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Modeling Fast Ion Losses During TAE Avalanches on NSTX

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E. D. Fredrickson, N. A. Crocker[1], M. Podesta[2], D. Darrow, N. N. Gorelenkov, G. J. Kramer, S. Kubota[1], F. M. Levinton[3], D. Liu[2], S. S. Medley, R. B. White, H. Yuh[3], R. E. Bell

and the NSTX Team

PPPL, Princeton University, Princeton, NJ
[1]UCLA, Los Angeles, CA
[2]UCI, Irvine, CA
[3]Nova Photonics, Princeton, NJ

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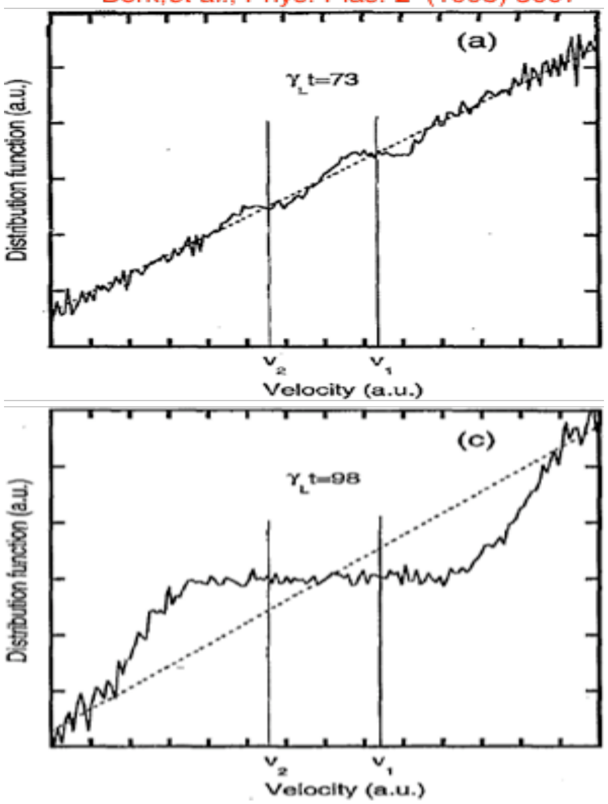
Validated Models of Fast Ion Redistribution are Needed for Design of Next Generation Devices

- Next step devices (ITER, NHTX, ST-CTF, etc) will have large, super-Alfvénic fast ion populations which may excite instabilities (energetic particle modes, Alfvén modes).
- Fast-ion driven instabilities cause diffusion and loss of fast ions, increasing ignition thresholds.
- Transient fast-ion losses can damage PFCs.
- Fast-ion redistribution affects beam-driven current profiles in AT operating regimes.
- Small ρ^* means transport is more likely through interaction of multiple modes.
- Understanding non-linear collective behavior is key to predictions for ITER.

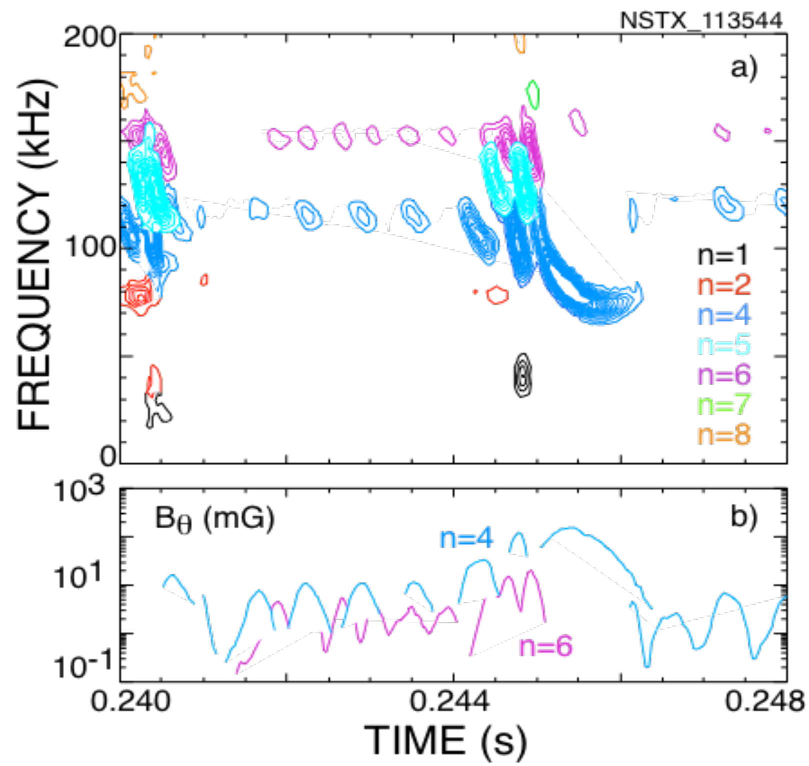
Multi-mode interaction of Toroidal Alfvén Eignmodes can greatly enhance fast ion transport

NSTX

Berk, *et al.*, Phys. Plas. **2** (1995) 3007



- Large amplitude modes overlap in fast-ion phase-space.
- Interaction results in new modes, stronger drive.
- More free energy accessed, more transport
- TAE have multiple resonances, more complex physics.



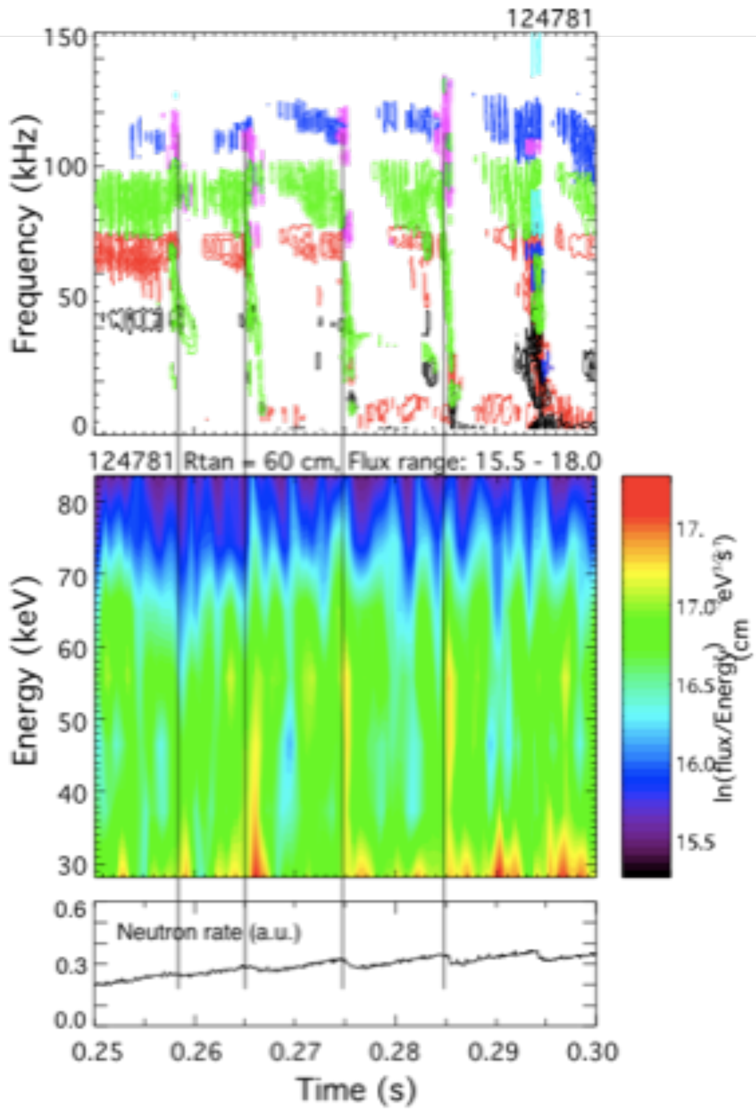
- No correlation of repetitive small bursts; increased amplitude leads to strong burst with multiple modes.

Non-linear physics of Alfvénic and Energetic Particle modes is research priority

- Fast ion transport and losses enhanced by Alfvénic or Energetic Particle modes can:
- Change beam-driven current profiles,
- Raise ignition threshold or damage PFCs on ITER.
- Non-linear physics necessary to understand saturation amplitudes, frequency chirps and fast ion transport.
- NOVA and ORBIT: Non-linear effects simulated by incorporating experimental data such as mode amplitude and frequency evolution, triggering of multiple modes.
- M3D-k: Some non-linear effects described here (enhanced fast ion transport from multiple modes, larger amplitude, frequency chirps) have been studied with M3D-k*.

Multiple, strong TAE bursts occur during NBI heating; identified as avalanches

NSTX



- Neutron drops correlated with D-alpha spikes - fast ions are lost.
- Neutral particle analyzers (NPA) measure spectrum of charge-exchanged neutral ions from plasma.
- Transport appears largest at lower energies.
- Chirping may play important role in fast ion loss.

Mode amplitudes, fast ion losses are measured during Avalanche events

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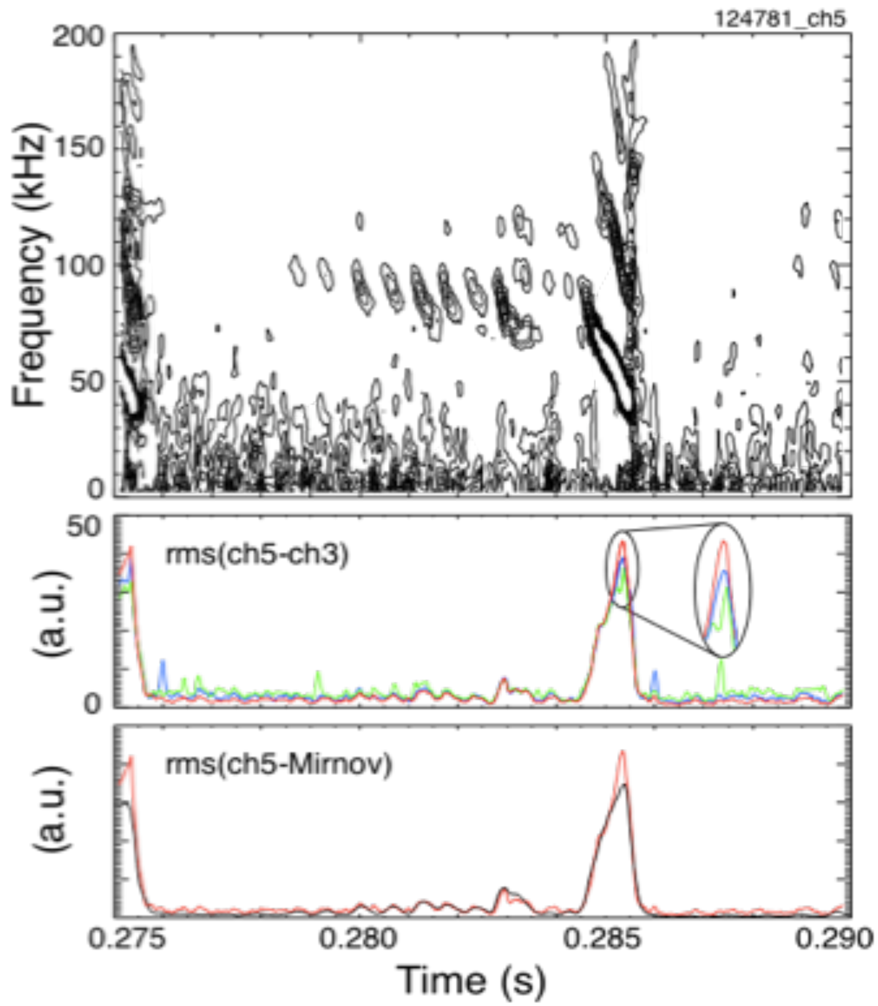
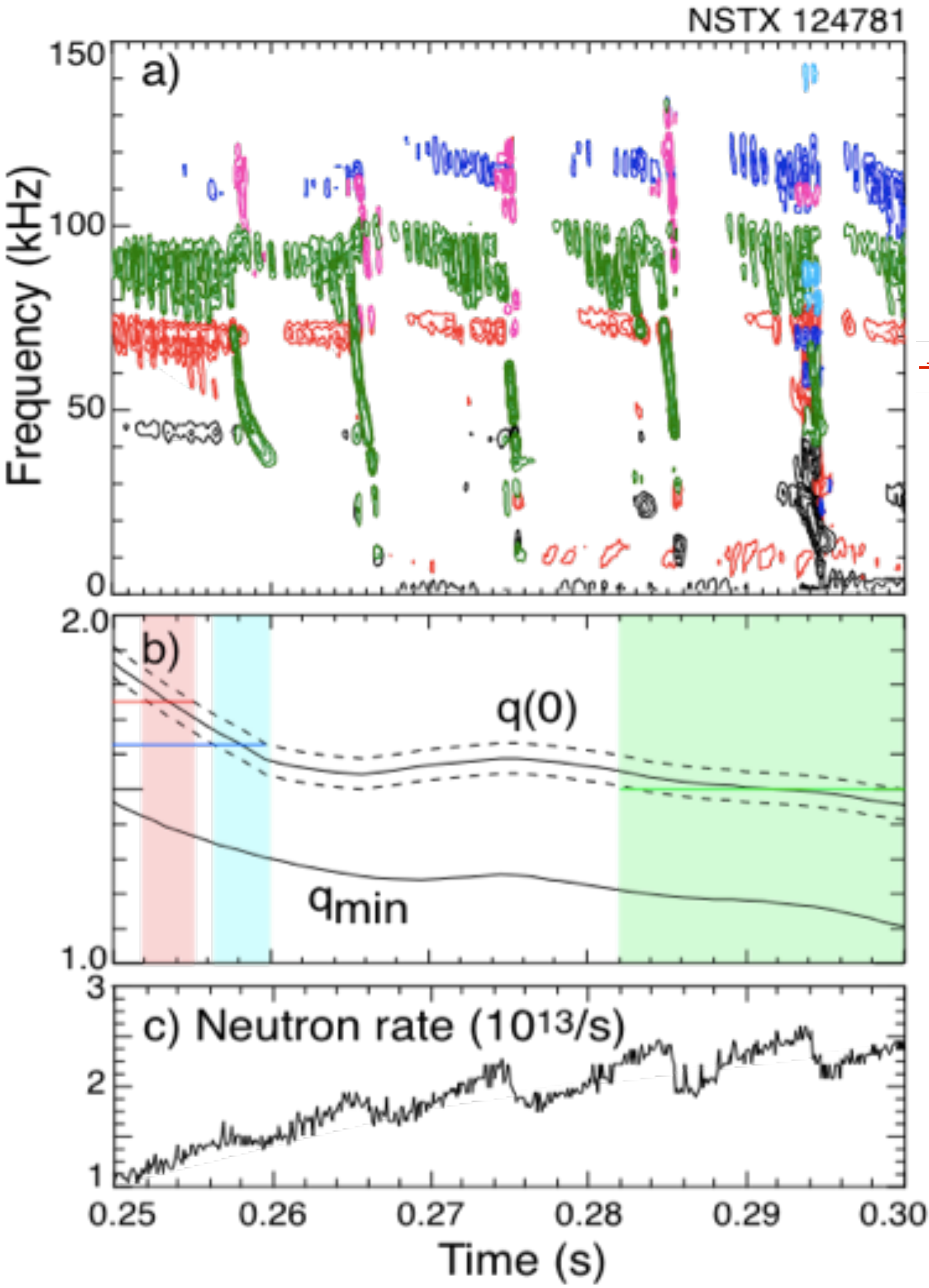
- Avalanches onset with 70 keV beam ions.
- Amplitude at time of avalanche much greater than earlier bursts.
- Relative amplitude tracks well through multiple modes, suggesting fixed mode structure...
- …except toward end of last burst, which suggests mode is becoming more core-localized.

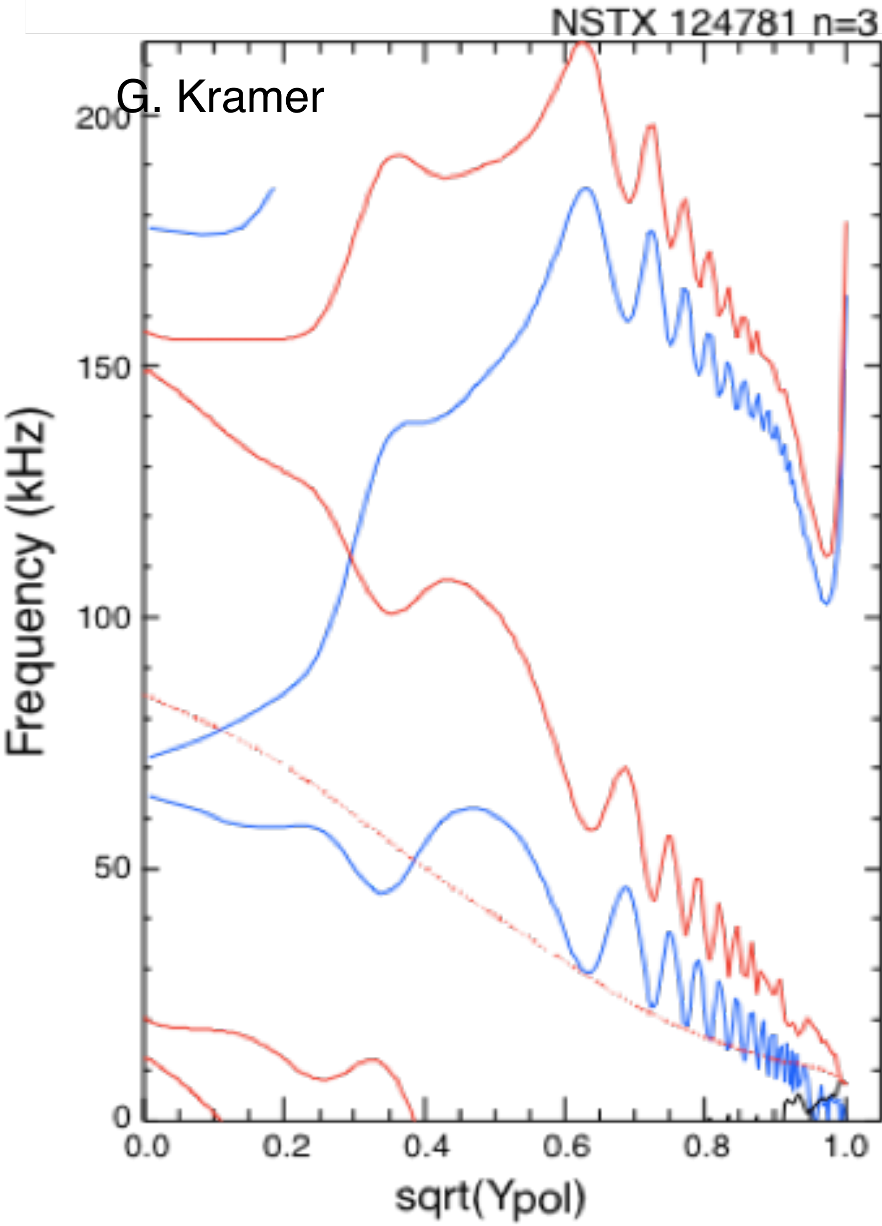




TAE Gaps Open/Close on Axis for "Small", $\delta q \approx 1/2n$, Changes

- Gaps for n=2, 3 and 4 modes open and close during q-profile evolution (without rotation shear!).
- Shaded regions show times when gaps are closed, modes should be weaker.
- Amplitude of n=4 consistent with gap evolution, n=2 and n=3 seem unaffected by gap closing.

Sheared rotation distorts TAE continuum



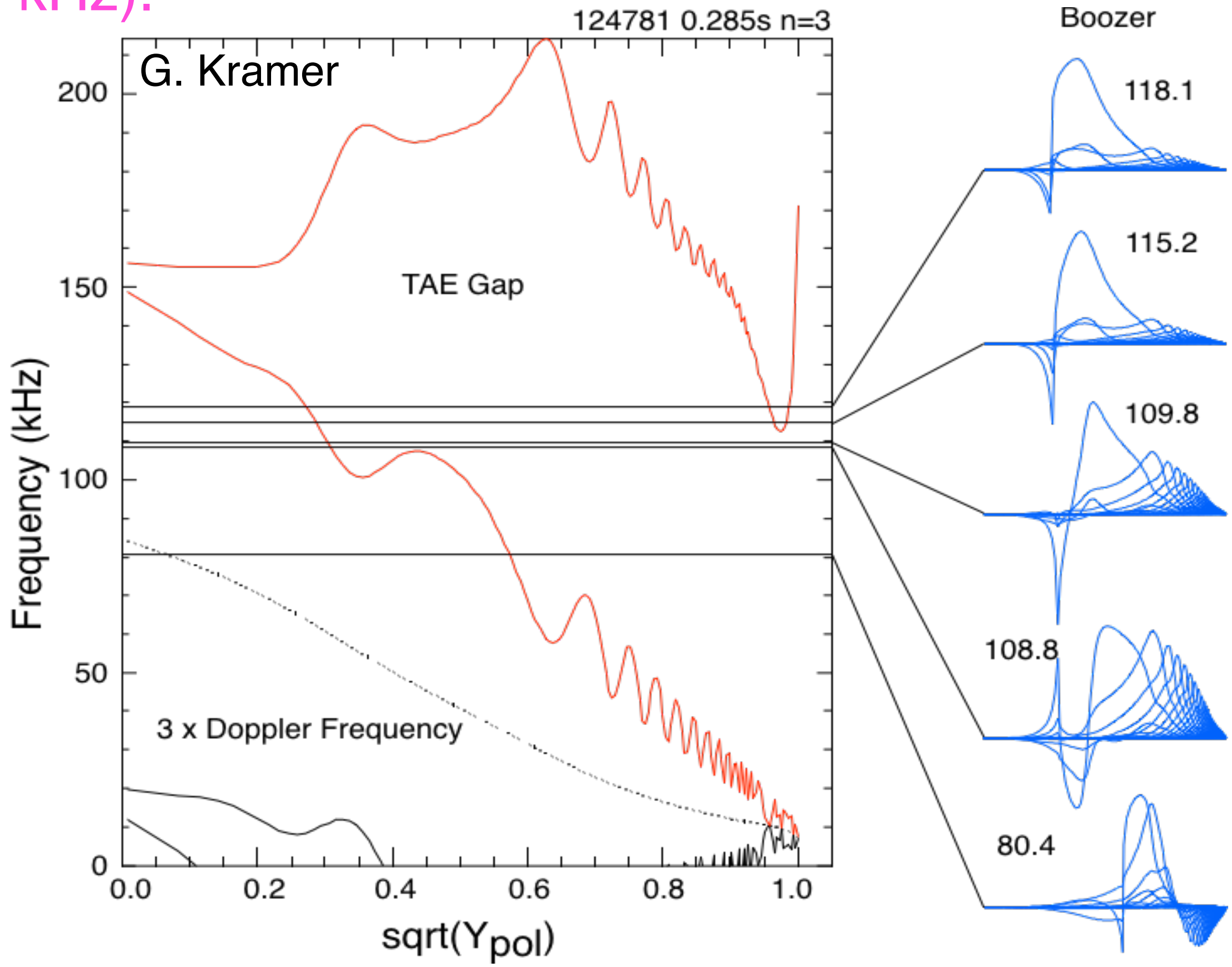
- Blue curves show n=3 Alfvén continuum neglecting sheared rotation.
- Solid red lines show continuum including rotation shear effects.
- Dashed red curve Doppler frequency for n=3 mode.
- Gap closed by rotation shear is insensitive to evolution of q(0).

NOVA typically finds multiple eigenmodes

- Five eigenmodes are shown to right of continuum figure including two degenerate modes caused by numerical interactions with the continuum (115.2, 118.1 kHz).

- Presently, choice of eigenmodes must be empirical, stability calculations unreliable.

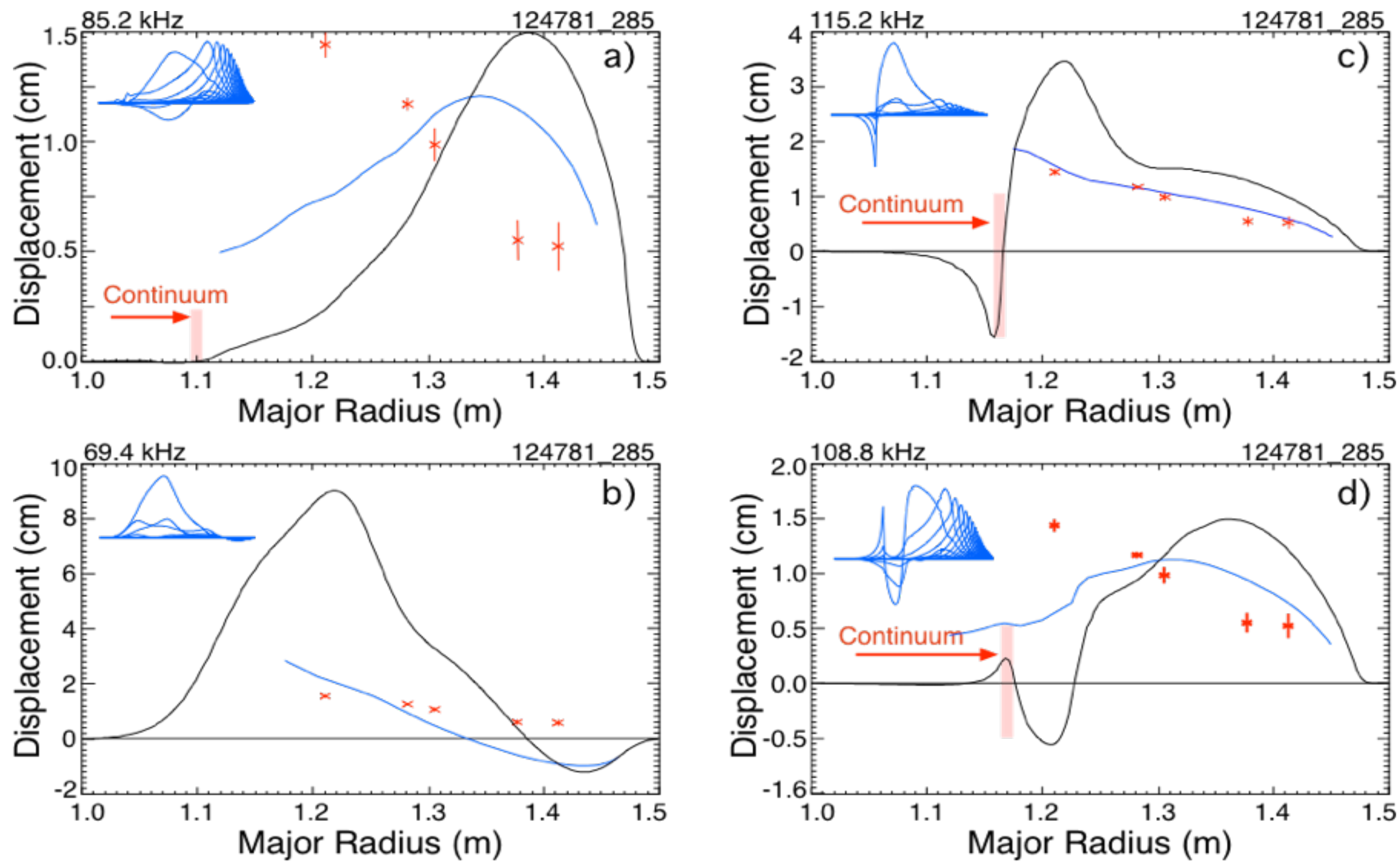
- Measured mode structures are used to select NOVA eigenmodes used in ORBIT simulations.



NOVA Eigenmodes with Doppler correction are better fit

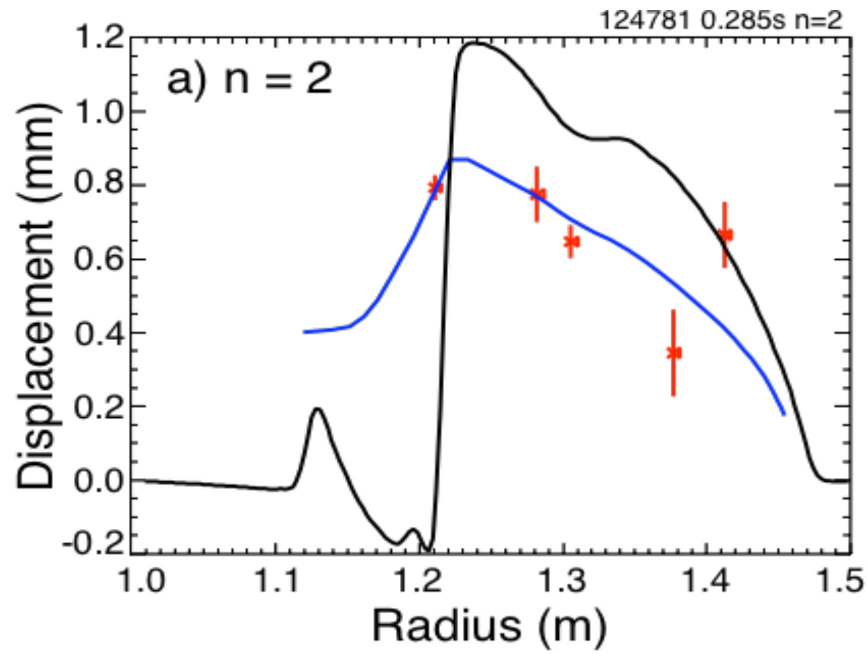
- No modes with good fit were found in non-sheared case.
- With shear, good fit was found to data.

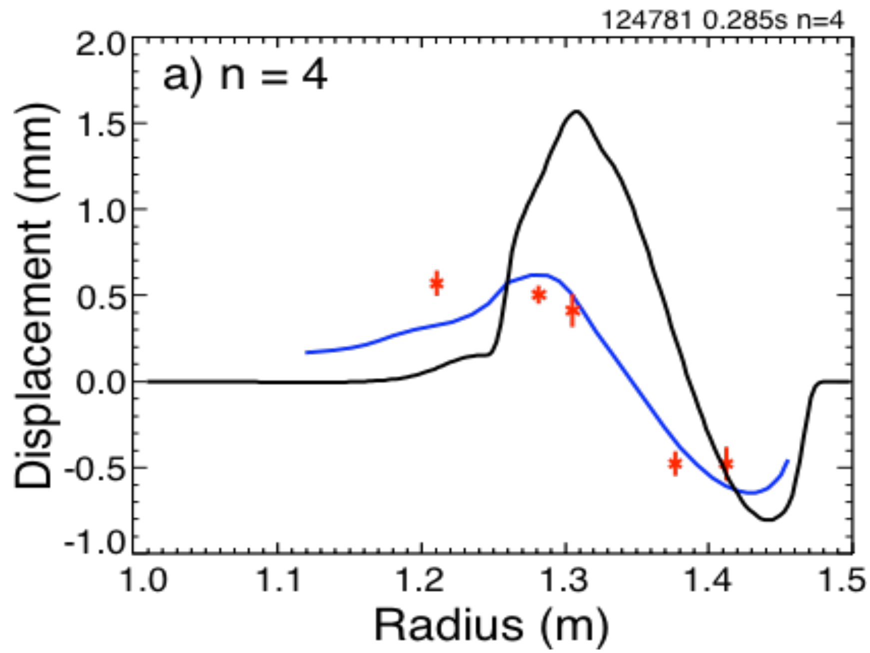
No Shear Correction | Doppler-corrected



Good fits for n=2 and n=3 modes

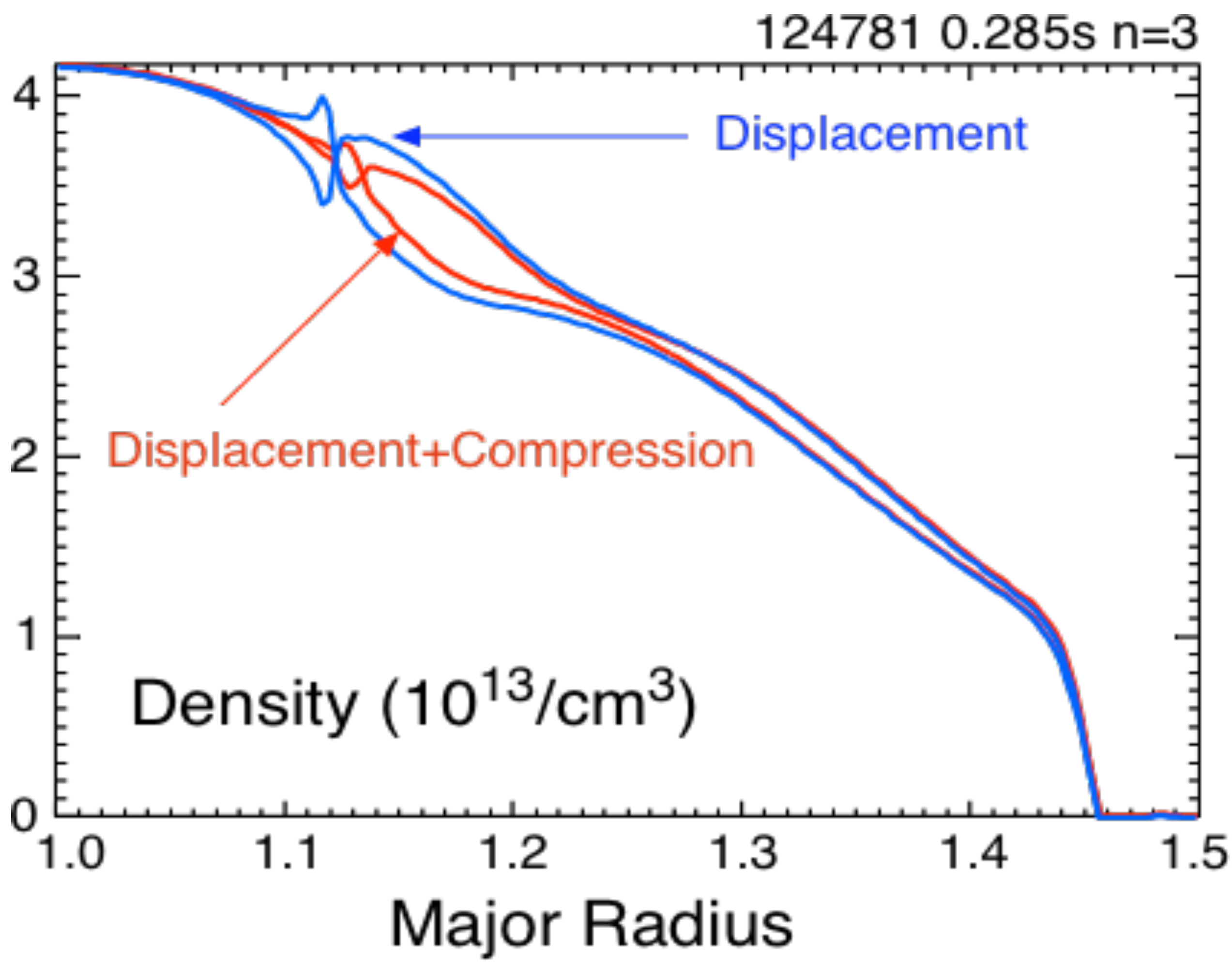
- Signal-to-noise not so good towards plasma edge for these weaker modes.
- The n=4 mode probably does have phase inversion; consistent with NOVA simulation.
- These NOVA eigenmodes used in ORBIT simulations.





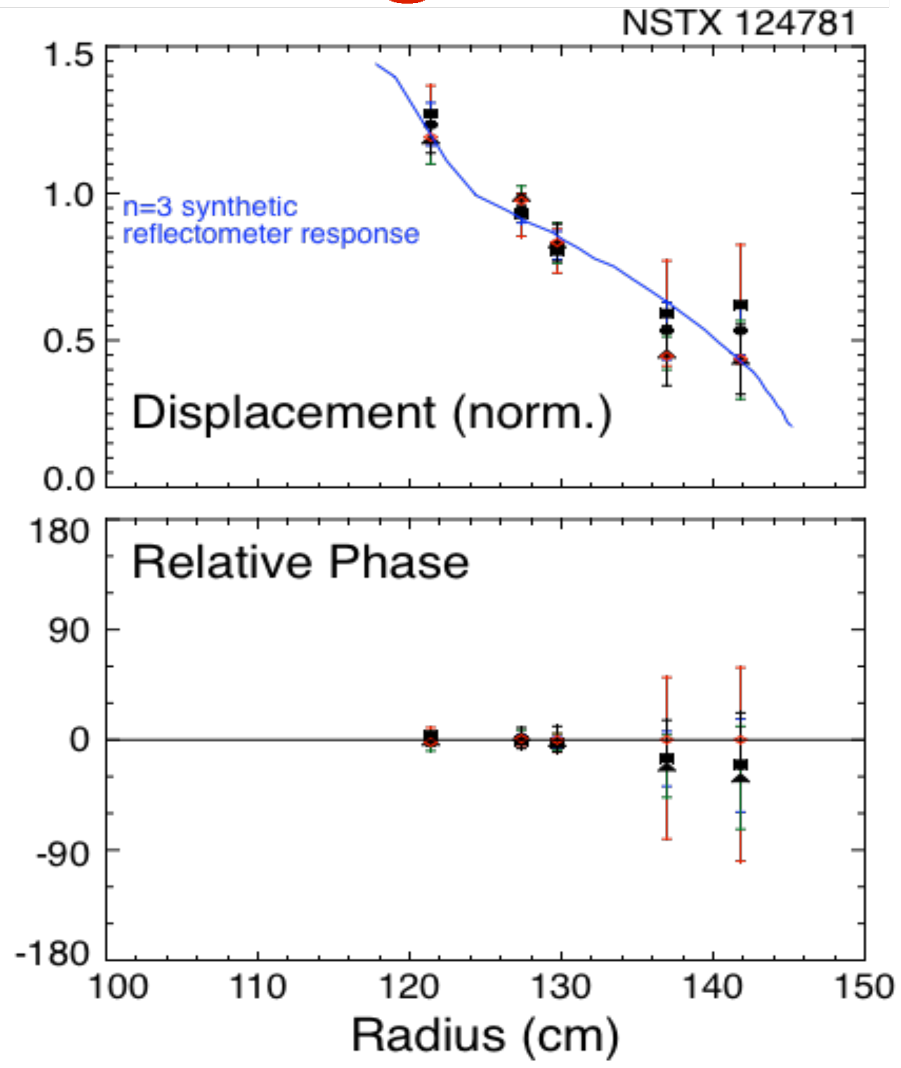
Density fluctuations are large

- Blue curve show density perturbation with only displacement, red curve shows perturbation with both displacement and compression.
- Should be measureable with Thomson Scattering.
- Difficult to imagine larger modes…



Shape of Mode Similar in Small Bursts and Large Amplitude Chirps

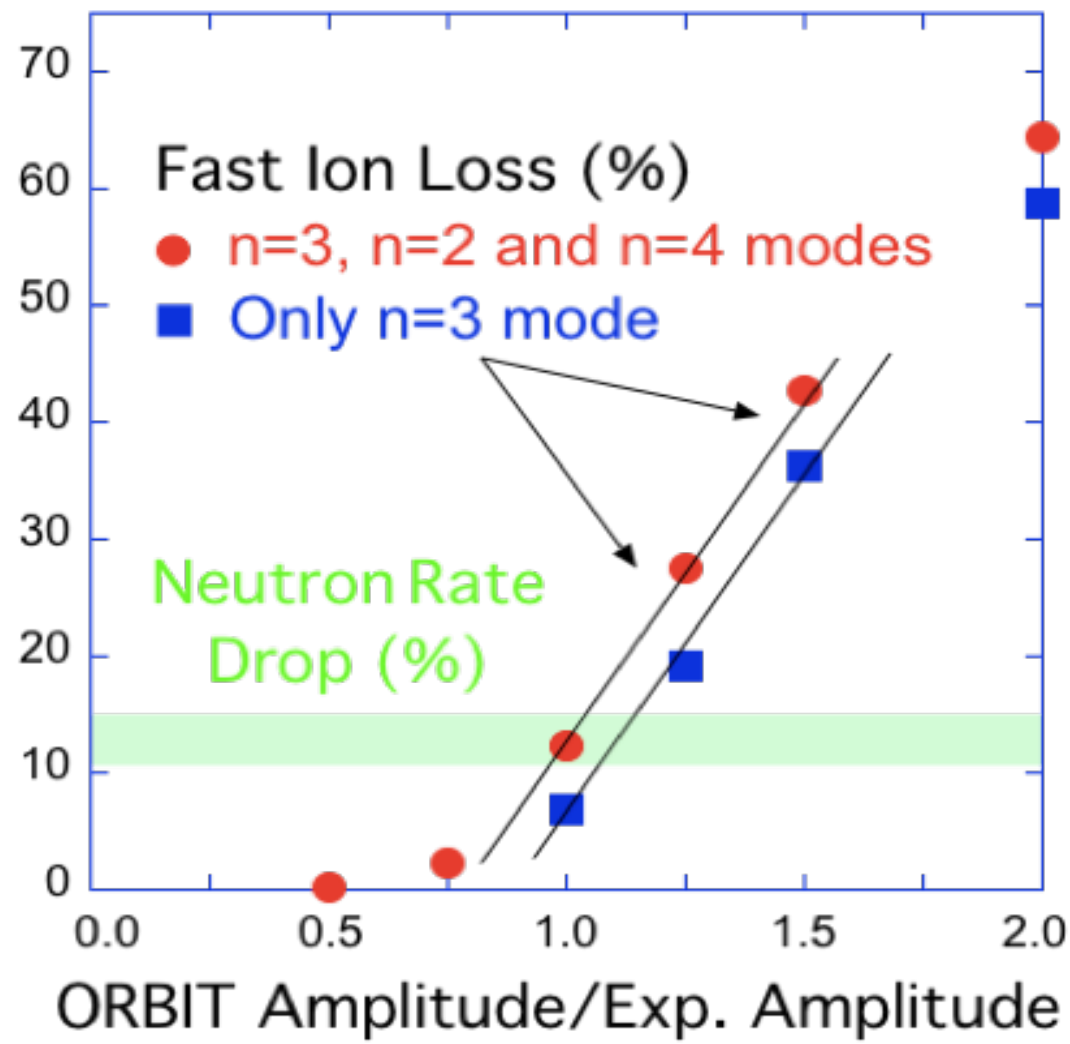
- Peak amplitude of n=3 burst in Avalanche event is ≈ 10 times larger than amplitude of pre-avalanche bursts.
- Mode structure appears similar; possibly less centrally peaked?
- Important to understand the limitations of using linear eigenmodes to simulate non-linear problem of fast ion transport in the avalanche.



ORBIT simulations predict losses in good agreement with observed neutron rate drop

NSTX

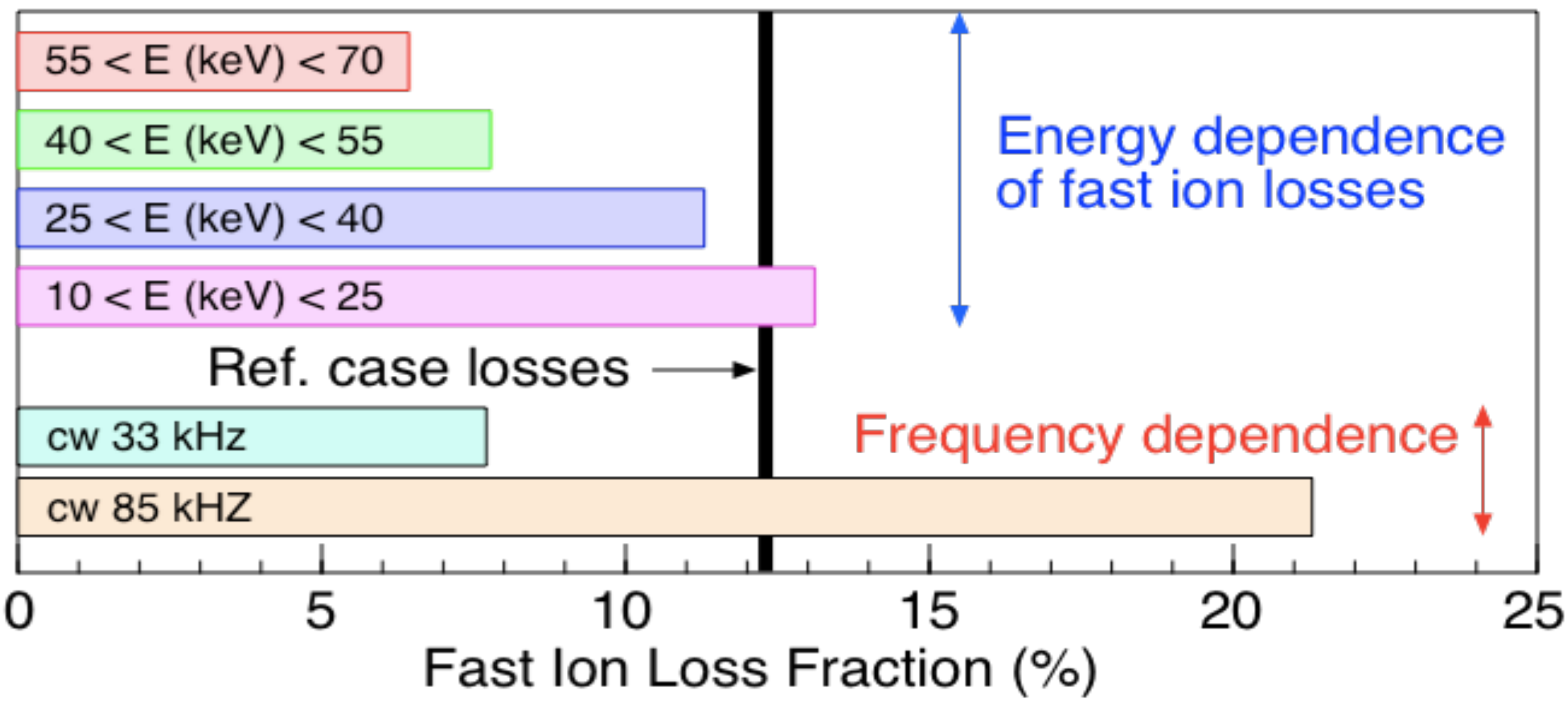
- ORBIT simulation is done for 1ms burst at 0.285s.
- Mode amplitude, frequency evolution in ORBIT are from experimental measurements.
- Mode structure from NOVA.
- Initial fast ion distribution is from unperturbed TRANSP calculation – not necessarily self-consistent.
- Losses are strongly non-linear with mode amplitude – as expected for avalanche.



Energy dependence and frequency dependence of losses also investigated

NSTX

- Losses seen at all energies, consistent with NPA measurements, but more at low energy; important for beam-driven current calculations..
- Fast ion losses larger at higher frequencies; need to add sheared rotation to ORBIT simulations.

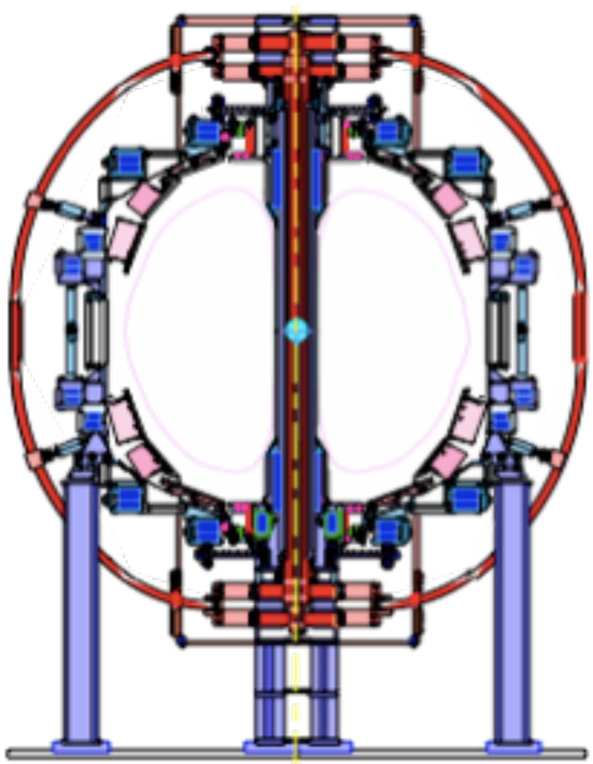


TAE bursts identified as avalanches based on NOVA and ORBIT simulations

- Magnitude of losses roughly consistent with ORBIT simulations.
- Plasma equilibrium reconstructed using MSE data; these avalanches are in reversed-shear plasma.
- Avalanches have 1) long, low amplitude period followed by strong increase in amplitude, 2) large, downward frequency chirp and 3) multiple modes.
- Mode radial structure measured with 5-channel reflectometer.
- Fast-ion loss indicated by neutron drops (D_{α} bursts) and redistribution measured with NPA.
- Fast-ions losses are seen down to 30 keV (< half of full beam energy).
- Mode structure shows small changes during 1 ms frequency chirp.
- NOVA simulations find reasonably good agreement in mode structure and eigenmode frequency (pre-chirp).
- Fast-ion losses are being simulated using measured mode amplitudes to scale NOVA eigenfunctions.
- ORBIT finds strong frequency dependence of losses
  - Sheared rotation may be important, but not included in present simulations
- ORBIT predicts stronger losses at lower energy, consistent with V_{fast} being closer to $V_{Alfvén}$.

NSTX has low field, high density and current; perfect for study of fast ion-driven modes

- Low field, high density $V_{Alfvén} \approx 0.5 - 2.7 \times 10^6$ m/s.
- Beam injection energy 60 - 100 kV, Vfast $\approx 2.6 - 3.1 \times 10^6$ m/s
- Reactors would have higher field, fusion α's and $V_{fast}/V_{Alfvén} > 1$



$R_0 = 0.86$ m

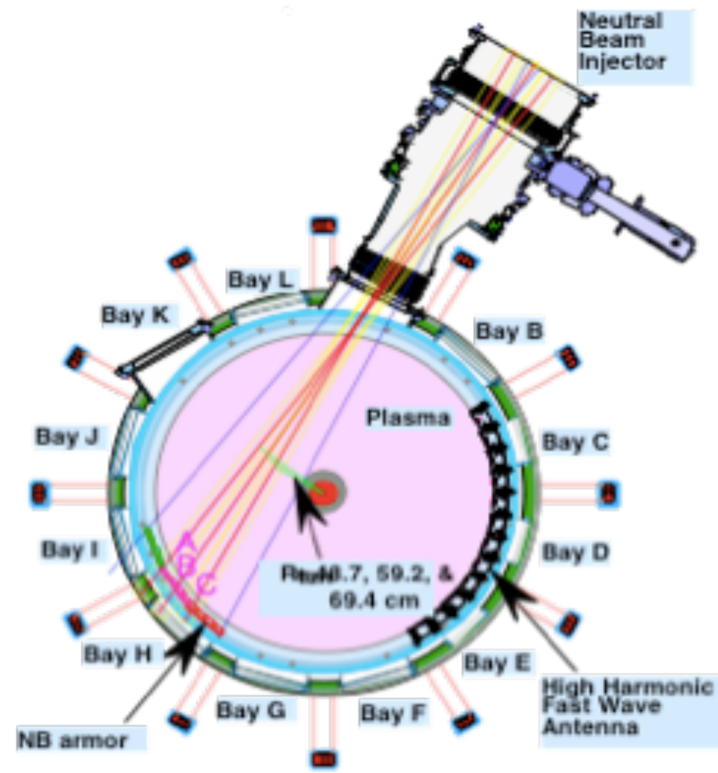
$a = 0.68$ m

$B_0 = 0.3\text{-}0.55$ T

$I_p \leq 1.2$ MA

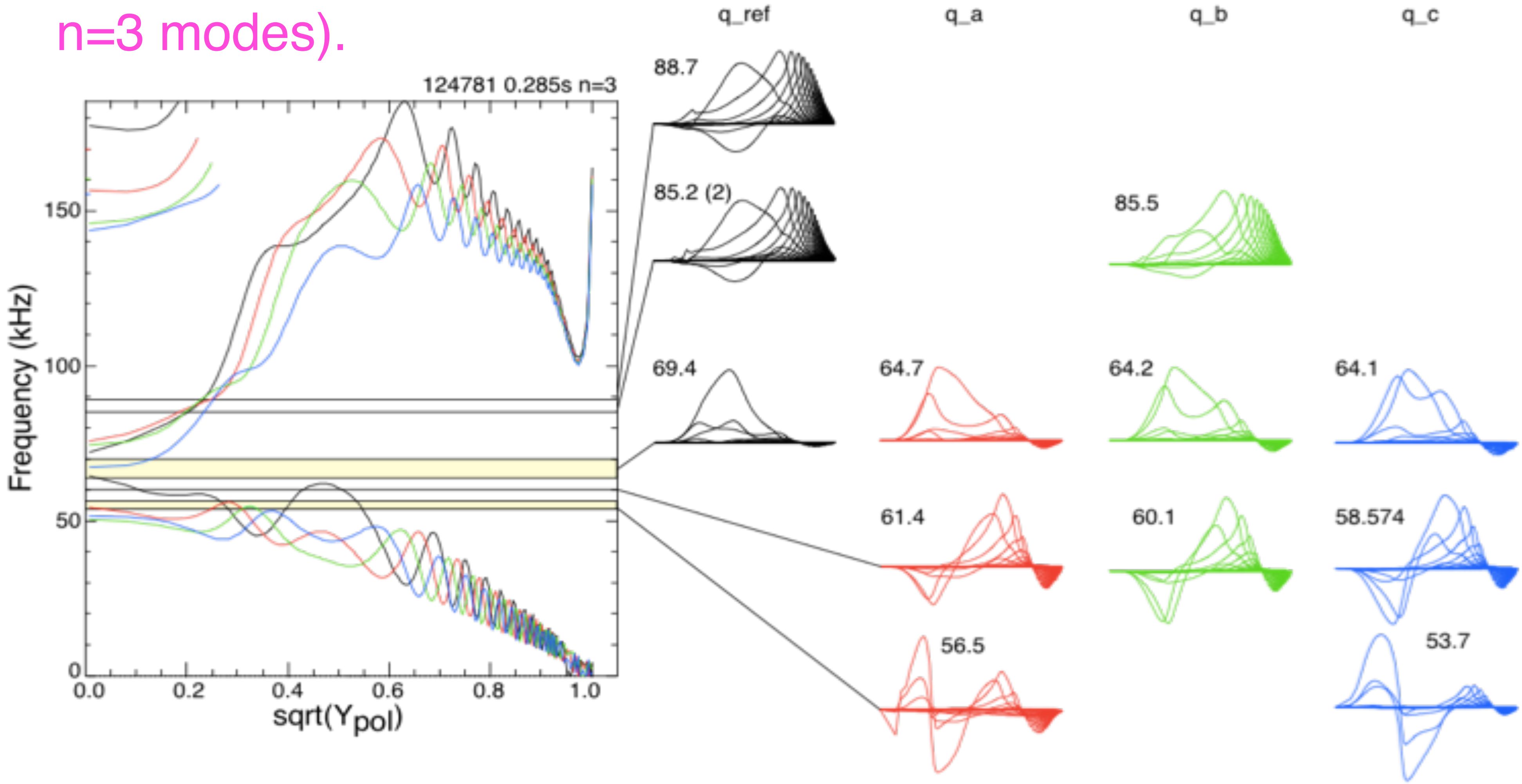
$\beta_{tor} \leq 40\%$

$n_e \leq 10 \times 10^{19}/m^3$



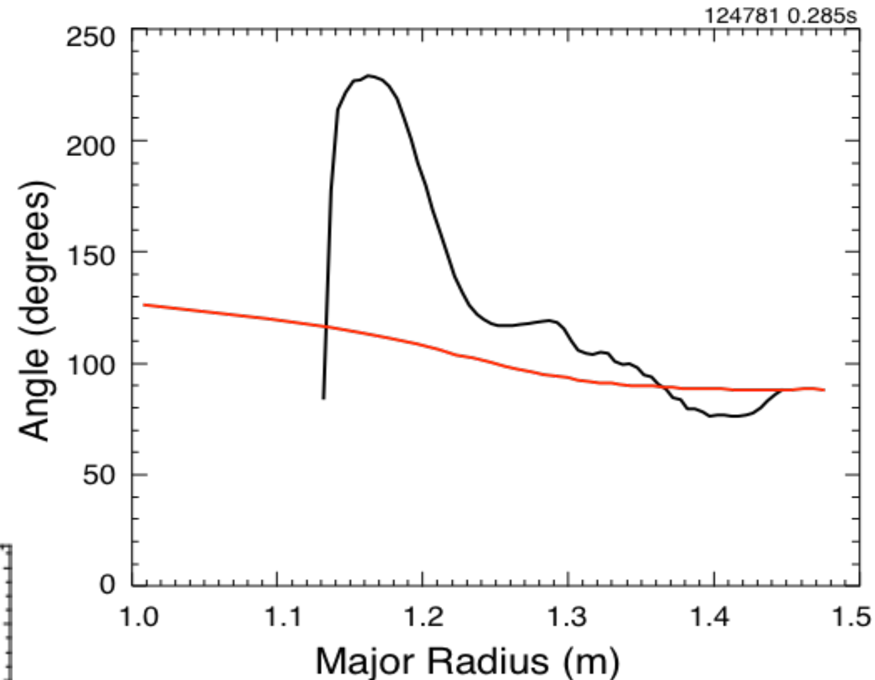
TAE Gaps Open/Close on Axis

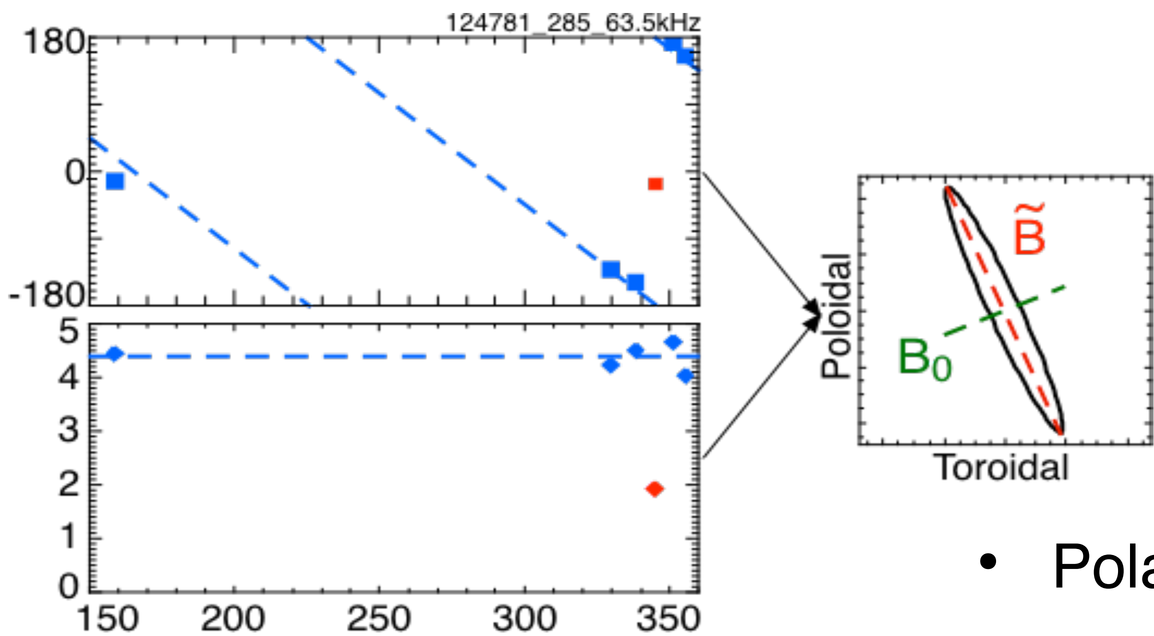
- NOVA predicts that modes come and go depending on continuum shapes (except for mode in open gap, see below for n=3 modes).



TAE have compressional components

- Within uncertainty, phase/amplitude relation of poloidal and toroidal fluctuations consistent with expected shear-type Alfvén mode.

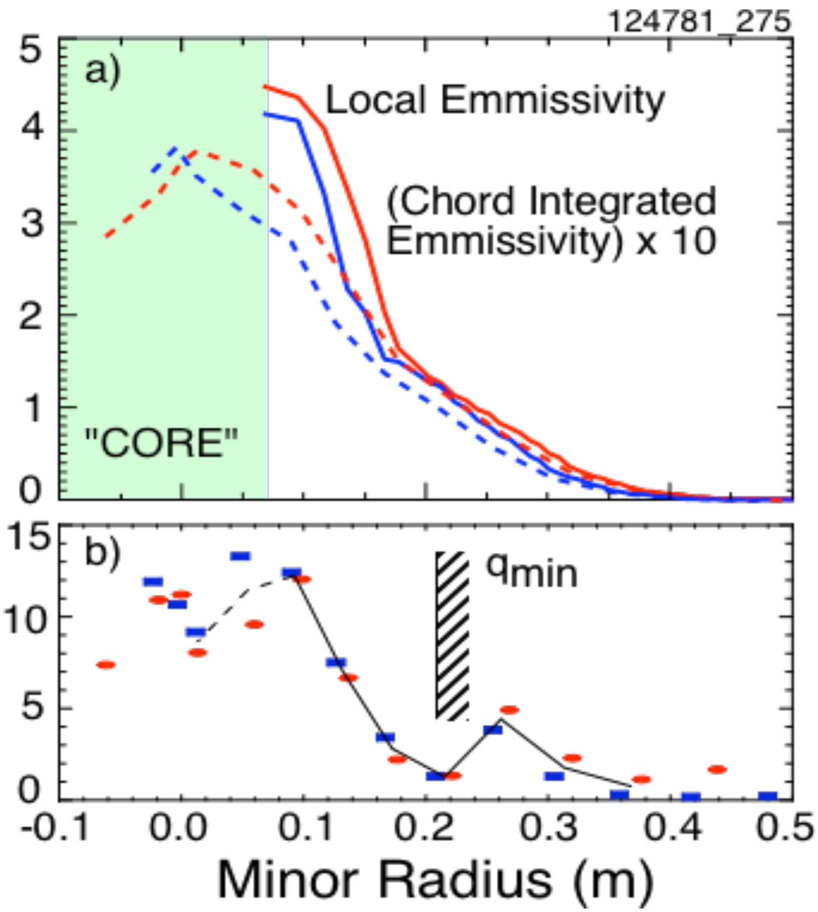


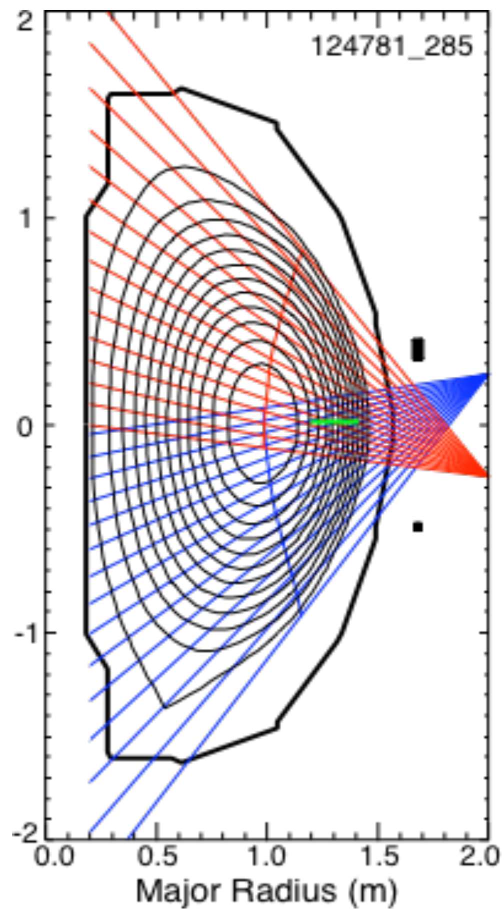


- Polarization in θ-ϕ plane measured with Mirnov coil array.

Soft x-ray camera data indicates strong fluctuations in core

NSTX





- Soft x-ray cameras also measure mode internal structure and amplitude.
- Soft x-ray response not yet simulated fo NOVA eigenmoes.