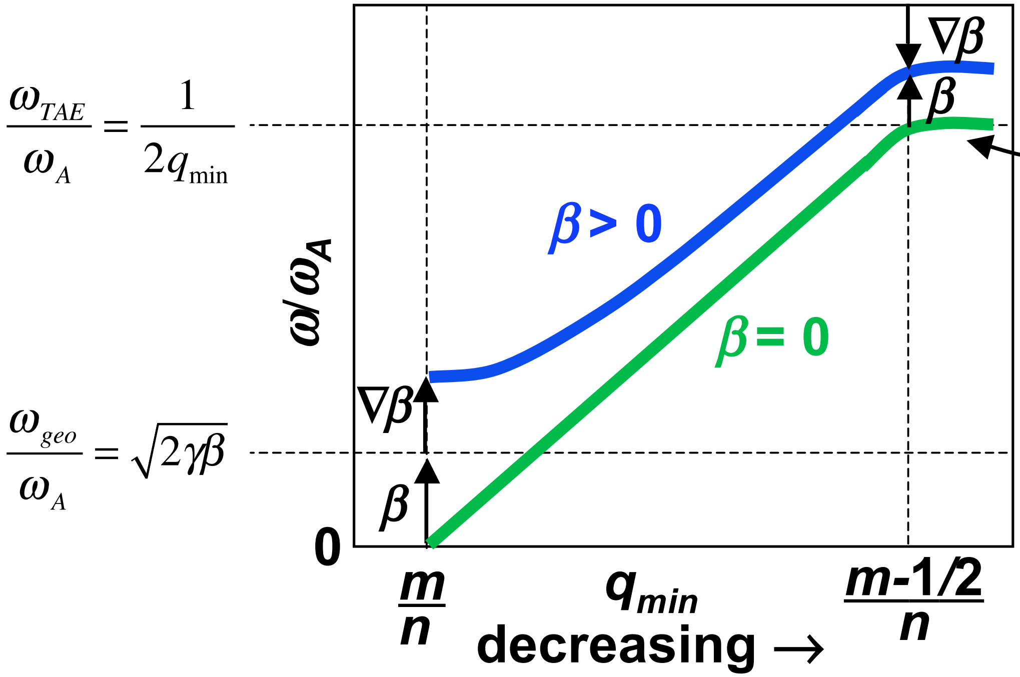
NSTX (low β)



- low β AC spectrum easily recognizable
  - large upward frequency sweeps, starting at low *f*
  - toroidal mode numbers appearing in sequences
  - seen on conventional tokamaks JT-60U, TFTR, JET, DIII-D, Alcator C-MOD

- NSTX low β AC spectrum similar to conventional tokamaks

Current understanding of AC modes: $q_{min}(t)$ evolution causes AC frequency to sweep up



conversion to TAE

$\underline{\beta = 0}$

$\omega = k_{\|} v_{A},\ k_{\|} = (m/q_{min} - n)/R$

$\underline{\beta > 0}$

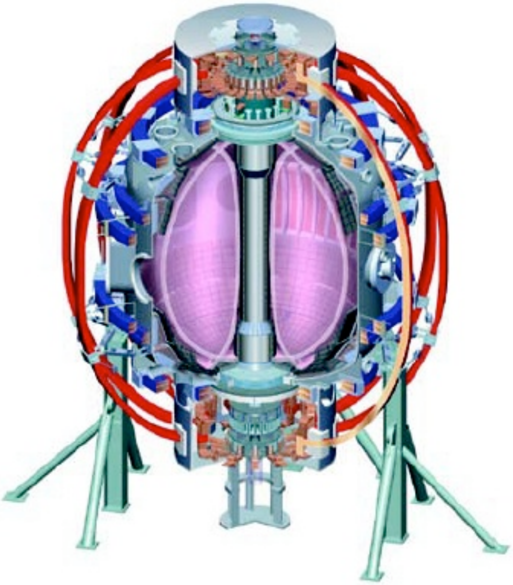
$\omega^2 = k_{\|}^2 v_A^2 + \omega^2_{geo} + \omega^2_{\nabla\beta}$

- **ACs shear Alfvén eigenmodes ($\omega \approx k_{\|} v_A$) localized to q_{min}**
  - **single n & ~ single $m \Rightarrow k_{\|} = 0$ when q_{min} = m/n**
  - **$\Delta k_{\|} > 0$ for $\Delta q_{min} < 0$: $dq_{min}/dt < 0 \Rightarrow$ frequency sweeps up**
- **$\beta > 0$ reduces relative sweep – "geodesic curvature" & $\nabla\beta$**
- **q_{min} may be deduced from spectrum: "MHD spectroscopy"**

G. J. Kramer et.al., Plasma Phys. Contr. Fusion **46**, L23 (2004);
B. N. Breizman et.al., Phys. Plasmas **12**, 112506 (2005);
G. Y. Fu et.al., Phys. Plasmas **13**, 052502 (2006);
Gorelenkov et.al., Plasma Phys. Contr. Fusion, **48**, 1255 (2006);

NSTX* is well suited to study AC modes in little-explored high β and high ε regimes

- **Reverse-shear demonstrated in NSTX**
  - **verified via Motional Stark Effect (MSE)†**
  - **NSTX is only ST with MSE – useful since AE spectrum very sensitive to *q* profile**
- **AC modes observed in NSTX at β_0 up to 25 % – much higher than conventional tokamaks**
- **AC modes studied extensively in conventional tokamaks (very low β, low ε), but very little in STs§**
  - **NSTX achieves low β_0 – isolates ε effects**



Major Radius:	R_0 = 1 m
Minor Radius:	a = 0.65 m
Inverse Aspect Ratio:	ε = a/R = 0.65
Elongation	κ = 2
Triangularity	δ = 0.35

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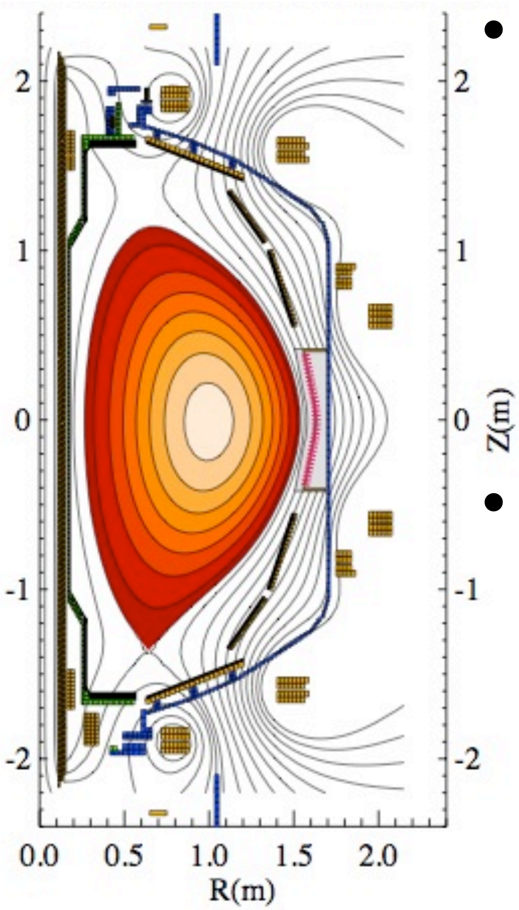
*see NSTX Poster (**TP8**) and Oral (**CO3**) sessions

†see TP8.00076, F. Levinton

§AC modes observed in MAST; S. D. Pinches, et al., Proc. of 21st IAEA Fusion Energy Conf. 2006, EX/7-2Ra

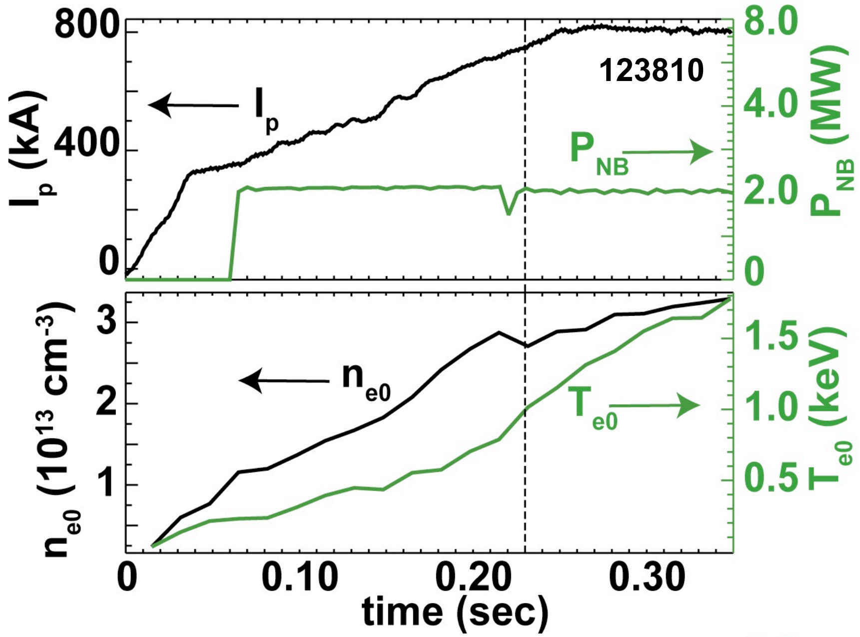
Comprehensive set of experimental and theoretical tools used to study AC Modes in NSTX

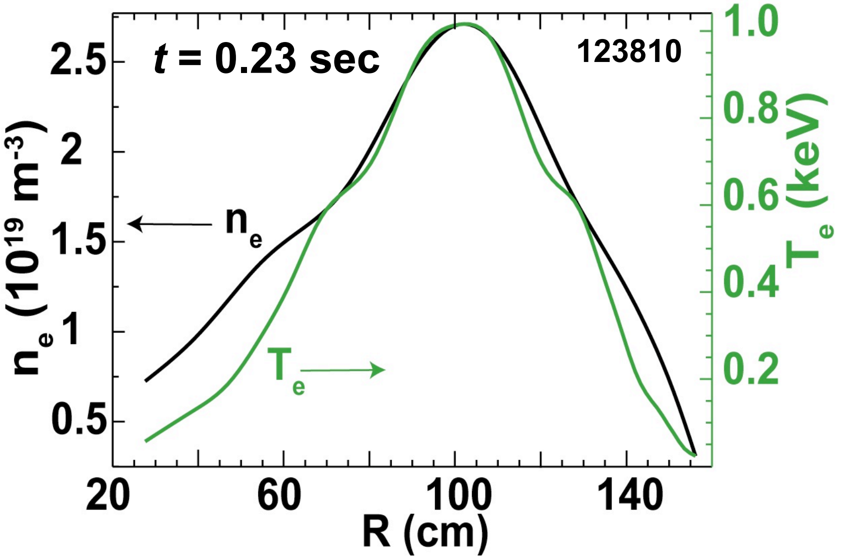


- **NSTX features diagnostics to study AC modes and impact on plasma**
  - Equilibrium: MSE (B pitch), MPTS (T_e, n_e), CHERS (T_i, v_{tor})
  - Mode structure: reflectometers (local δn), Mirnov coils
  - Fast ion population: Neutron detectors, sFLIP (fast-ion loss detector)
- **Suite of codes applicable to AC modes in NSTX equilibrium**
  - Equilibrium & beam deposition: LRDFIT, EFIT, TRANSP
  - AC mode structure, stability and growth rates: NOVA-K
  - Synthetic diagnostics: reflectometer modeling
- **Detailed comparison of AC experiment and theory possible**

AC mode studied over range of β in He L-mode plasmas

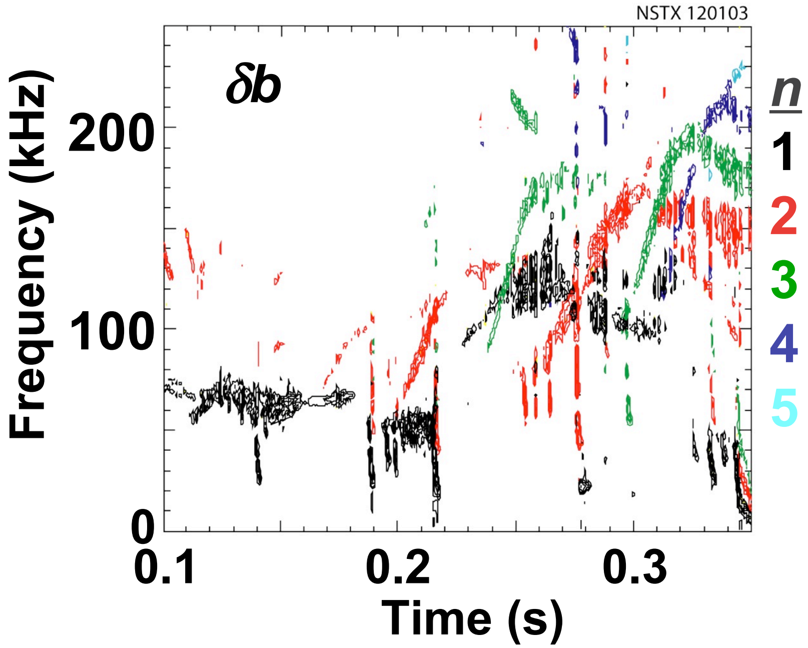
- Reverse shear, lower single null
- B_{TOR} = 0.45 T, I_p = 0.8 MA
- 2 MW Neutral beam heating
  - 90 keV, Deuterium
- β_{tor} at q_{min} up to 11% (including fast ions)
  - n_{e0} ~ 1 – 3.5x10^{19} m^{-3}
  - T_{e0} ~ 0.5 – 1 keV
- n_e and T_e strongly peaked



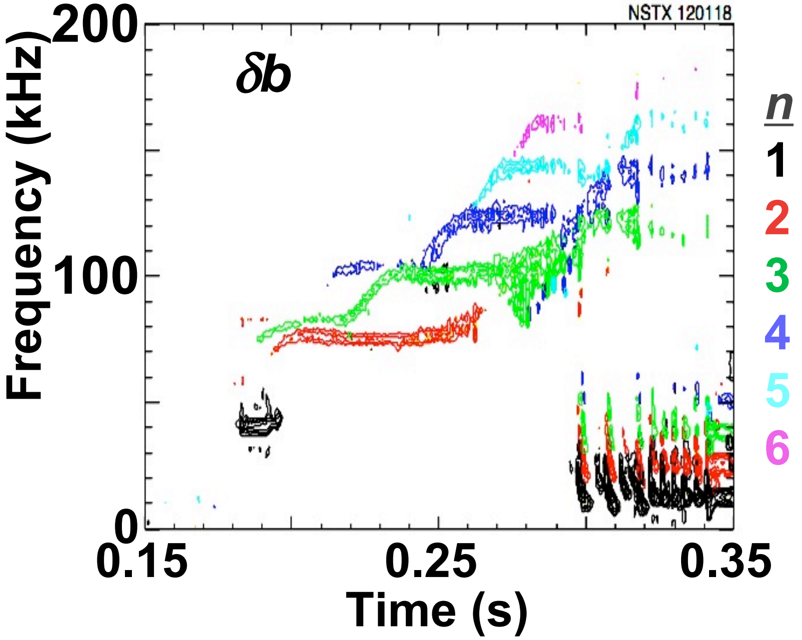


Distinctive AC spectrum evolution significantly changed by increasing β

β_{tor}(at q_{min}) ~ 6%



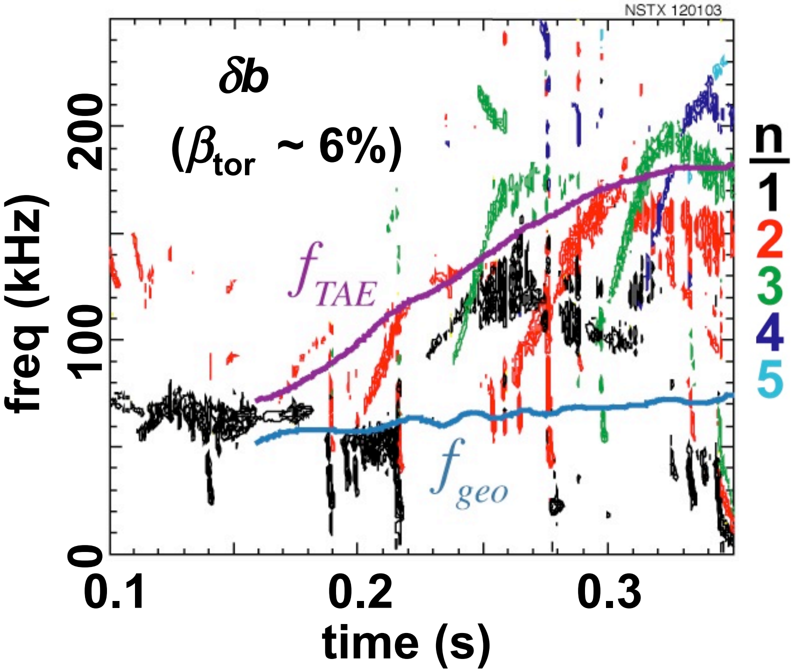
β_{tor}(at q_{min}) ~ 11%



- **Increasing β (and $\nabla\beta$) significantly reduces frequency sweep – consistent with theory**
- **Do unrecognized AC modes occur at very high β?**
  - **AC modes historically not observed in STs: suppressed or unrecognized?**
  - **Theory predicts suppression due to $\nabla\beta$ effects – area for future study**

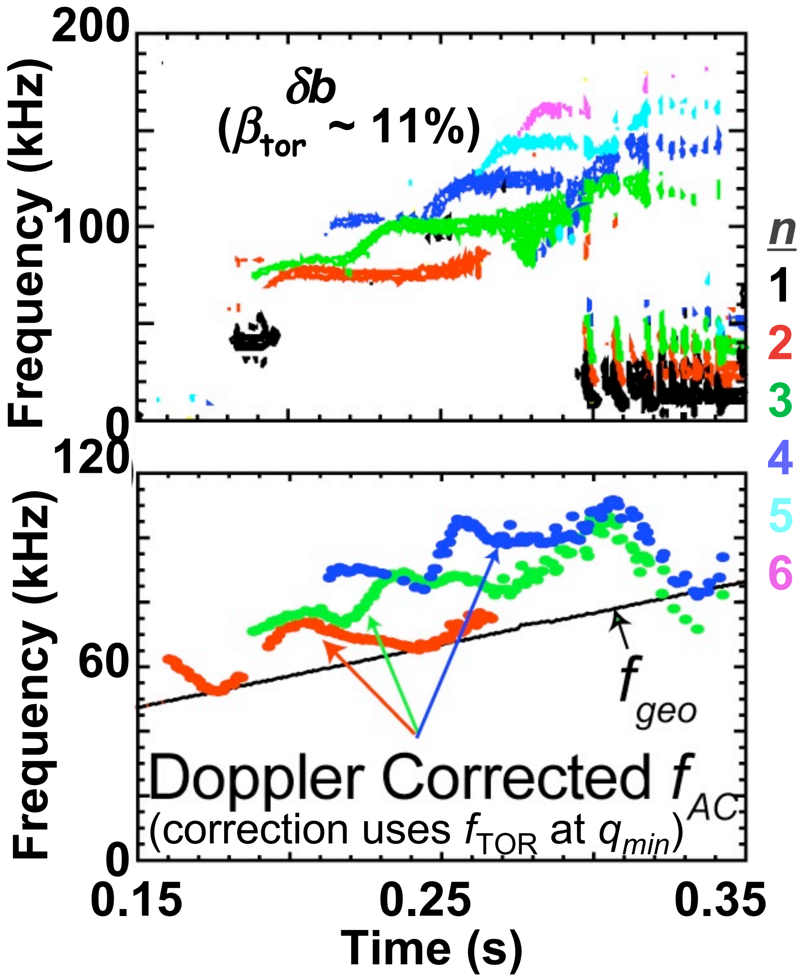
At low β, AC mode frequency sweeps from f_{geo} to f_{TAE}, consistent with theory

- β_{tor} ~ 6% at q_{min} at t = 0.27 s
  - β dominated by fast-ions at q_{min} at t = 0.27 s
- frequency sweeps over expected range for low β: ~ f_{geo} – ~ f_{TAE}
  - Consistent with theory



$\nabla\beta$ modification of AC frequency sweep is substantial at high β

- β_{tor} ~ 11% at q_{min} at t = 0.27 s
- minimum AC frequency (f_{min}) sensitive to n – expected $\nabla\beta$ effect*
  - $f_{min} > f_{geo}$
  - $f_{min} \rightarrow f_{geo}$ as n → 1



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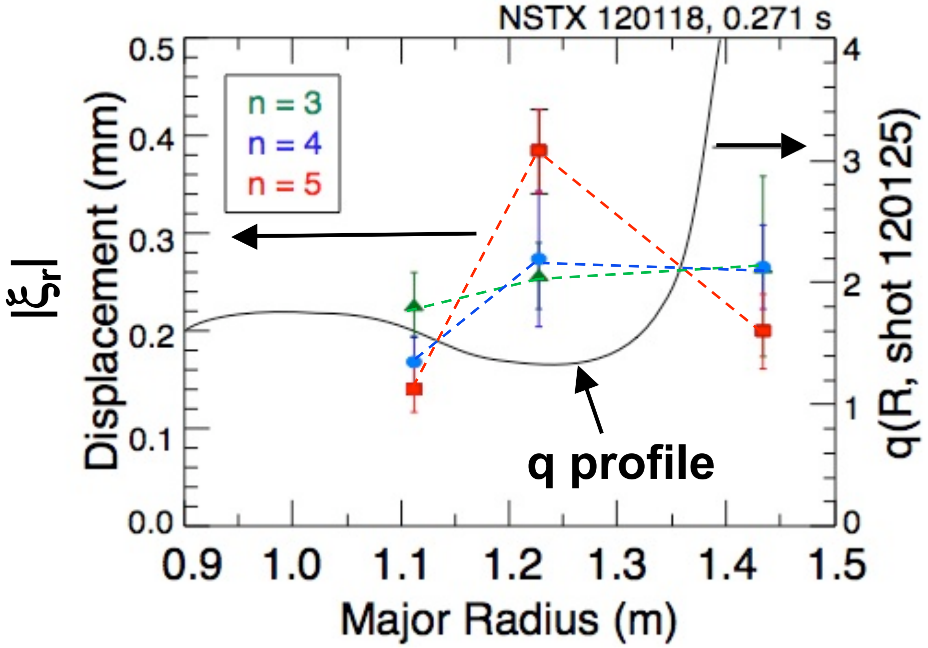
*G. J. Kramer, Plas. Phys. Contr. Fus. **46**, L23 (2004)

At high β, AC mode structure measurement consistent with peaking near q_{min}



- **Internal structure of AC modes measured with reflectometers**
- ***q*** **profile from similar shot shows minimum at R ~ 1.25 m.**
- **Structure consistent with localization at** q_{min}
  - **Stronger localization for highest n mode, as expected from theory**

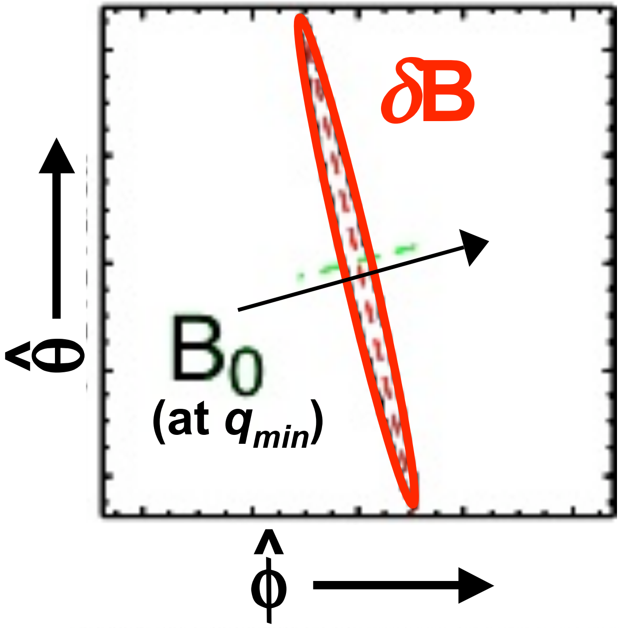
Polarization of AC δB at plasma edge is consistent with "shear Alfvén wave" localized near q_{min}

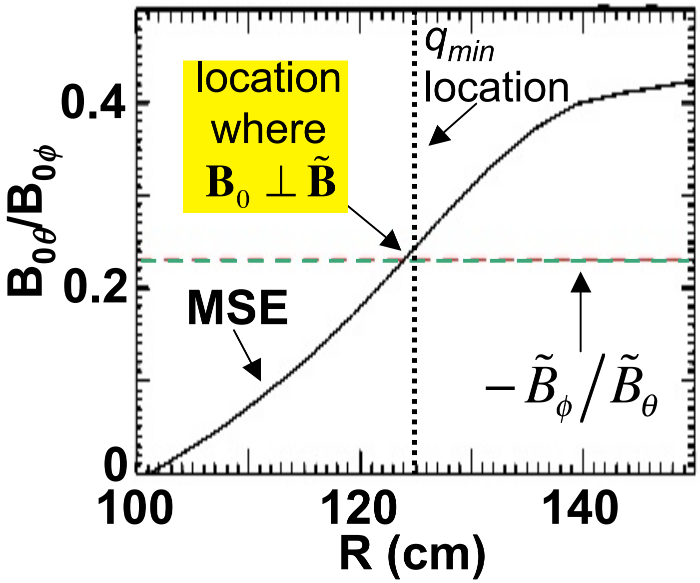
- **For shear Alfvén waves: $\delta B \perp B_0$**

- **AC mode localized around q_{min} (R ~ 125 cm) ⇒ expect (B_0 at R ~ 125 cm) $\perp \delta B_{AC}$**

- **AC polarization measured at plasma edge – gives direction of δB_{AC}**

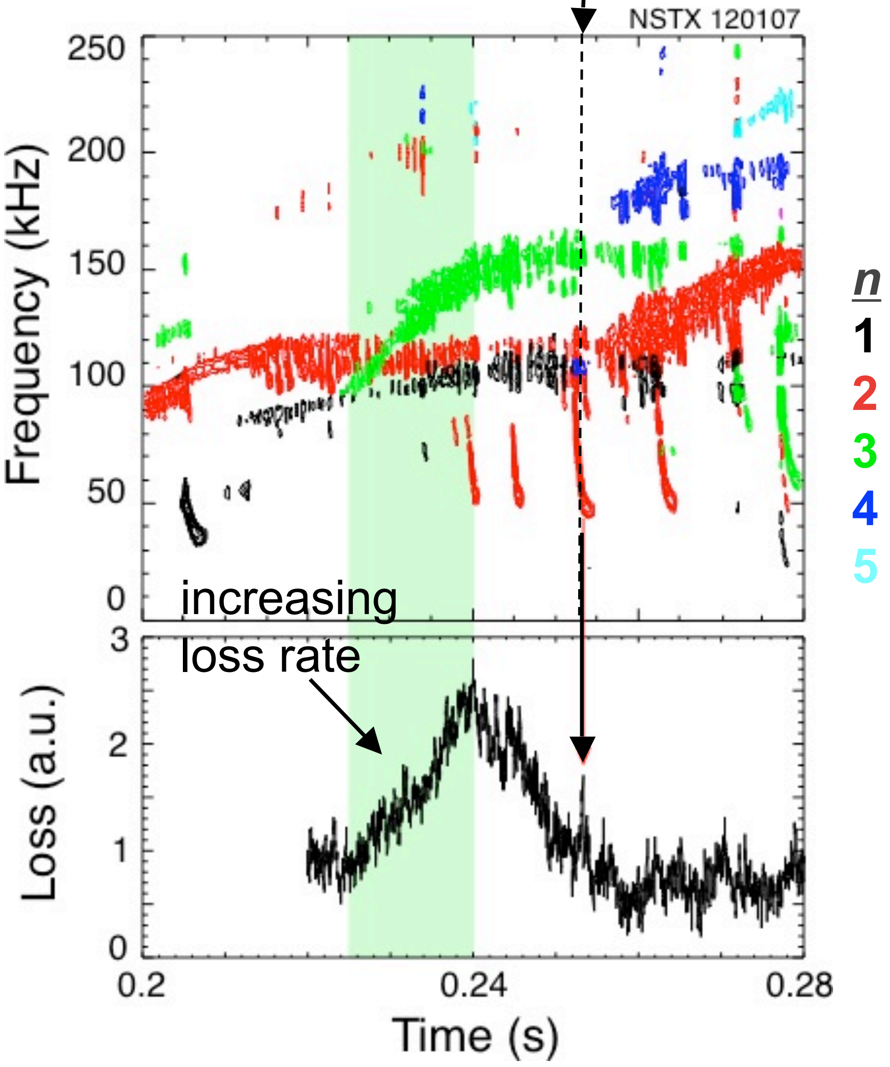
- **from MSE and edge Mirnov coils: B_0(R=124 cm) $\perp \delta B_{AC}$**





AC modes in NSTX cause fast ion loss

- **Direct loss of fast-ions from plasma measured at wall with sFLIP***
  - **sFLIP is spatially localized – doesn't detect all lost fast-ions**
- **Multi-mode "avalanche" accompanied by spike in loss rate†**
- **Increasing loss rate simultaneous with *n* = 3 AC mode**
  - **Loss rate decreases when mode converts to TAE (mode frequency saturates)**



multi-mode avalanche

increasing loss rate

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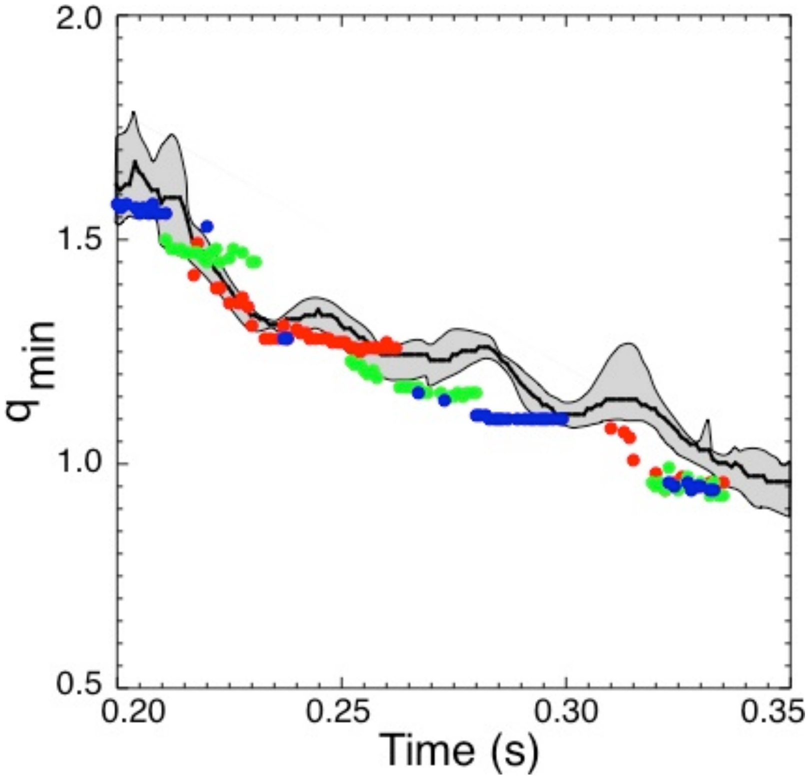
*see TP8.00082, D.S. Darrow; †see CO3.00007, E.D. Fredrickson

q_{min} evolution determined from AC spectrum at low β

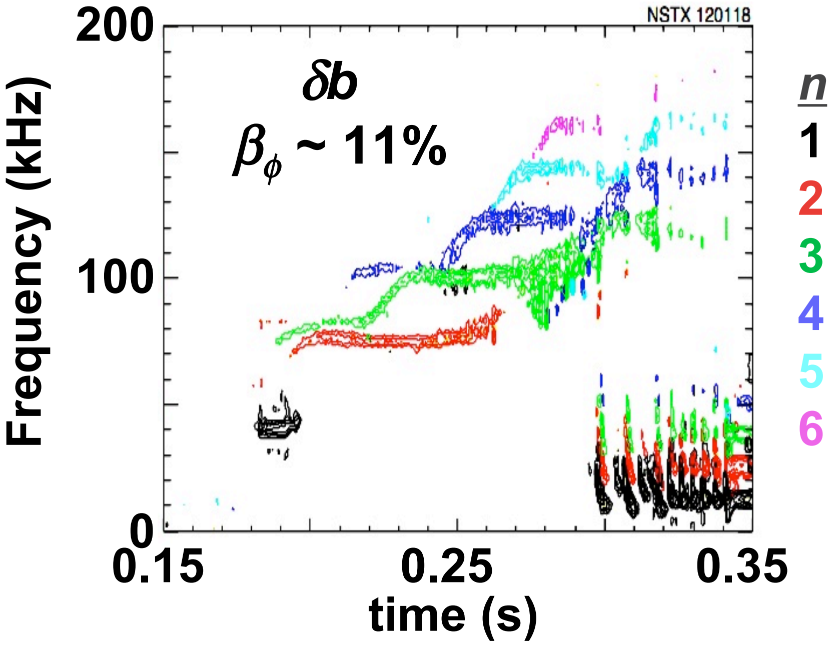
- $q_{min}(t)$ determined from AC mode using low β relation: $\omega = k_{\|} v_A$
  - AC *f* only gives q_{min} sweep – not after conversion to TAE
  - *n* measured, *m* chosen for consistency
- $q_{min}(t)$ determined by MSE
  - Multiple similar shots averaged
- MSE $q_{min}(t)$ consistent with determination from AC modes

For low β:

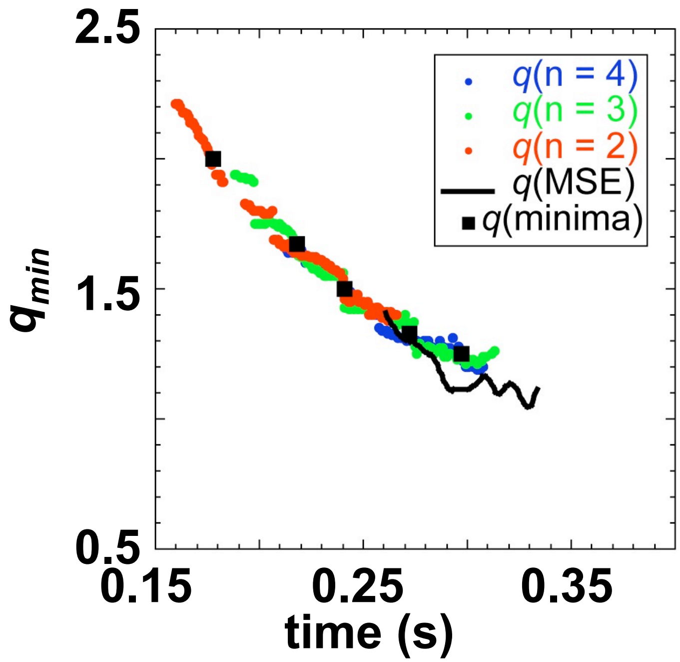
$$q_{min} = mV_{Alfvén}\left(nV_{Alfvén} + R(\omega_{mode}^2 - \omega_{min}^2)^{1/2}\right)^{-1}$$



MHD spectroscopy works even at high β – q_{min} determined from AC spectrum



$$q_{min} = mV_{Alfvén}\left(nV_{Alfvén} + R(\omega_{mode}^2 - \omega_{min}^2)^{1/2}\right)^{-1}$$



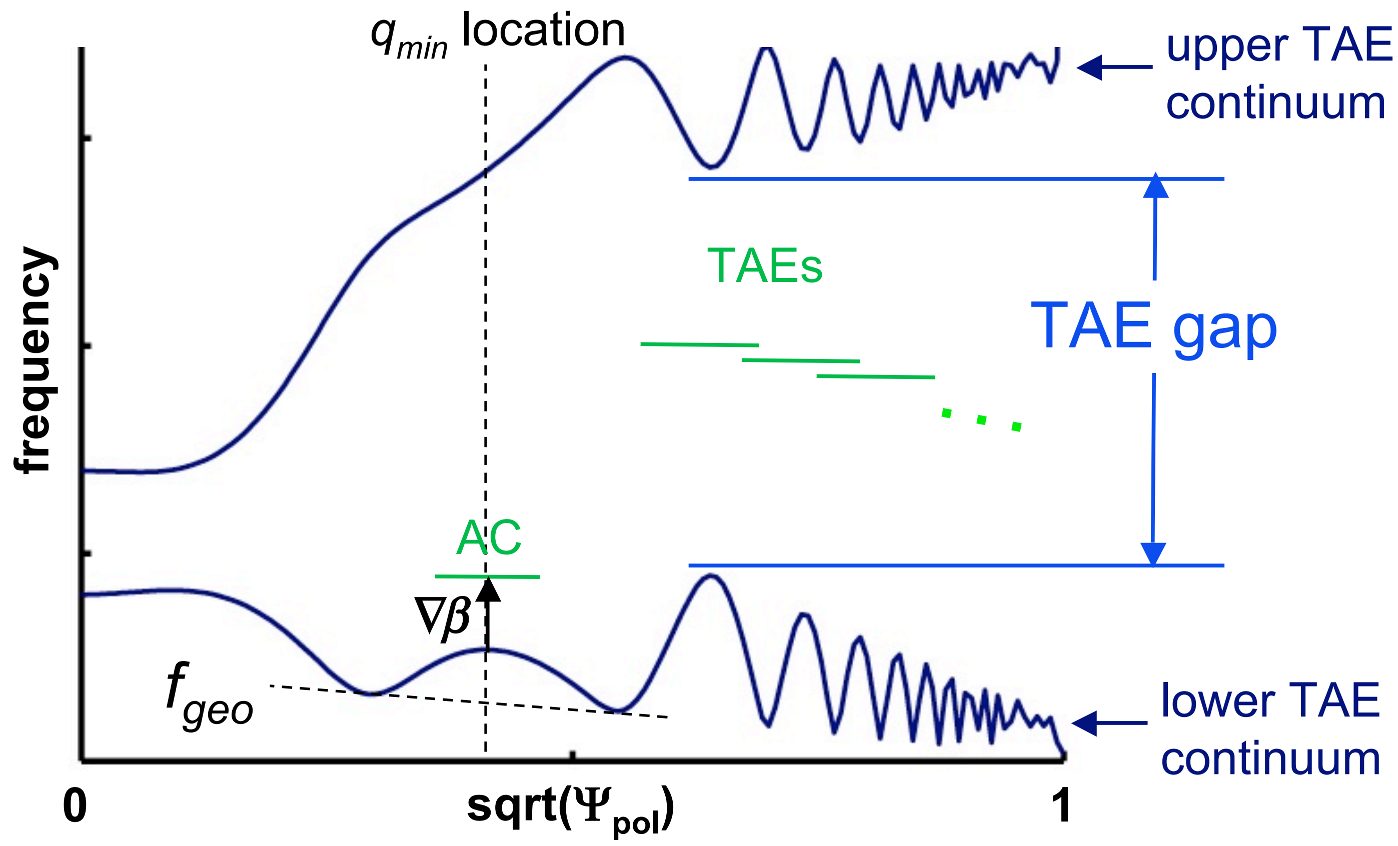
- **$q_{min}(t)$ inferred from AC spectrum**
  - **n measured, m chosen: (m,n) = (5,2), (4,2)&(2,1), (5,3), (3,2), (4,3), (5,4)**
  - **ω_{min} from observation**
  - **Doppler correction from rotation near q_{min}, R ~ 1.25 m**
- **Inferred $q_{min}(t)$ consistent with q_{min} from MSE in similar shot**

NOVA-K* code explores high β AC physics

- **Linear, ideal MHD, hybrid/kinetic code.**
- **Computes Alfvén eigenmode (AE) structure, frequency, growth**
  - **fast ion treated perturbatively**
  - **“Chu” filtering scheme† eliminates acoustic singularities**
  - **geodesic curvature, β effects included**
- **Success demonstrated at predicting mode structure and frequency at low β and low ε**
  - **AC, TAE modes in DIII-D (Van Zeeland'06 APS), JET (Kramer'05 APS), TAE/GAEs in NSTX (Gorelenkov'03 APS)**

*C. Z. Cheng et al, Phys. Reports (A Review Sec. of Phys. Letters.), **211**, 1 (1992)
†M. S. Chu et al., Phys. Fluids B **4**, 3713 (1992)

NOVA-K calculates local shear Alfvén frequency (a.k.a. “Alfvén continuum”*)

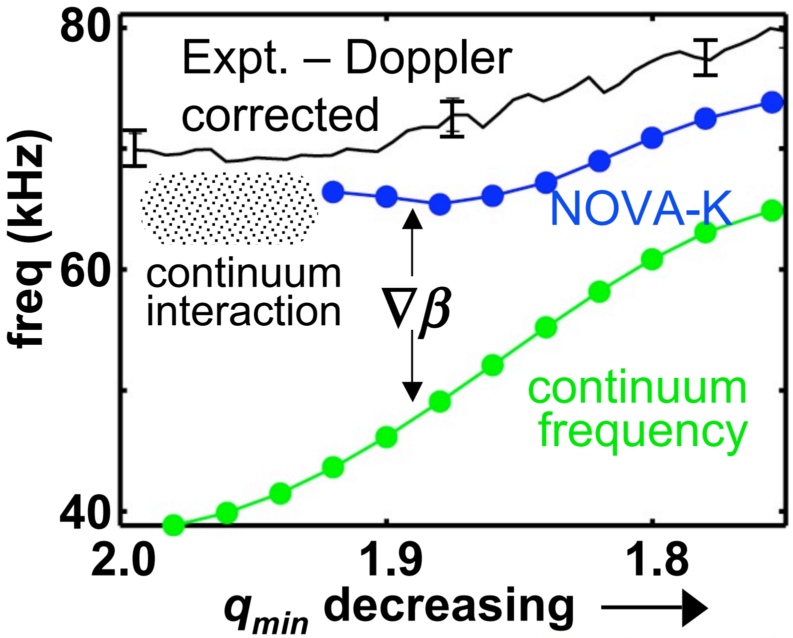


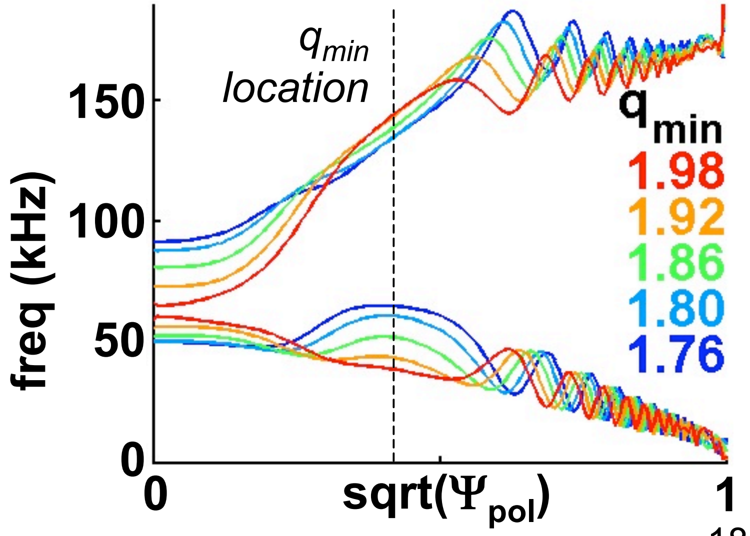
- **Toroidal coupling of poloidal harmonics opens “TAE gap” ⇒ TAEs live in gap**
- **AC mode lives above continuum at q_{min}**

*see XR1.00001, W.W. Heidbrink

NOVA-K AC frequency is consistent with observed mode frequency

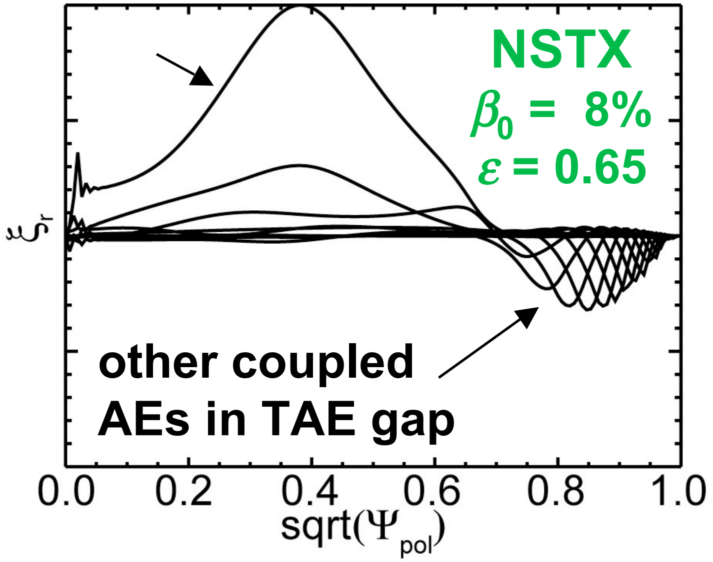
- **AC frequency sweep modeled by offsets to *q* profile**
  - **experimental *q* and *p* profiles used**
- **NOVA-K and experimental frequency consistent**
  - **q_{min} assumed linear with time**
  - **Doppler shift: v_ϕ at q_{min} (valid?)**
  - **statistical error bars: Doppler + mode Δf**
  - **error neglects strong v_ϕ' ~ 0.5 kHz/cm**
- **NOVA-K frequency significantly above continuum - $\nabla\beta$ effect**
- **continuum interaction near q_{min} ~ 2 ⇒ NOVA-K frequency uncertain**

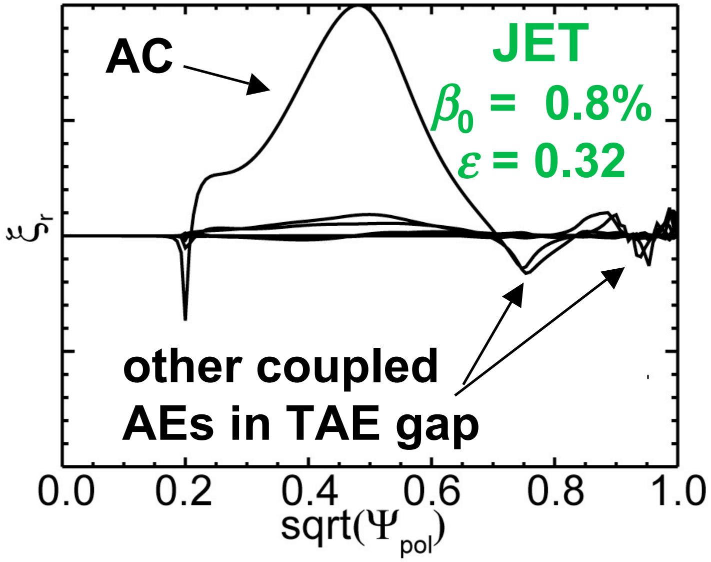




AC modes couple to other AEs at high ε and high β

- **AC linearly couples strongly to other AEs in TAE gap***
  - High ε widens gap $\Rightarrow$ many modes in gap
  - High ε and high $\beta \Rightarrow$ stronger poloidal coupling than conventional tokamaks
- **Strong coupling could lead to enhanced transport**
  - multiple fast-ion resonances
  - suppression of ACs desirable
- **Strong coupling enhances edge δB $\Rightarrow$ Mirnov coils see AC modes**
  - Mirnov coils relatively insensitive to ACs in conventional tokamak

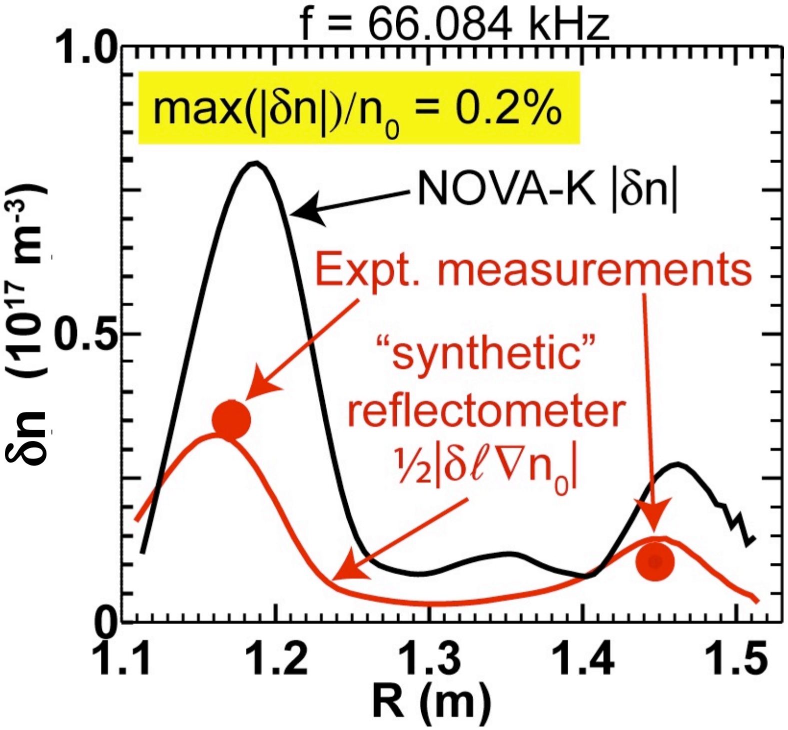




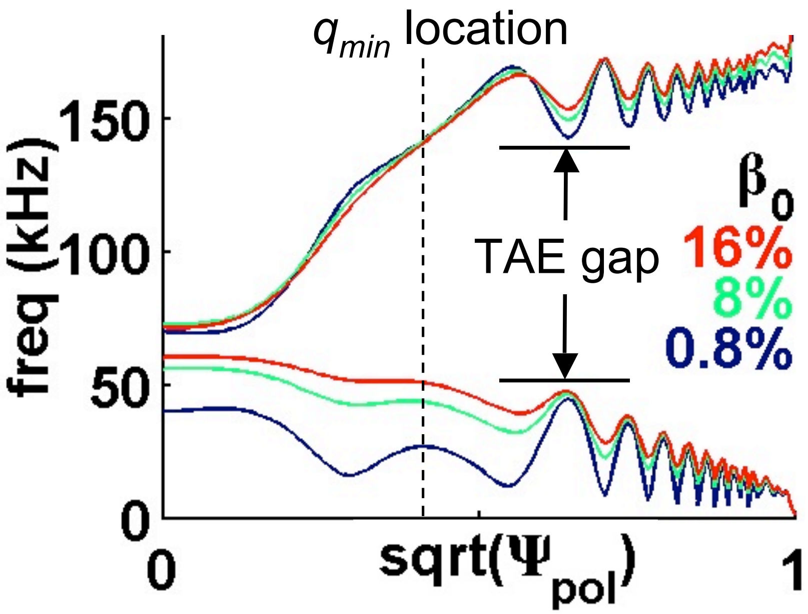
*see also M. A. Van Zeeland et al, Phys. Plasmas **14**, 056102 (2007)

Measured AC fluctuation levels consistent with NOVA-K calculation

- δn measured by 2 fixed frequency reflectometers (O-mode)
  - horns 12 cm above midplane at R = 1.71 m, looking down 5.4°
- "synthetic diagnostic" applied to NOVA-K calculation
  - reflectometer model: 1-D along line of sight
  - normalized for best fit
- Fluctuation levels roughly agree
  - relative phase of measurement doesn't fit
    - Modeling is rough- e.g. no refraction, 2-D effects
    - Physics missing in NOVA-K: kinetic effects, rotation, up-down asymmetry



Increasing β promotes AC mode coupling of to edge AEs



- β **scan performed by rescaling pressure**
    - **Using experimental *p* and *q* profiles**

- **Increasing β elevates continuum near q_{min} raises AC frequency into TAE gap**

- **Elevation into TAE gap ⇒ coupling with edge AEs**

Conclusions

- **AC modes identified in low and high β NSTX plasmas**
  - **AC frequency sweep reduction with increasing β suggests ACs may not be recognized at sufficiently high β**
  - **ACs not observed at *very high* β (i.e. normal NSTX β)**
  - **AC modes can cause fast-ion loss**
- **MHD spectroscopy works even at high β**
- **AC modes observed at high β consistent with theory and NOVA-K calculation**
  - **Changes in AC spectrum with increasing β consistent with theoretical β and $\nabla\beta$ effects**
  - **Observed structure and frequency consistent with NOVA-K calculation**
- **Ideal MHD modeling (NOVA-K) of ACs at high β and high ε indicates:**
  - **$\nabla\beta$ contributes significantly to frequency sweep reduction at high β**
  - **strong coupling to edge AEs $\Rightarrow$ possible enhanced fast-ion transport**

Future work

- **Detailed study of fast-ion transport cause by AC modes**
- **More detailed structure measurements – compare with NOVA-K calculation**
  - **Use all reflectometers**
  - **Use interferometry, soft x-rays**
- **Explore $\nabla\beta$ dependence of AC modes**
  - **H-mode vs. L-mode**
- **Explore species contributions to geodesic coupling of ACs (i.e. to specific heat, γ)**
- **Determine conditions for suppression vs. lack of recognition (i.e. severe sweep reduction)**

See also …

- **NSTX Poster (TP8) and Oral (CO3) sessions**

- **Assorted Fast-ion and AE presentations…**
  - **XR1.00001: Instabilities Driven by Energetic Particles in Magnetized Plasmas**
  - **CO3.00007: Toroidal Alfvén Eigenmode Avalanches on the National Spherical Torus Experiment**
  - **TP8.00083: Neutral Particle Analyzer Vertically Scanning Measurements of MHD-induced Fast Ion Redistribution or Loss in NSTX**
  - **TP8.00087: Development of a Fast-Ion D-Alpha diagnostic for NSTX**
  - **TP8.00085: Excitation of Beta-induced Alfvén-acoustic eigenmodes and q-profile MHD spectroscopy in NSTX**
  - **TP8.00082: MHD Induced Neutral Beam Ion Loss from NSTX**
  - **TP8.00073: Beam Modulation Effects on NSTX Ion Power Balance**
  - **TO4.00003: Reversed shear Alfvén Eigenmodes in the frequency range of the triangularity induced gap on JET**
  - **NP8.00094: Mode structure and stability analysis of reversed shear Alfvén eigenmodes with NOVA-K**
  - **JP8.00088: Central Flattening of the Fast-Ion Profile in Reversed-Shear Discharges With Alfvén Eigenmode Activity**

- **NSTX Research Forum, Nov. 27-29, 2007 (nstx-forum-2008.pppl.gov)**