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Experimental studies of TAE dynamics and induced fast ion losses on NSTX

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- *U St. Andrews*
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Abstract

The dynamics of toroidicity-induced Alfvén eigenmodes (TAEs) is studied in neutral beam heated NSTX plasmas. The results from similar discharges conducted in helium and deuterium plasmas are compared. Emphasis is put on investigating the transition of the modes from a quasi-stationary behavior into a phase characterized by frequency chirps and amplitude bursts as the injected neutral beam power is increased. The fast ion transport associated with bursting TAE activity is measured through Fast Ion D-Alpha spectroscopic diagnostics, neutral particle analyzers, neutron rate measurements and a fast ion loss probe. In particular, drops of the fast ion profile and neutron rate on time scales of ~1ms are observed during so called *TAE avalanches*, i.e. large bursting events accompanied by a frequency down-chirp which involve multiple TAEs.

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Focus on dynamics of toroidicity-induced Alfvén eigenmodes (TAEs) and induced fast-ion transport

- Multiple TAEs can be simultaneously destabilized
  - Possible overlap of many resonances in phase space
  - Non-linear development into "TAE ***avalanches***"

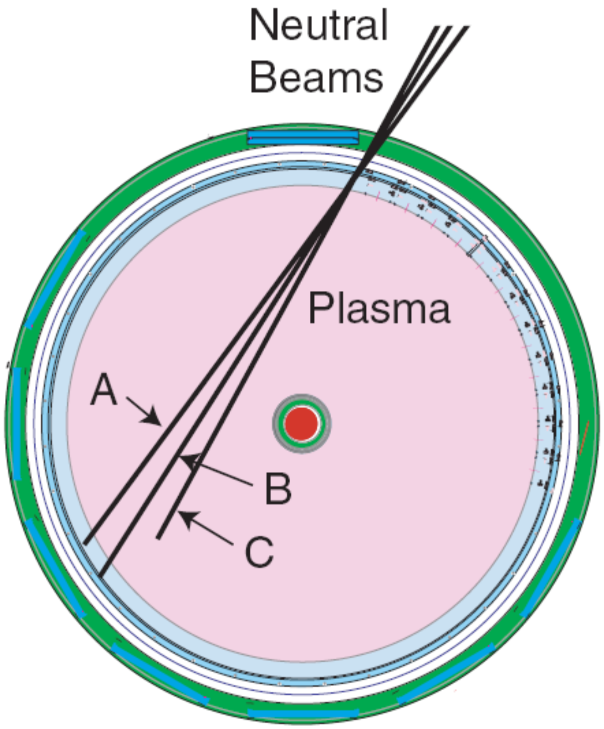
➔ **increased fast-ion losses**

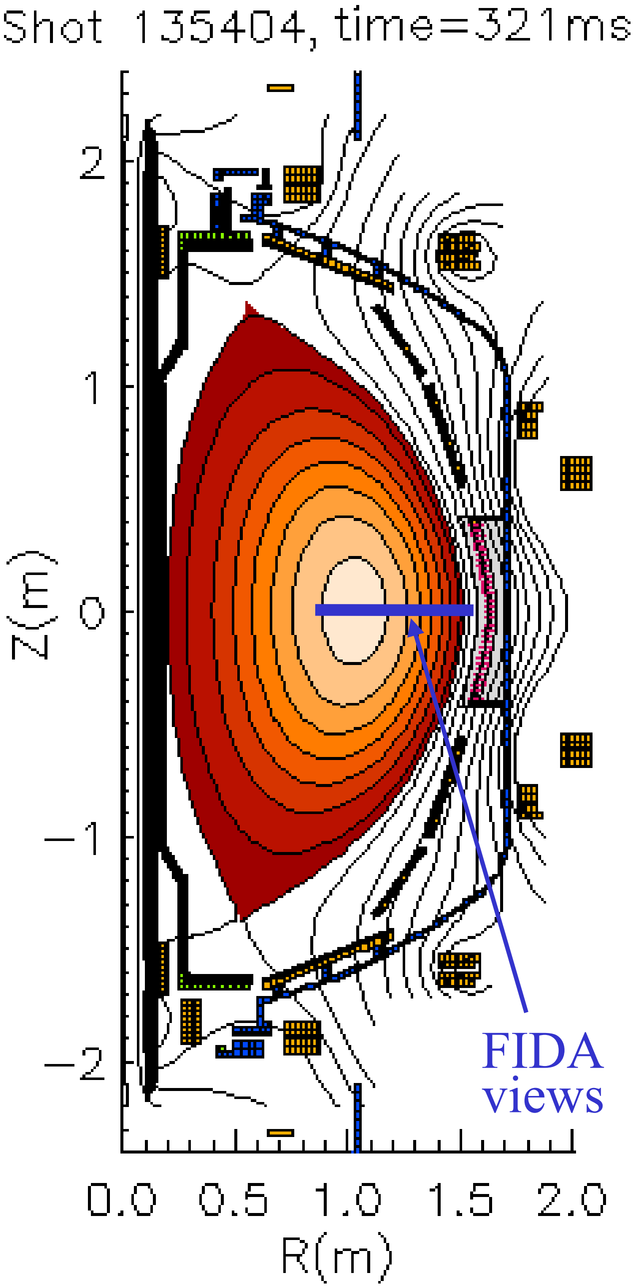
- "*Sea of TAEs*" expected in ITER: effects on fast ions?

- This work investigates:
  - Dynamics of TAEs in L-mode, Neutral Beam (NB) heated NSTX plasmas
    - Different regimes observed: why?
  - Effects of TAEs and TAE avalanches on fast-ion profile and energy distribution in NSTX

The National Spherical Torus Experiment, NSTX

Major radius	0.85 m
Aspect ratio	1.3
Elongation	2.7
Triangularity	0.8
Plasma current	~1 MA
Toroidal field	<0.6 T
Pulse length	<2 s





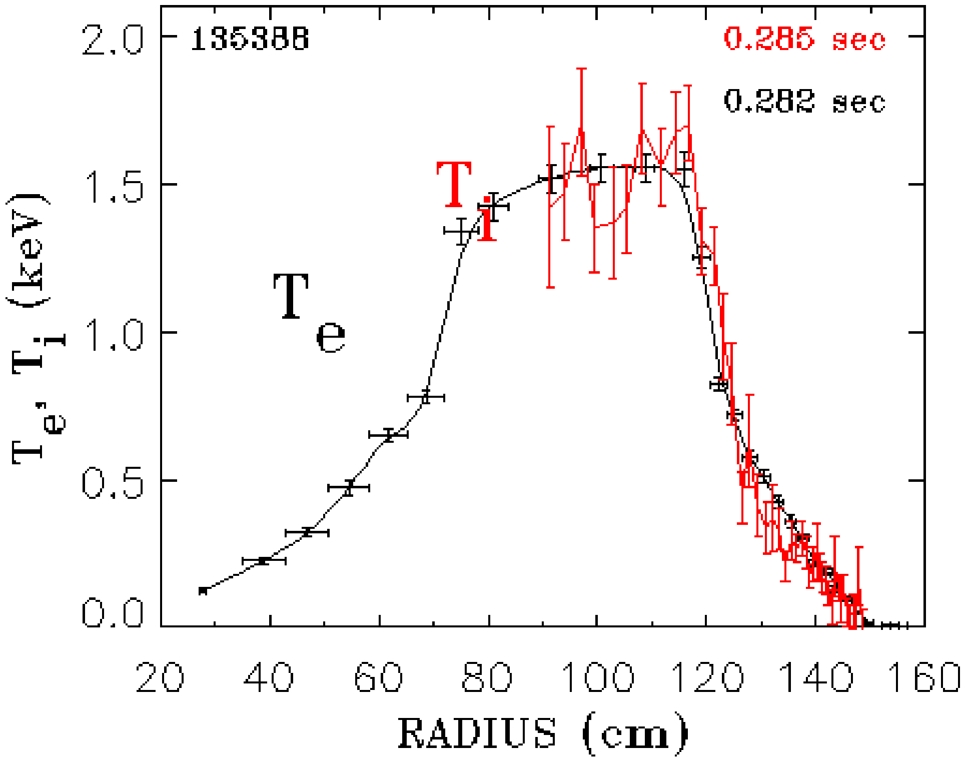
Neutral Beam (NB) auxiliary heating:

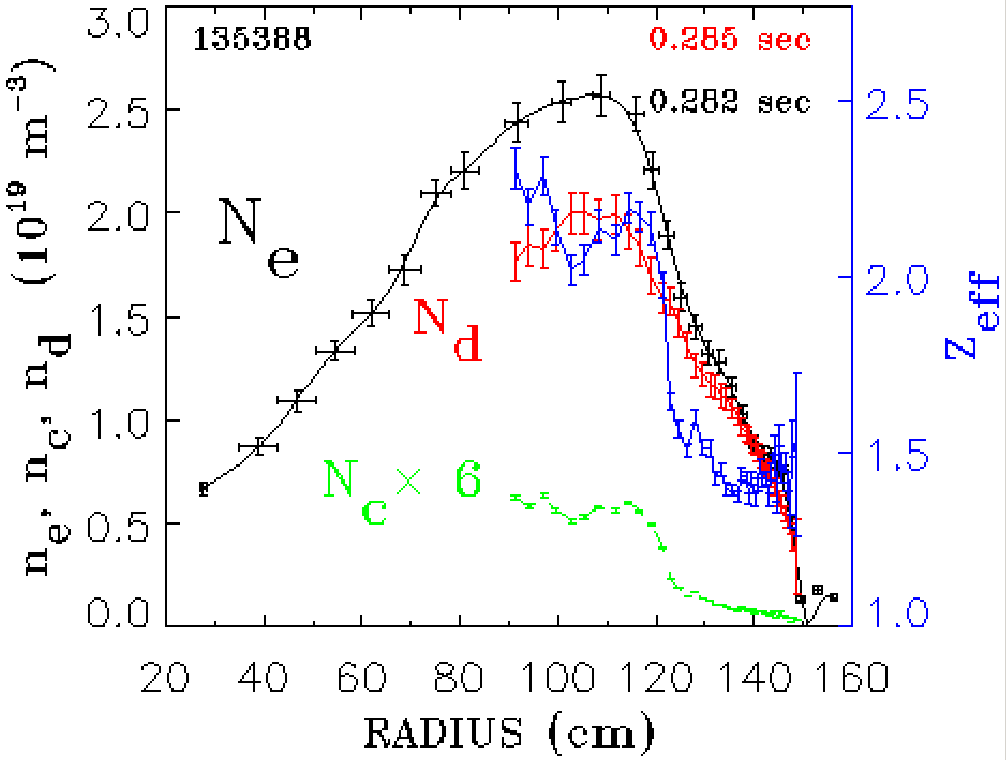
3 sources: A, B, C (different tangency radius)

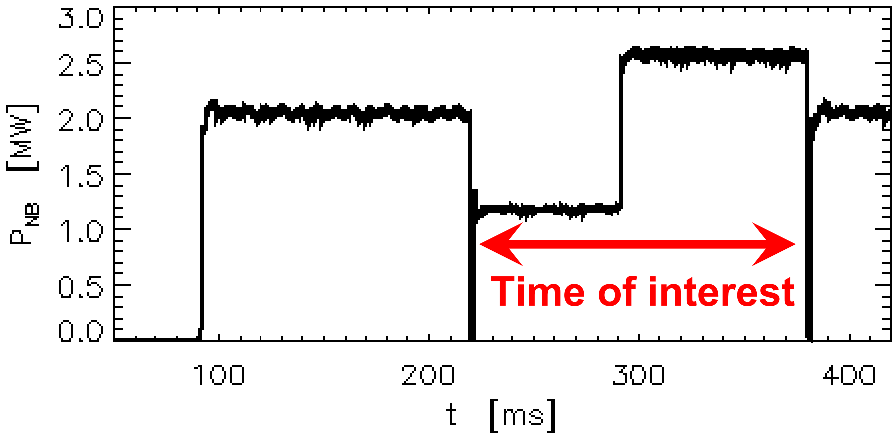
$P_{NBI} \leq 6$ MW ($V_{injection} \leq 95$ kV)

Center-stack limited deuterium plasma
B_{tor}=0.55 T, I_p=0.9 MA

Experimental scenario: L-mode, center-stack limited deuterium plasma with NB heating



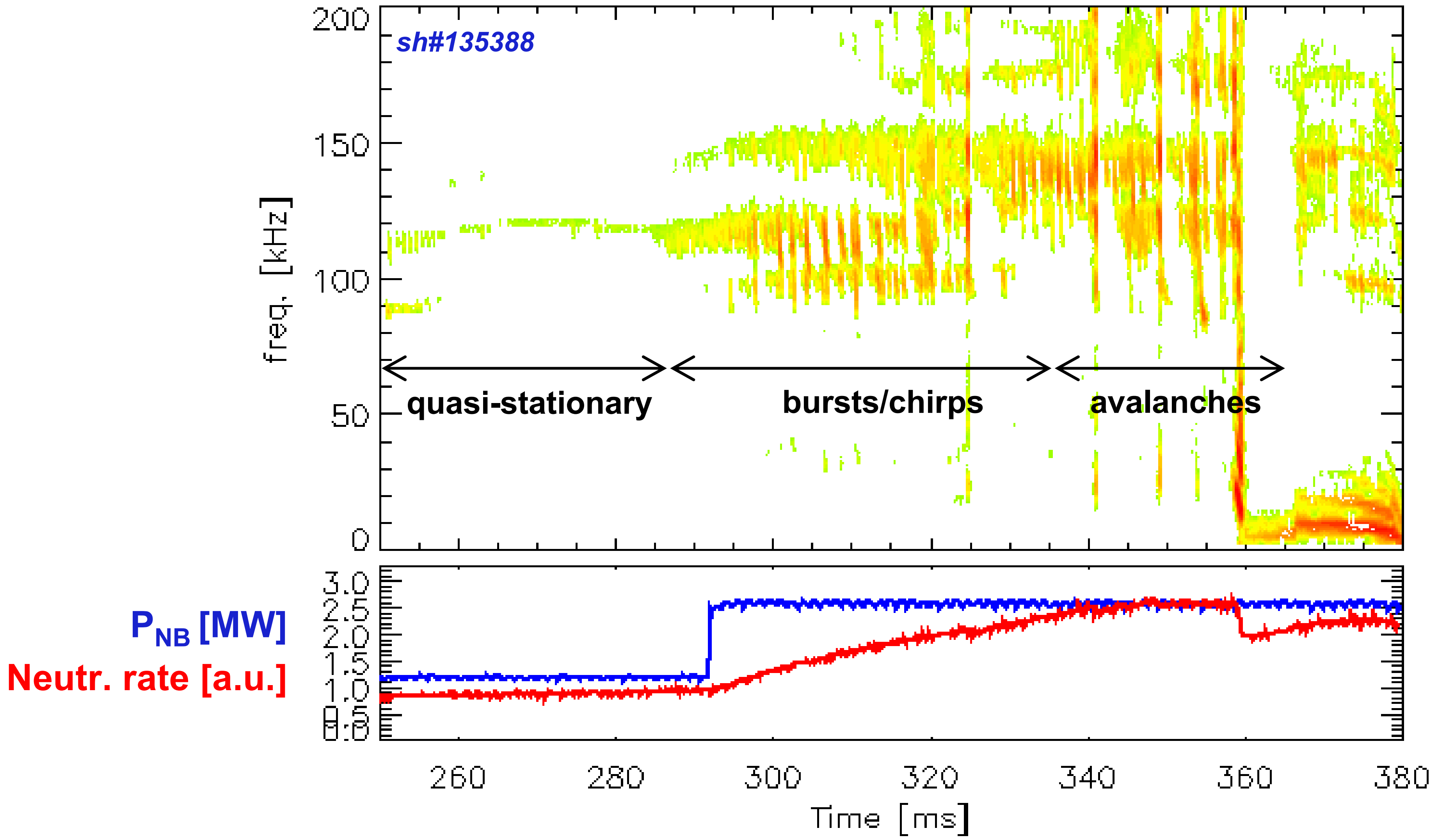




Time of interest

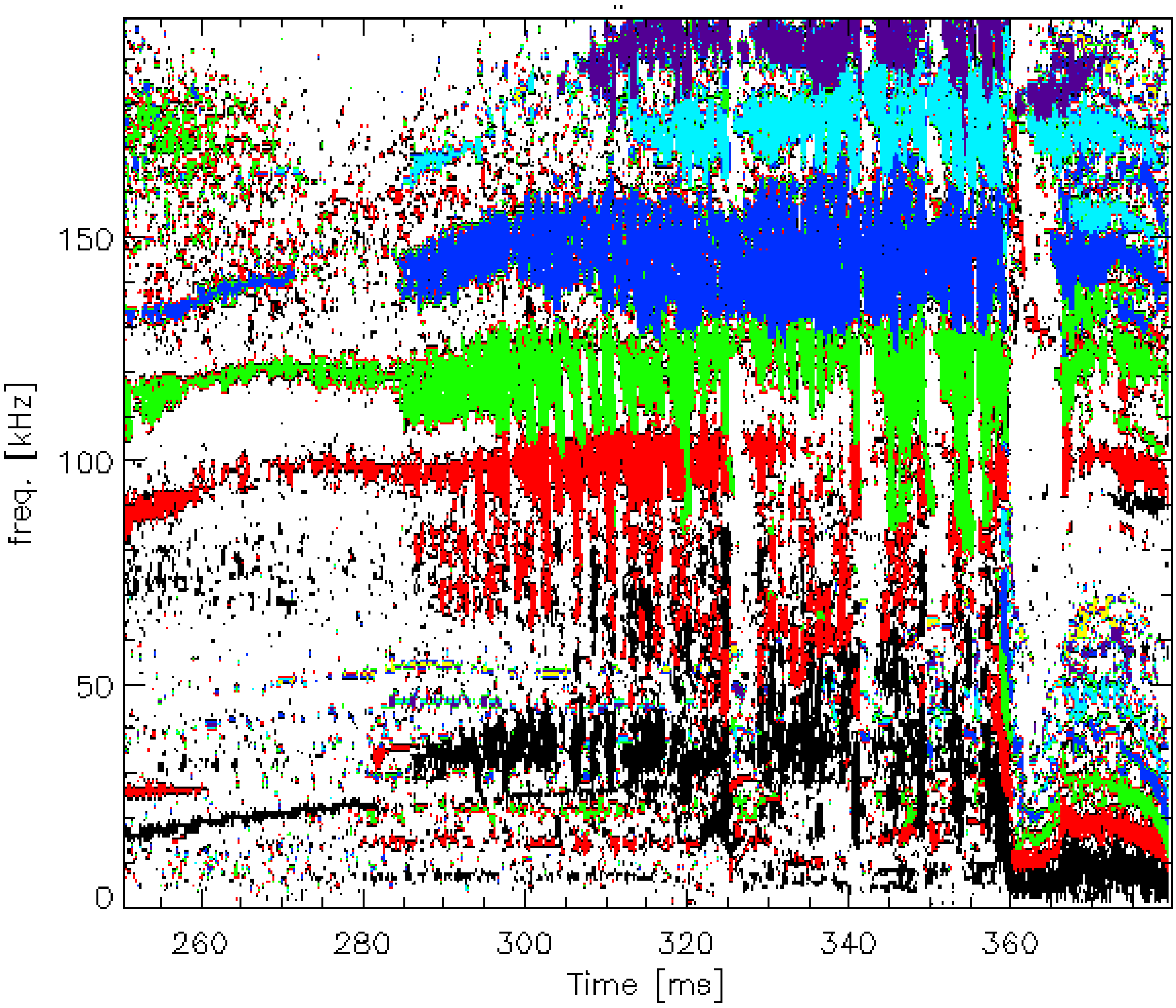
- Reverse-shear profile, q_{min}=2.5→1.5
- “Limited” plasma: simplified magnetic geometry, easier to simulate
- NB power and density varied to afffect drive/damping of TAEs
- L-mode allows mode structure measurements through reflectometry

Three TAE “regimes” are (qualitatively) observed, with gradual transition from one to the other



As the discharge evolves, modes change from quasi-stationary to bursting/chirping behavior - then avalanches occur

TAEs have low toroidal mode numbers (n=2→7), with dominant n=2,3 modes



n=1

n=2

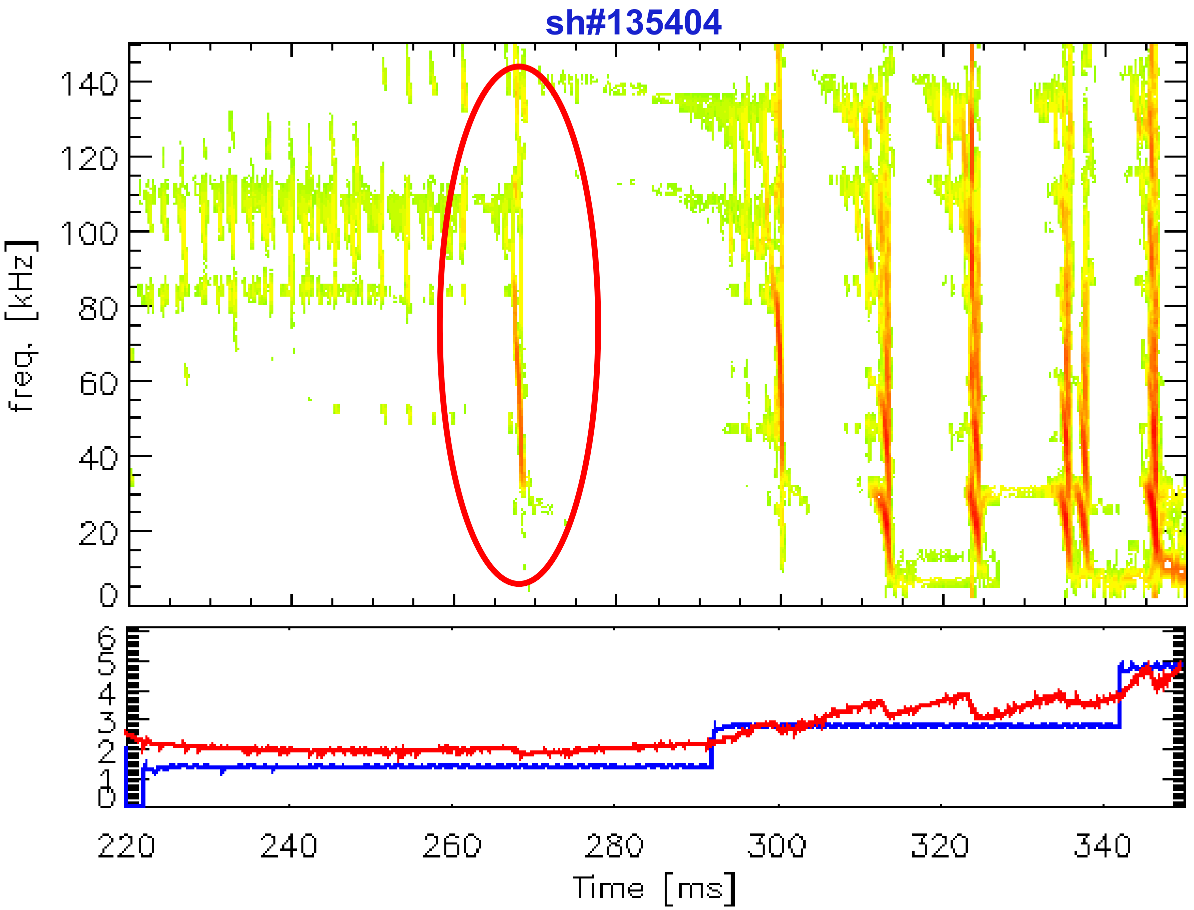
n=3

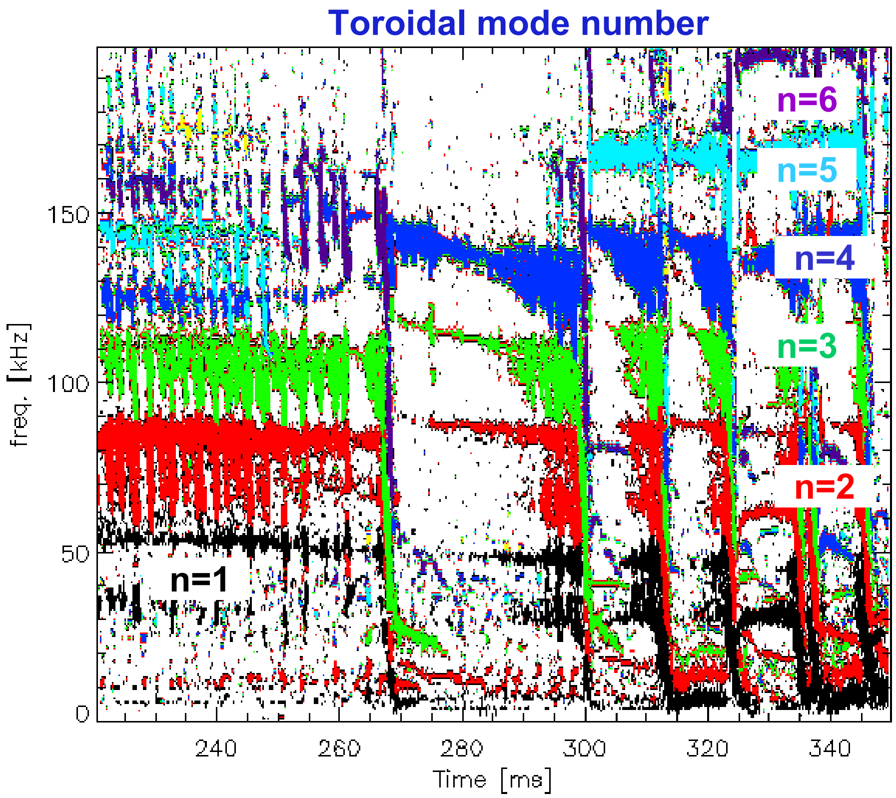
n=4

n=5

n=6

Small variations of background parameters have significant impact on mode dynamics

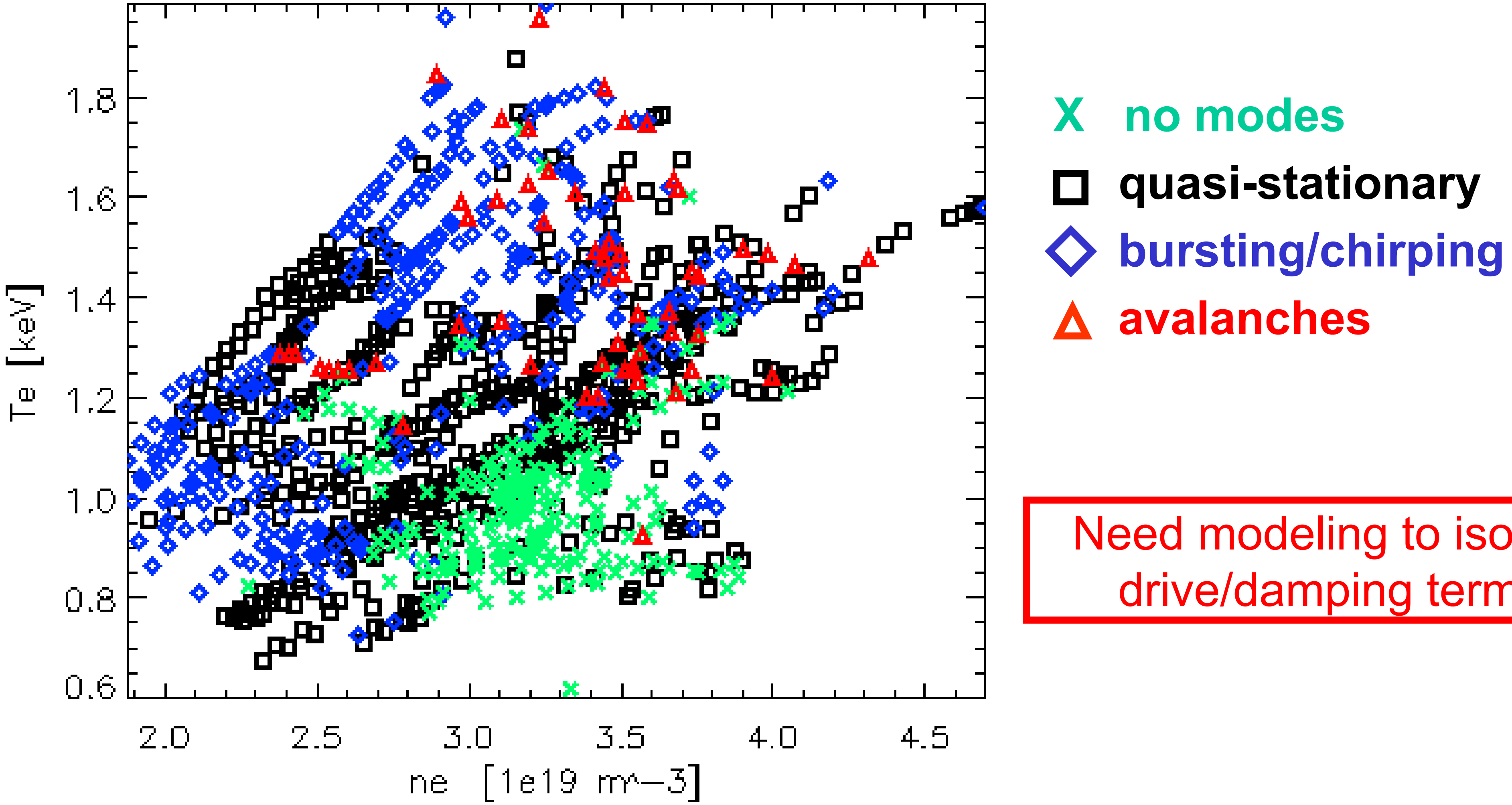




- Density higher than in reference shot ($4\times10^{19}m^{-3}$ *vs.* $2.5\times10^{19}m^{-3}$ @t=275ms)
  - More frequent avalanches, even at low NB power (t=268ms, P_{NB}~1.2MW)
  - Multiple bursts as second NB source is turned ON
- Presence of **weak n=1 mode**, barely seen on spectrogram
  - Appearance of n=1 mode seems a quite general feature for TAE avalanches

Statistical analysis indicates that mode behavior is strongly related to the fast ion drive (NB power)

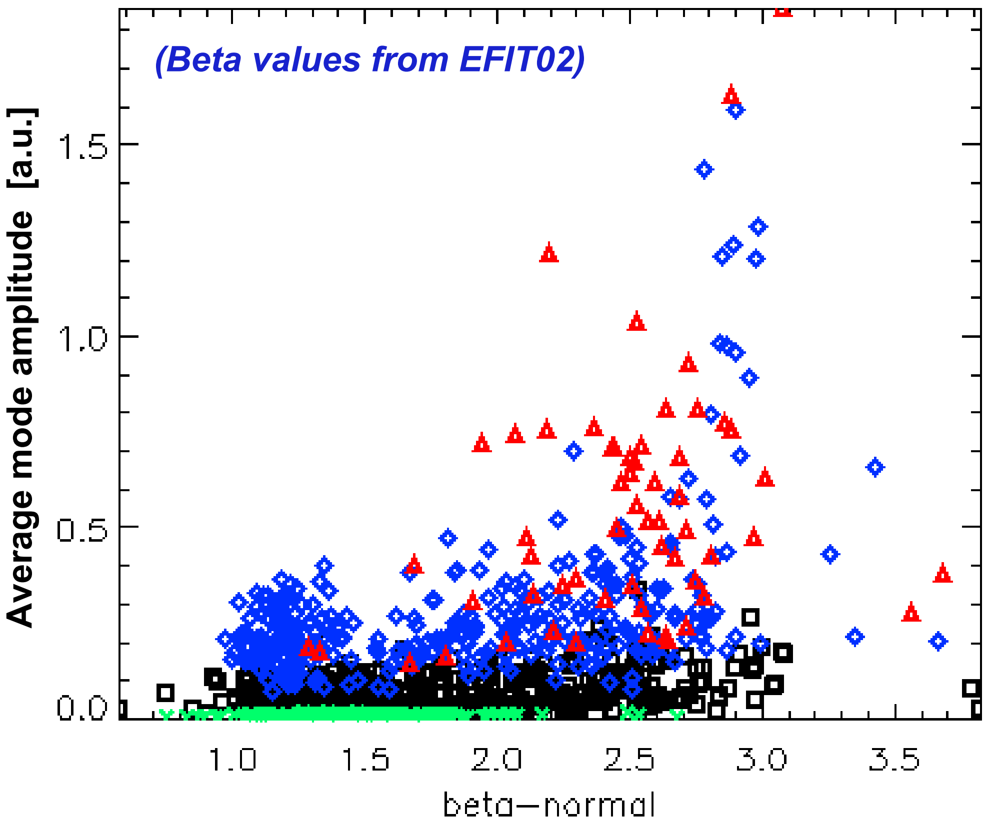
- Data from ~30 shots, focus on t=200→380ms, time-bin of 5ms
  - Characterize mode behavior depending on amplitude, frequency chirps, …
- Classification based on magnitude of amplitude/frequency variations



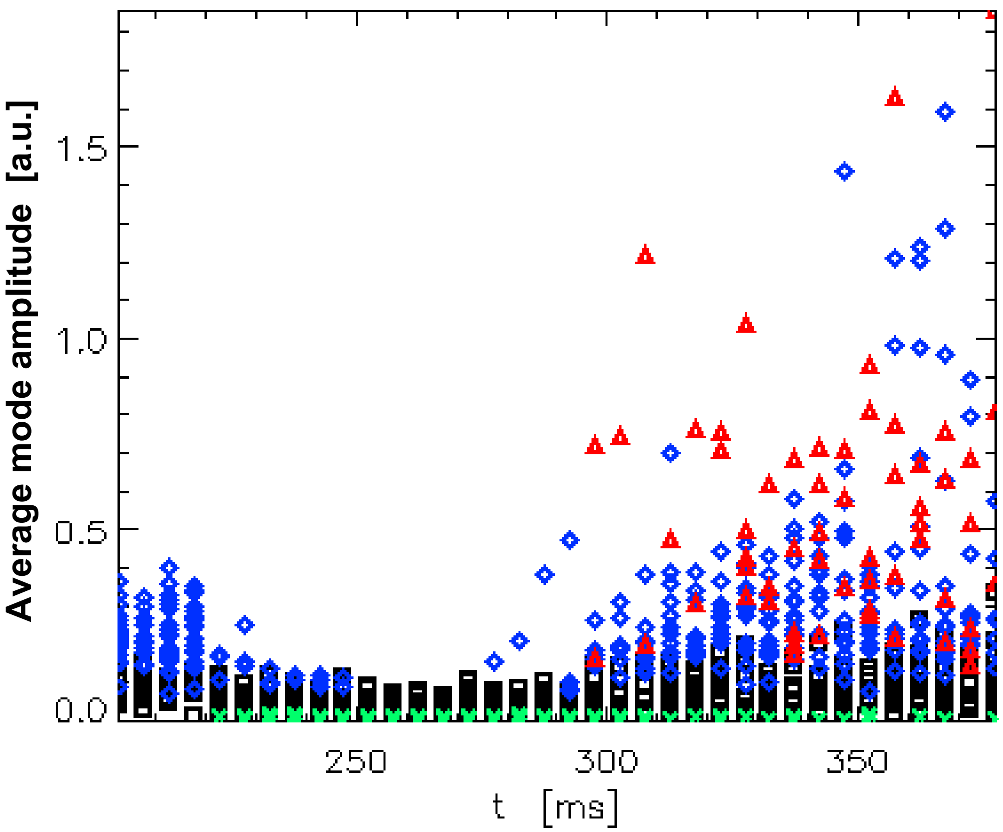
Need modeling to isolate drive/damping terms

However, most of parameters evolve in time with similar trends

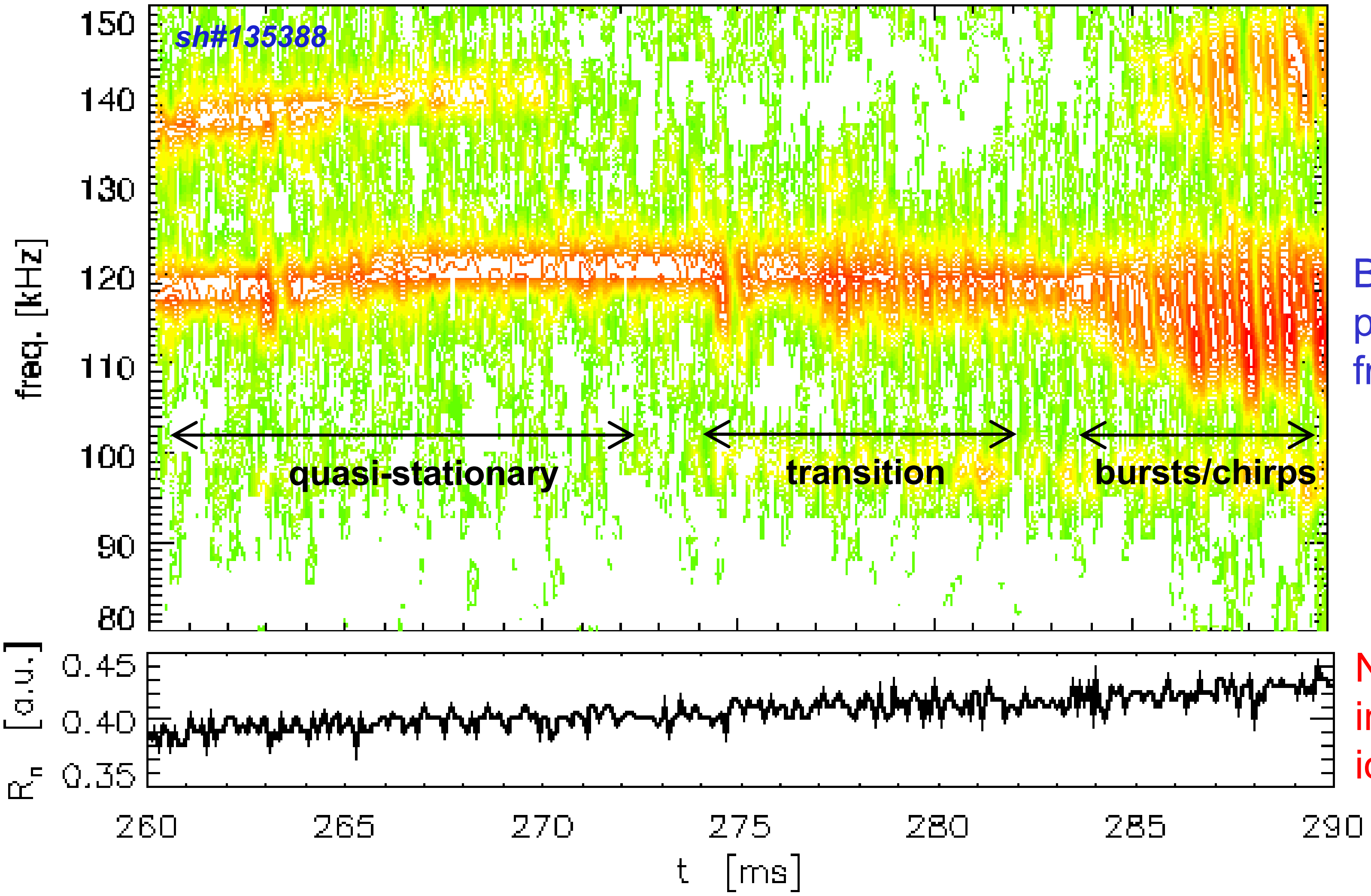
- Need careful analysis to separate contributions from single parameters
- Need to separate contribution to Beta from thermal/fast particles: modeling (TRANSP)
- Example: beta-dependence reflects distribution in time



(Beta values from EFIT02)



Transition between regimes can occur without an abrupt change in the NB power

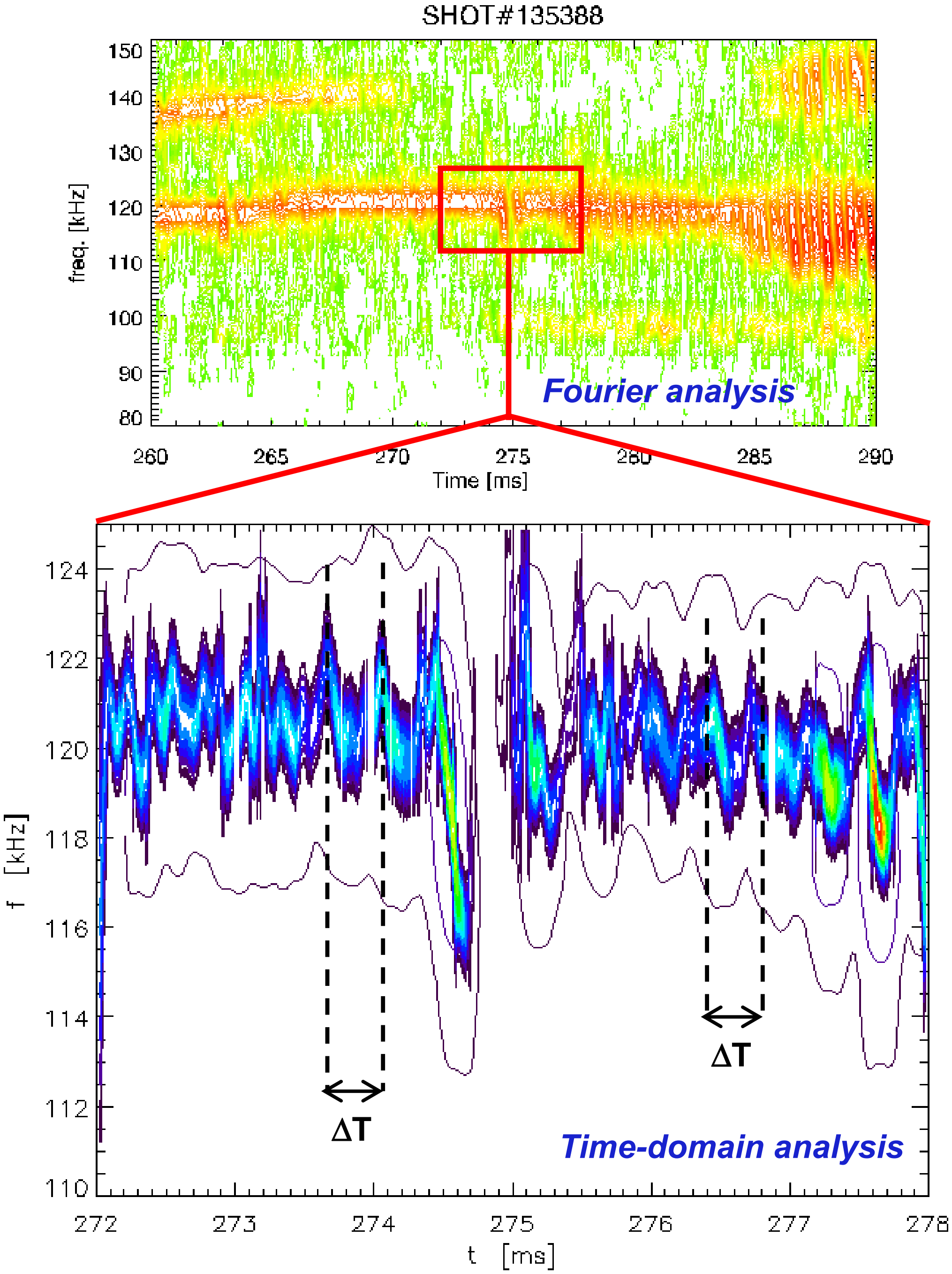


Bursting phase preceded by small frequency chirp

Neutron rate increase indicates larger fast ion population

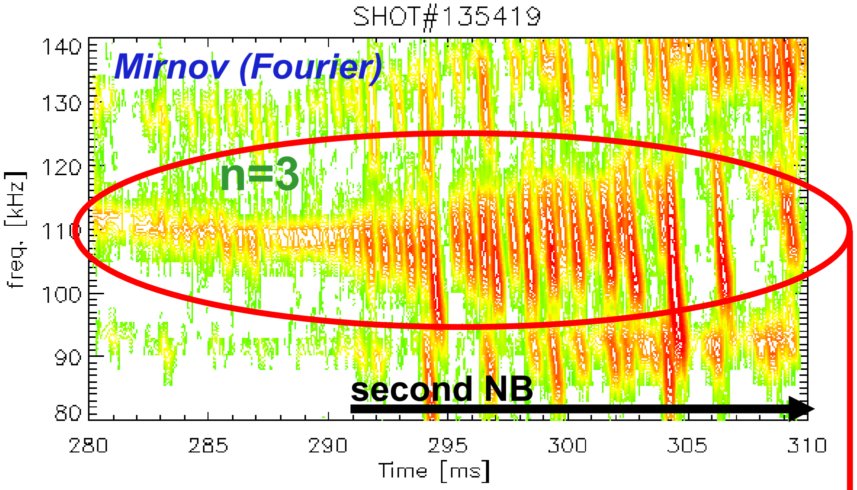
- Transition easily “triggered” by stepping up the injected NB power

Time-domain analysis reveals similarity between "quasi-stationary" and "bursting/chirping" phases

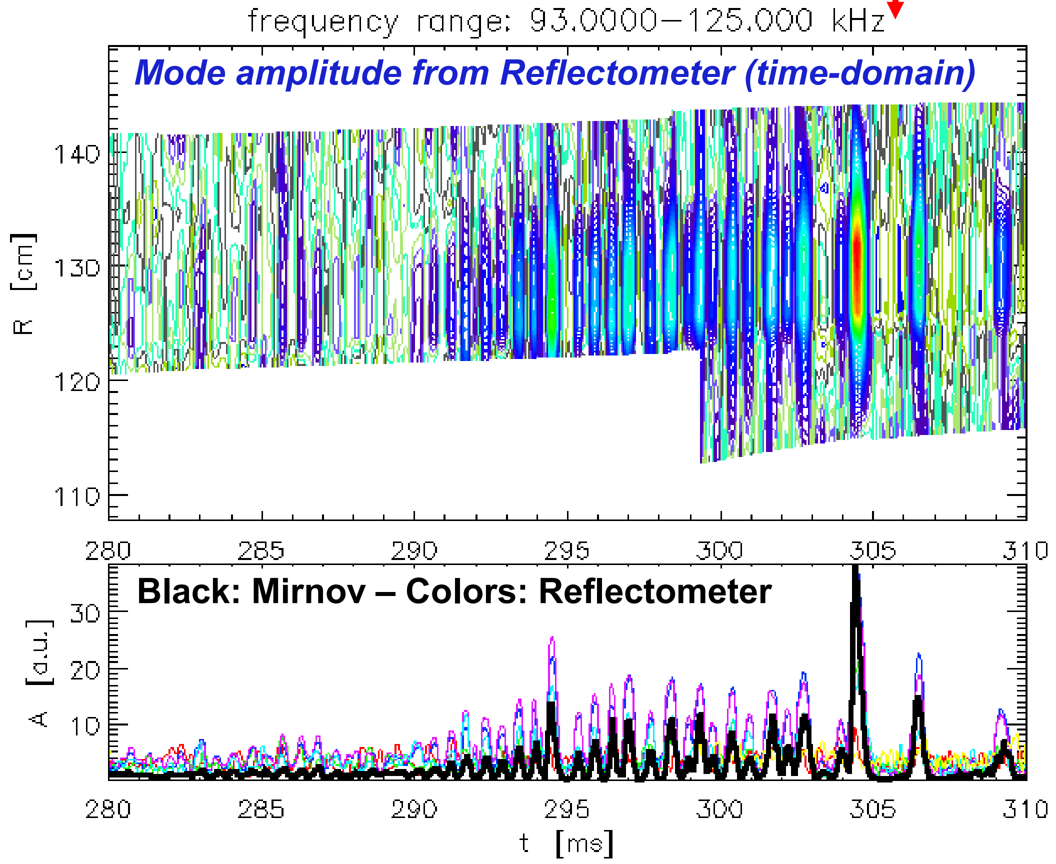


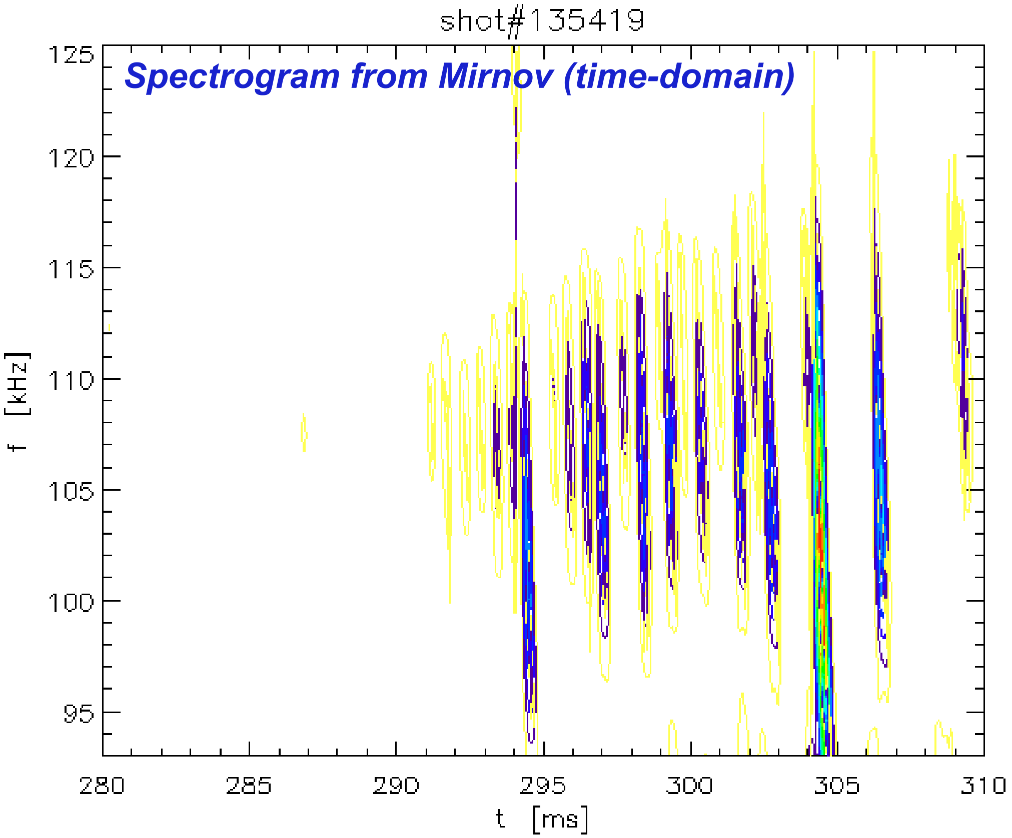
- Approach: use information from FFT of Mirnov signals to band-pass filter reflectometer data
  - Reconstruct frequency, amplitude evolution on "fast" time-scales
- Amplitude varies, with occasional "large" bursts
  - e.g. @ 274.6ms
- Frequency variations within +/-1kHz around time-averaged value
  - Consistent with FFT spectra
  - "Natural" fluctuations (time scale ΔT~0.5ms) in plasma parameters?
  - Increasing with injected NB power

For small bursts, mode structure does not change significantly in time



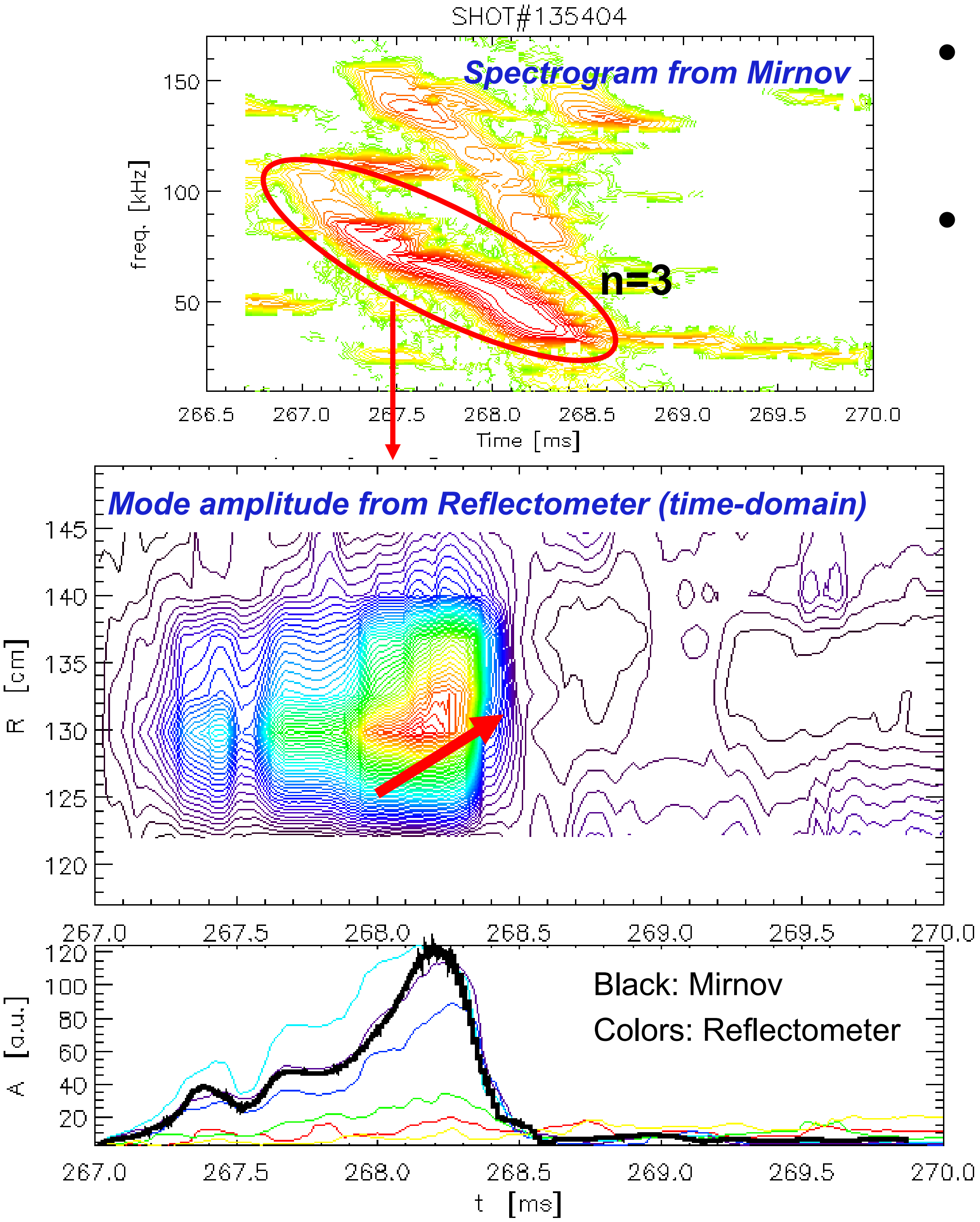
- Up to six reflectometer channels measure displacement for R=110→145cm
- Good correlation here between Mirnov and reflectometer





Variations of mode structure for same mode number can be observed during avalanches

- Mode peaks toward LFS as amplitude increases
- Reflectometer and magnetics do not always track well each other on short time-scales

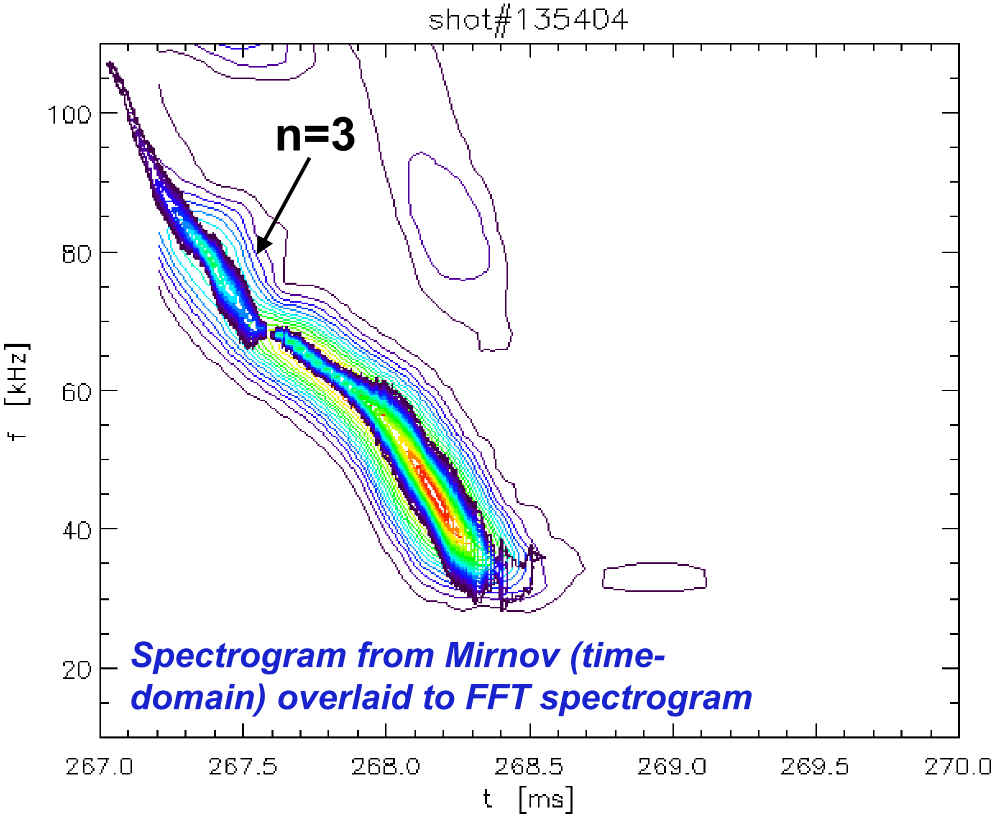


Spectrogram from Mirnov

Mode amplitude from Reflectometer (time-domain)

Black: Mirnov

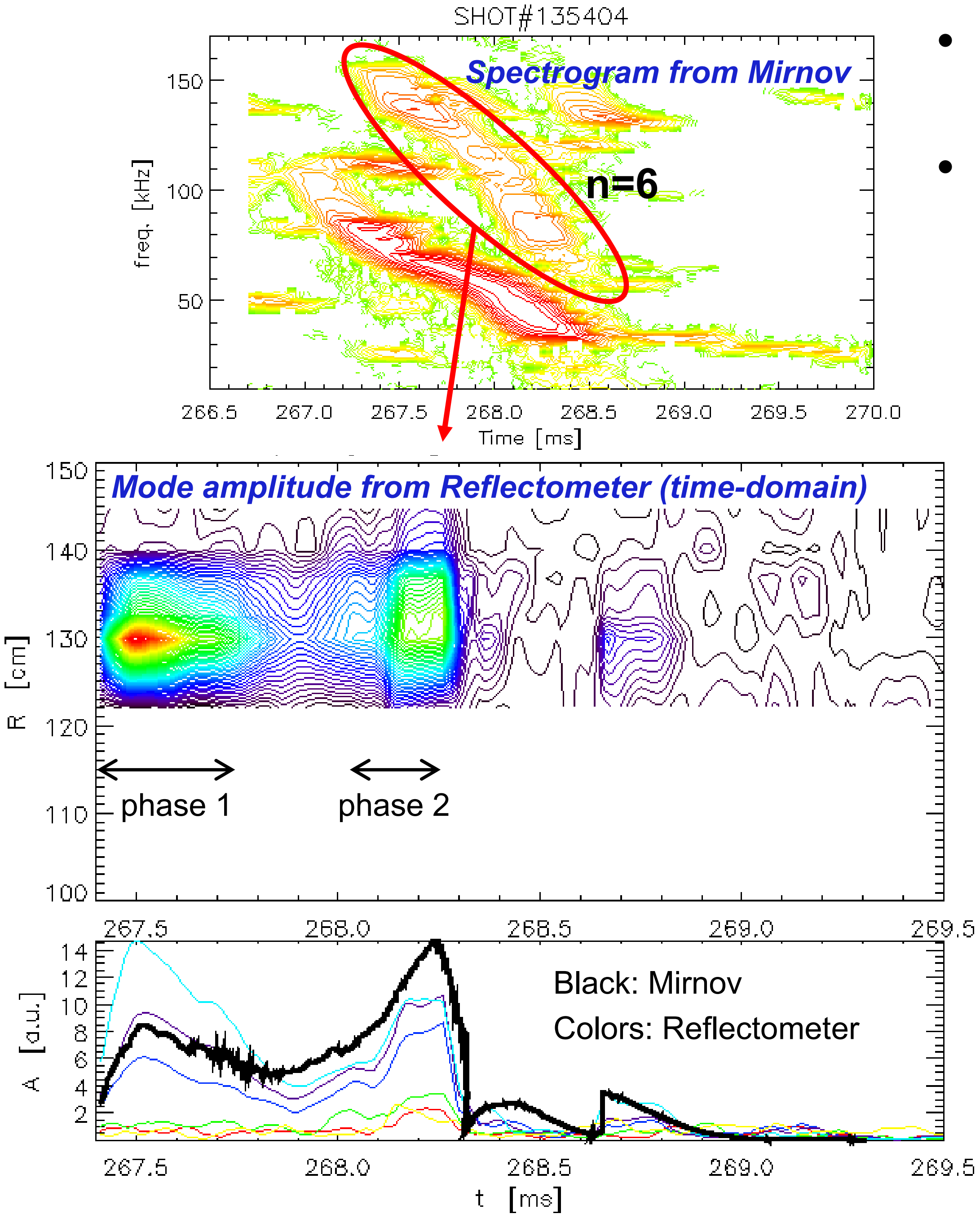
Colors: Reflectometer



Spectrogram from Mirnov (time-domain) overlaid to FFT spectrogram

Different n's may show quite different temporal evolution, too

- Measured structure not too different from that of n=3 mode
- Two "phases" with different spatial structure?



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Spectrogram from Mirnov

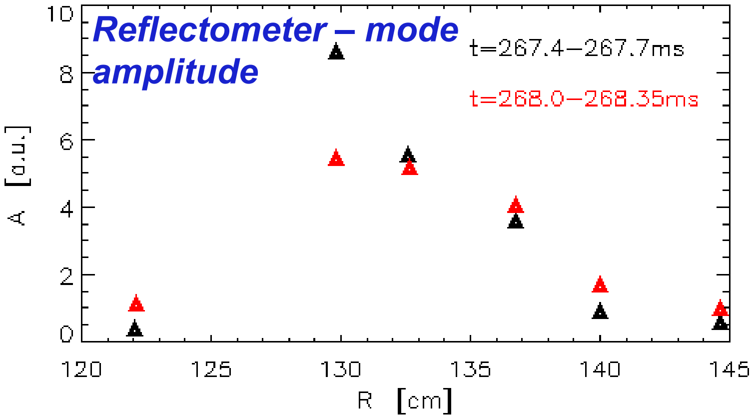
Mode amplitude from Reflectometer (time-domain)

phase 1

phase 2

Black: Mirnov

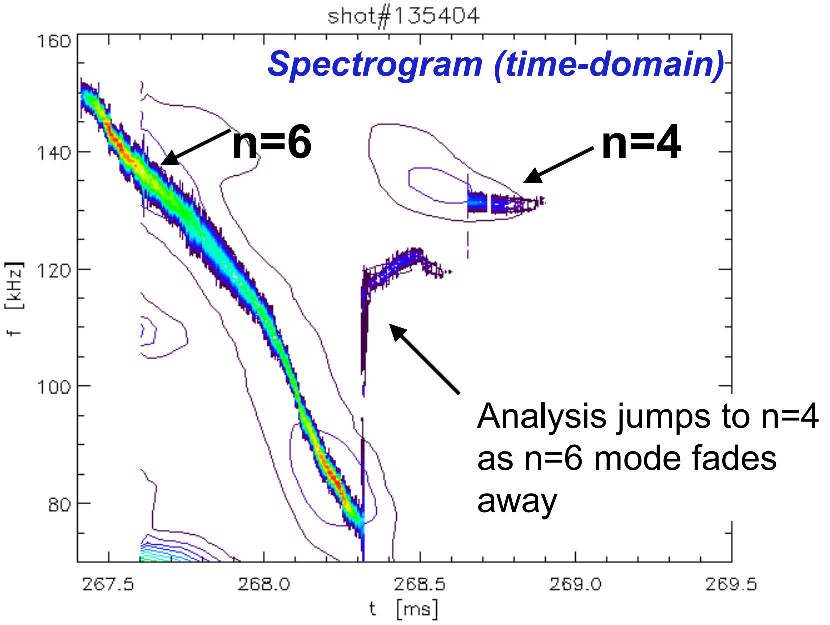
Colors: Reflectometer



Reflectometer – mode amplitude

t=267.4–267.7ms

t=268.0–268.35ms



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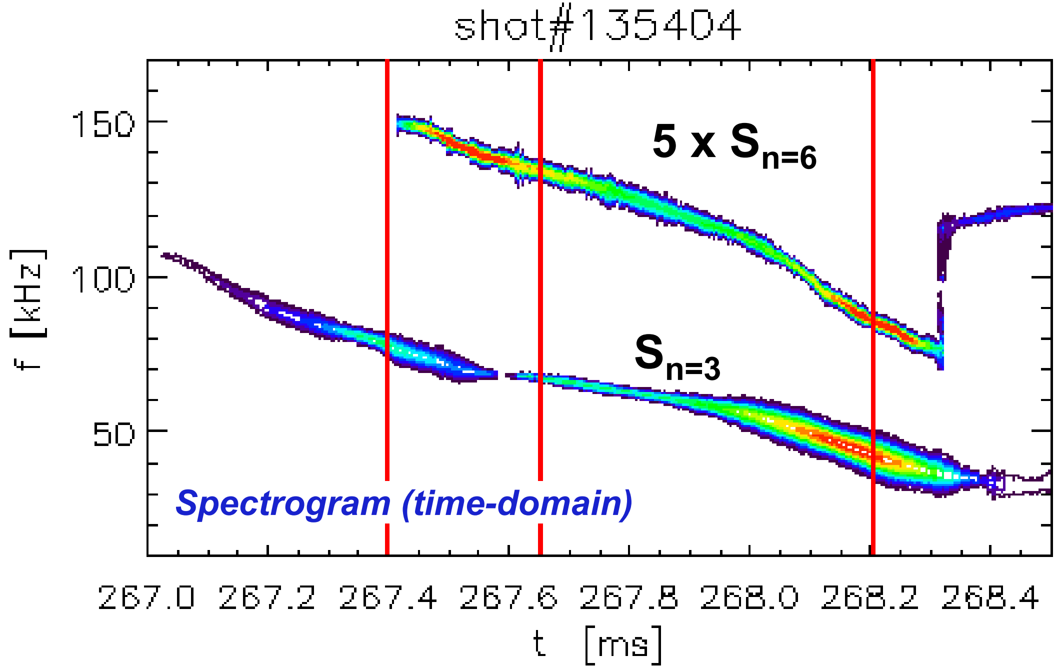
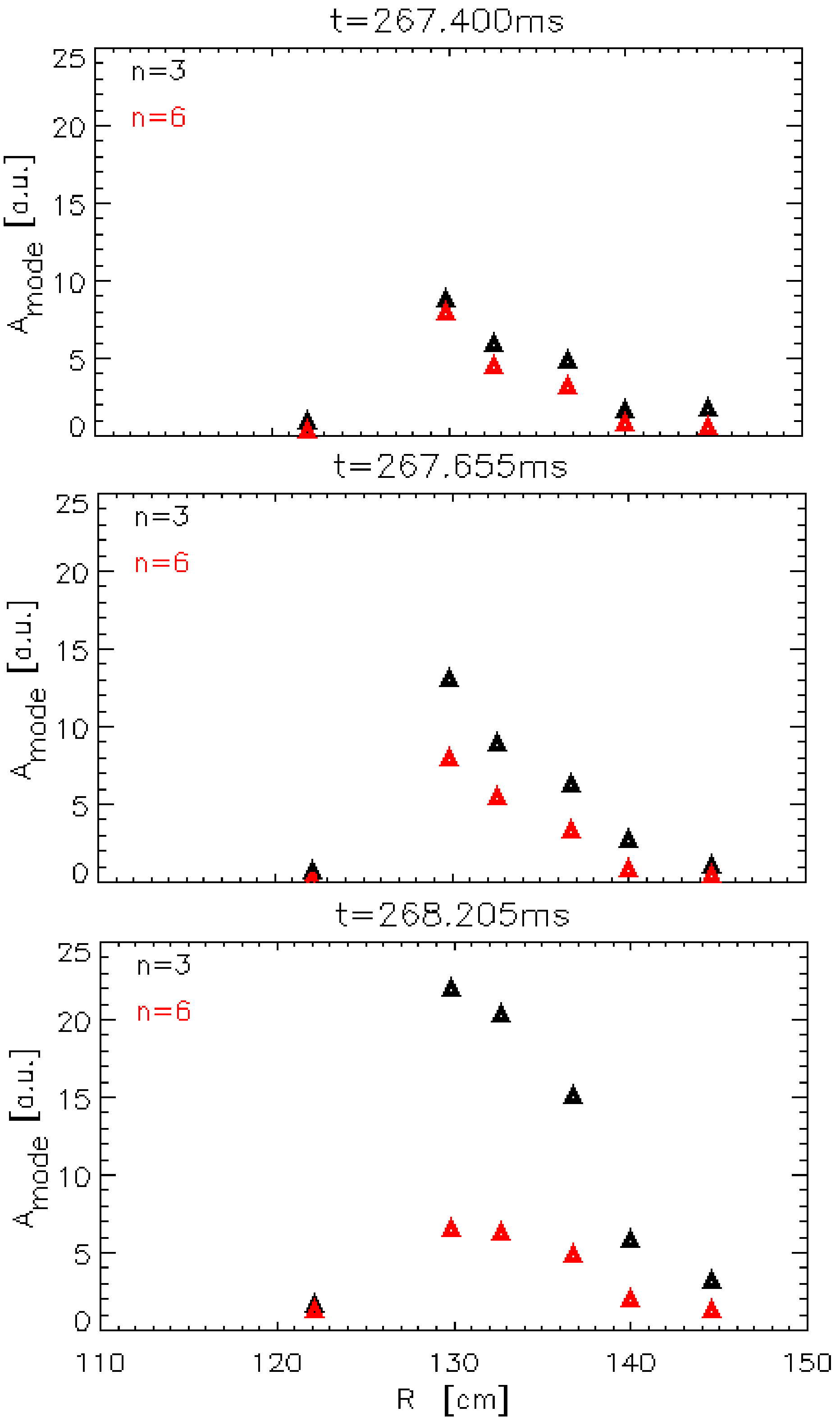
Spectrogram (time-domain)

Analysis jumps to n=4 as n=6 mode fades away

Combined analysis of n=3,6 modes during avalanche

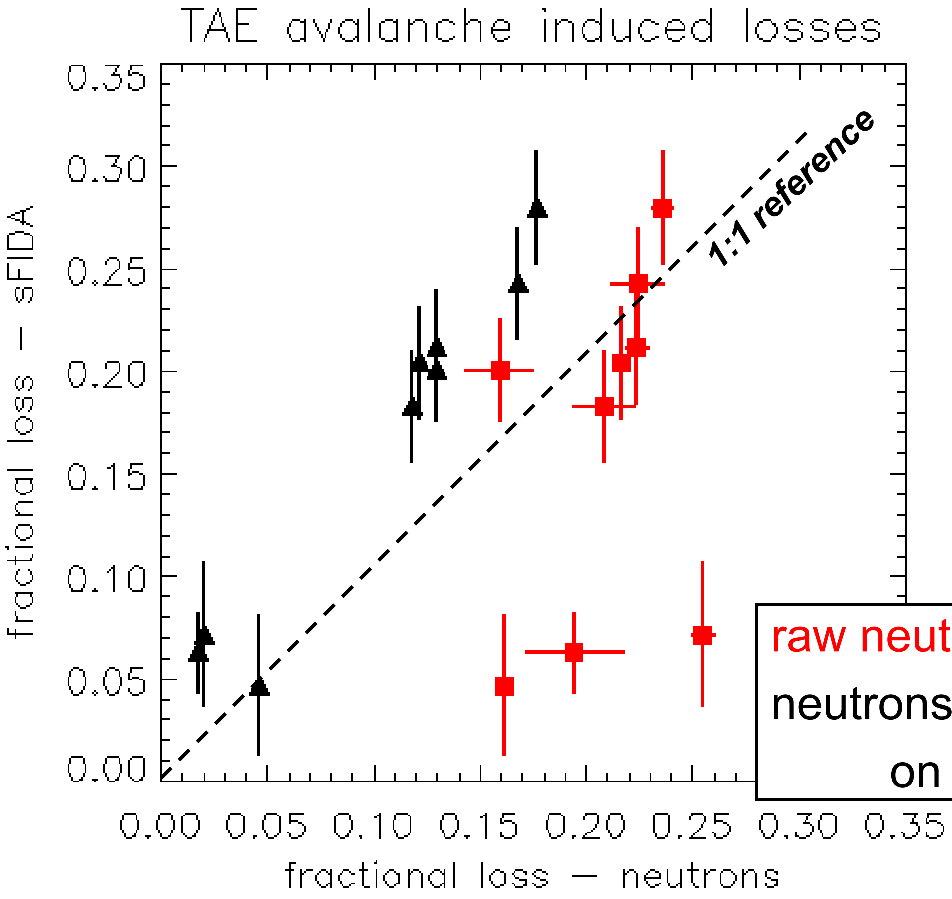


- The two modes have similar structures
  - Slightly change for last ~400µs
- Temporal evolution is different
  - n=3 has faster growth, especially at the end of the avalanche (t~268.2 ms)

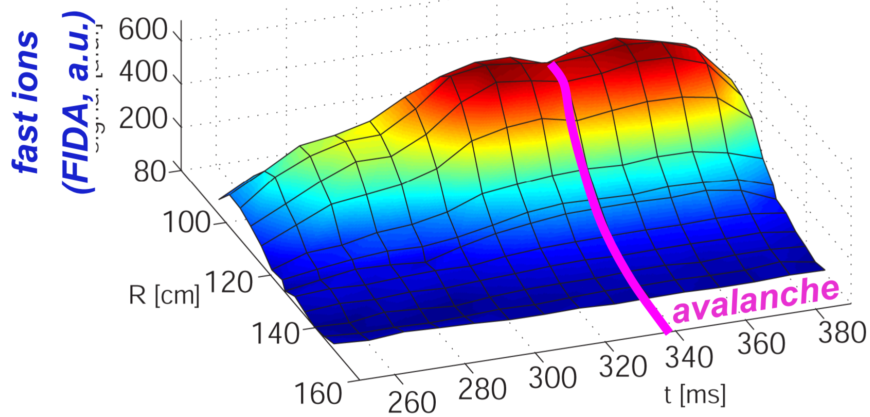

Mode amplitude from Reflectometer (time-domain)

Up to ~30% of fast ions can be lost during a single TAE avalanche

- Dominant modes during avalanches have n=2,3
- Good correlation between neutrons and FIDA



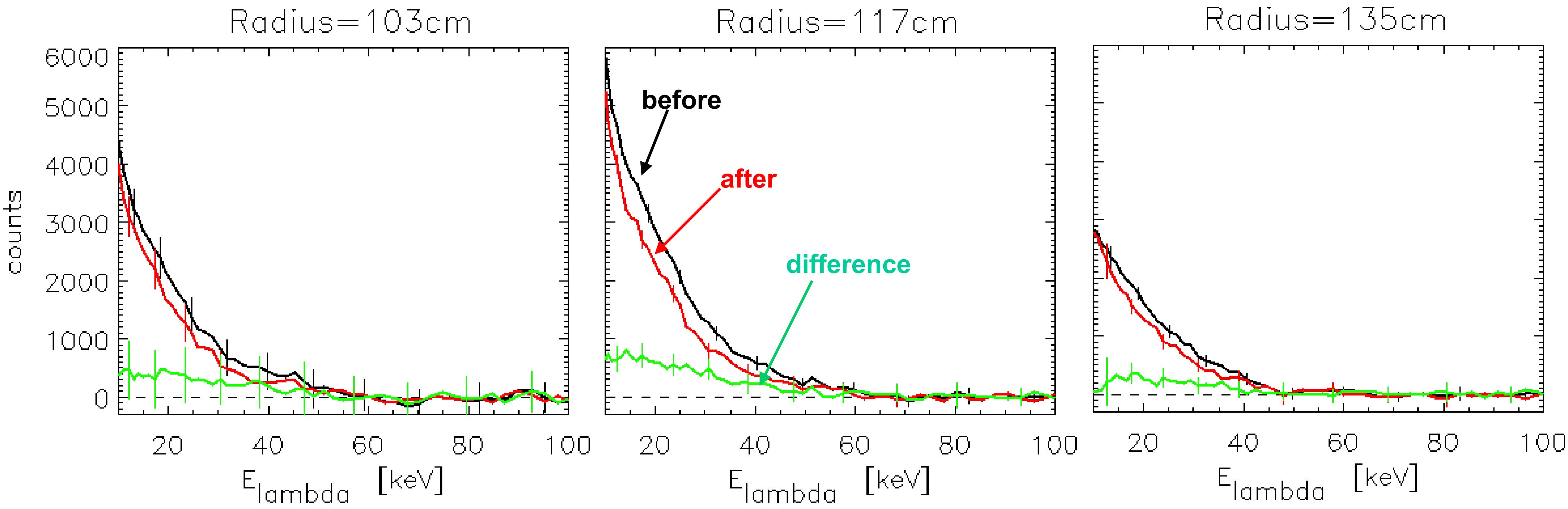
Spatial profile of confined fast ions measured through Fast-Ion D-Alpha (FIDA) diagnostic



- FIDA overestimates the losses: effect of different “weight function” in pitch, energy space?

Broad energy region affected by avalanche-induced loss

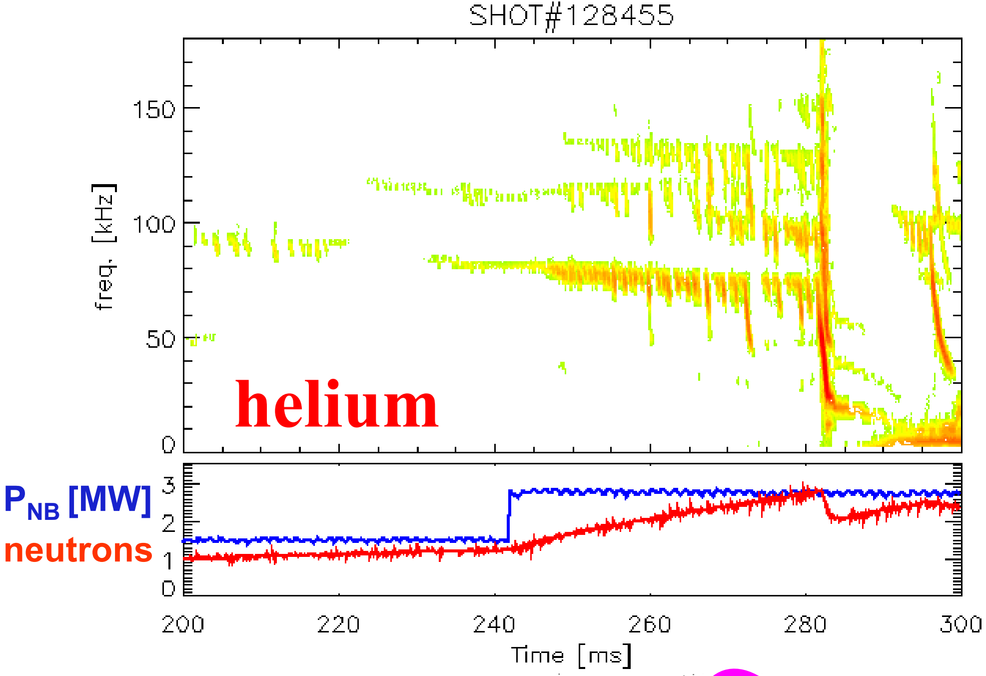
FIDA spectra from three different chords measured **before** and **after** an avalanche event (shot 135395, t=364ms).

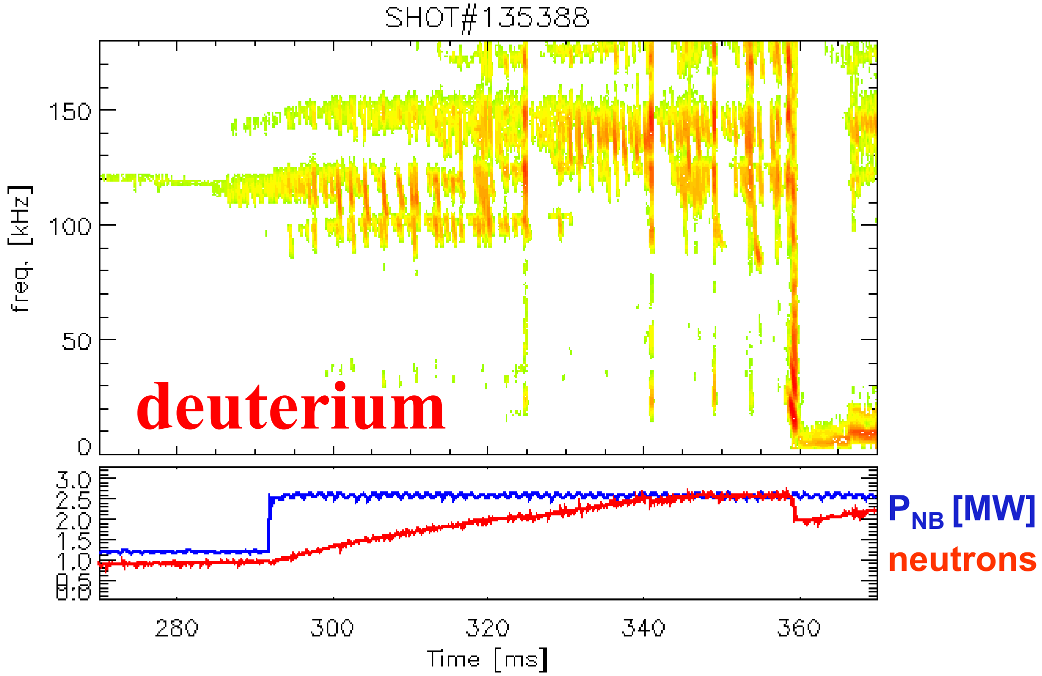


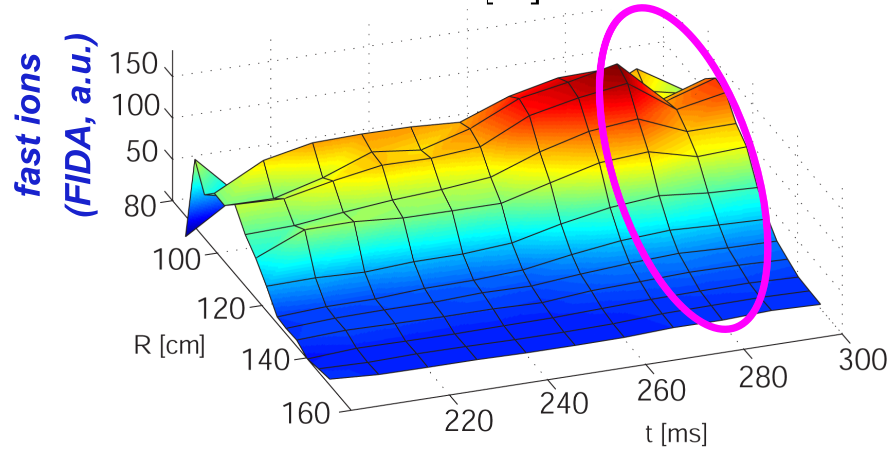
- Central channels show larger depletion
- This seems qualitatively different from EPM-induced losses
  - Need to analyze more cases to confirm

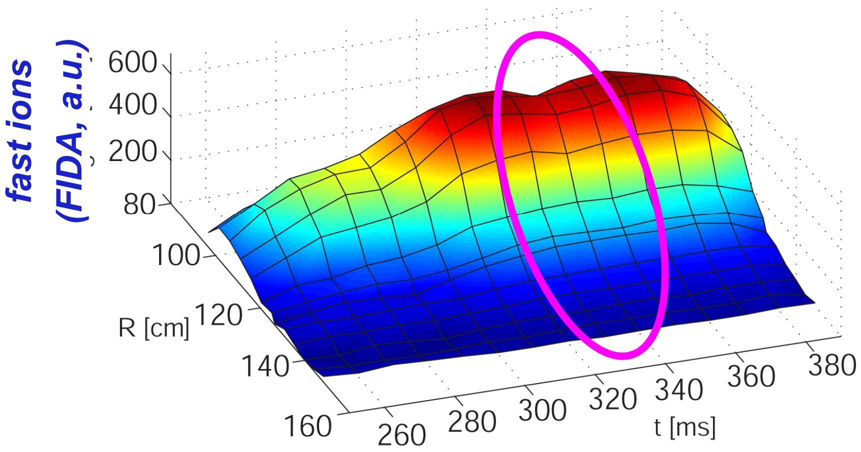
Similar TAE and TAE avalanches' behavior observed in Helium and Deuterium plasmas

- Low-*n*, quasi-stationary TAEs evolve into bursty behavior & *avalanches*
- Fast ion losses ≤30% observed (e.g. FIDA, neutrons) during avalanches
- Similar $n_{e,i}$, $T_{e,i}$, I_p, B_{tor}, P_{NB} (but different plasma shape: LSN *vs* limiter)









Summary

- Different TAE regimes achieved on NSTX
  - TAEs acquire more “turbulent” character as the fast ion population increases
  - For sufficiently large drive, TAEs develop in ***avalanches***
  - Very similar features observed in helium and deuterium plasmas
- Up to ~30% of fast ions **lost** following TAE avalanche
- Whole $N_f(R)$ involved: **relaxation** of fast-ion profile
- **Depletion** in fast-ion spectra over broad energy range