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Modeling Fast Ion Losses During TAE Avalanches on NSTX

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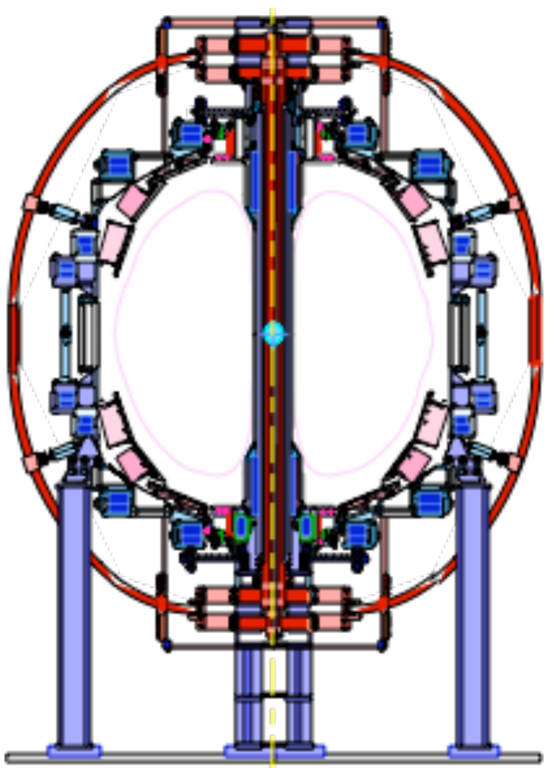
Validated Models of Fast Ion Redistribution are Needed for Design of Next Generation Devices

- 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.

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, $V_{fast} \approx 2.6 - 3.1 \times 10^6$ m/s
- Reactors would have higher field, fusion α's and $V_{fast}/V_{Alfvén} > 1$



$R_0 = 0.86$ m

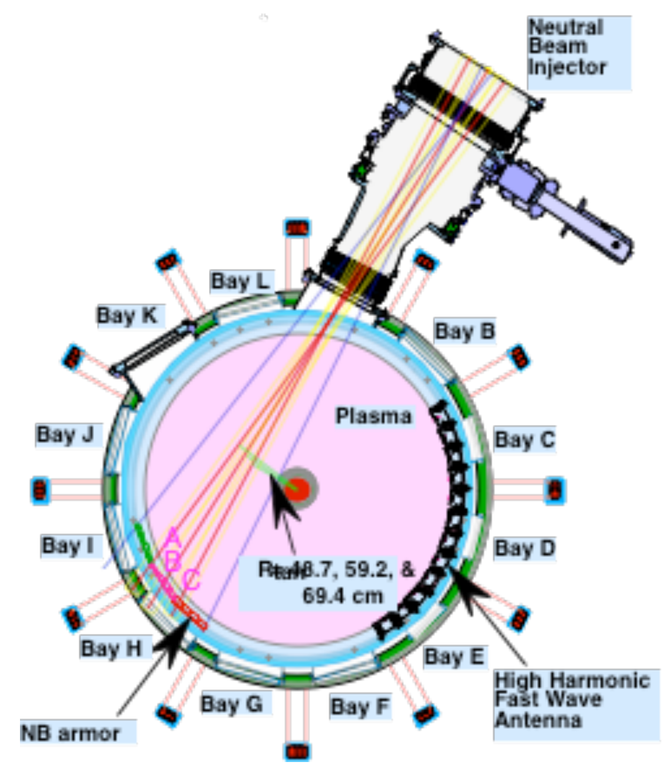
$a = 0.68$ m

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

$I_p \leq 1.2$ MA

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

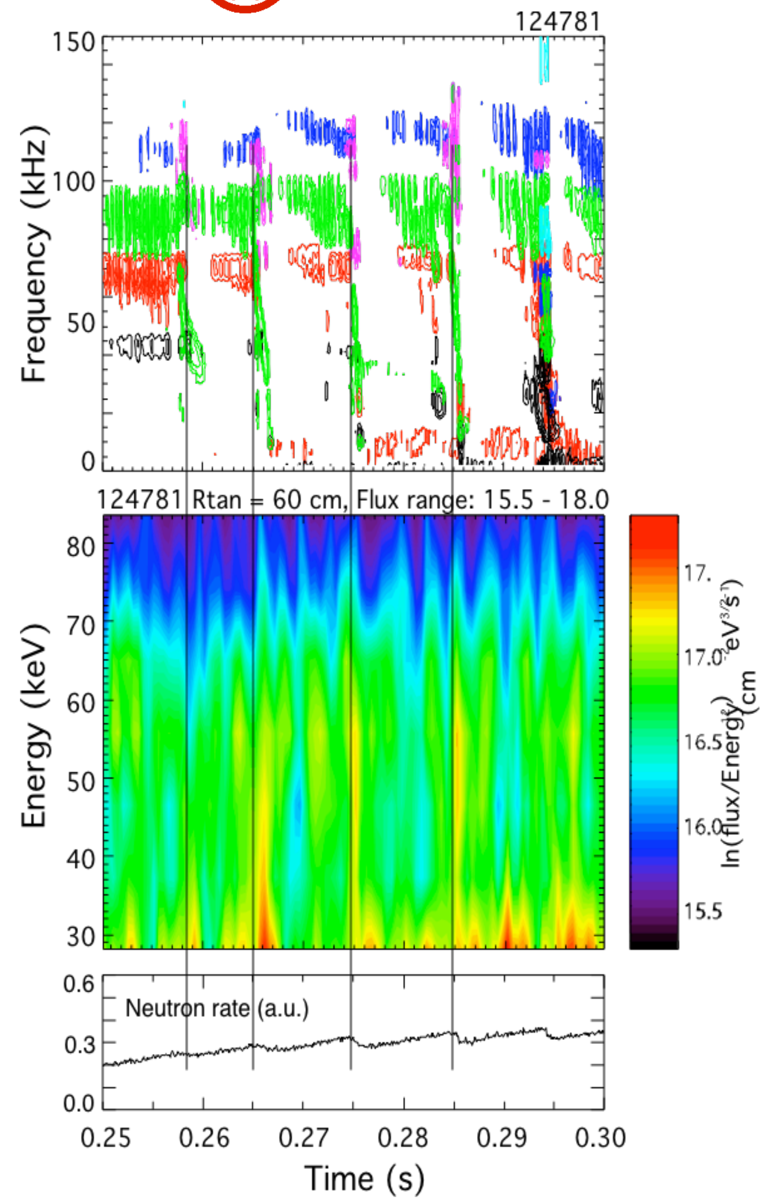
$n_e \leq 10 \times 10^{19}/m^3$



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.



Outline: The modeling of fast ion losses during TAE avalanches

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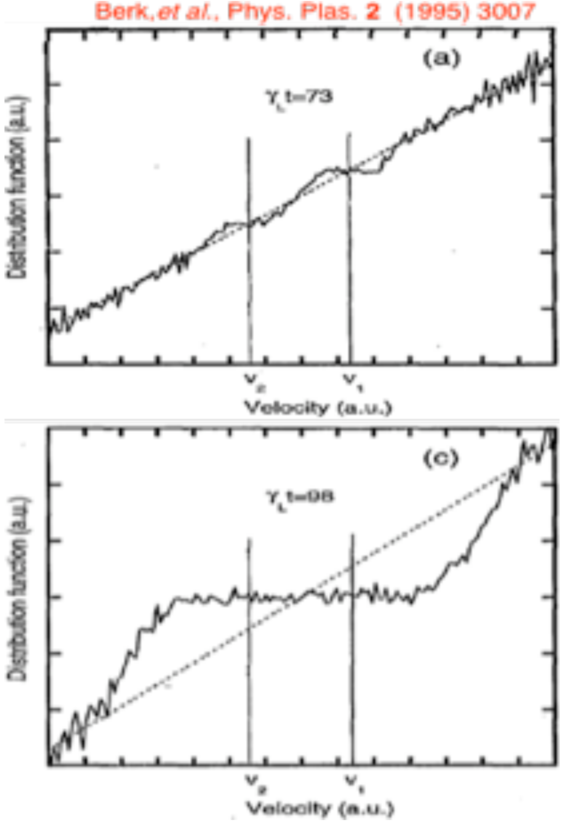
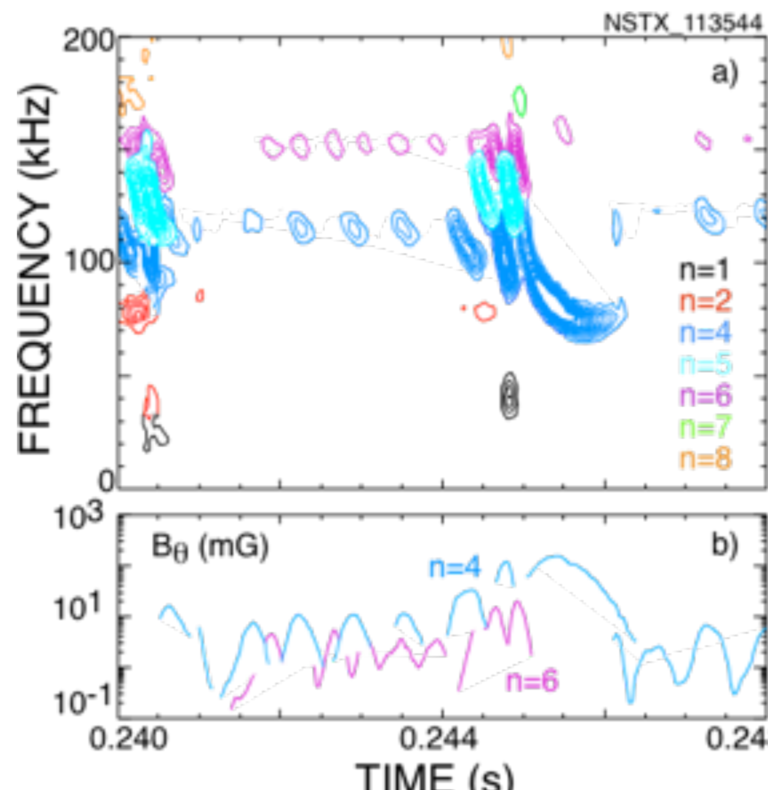
- Introduction to TAE avalanches.
- Description of experimental conditions, diagnostics and analysis of the data.
- Calculations of TAE gap structure for range of equilibria in experiment.
- NOVA calculation of eigenmodes; comparison with experimental measurements.
- ORBIT simulations of fast ion transport
- Summary

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

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



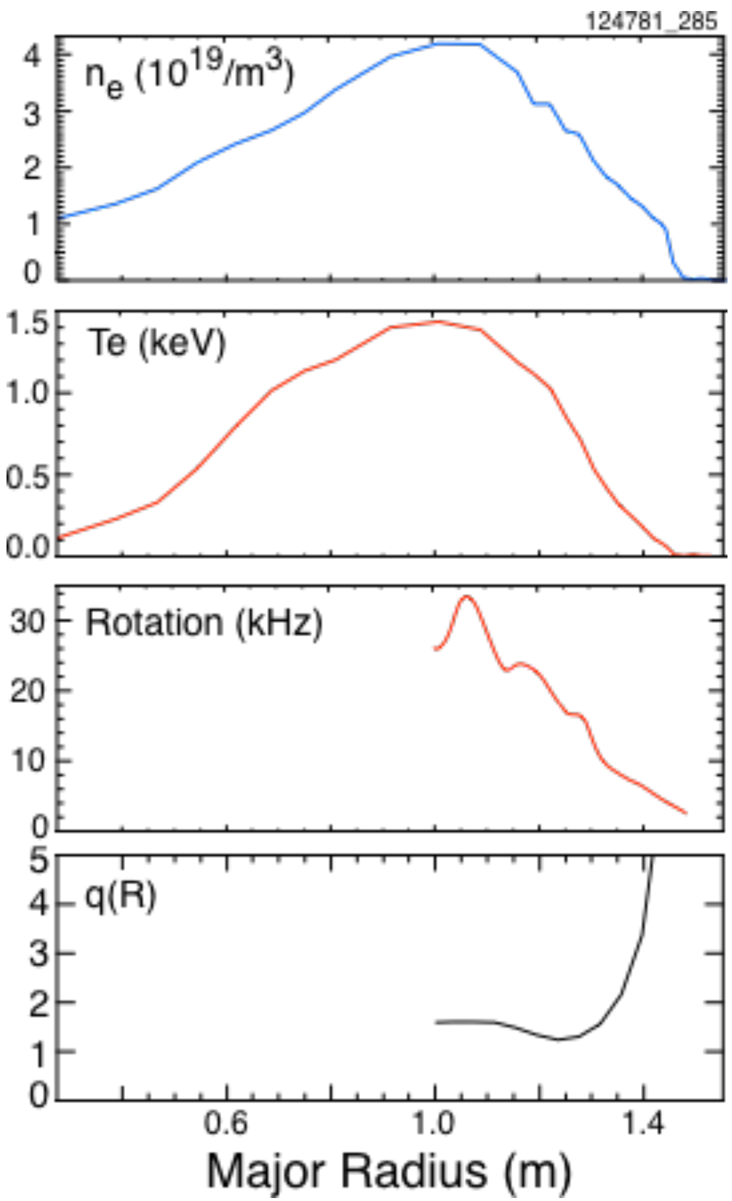
- Large amplitude modes overlap in fast-ion phase-space.
- Interaction results in new modes, stronger drive.
- More free energy accessed, more transport
- TAE have multiple resonances, more complex physics.



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

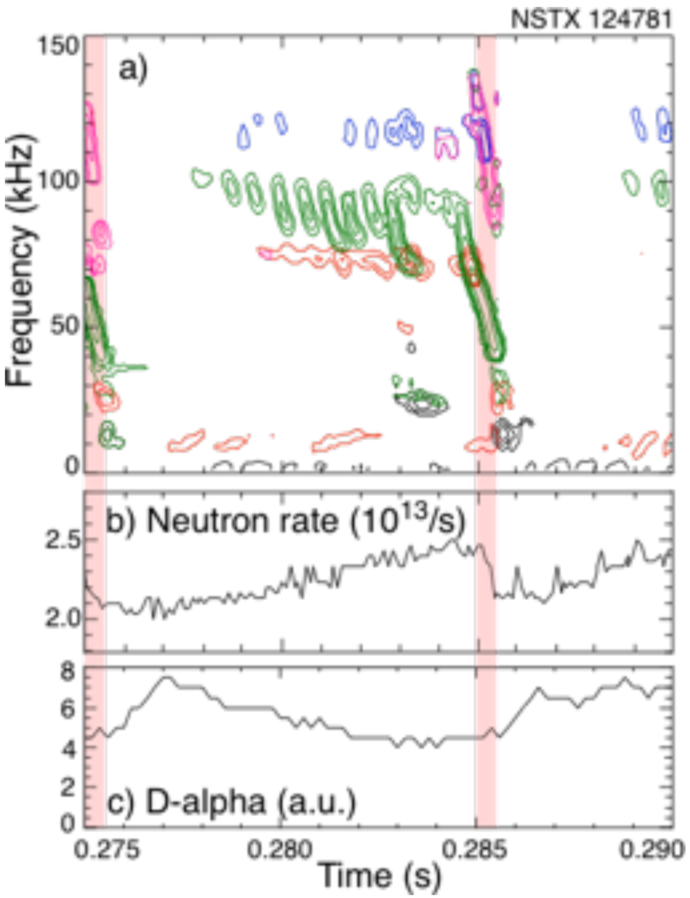
Analysis starts with equilibrium data, uses TRANSP, NOVA and ORBIT

NSTX

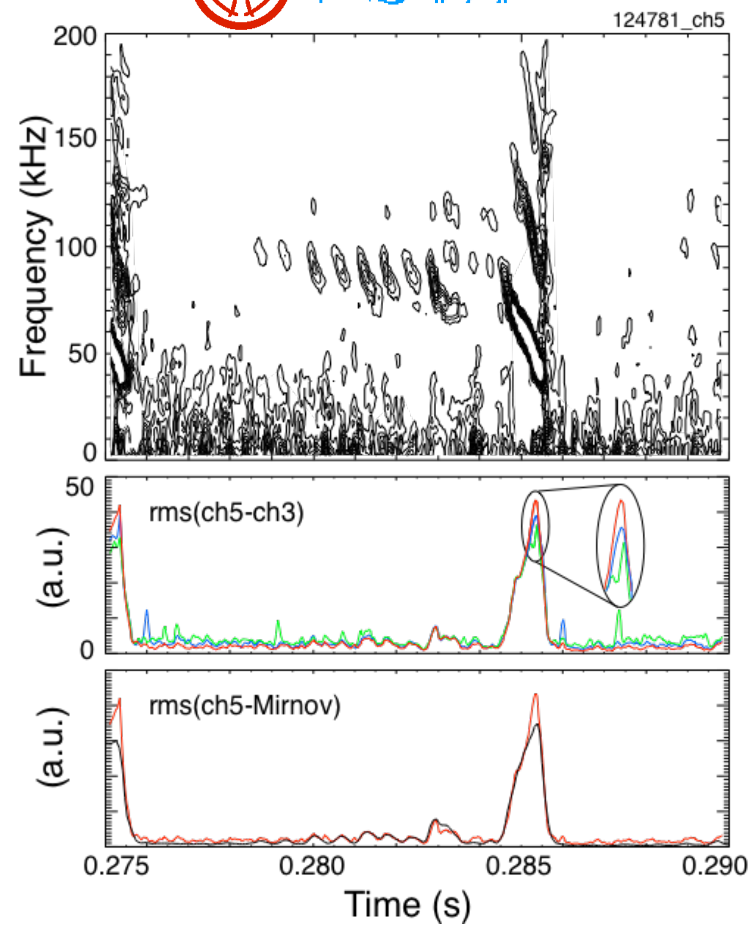


- LRDFIT (equilibrium code) used to map data, derive q from MSE pitch angle data.
- TRANSP is used to calculate fast ion distribution using time-dependent Monte Carlo deposition package.
- NOVA uses TRANSP output to recalculate equilibrium, find TAE eigenmodes.
- ORBIT uses TRANSP fast ion distribution, NOVA eigenfunctions, scaled to time-dependent reflectometer amplitudes, to simulate fast ion redistribution

Mode amplitudes, fast ion losses are measured during Avalanche events

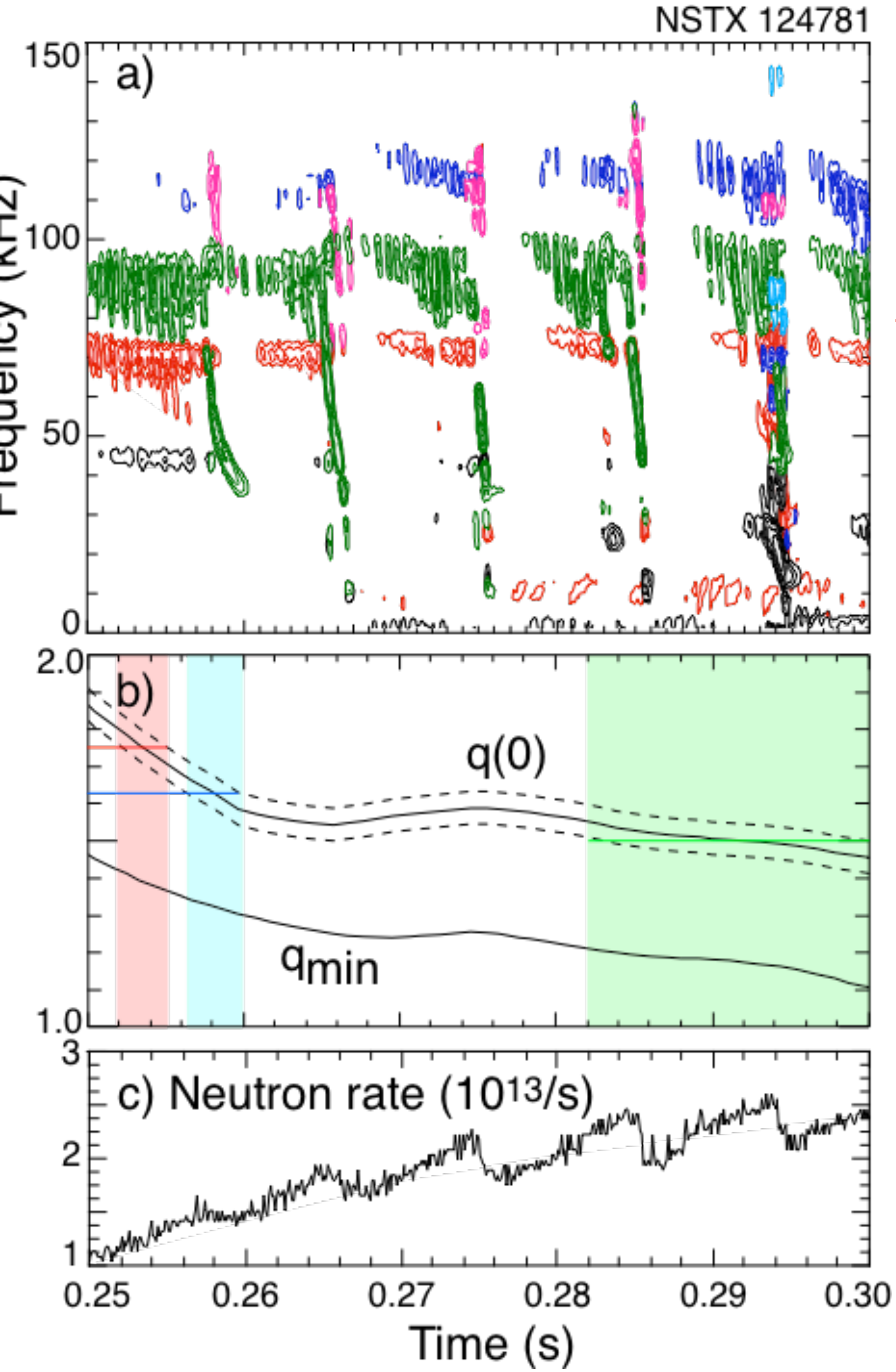


- Mirnov coils provide toroidal mode numbers, reflectometers internal mode structure and amplitude.
- Fast ion losses inferred from neutron rate, (D-alpha)



- 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

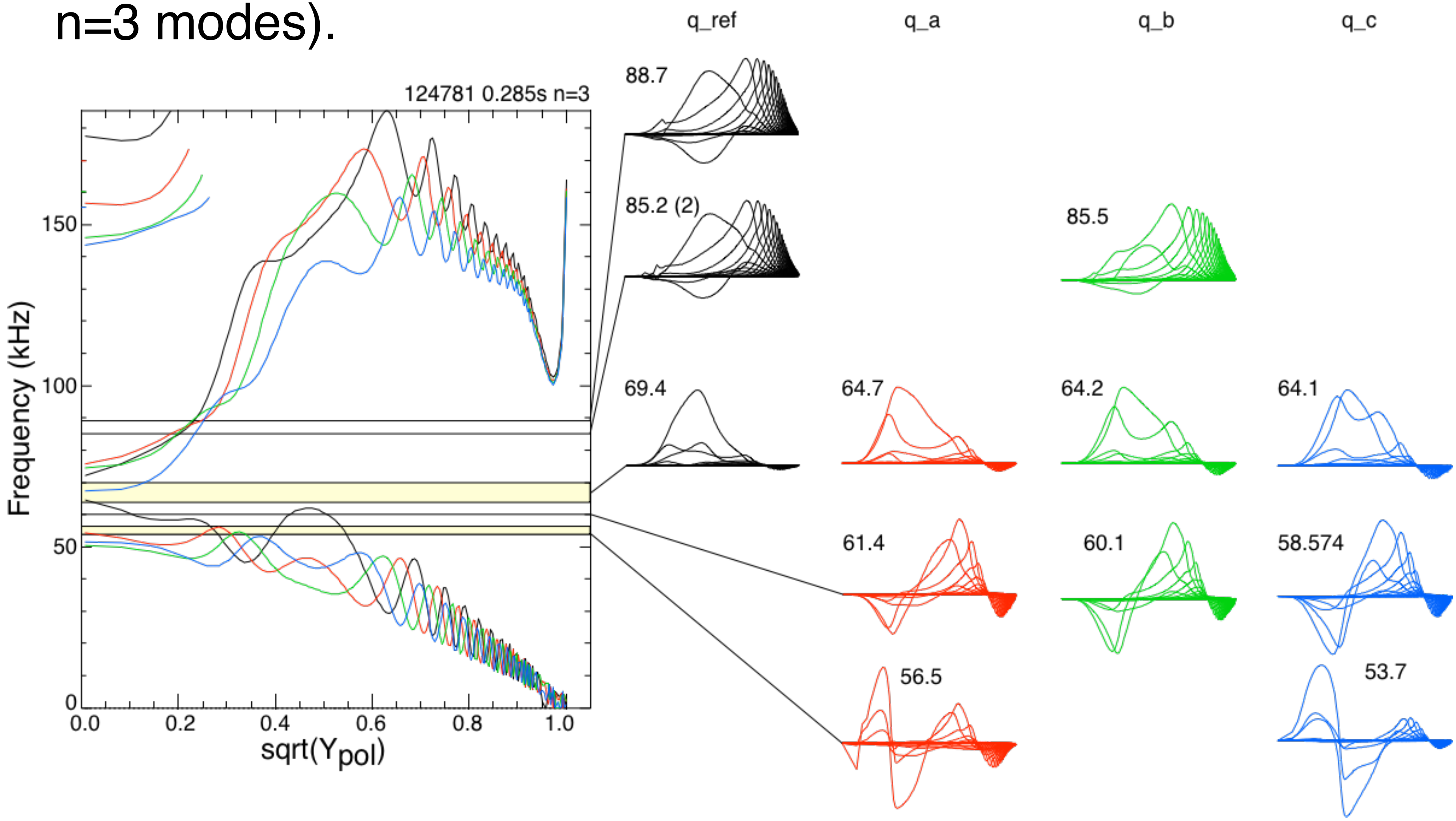
TAE Gaps Open/Close on Axis for "Small", $\delta q \approx 1/2n$, Changes



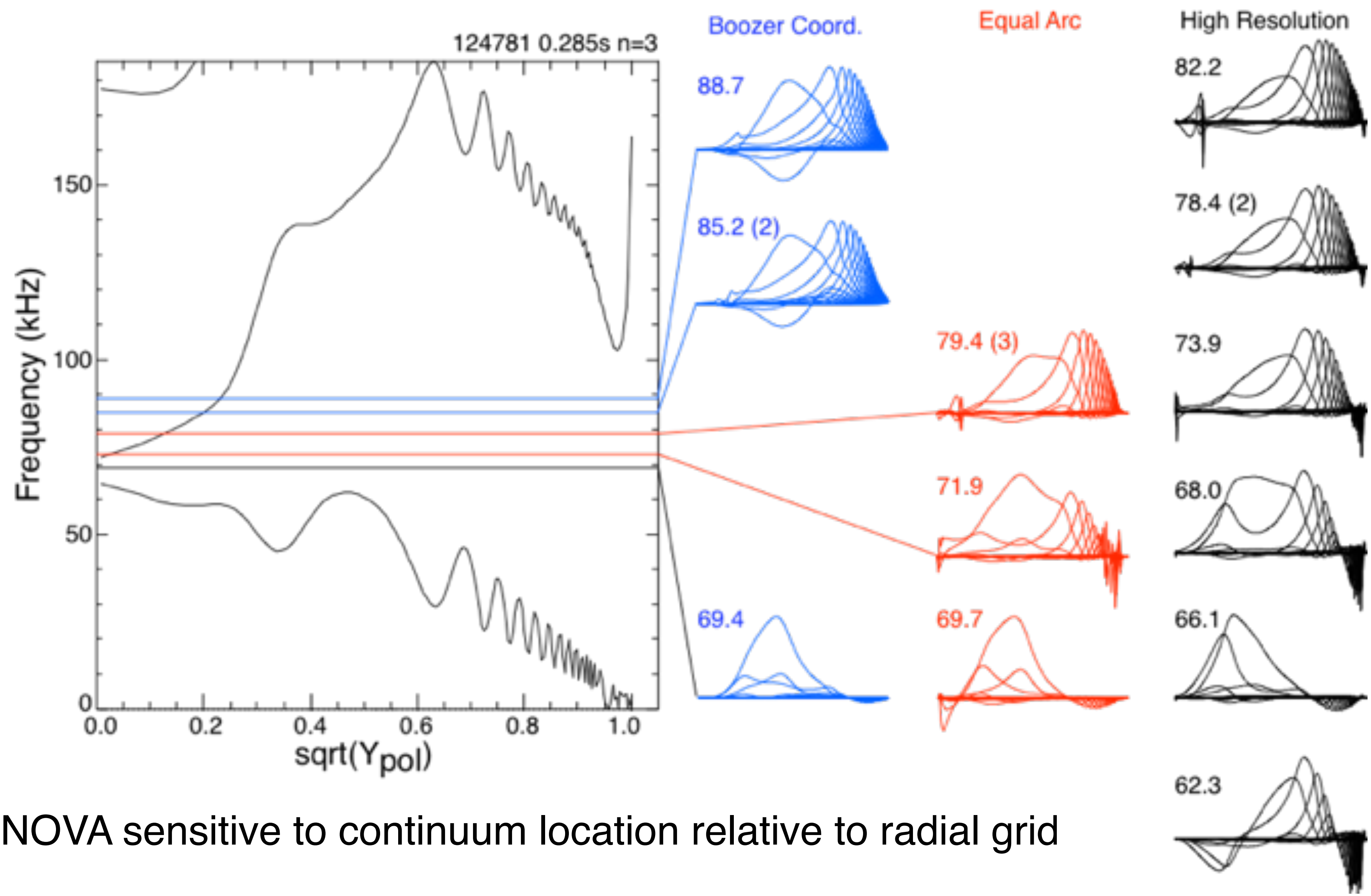
- Gaps for n=2, 3 and 4 modes open and close during q-profile evolution (without rotation shear!).
- Shaded regions show times when gaps are closed, modes should be weaker.
- Amplitude of n=4 consistent with gap evolution, n=2 and n=3 seem unaffected by gap closing.

TAE Gaps Open/Close on Axis

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



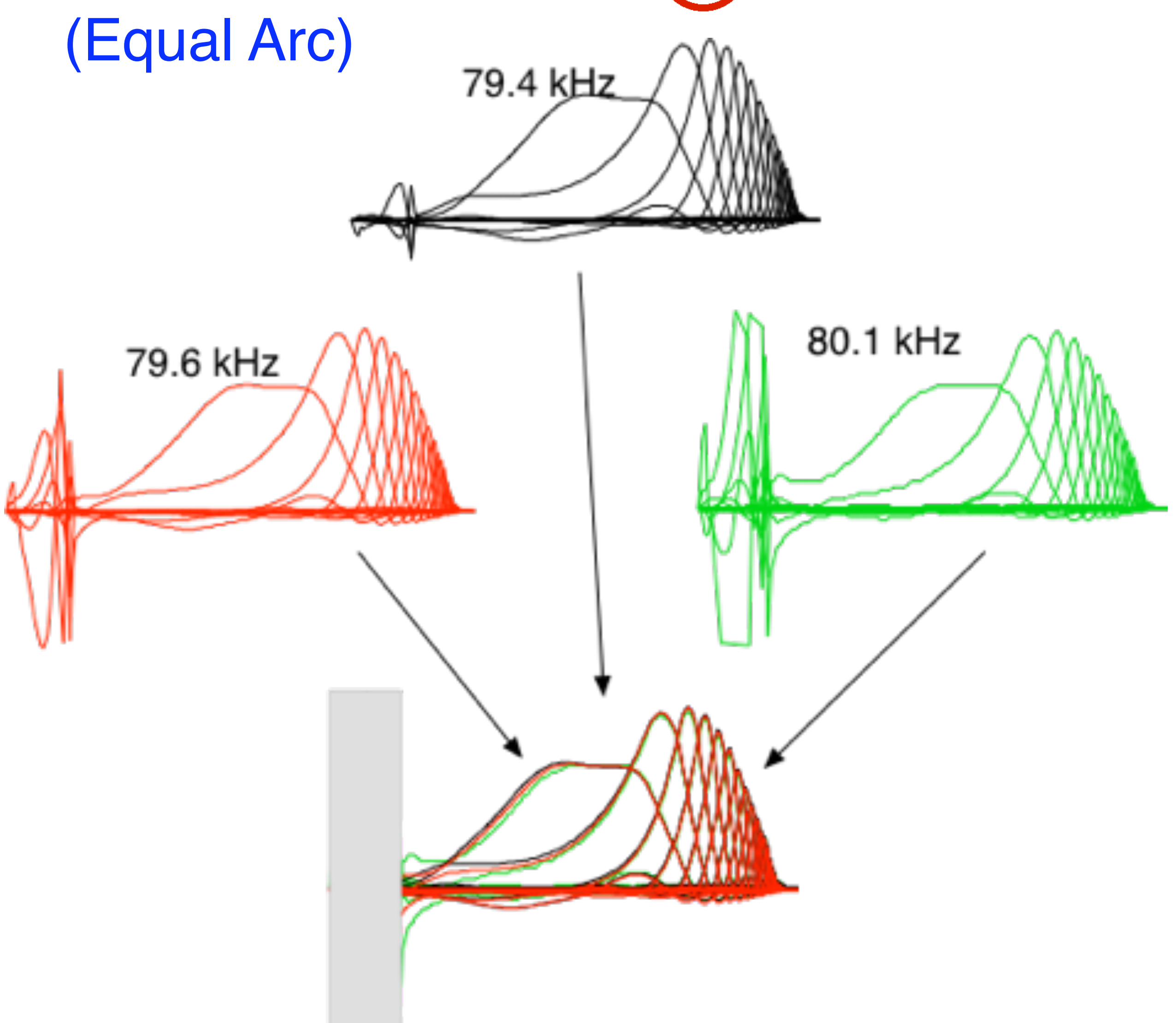
NOVA results surprisingly sensitive to choice of analysis grid



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

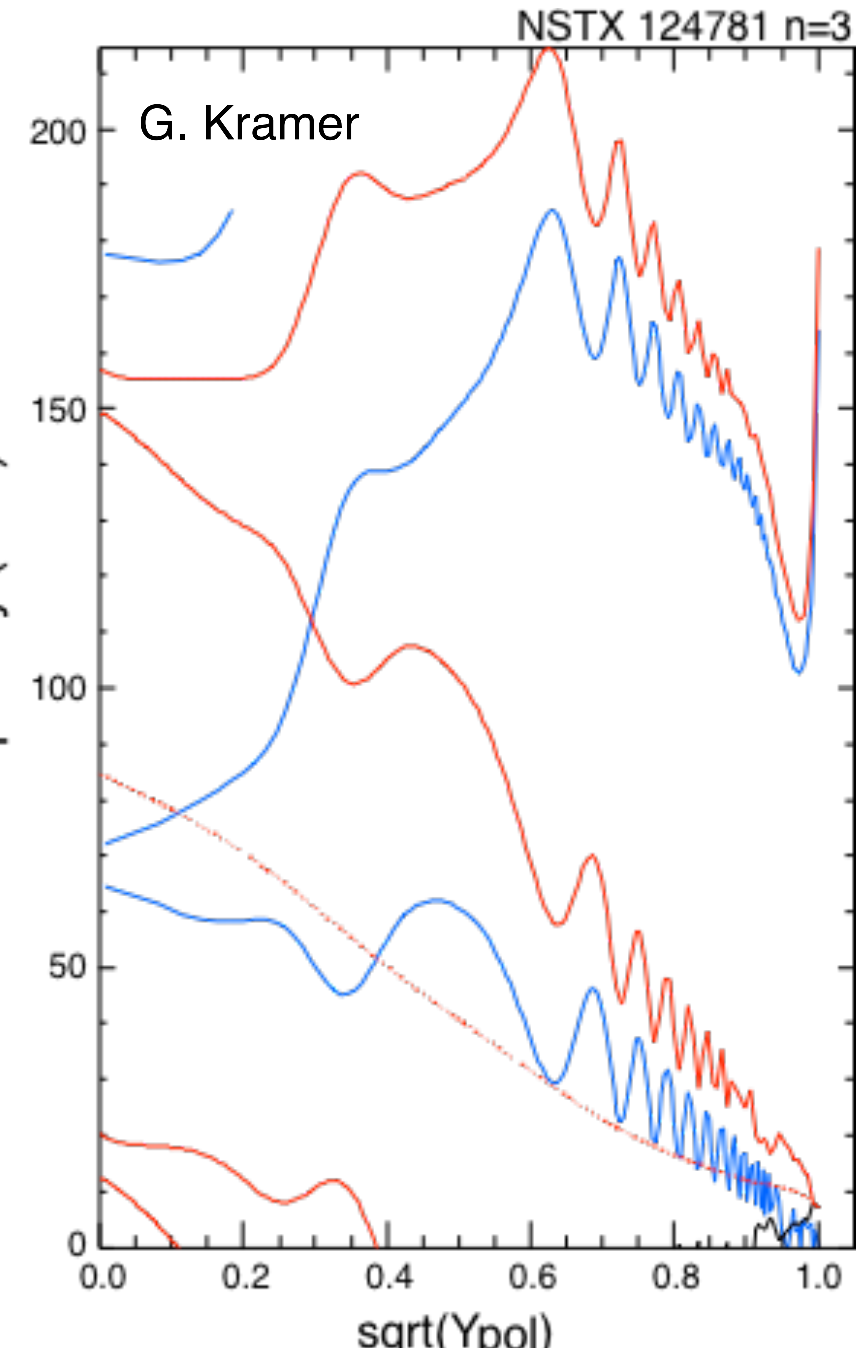
Interaction with Continuum Introduces Degenerate Eigenmodes

- 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 to accurately find solutions.



Sheared rotation distorts TAE continuum

NSTX



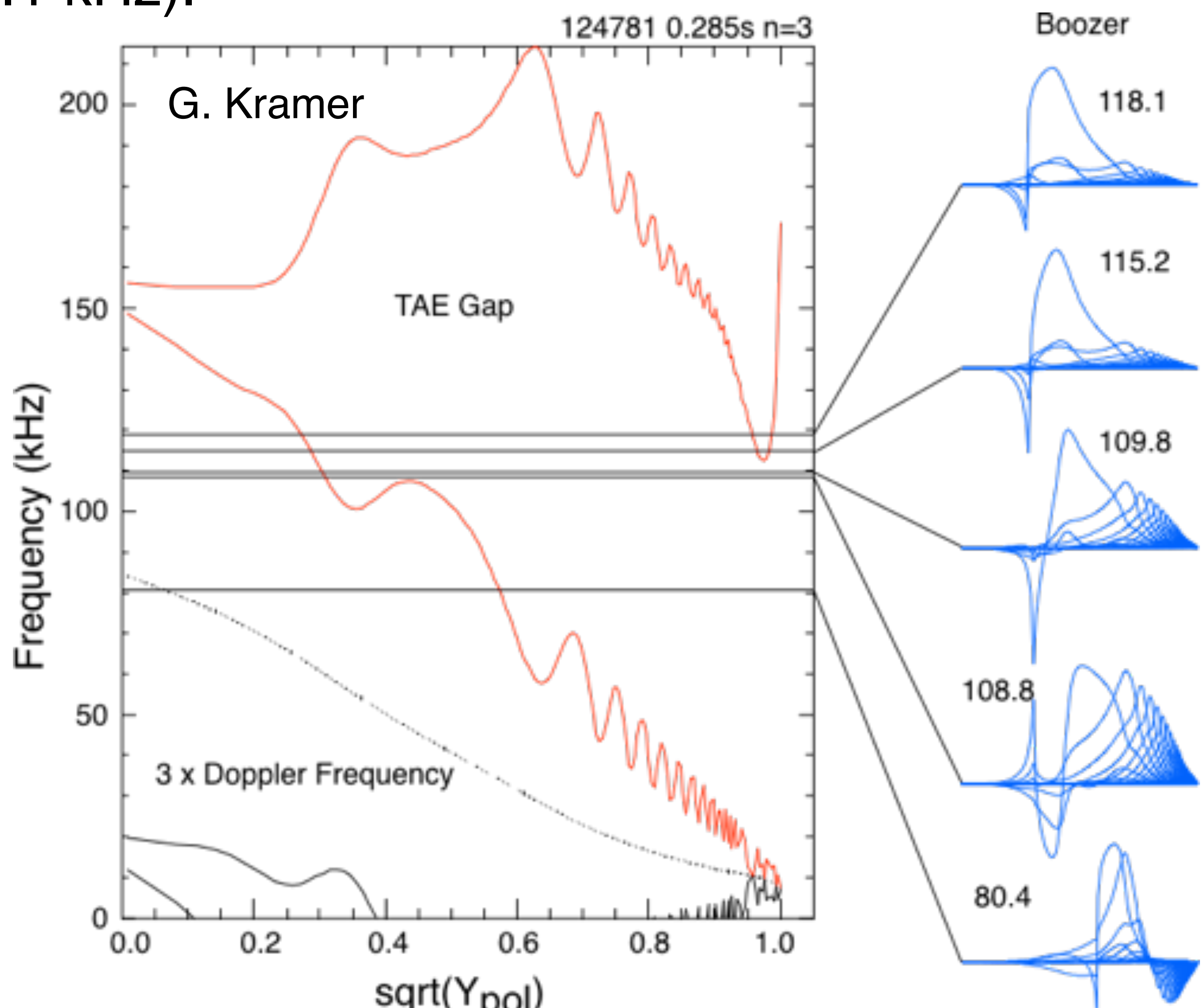
- Blue curves show n=3 Alfvén continuum neglecting sheared rotation.
- Solid red lines show continuum including rotation shear effects.
- Dashed red curve Doppler frequency for n=3 mode.
- Gap closed by rotation shear is insensitive to evolution of q(0).

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.

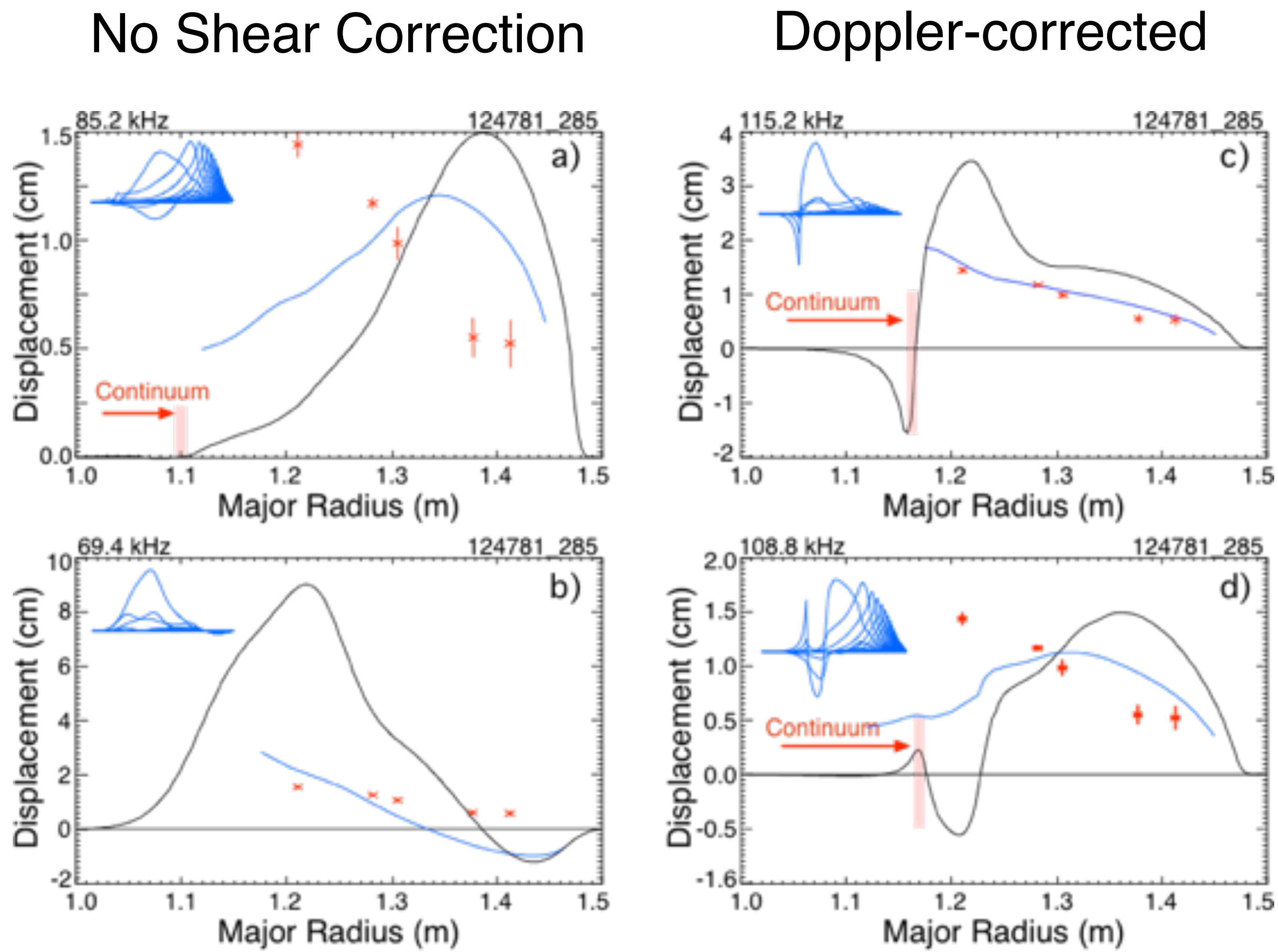
- Measured mode structures are used to select NOVA eigenmodes used in ORBIT simulations.



NOVA Eigenmodes with Doppler correction are better fit

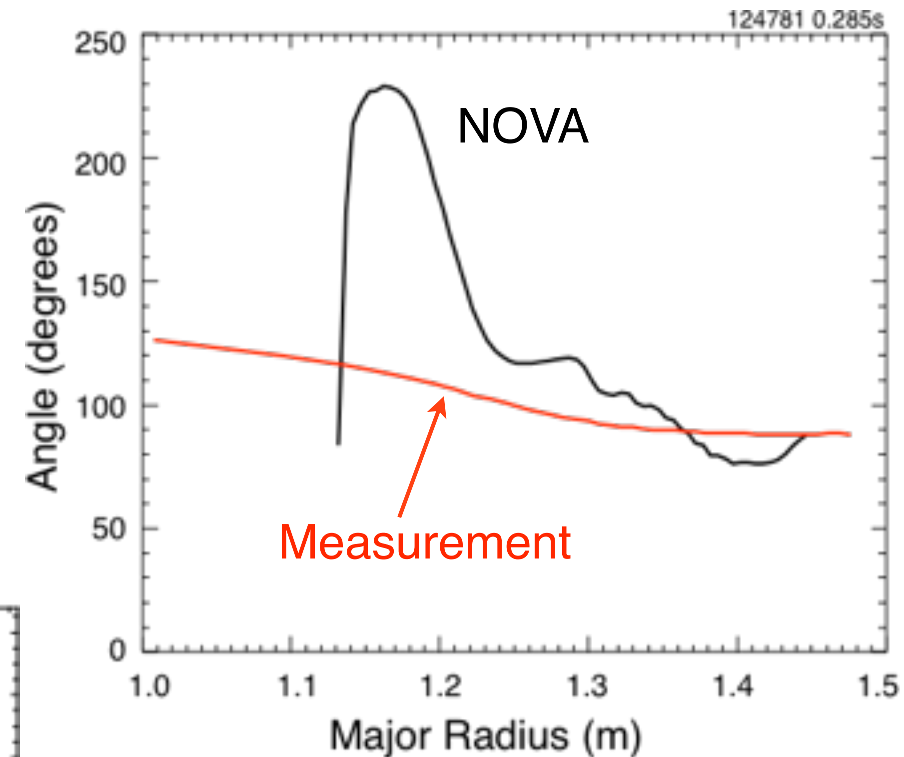
NSTX

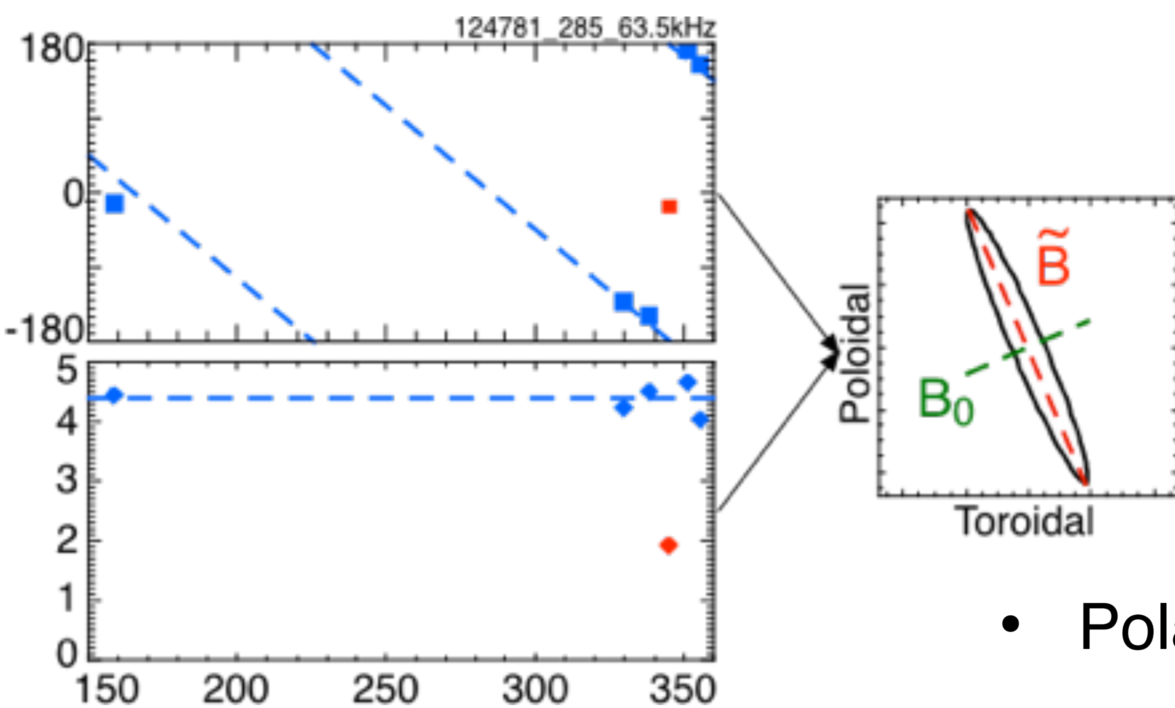
- No modes with good fit were found in non-sheared case.
- With shear, good fit was found to data.



TAE have compressional components

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

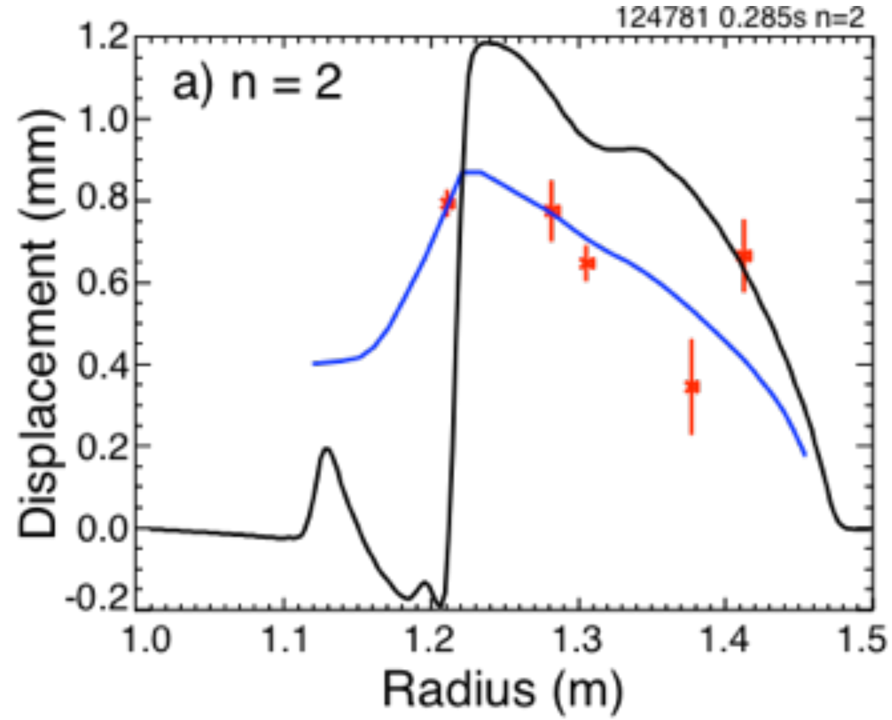


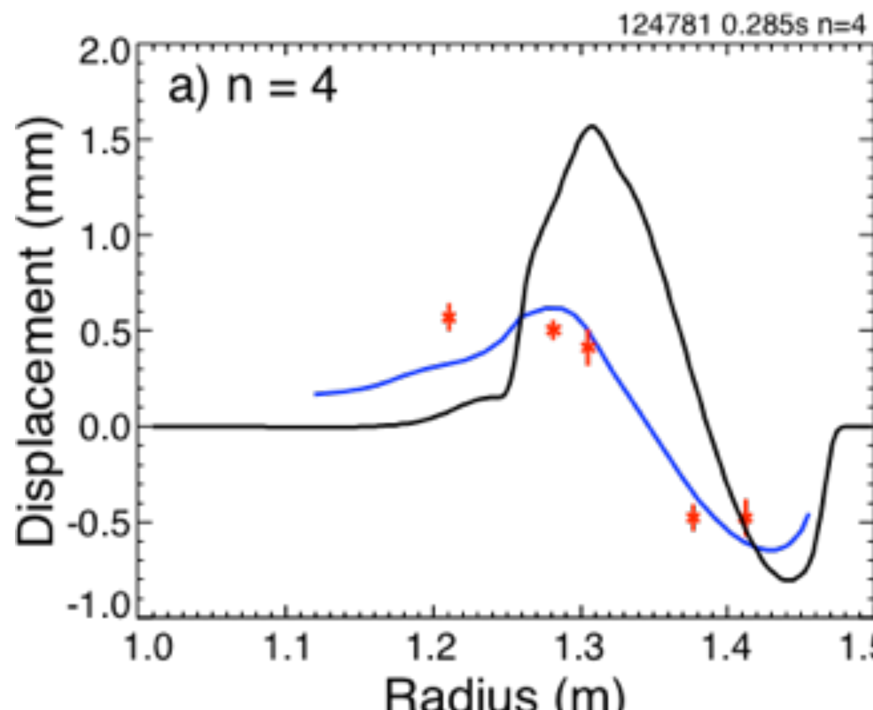


- Polarization in θ-φ plane measured with Mirnov coil array.

Good fits 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.

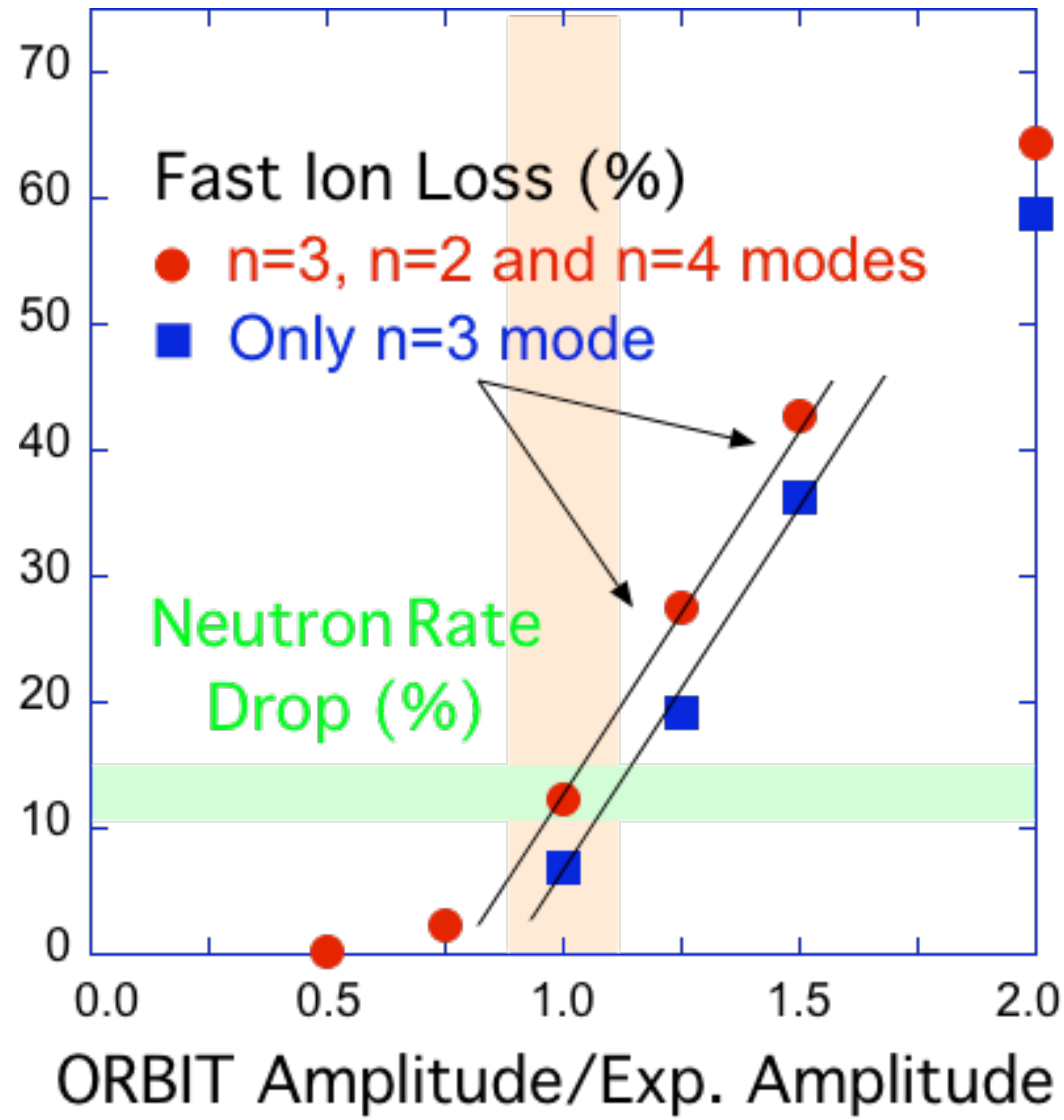




ORBIT simulations predict losses in good agreement with observed neutron rate drop

NSTX

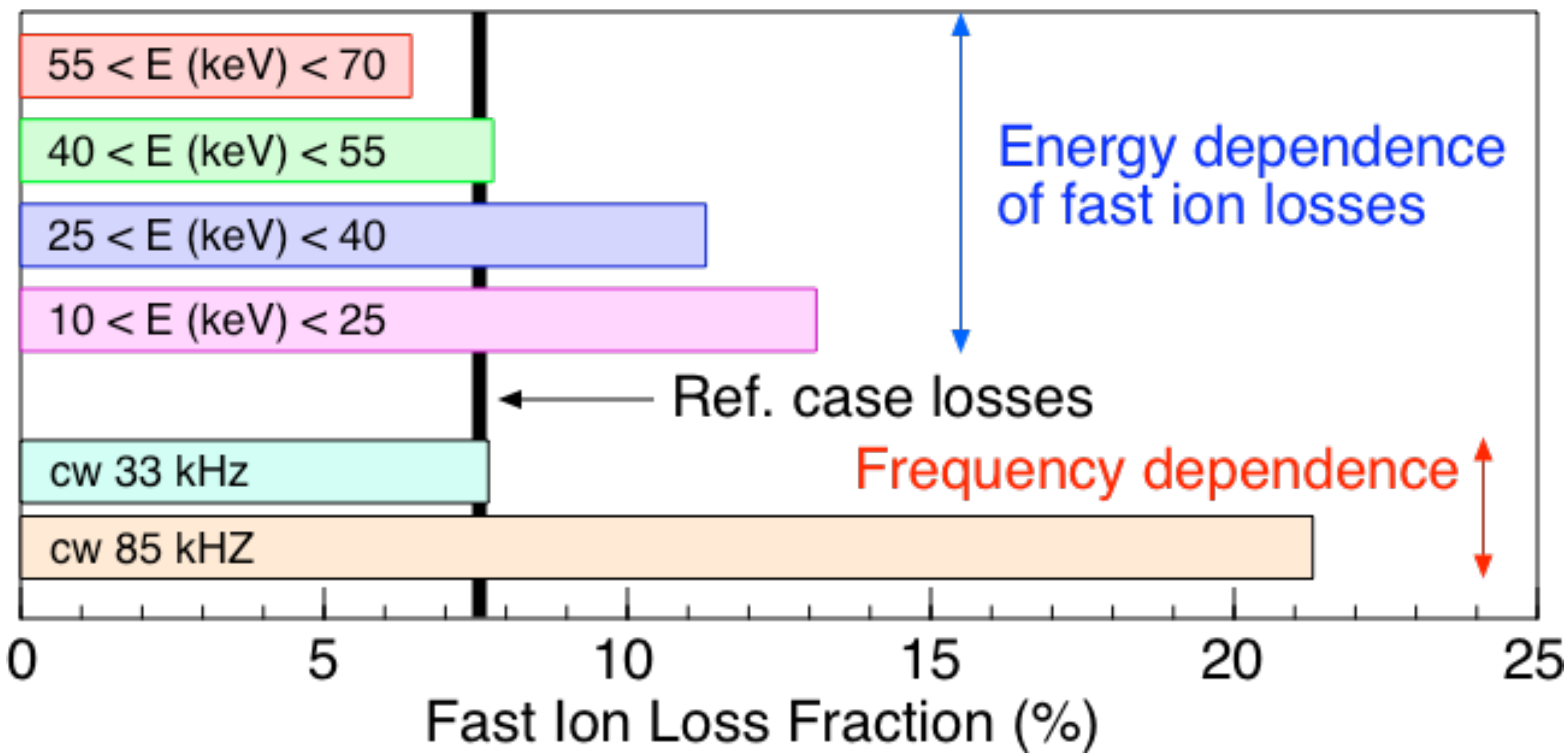
- ORBIT simulation is done for 1ms burst at 0.285s.
- Mode amplitude, frequency evolution in ORBIT are from experimental measurements.
- Mode structure from NOVA.
- Initial fast ion distribution is from unperturbed TRANSP calculation – not necessarily self-consistent.
- Losses are strongly non-linear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



Energy dependence and frequency dependence of losses also investigated

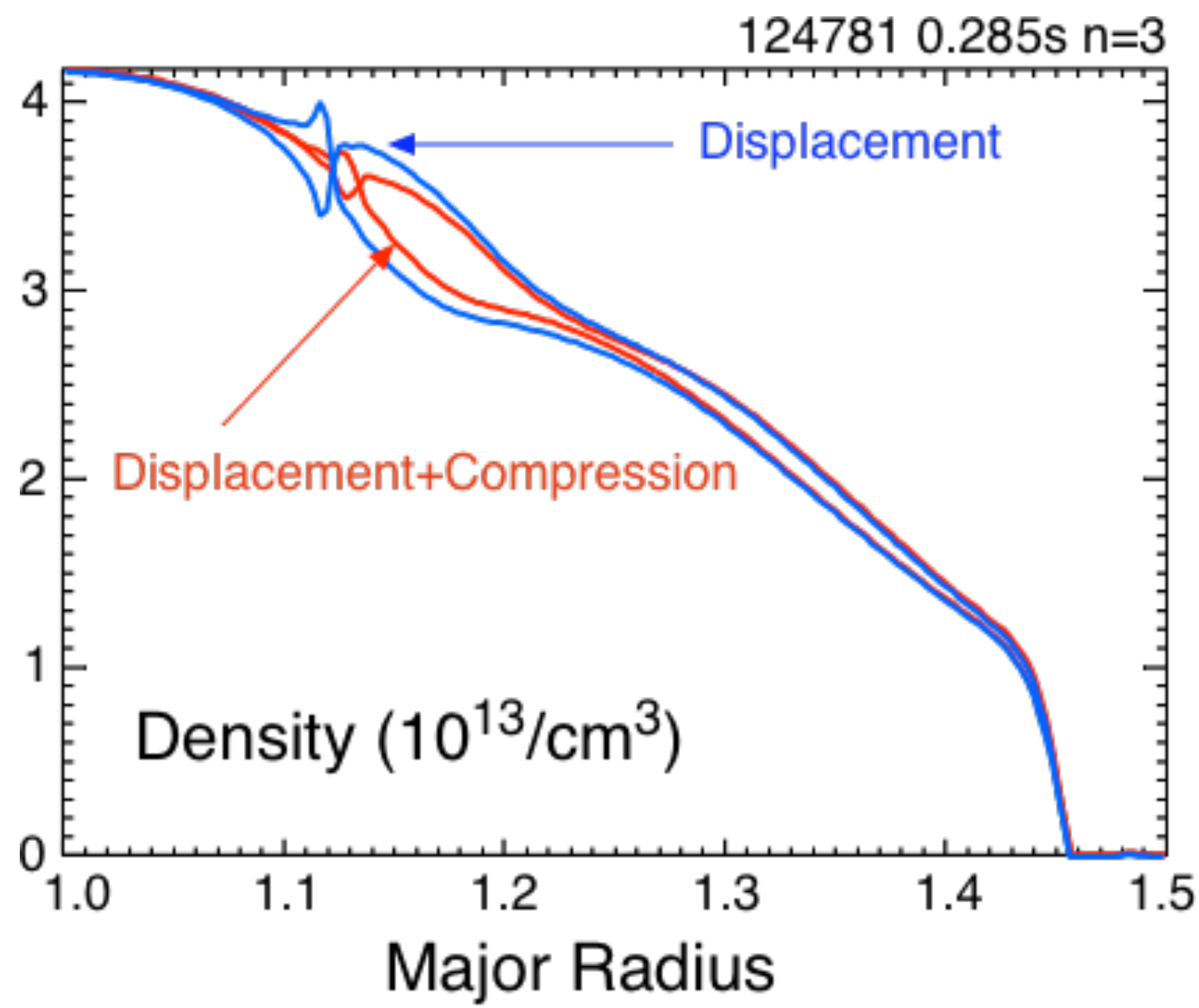
NSTX

- 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 are large

- 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…



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 missing from present codes
  - Rotation will probably enhance continuum interactions in NSTX
- Separatrix also not modeled in NOVA, needs further work.

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 2009 (better spatial resolution)