NSTX-U

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Modeling of beam ion transport during TAE Avalanches on NSTX

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Eric Fredrickson

M. Podestà, A. Bortolon, N.Crocker,D. Darrow, G. Fu, N. Gorelenkov, G Kramer, R. White

and the NSTX Research Team

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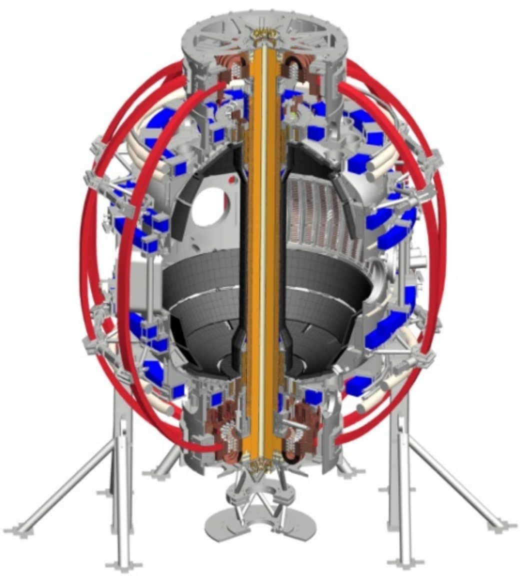

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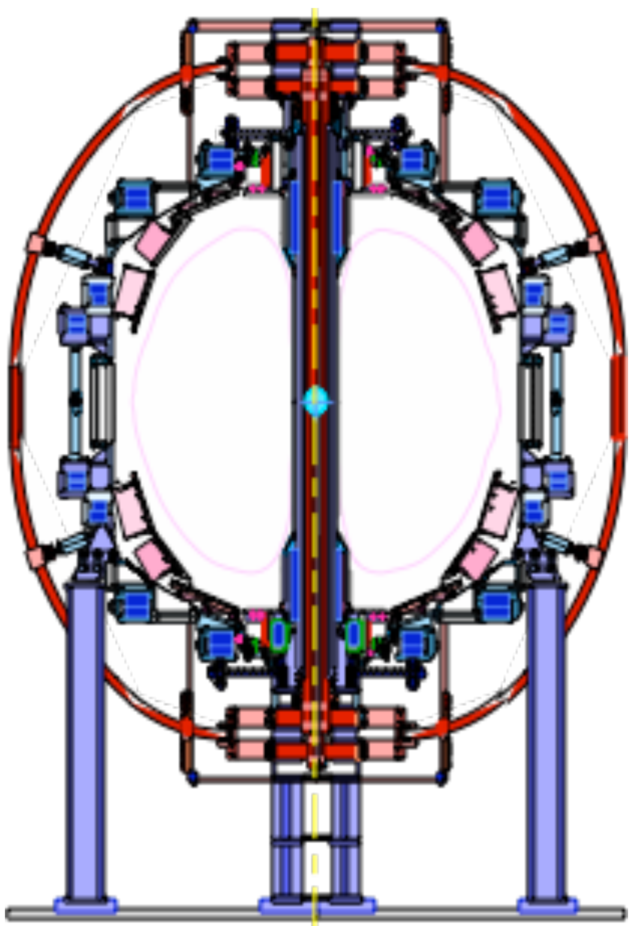
NSTX has low field, high density and current; perfect for study of fast ion-driven modes

- *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 $V_{fast}/V_{Alfvén} > 1$*



$$R_0 = 0.86 \text{ m}$$

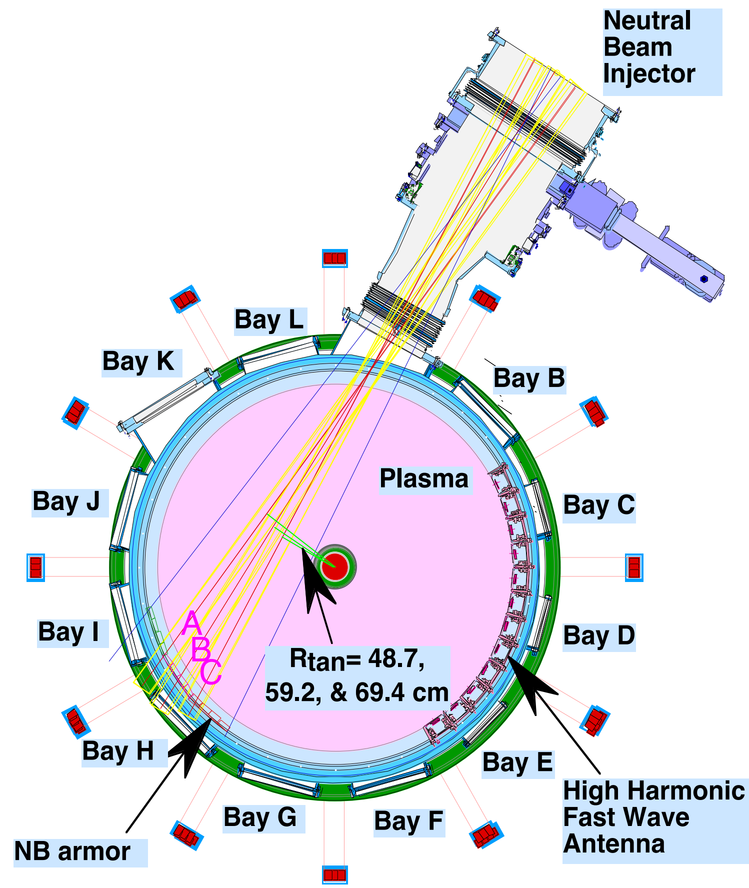
$$a = 0.68 \text{ m}$$

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

$$I_p \leq 1.2 \text{ MA}$$

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

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



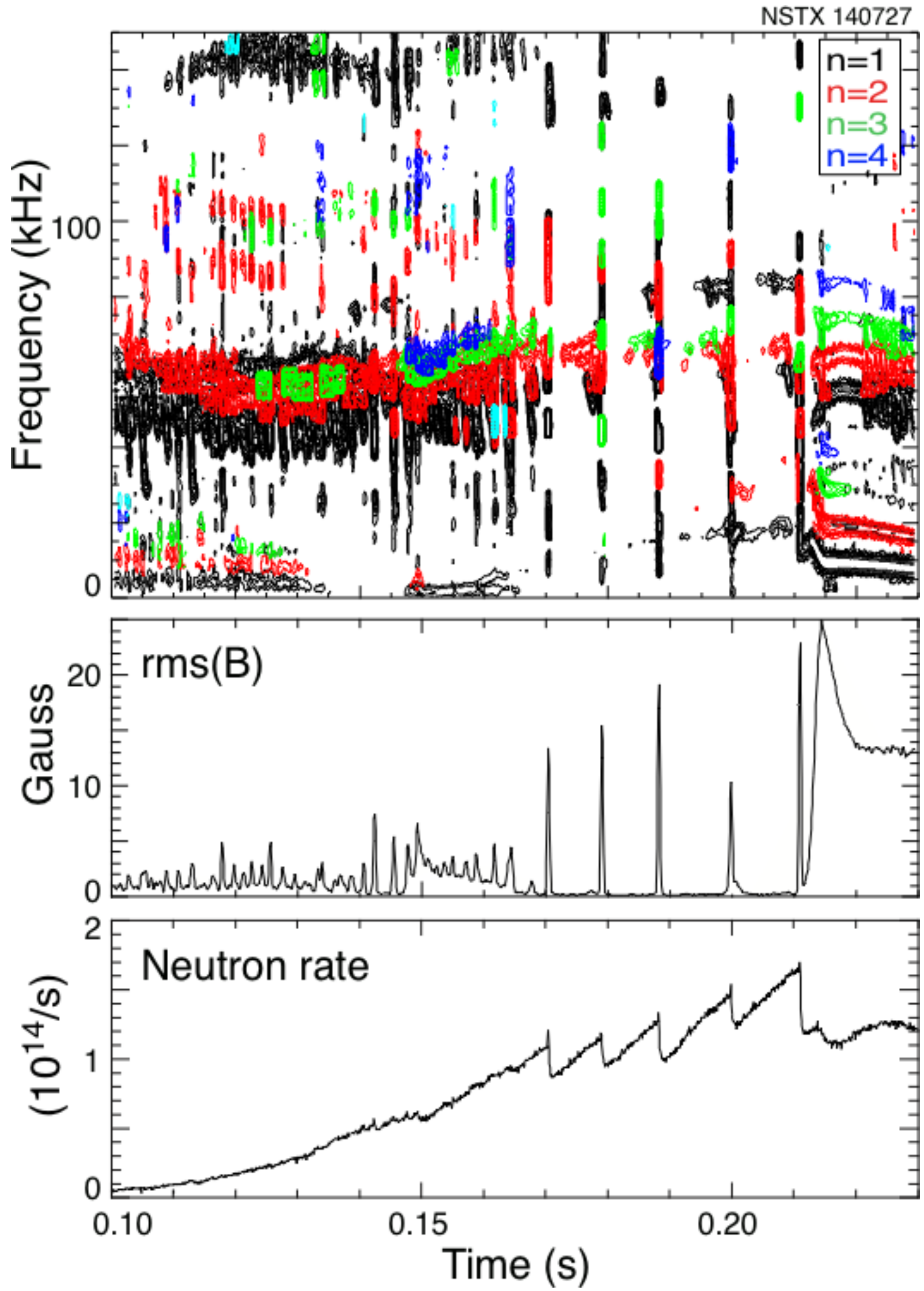
Non-linear physics of Alfvénic and Energetic Particle modes is research priority for NSTX(-U)

Outline of talk:

- Two classes of instabilities cause fast ion transport and loss:
  - Toroidal Alfvén Eigenmode (TAE) avalanches,
  - Energetic Particle modes (EPM), i.e., modes which only exist in presence of fast ion population.
- Both EPM/TAE show linear scaling of neutron rate drop with mode amplitude
  - EPM/TAE fast ion redistribution affects current/heating profiles.
- TAE avalanches seen for $\beta_{fast}/\beta_{total} > 0.3$,
  - quiescent plasmas are found for $\beta_{fast}/\beta_{total} > 0.3$.
- TAE neutron rate drops modeled with ORBIT and NOVA
  - semi-empirical approach using measured amplitude and frequency
  - ideal, linear code NOVA is used to find eigenmodes to match data
  - NOVA eigenmodes used in guiding center particle following code ORBIT

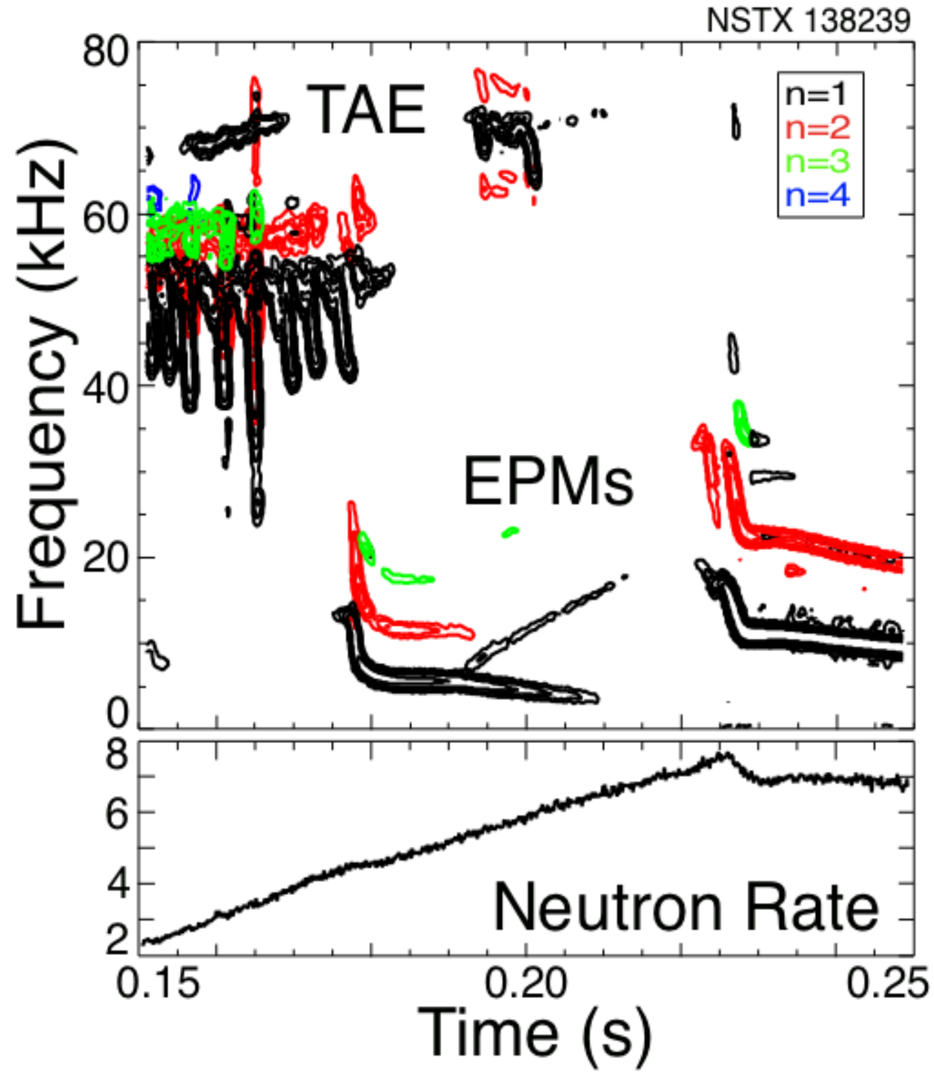
Both TAE avalanches and Energetic Particle Modes (e.g., "fishbones") cause large neutron rate drops

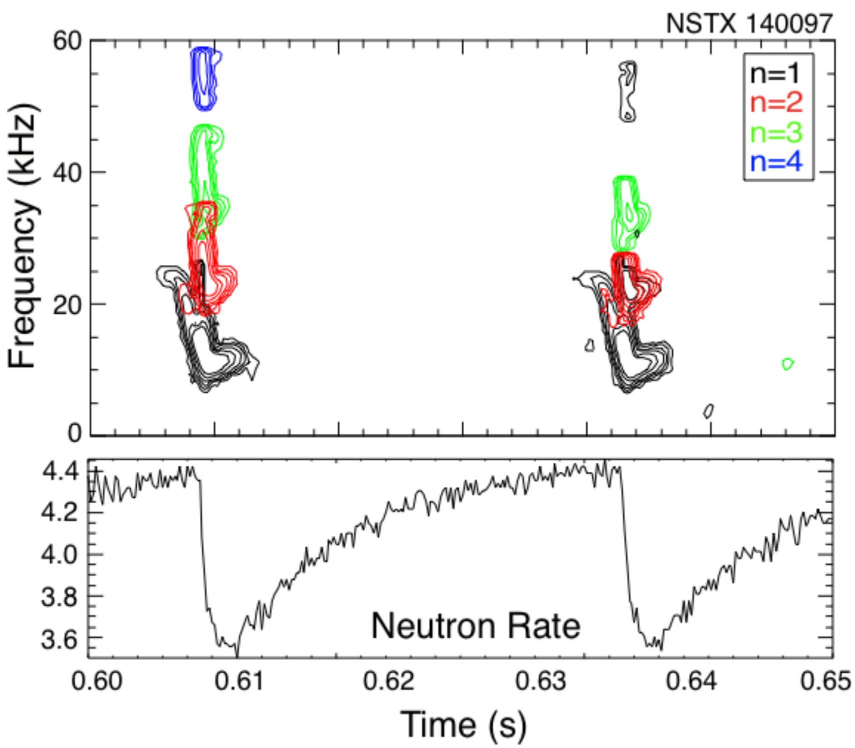
- TAE avalanches more common early in discharge.
  - higher $\beta_{fast}/\beta_{thermal}$
  - elevated, reversed shear q?
- Energetic Particle Modes (EPMs) happen throughout discharge.
- Both types of events show frequency chirping and often multiple modes.
- Goal is to develop some method for classifying these events, scaling of losses.



Many qualitatively different types of Energetic Particle Modes are seen on NSTX

- The most common EPMs are represented by the two types shown here.
- EPMs early in discharge, when $q_{min} >> 1$, often saturate to long-lived n=1 modes.

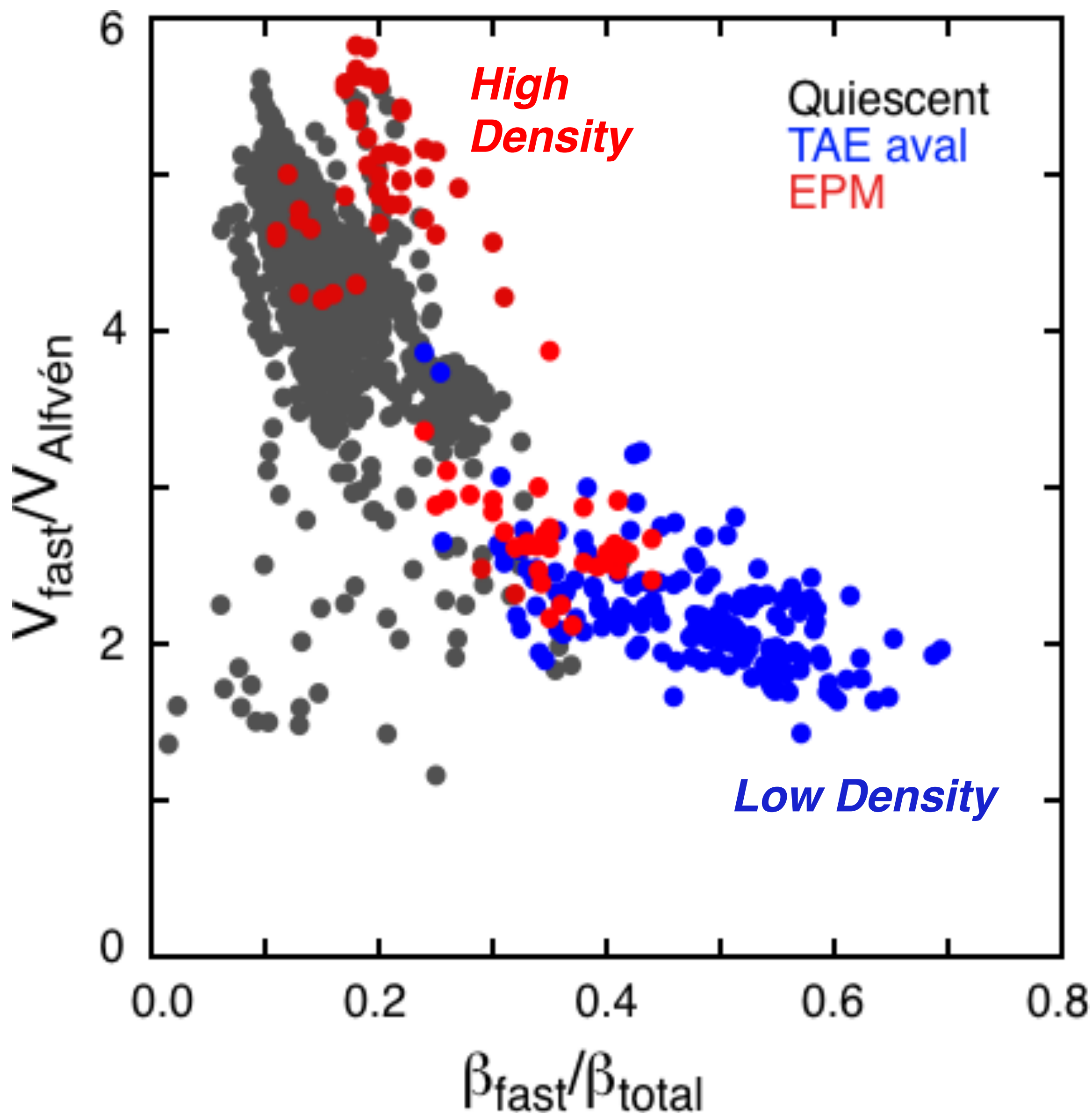




- EPMs later in discharge, with $q_{min} => 1$, are more fishbone-like.

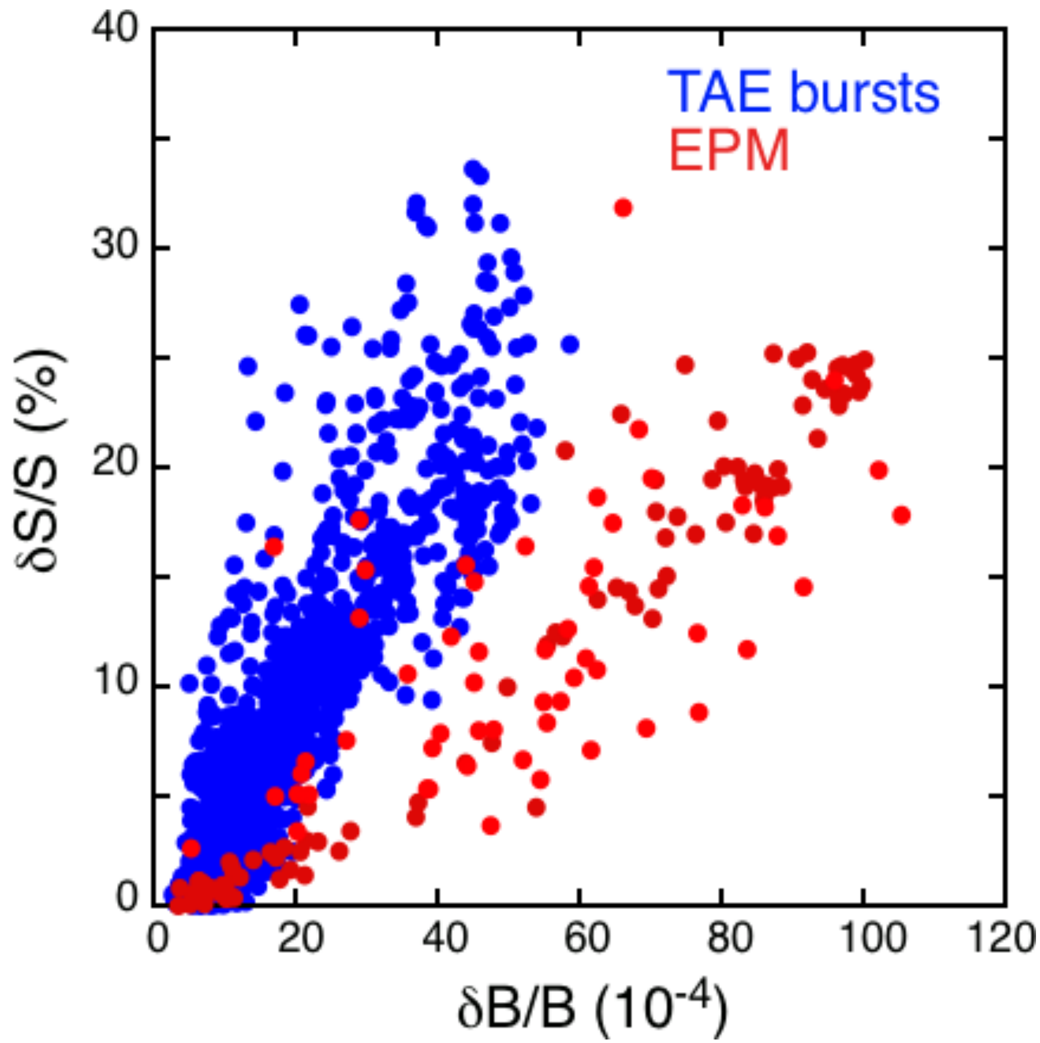
Parametric dependence of EPM and TAE avalanche occurrences is helpful for understanding, planning

- $V_{fast}/V_{Alfvén}$ is measure of resonances fast ions can have with TAE.
- $\beta_{fast}/\beta_{Alfvén}$ is measure of drive to damping.
- Plasmas typically evolve from lower-right towards upper left.
- TAE avalanches only occur for $\beta_{fast} > 0.3\beta_{total}$.
- Conversely, quiescent plasmas were only seen where $\beta_{fast} < 0.3\beta_{total}$.



TAE avalanche induced fast ion transport scaling is roughly linear (or offset-linear) with mode amplitude

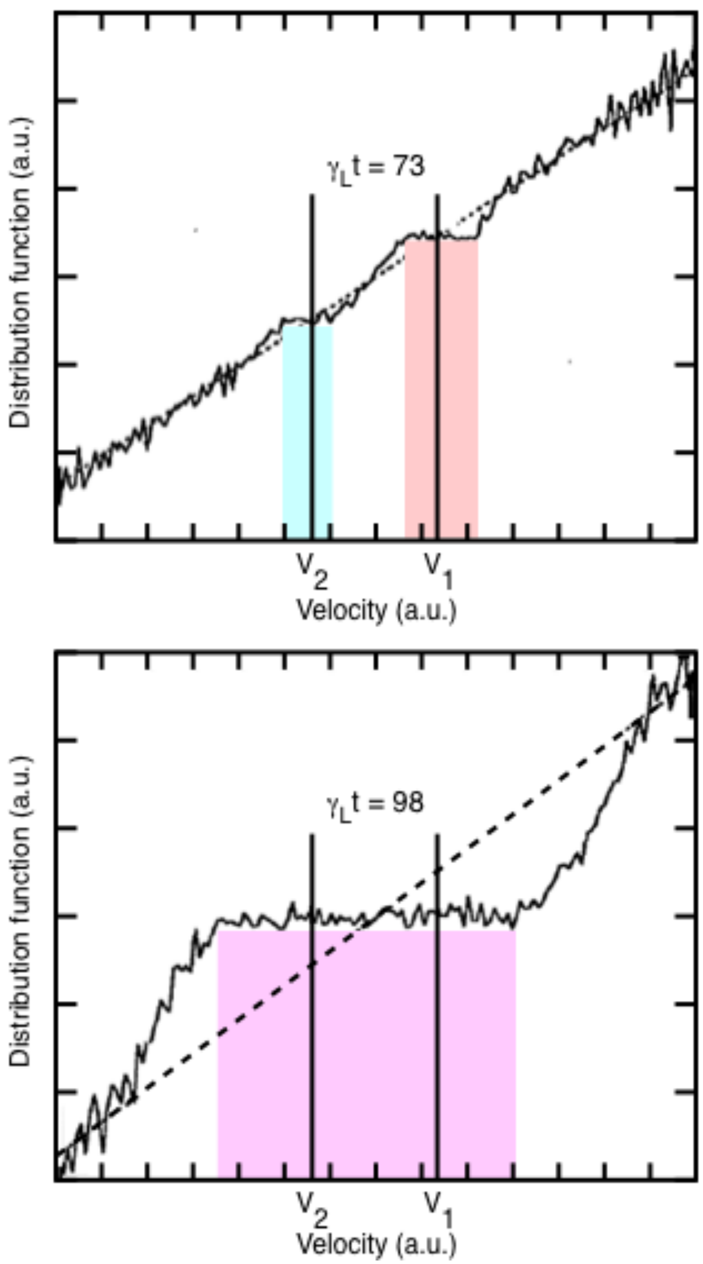
- Magnitude of neutron rate drops is comparable for EPM and TAE avalanches.
- Largest events cause >20% transient drops in neutron rate.
- EPM typically show larger magnetic fluctuation level for same amplitude neutron drop as TAE avalanche.



- In remainder of talk, TRANSP, ORBIT and NOVA (with experimental mode amplitude and frequency evolution) will be used to model fast ion redistribution by TAE avalanches.

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

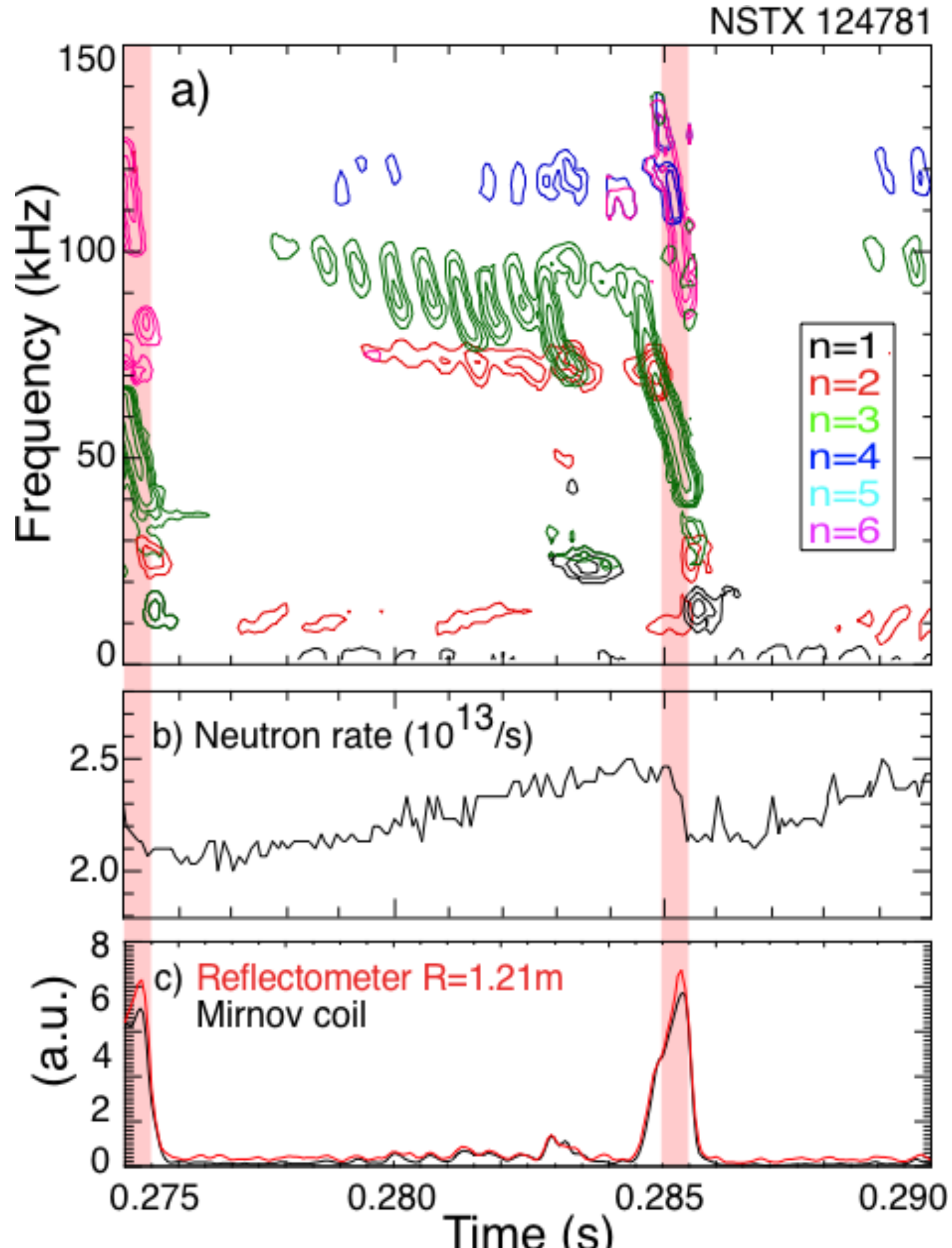
Berk, *et al.*, Phys. Plasma **2** 1995 2007



- Low amplitude modes don't overlap in fast-ion phase-space.
- When modes overlap at larger amplitude can cause 'avalanche', accessing more free energy; driving stronger modes, new modes.
- Interaction of multiple modes enhances fast ion transport.
- TAE avalanches have strong mode bursts consisting of multiple modes.
- TAE have multiple resonances, more complex physics.

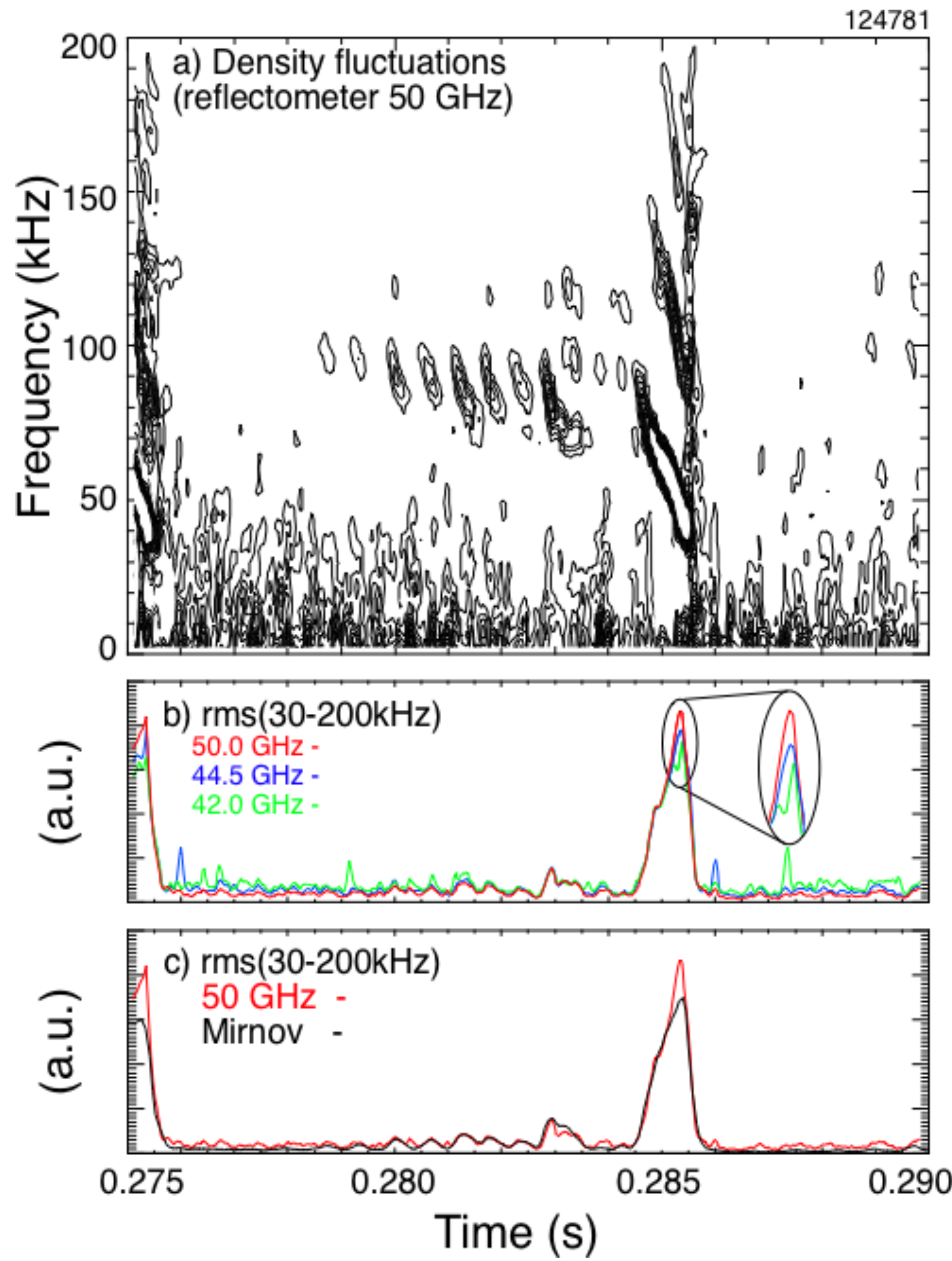
Large TAE bursts in NSTX show sudden growth to large amplitude, large increase in fast ion transport

- As in avalanche model, multiple modes are present; however each mode has also multiple resonances allowing potentially an “avalanche of one”.
- Amplitude of final burst in sequence is typically 10 times larger than previous bursts.
- Last burst is accompanied by neutron rate drop and is followed by a quiescent period.
- Large frequency chirps are characteristic of NSTX TAE bursts.
- Simulation and comparison has been done for avalanches in both H-mode and L-mode plasmas.

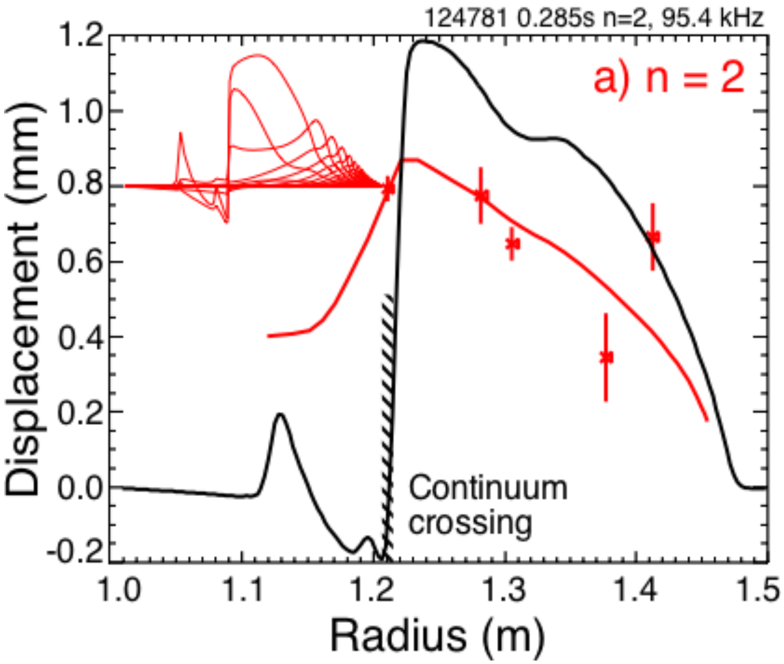


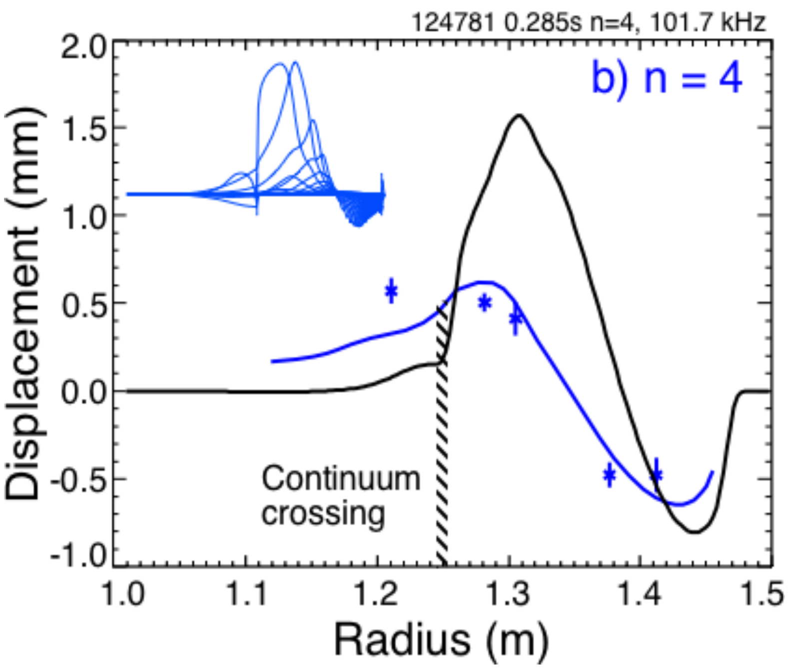
Use of scaled linear eigenmodes validated by multi-channel reflectometer measurements

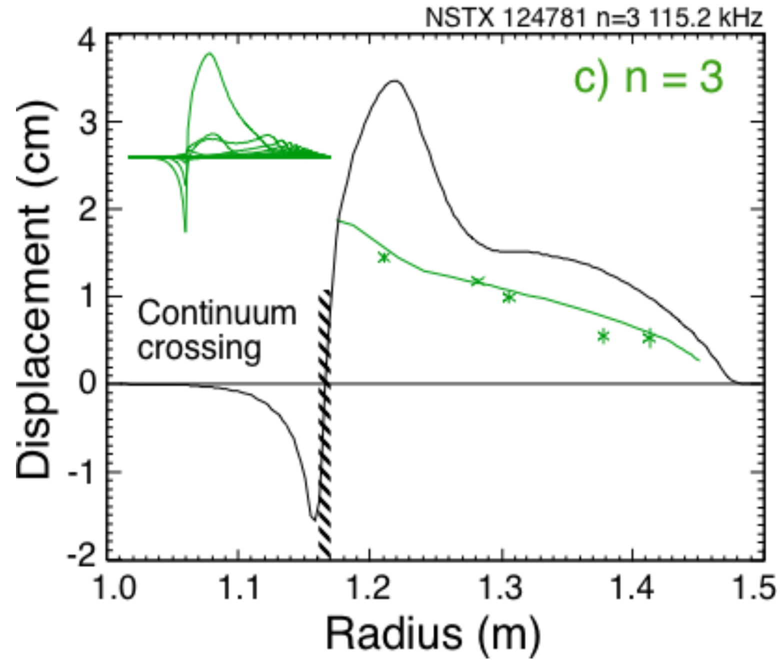
- NOVA linear eigenmodes are scaled by multi-channel reflectometer data for ORBIT simulations.
- Linear mode structure relatively unaffected by frequency chirp, mode growth in multiple reflectometer channels...
- …except toward end of burst, where some distortion is seen.
- Amplitude at time of avalanche much greater than earlier bursts.



Mode structure, measured with reflectometer array, well modeled for L-mode avalanches



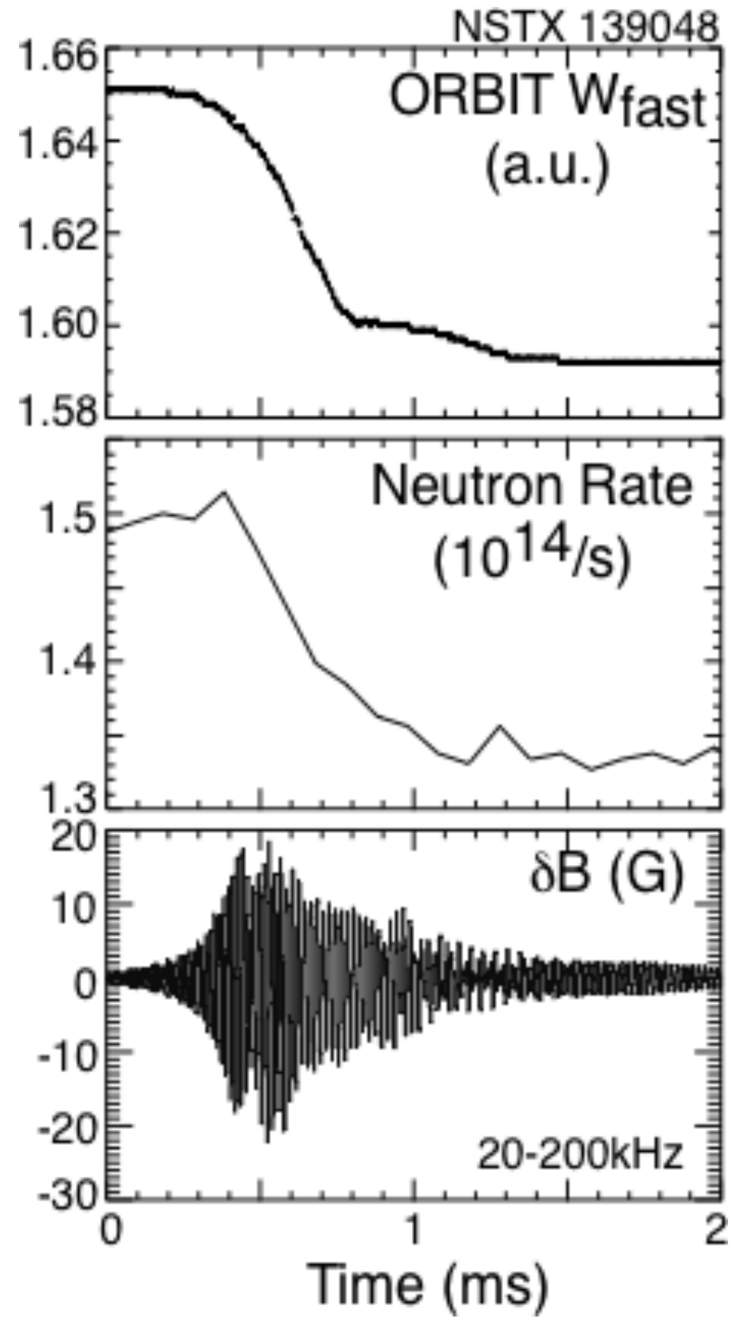




- Best fit NOVA eigenmodes selected by simulating reflectometer response.
- Solid colored lines show simulated reflectometer, overlaid by reflectometer data.
- The black curve shows the total flux surface displacement inferred from the above fitting.
- Similar agreement found for avalanches in H-mode plasmas.

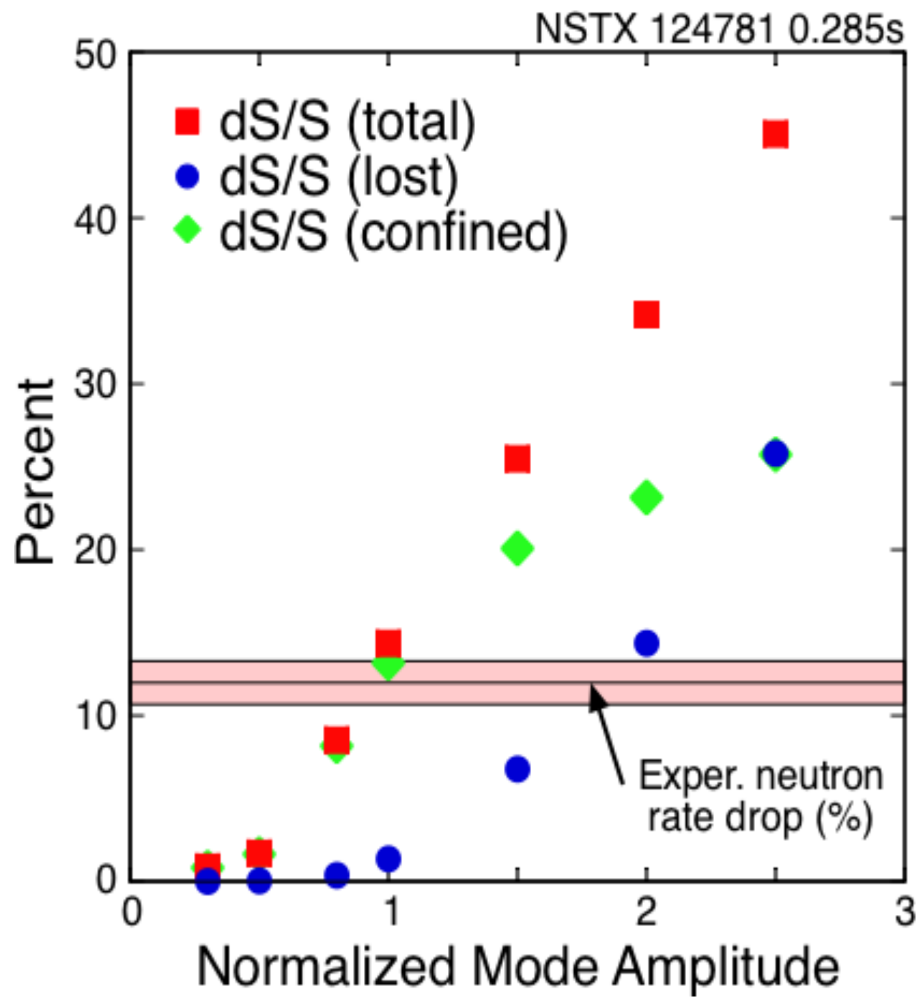
β_{fast} decay time in ORBIT simulation is consistent with measured drop in neutron rate δS

- Time evolution of fast ion beta in ORBIT simulation is consistent with measured neutron rate drop.
- Evolution of measured neutron rate (middle panel).
- Drop in β_{fast} is due primarily to energy loss and redistribution.
  - Fast ion losses become more important at higher mode amplitudes.
- Amplitude evolution of TAE (last panel).
- Peak in mode amplitude roughly coincides with maximum dS/dt.



Apparent onset of stochastic transport seen in ORBIT simulations

- The red squares show the estimated total neutron rate drop vs. scaled TAE amplitude.
- Threshold is seen for onset of significant neutron rate drop in ORBIT simulations (at ≈ 0.3 of nominal measured mode amplitude).
- Neutron rate drop at low amplitude primarily from energy loss and from redistribution.

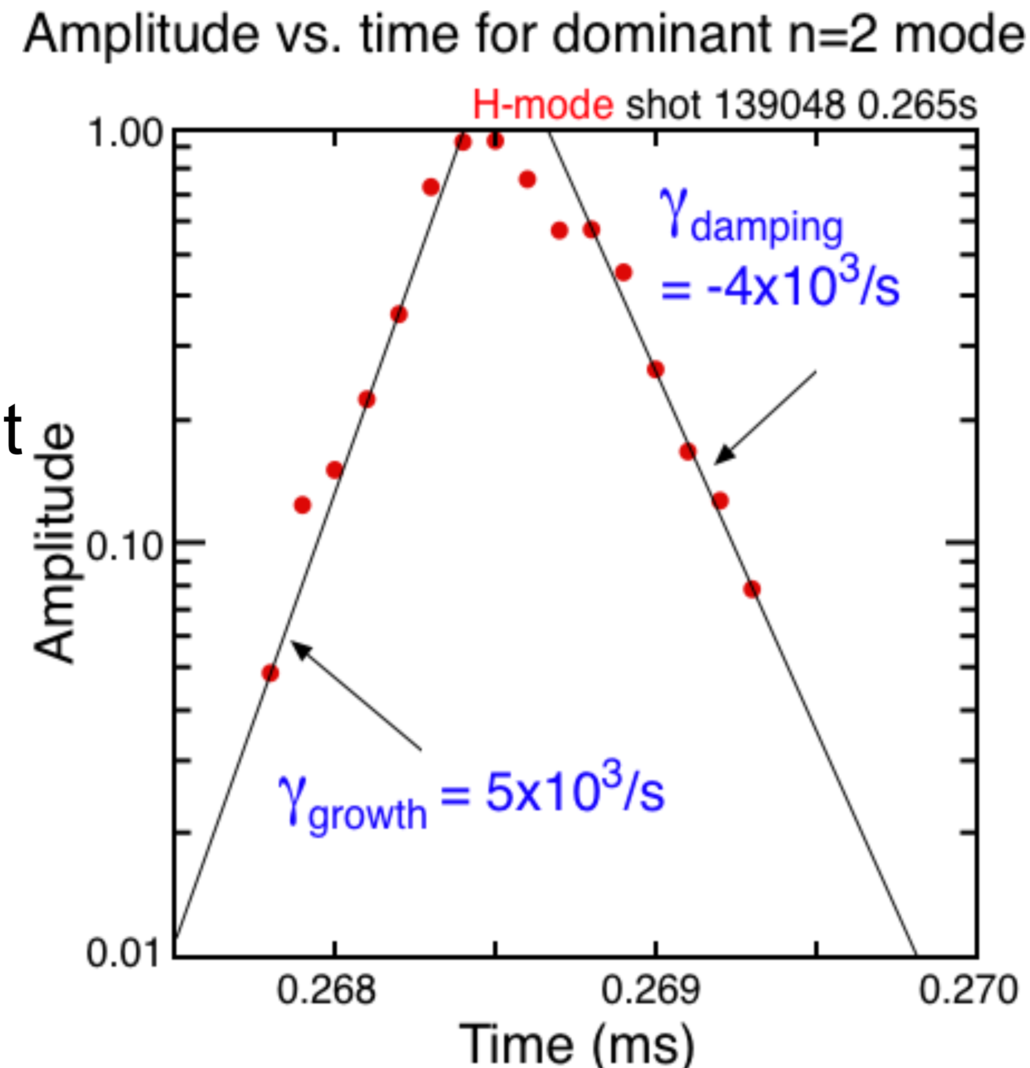


- In L-mode, neutron rate drop due to fast ion losses onsets at ≈ nominal mode amplitude (blue circles).

M. Podesta, NP8.00030, Development of a reduced model for resonant fast ion transport in TRANSP

Energy lost from fast ions consistent with estimated energy lost from TAE to thermal plasma

- The fast ion energy loss is calculated with ORBIT: net $\delta\beta_{fast} \approx 1.0 \times 10^{-3}$.
- Peak $\beta_{wave} \approx 1.9 \times 10^{-4}$ from NOVA scaled to measurement then $\delta\beta_{fast}/\beta_{wave} \approx 5.3$.
- The energy lost through TAE damping is calculated using NOVA eigenmodes and measured mode amplitude evolution:



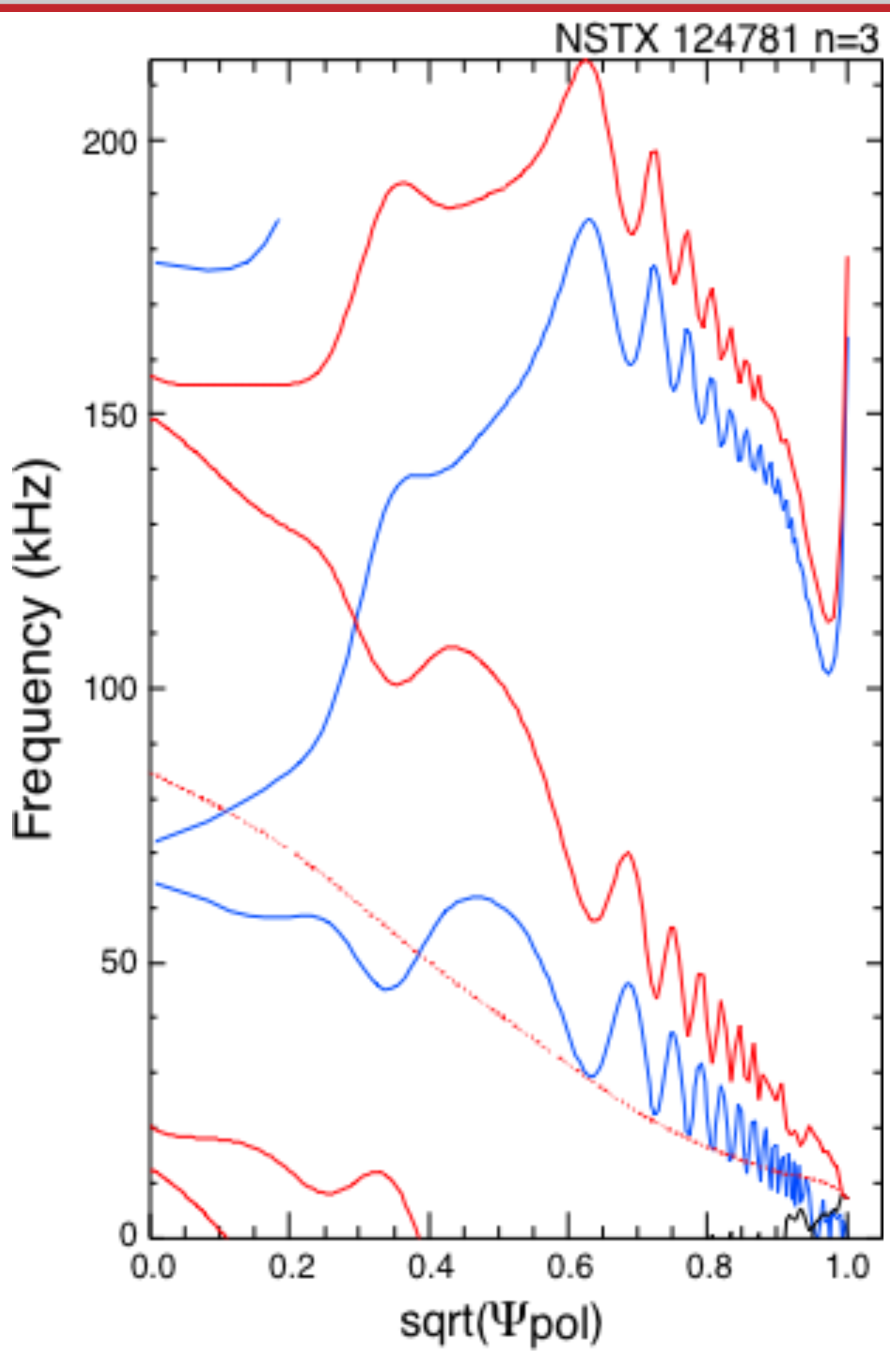
$$W_{loss}/W_{peak} = \delta\beta_{fast}/\beta_{wave} = 2\gamma_{damp}\int_0^{t_0}\left(A^2_{mode}(t)/A^2_{peak}\right)dt \approx 2\gamma_{damp}(0.5\times10^{-3}s)$$

- The empirical damping rate of 4×10^3/s yields $\delta\beta_{fast}/\beta_{wave} \approx 4.0$.

Semi-empirical modeling of fast-ion transport in TAE avalanches reproduces experimental results

- Neutron rate drops of up to ≈25% are correlated with both TAE avalanches and EPM bursts.
- TAE avalanches only seen for $\beta_{fast}/\beta_{total}>0.3$.
- NOVA ideal modes, scaled to experimental amplitude, used in ORBIT to simulate effect on fast ion population.
- Up to the measured mode amplitude, dominant effect is a reduction in net energy of the sample fast ion population.
- Reduction in fast ion energy reduces fusion rate; drop is consistent with experimental drop in neutron rate.
- Simulated energy lost from fast ions is comparable to estimated energy lost from TAE damping on thermal plasma.

Future work will address physics issues arising from strong sheared toroidal rotation.



- 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.
- Strong rotation allows coupling of off-axis TAE with core MHD.
- Plasma rotation also affects both calculations of resonant drive and damping.