Modeling Fast Ion Transport in TAE Avalanches in NSTX*

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

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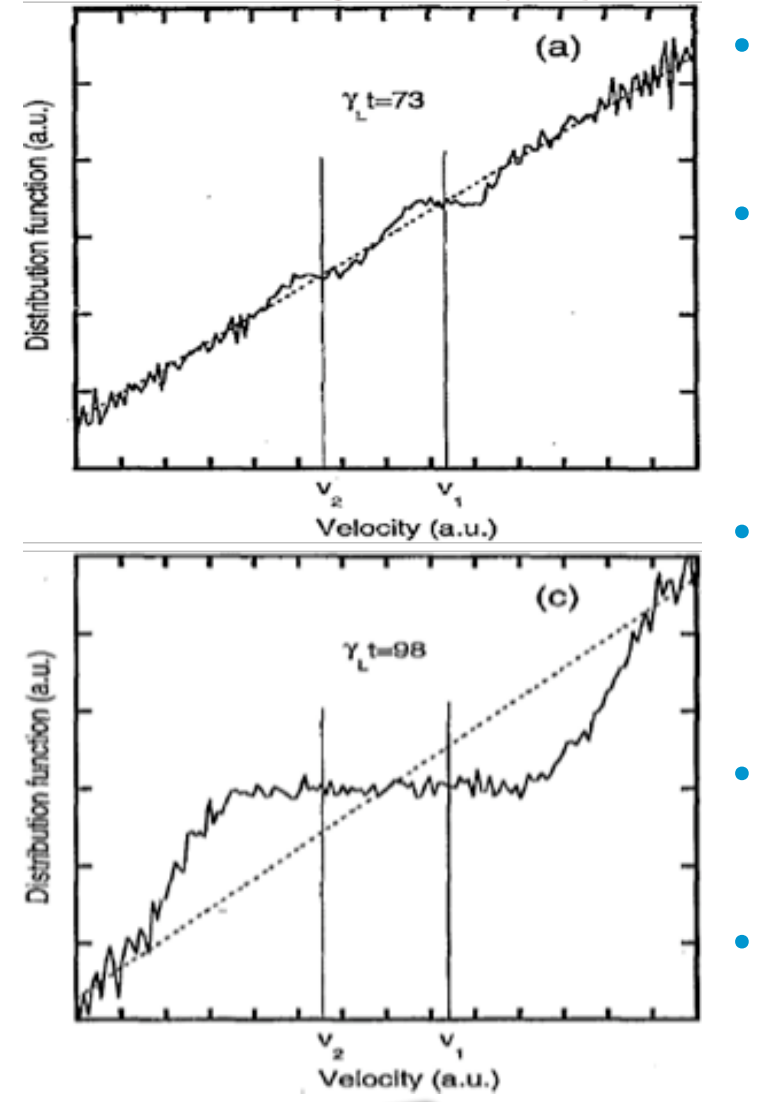
Validated Models of Fast Ion Redistribution are Needed for Design of Next Generation Devices

- 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

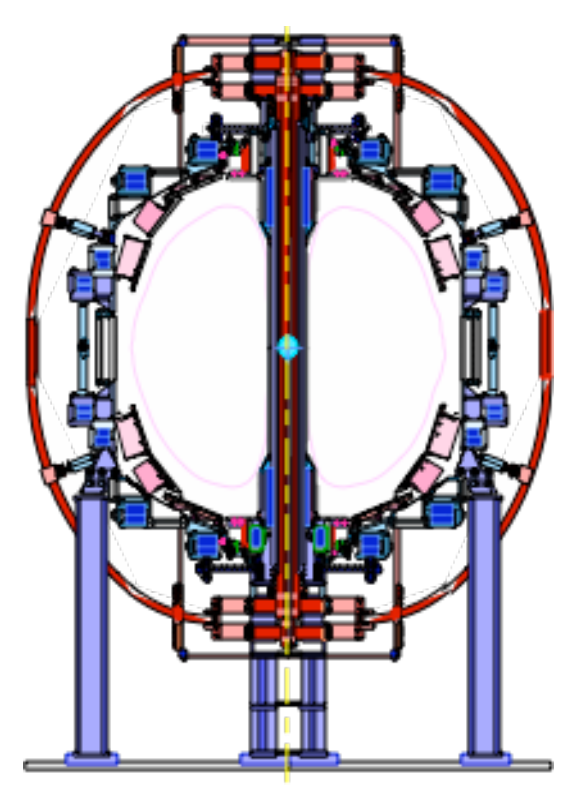
Berk, *et al.*, Phys. Plas. **2** (1995) 3007



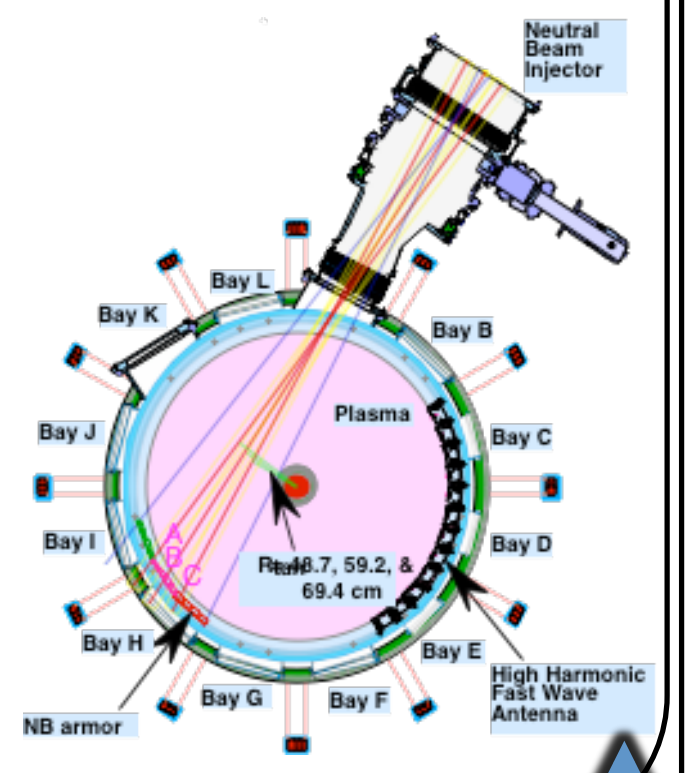
- Large amplitude modes overlap in fast-ion phase-space.
- Interaction accesses more free energy; resulting in stronger modes, destabilizes new modes; leading to more fast ion transport.
- Interaction of multiple modes can also move ions further in phase-space, again enhancing losses.
- TAE avalanches have strong mode bursts consisting of multiple modes.
- TAE have multiple resonances, more complex physics.

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

- Low field, high density $V_{Alfvén} \approx 0.5$ - 2.7×10^6 m/s.
- Beam injection energy 60 - 100 kV, $V_{fast} \approx 2.6$ - 3.1×10^6 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 = 0.3-0.55 T
$I_p \leq 1.2$ MA
$\beta_{tor} \leq 40\%$
$n_e \leq 10 \times 10^{19}/m^3$

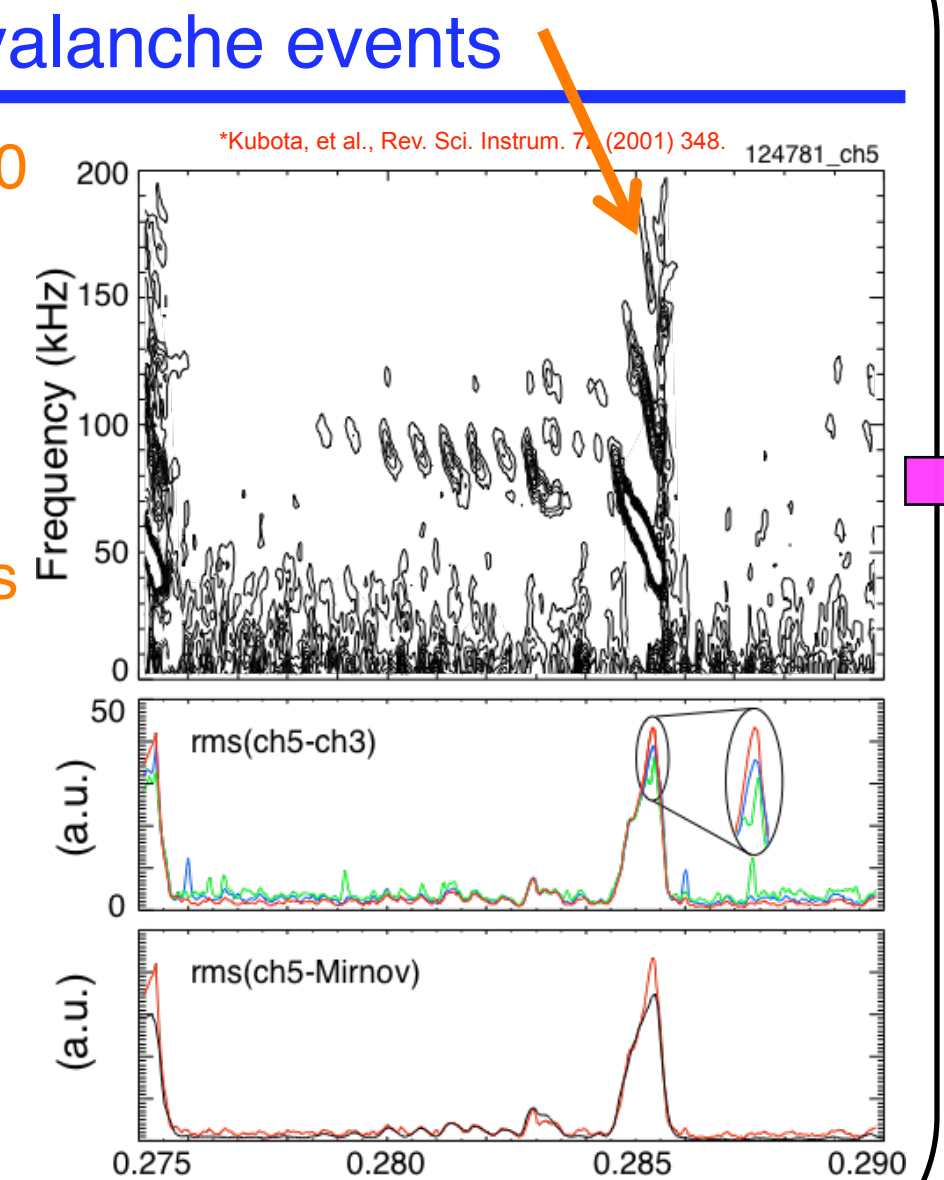


Non-linear physics of Alfvénic and Energetic Particle modes is research priority

- 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*.

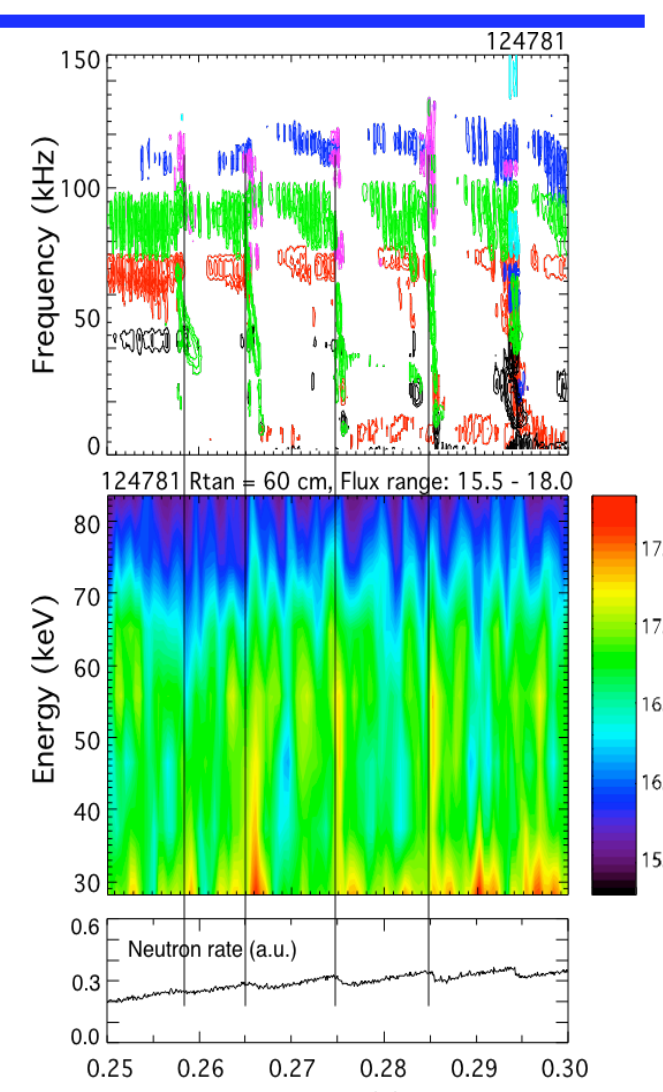
Mode amplitudes, fast ion losses are measured during Avalanche events

- 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.

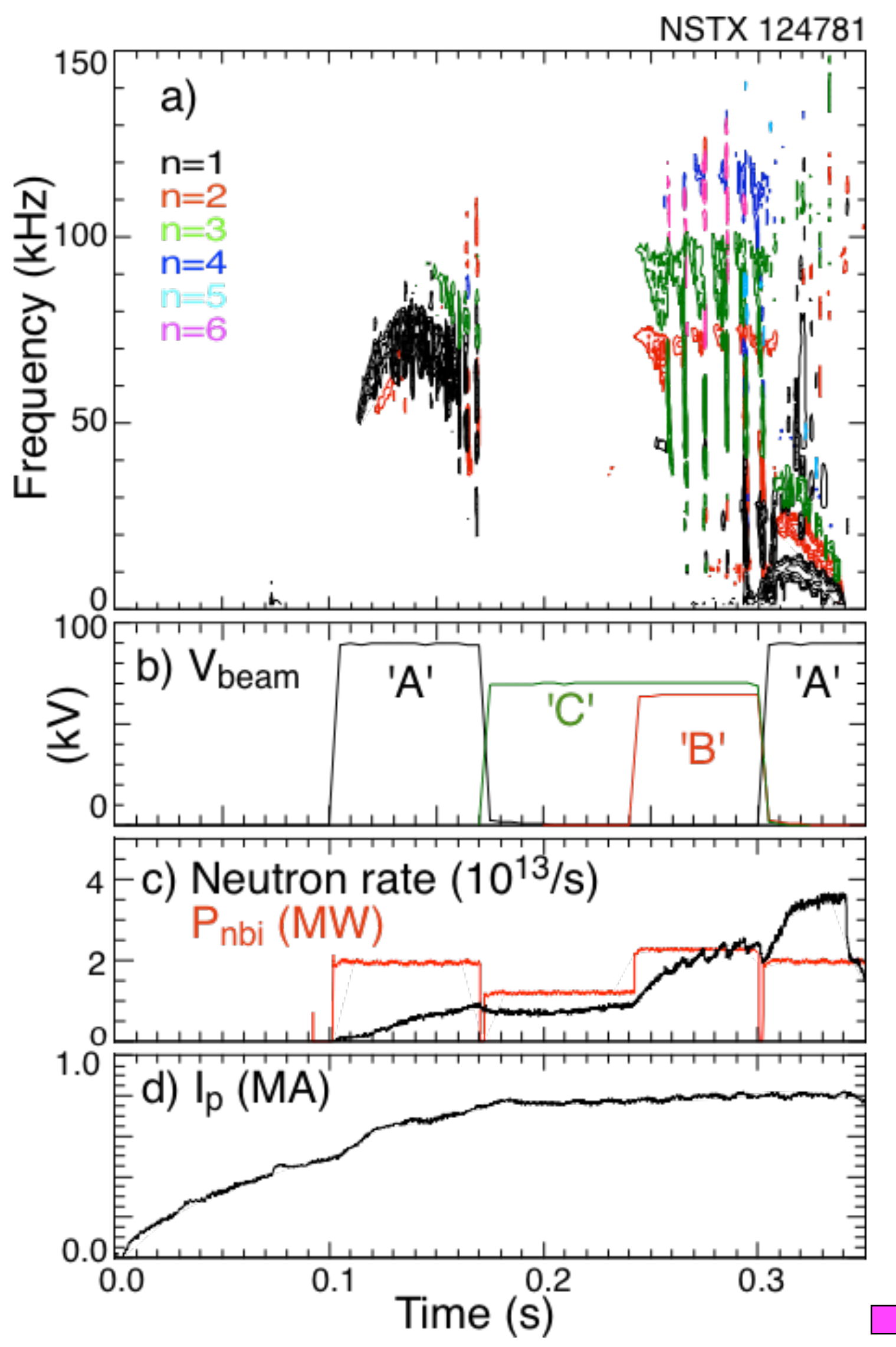

*Kubota, et al., Rev. Sci. Instrum. 72 (2001) 348.

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

- 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.



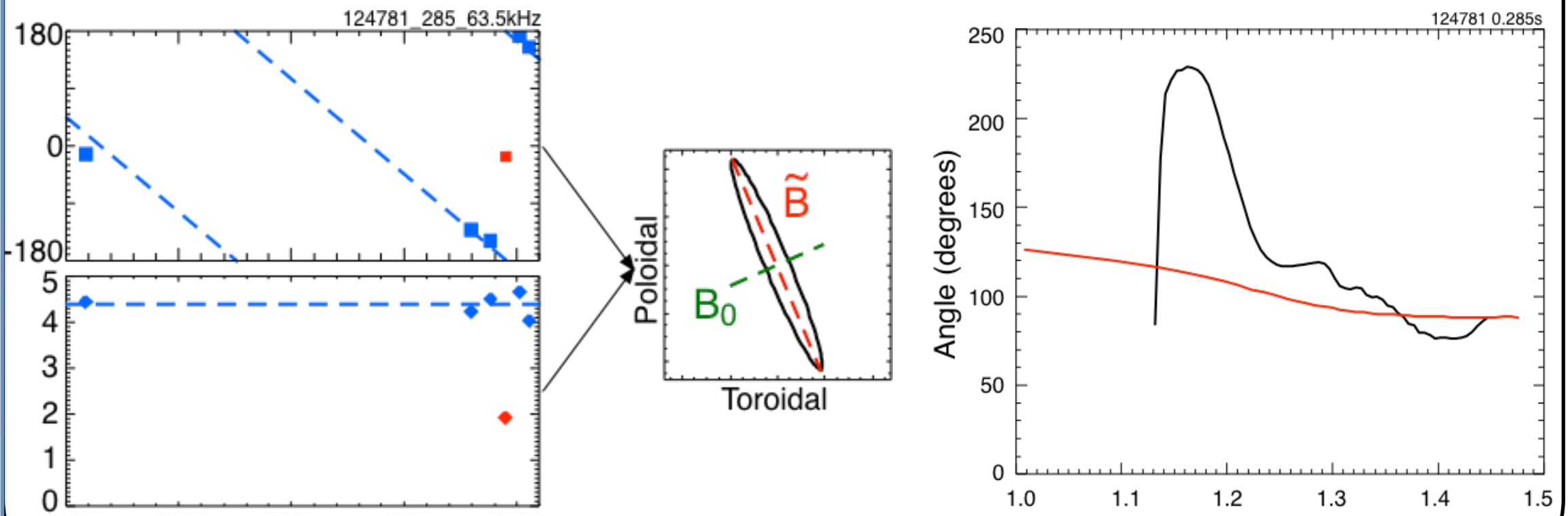
Avalanches easiest to produce with reduced neutral beam voltage



- 90 kV beam needed for MSE diagnostic.
- Helium target plasma used to maintain L-mode.
- Discharge evolution complicated.

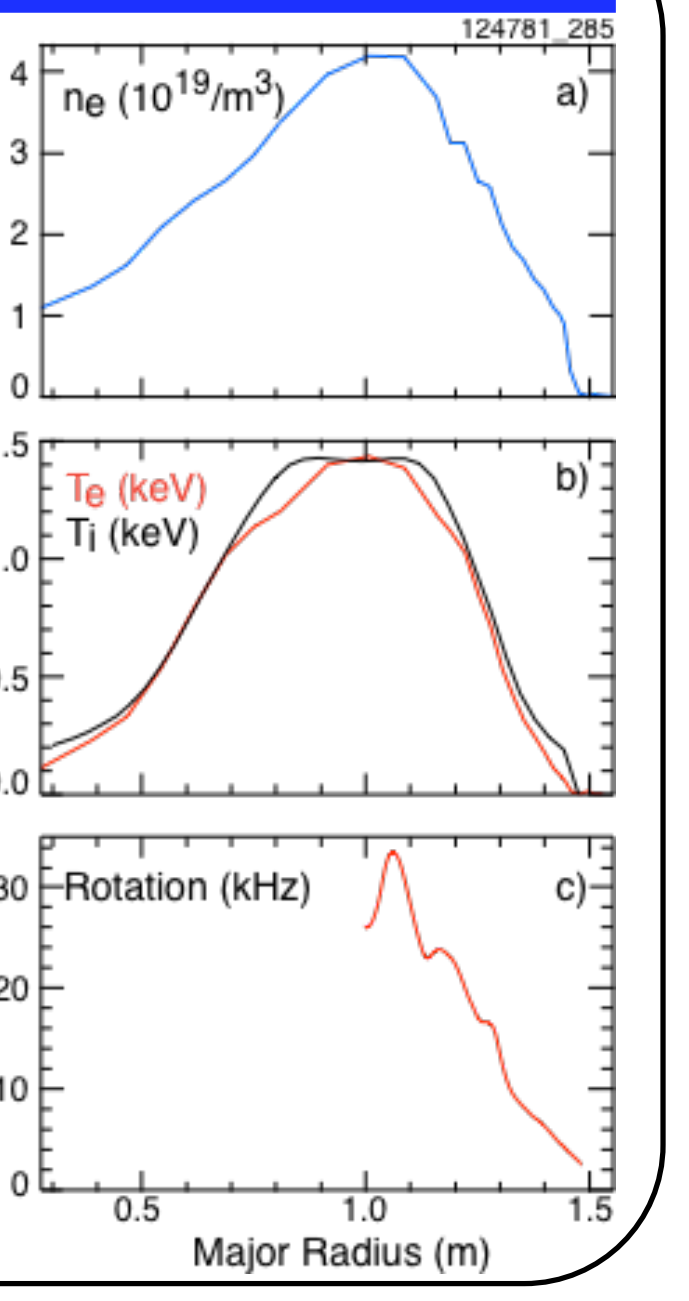
External δB pitch in agreement with NOVA simulations – TAE have compressional components

- Pitch of magnetic fluctuations is measured with an array of coils.
- Within uncertainty, phase/amplitude relation of poloidal and toroidal fluctuations consistent with expected shear-type Alfvén mode.

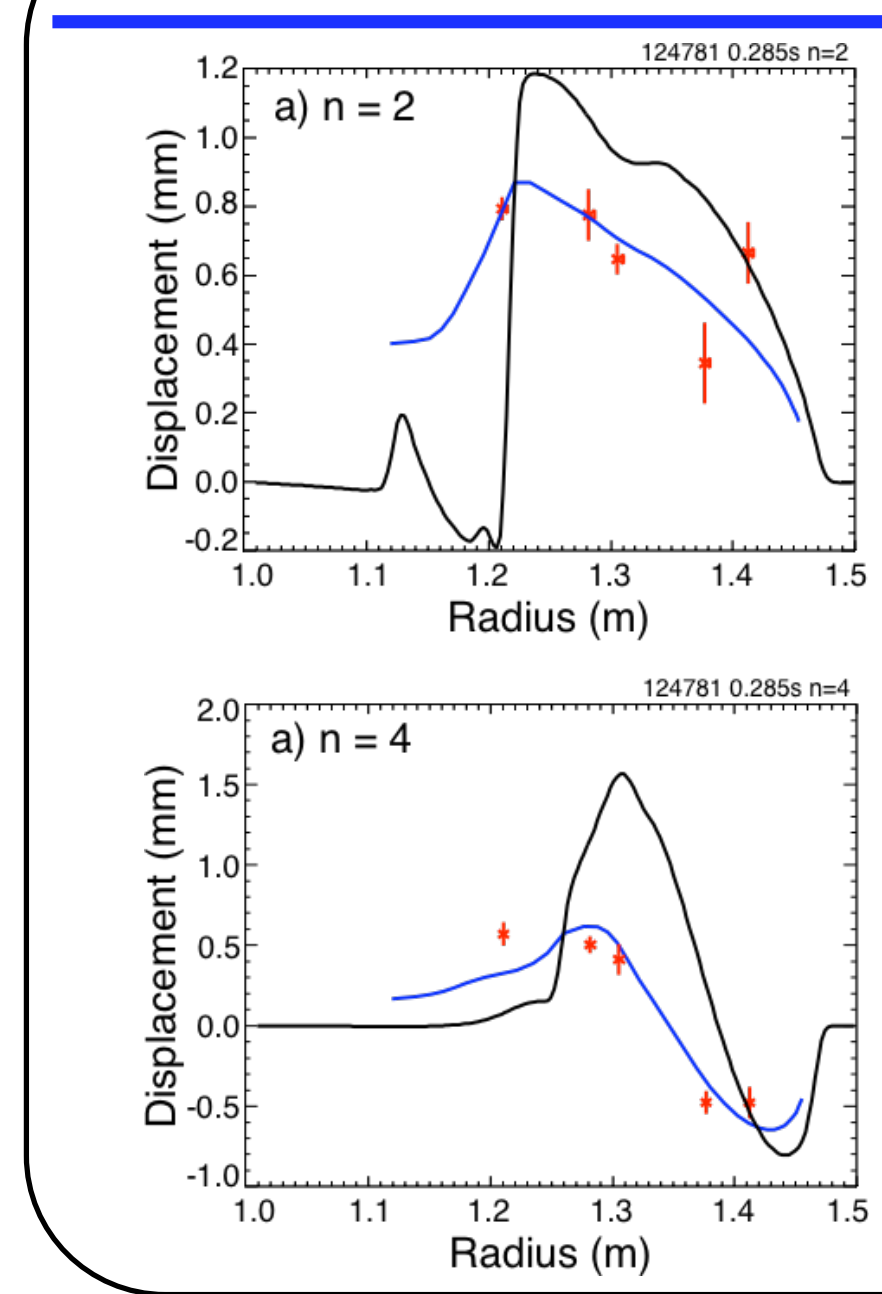


Equilibrium profiles used in simulations

- Density profile is L-mode with good reflectometer coverage of mode structure.
- Core plasma rotation frequency is about 30 kHz.



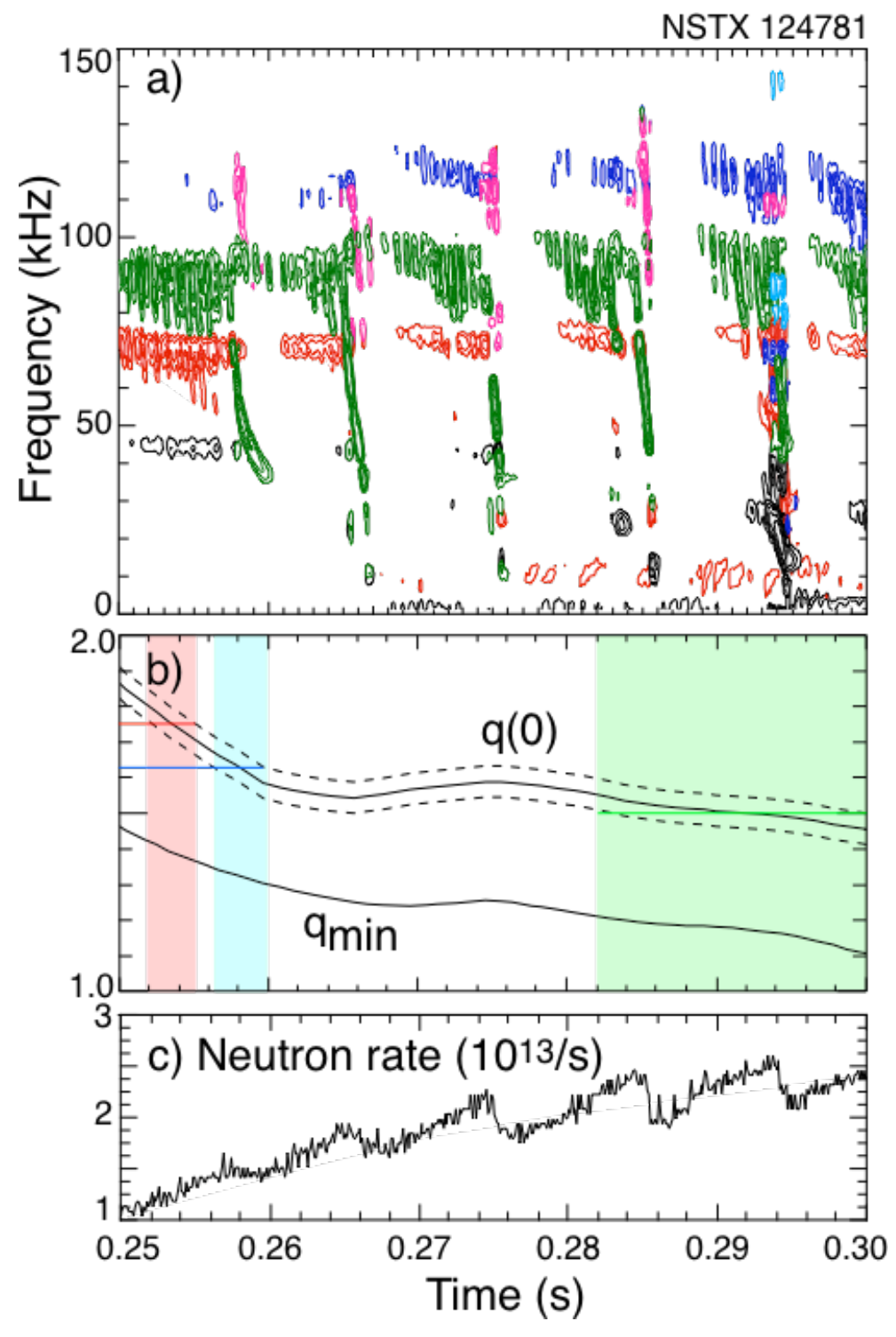
Good agreement found for n = 2 and 4 modes, also

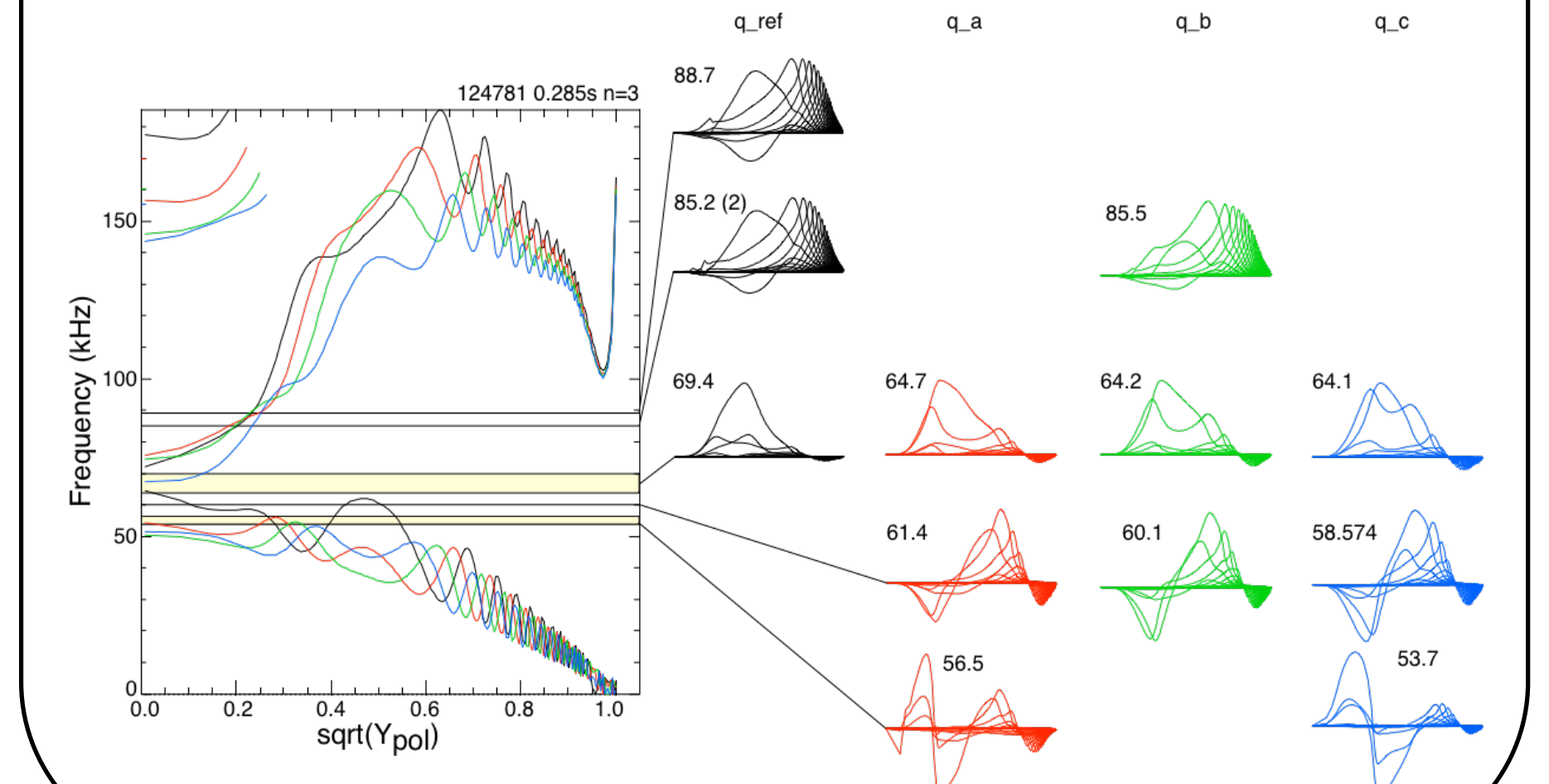


- Best fit to the n = 2 is reasonably good, signal-to-noise is low for outer reflectometer point.
- n = 4 mode has phase inversion, which is well fit with NOVA eigenmode.
- Both modes intersect continuum between two innermost reflectometer points.
- These were the eigenmodes used in ORBIT simulations.

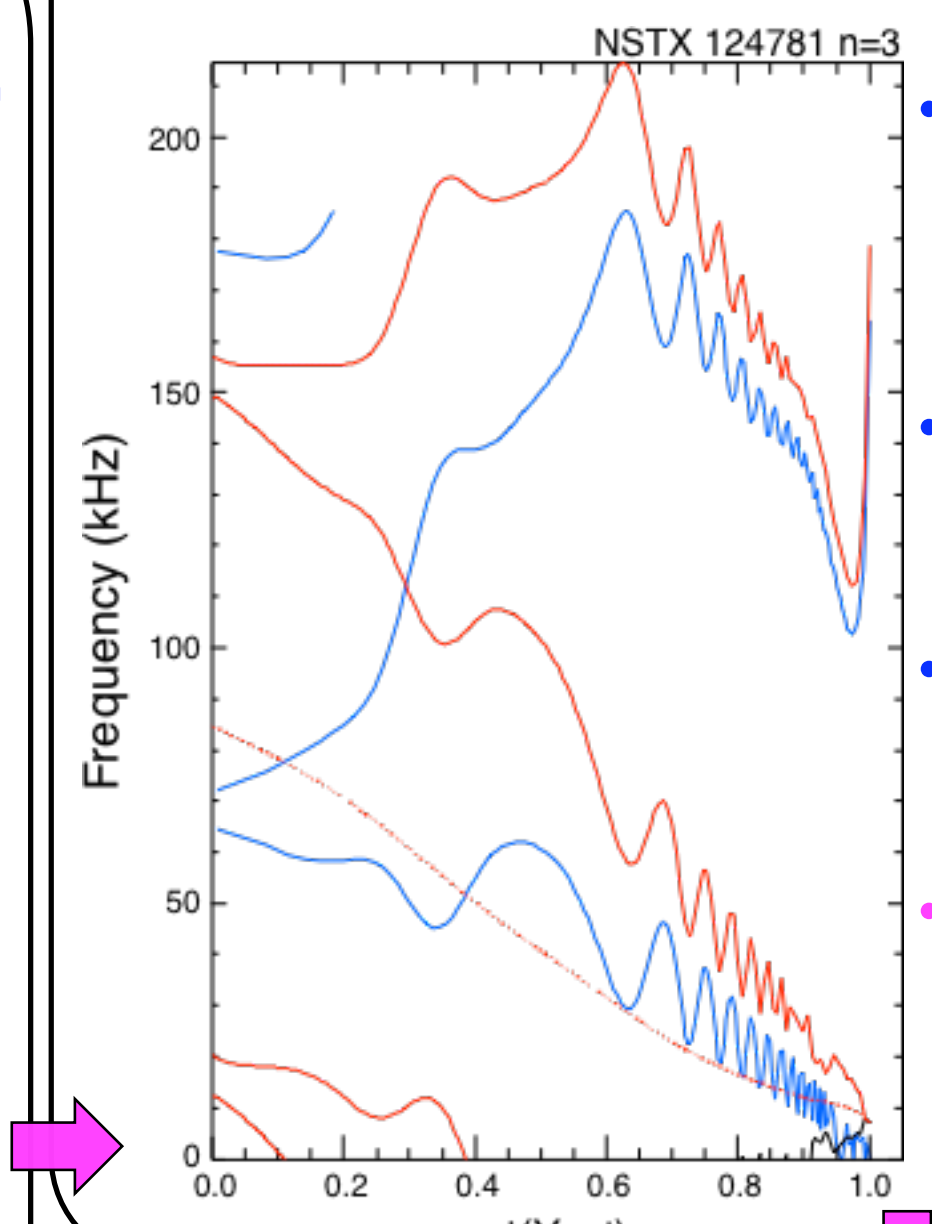
TAE Avalanches, with multiple modes, persist through evolution of q-profile

- 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.
- NOVA predicts that modes come and go depending on continuum shapes (except for mode in open gap, see below for n=3 modes).
- Calculation of gaps with sheared rotation have gaps always closed, consistent with experiment?





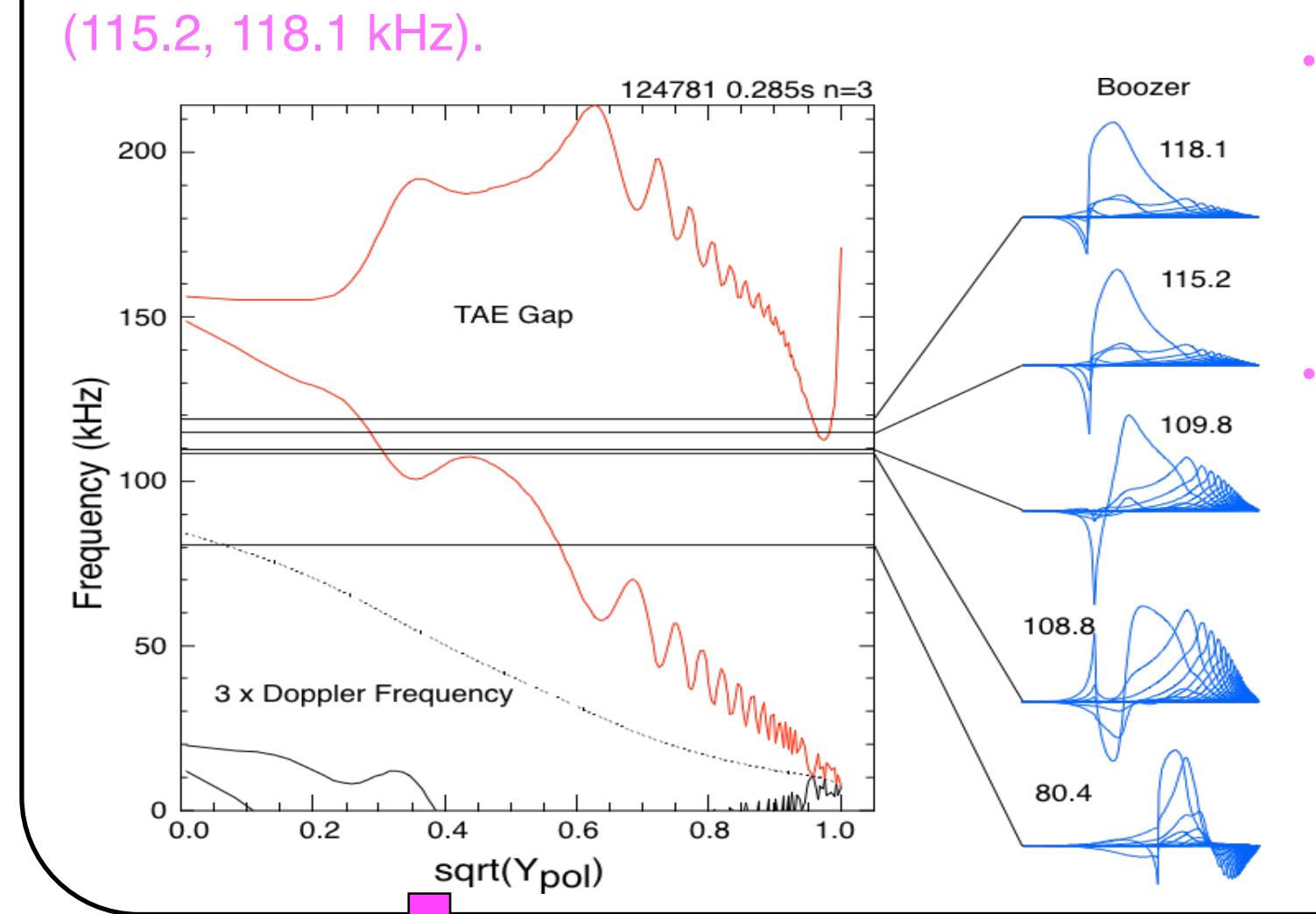
Sheared rotation distorts TAE continuum



- 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).

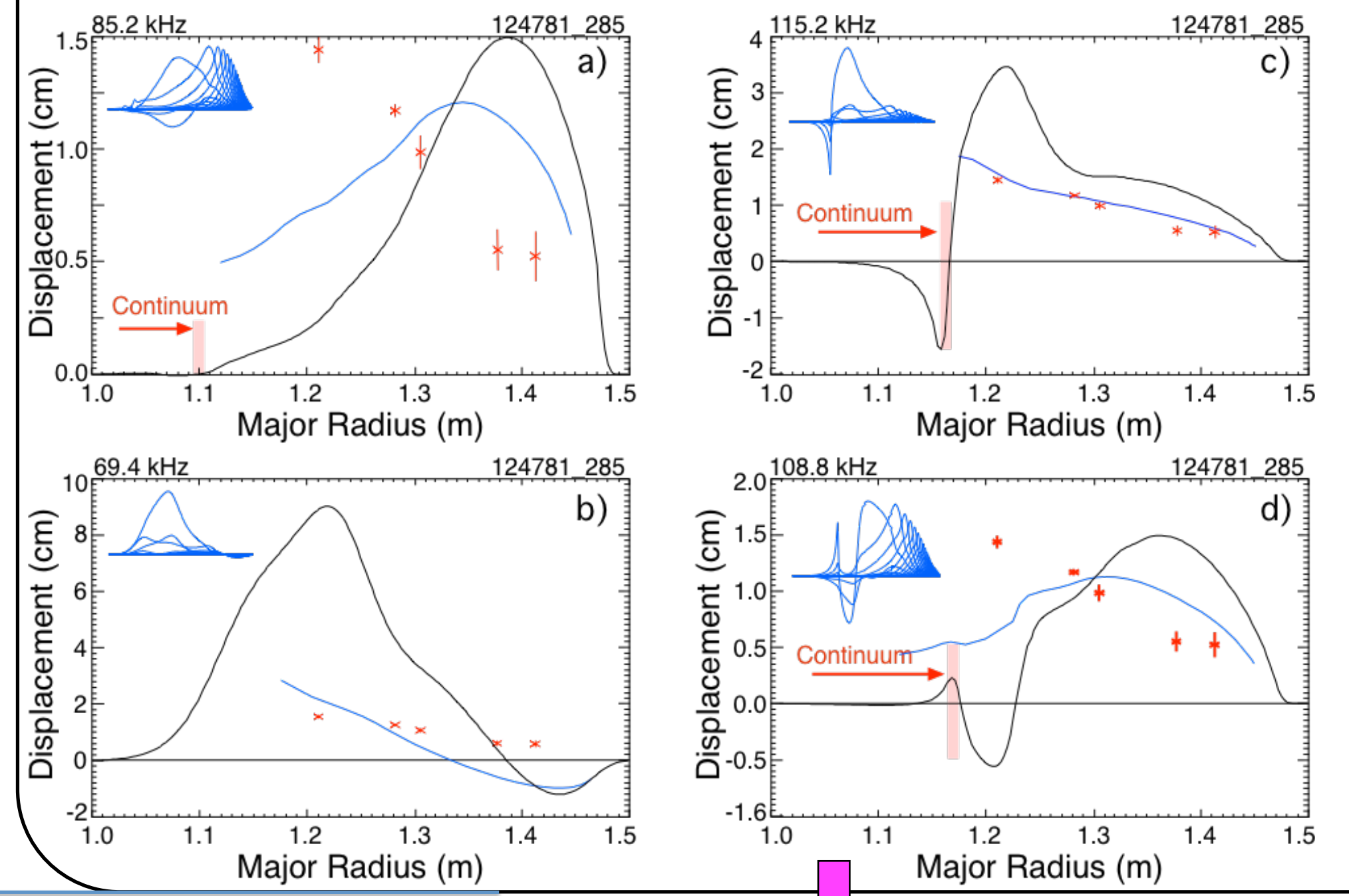
NOVA typically finds multiple eigenmodes

- 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.

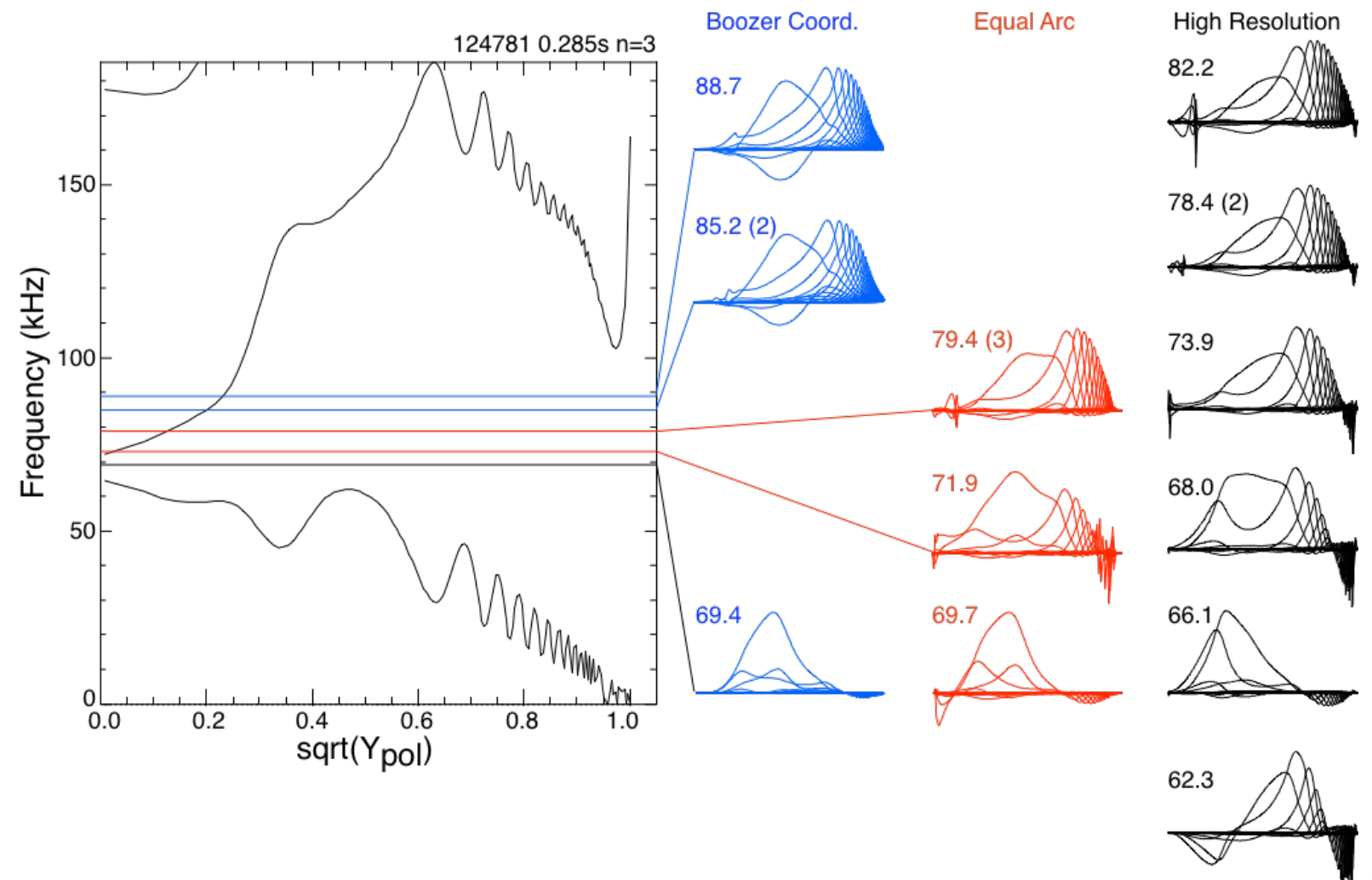
NOVA simulations find good fit to frequency, radial structure and amplitude for dominant n=3 mode



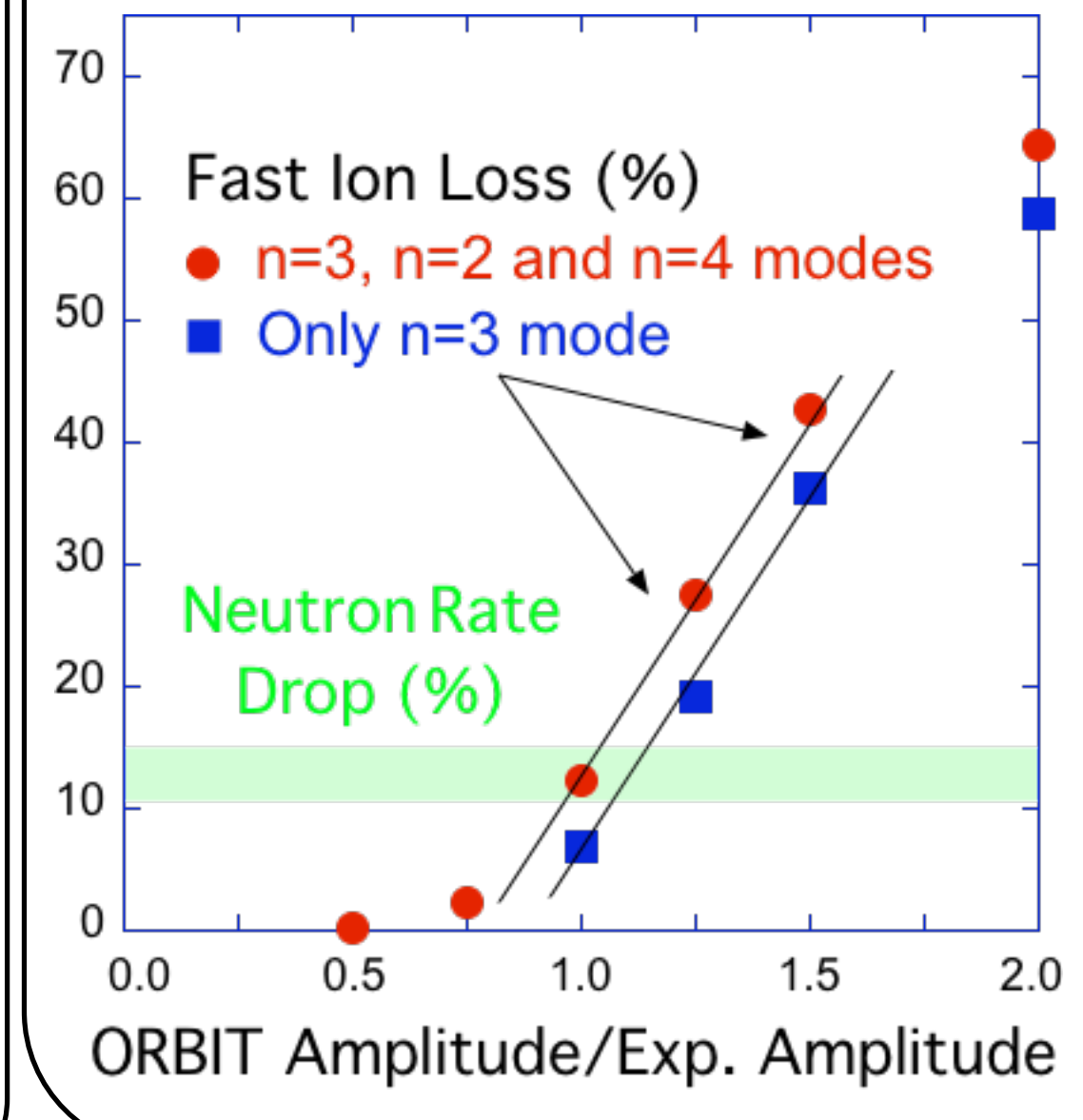
- NOVA finds multiple modes in TAE gap.
- Sheared rotation in NOVA analysis changes gap structure and character of eigenmodes.
- n=3 modes on left neglect the sheared rotation, the examples on the right include sheared rotation as a local Doppler shift.
- The best fit to the reflectometer data is the 115 kHz eigenmode, which includes Doppler-shift corrections.
- The blue insets show the poloidal harmonics, Black curve shows total displacemen,blue line shows simulated reflectometer , overlayed by reflectometer data (red points).

NOVA doesn't have enough physics, resolution to properly model continuum interactions

- 'Degenerate' eigenfunction solutions generated by continuum interaction.
- Eigenfunctions and eigenvalues very sensitive to location of continuum relative to grid.



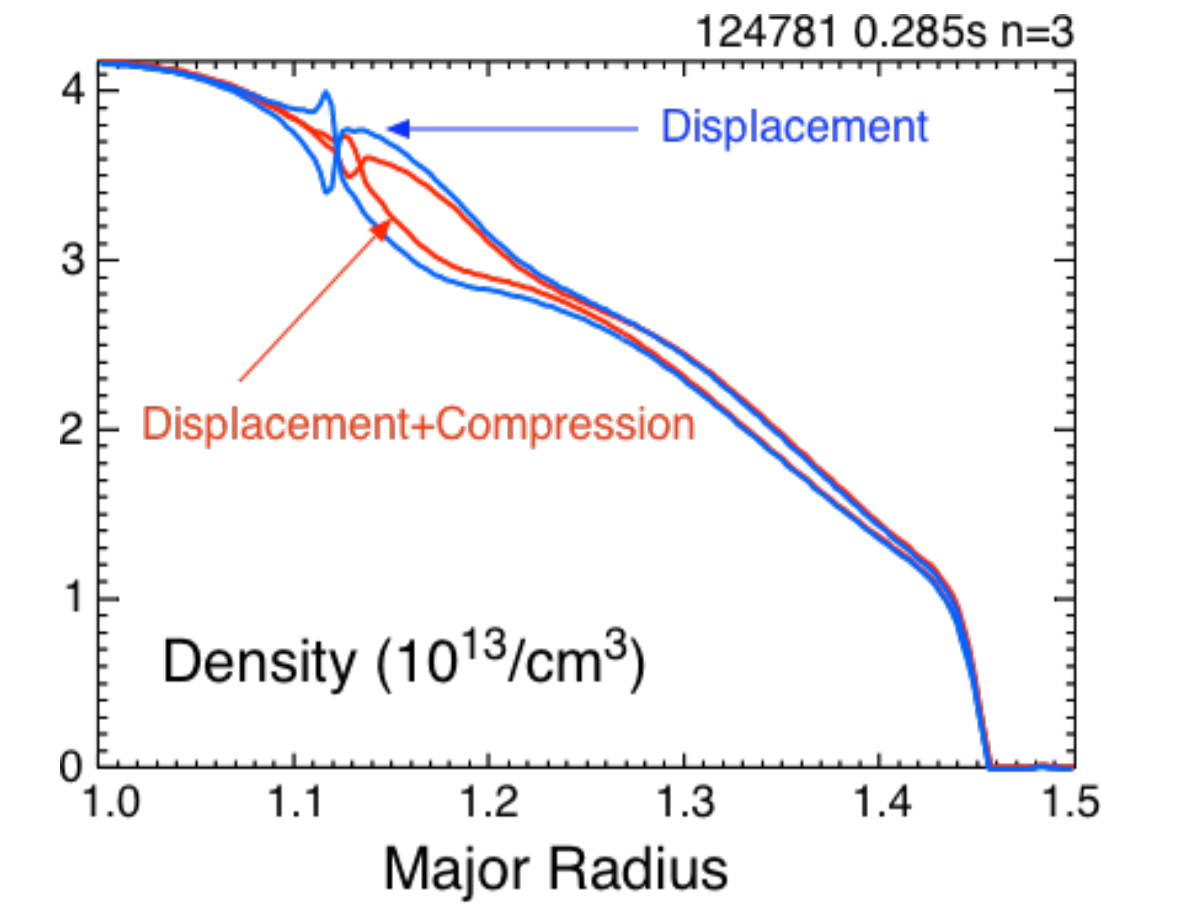
ORBIT simulations predict losses in good agreement with observed neutron rate drop



- 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.

n=3 mode amplitude is large

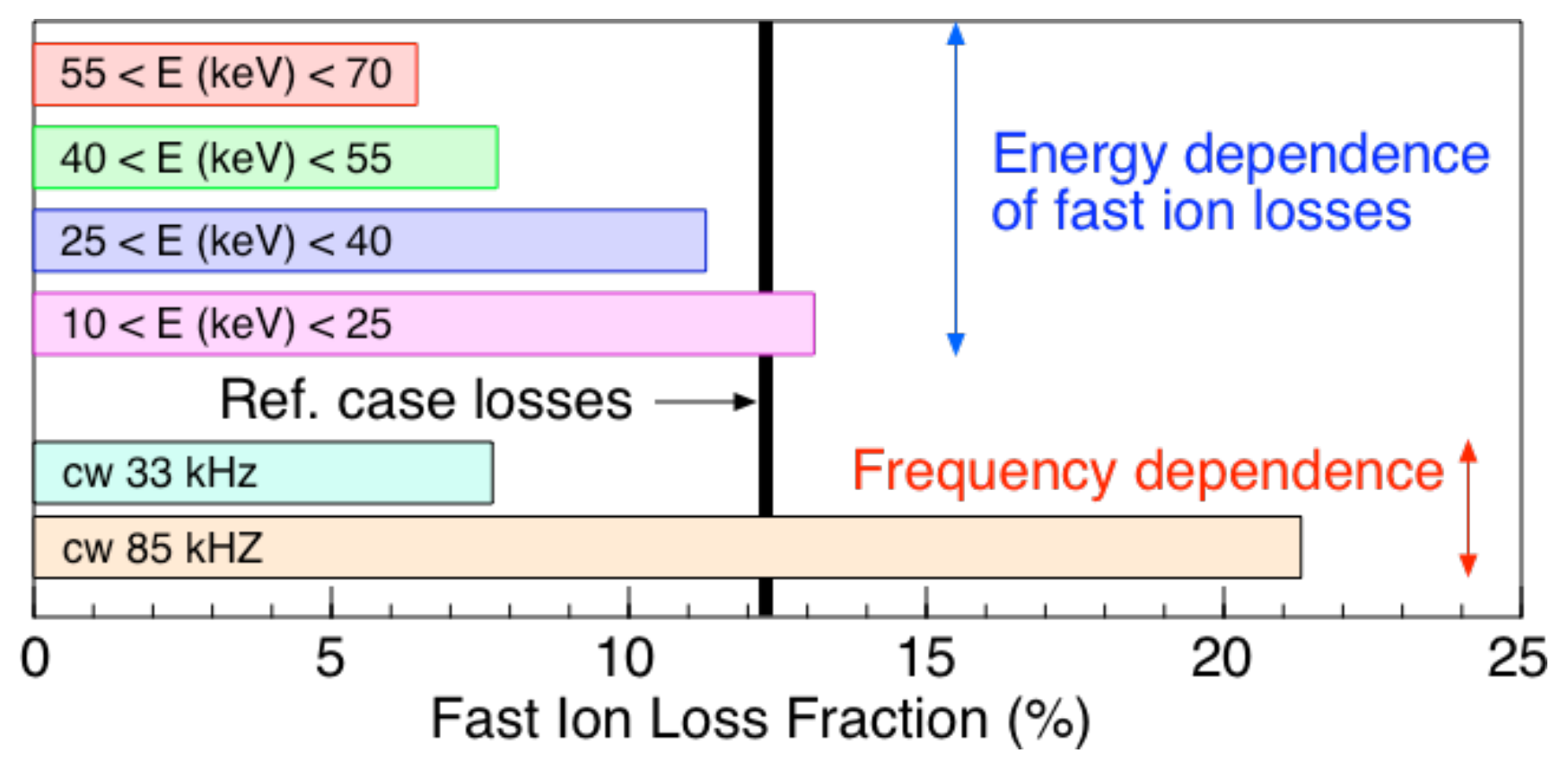
- Blue curve show density perturbation with only displacement, red curve shows perturbation with both displacement and compression.



- Should be measureable with Thomson Scattering.
- Difficult to imagine larger modes…

Energy dependence and frequency dependence of losses also investigated

- Losses seen at all energies, consistent with NPA measurements, but more at low energy.
- Fast ion losses larger at higher frequencies; need to add sheared rotation to ORBIT simulations
- Energy dependence of losses is important for estimating impact on fast ion current drive.



- Strong frequency dependence suggests that including rotational shear (potential profile) in ORBIT will affect losses, as modes will have different effective frequencies in plasma

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 $V_{Alfvén}$.