NSTX PPPL PRINCETON PLASMA PHYSICS LABORATORY *Supported by* U.S. DEPARTMENT OF ENERGY Office of Science

Impact of multi-mode TAE dynamics on fast ion transport in NSTX

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Toroidicity-induced Alfvén eigenmodes (TAEs) can strongly affect fast ion confinement

- 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 Neutral Beam (NB) heated NSTX plasmas
  - TAE-induced fast ion losses on NSTX

Outline

- Diagnostics and Experimental techniques
- TAE dynamics on NSTX
- TAE-induced fast ion transport
- Summary and outlook

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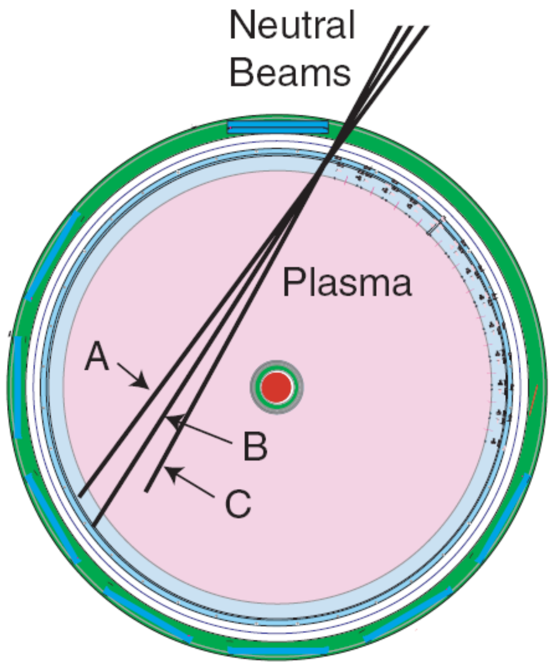
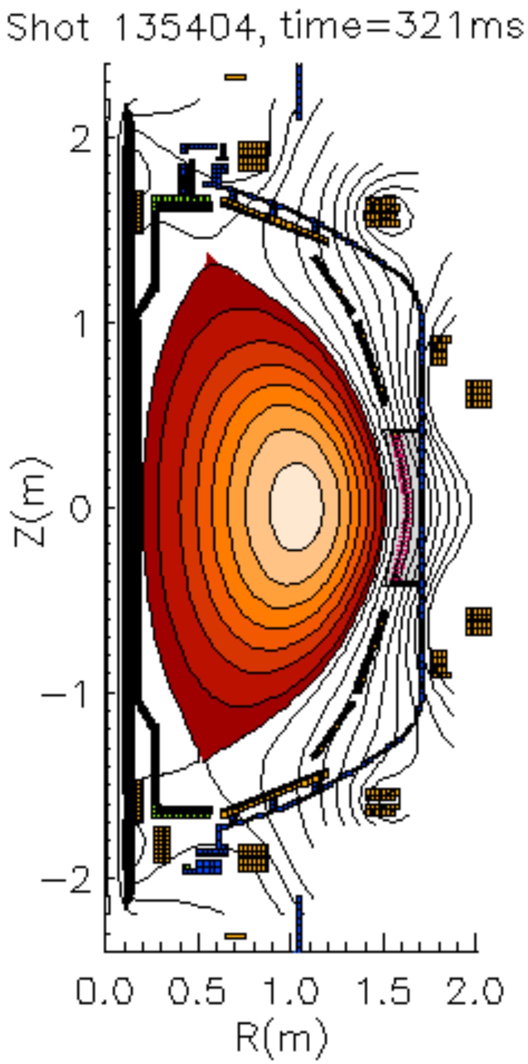
The National Spherical Torus Experiment, NSTX



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

3 Neutral Beam sources

High ratio v_{fast}/v_{Alfven} leads to destabilization of Alfvenic instabilities over broad frequency range



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Pulse length	<2 s

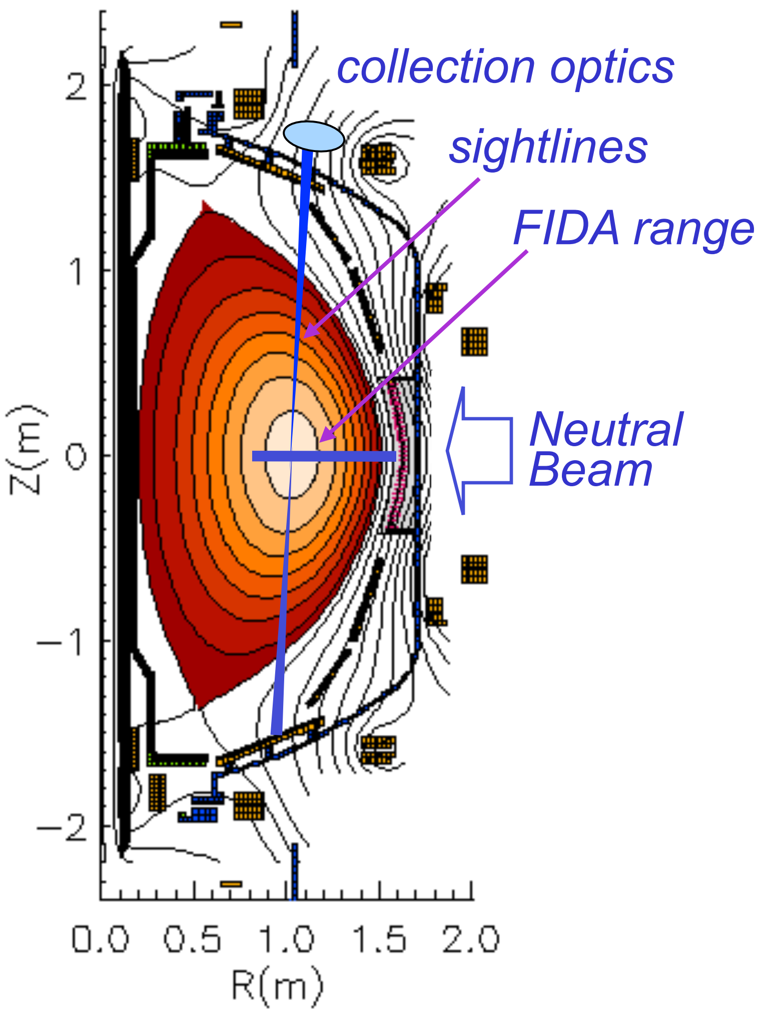
3 Neutral Beam sources

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

⇒ 1 < v_{fast}/v_{Alfven} < 5

This talk:
Focus on Toroidicity-Induced Alfven Eigenmodes
Center-stack limited deuterium plasma
B_{tor}=0.55 T, I_p=0.9 MA

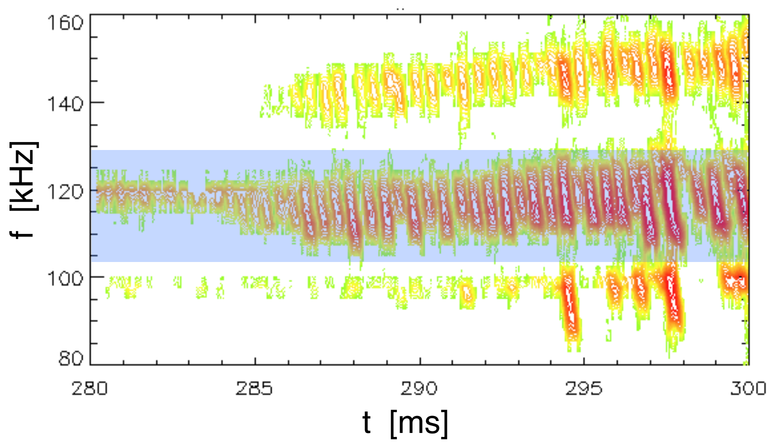
Fast ion and mode activity diagnostics on NSTX



- Mirnov coils
  - Magnetic fluctuations up to 2.5 MHz
- 5-Channel reflectometer
  - Mode structure (L-mode)
- Fast Ion D-Alpha (FIDA) system
  - Fast ion profile and spectrum through active charge-exchange recombination spectroscopy
  - 16 channels, 5cm/10ms/10keV resolution
- Volume-averaged neutron rate

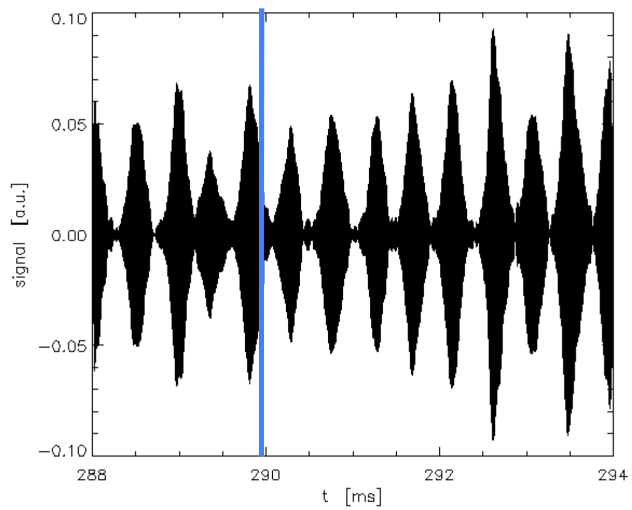
Time-domain analysis of Mirnov's and reflectometer signal provides details on *fast* mode dynamics

1. Select frequency band from FFT

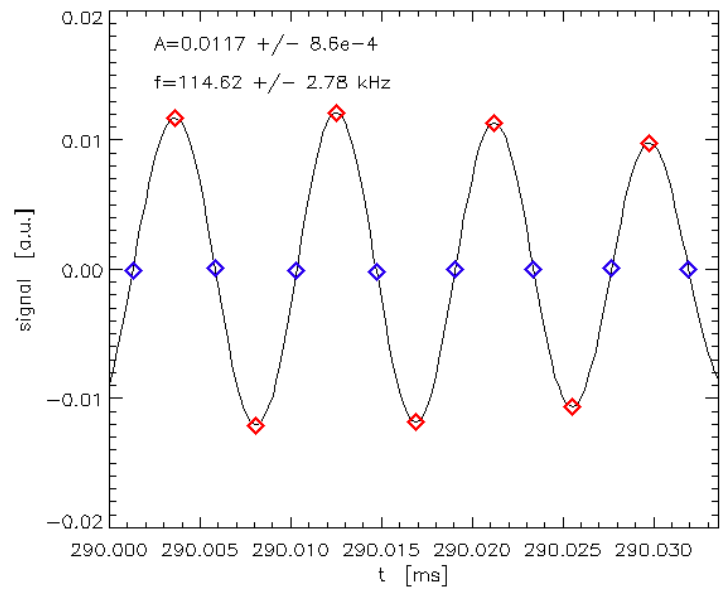


- Mirnov coils
  - Magnetic fluctuations up to 2.5 MHz
- 5-Channel reflectometer
  - Mode structure (L-mode)

2. Band-pass filter raw signal; time windowing over ~5 wave cycles



3. Get wave amplitude/frequency from peak-to-peak values & peak separation



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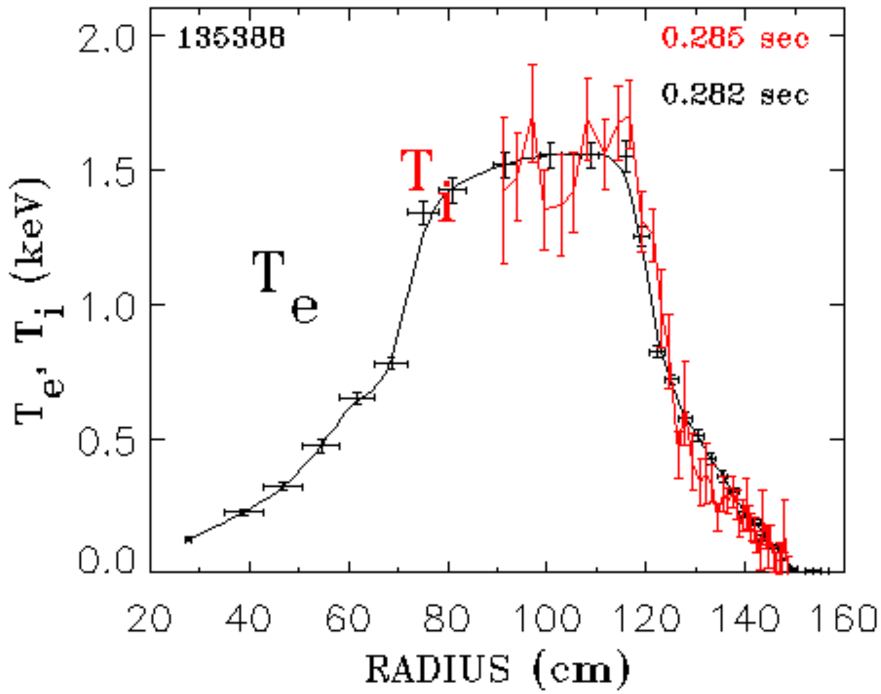
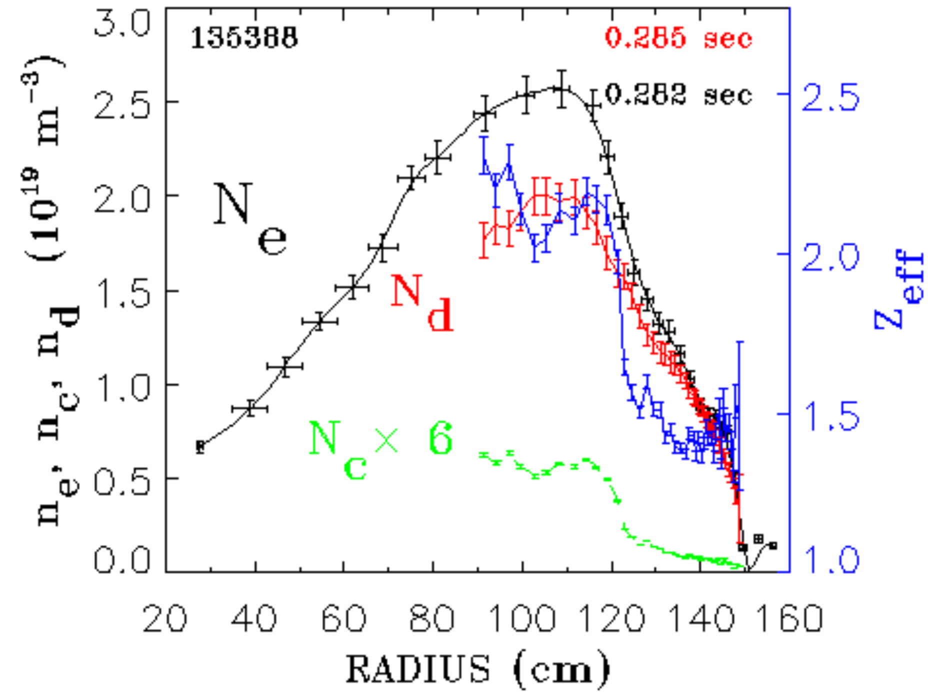
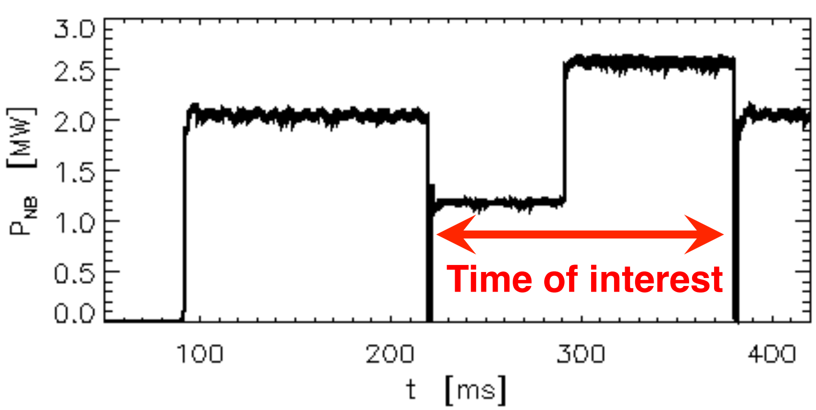
Experimental scenario: L-mode, center-stack limited deuterium plasma with NB heating

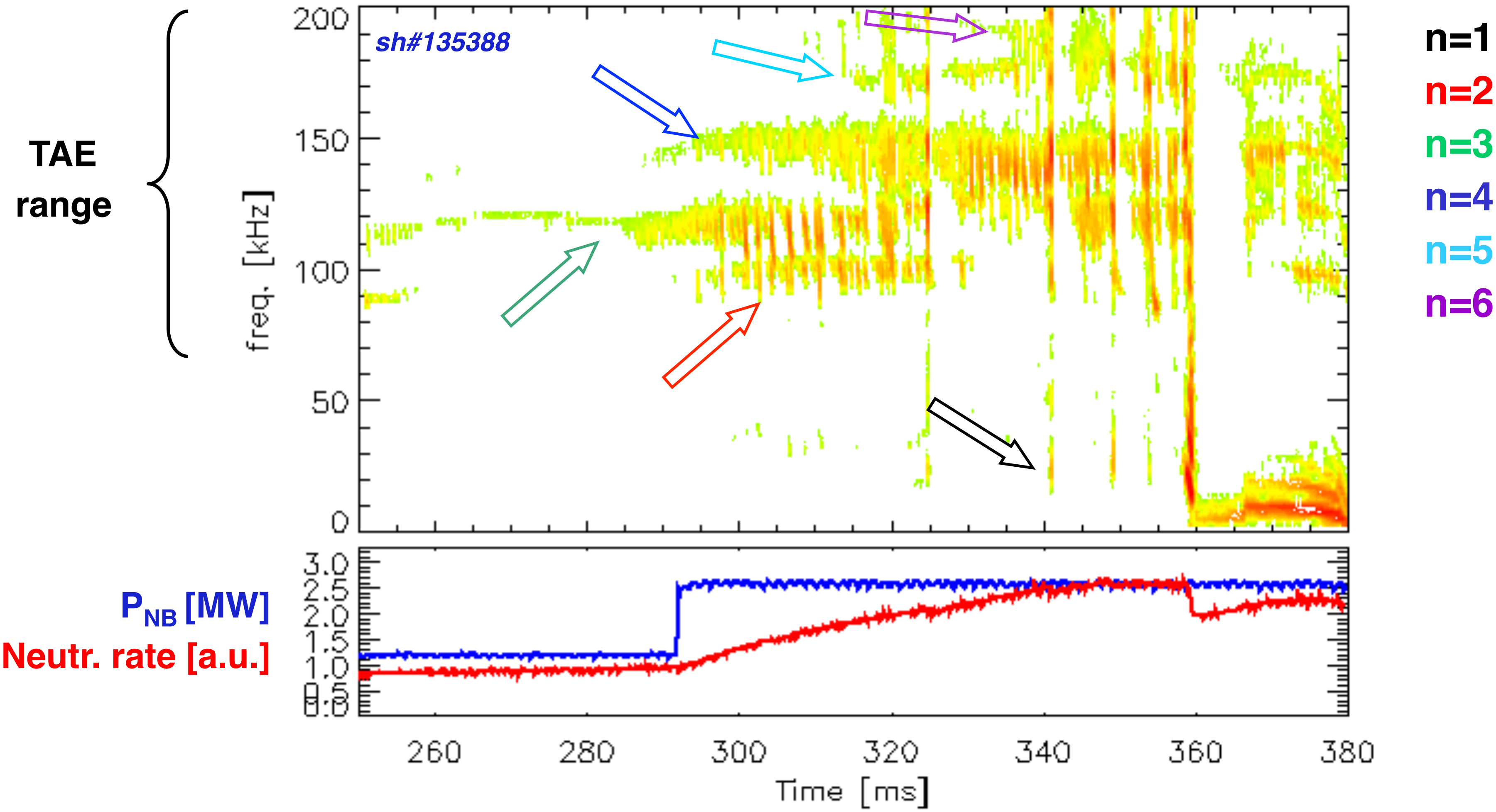






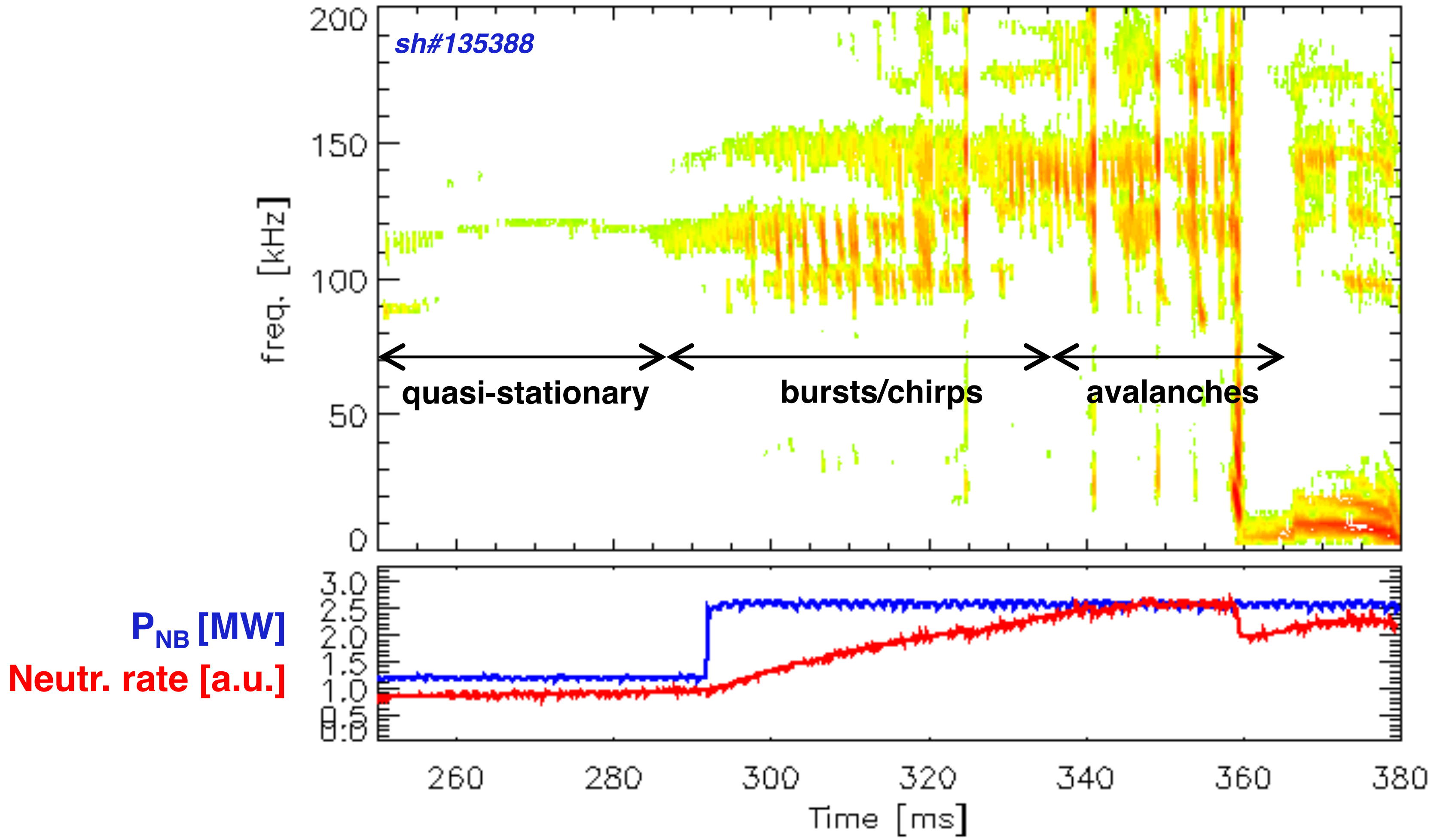
- Reverse-shear profile, q_{min}=2.5→1.5
- NB power and density varied to afffect drive/damping of TAEs
- Monotonic profiles allows mode structure measurements through reflectometry

TAEs with low toroidal mode numbers (n=2→7) are observed, with dominant n=2-4 modes



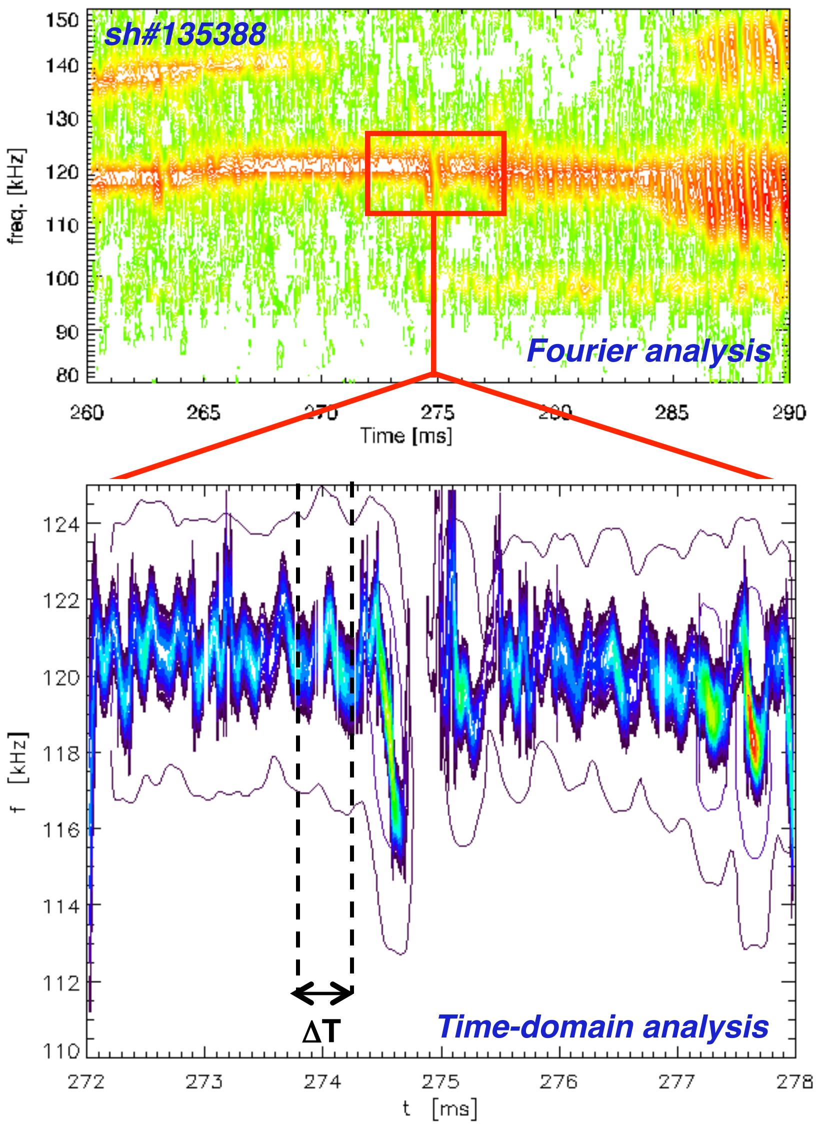
Other *fluctuations* observed during large TAE bursts only, e.g. *n=1*

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



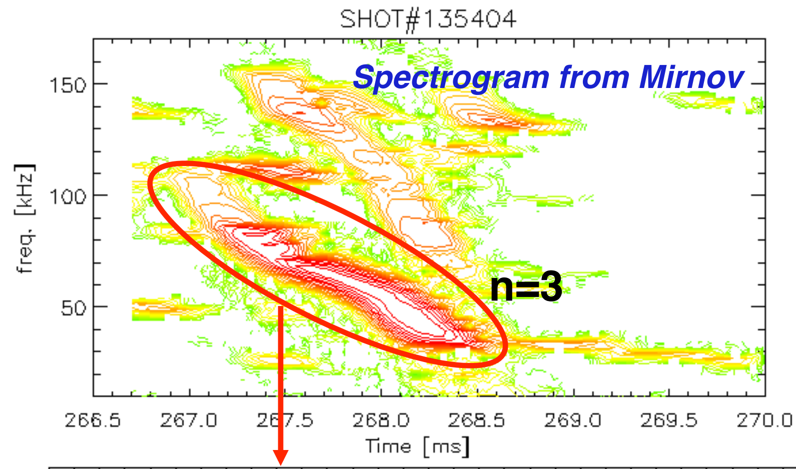
- Transition between regimes can occur without an abrupt change in the NB power

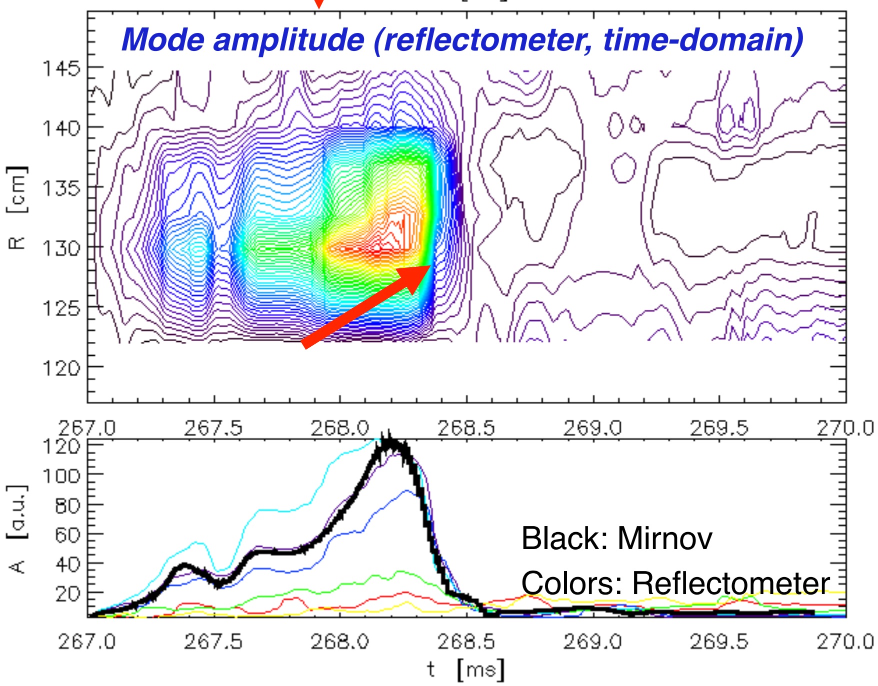
Time-domain analysis reveals similarity between "quasi-stationary" and "bursting/chirping" phases



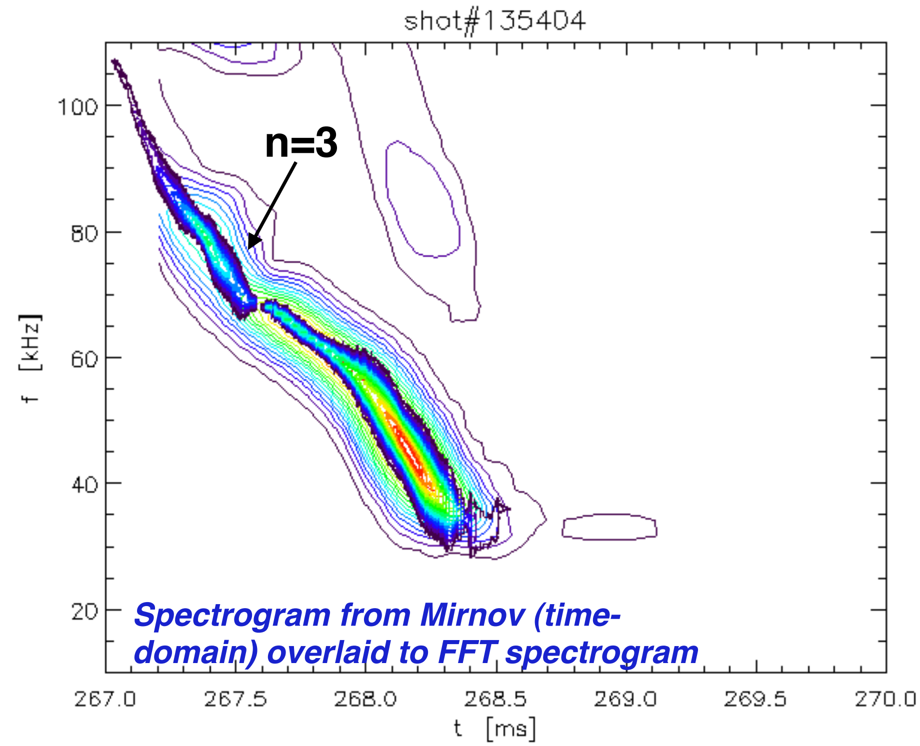
- Amplitude varies, with occasional, larger bursts
  - e.g. @ 274.5ms
- Frequency variations within +/-1kHz around time-averaged value
  - Fluctuations with time-scale $\Delta T \leq 0.5$ms in plasma parameters?
  - Frequency sweep range increases with injected NB power
- No detectable variation of mode structure (from reflectometers)

Variations of mode structure can be observed during final phase of avalanches





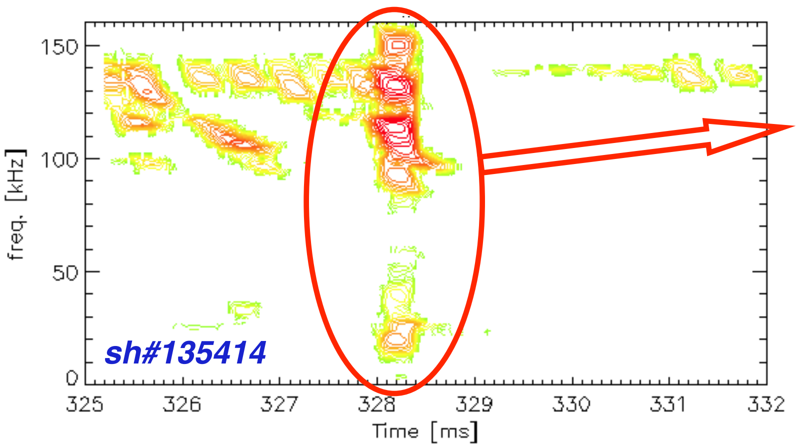
- Dynamics may differ for different *n*'s
- Reflectometer and magnetics do not always track well each other at the end of avalanches

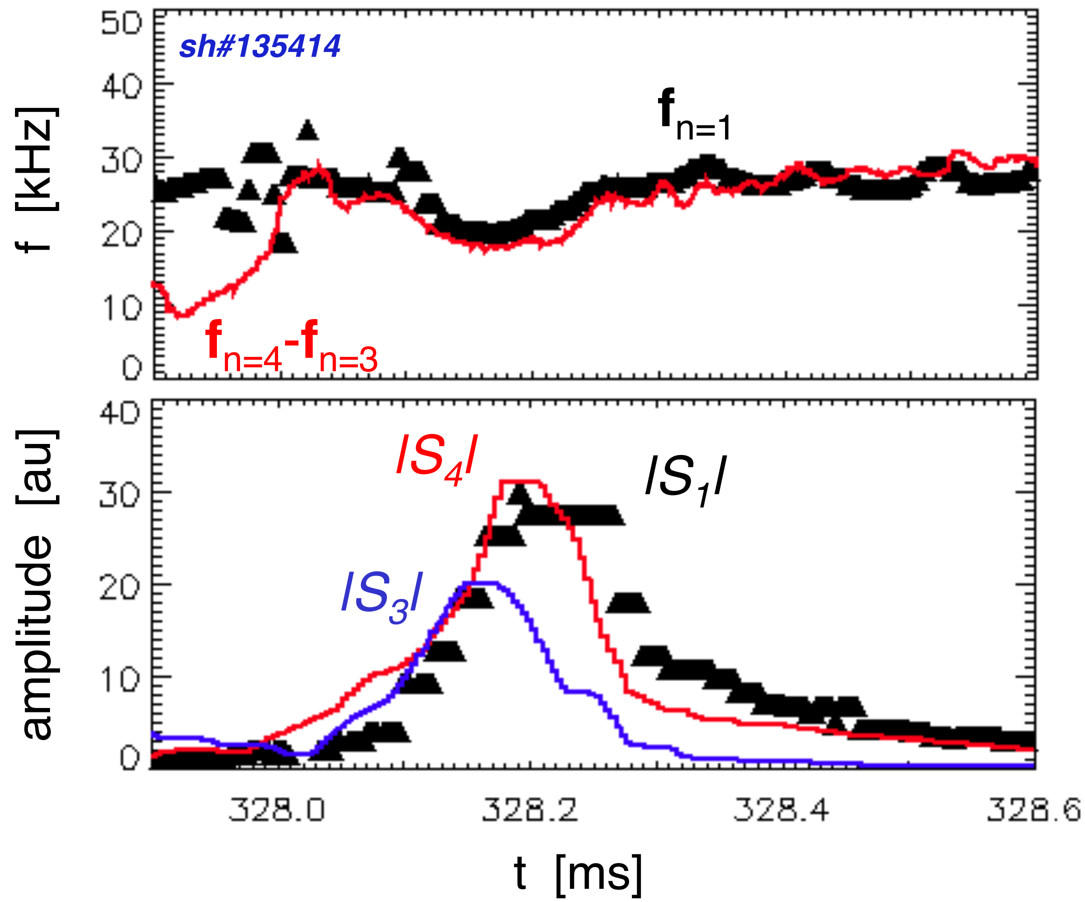


Frequency and wave-number satisfy matching conditions for mode coupling during large bursts

- Mode evolution from time-domain analysis
- Assume bilinear interactions:

$$S'_1 \sim < c_{(n+1,n)} S_{n+1} S_n >_{f_{n=1}}$$



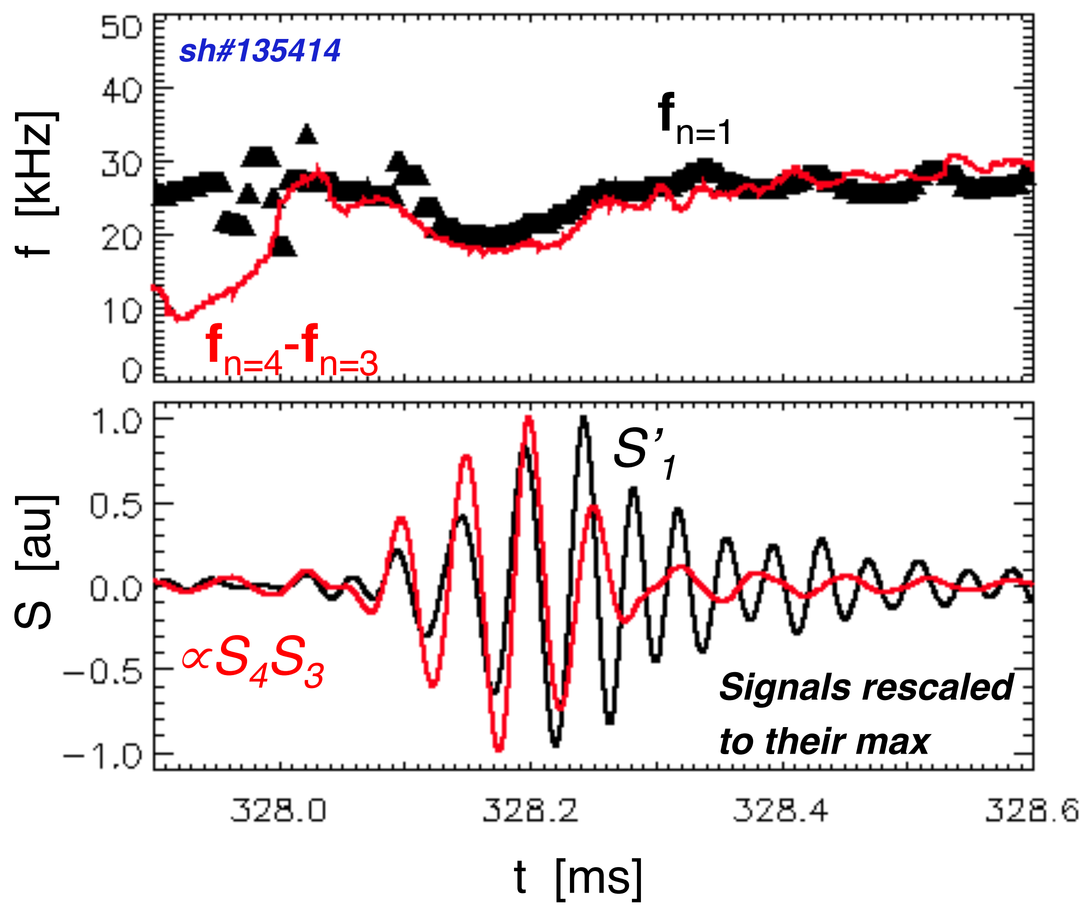


Results suggest (enhanced) coupling of TAEs mediated by *n=1* fluctuation

- Mode evolution from time-domain analysis
- Assume bilinear interactions:

$$S'_1 \sim < c_{(n+1,n)} S_{n+1} S_n >_{f_{n=1}}$$

- Reconstructed S'_1 matches well the measured *n=1* signal
  - 180 degree phase shift
- S_1 signal decays when
  - "Pump" amplitude → 0

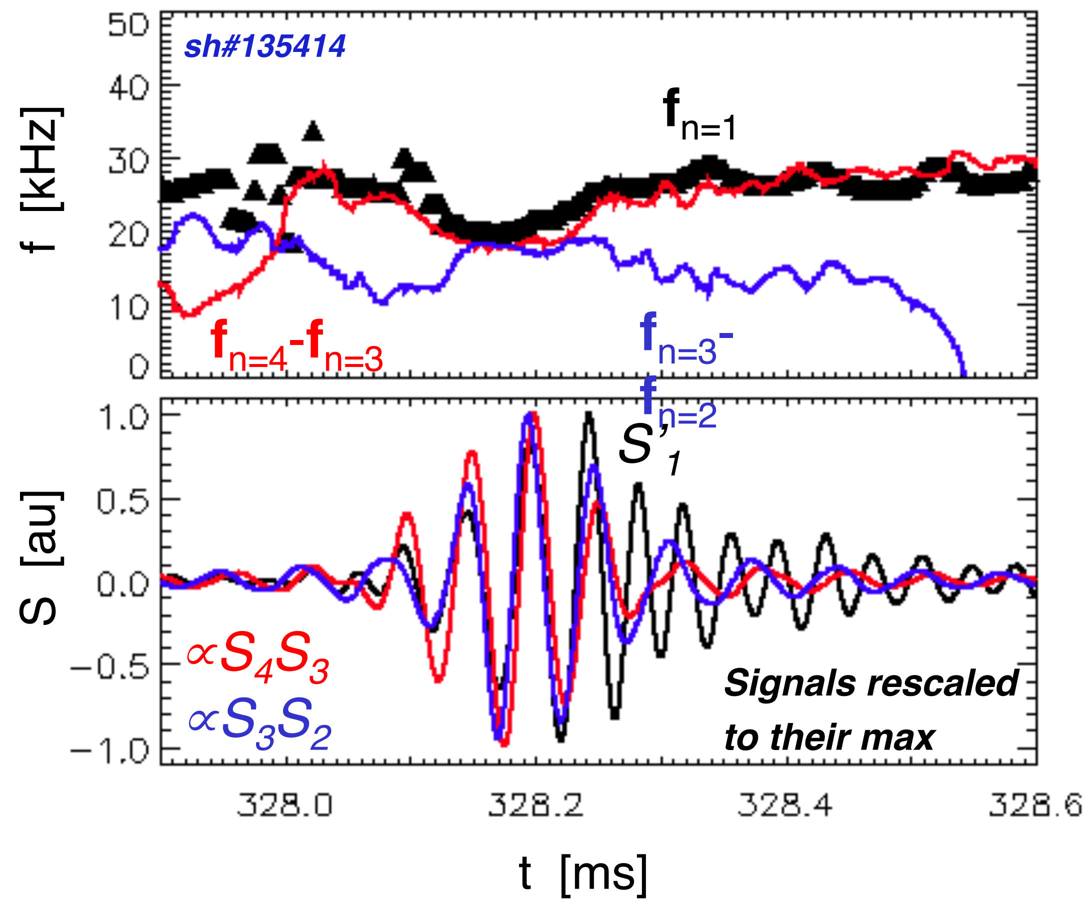


Same "difference frequency" $f_{n=1}$ for coupling between n_3-n_2, n_4-n_3, n_5-n_4, …

- Mode evolution from time-domain analysis
- Assume bilinear interactions:

$$S'_1 \sim \langle c_{(n+1,n)} S_{n+1} S_n \rangle_{f_{n=1}}$$

- Reconstructed S'_1 matches well the measured *n=1* signal
  - 180 degree phase shift
- S_1 signal decays when
  - "Pump" amplitude → 0
  - Poor frequency match



What is the fluctuation at $f_{n=1}$?

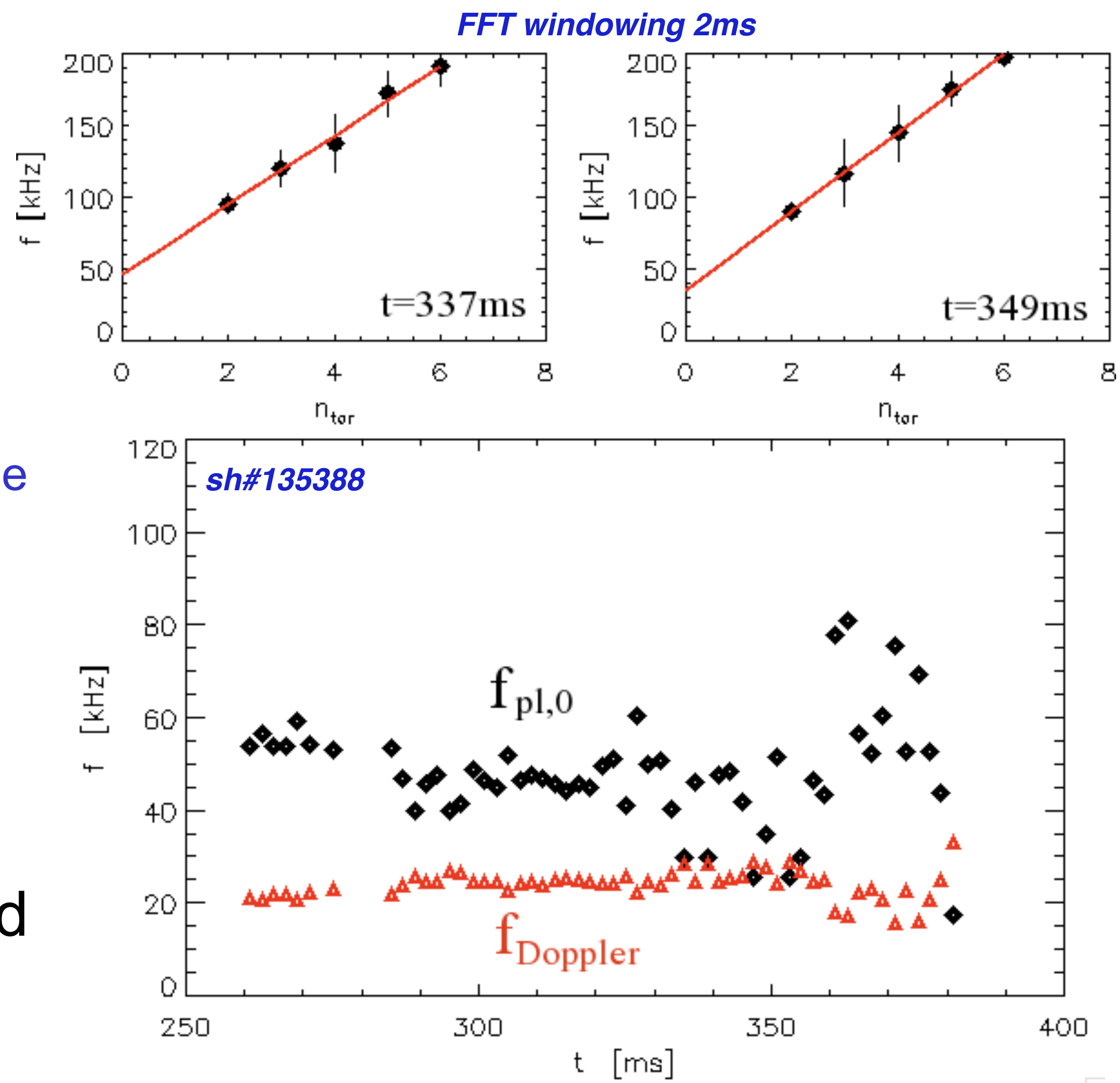
In general, time-averaged FFT spectra are consistent with a common TAE frequency *in the plasma frame*

- Consider *n=2-6*
- Measured frequencies:

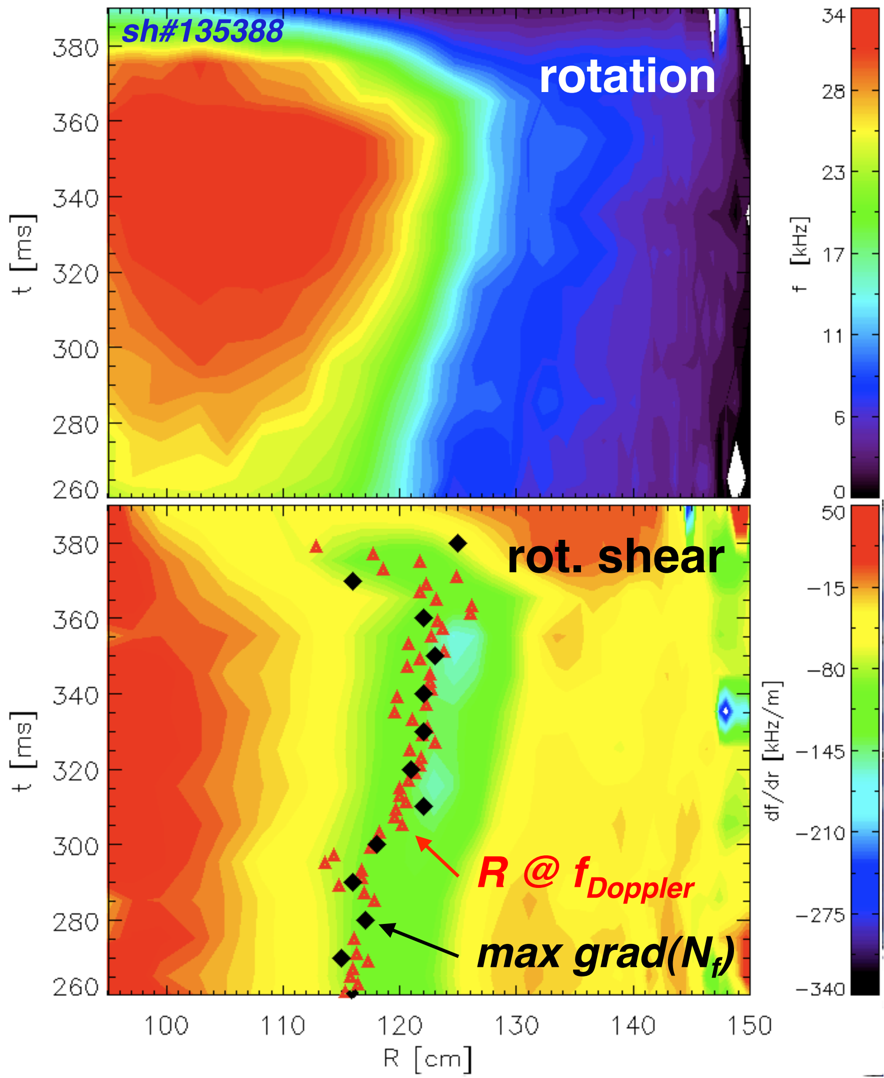
$$f_{lab,n} = f_{pl,0} + n\, f_{Doppler}$$

$f_{lab,n}$: mode freq. in lab frame
$f_{0,pl}$: mode freq. in plasma frame
$f_{Doppler}$: shift from plasma rotation

- $f_{Doppler} \sim f_{n=1}$
- Modes' location obtained from $f_{Doppler}$ and rotation profile



Sheared plasma rotation may lead to de-correlation of TAEs: role in bursts' dynamics?



- Max rotation shear and max fast ion gradient at same location
  - Both fast ion and torque sources are from NB
- De-correlation rate:

$$\tau_{dec}^{-1} = k_{\|} \Delta R_{mode} \, 2\pi R_{mode} \frac{\partial f_{rot}(r)}{\partial R}$$

wave number ($k_{\|}$), ***mode width*** (ΔR_{mode}), ***mode location*** (R_{mode}), ***shear*** ($\partial f_{rot}(r)/\partial R$)

  - τ_{dec}~50-250μs, comparable with time scale of frequency sweep

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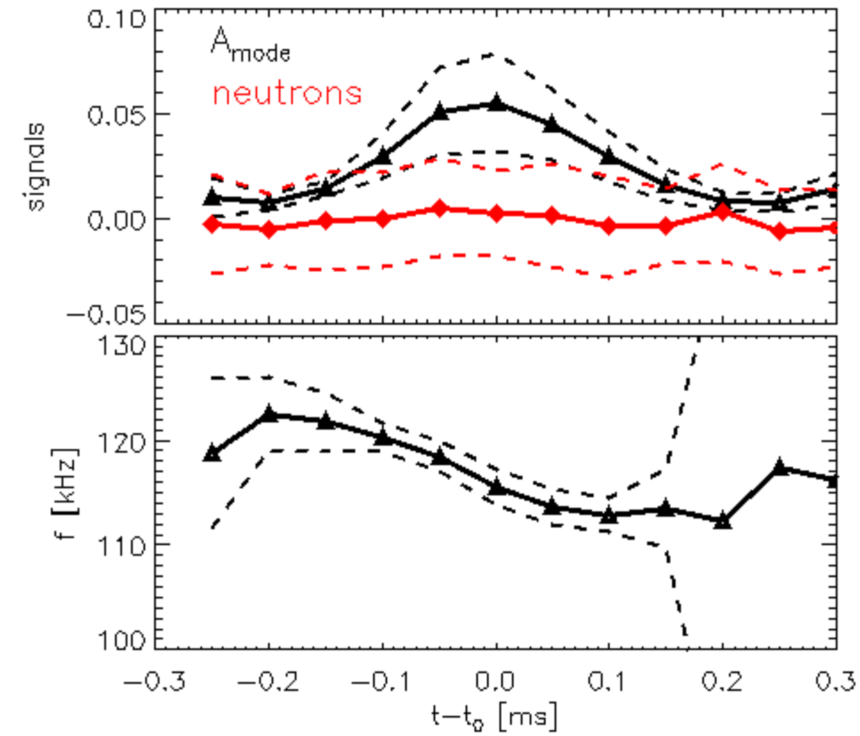
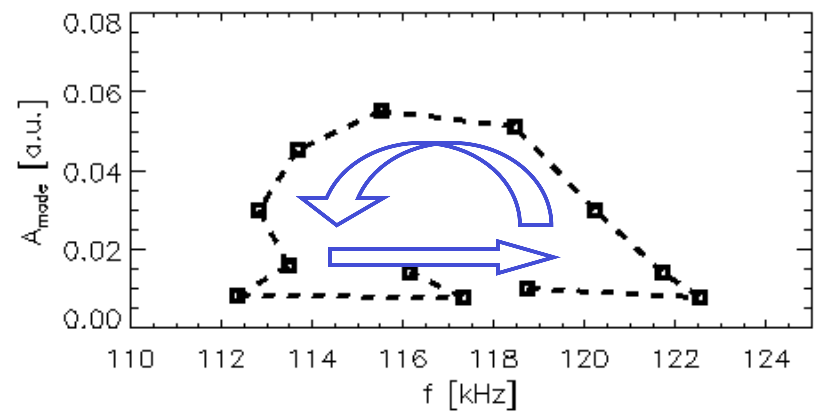
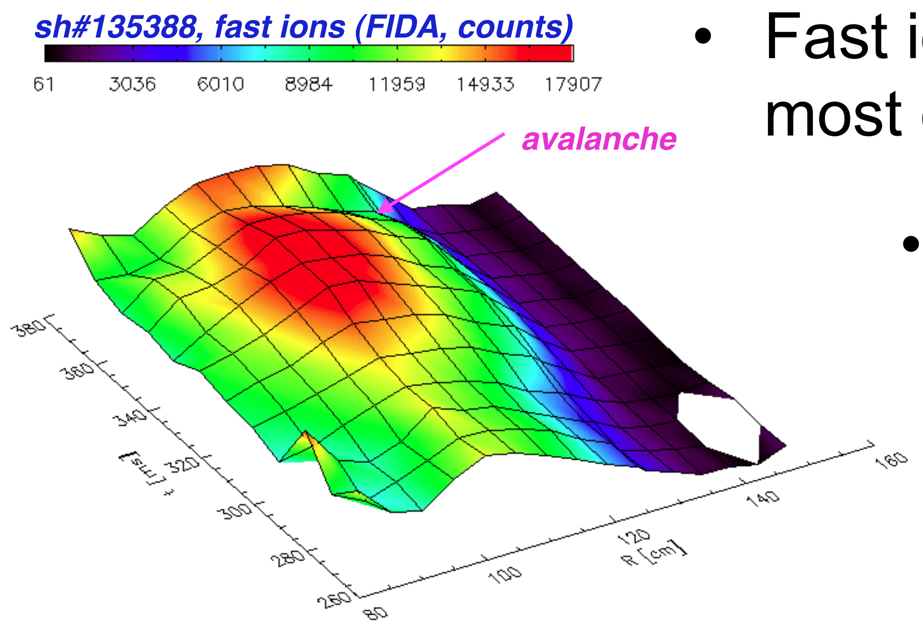
No detectable fast ion losses are observed during bursting/chirping phase

- Statistical average over ~20 events (~10ms)
- Mode amplitude and frequency follow a regular cycle
- No evidence of losses from neutrons, FIDA

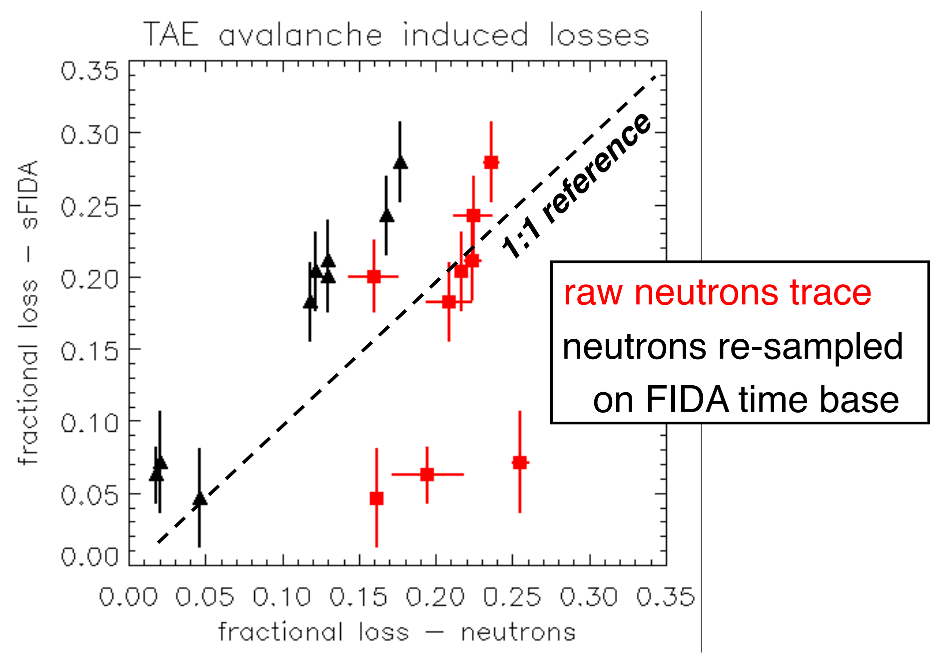




Up to ~30% of fast ions can be lost during a single TAE avalanche

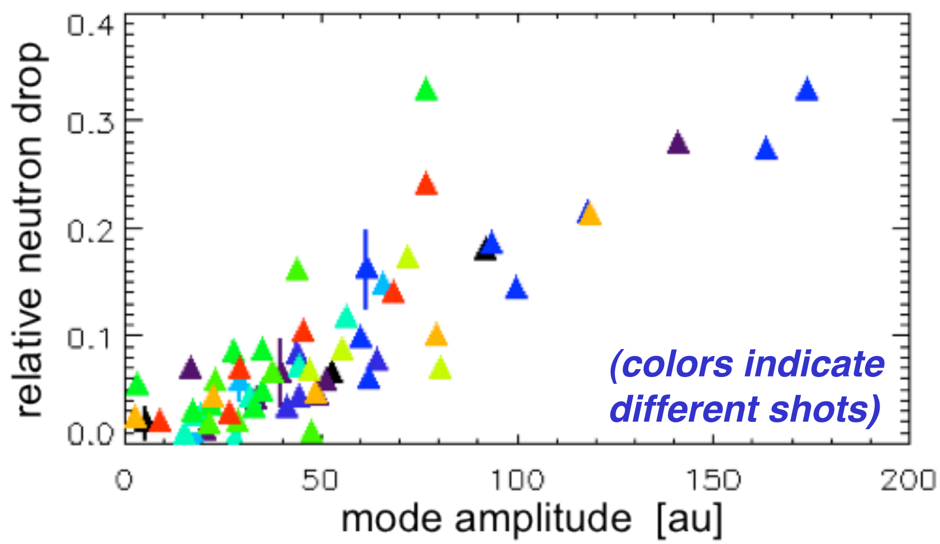


- Fast ion density (FIDA) drops over most of minor radius
  - Loss results in a relaxation of the radial gradient → drive for TAEs is reduced



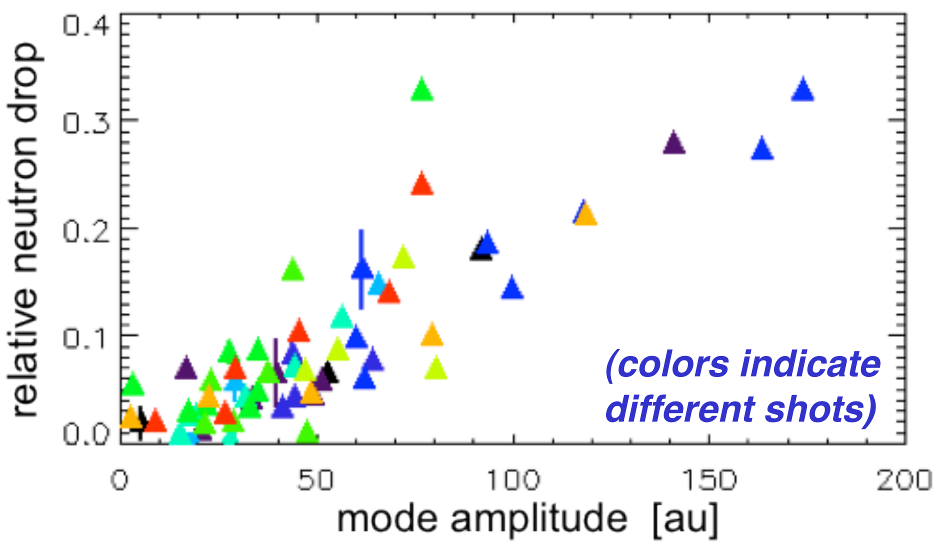
- Comparable losses measured from (volume-averaged) neutron rate

As expected, fast ion losses from large bursts increase with mode amplitude



- Dependence looks more-than-linear, but…
- No clear threshold identifiable
  - Large variations (*n*'s, frequency, …) between different shots
  - Mode amplitude from Mirnovs @ plasma edge; need entire structure?

Comparison with codes is required for quantitative conclusions and extrapolation to other regimes



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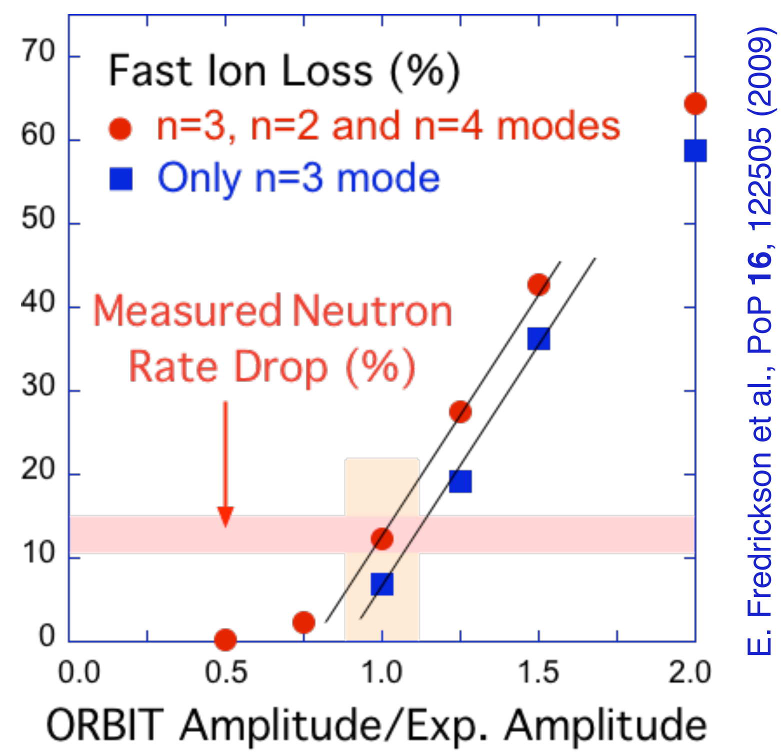

Example: linear analysis with NOVA-K + ORBIT can reproduce lost fraction *vs.* mode amplitude

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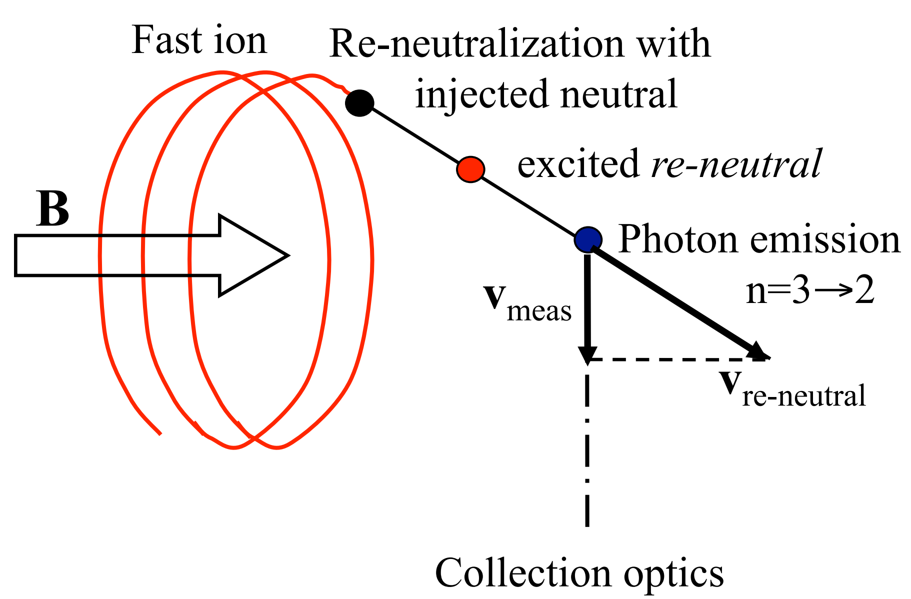
Summary and outlook

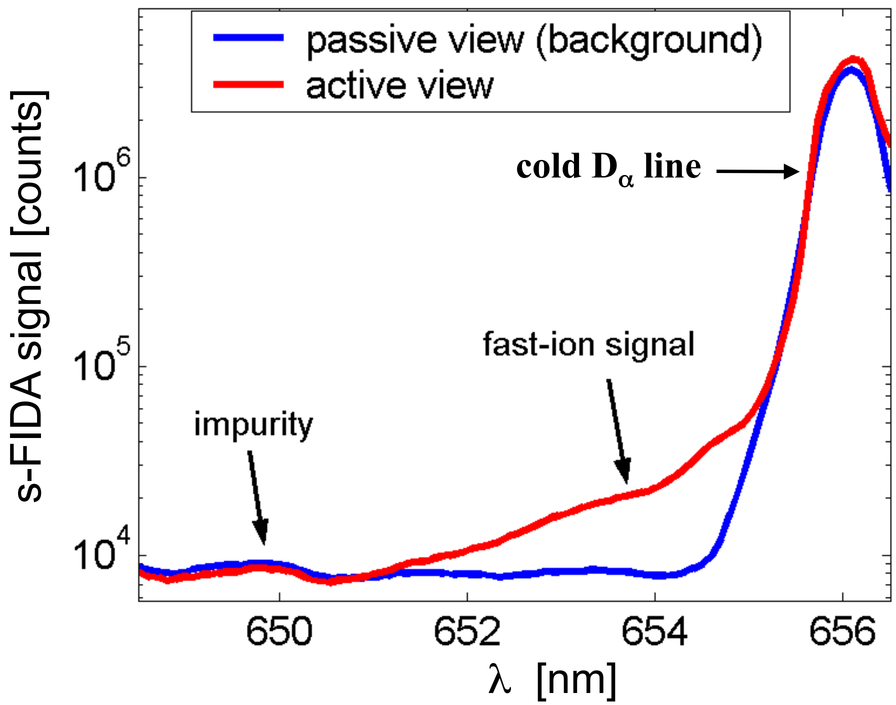
- Different TAE regimes observed on NSTX
  - More “turbulent” character as the fast ion population increases
  - Evidence of increasing coupling (mediated by *n=1* fluctuation) as TAE amplitude increases
  - Possible role of rotation shear? Competition with kinetic (phase-space) effects?
- Up to ~30% of fast ions lost following TAE avalanches
  - No evidence of losses during small bursts/chirps
- Future experiments dedicated to detailed measurement of mode structure evolution
  - Comparison with M3D-K code planned (plasma rotation included)
  - Will continue “linear” analysis (NOVA-K + ORBIT)

Backup viewgraphs

Fast ions diagnosed through active charge-exchange D-alpha spectroscopy (FIDA technique)

- Exploit wavelength Doppler shift from cold D-alpha line of photons emitted by re-neutralizing fast ions
  - Distinguish fast-ion features from dominant cold D-alpha emission
- *Passive* views missing the neutral beam for background subtraction





FIDA signal results from convolution in energy, pitch of fast-ion distribution and response function

- **Measured fast ion signal**:

  $s(\lambda) = \iint F * W \, d(v_{||}/v) \, dE$

  $F(v_{||}/v,E)$: fast-ion distribution

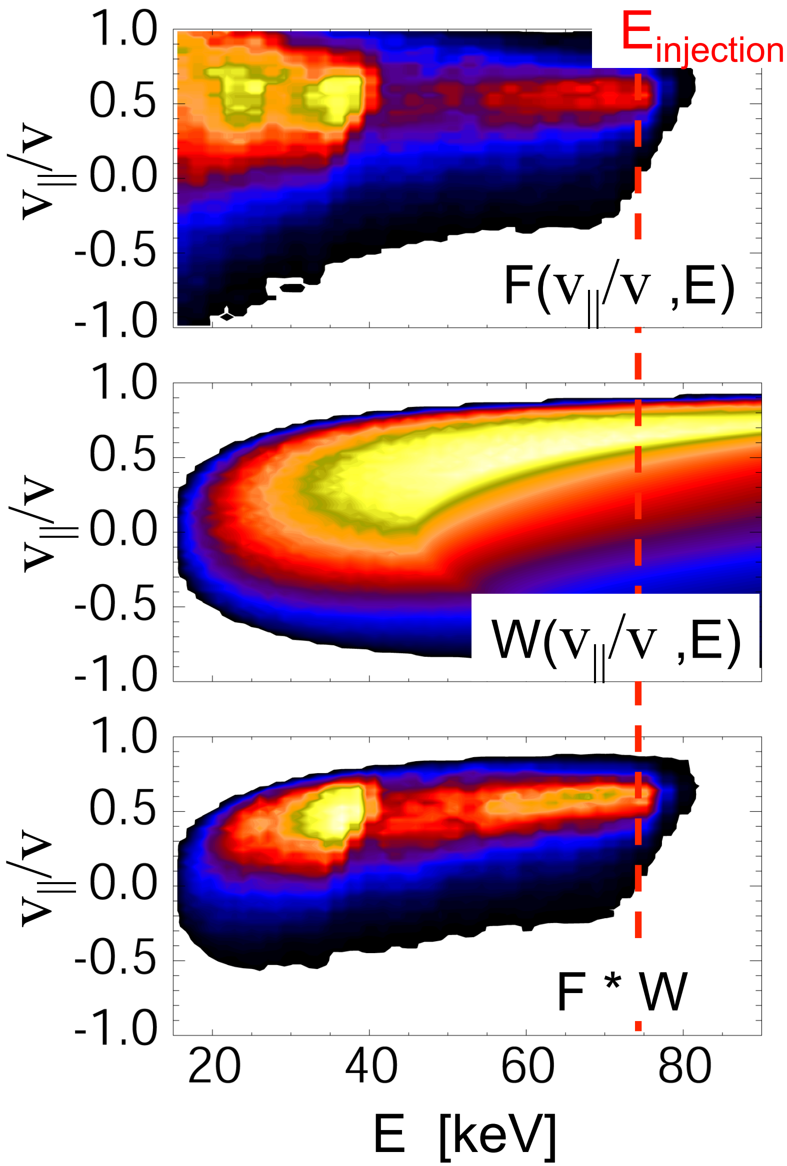
  $W(v_{||}/v,E \mid \underline{g}_i)$: weight function

  $v_{||}/v$: pitch, E : energy, $\underline{g}_i$: geometry & NB

  λ : wavelength from Doppler shift formula

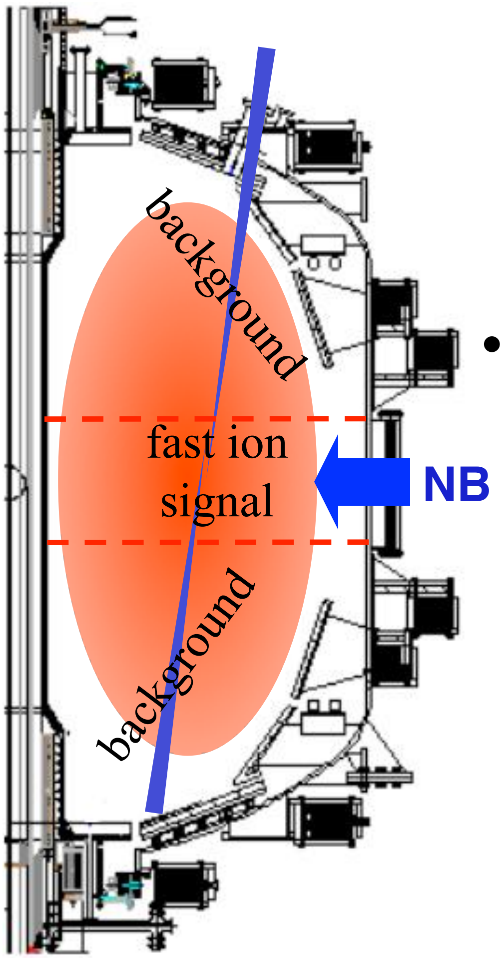
  $E_\lambda=E(\lambda)$: measured photon energy

- **FIDA density,** N_f ($\propto$fast-ion density) obtained by integrating spectrum over energy E_λ and taking into account local neutral density in W
- **Vertical views:** signal weighted toward perpendicular velocities
- **$s_{tot}=s(\lambda) + B(\lambda)$: Background** $B(\lambda)$ is main source of experimental error



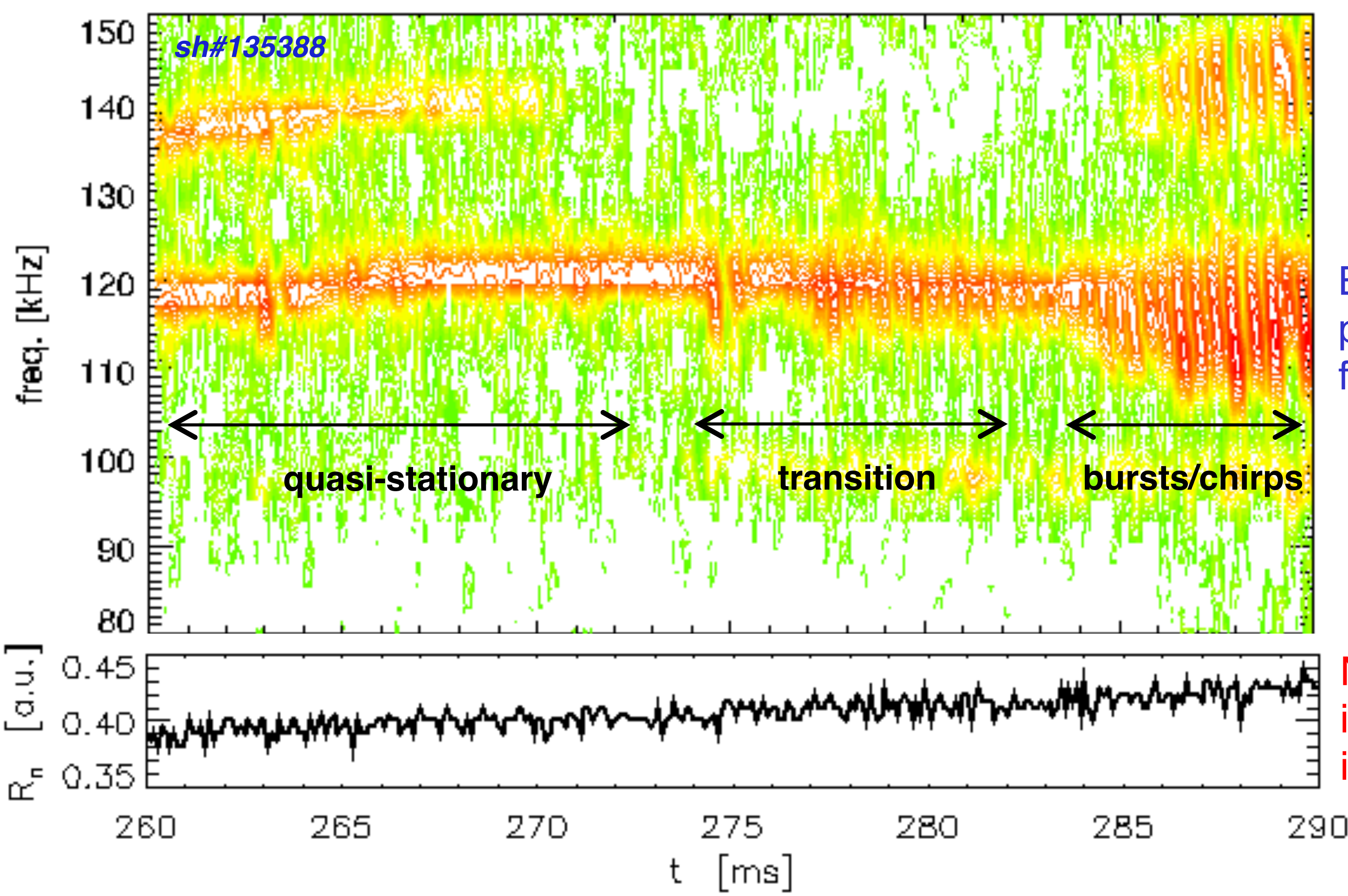
[Heidbrink, PPCF **49** (2007)]

Measured signal = fast ion signal + background. Background is a significant fraction of total signal



- Main contributions to background:
  - Bremsstrahlung, impurity emission
  - Light from divertor & plasma facing components
  - Scattered light
- Two techniques can be used to measure background contribution:
  - ON/OFF modulation of Neutral Beam
    - ✓ Same views for active/background measurements
    - ✗ Temporal resolution reduced; specific NB waveform required
  - *Passive* views, toroidally displaced, missing the neutral beam for background measurement
    - ✓ Temporal resolution not affected
    - ✗ Number of views doubles; toroidal symmetry required

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

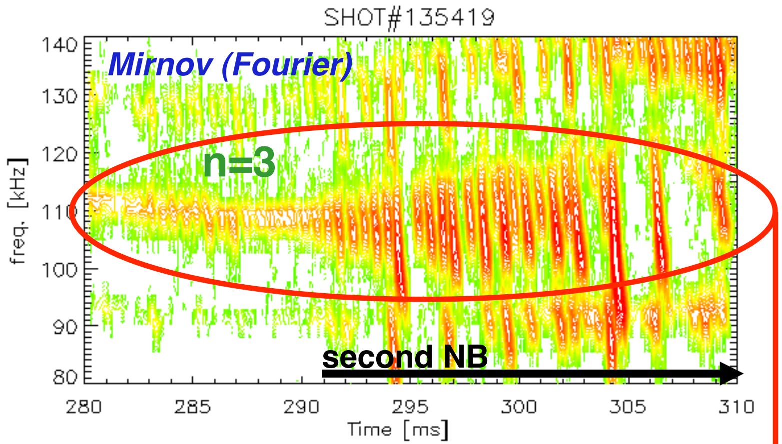


Bursting phase preceded by small frequency chirp

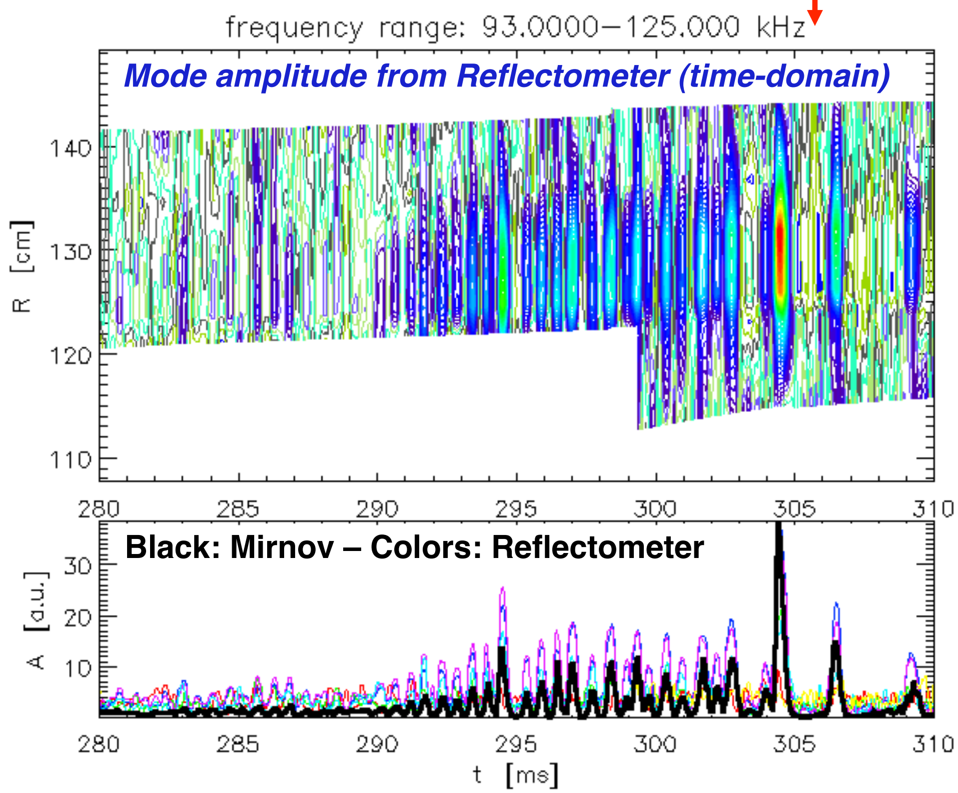
Neutron rate increase indicates larger fast ion population

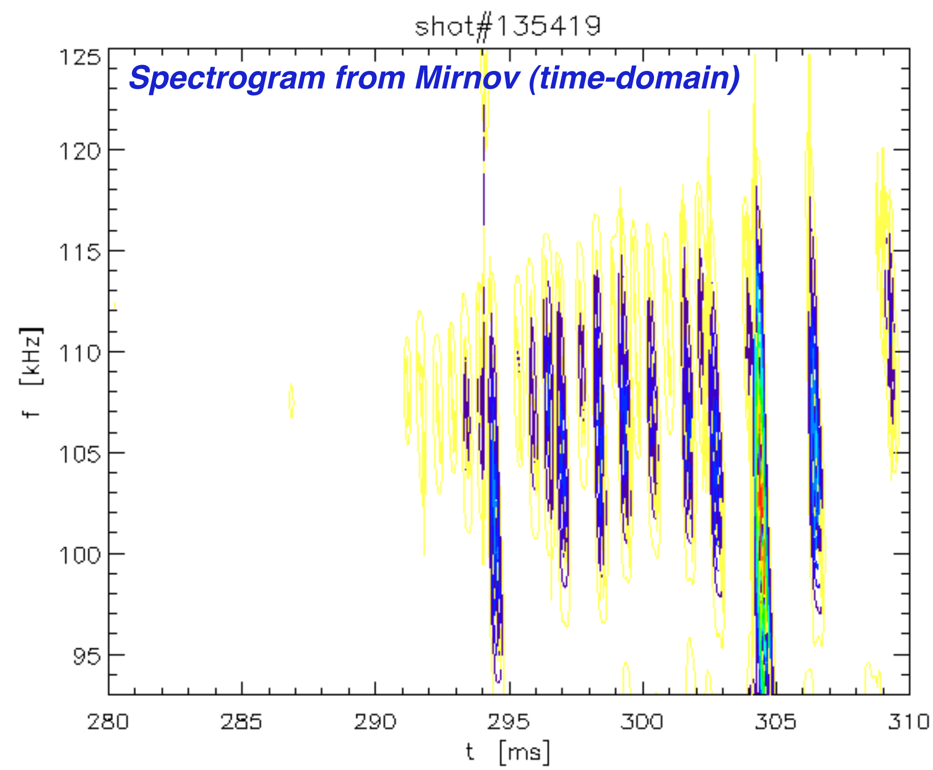
- Transition promptly triggered by stepping up the NB power

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

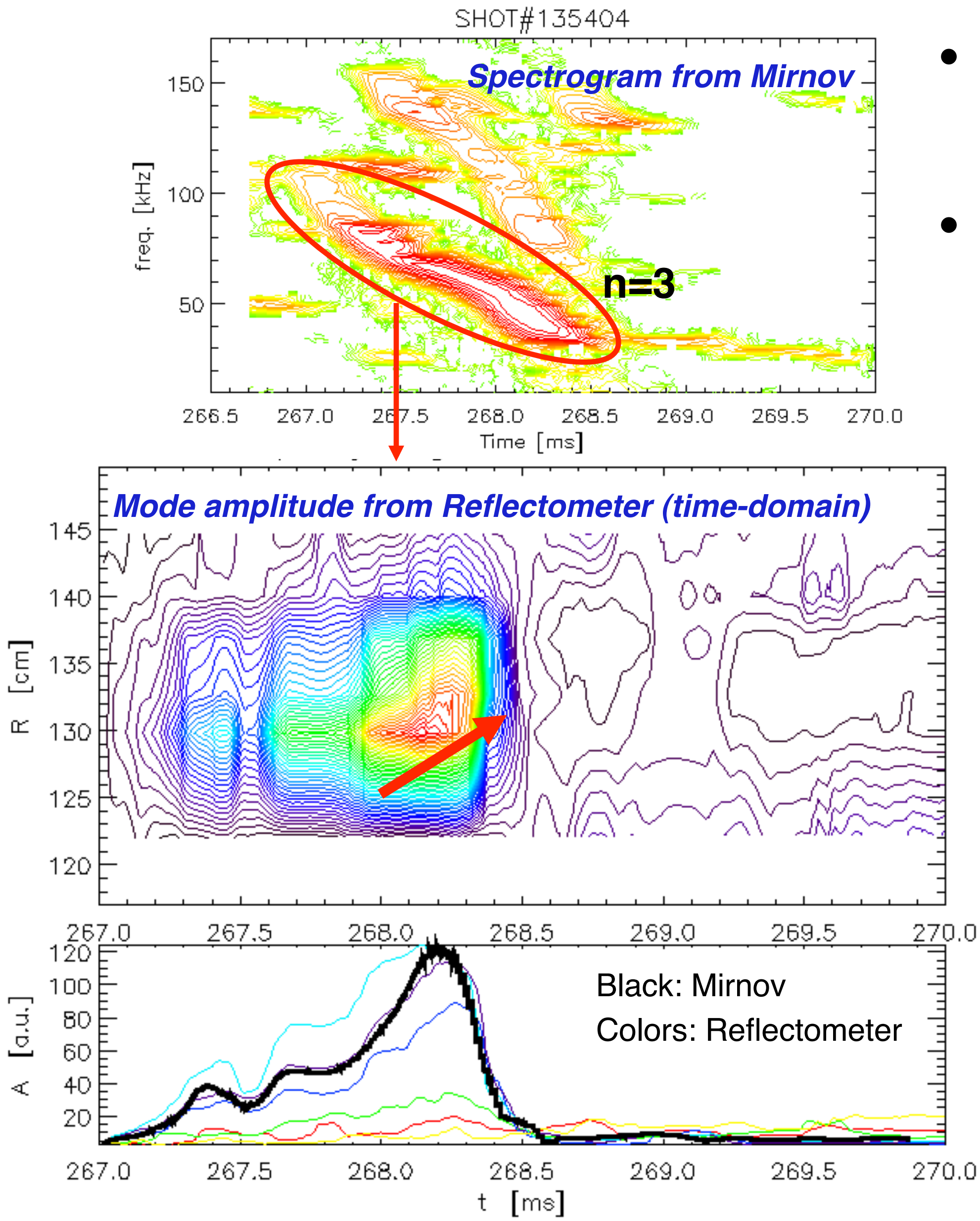


- Up to six reflectometer channels measure displacement for R=110→145cm
- Good correlation here between Mirnov and reflectometer

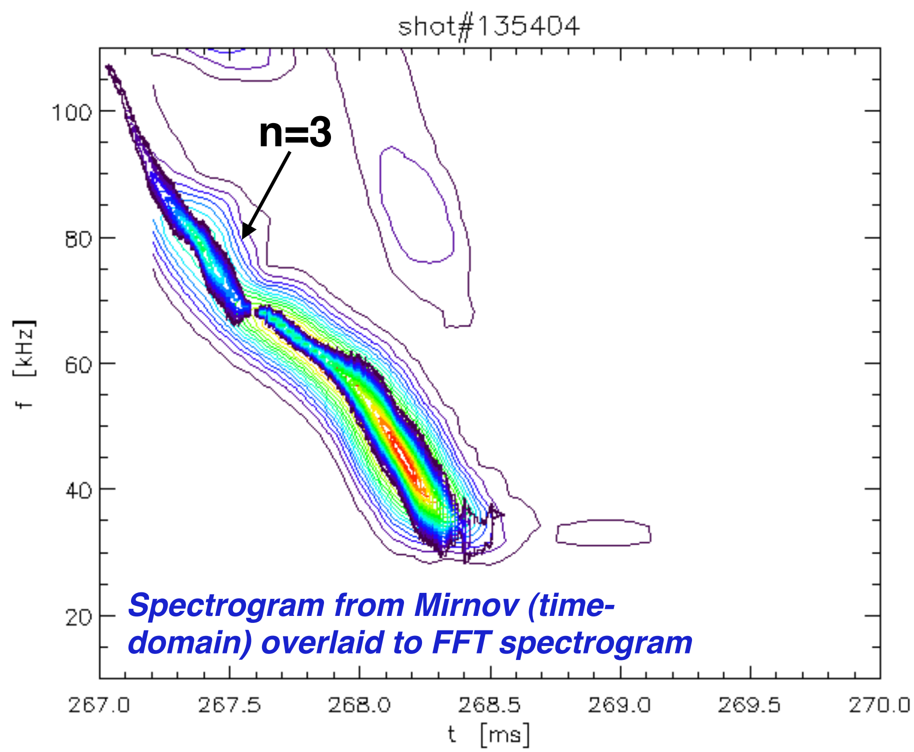




Variations of mode structure for same mode number can be observed during avalanches

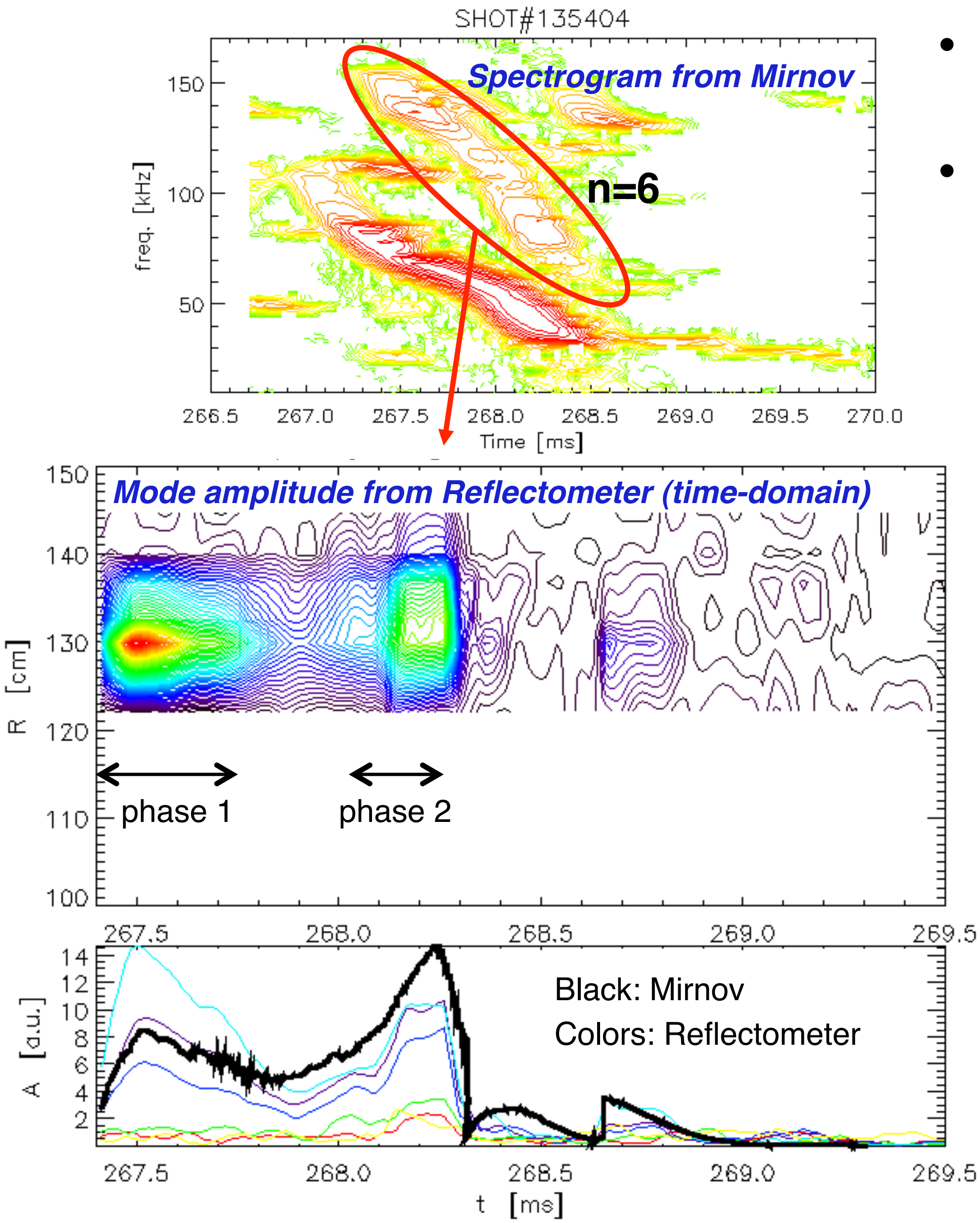


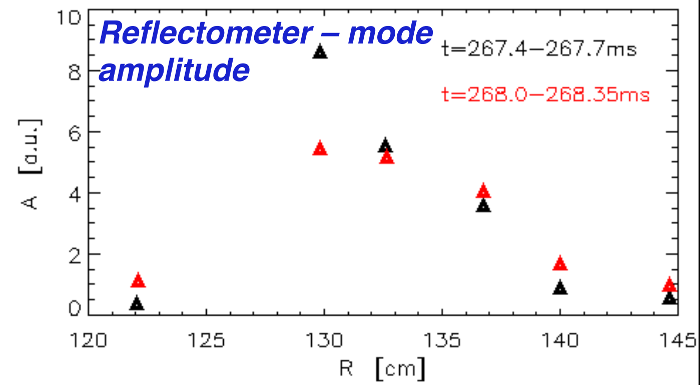
- Dynamics may differ for different *n*'s
- Reflectometer and magnetics do not always track well each other at the end of avalanches

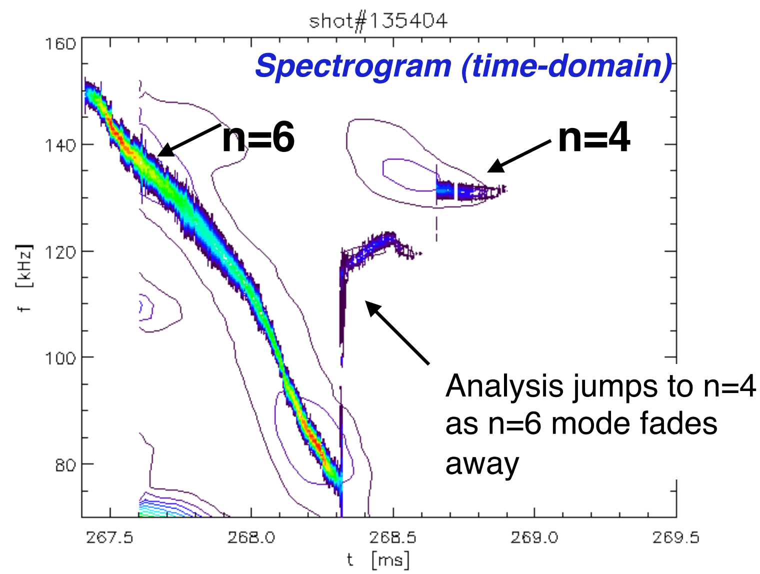


Different n’s may show quite different temporal evolution, too

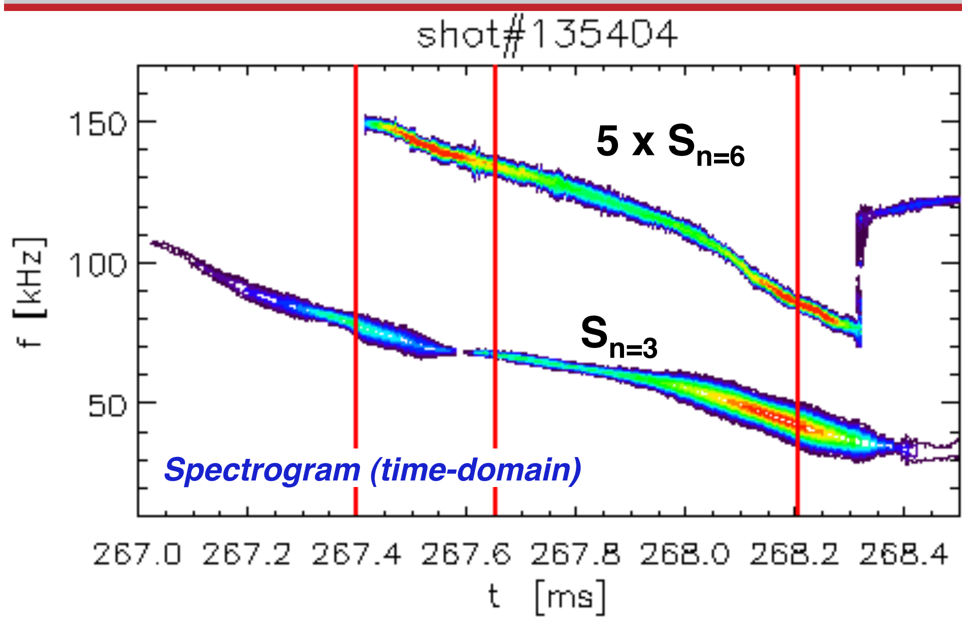
- Measured structure not too different from that of n=3 mode
- Two “phases” with different spatial structure?



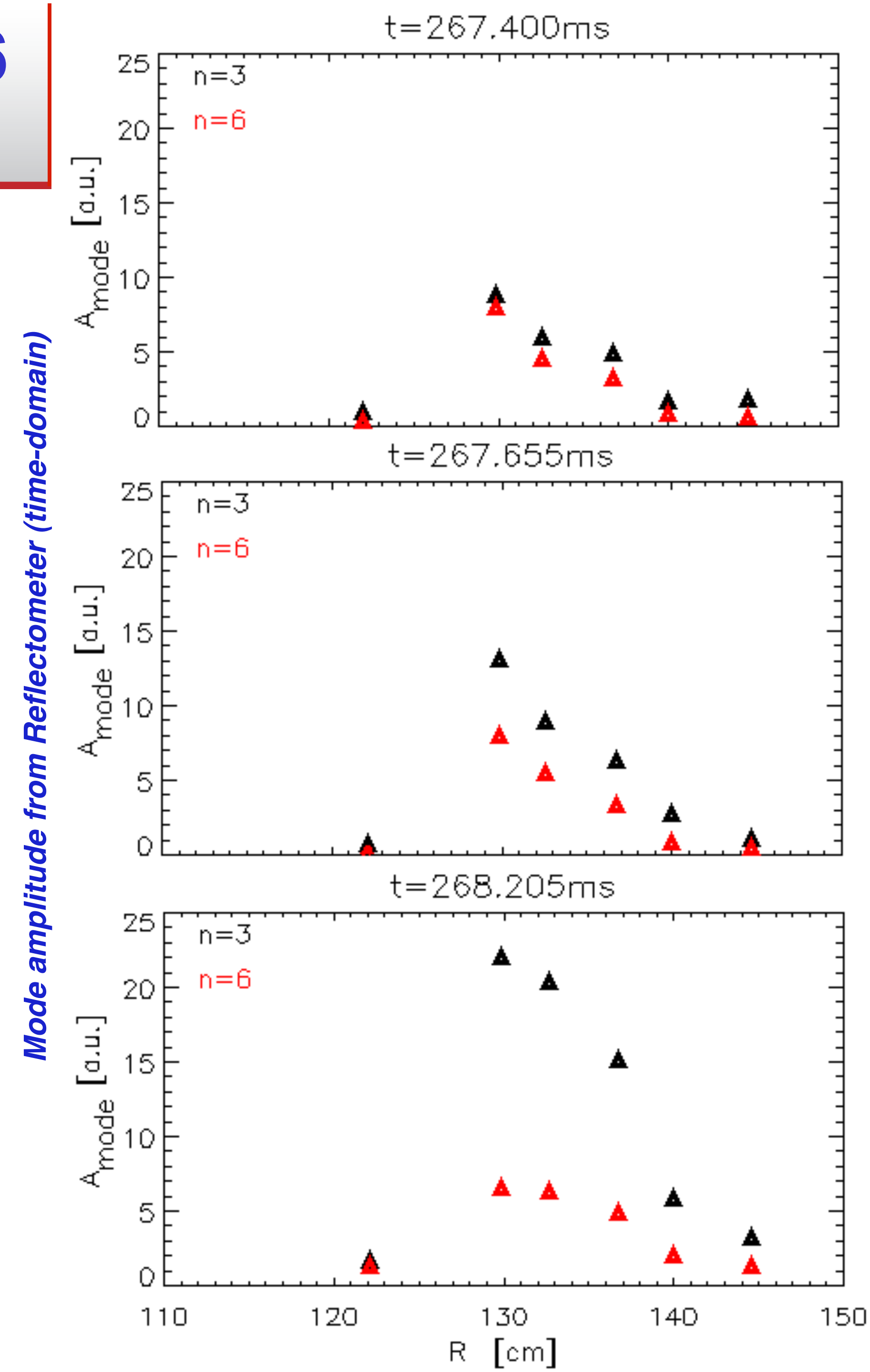




Combined analysis of n=3,6 modes during avalanche

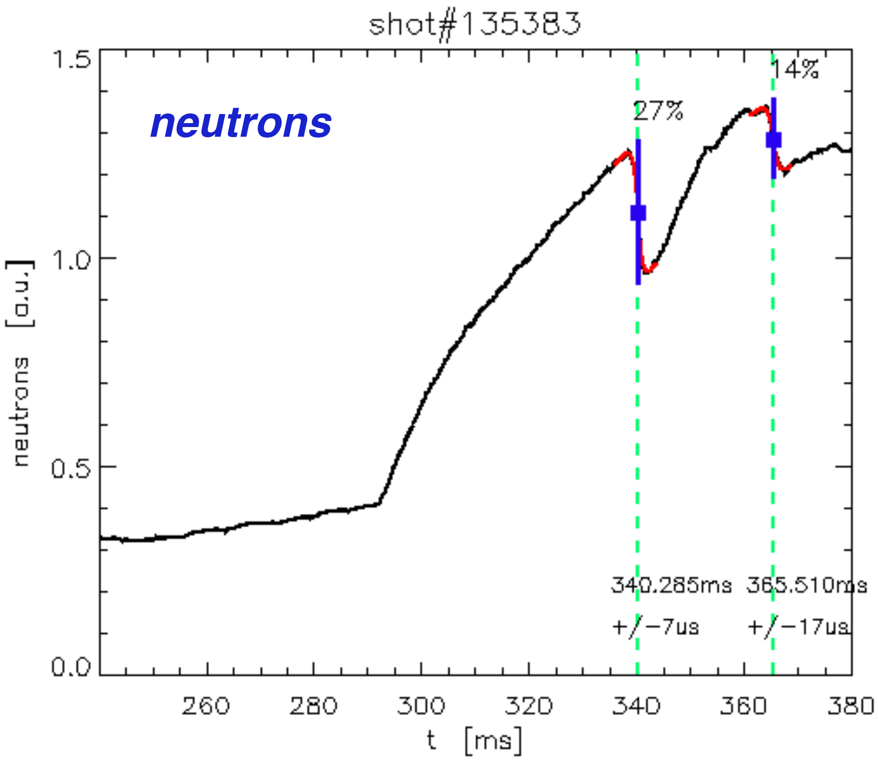


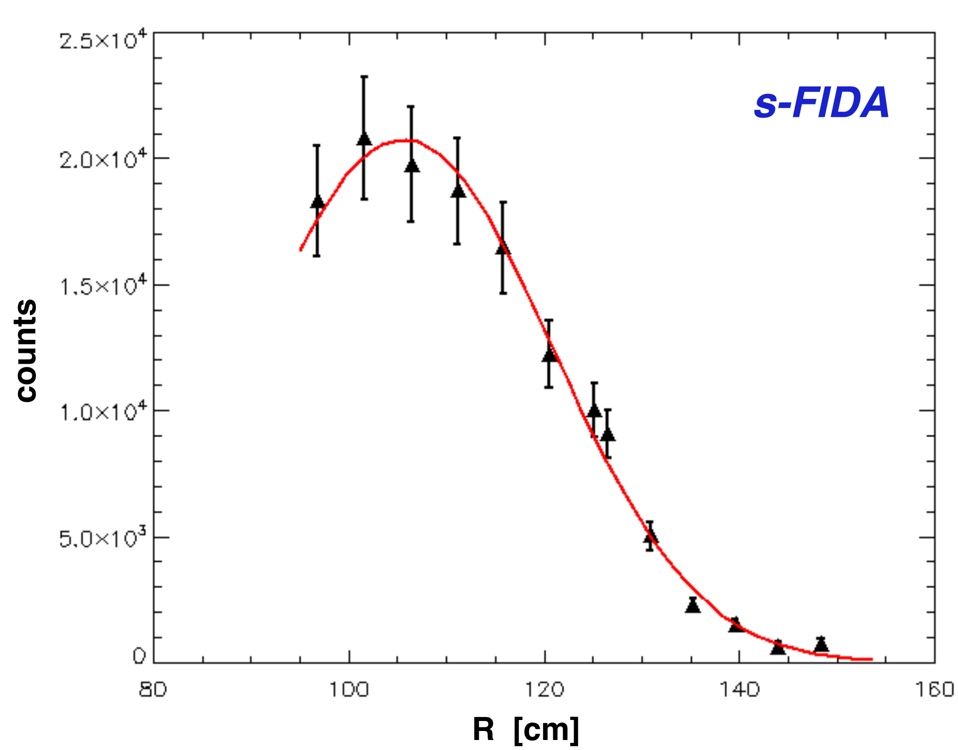
- The two modes have similar structures
  - Slightly change for last ~400μs
- Temporal evolution is different
  - n=3 has faster growth, especially at the end of the avalanche (t~268.2 ms)



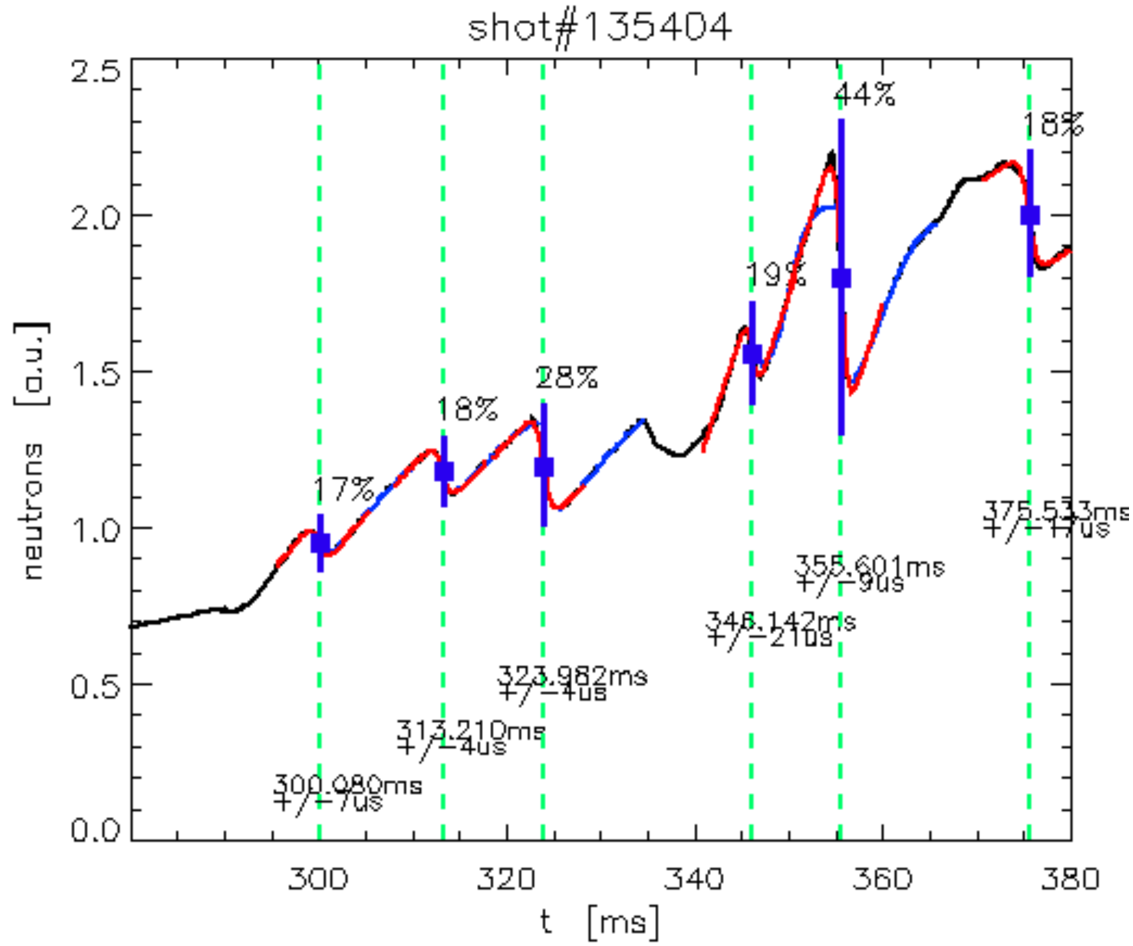
Analysis of *drops* in neutron rate & sFIDA profiles

- Fit neutron rate time trace to infer amplitude, duration and exact time of the drop
- Fit sFIDA radial profiles with modified gaussian function, then calculate losses from temporal evolution of the fit
  - Fit reduces errors; constraints on radial profile look OK





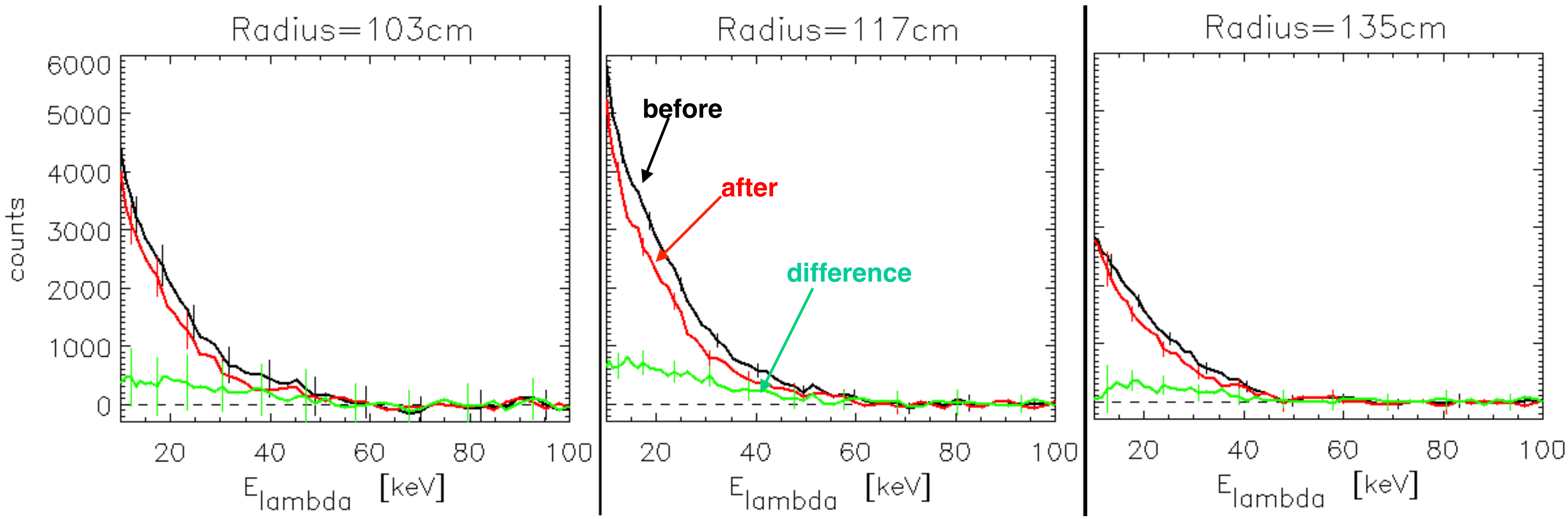
No correlation found between spacing between avalanches and amount of lost fast ions



- No "memory" of fast ion (or plasma) evolution
- Indication of strongly non-linear phenomenon?

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
- No clear evidence of redistribution for small amplitude activity

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

- Low-*n*, quasi-stationary TAEs evolve into bursty modes & *avalanches*
- Fast ion losses up to ~30% during avalanches
- Similar $n_{e,i}$, $T_{e,i}$, I_p, B_{tor}, P_{NB} , but different plasma shape (LSN *vs* limiter)