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Fast ion loss and redistribution by MHD on NSTX

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

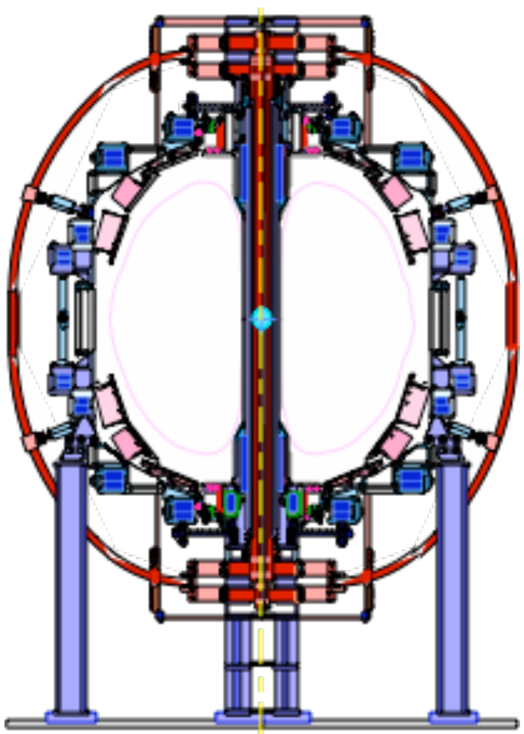
NSTX

- 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.

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

NSTX

- Low field, high density $V_{Alfvén} \approx 0.5 - 2.7 \times 10^6$ m/s.
- Beam injection energy 60 - 100 kV, $V_{fast} / V_{Alfvén} \approx 1 - 4$
- Reactors would have higher field, fusion α's and $V_{fast}/V_{Alfvén} > 1$



$R_0 = 0.86$ m

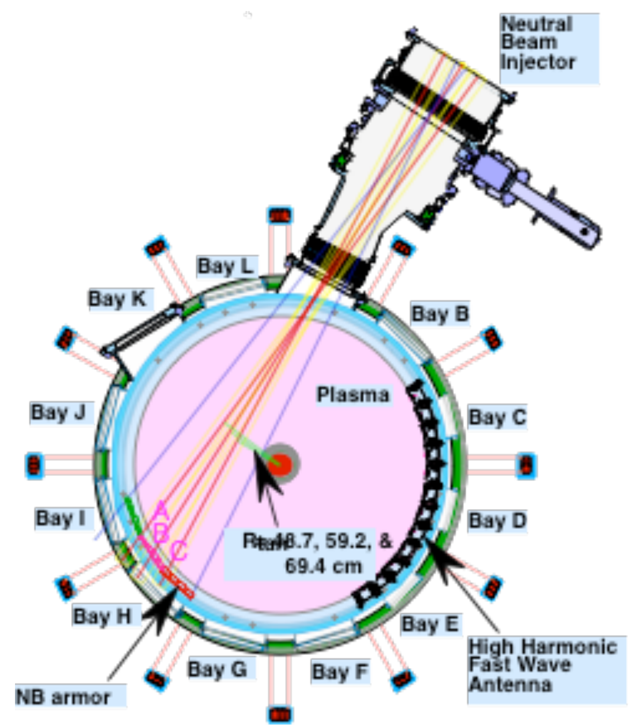
$a = 0.68$ m

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

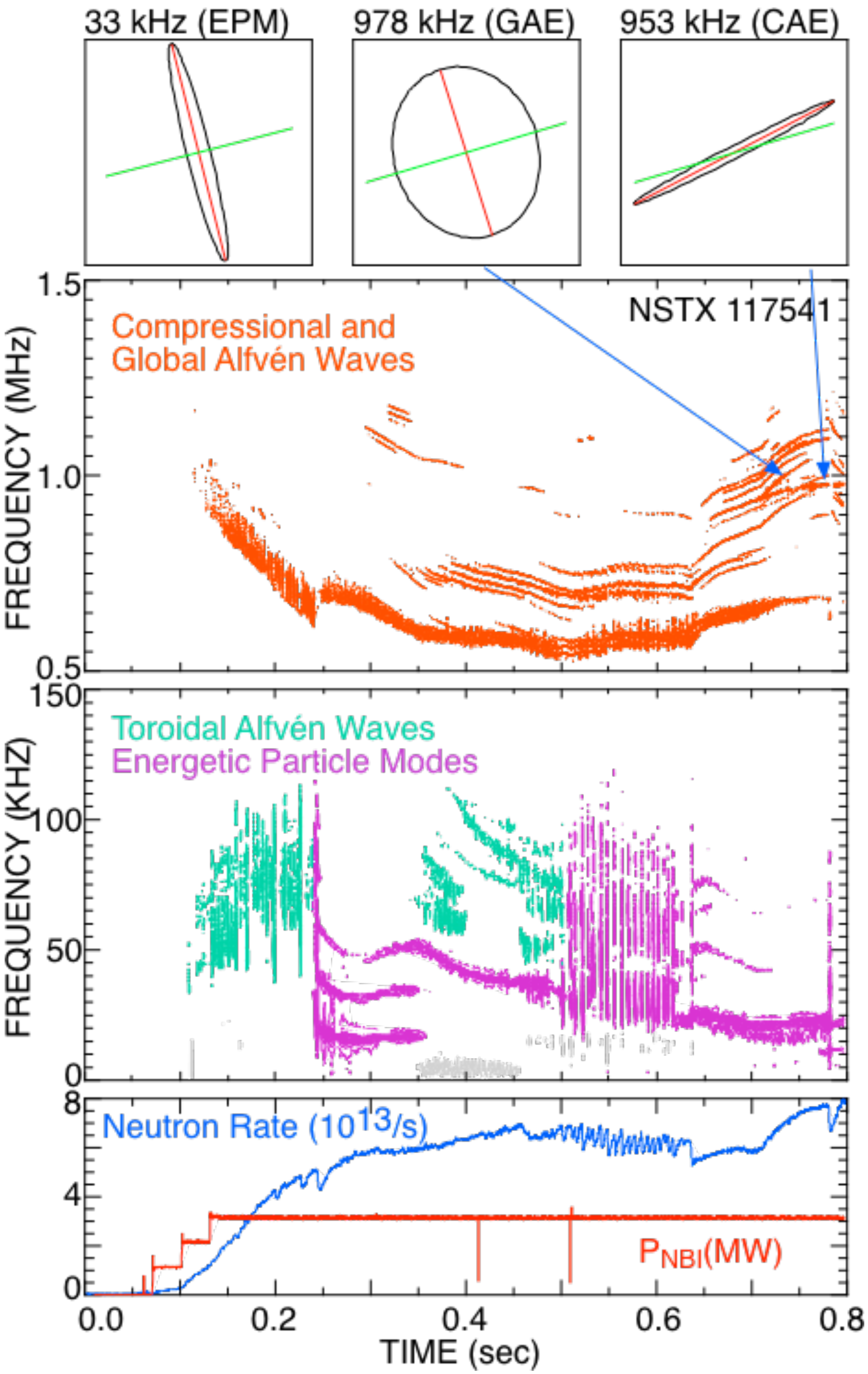
$I_p \leq 1.2$ MA

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

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



Broad range of fast-ion driven modes are seen



- Modes in 0.5 MHz to 2.5 MHz range aren't directly correlated with measurable losses.
- Mix of compressional and shear (fast and slow) waves are seen.
- Lower frequency range includes broad range of modes.
- Low field pushes modes into same frequency range sheared rotation and high β add further mixing.

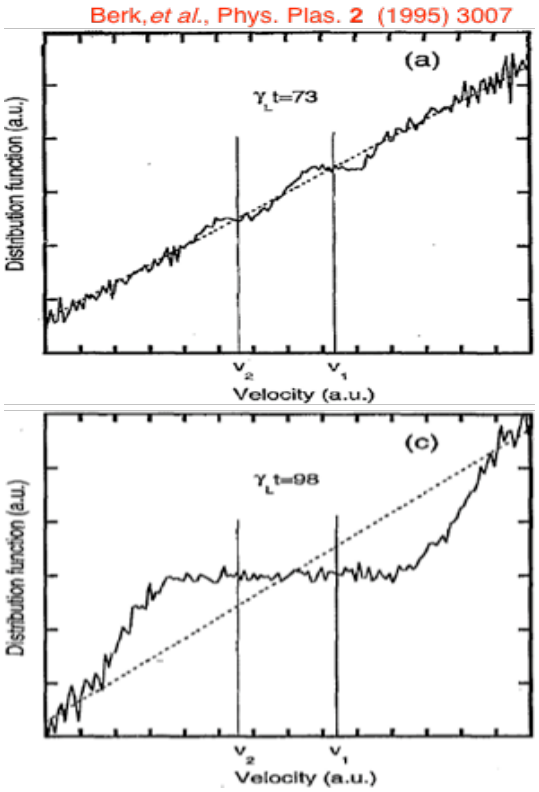
NSTX fast-ion loss studies are concentrated on high priority modes

- Fast ion loss or redistribution seen primarily with two types of energetic particle driven instabilities on NSTX:
  - TAE avalanches - of interest beyond NSTX because they represent a form of non-linear losses which might be important in bigger, higher field machines (ITER, DEMO)
  - EPMs - a fishbone like mode. Losses on NSTX tend to be larger than for avalanches but scaling beyond NSTX is uncertain.
- It is expected that all energetic particle driven modes cause redistribution in fast ion phase space, but not necessarily losses
  - e.g., CAE/GAE take perpendicular energy, improve fast ion confinement?
- Goal of NSTX experiments is to provide data suitable for validating predictive codes.
- Fast ion losses also seen with other MHD:
  - sawteeth cause substantial losses,
  - internal kink modes,
  - NTMs.

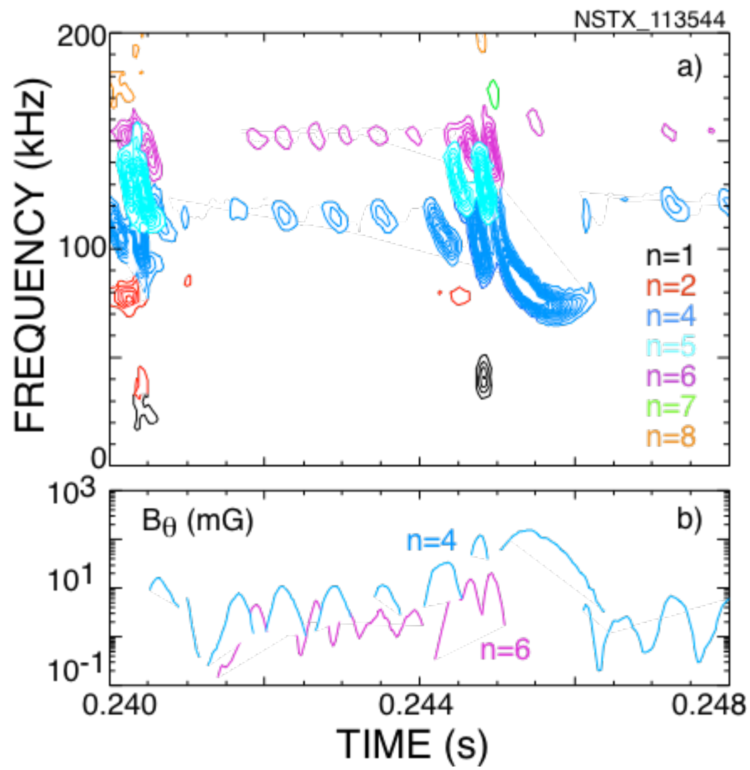
Outline: The modeling of fast ion losses during TAE avalanches furthest advanced

- Introduction to TAE avalanches.
- Description of experimental conditions, diagnostics and analysis of the TAE avalanche data.
- Simulations of TAE avalanches, fast ion losses
- Description of Energetic Particle Modes (EPMs) and plans for further analysis.
- Non-linear simulations: M3D-k
- Summary

Interaction of multiple Toroidal Alfvén Eignmodes may greatly enhance fast ion transport



- Above threshold, large amplitude modes can 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.

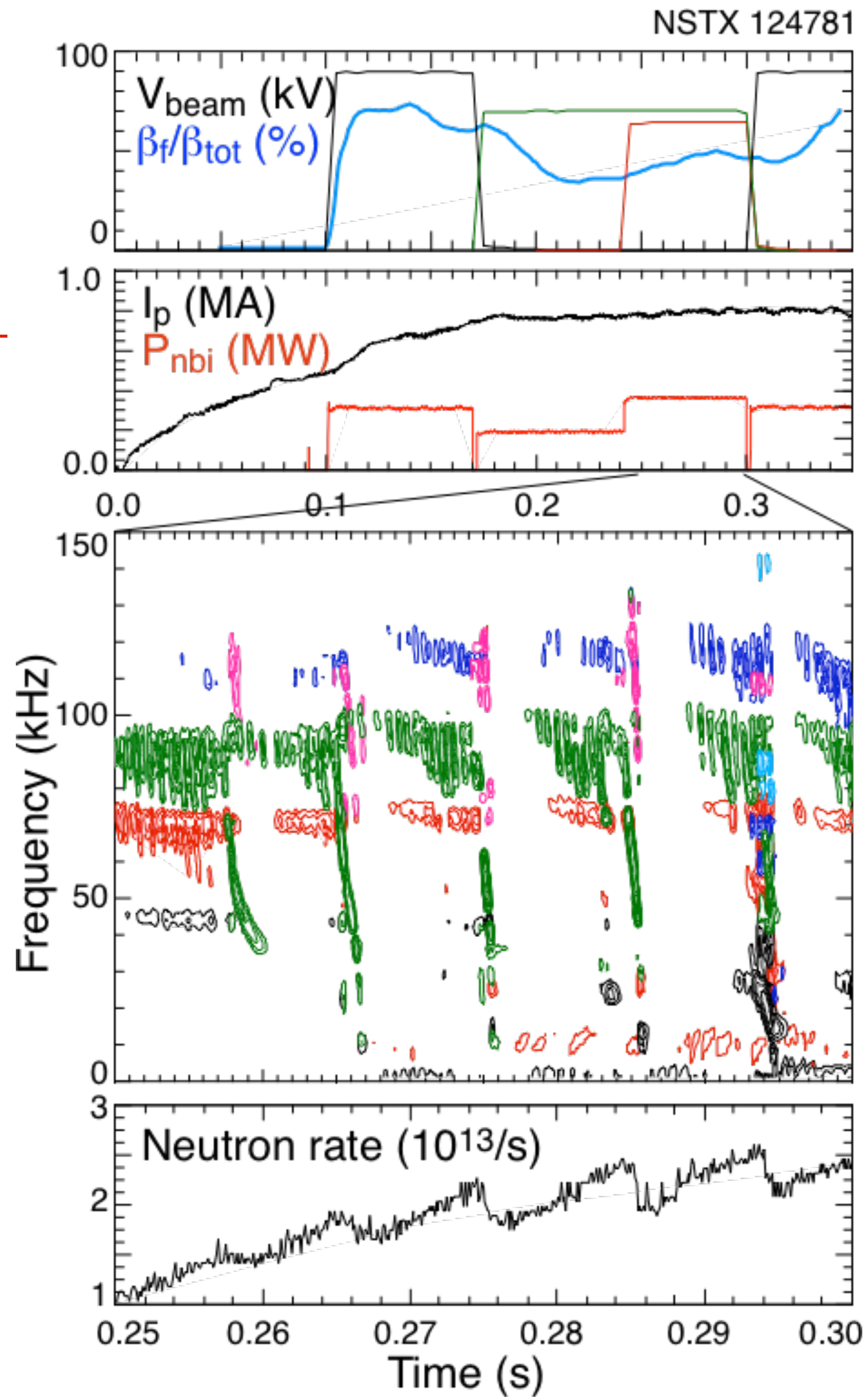


- No correlation of repetitive small bursts; increased amplitude leads to strong burst with multiple modes.

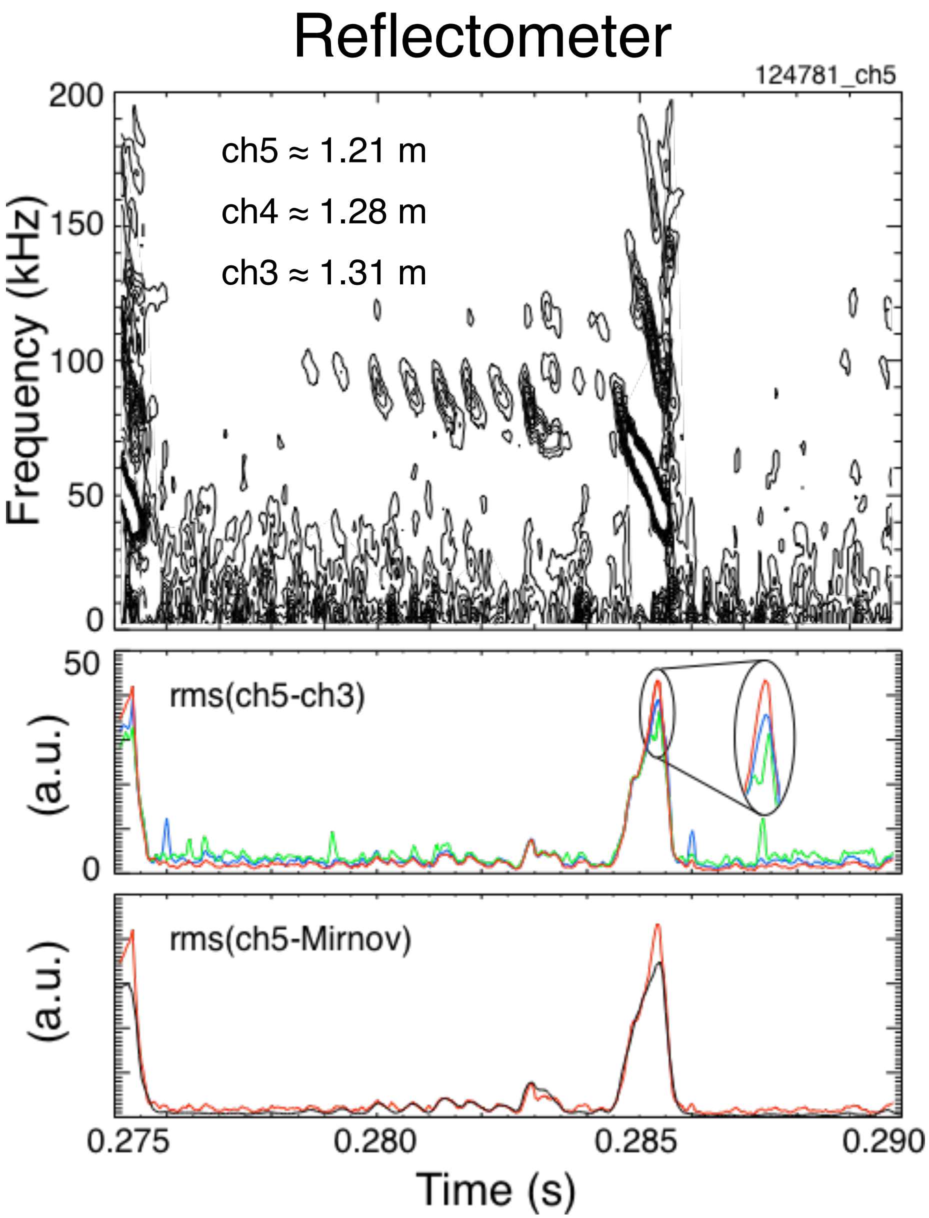
Well Diagnosed Equilibrium with multiple avalanches

NSTX

- TAE and avalanche onset controlled through beam power and voltage.
- Avalanches in L-mode most easily found with reduced beam voltage.
- Weakly reversed shear is present in the avalanching shots studied to date; possibly some coupling of TAE and rsAE.
- Strong frequency chirps common for fast-ion driven modes on NSTX.
- Helium target plasmas used to keep L-mode density profiles.



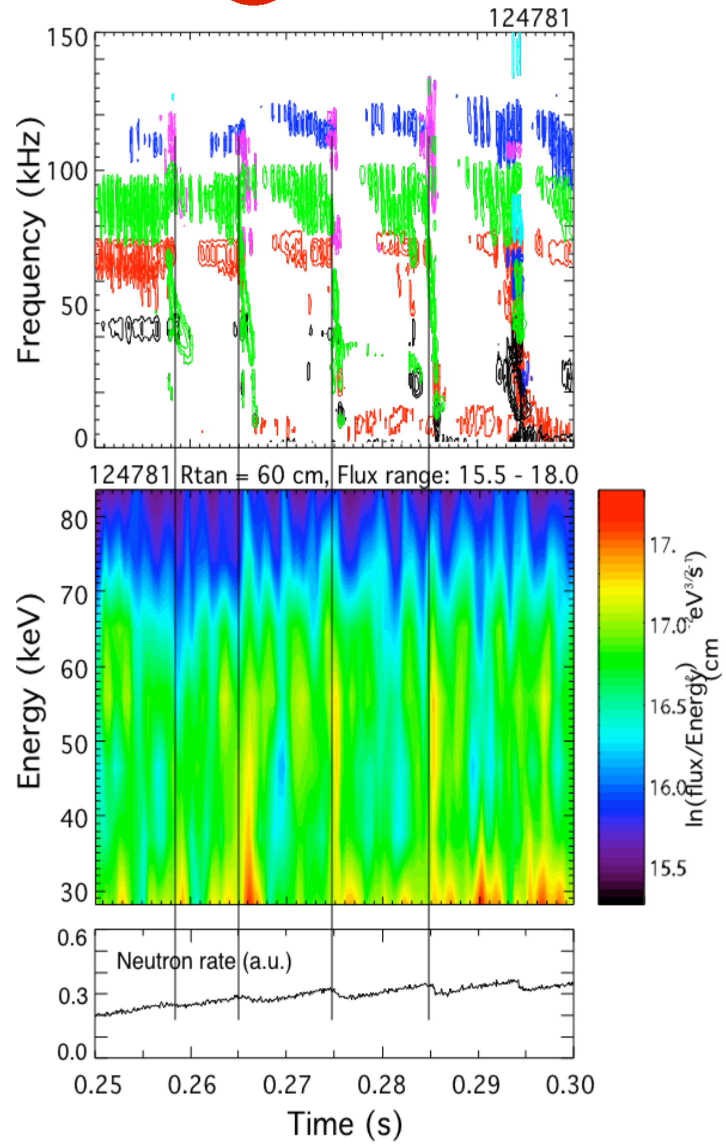
Mode amplitudes, internal structure during Avalanche events from reflectometers



- Amplitude at time of avalanche much greater than earlier bursts.
- Relative amplitude tracks well through multiple modes, suggesting NOVA linear mode structure might be reasonable approximation, ...
- …except becoming more peaked toward end of last burst.
- Amplitude evolution, frequency sweep of last burst modeled linearly in ORBIT simulation.

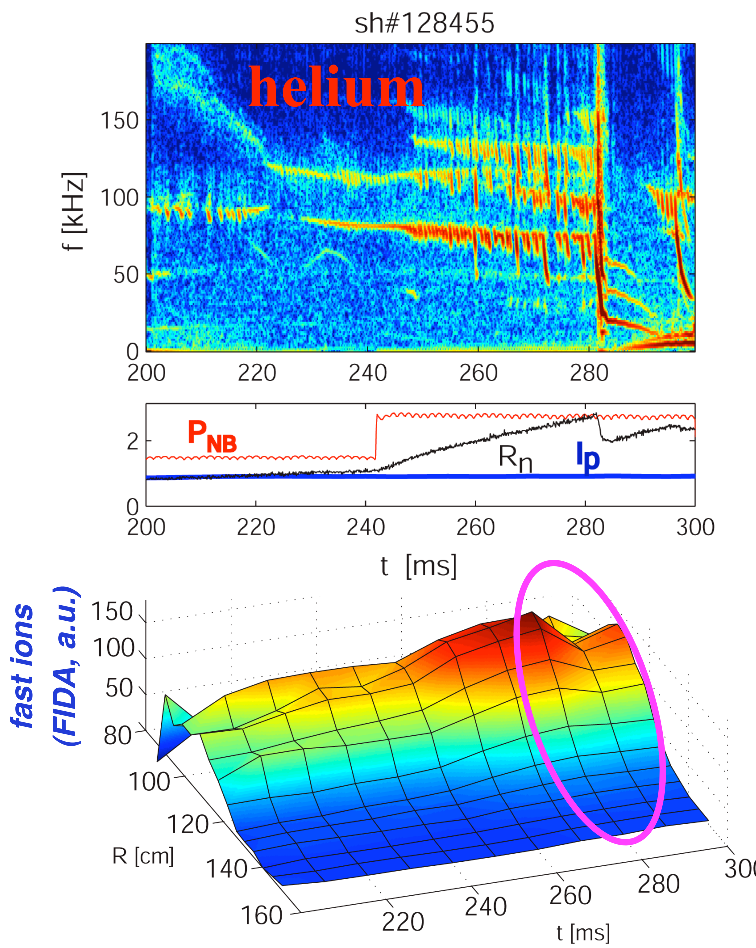
Two NPA diagnostics provide information on energies of redistributed fast ions

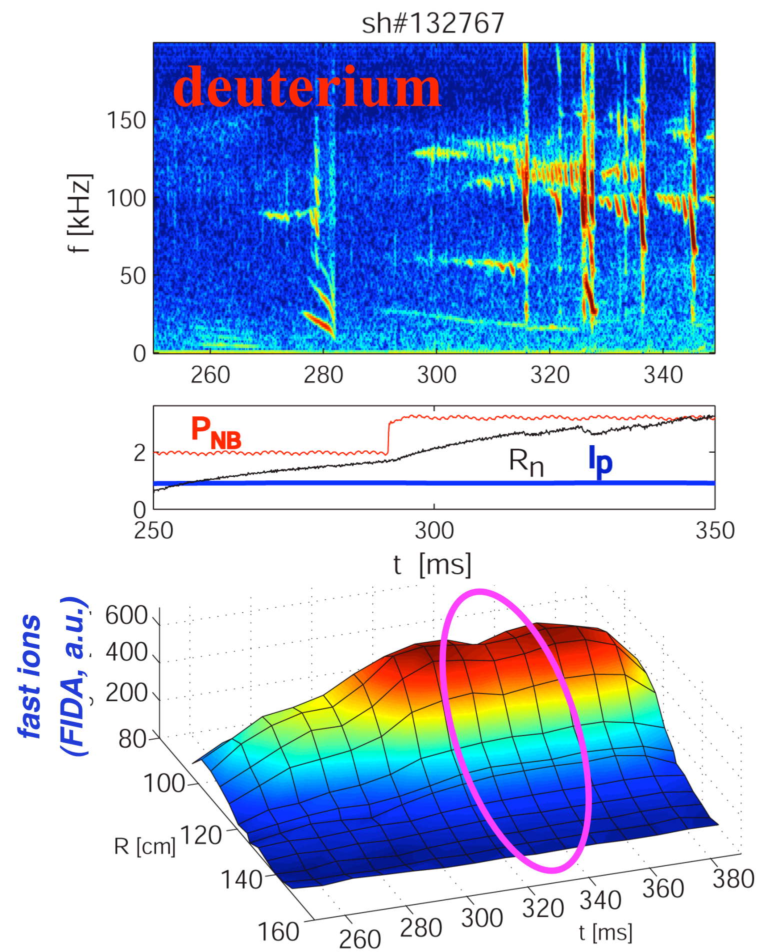
- Neutron drops correlated with D-alpha spikes - fast ions are lost.
- Neutral particle analyzers (NPA) measure spectrum of charge-exchanged neutral ions from plasma.
- Transport appears largest at lower energies.
- Chirping may play important role in fast ion loss.

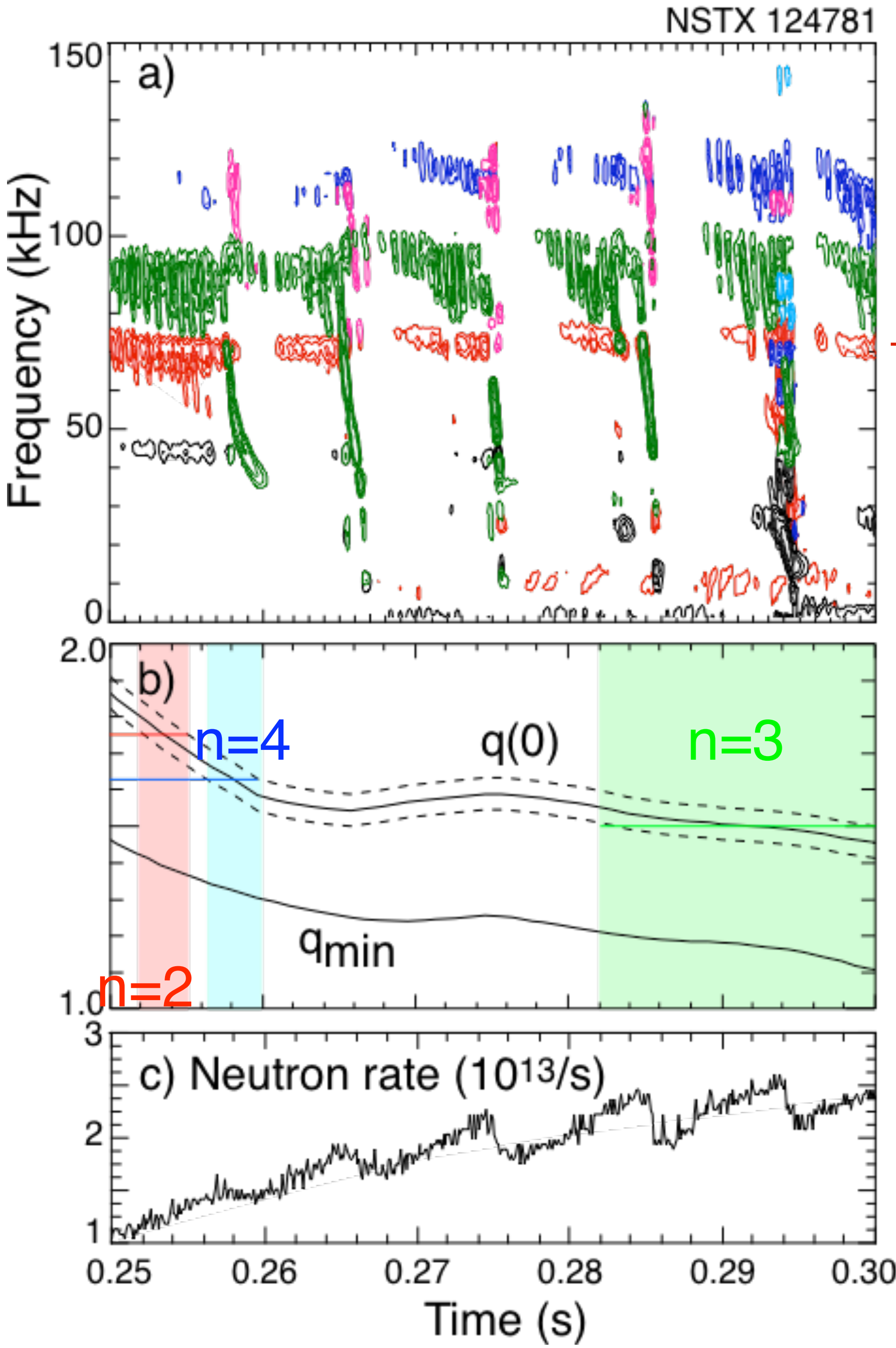


Newer shots have also FIDA data, data with limited plasmas, and deuterium target plasmas

- Present data set has nominally Helium target plasma, neutrons also from beam-beam...
- sFLIP data also sees losses in recent data (e.g., Darrow Tuesday morning)





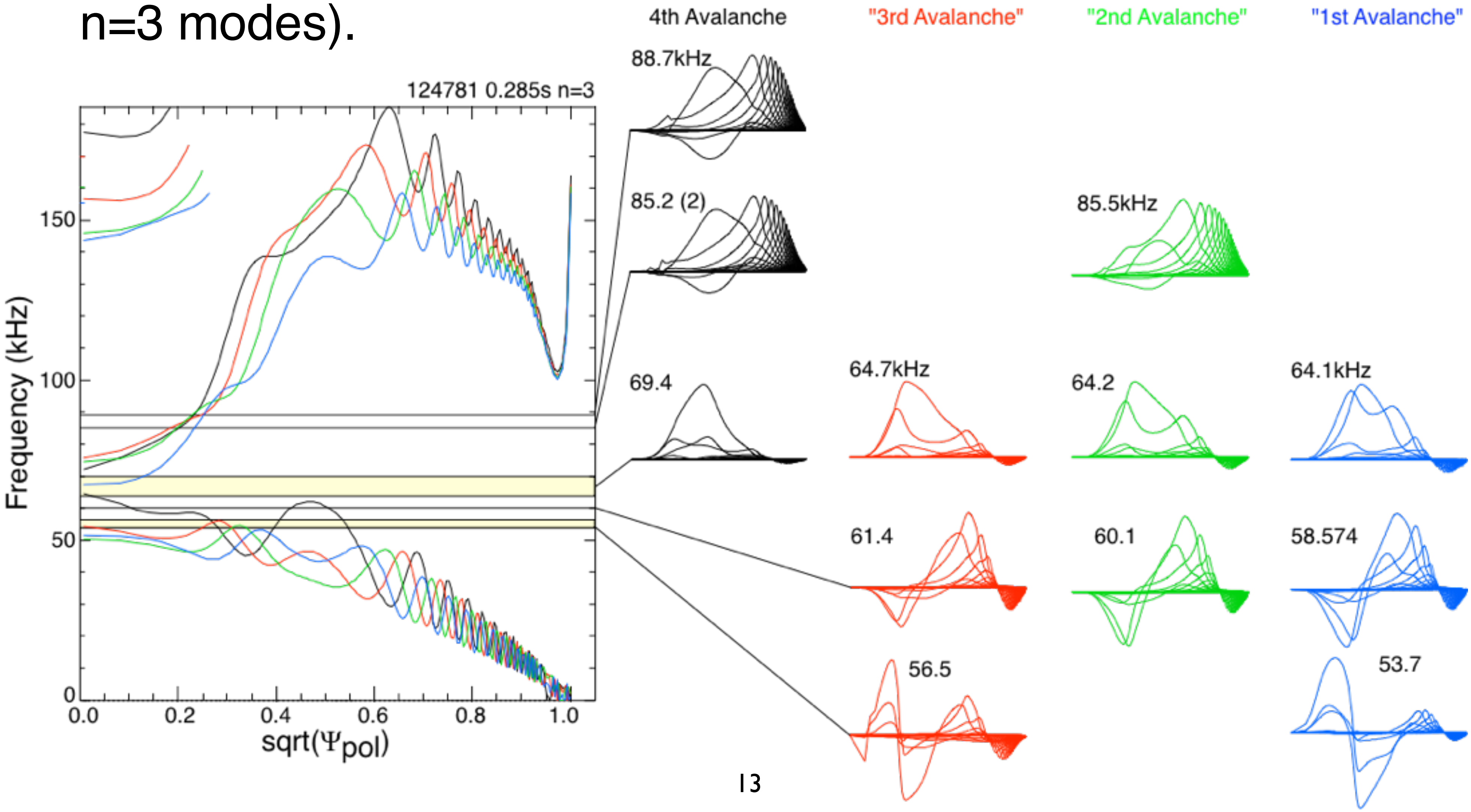


TAE Gaps Open/Close on Axis for "Small", $\delta q \approx 1/2n$, Changes

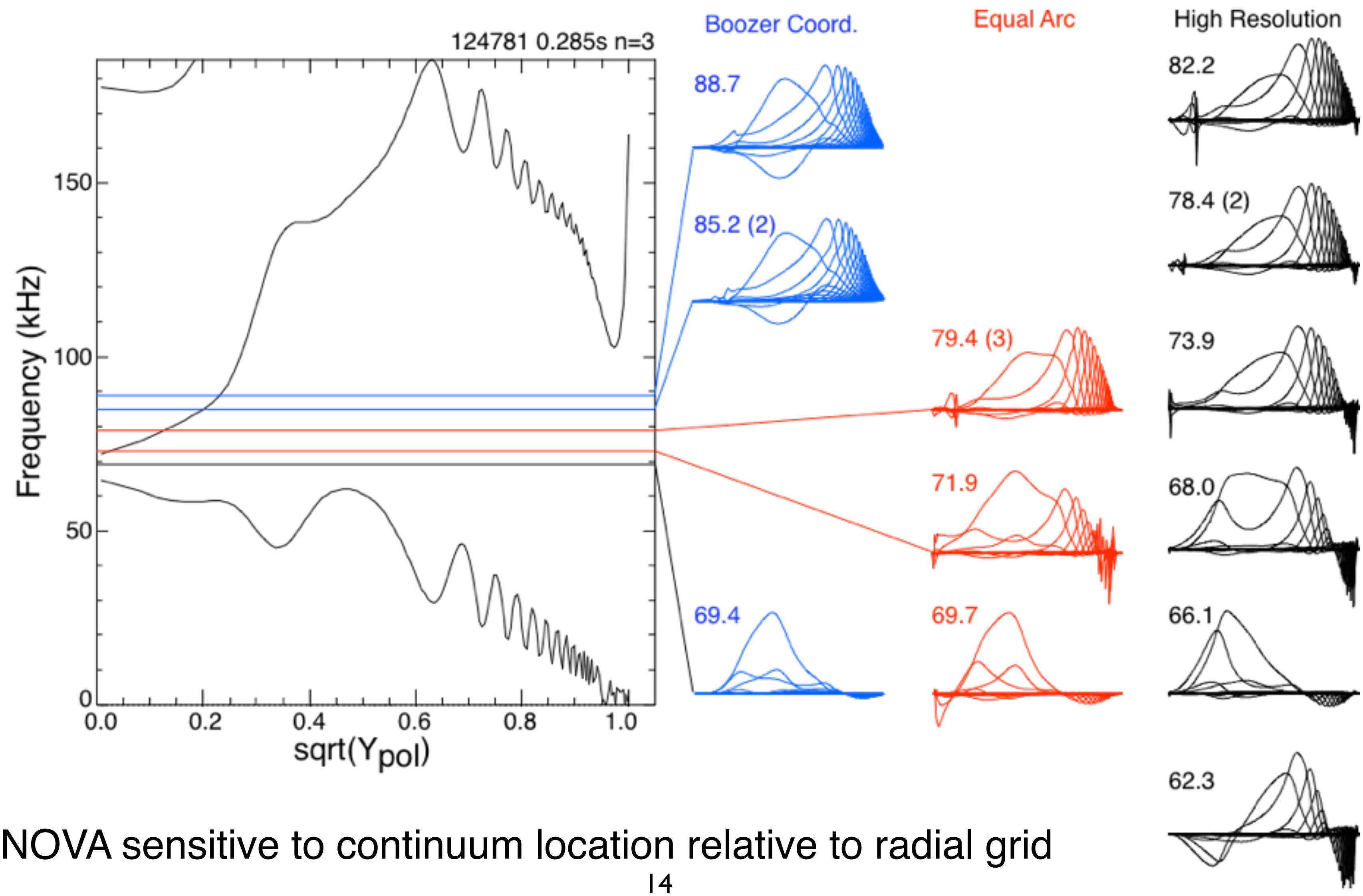
- Gaps for n=2, 3 and 4 modes open and close during q-profile evolution (without rotation shear!).
- Shaded regions show times when gaps are closed, modes should be weaker.
- Amplitude of n=4 consistent with gap evolution, n=2 and n=3 seem unaffected by gap closing.

TAE Gaps Open/Close on Axis as q(0) evolves

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



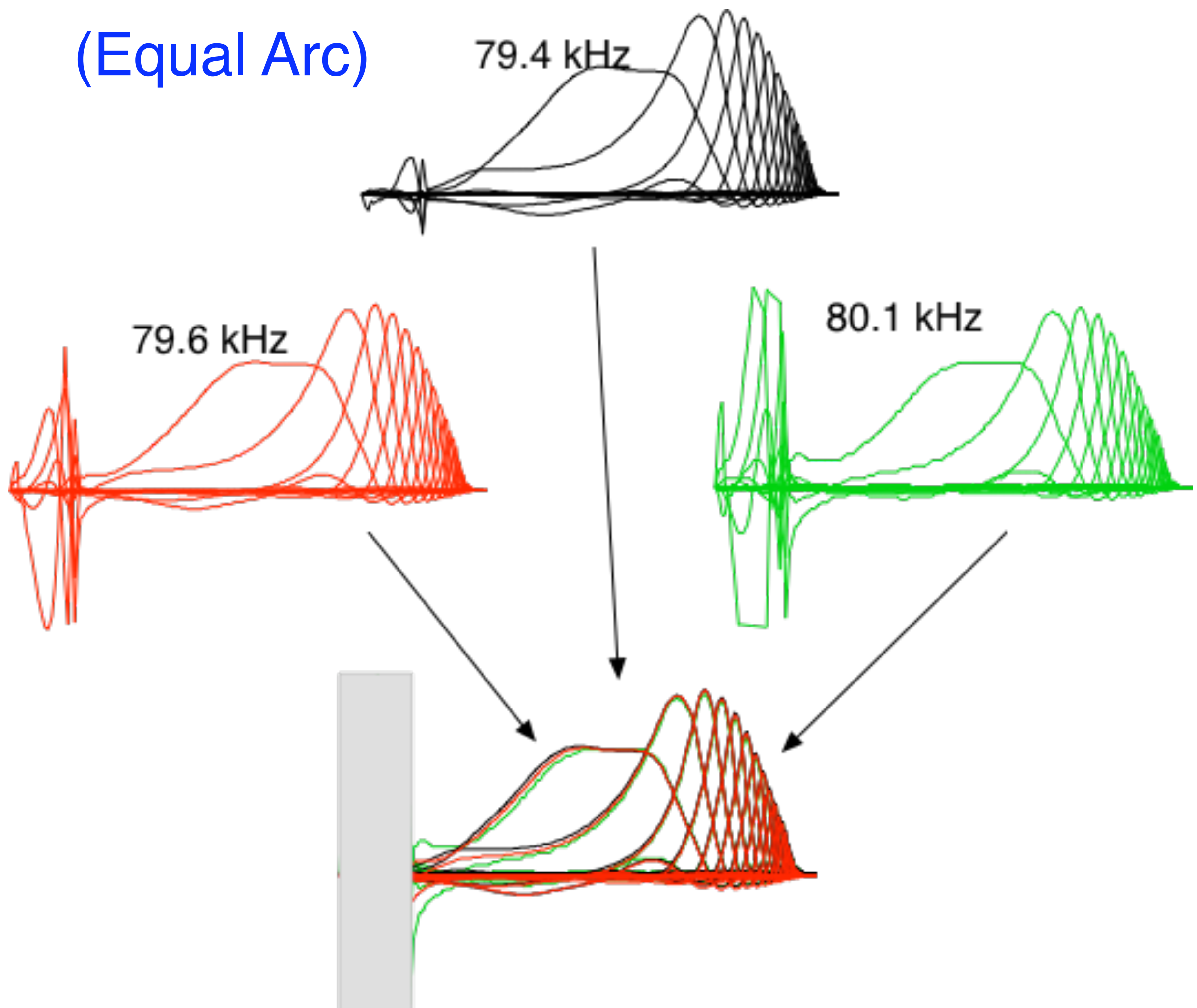
NOVA results very sensitive to choice of Boozer, Equal-Arc or higher radial resolution grids



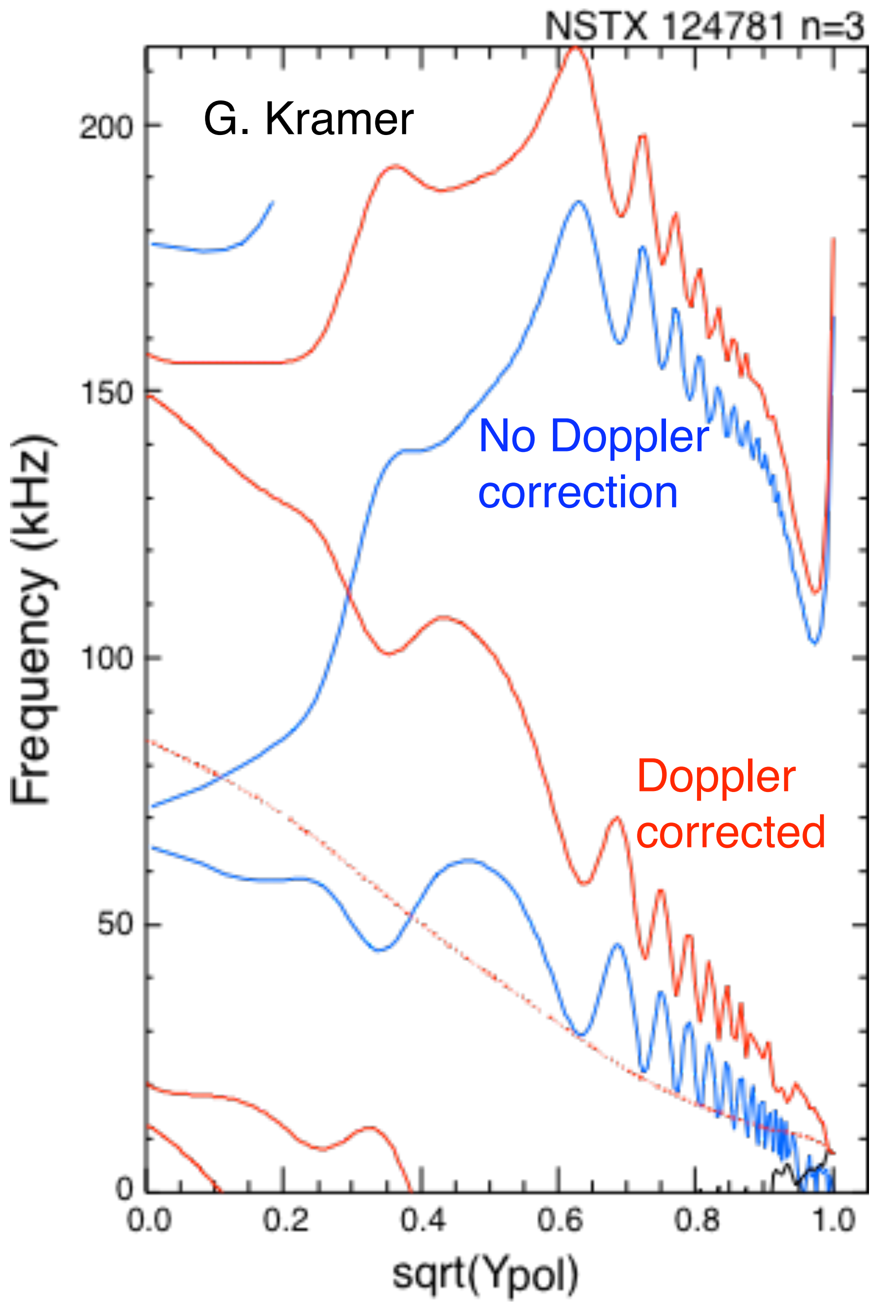
- *e.g.,* NOVA sensitive to continuum location relative to radial grid

Interaction with continuum introduces multiple degenerate eigenmodes

- These three nearly degenerate eigenmodes differ hardly at all in structure.
- The small differences could be attributed to matching across the continuum boundary where NOVA lacks the spatial resolution and physics to accurately find solutions.



Sheared rotation distorts TAE continuum



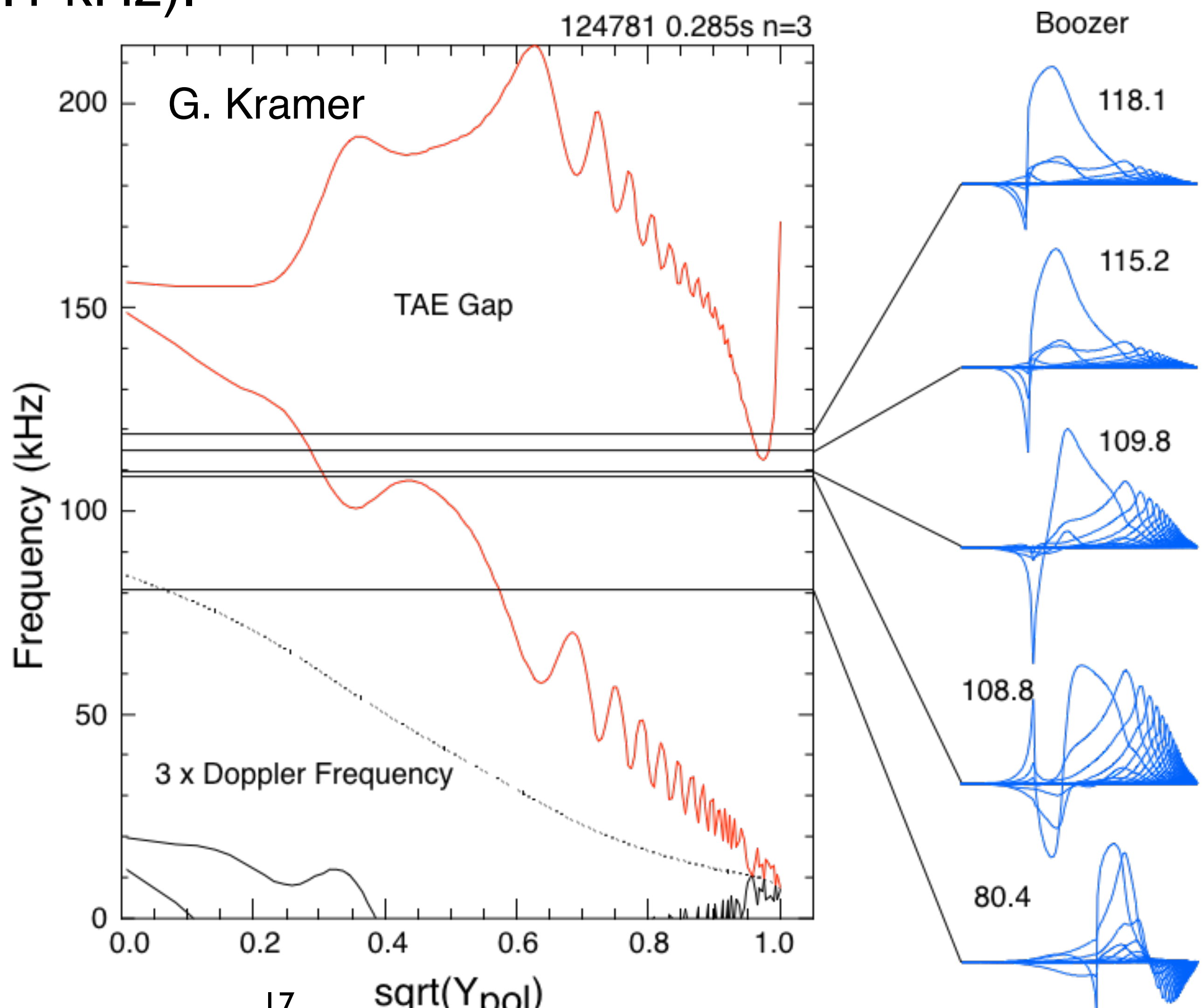
- Blue curves show n=3 Alfvén continuum neglecting sheared rotation.
- Solid red lines show continuum including rotation shear effects.
- Dashed red curve Doppler frequency for n=3 mode.
- Gap closed by rotation shear is insensitive to evolution of q(0).

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.

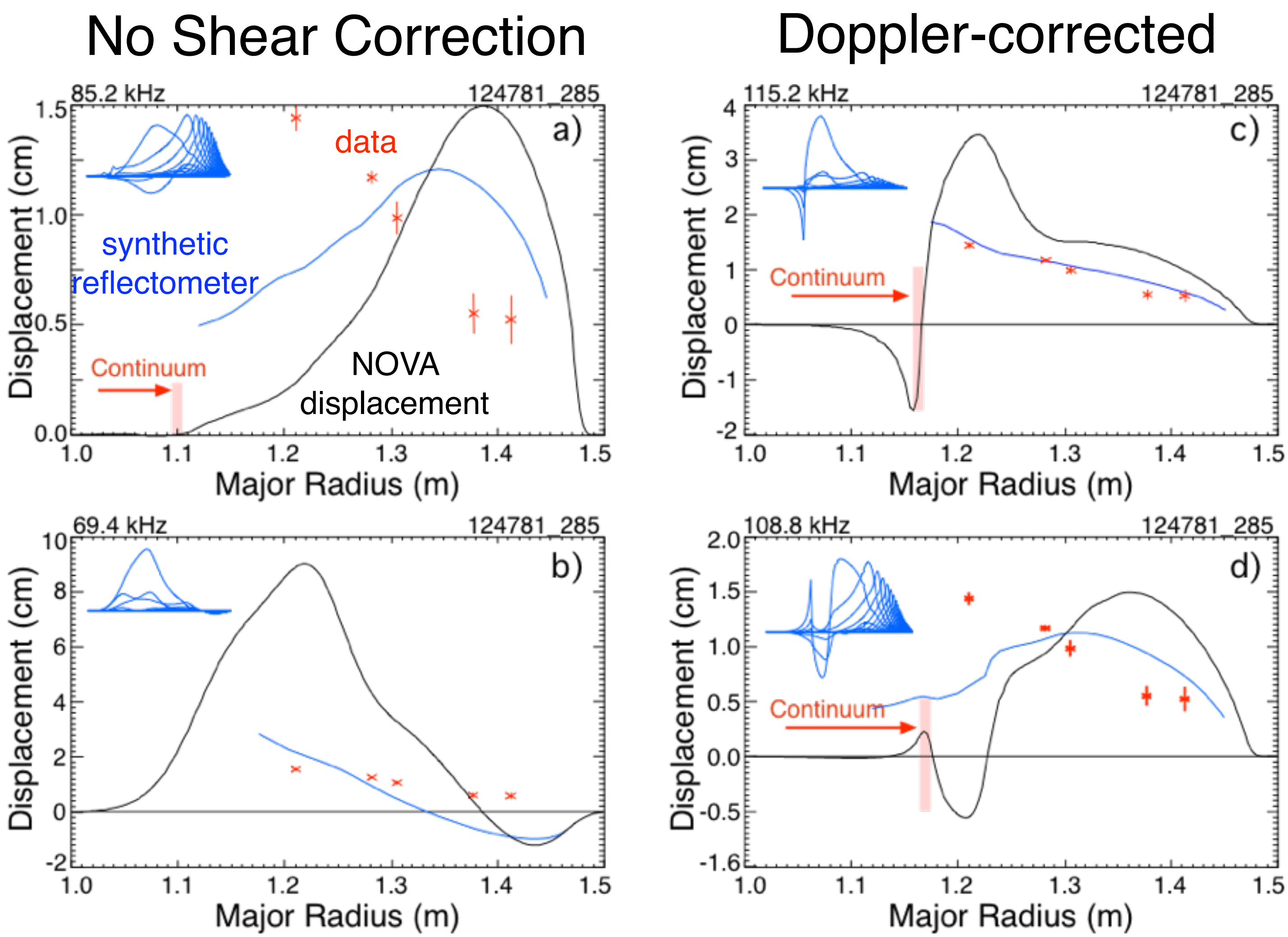
- Measured mode structures are used to select NOVA eigenmodes used in ORBIT simulations.



A NOVA Eigenmode, with Doppler correction, gives the best fit to reflectometer data

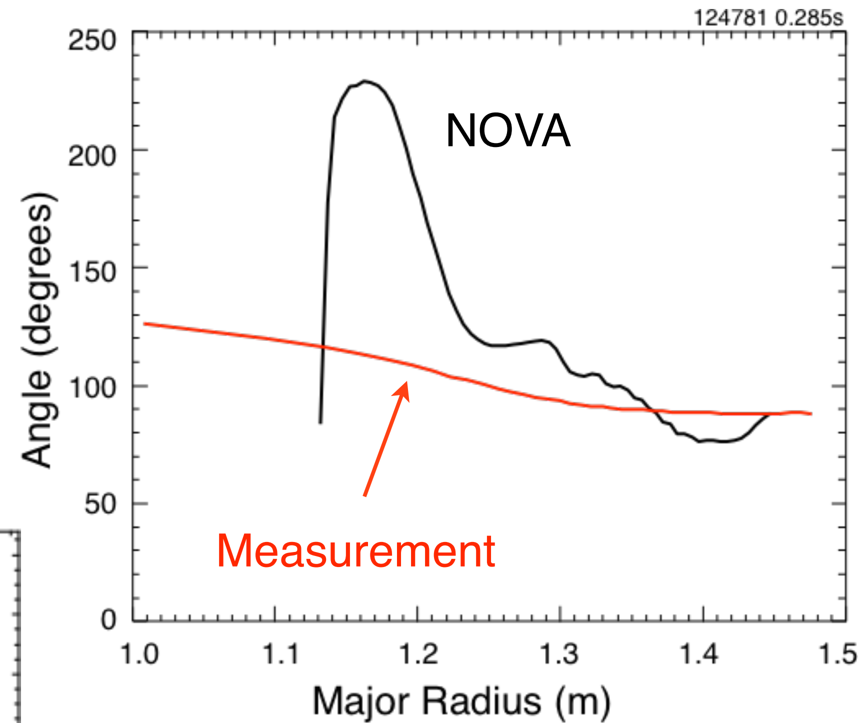
NSTX

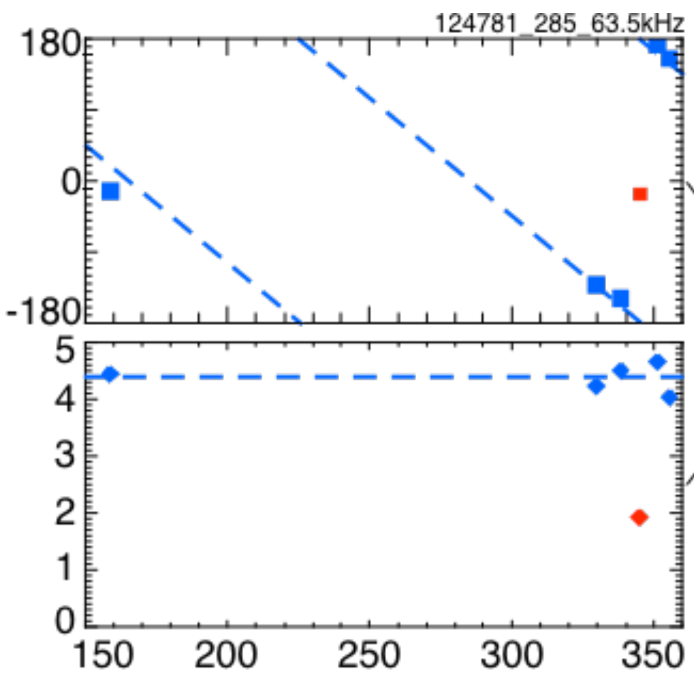
- No modes with good fit were found in non-sheared case.
- With shear, good fit was found to data.

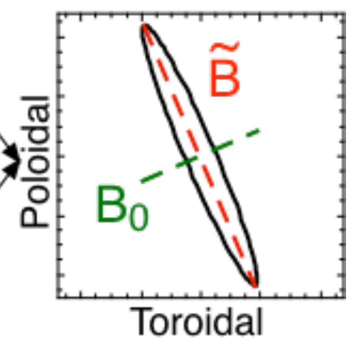


TAE have compressional components

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



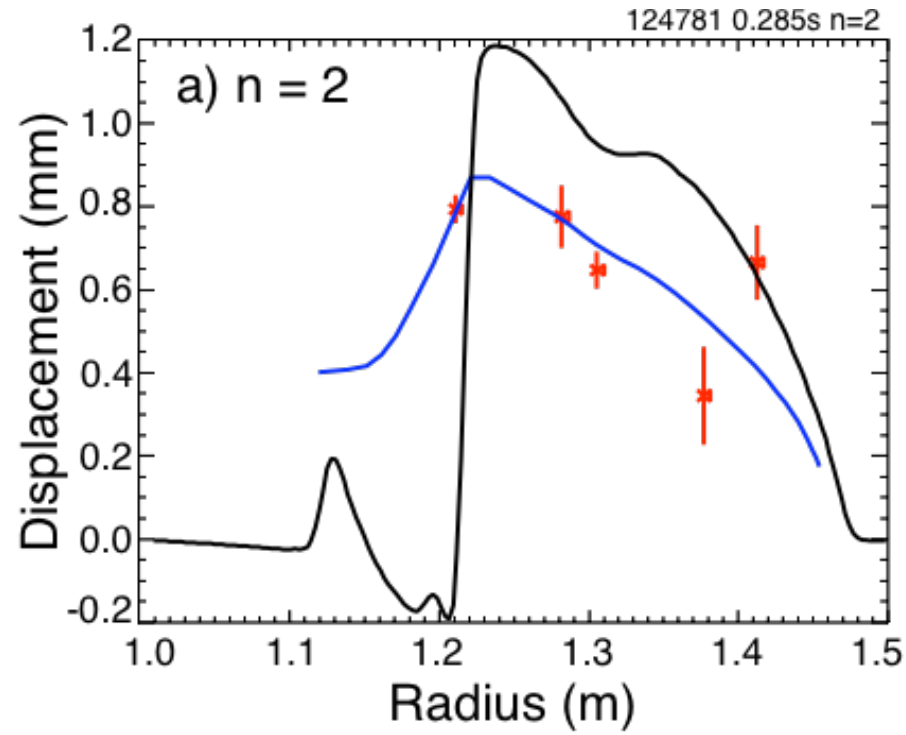


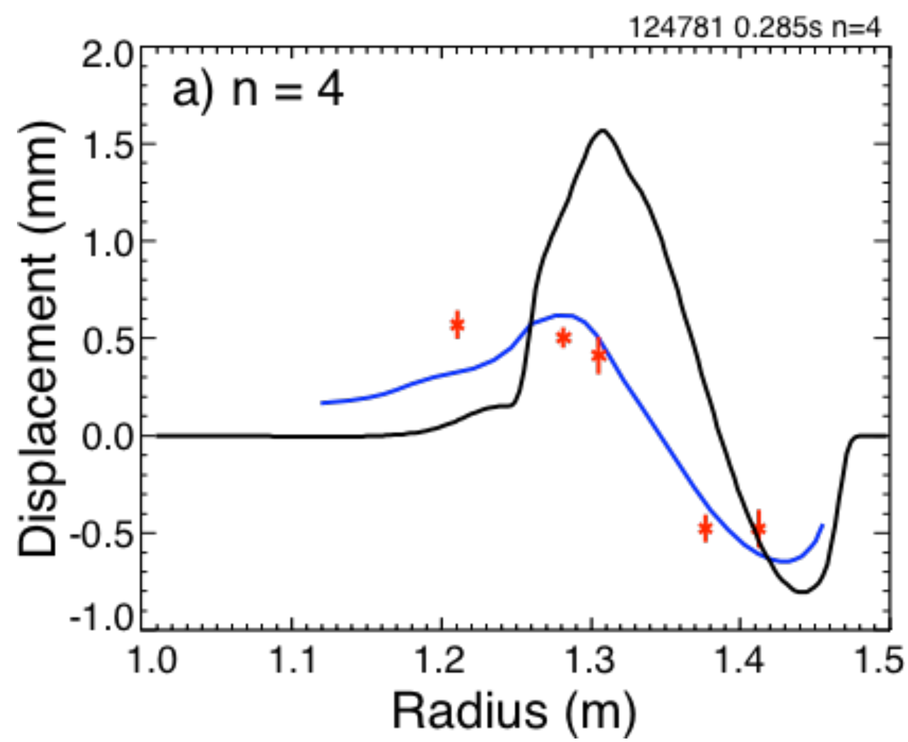


- Polarization in θ-φ plane measured with Mirnov coil array.

Good fits also found for n=2 and n=4 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.

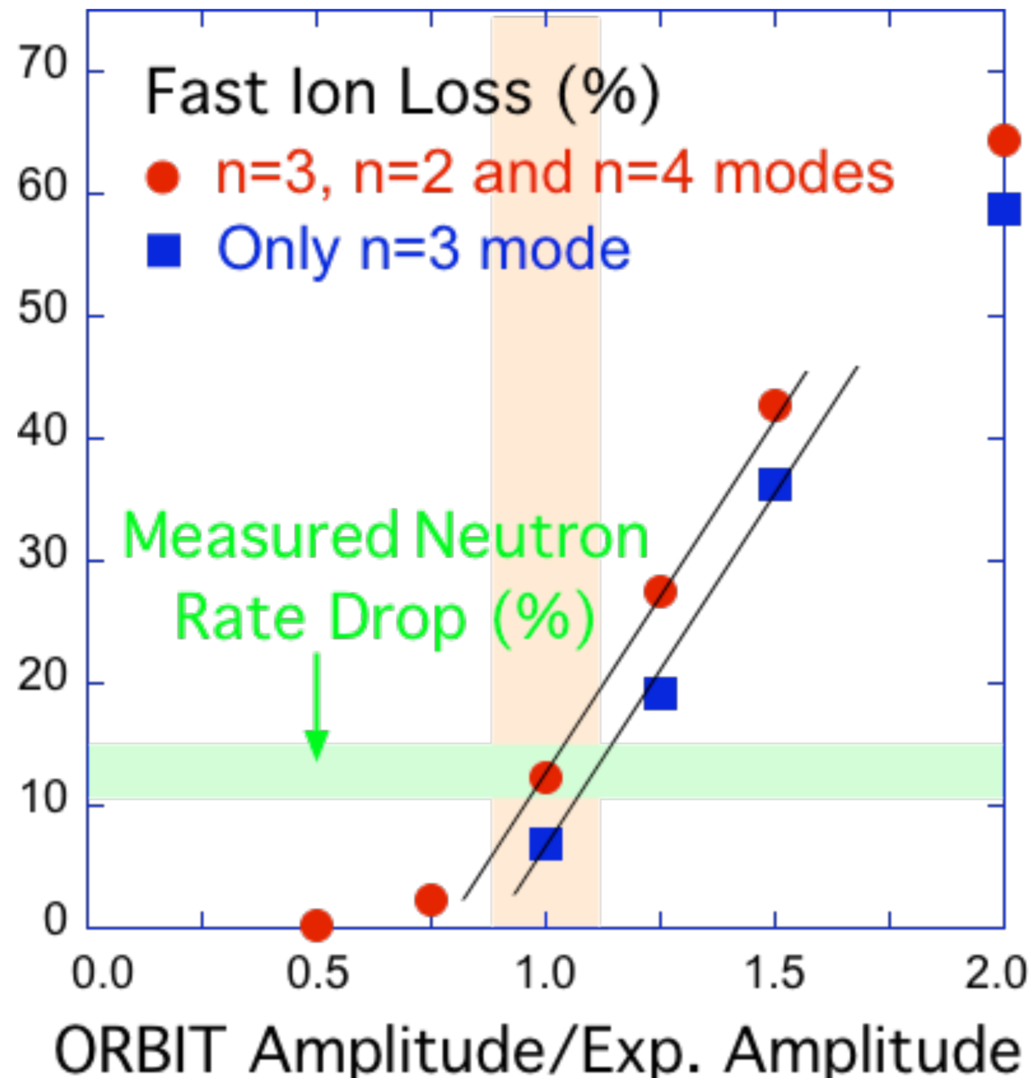




ORBIT simulations predict losses in good agreement with observed neutron rate drop

NSTX

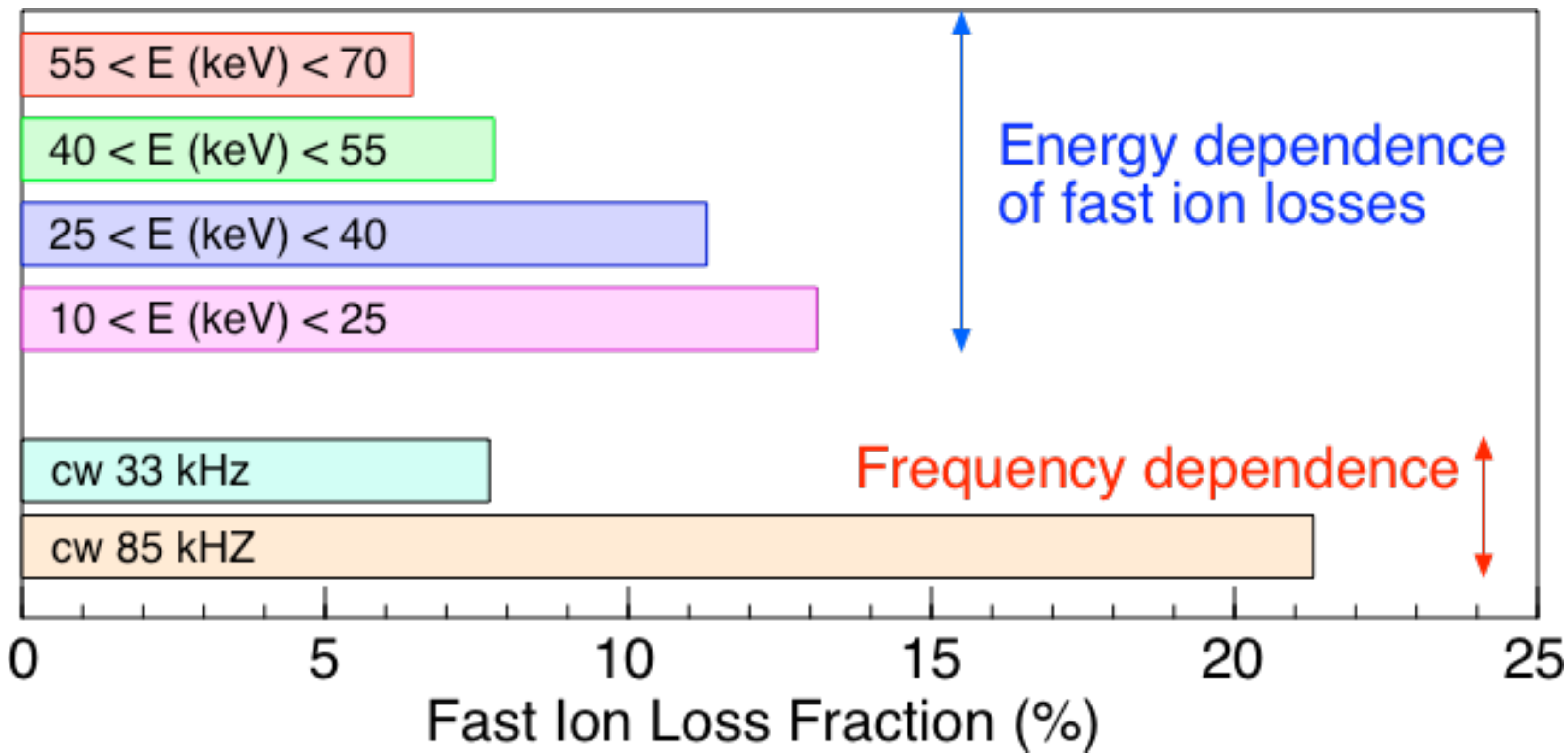
- ORBIT simulation is done for 1ms burst at 0.285s.
- Mode amplitude, frequency evolution in ORBIT are from experimental measurements.
- Mode structure from NOVA.
- Initial fast ion distribution is from unperturbed TRANSP calculation – not necessarily self-consistent.
- Losses are strongly non-linear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



Energy dependence and frequency dependence of losses also investigated

NSTX

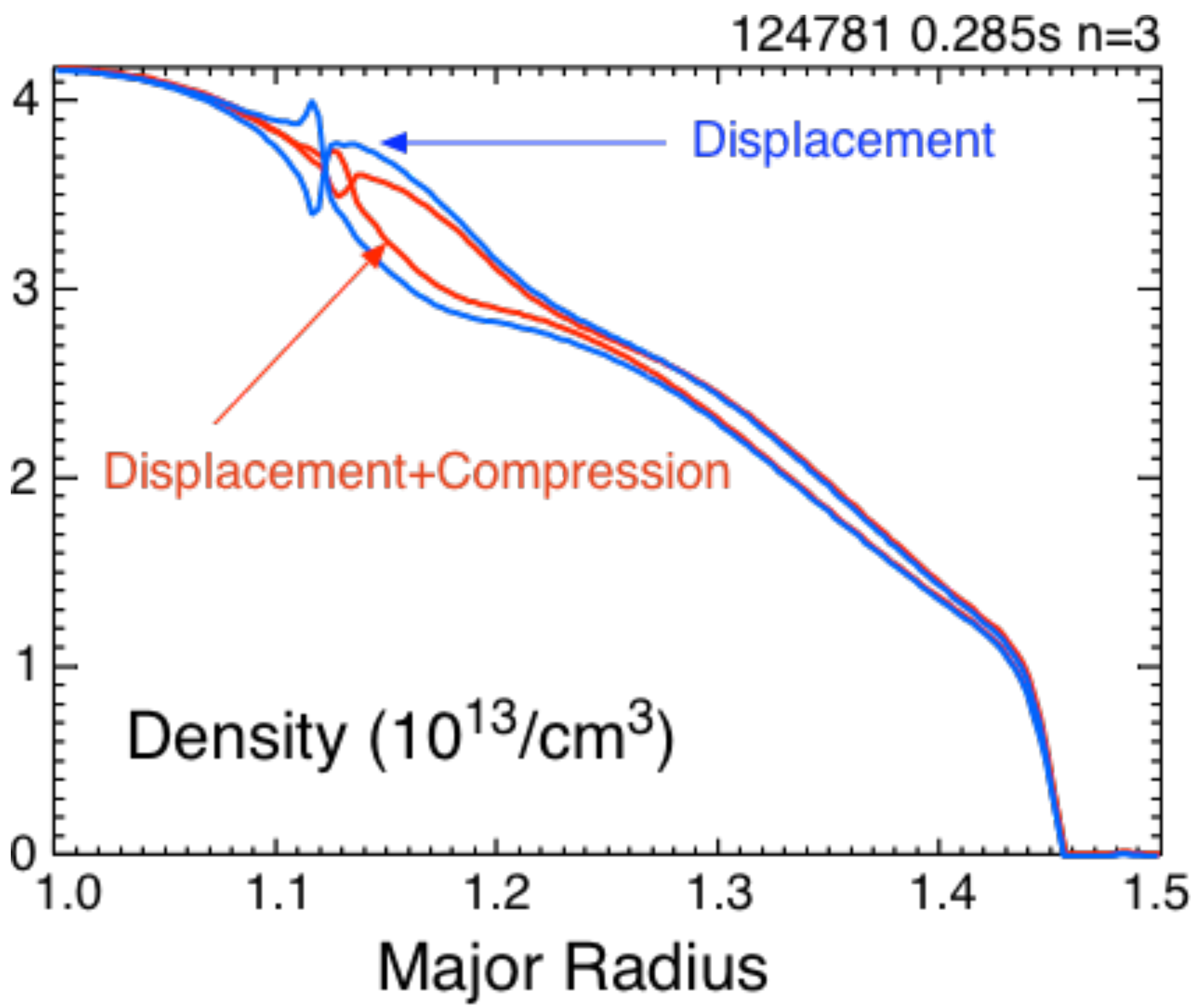
- Losses seen at all energies, consistent with NPA measurements, but more at low energy; important for beam-driven current calculations..
- Fast ion losses larger at higher frequencies; need to add sheared rotation to ORBIT simulations.



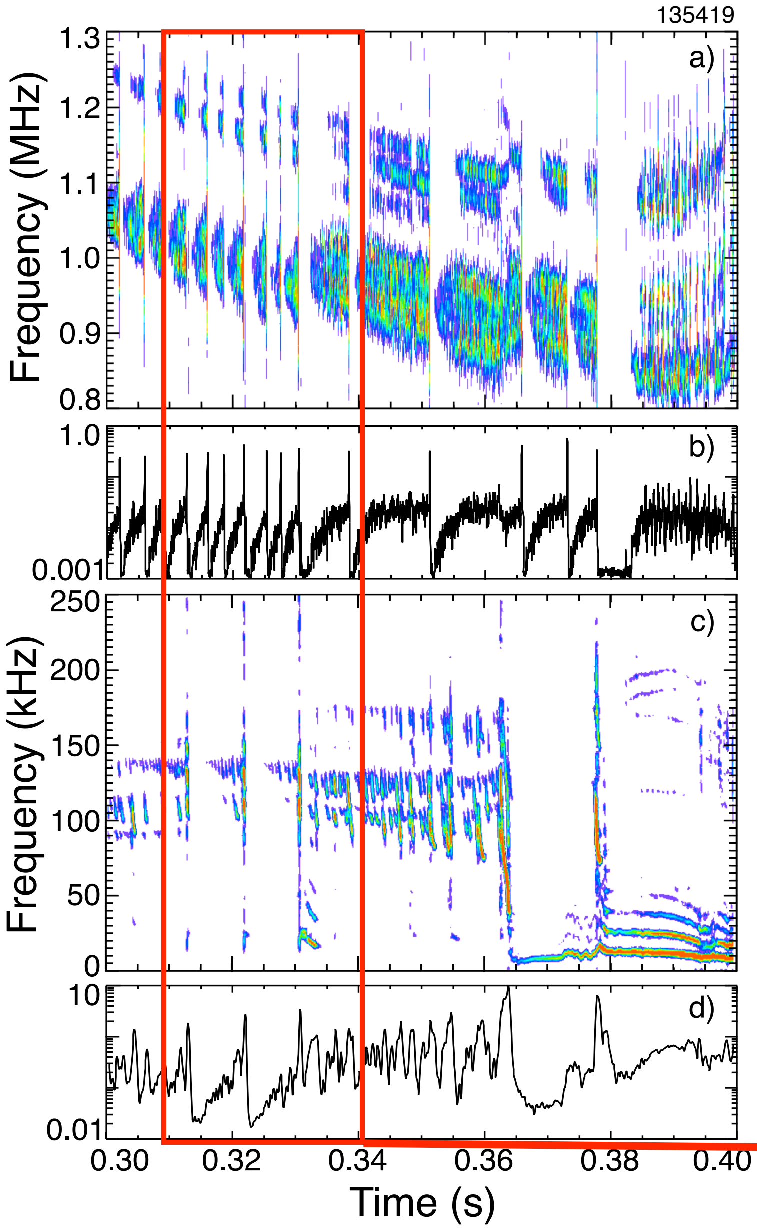
Density fluctuations for n=3 are very large at peak mode amplitude

NSTX

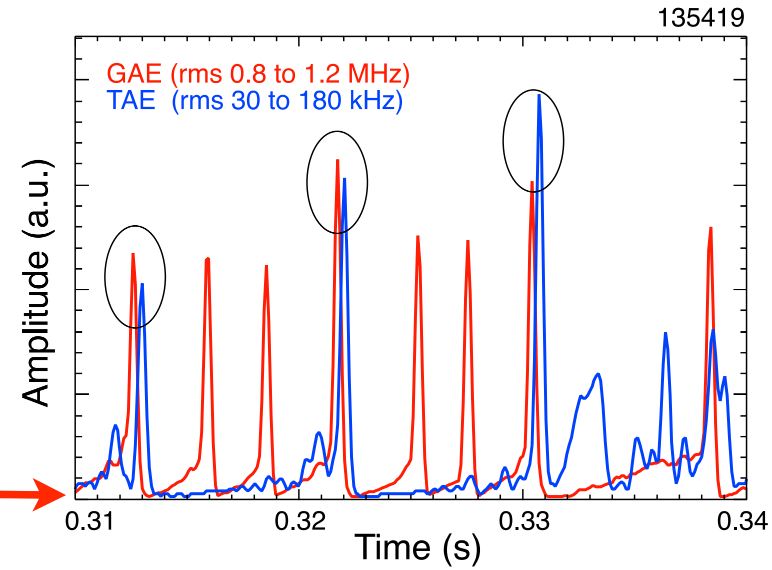
- Blue curve show density perturbation with only displacement, red curve shows perturbation with both displacement and compression.
- Density perturbation even larger on inboard side.
- Should be measureable with Thomson Scattering.
- Difficult to imagine larger modes…



GAE avalanches trigger for TAE avalanches?



- Fast-ion driven modes by definition move fast ions in phase-space.
- Not all GAE avalanches trigger TAE avalanches; must be near threshold?
- GAE avalanche very close to TAE avalanche; early enough to be trigger?



ORBIT/NOVA simulations of fast ion losses qualitatively consistent with experiment

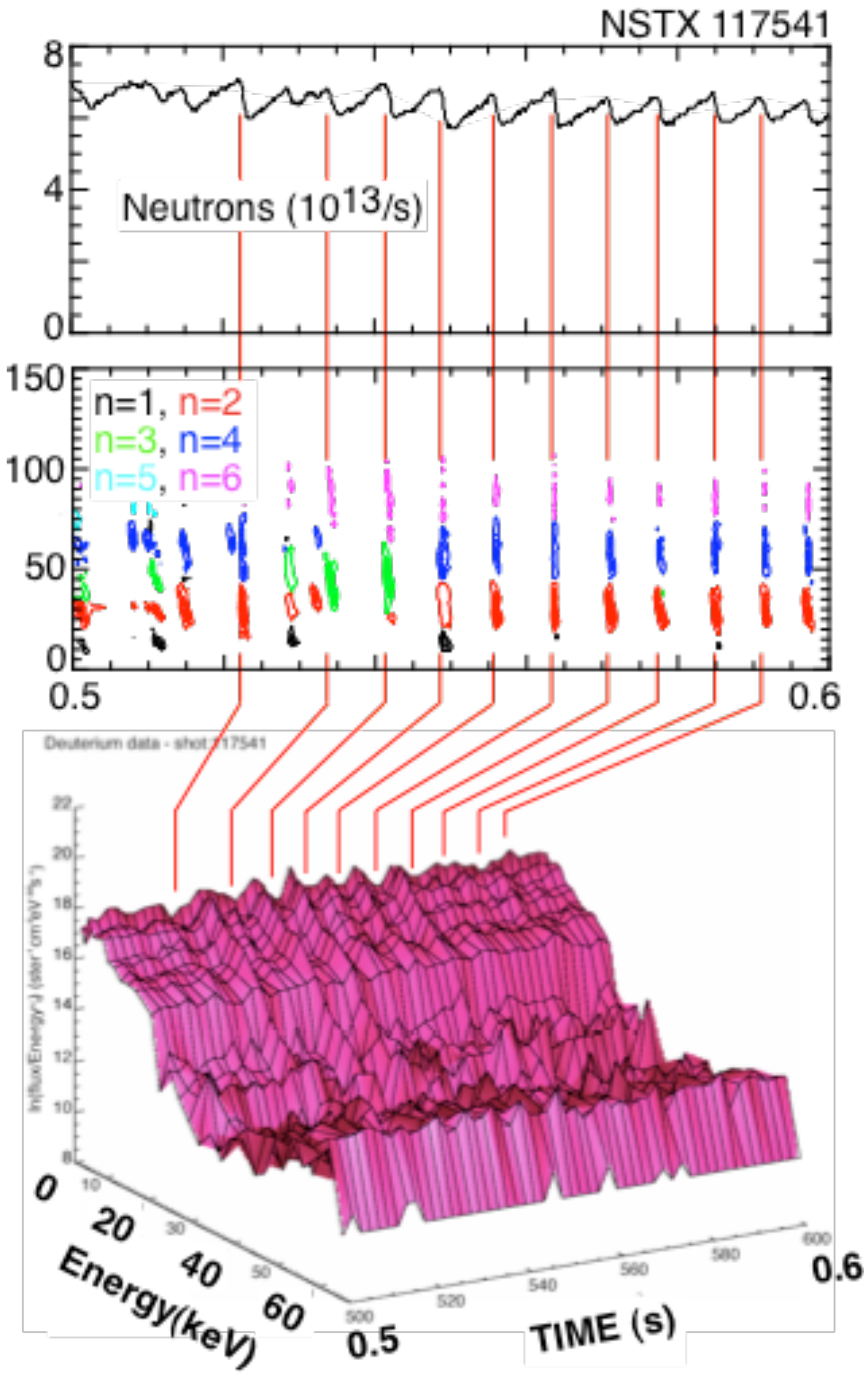
NSTX

- Fast ion transport from TAE avalanches studied on NSTX
  - Transient losses of ≈10% of fast ions are inferred.
  - Similar loss mechanism possible on ITER.
- TAE structure and onset frequency consistent with NOVA simulations.
  - No significant non-linear changes to mode structure are seen as mode grows and saturates.
- Tracking changes in modes through small equilibrium changes with NOVA can be difficult.
  - Interaction with continuum possibly not well modeled.
  - Drive very strong in NSTX, continuum damping not so important?
  - Multiple modes found in NOVA; which ones in experiment? Spectrum of modes defined from experimental data.
- Sheared rotation physics incomplete in NOVA, not used in ORBIT
  - Rotation probably enhances continuum interactions in NSTX
- Separatrix also not modeled in NOVA, needs further work.

Both precession drift and bounce resonant Energetic Particle Modes (‘fishbones’) seen

NSTX

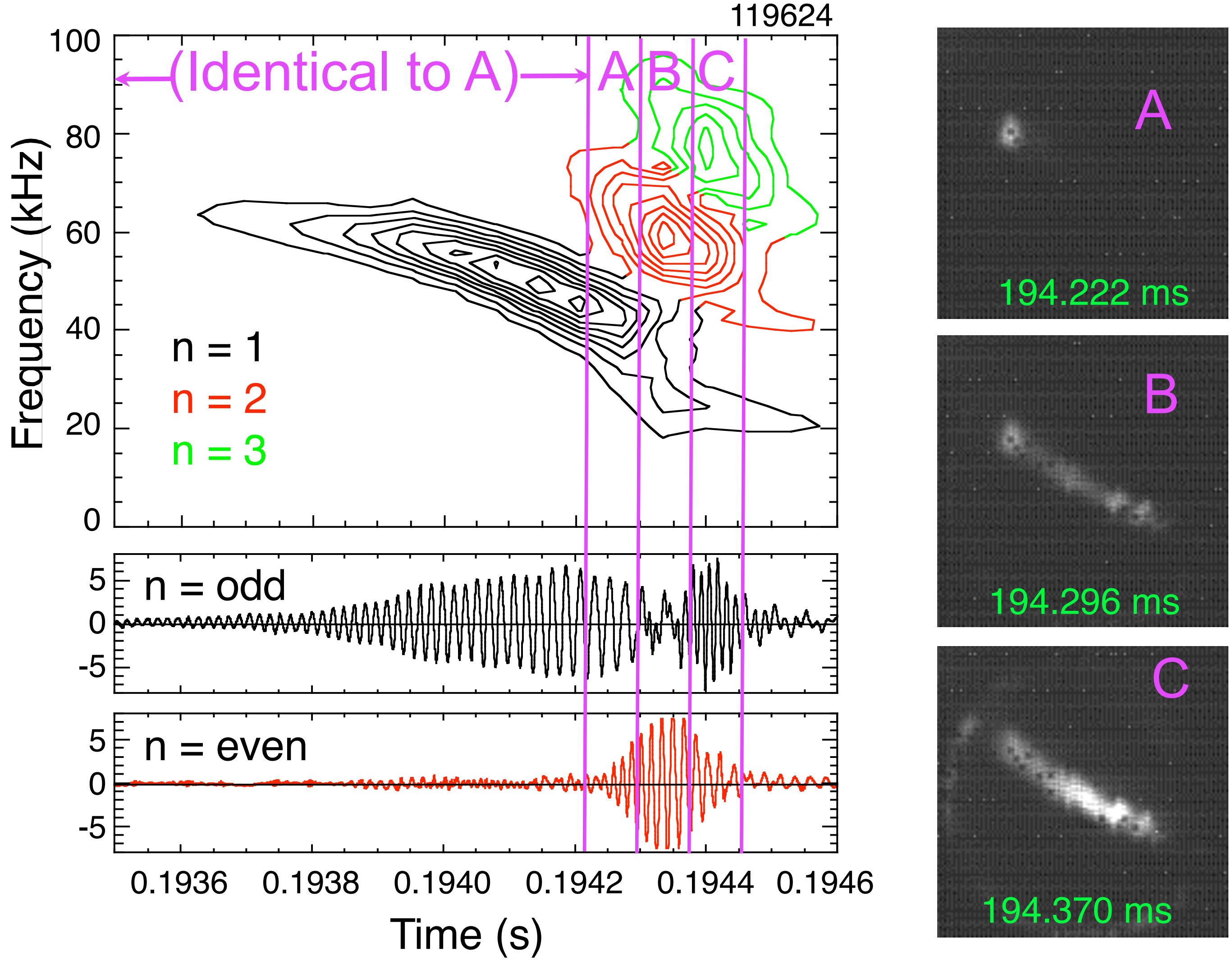
- The core rotation frequency is typically greater than the precession frequency, and comparable to the bounce frequency.
- The high rotation frequency makes definition of “mode frequency” difficult, mixes ideal, BAAE, BAE and TAE frequency bands.
- Strongly chirping modes are seen over the frequency range from a few kHz up to 100 kHz, at which time the EPMs are interacting with the “first” TAE gap.
- Modes have toroidal numbers in the range $1 \leq n \leq 6$, of apparently several different types.
- Coupling to higher toroidal harmonics is common.
- Some of these modes, often combined with TAE avalanches, are responsible for the largest fast ion losses on NSTX.



Fast ions affected over all energies

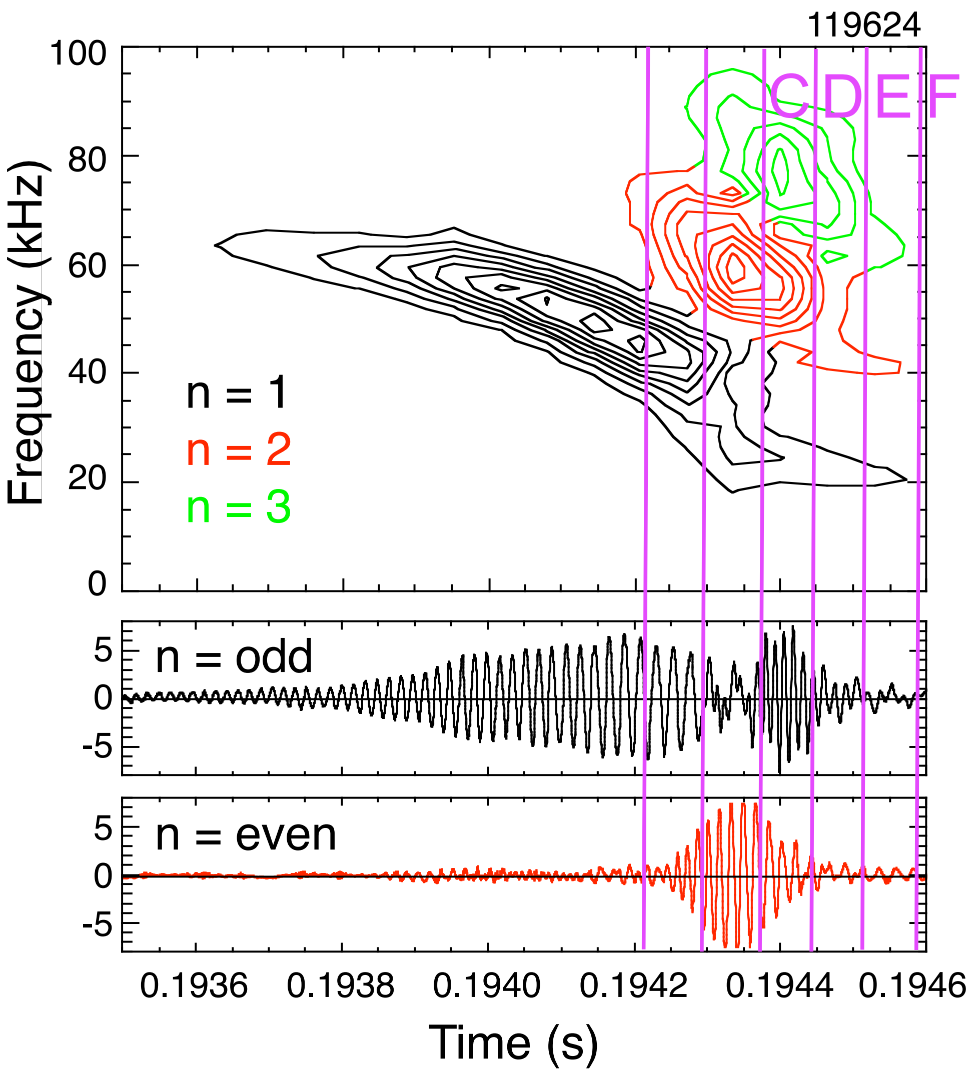
- NPA measures redistribution, not necessarily losses
- Strongest modulation is seen for lowest energies; below the "half" energy.
- Neutron drops of 10% suggest high energy ions also lost.
- Broad range of energy interaction consistent with bounce-resonances.

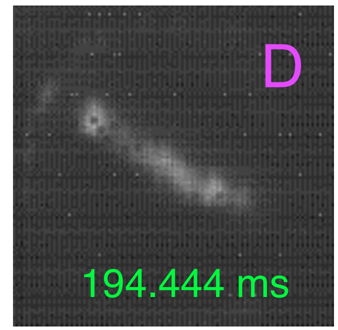
Loss in broad pitch range when modes overlap

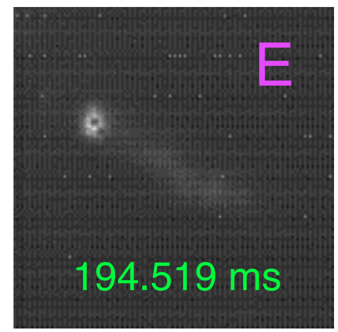


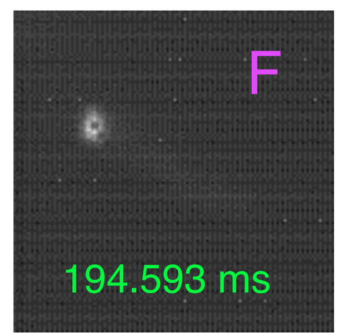
- Peak in fast ion losses correlated with multi-mode period.

Broad pitch loss gone after mode overlap ends



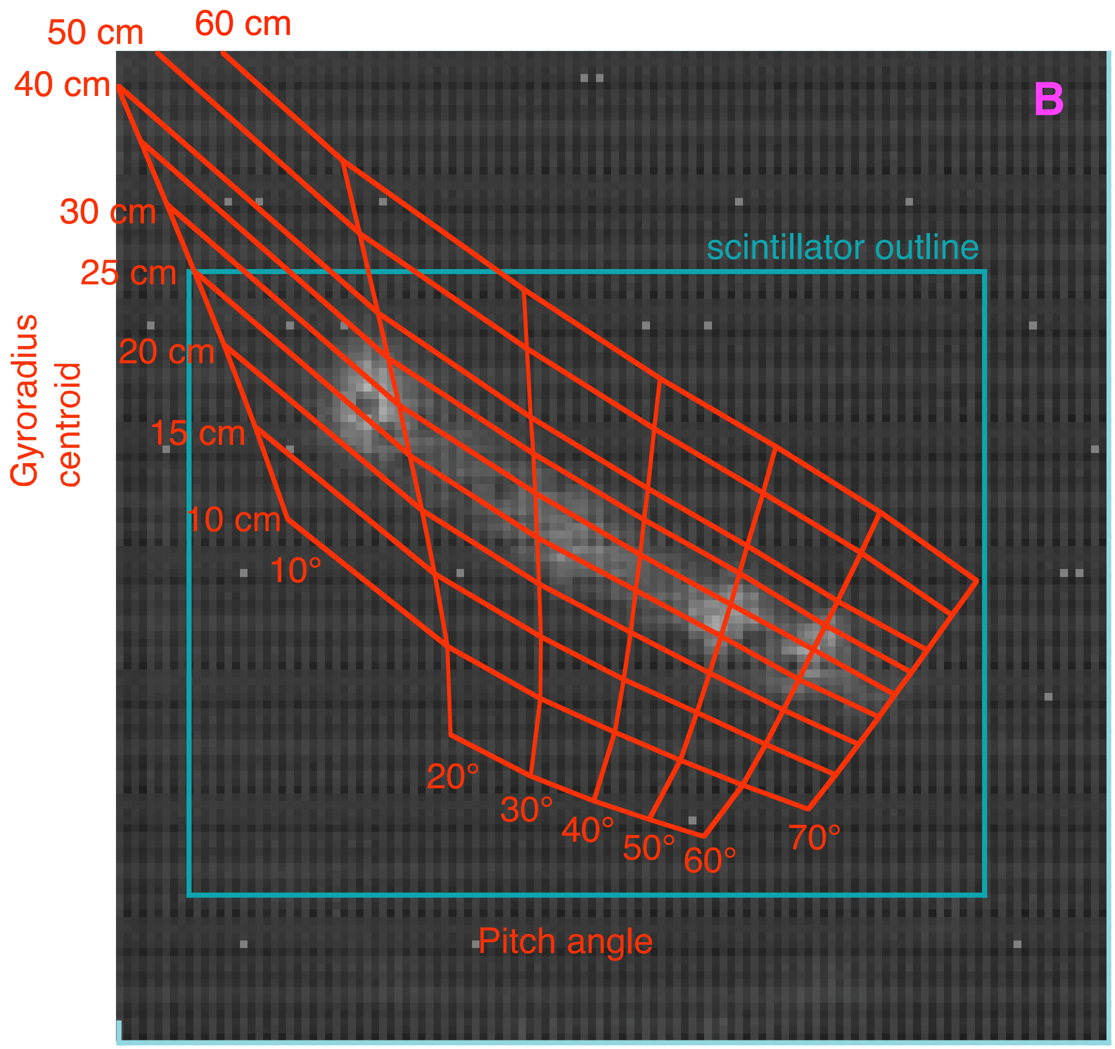






- Returns to pre-burst steady prompt loss spot

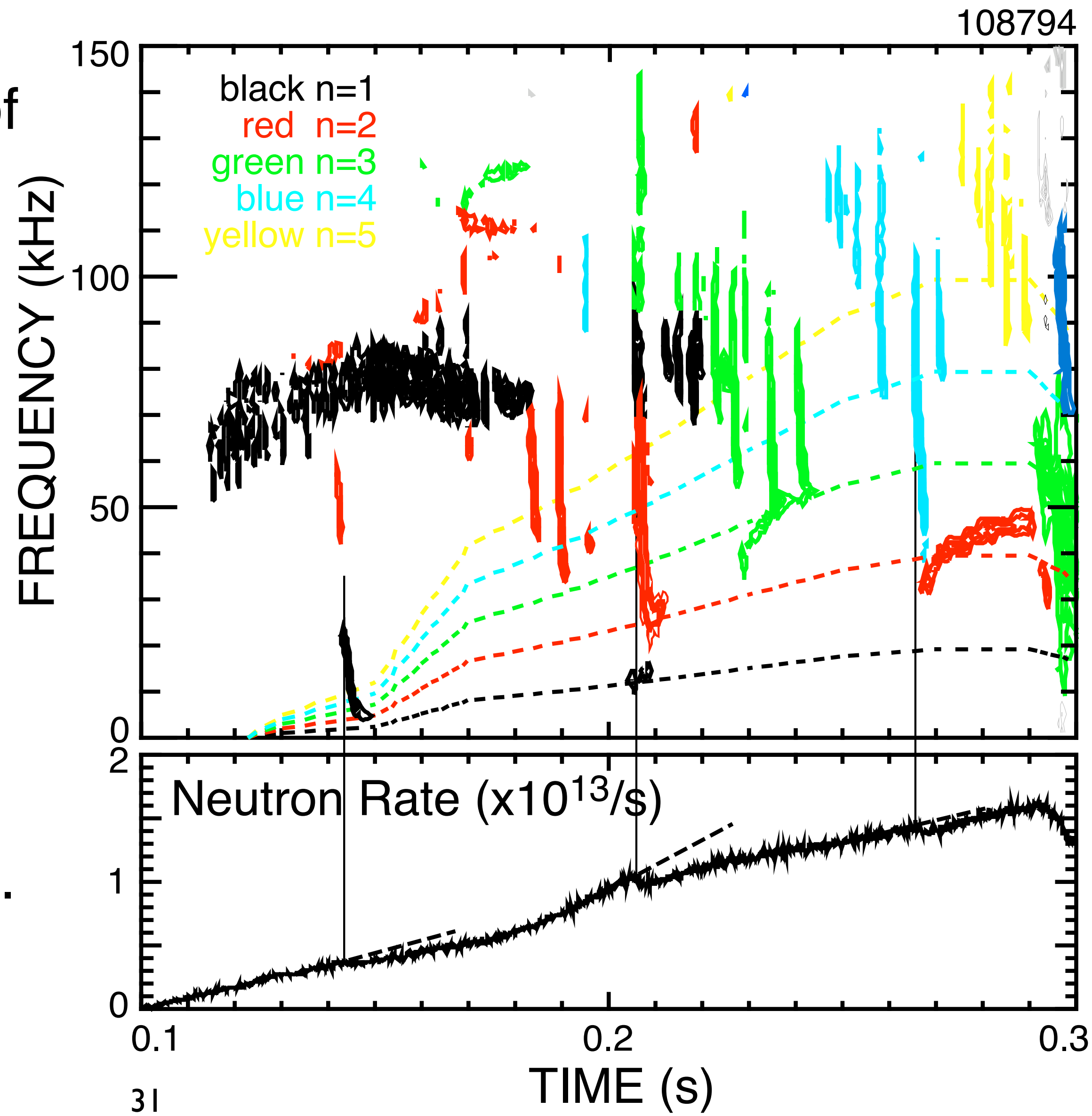
All losses near injection energy



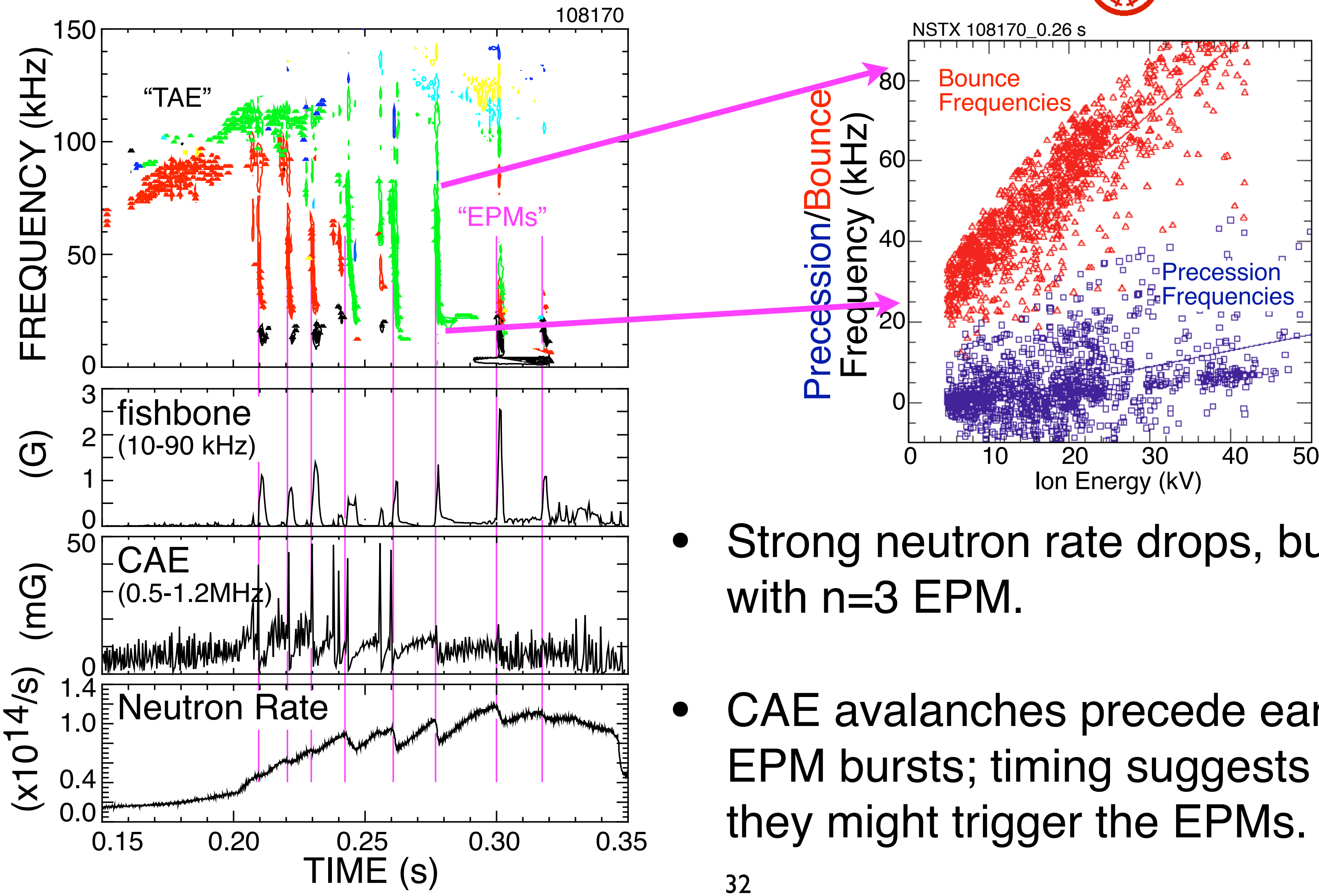
- All pitch angles are at $r_{Larmor} \approx$ 25cm.
- Predict ≈ 20cm @90 keV at this condition.
- Discrepancy most likely due to residual calibration errors, not mode physics.

EPMs with n > 1 are also seen

- Mode frequencies at ends of chirps are consistent with rotation frequency near core.
- Frequency chirps start in TAE gap.
- Toroidal mode number progresses upwards from n=1 to n=5 through a series of multiple bursts for each n.



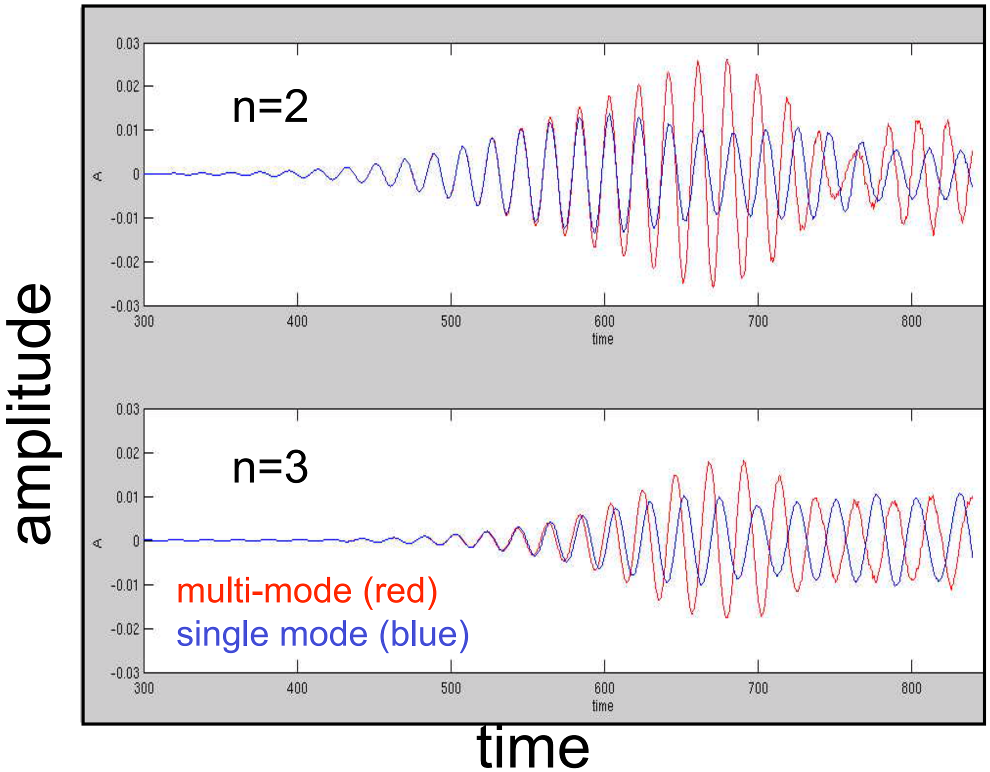
Range of frequency chirps matches range of bounce frequencies



- Strong neutron rate drops, but only with n=3 EPM.
- CAE avalanches precede earlier EPM bursts; timing suggests that they might trigger the EPMs.

M3D-K self-consistently models multi-mode TAE

- Mode amplitude larger in multi-mode simulation (red).
- Individual modes saturate at lower amplitude.
- Simulation also reproduces frequency chirping

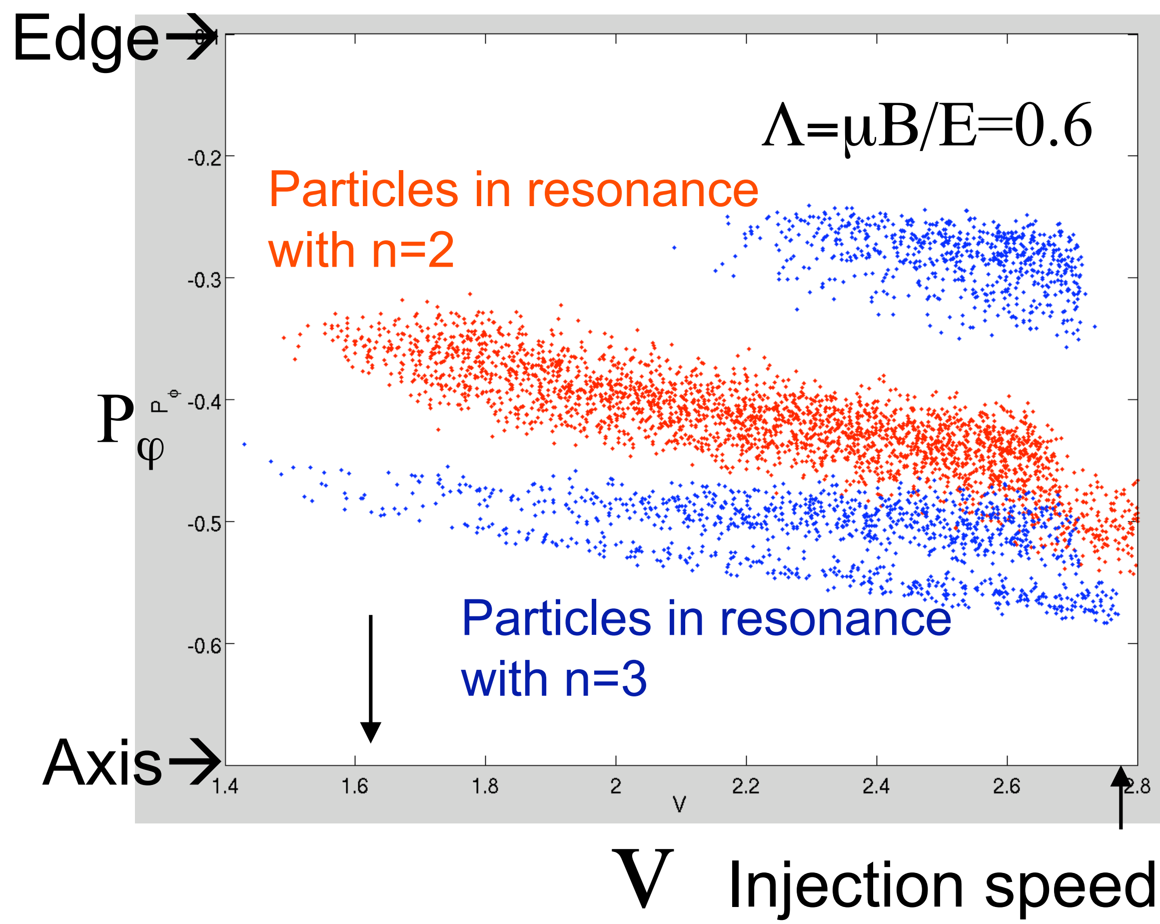


M3D-k simulation captures physics of avalanche

- Modes interact with broad range of fast ion energies; consistent with NPA measurements.

- Fast-ion resonances from single mode simulations show that resonances can (do) overlap.

- Multiple resonances are seen for n=3 mode.

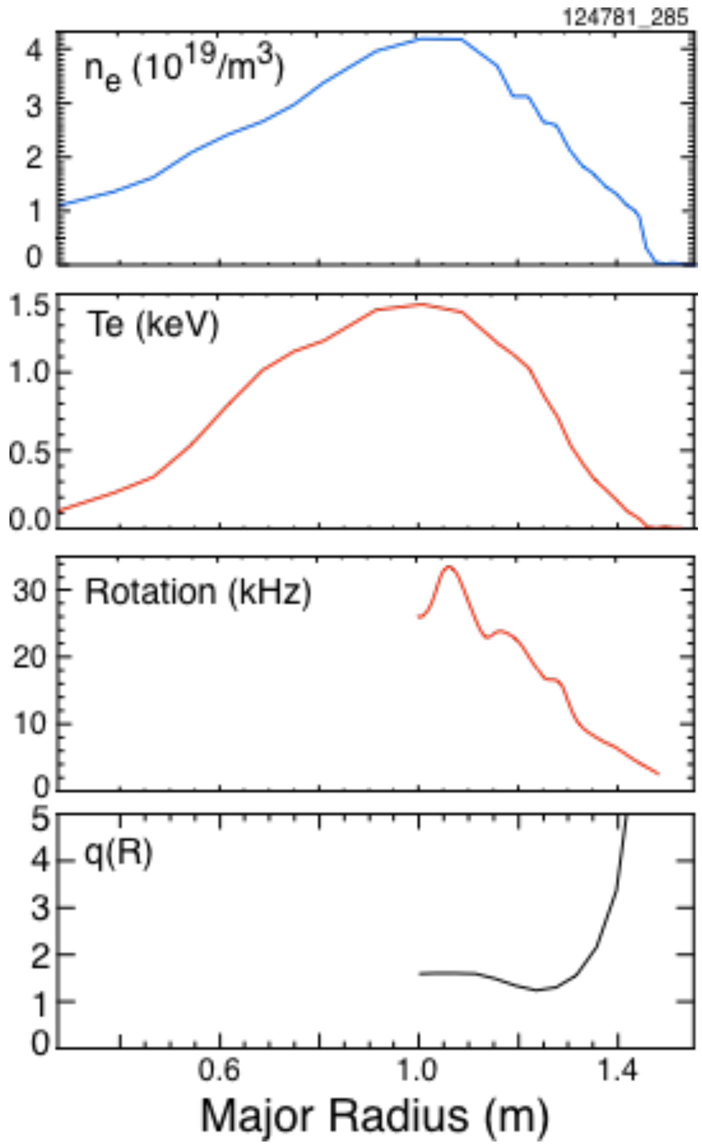


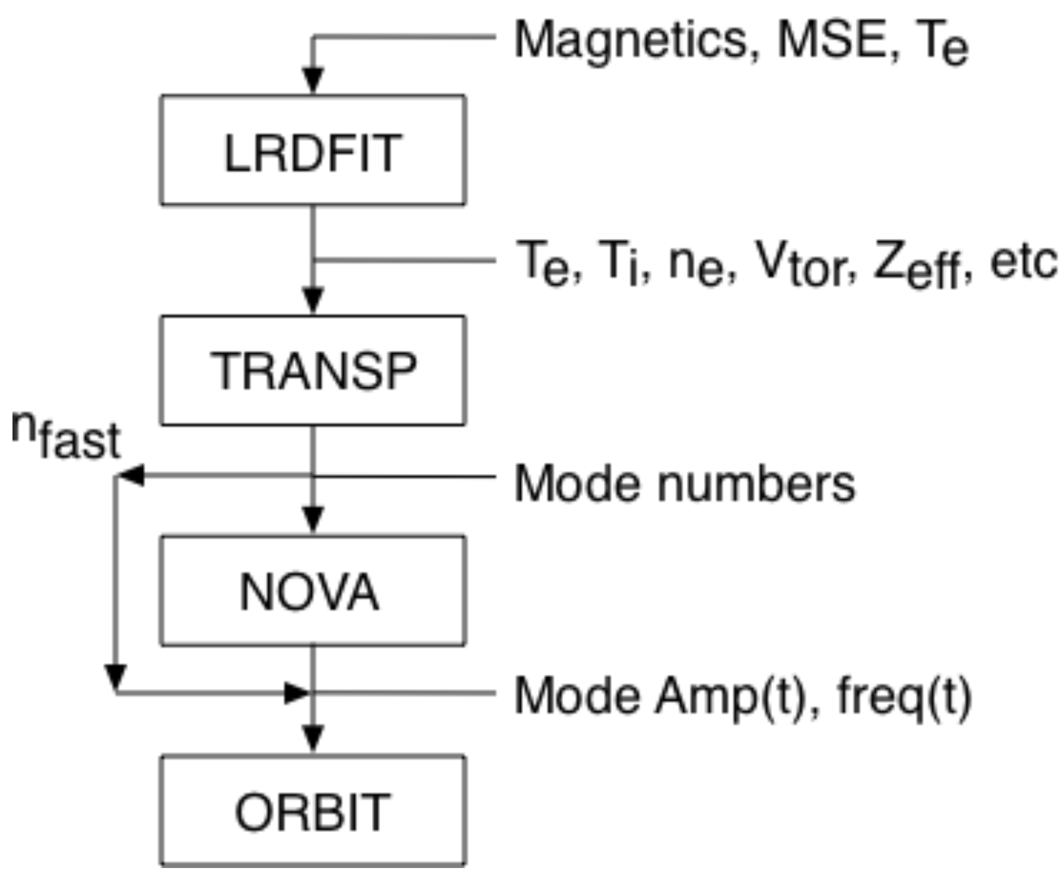
- Simulation is for "generic" NSTX equilibrium; benchmarking for same equlibrium between NOVA and M3D is underway.

Issues for future work

- More complete physics model for NOVA?
  - Better model of sheared rotation
  - Better treatment of continuum interactions
  - Better modeling of plasma edge (separatrix)
  - Use NOVA-k for linear stability analysis
- Full-orbit simulations
  - inclusion of error fields?
  - Include rotation
- Fully consistent, non-linear simulations (M3D-k)
  - Simulations on this equilibrium have been started (G. Fu)
- New experimental data
  - “Perpendicular” FIDA data from 2008
  - “Parallel” FIDA diagnostic in 2009
  - BES diagnostic in 2010 (better spatial resolution)

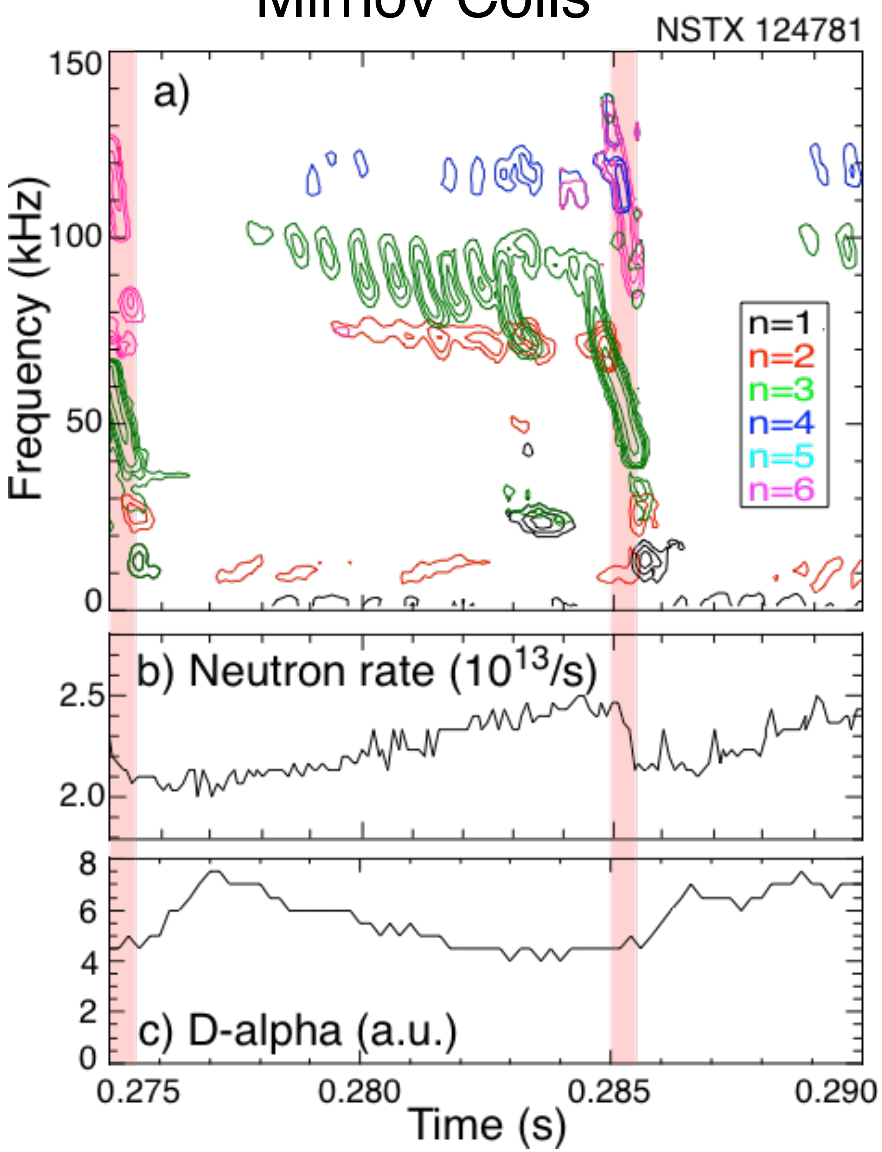
Analysis starts with equilibrium data, uses TRANSP, NOVA and ORBIT





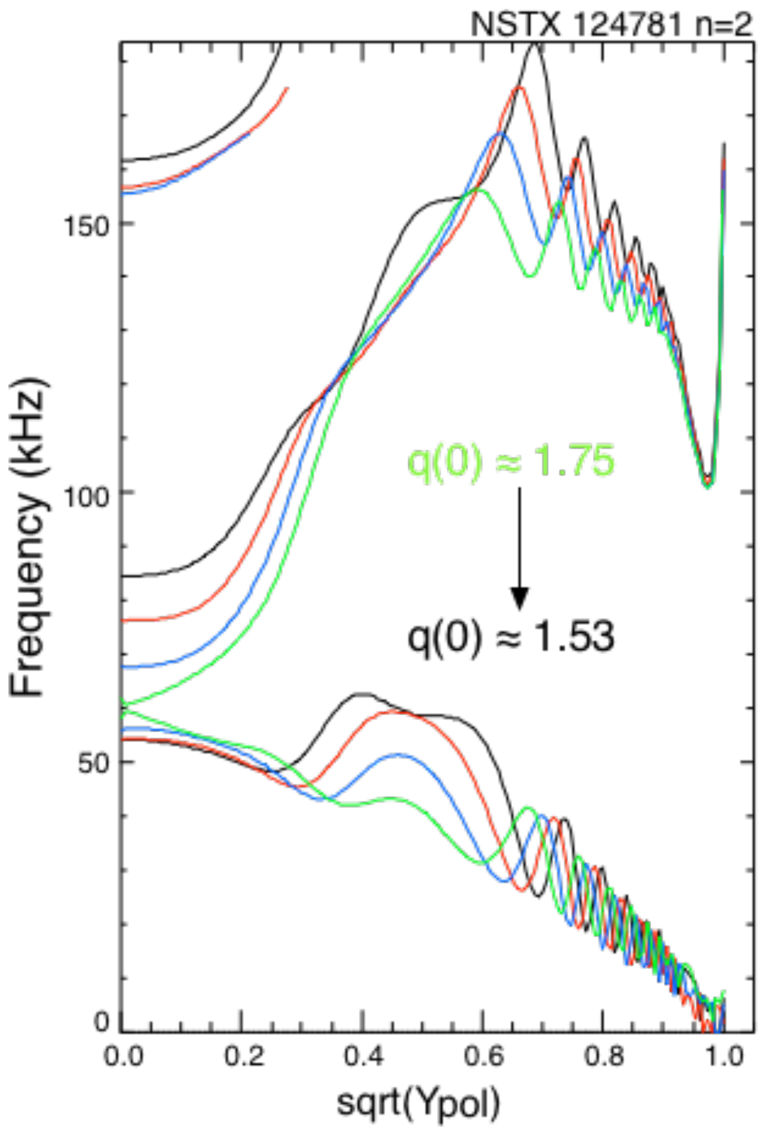
Mode numbers, fast ion losses are measured with Mirnov coils during Avalanche events

Mirnov Coils



- Mirnov coils provide toroidal mode numbers, reflectometers internal mode structure and amplitude.
- Fast ion losses inferred from neutron rate, (D-alpha)
- More recent data has sFLIP and FIDA measurements of fast ion redistribution

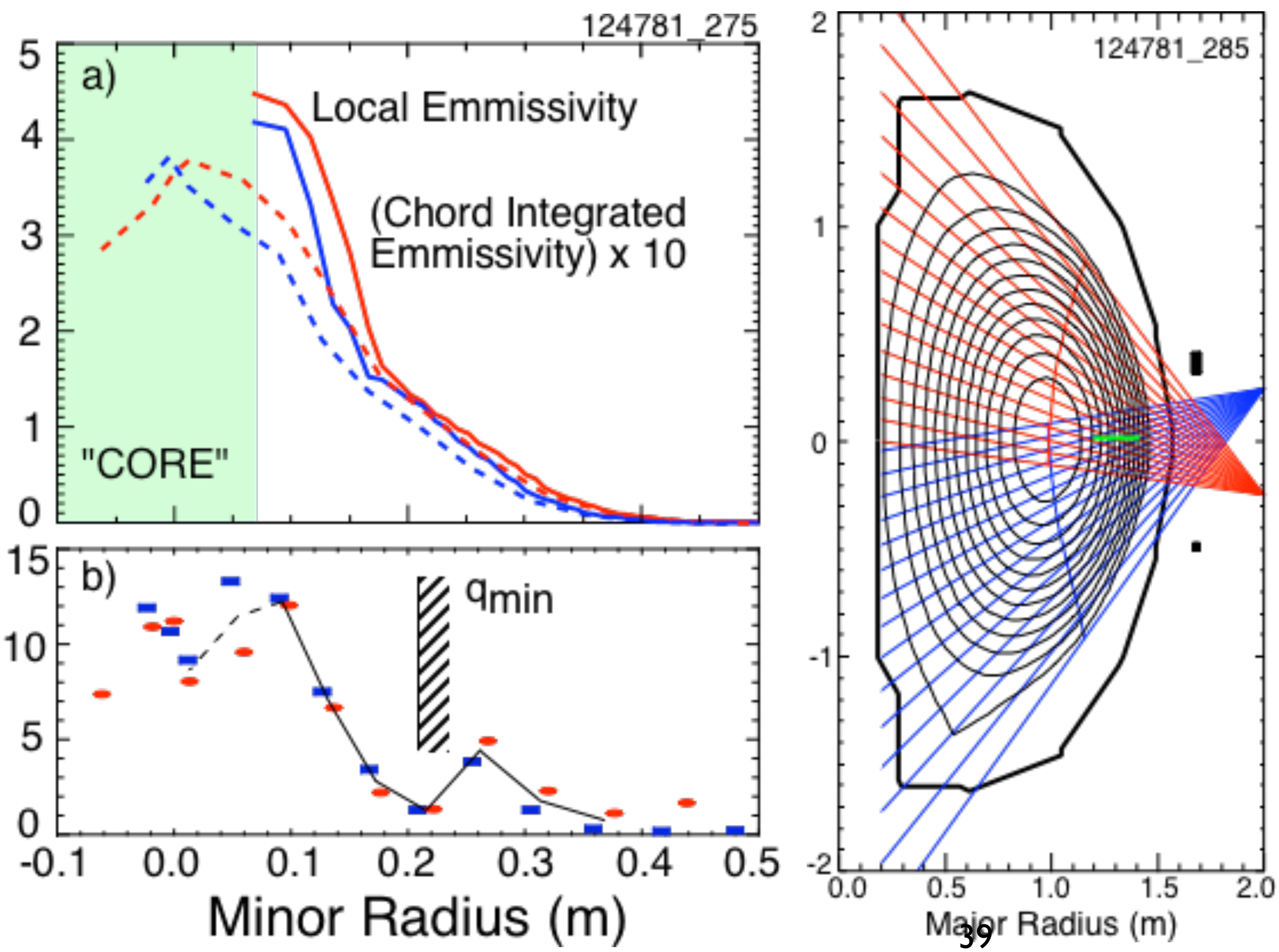
TAE Gaps Open/Close on Axis for "Small", $\delta q \approx 1/2n$, Changes



- When avalanches start, n=2 TAE gap is nearly closed on axis.
- At end of avalanching period, gap is fairly open, neglecting rotational shear effects.
- If measurements of q-profile are accurate, the opening and closing of gap has little impact on n=2 TAE stability.
- With rotational shear, gap is probably always closed.

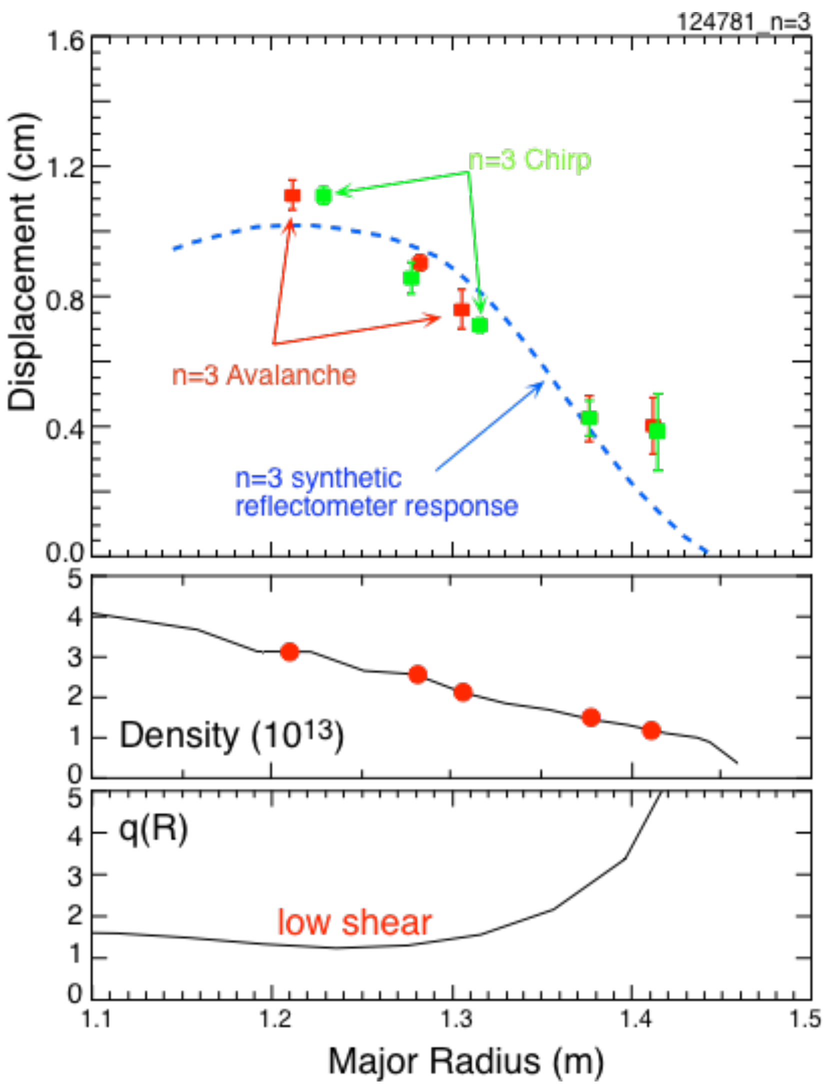
Soft x-ray camera data indicates strong fluctuations in core

NSTX



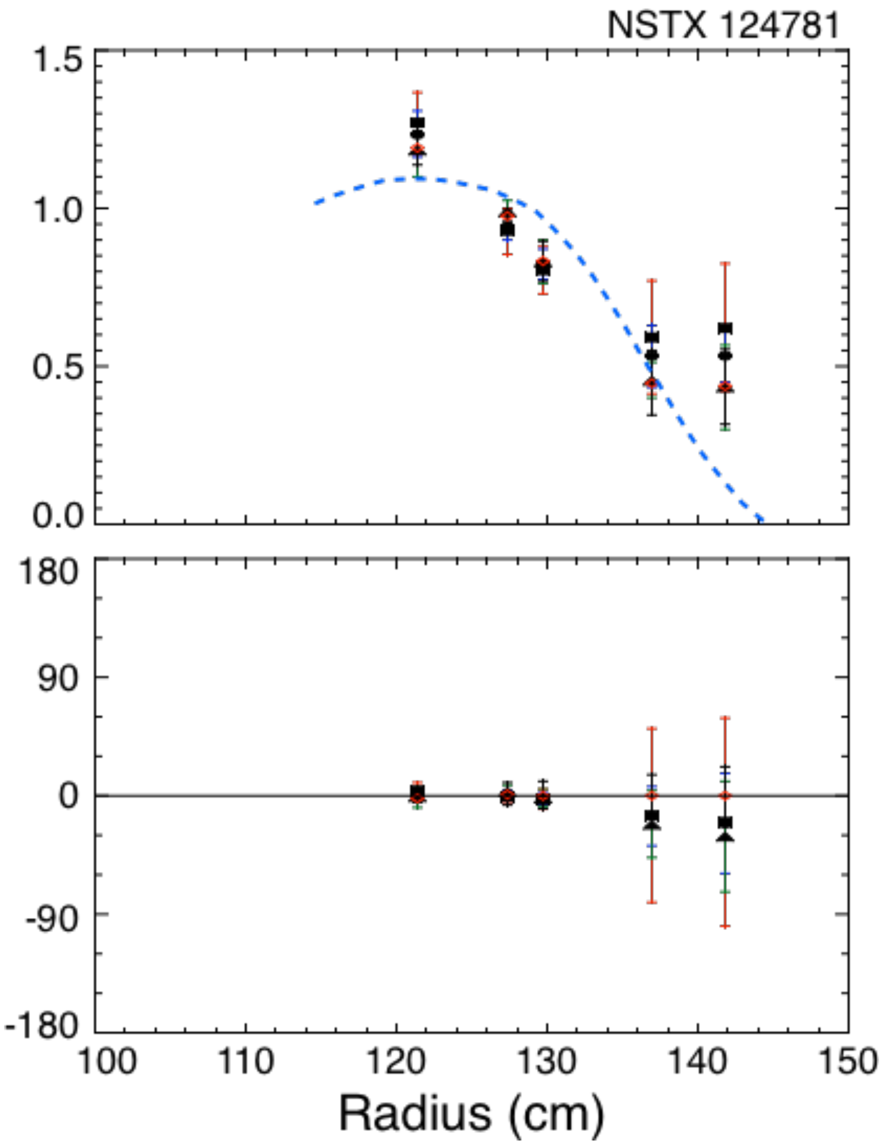
- Soft x-ray cameras also measure mode internal structure and amplitude.
- Soft x-ray response not yet simulated fo NOVA eigenmoes.

Five-channel Reflectometer Array Measures Mode Profile



- Radial profile of modes found by amplitude-weighted average through frequency chirp.
- Red points n=3 chirp from avalanche, green from non-avalanche n=3 chirp
- Synthetic reflectometer response calculated from NOVA data in blue.
- Simulation here doesn't include compressional effects - just displacement on gradient.
- Reflectometer phase shifts normalized by free-space wavelength.

Mode Structure Nearly Same for All Avalanche Chirps



- Averages of the normalized profile shapes for the n=3 TAE in each of the four avalanche events are overlaid.
- Signal-to-noise worse in plasma edge, more care will be needed to get better comparison.
- Only towards end of chirp is amplitude large enough for clean measurement in outer channels.
- In future, a BES diagnostic may give better constraints.

Radial Profile Data Shows Phase Inversions for some Modes

NSTX

- The profile of the n=4 TAE in the avalanche burst.
- Solid red line is NOVA calculation of displacement on outboard mid-plane.
- Dashed red line shows calculated reflectometer response including interferometric response, but neglecting compressional terms for the TAE.