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Fast Ion Losses in Toroidal Alfvén Eigenmode Avalanches in NSTX

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NSTX focus is on non-linear physics of Alfvénic and Energetic Particle modes

- Fast ion transport and losses enhanced by Alfvén 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.
- NSTX experiments simulated by linear and non-linear codes.
  - 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*.

*G. Fu, APS 2007, Inv. Talk BI4

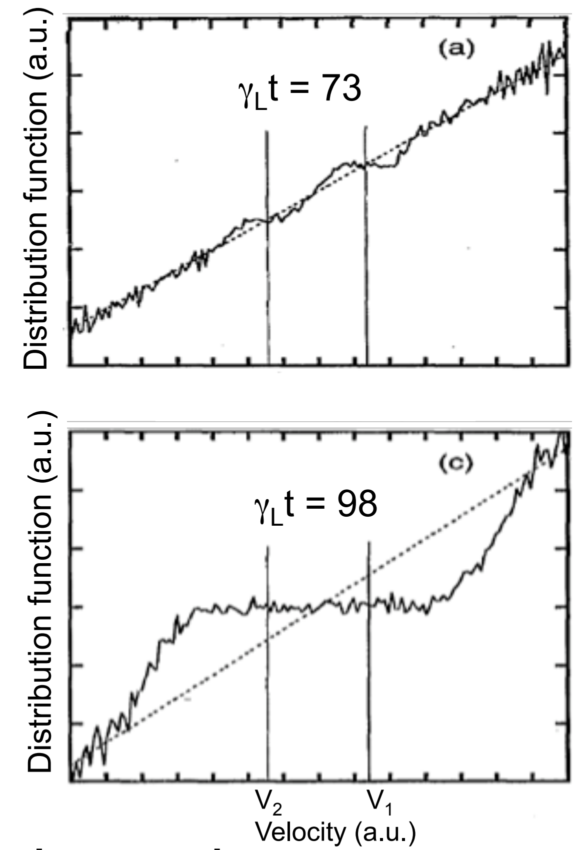
This presentation will describe simulations of TAE avalanches

NSTX

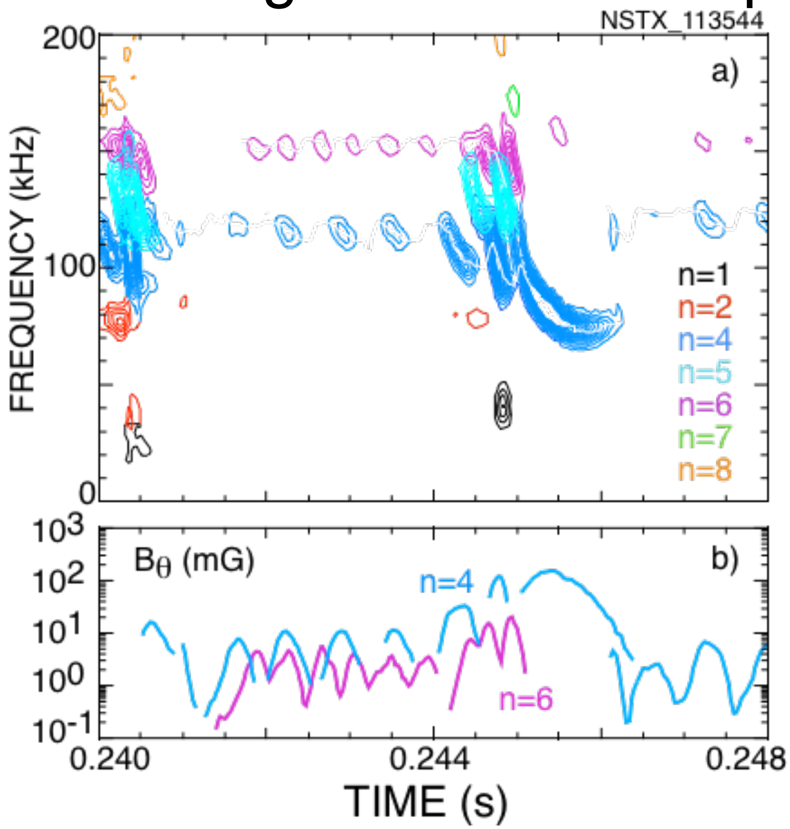
- TAE-avalanching condition identified:
  - Beam power scan from quiescent to avalanching plasmas
    - Fast ion β threshold to trigger TAE and TAE avalanches found.
- NOVA calculation of Alfvén continuum
  - Use equilibrium parameters, including MSE constraint on q-profile
    - Experimental mode frequencies with TAE gap.
- Internal structure of the modes is measured
  - compared with NOVA ideal linear simulations.
- Fast ion losses simulated with the ORBIT code
  - compared to NPA data and global neutron rate changes.
- Good agreement with simulated and measured mode structure and fast ion losses is found.

TAE bursts suggest "Avalanche" physics

NSTX



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



Berk, et al., PoP **2** p 3007

- Large amplitude modes overlap in fast-ion phase-space.
- Interaction results in stronger modes, destabilizes new modes; more fast ion transport
- TAE have multiple resonances, more complex physics

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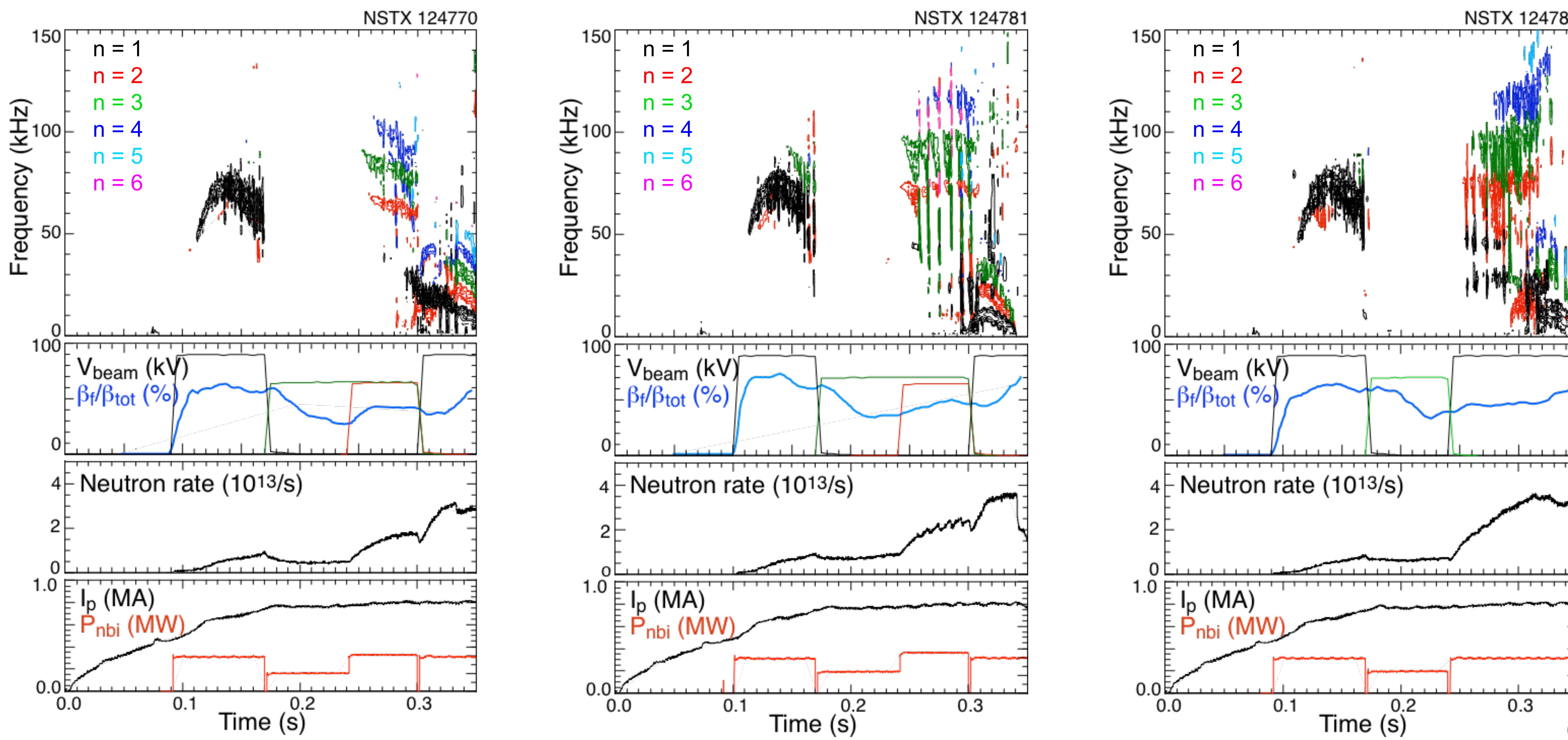
TAE avalanches are seen in both L-mode and H-mode plasmas

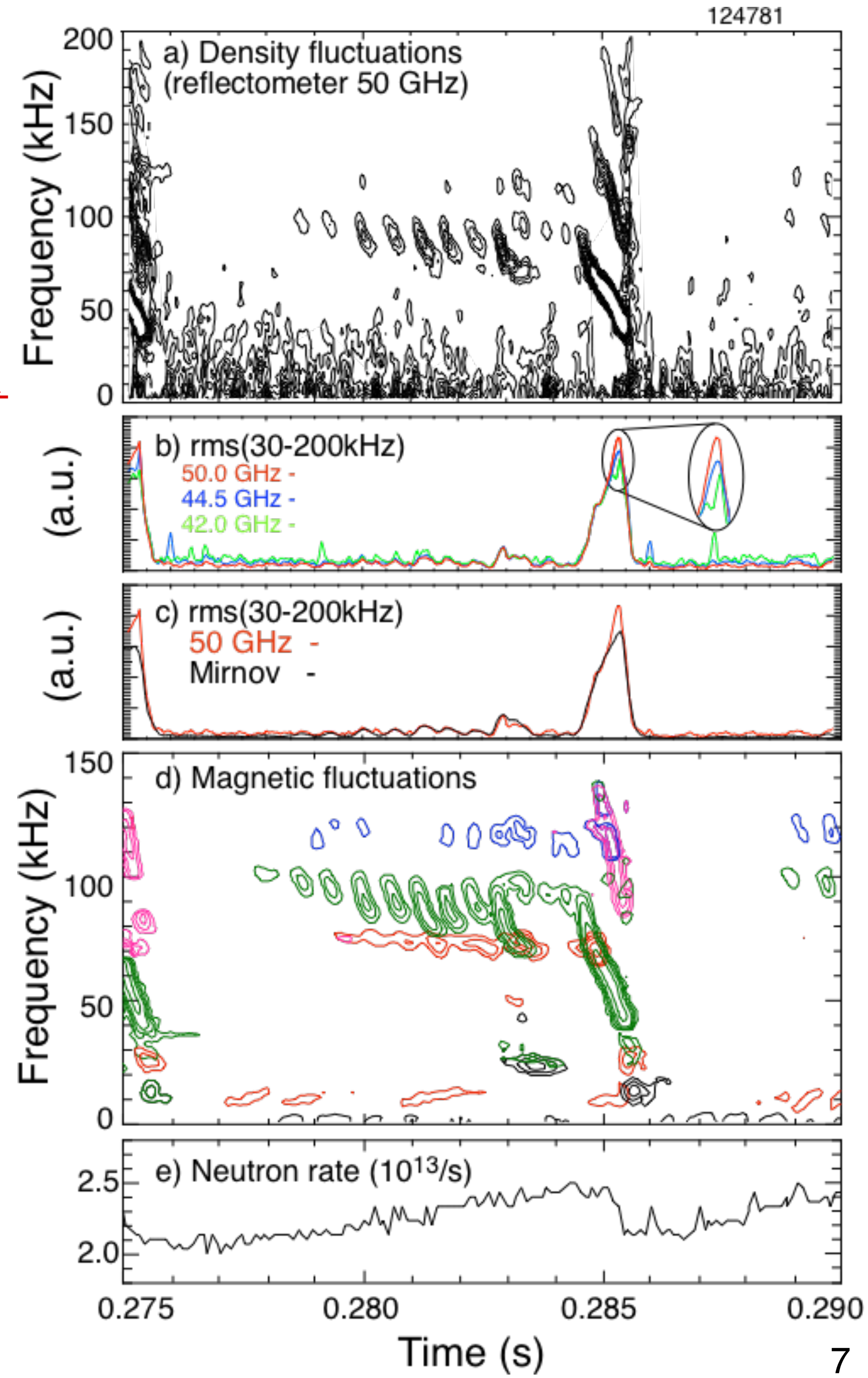
- Avalanche threshold in β_{fast} is 10% above TAE threshold
- TAE and Avalanches thresholds affected by beam energy.



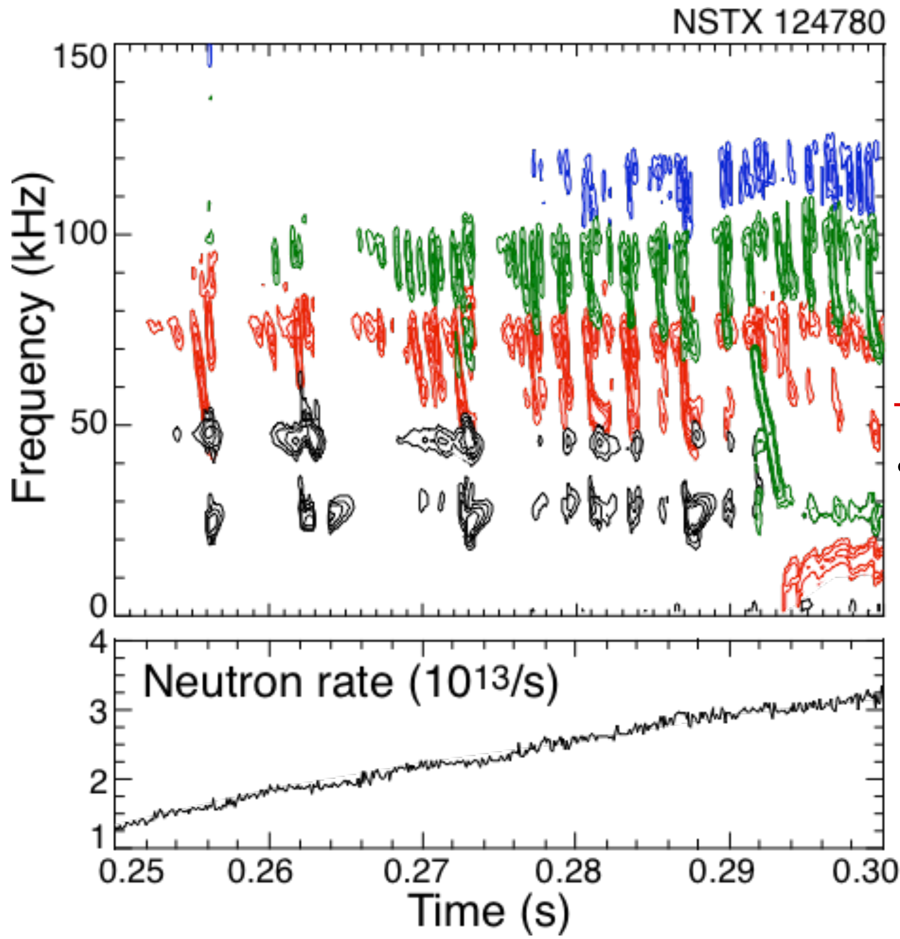
Mode nearly rigid through avalanche, chirp evolution

NSTX

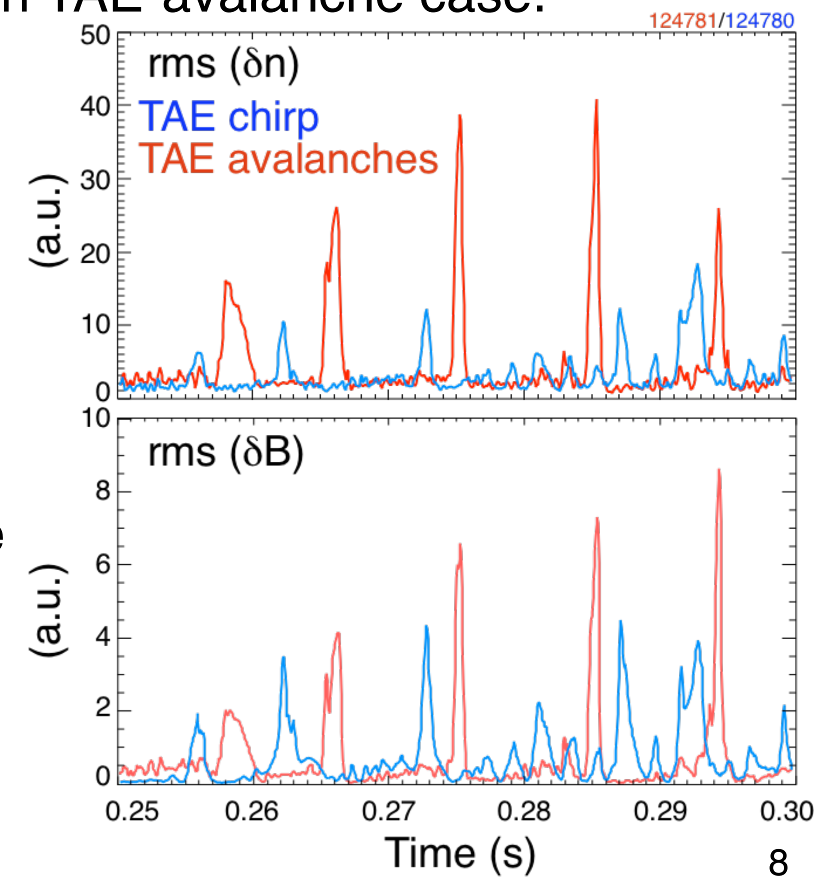
- Relative amplitude tracks well through multiple modes, suggesting rigid mode structure...
- …except mode becomes more core-localized at end.
- Amplitude at time of avalanche much greater than earlier bursts.
- All TAE bursts chirp, important for fast ion transport?



Weak neutron rate drops in higher beam voltage shot



- Mode amplitude 2 - 3 times smaller than in TAE-avalanche case.



- Multiple modes present here, also.
- Stronger chirping shot has higher voltage beams, more tangential injection.
- Chirp at 0.293 is simulated with NOVA and ORBIT; compared to avalanche.
- Are these modes similar?

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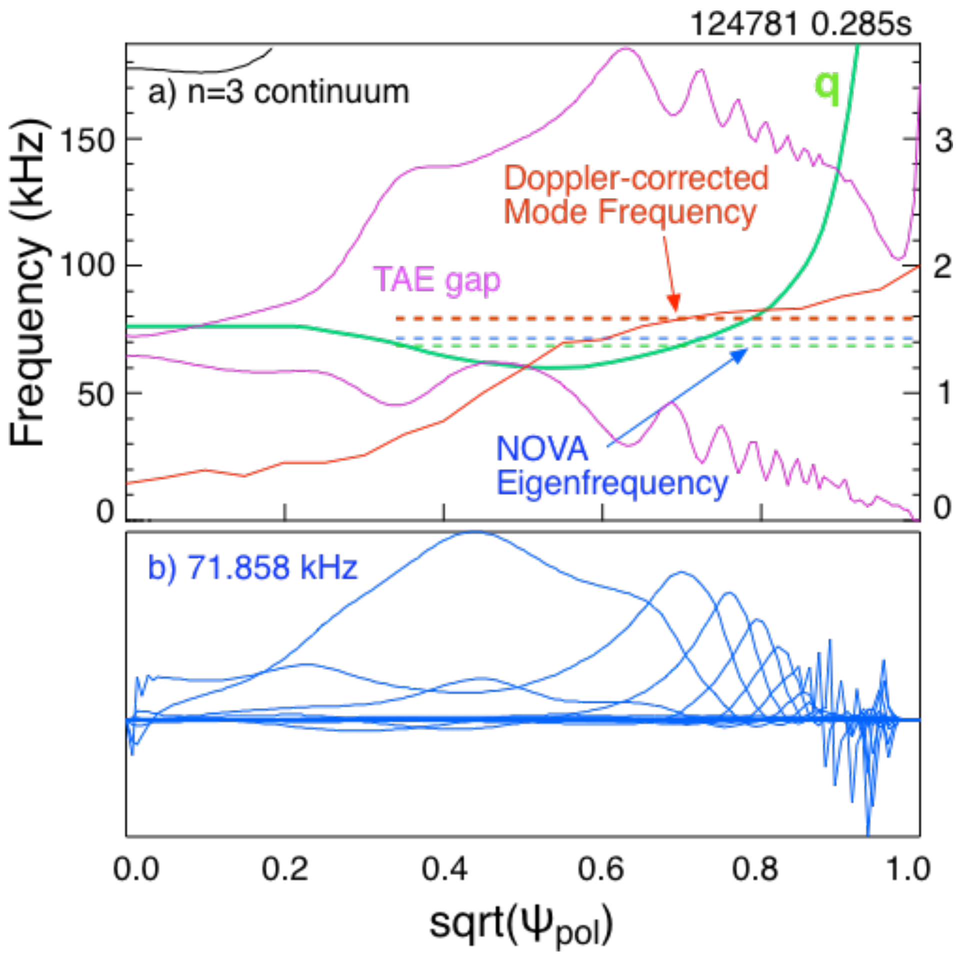
Mode frequency sits in TAE gap, but multiple modes



- Magenta curves show β-corrected Alfvén continuum.
  - Solid red line shows n = 3 mode frequency in local plasma frame.
- Green curve shows q-profile
- Poloidal harmonics of one n=3 TAE mode (blue).
- Multiple eigenmodes found, Which eigenmode is right?

- Is linear eigenfunction shape good match to experiment?
- Are non-linear effects during mode growth significant?

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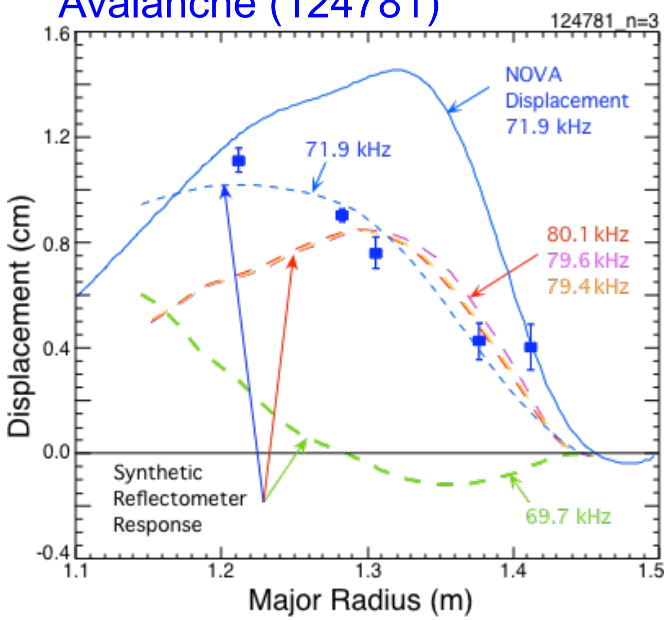
"Best fit" of experimental mode profile is to NOVA eigenmode at 72 kHz

NSTX

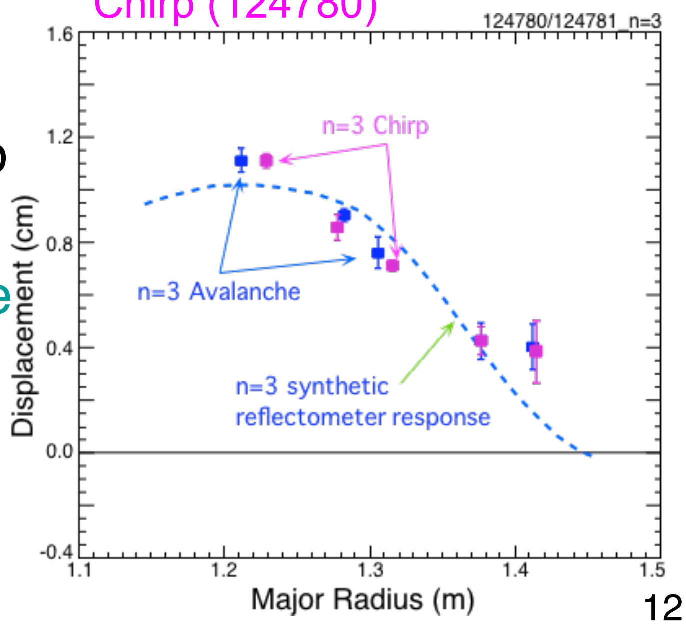
- Synthetic reflectometer responses are shown for the five TAE-like eigenmodes at frequencies of ≈ 69 kHz, 72 kHz and three at ≈ 80 kHz.
- In blue are shown the five reflectometer measurements of mode amplitude, interpreted by simple "mirror" model.
- The solid blue line is the NOVA outboard displacement giving best fit.

Avalanche (124781)



- Measured mode structures are very similar for n=3 chirp and avalanche.
- Eigenmodes can be scaled, used in ORBIT to simulate fast-ion losses.

Chirp (124780)



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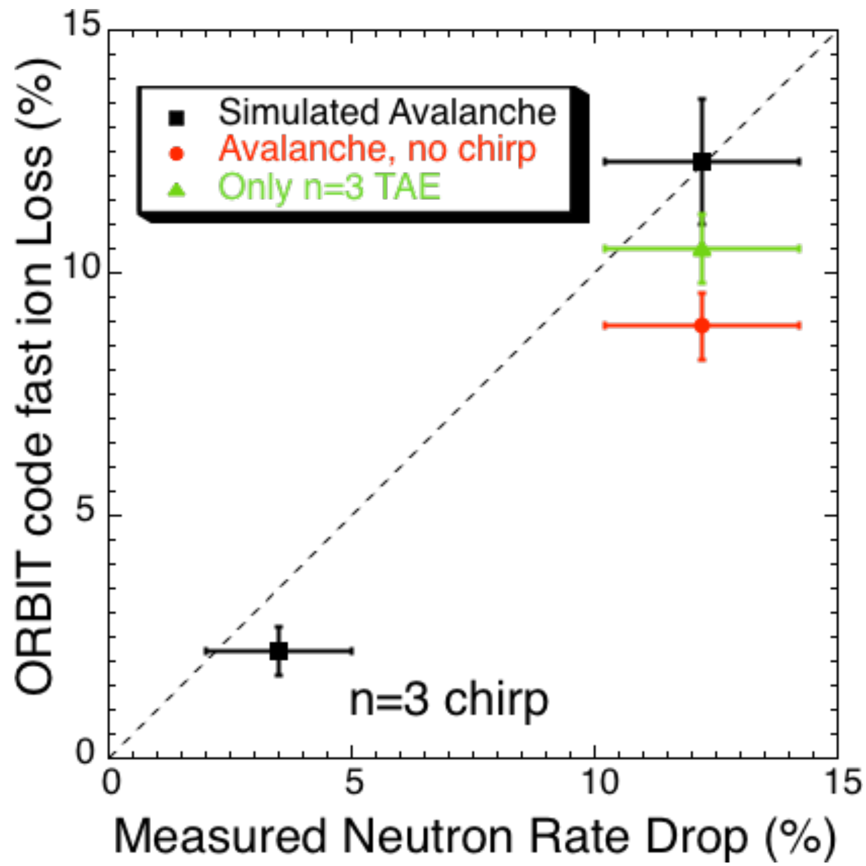
NOVA eigenfunctions scaled to reflectometer used in ORBIT to simulate fast ion losses

Avalanche:

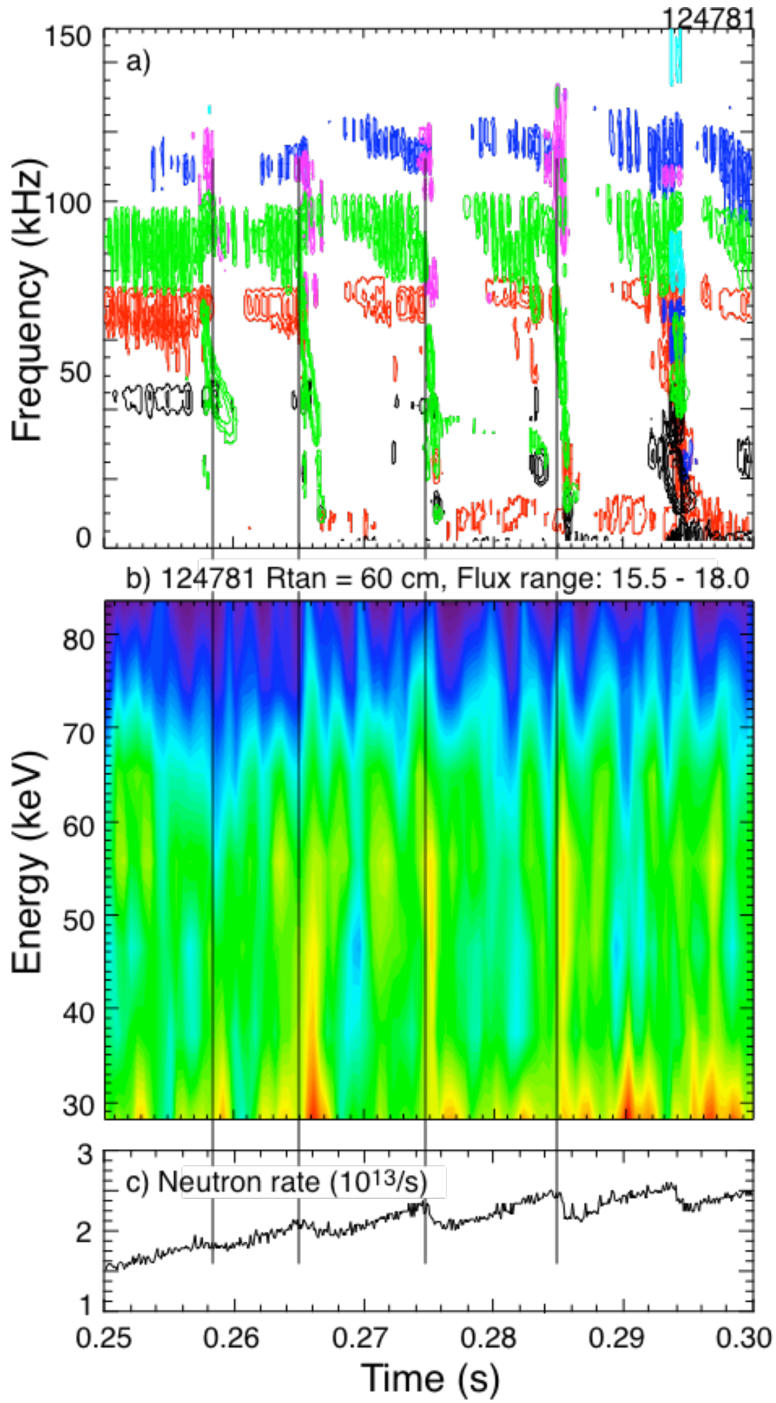
- n = 2, 3, 4, 6 eigenmodes used in ORBIT.
  - Only first 12 poloidal harmonics kept
- Most (≈ 85%) losses ORBIT simulation from n=3 mode alone.
- ≈ 40% enhancement in losses when frequency is chirped.

Principal non-linear effect is the larger mode amplitude in Avalanche.

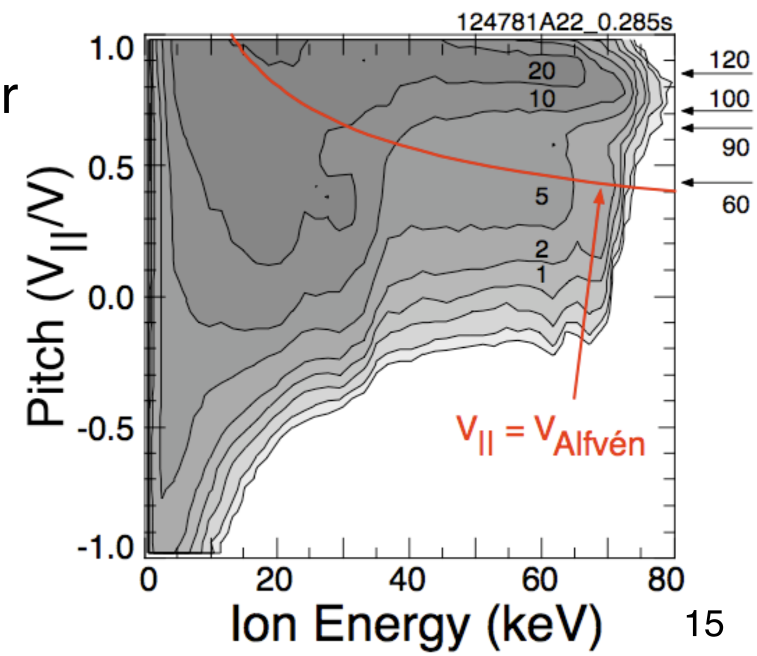
Frequency chirp is also important, increasing losses by ≈40%



Fast ion losses extend to low-energy

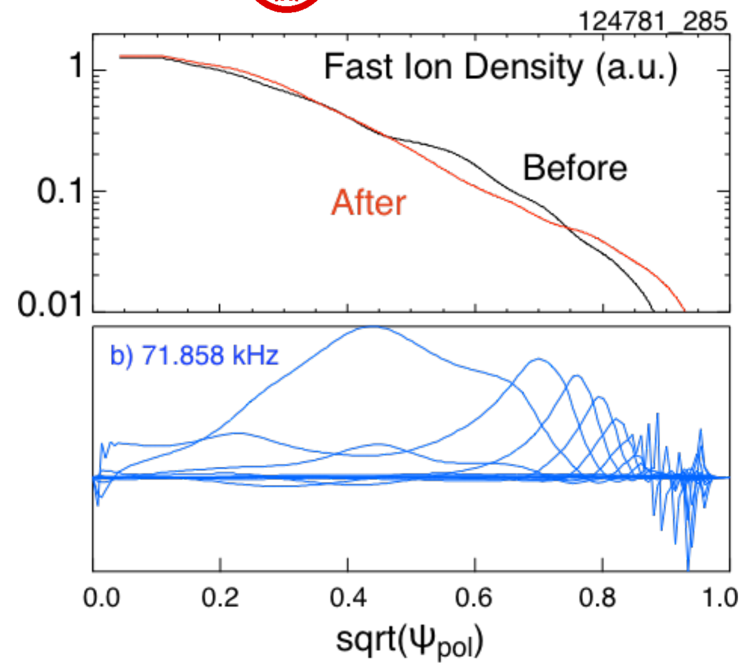


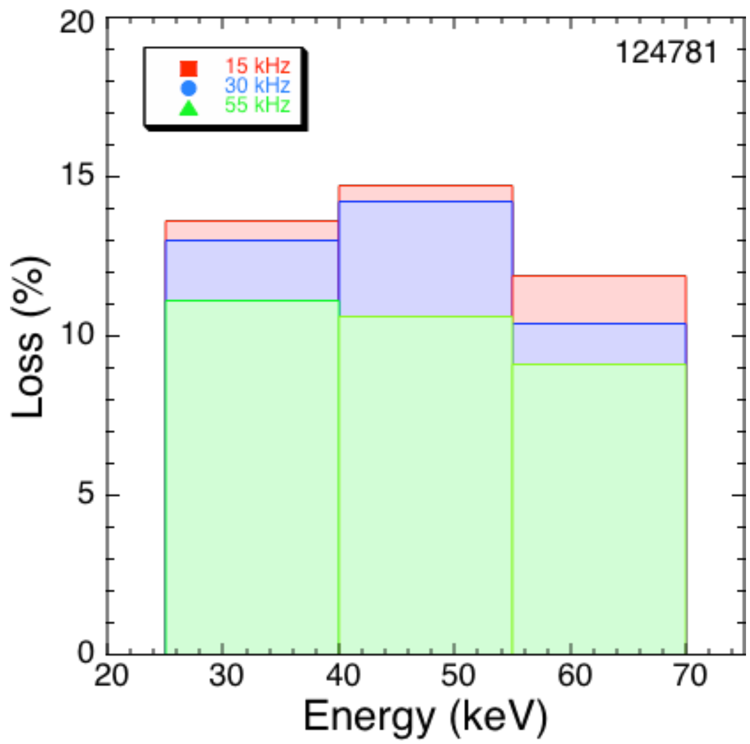
- NPA measures energy spectrum of charge-exchange fast-ions from plasma.
- D-alpha spikes at neutron drops - fast ions are lost.
- Beam ion velocity well above $V_{Alfvén}$; many fast ions can be resonant.
- Distribution for r/a ≈ 0.5.



Similar fraction of ions are lost from 30 keV to 70 keV

- Mode interacts with a broad range of fast-ion energies, consistent with NPA measurements.
- Broad energy range of losses not affected by mode frequency.





- Profiles from ORBIT runs simulating Avalanche event, red, and with no TAE, black are shown.
- Small increase in fast ion density is seen on axis.

Fast-ion losses non-linearly enhanced by multi-mode interactions

- Fast ion transport from TAE avalanches studied on NSTX
  - Transient losses of ≈10% of fast ions are seen.
  - Similar loss mechanism possible on ITER.
- TAE structure and frequency are well modeled by NOVA.
  - No significant non-linear changes to mode structure are seen as mode grows and saturates.
- Simulations with the linear NOVA and ORBIT codes model the observed loss of fast ions in the avalanche event.
  - Enhanced transport affects a wide range of energies
  - Frequency chirping enhances losses
  - Enhanced saturation amplitude principal non-linear effect
- The simulations are not self-consistent; non-linear effects simulated by
  - Incorporating experimental mode amplitude and frequency evolution,
  - Spectrum of modes defined from experimental data.