NSTX

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Fast-ion transport by toroidicity-induced Alfvén eigenmodes on NSTX

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

- 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:
  - Effects of TAE avalanches on fast-ion profile and energy distribution in NSTX
  - Relationship between fast-ion profile and TAEs' drive
  - Modeling of TAE evolution, comparison with experiments

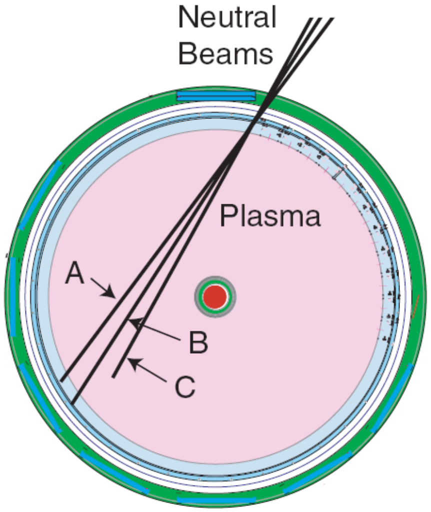
The National Spherical Torus Experiment, NSTX

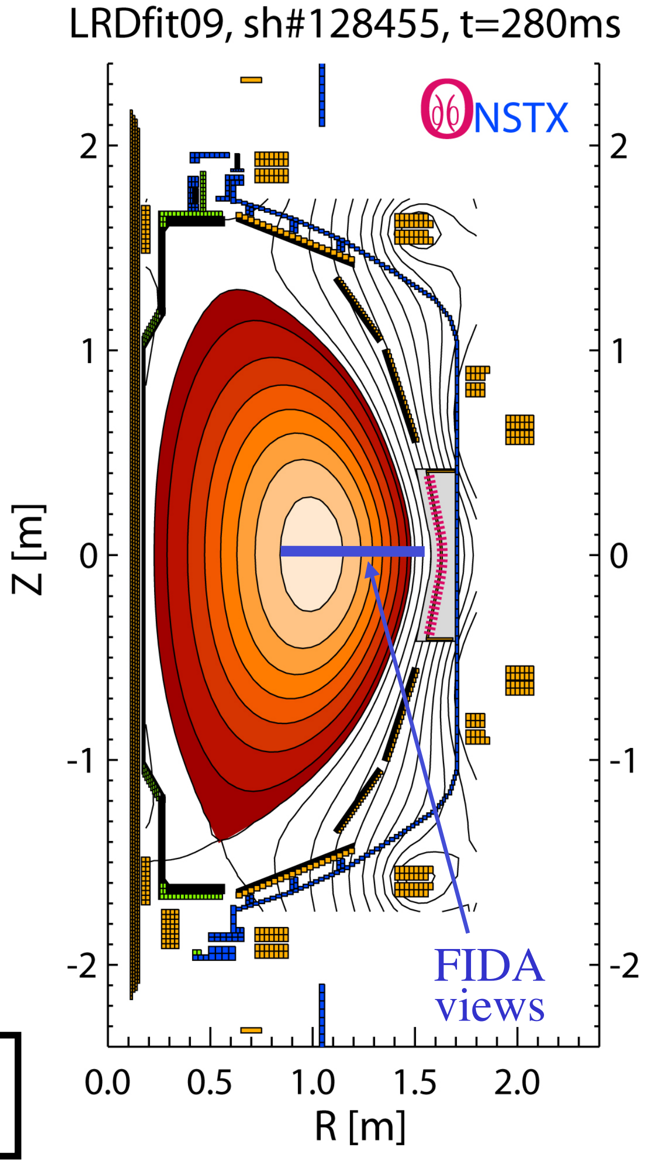
Major radius	0.85 m
Aspect ratio	1.3
Elongation	2.7
Triangularity	0.8
Plasma current	~1 MA
Toroidal field	<0.6 T
Pulse length	<2 s

Neutral Beam auxiliary heating:

3 sources: A, B, C

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



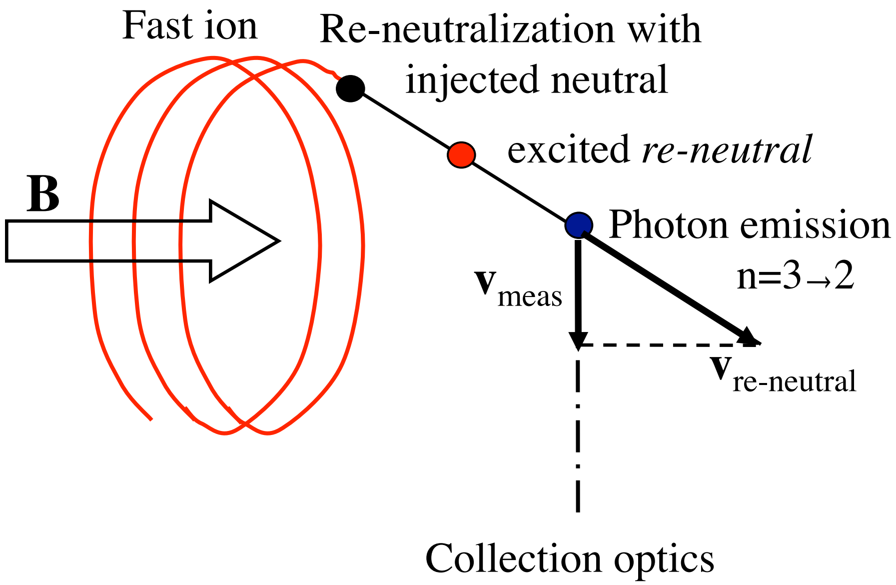


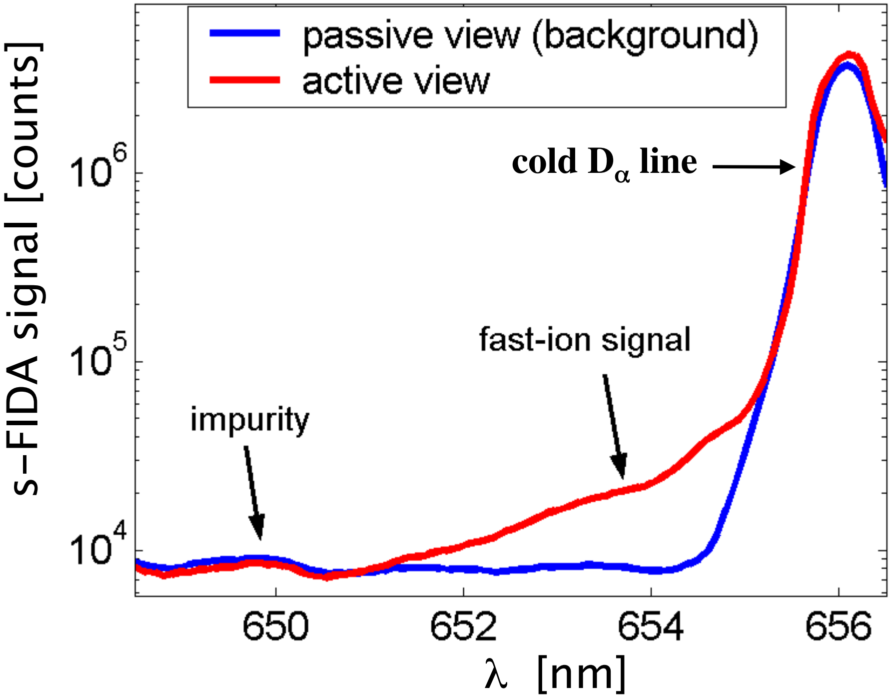
This work: Lower single-null, B_{tor}=0.45 T, I_p=0.9 MA

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

Heidbrink *et al.*, PPCF **46** (2004)

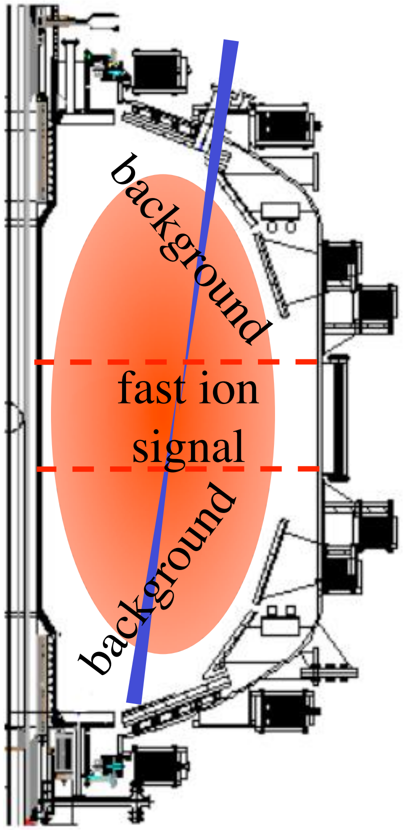
- Exploit wavelength Doppler shift from cold D-alpha line of photons emitted by re-neutralizing fast ions
  - Distinguish fast-ion features from dominant cold D-alpha emission
- *Passive* views missing the neutral beam for background subtraction





Measured signal = fast ion signal + background, but… background > fast ion signal

- Main contributions to background:
  - Bremsstrahlung, impurity emission
  - Light from divertor & plasma facing components
  - Scattered light

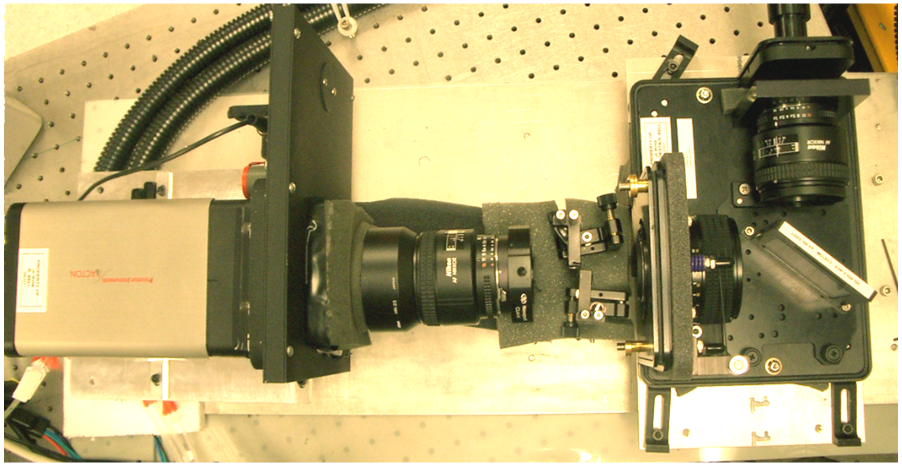


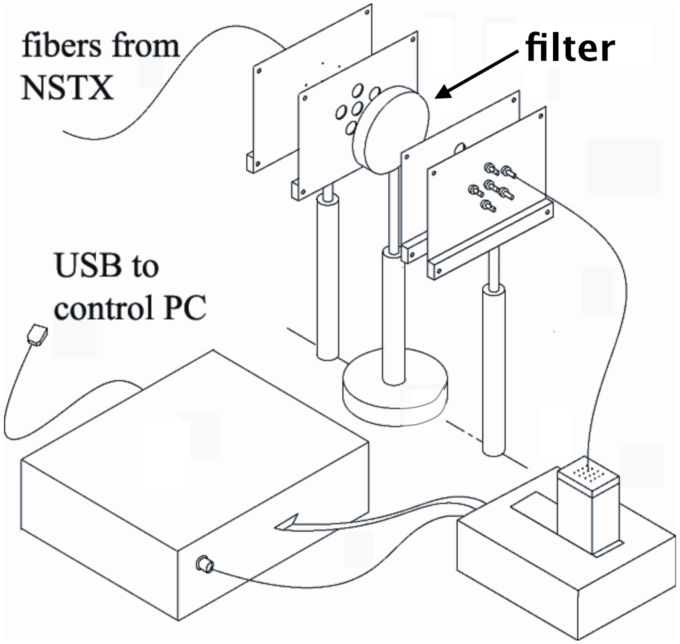
- Two techniques can be used to measure background contribution:
  - ON/OFF modulation of Neutral Beam (DIII-D, NSTX)
    - ✓ Same views for active/background measurements
    - ✗ Temporal resolution reduced; specific NB waveform required
  - *Passive* views, toroidally displaced, missing the neutral beam for background measurement (NSTX)
    - ✓ Temporal resolution not affected
    - ✗ Number of views doubles; toroidal symmetry required

[W.W. Heidbrink, PPCF **46** (2004)] [M. Podesta', RSI **78** (2008)]

NSTX: two FIDA systems provide space, time and energy resolved fast-ion measurements

- s-FIDA: spectrometer
  - 16 channels, R = 85 – 155 cm
  - 10 keV energy resolution
  - 10 ms time resolution
- f-FIDA: filter system
  - 3 channels, R = 100, 120, 140 cm
  - Signal integrated over fast ion energy range through bandpass filter
  - 20 μs time resolution (typical)
- FIDA systems complement other NSTX fast-ion diagnostics:
  - Neutron rate measurements, neutral particle analyzers (NPAs), scintillator fast-ion loss probe (sFLIP)

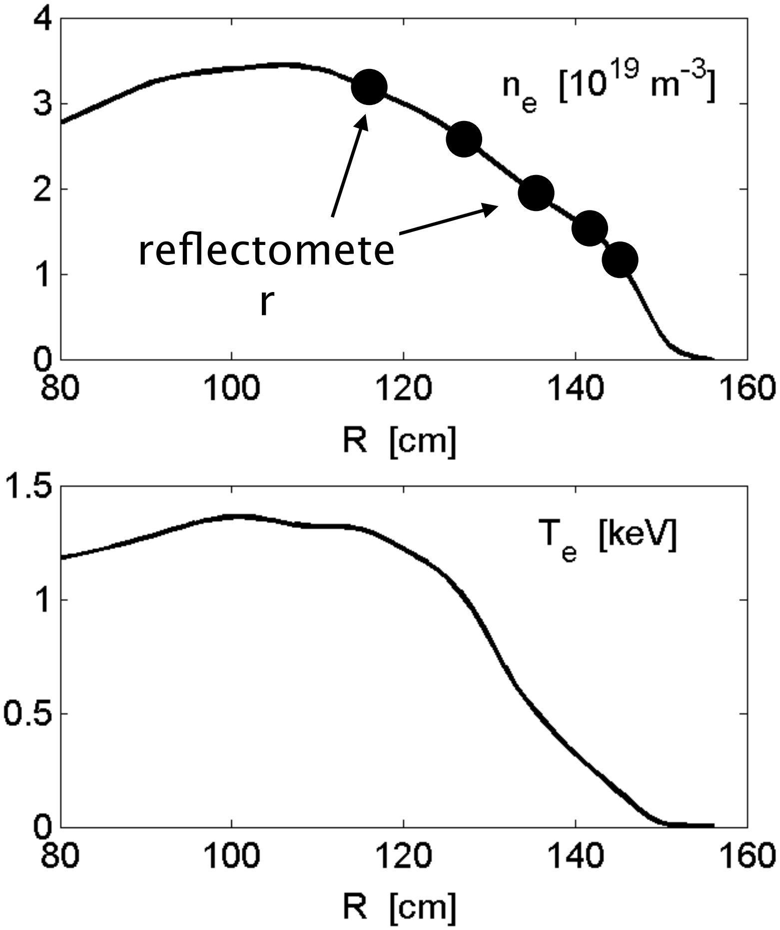


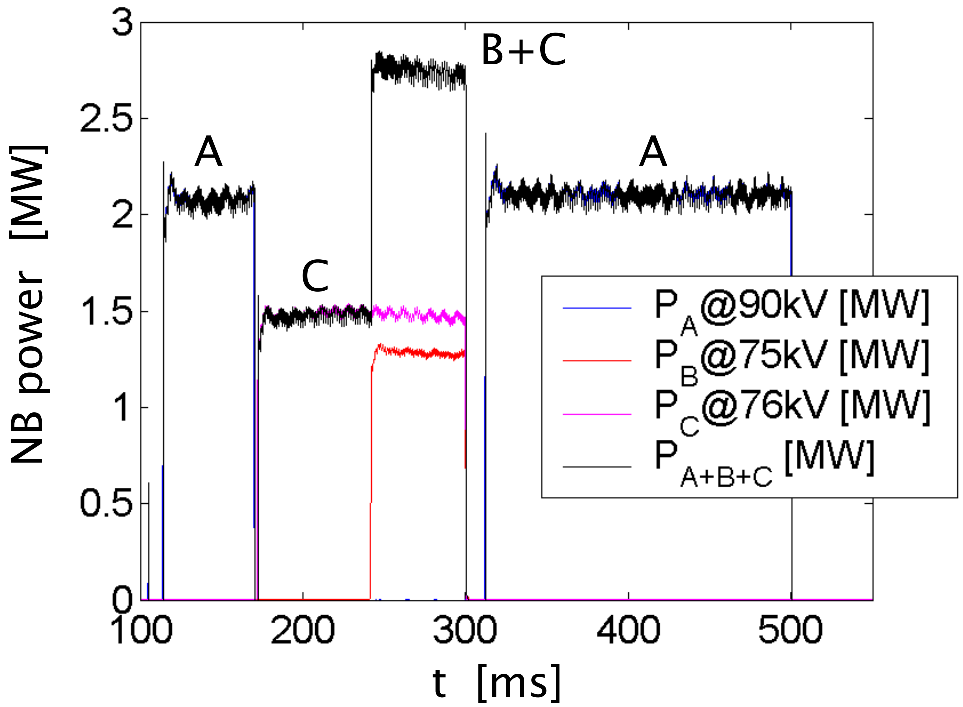


[Podestà *et al.*, RSI **79** (2008)]

Experimental scenario: L-mode Helium plasma, slightly reversed *q*-profile, low injected NB power

- Helium plasmas have higher L→H mode transition threshold
- Low density, L-mode: reflectometer data over whole profile

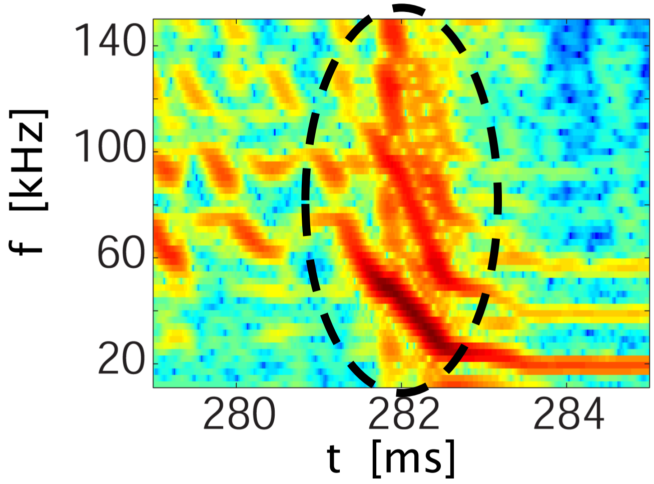


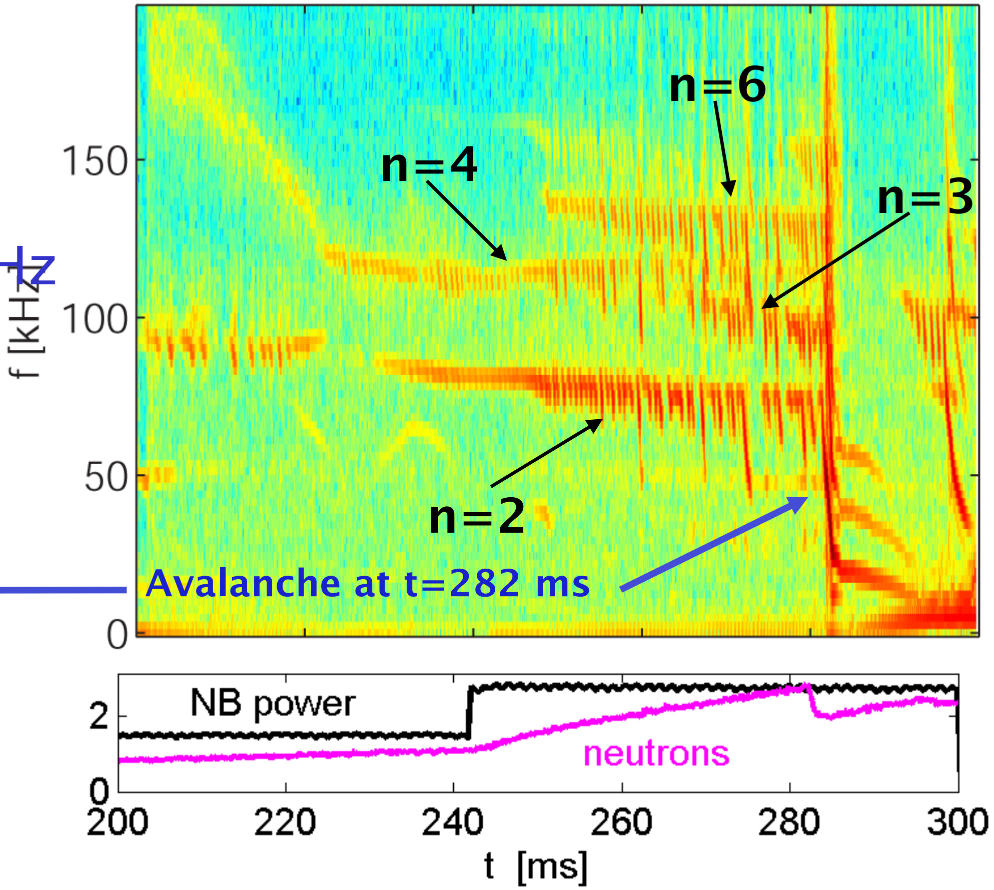


- NB waveform to have *q*-profile data before/after TAE phase (200-300ms)
- TAE avalanches observed for $V_{B,C}$=75kV

Avalanches manifest as bursty frequency down-shift of TAEs, associated with prompt neutron rate drop

- TAEs:
  - Toroidal mode numbers n ≤ 6
  - Frequency *f* = 60–160 kHz
- Avalanche:
  - Frequency down-chirp of 50kHz in ~1 ms, all modes involved

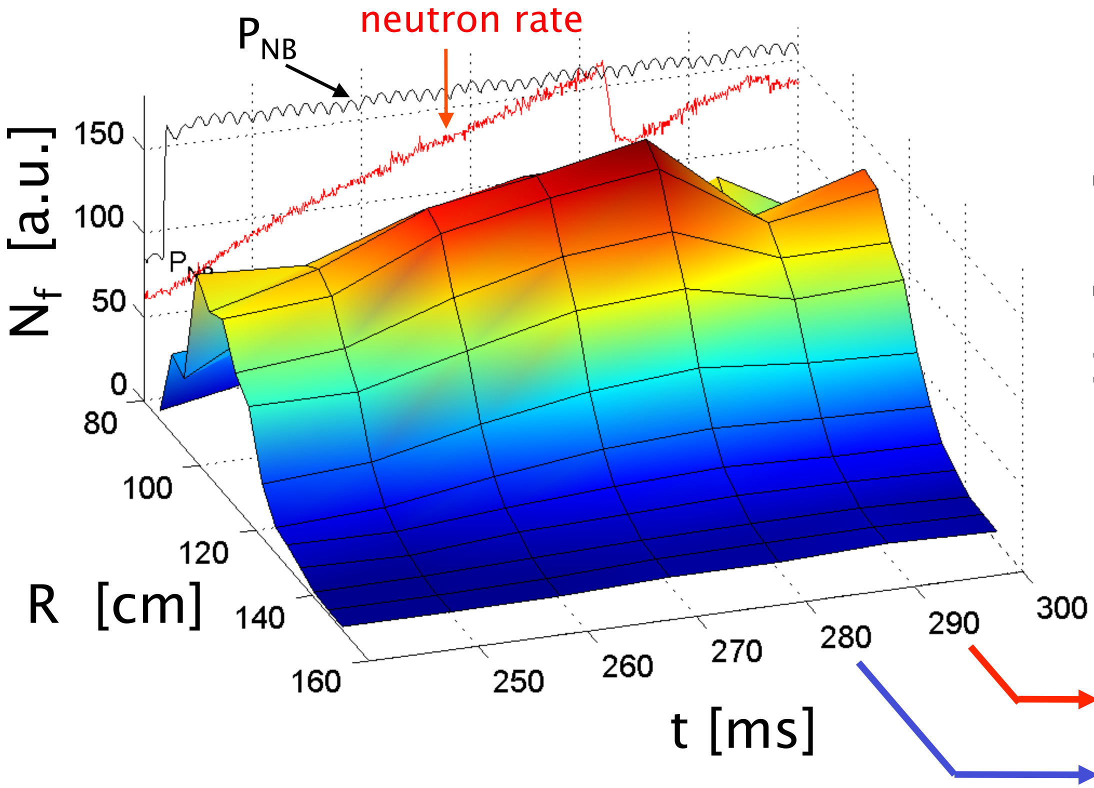


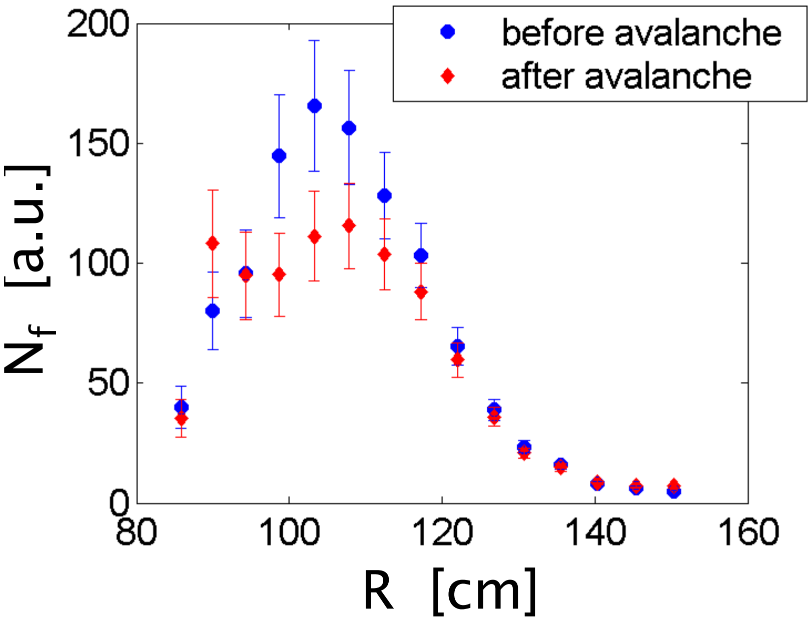


  - Neutron rate drops by up to 35%

Strong fast-ion density decrease observed after avalanche, consistent with neutron rate drop

- Strong central depletion of fast-ion density, N_f
- Profile remains centrally peaked



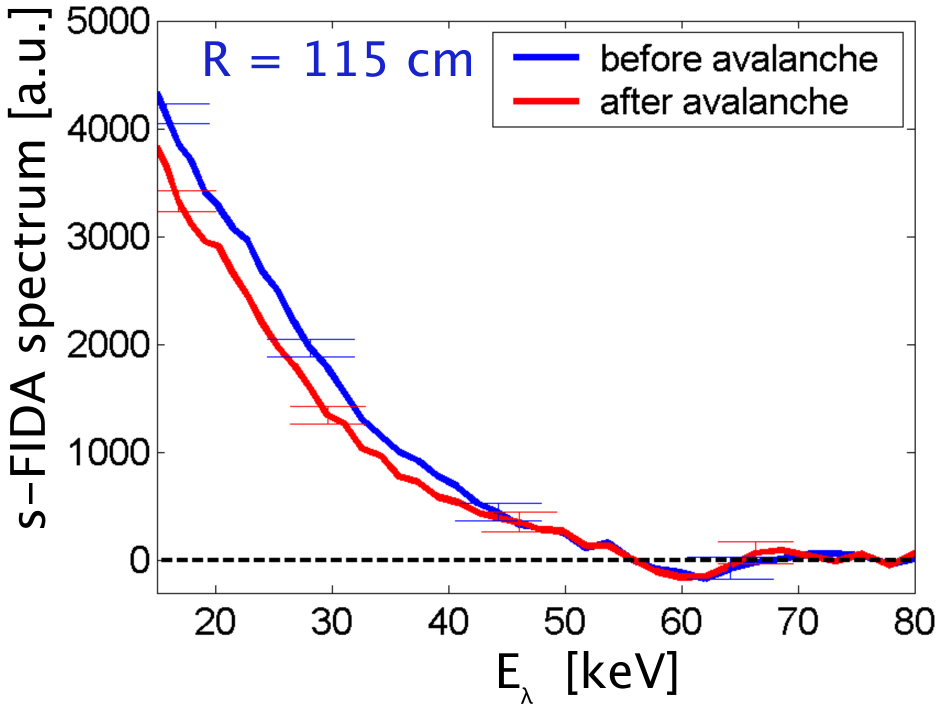


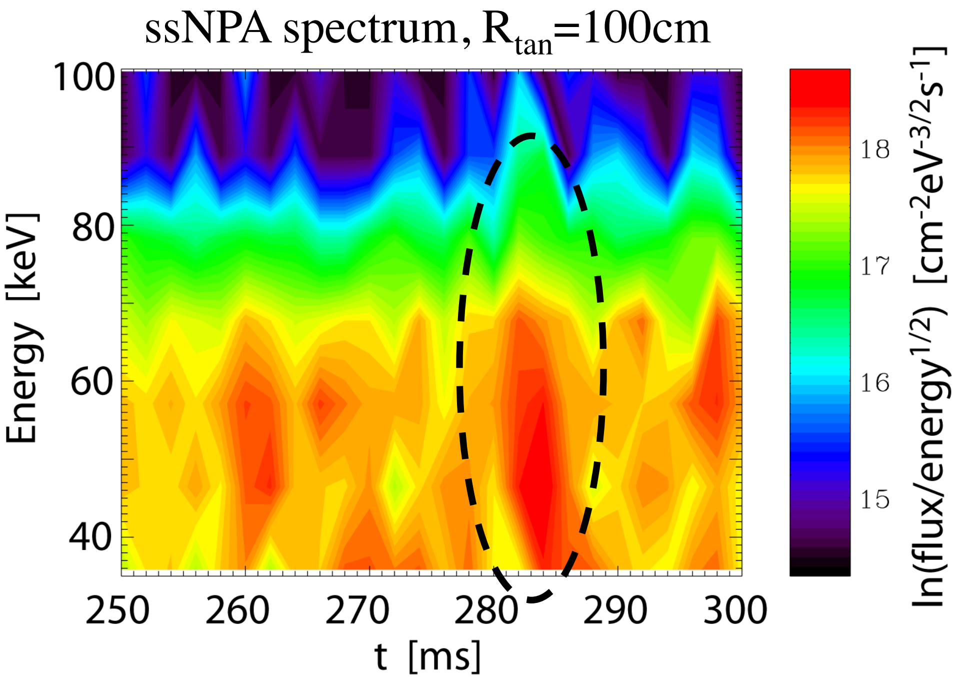
after avalanche

before avalanche

s-FIDA spectra show depletion over broad range of energies

- Similar behavior on all channels
- ssNPA also detects lost fast ions with energy up to injection energy (75keV)
- Fast-ion losses from sFLIP observed at injection energy only



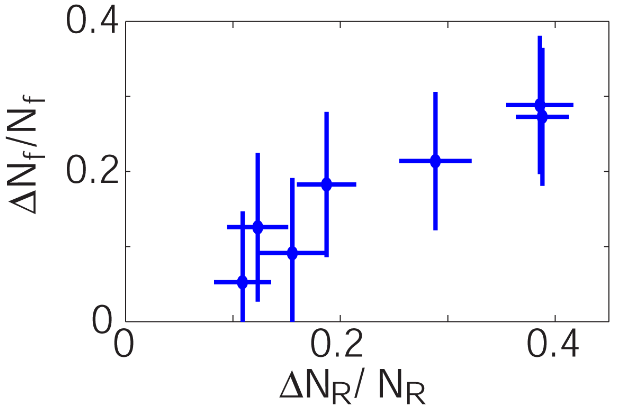


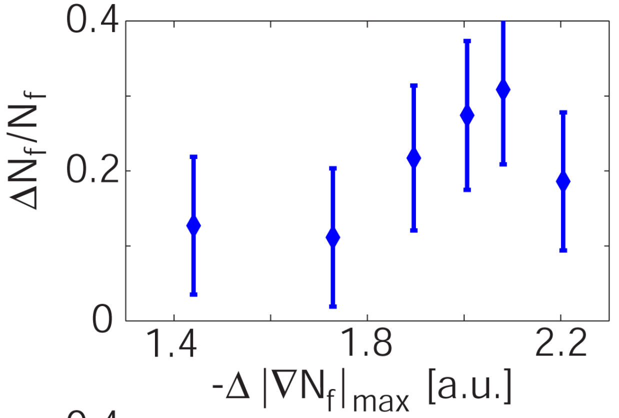
Avalanches lead to gradient relaxation and outward shift of steepest gradient location

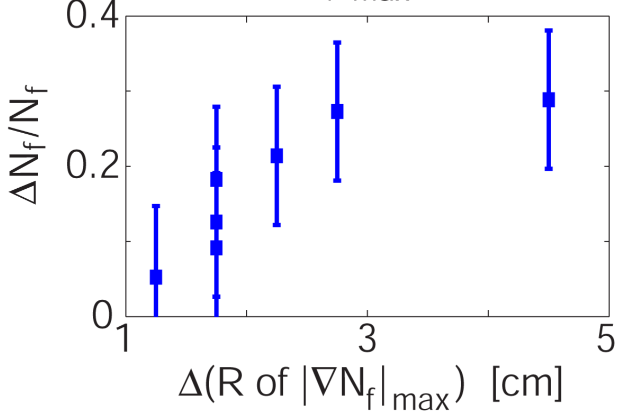
- Good agreement between fractional losses from neutrons, $\Delta N_R/N_R$, and s-FIDA, $\Delta N_f/N_f$ (sum over radius)

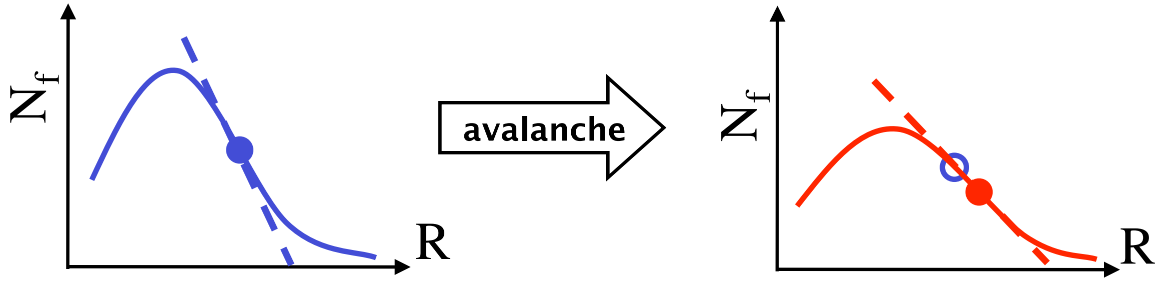
Δ : after avalanche – before avalanche

- Radial gradient at low-field side decreases ⇨ TAE drive reduced
- *Position* of maximum gradient (absolute value) shifts outward
- Trend: larger losses ⇨ stronger relaxation





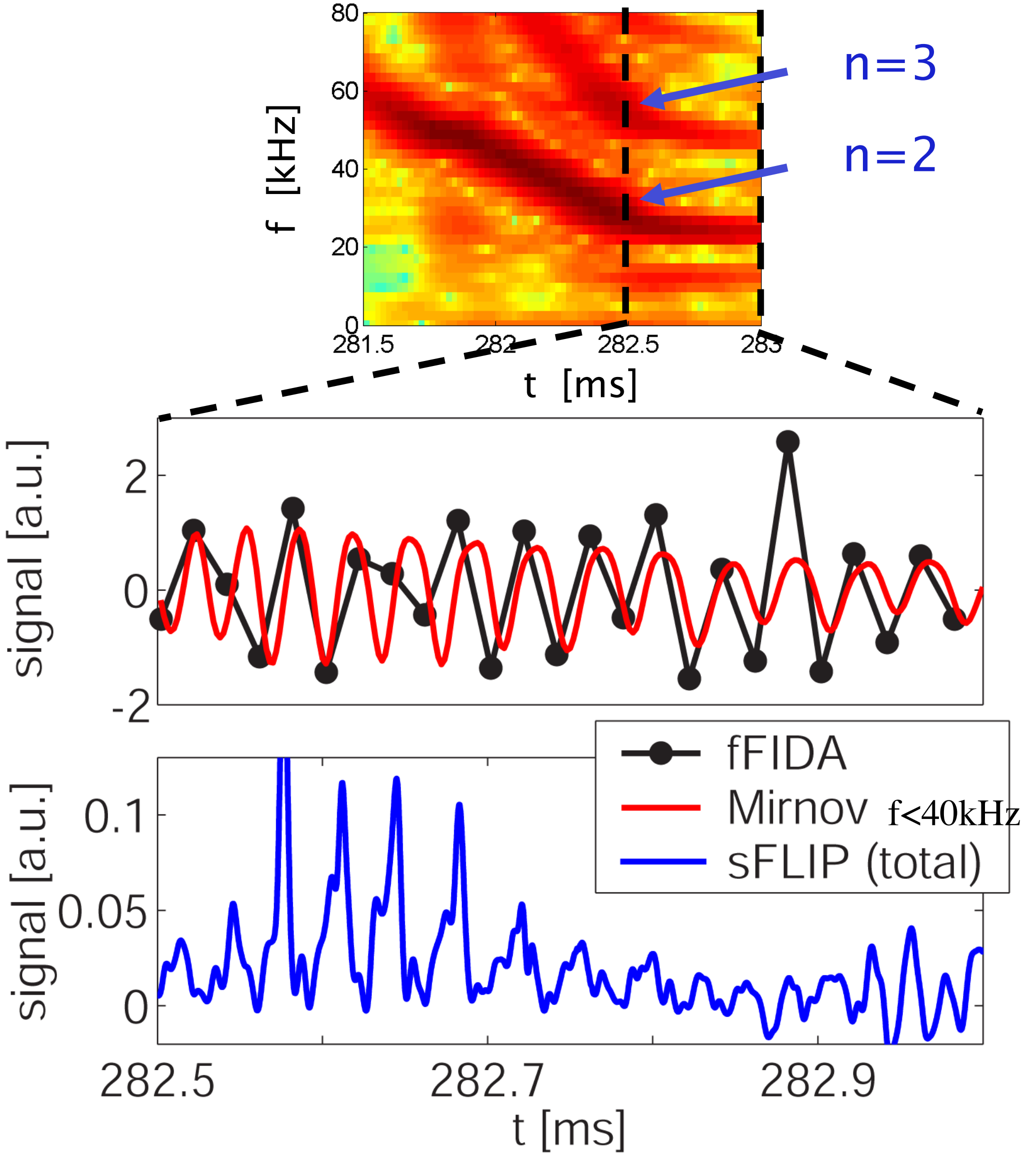




Dynamics preserved on short time-scales?

High temporal resolution data shows correlation with neutrons, magnetics and fast ion losses at the edge

- f-FIDA: fluctuation at f~25kHz in N_f
  - R=120cm, $f_{sampling}$=50kHz
- sFLIP: similar modulation in fast-ion loss signal
  - Edge, $f_{sampling}$=5MHz
  - Total signal integrated over energy and pitch angle
- Frequency down-chirp 60→25kHz observed



n=2 dominant mode strongly interacting with fast-ions

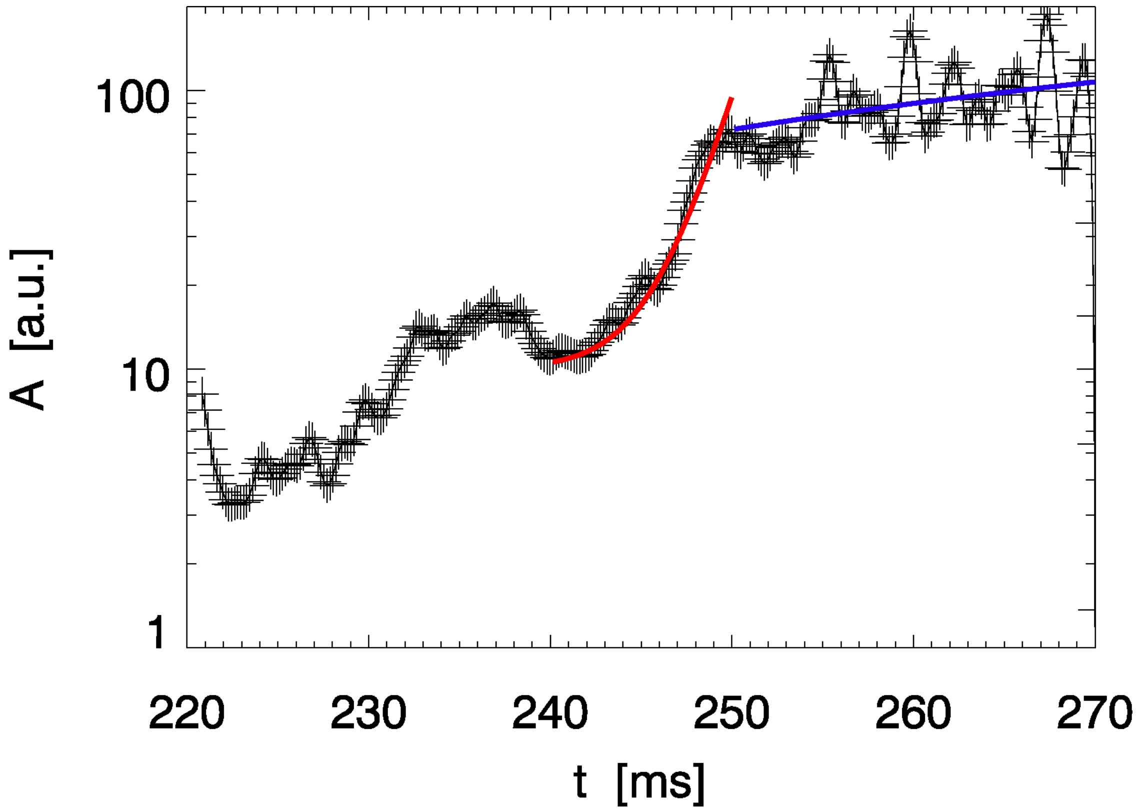
Can the observed features be satisfactorily modeled?

Two main subjects

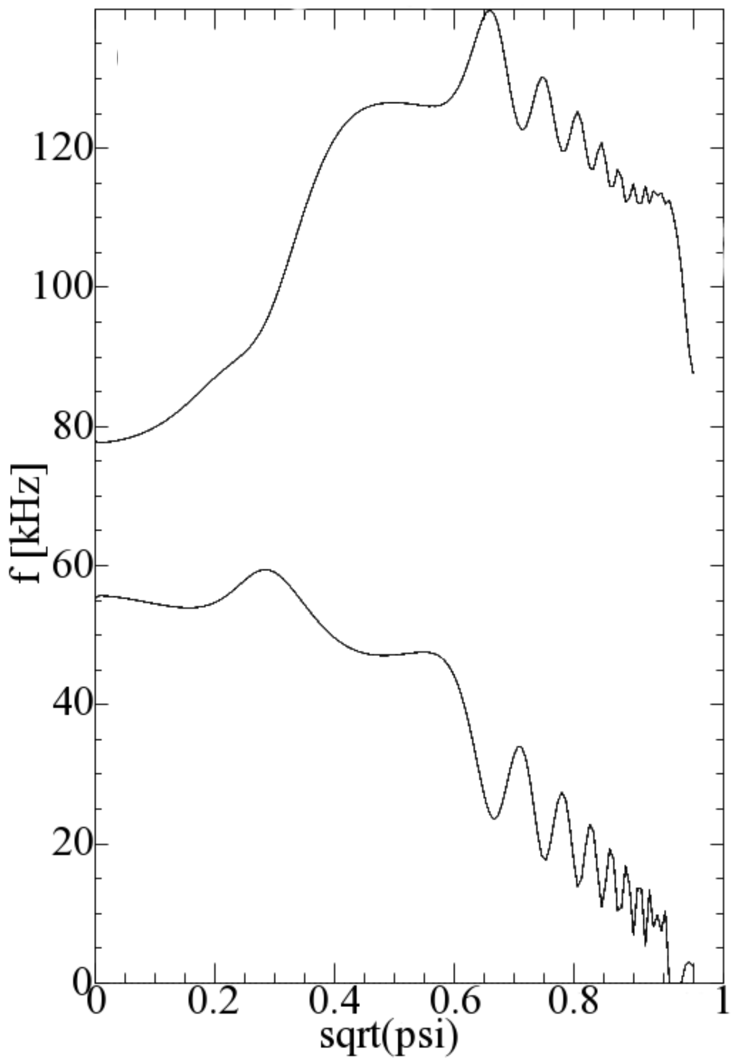
- Fast ion losses by avalanches → see E. Fredrickson's poster
- Analysis of TAE stability and temporal evolution
  - Focus on the conditions that lead to *avalanches*
  - Compare predictions from linear MHD stability analysis code NOVA-k with observed evolution of TAEs
    - Can we understand/explain the experimental data?
    - Do we get qualitative agreement, e.g. on mode structure?
    - Do we get quantitative agreement, e.g. growth/damping rates?

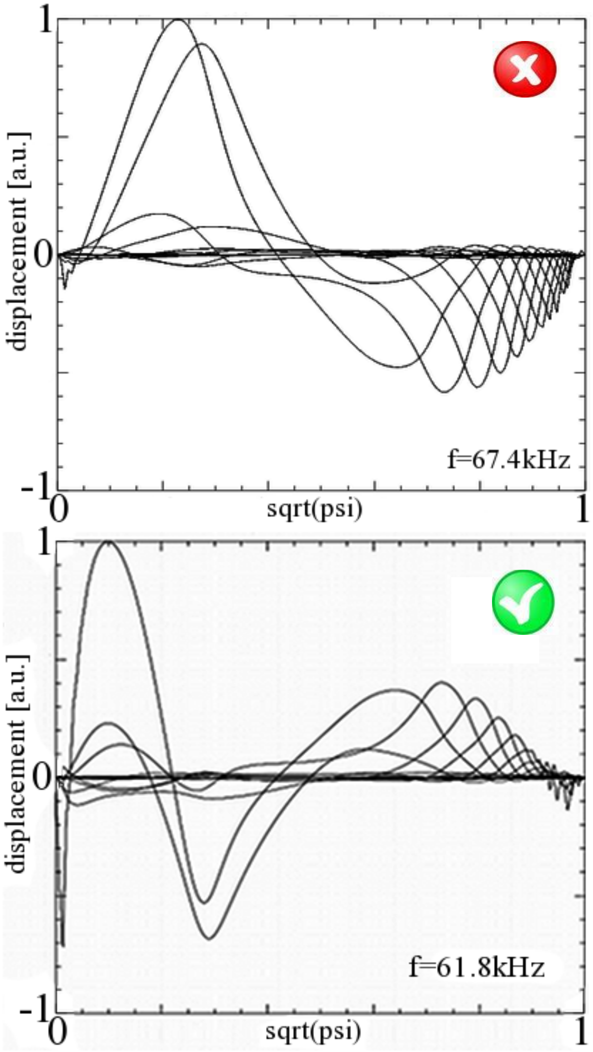
Temporal evolution of dominant n=2 mode

- Destabilized at t~225 ms
- Initial growth, but mode amplitude is quasi stationary
- Second NB turn on at t=240 ms
- Rapid growth up to t=250ms
- More turbulent dynamics
  - Amplitude bursts
  - Frequency chirps
- Mode terminates into avalanche at t=282ms



Select mode(s) on the basis of frequency consistency and data from multi-point reflectometer



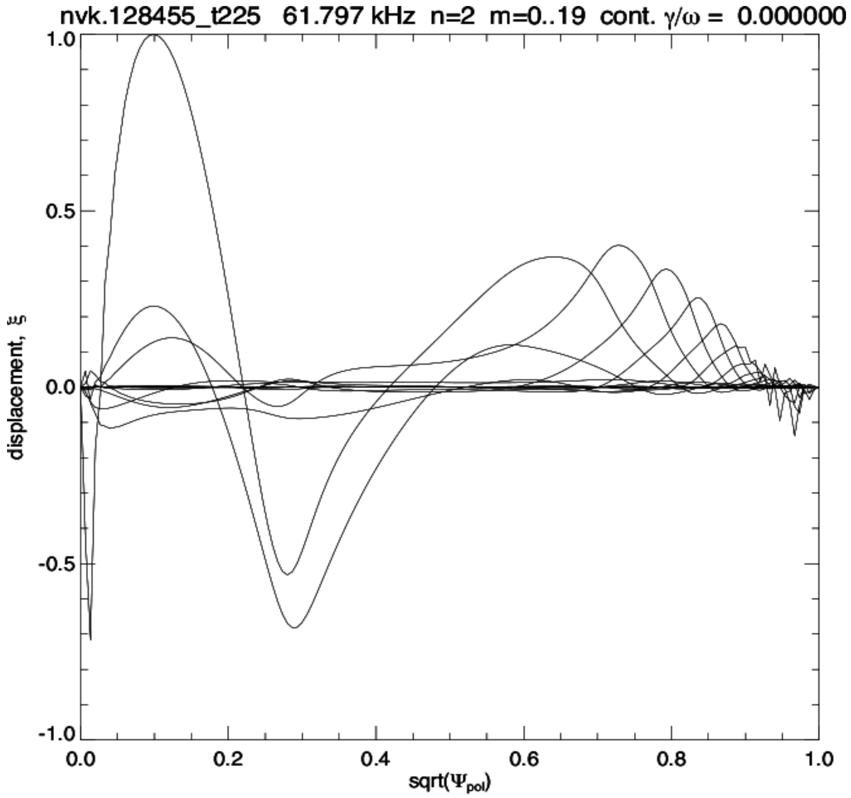


Focus on t=225ms: must find marginally unstable mode

Reflectometer indicates two phase (sign) inversions in eigenmode structure

Mode at f=61.8kHz is best candidate for measured mode

Calculate stability (NOVA-K) and compare with experimental observations



t [ms]	γ_L/ω	γ_D/ω
225	2.17%	2.22%
245	2.03%	2%

- Mode stable at t=225ms, unstable at t=245ms, but...
- Difference between growth and damping rates is within NOVA-K uncertainty

- Radiative & electron collisional damping neglected
  - Treatment in NOVA-K not adequate for highly shaped plasmas; some effects due to large fast ion Larmor radius not included
- Unusual plasma composition
- Spatial dependence of pitch neglected in beam ion distribution

Summary

- Up to 35% of fast-ion **losses** induced by TAE avalanches on NSTX
- Whole *$N_f(R)$* involved: **relaxation** of fast-ion profile
- **Depletion** in fast-ion spectra over broad energy range
- Strong **interaction** between modes and fast ions during avalanche (FIDA, sFLIP)
- **Comparison** with *linear* MHD theory ongoing
  - Stability results compatible with experiments
  - Need to address open issues in modeling for quantitative comparison

Backup viewgraphs

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

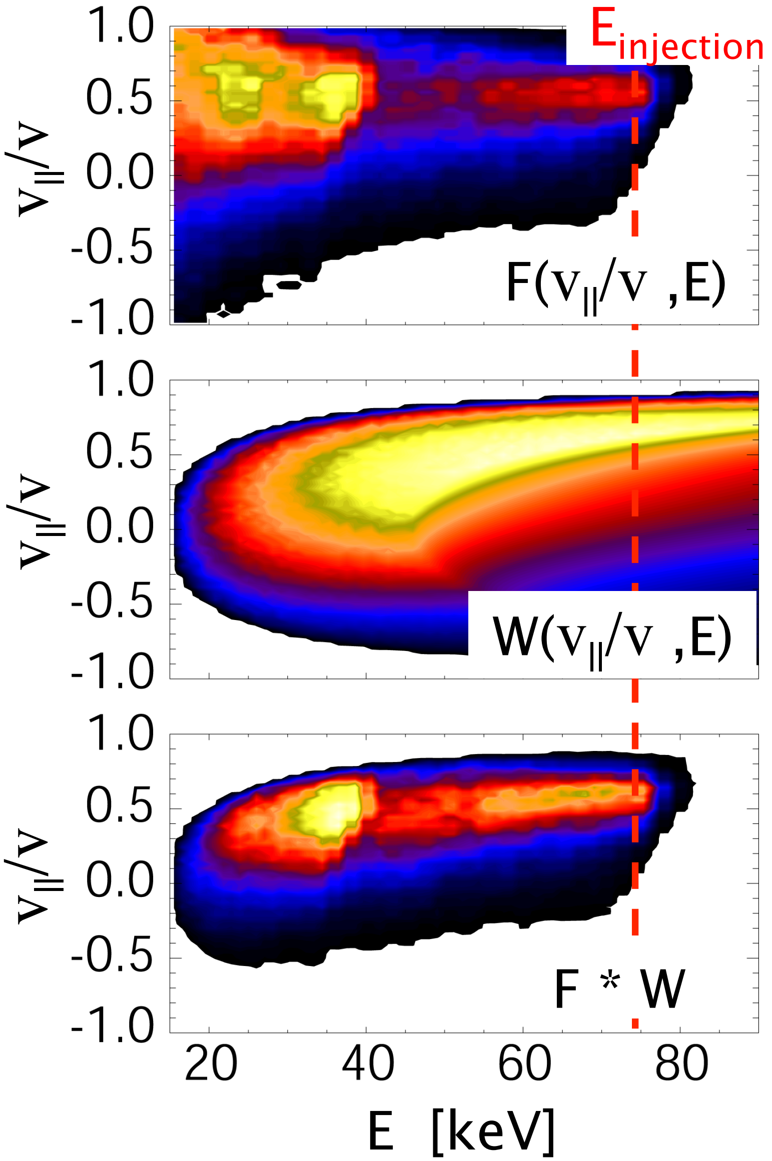
$W(v_{||}/v,E \mid \underline{g}_i)$: weight function

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

λ : wavelength from Doppler shift formula

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

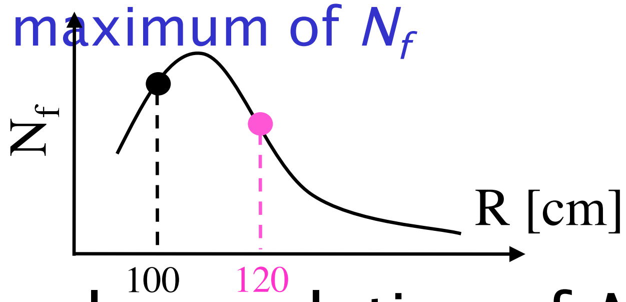
- **FIDA density,** N_f ($\propto$fast-ion density) obtained by integrating spectrum over energy E_λ and taking into account local neutral density in W
- **Vertical views:** signal weighted toward perpendicular velocities
- **$s_{tot}=s(\lambda) + B(\lambda)$: Background** $B(\lambda)$ is main source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



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

High temporal resolution data shows correlation with neutron rate and fluctuations from magnetics

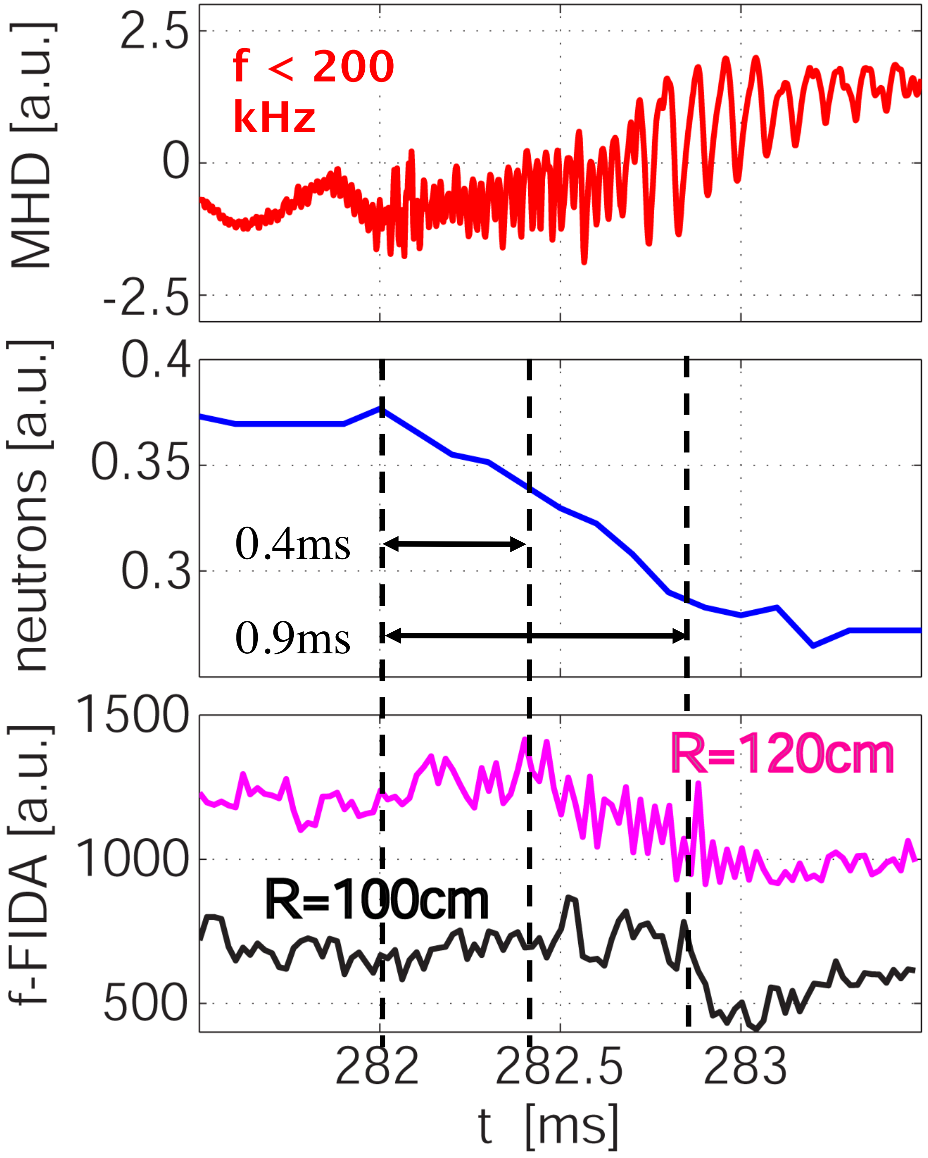
- f-FIDA: different features at **R=100cm** and **R=120cm**, e.g. *delay* compared to neutrons
  - On opposite side with respect to maximum of N_f



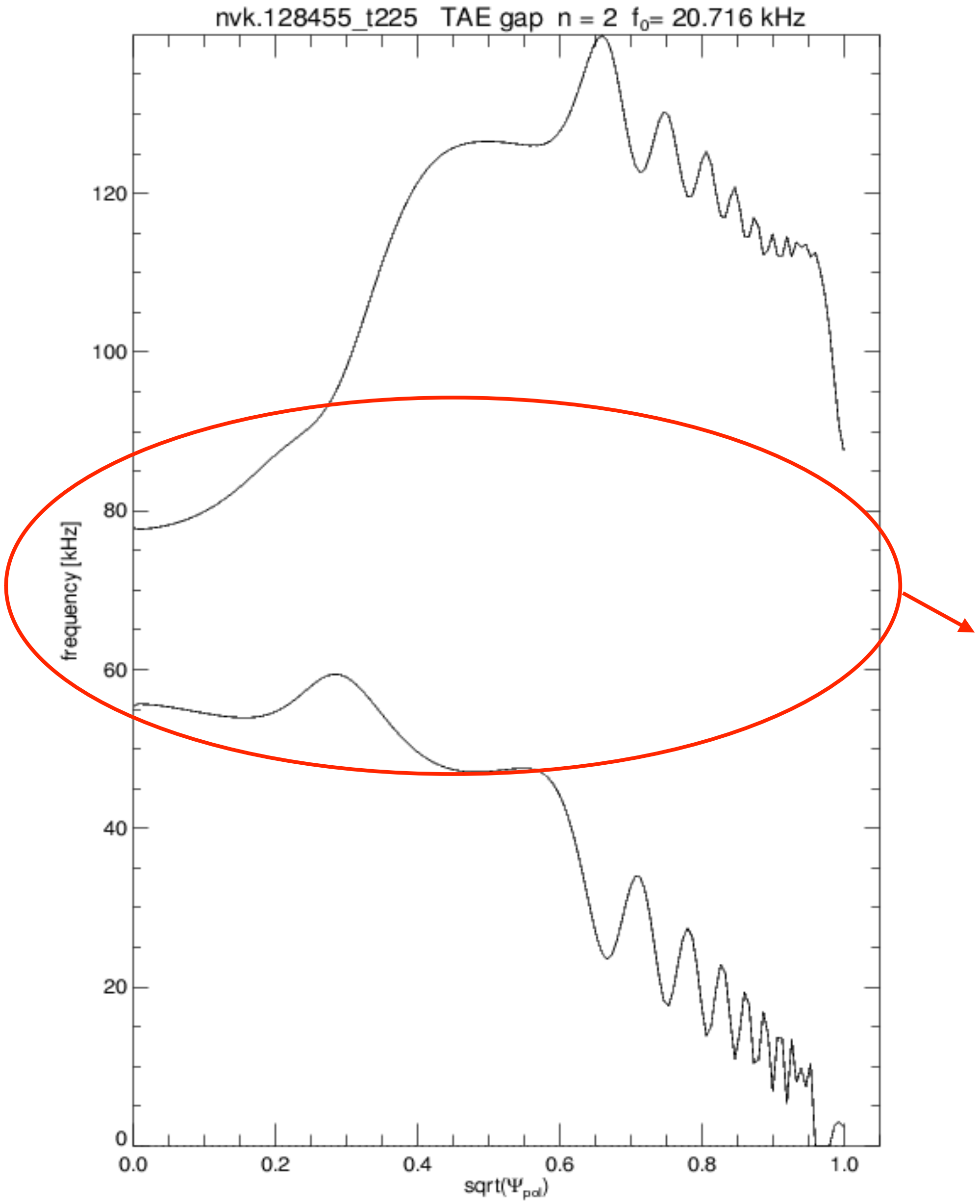
⇨ Complex evolution of $N_f(R)$ on short time-scales

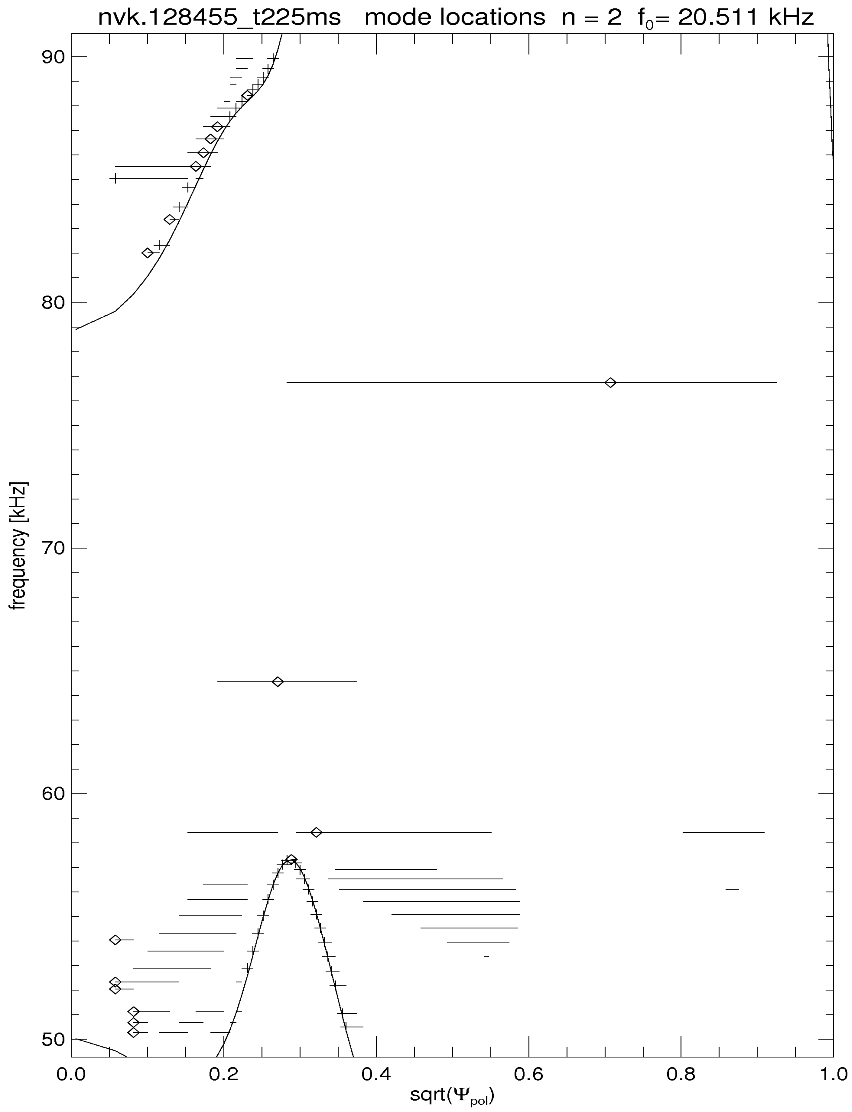
- Mode visible on **outward channel** only

Do measured fluctuations correlate with losses (sFLIP)?

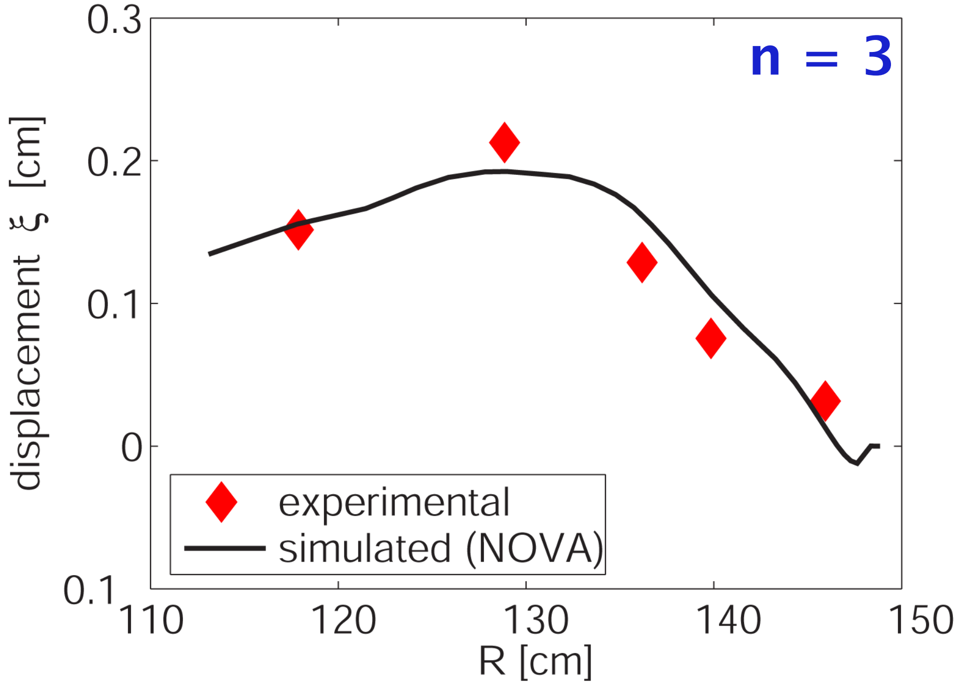


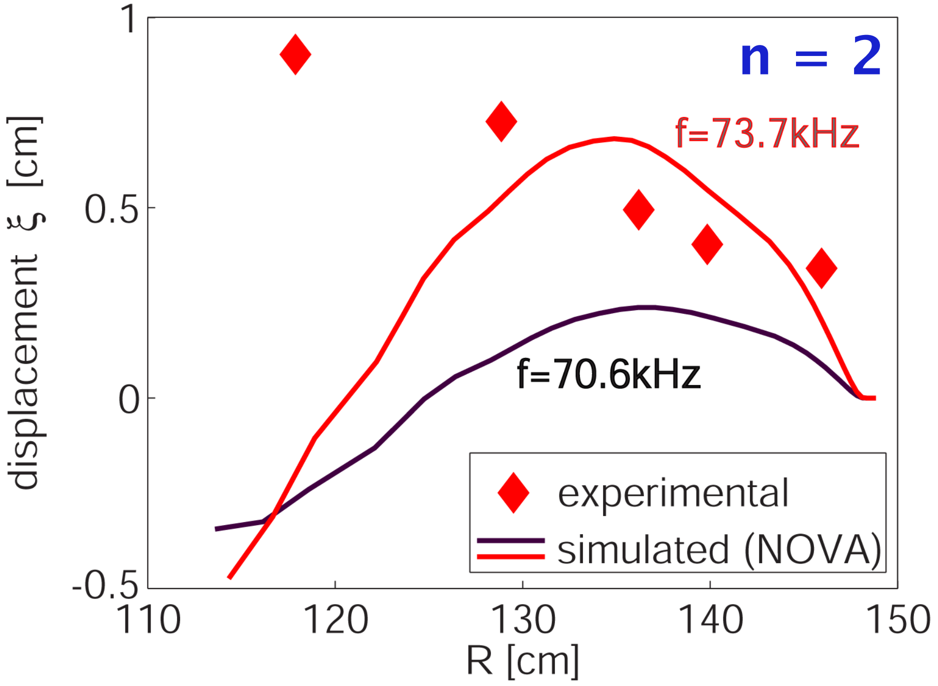
NOVA-K results for continuum and *AE modes at t=225ms





Reflectometer and NOVA-k eigenfunctions agree for n=3 mode, but comparison fails for (dominant) n=2





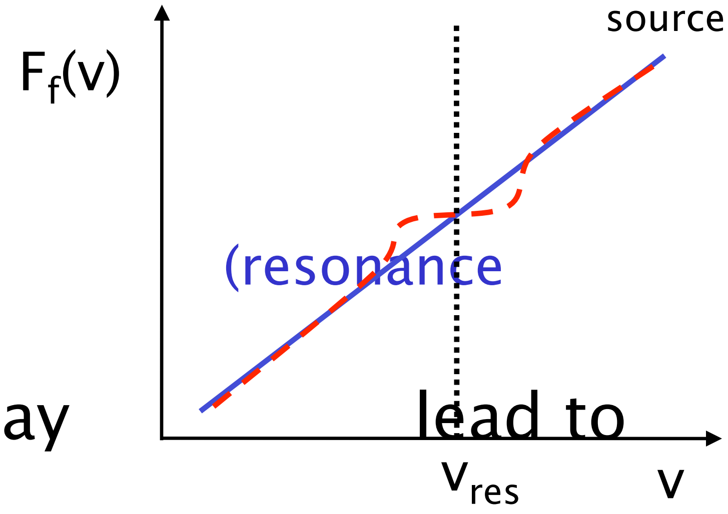
- Other cases with lower (15%) losses show good agreement for eigenfunctions [See E. Fredrickson, **NP6.095**]
- Here strong *f* down-chirp, 40% losses: non-linearities important

Need to assess reason(s) for discrepancy to proceed with comparison between theory and experiments

Weak turbulence theory

Berk *et al.*, PoP **3** (1996)

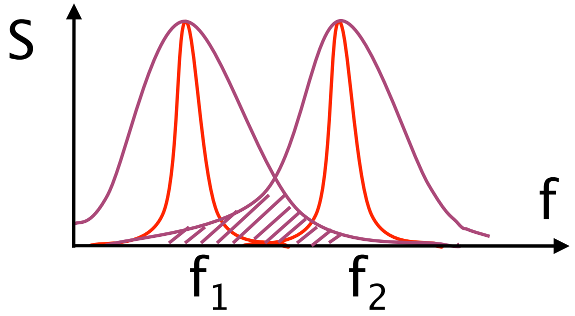
- Predict non-linear response of driven systems
- Based on *bump-on-tail* problem, extended to other drive mechanisms (gradients in phase space)
- Time scales involved:
  - growth rate, γ_L
  - damping rate, γ_D
  - effective scattering rate, ν_{eff} (resonance decorrelation)
- Competition of drive/damping may lead to different regimes:
  - steady-state ⇒ chaotic (oscillatory) ⇒ chaotic (blow-up in finite time)

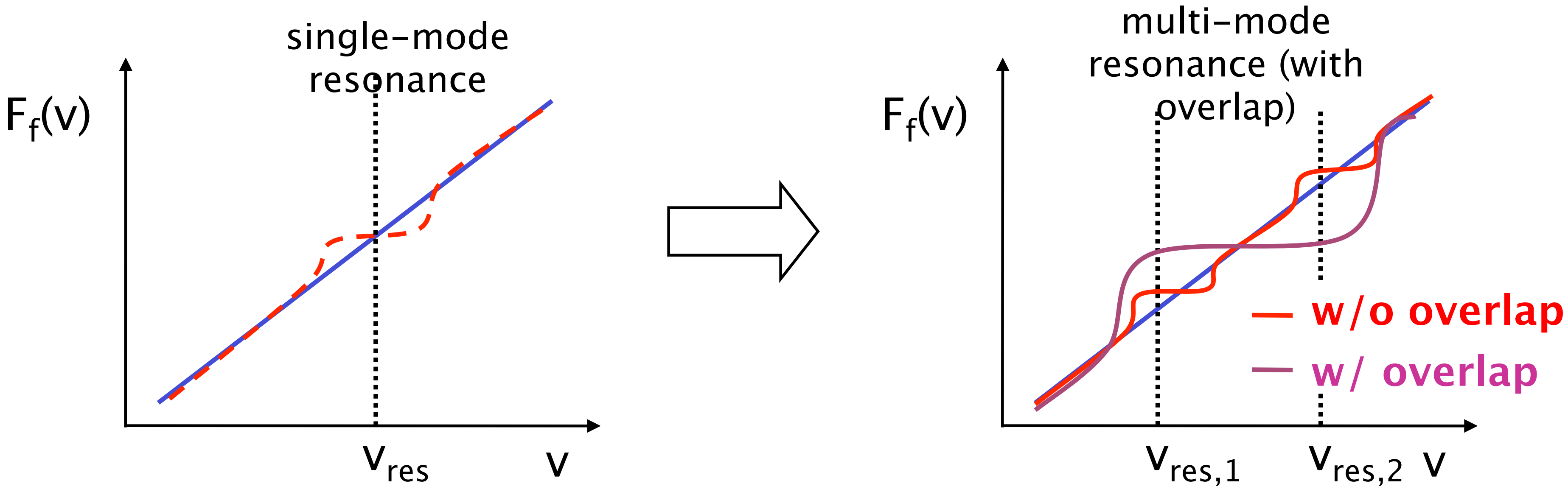


Multi-mode resonance overlap

Berk *et al.*, PoP **3** (1996)

- Spectrum of *discrete* modes, e.g. TAEs
- Broadening of phase-space region affected by resonances
  - Stochastization of phase space
- Enhanced free energy availble
  - Increase of saturation level
  - Enhanced transport in real space
- Non-linear saturation level increases





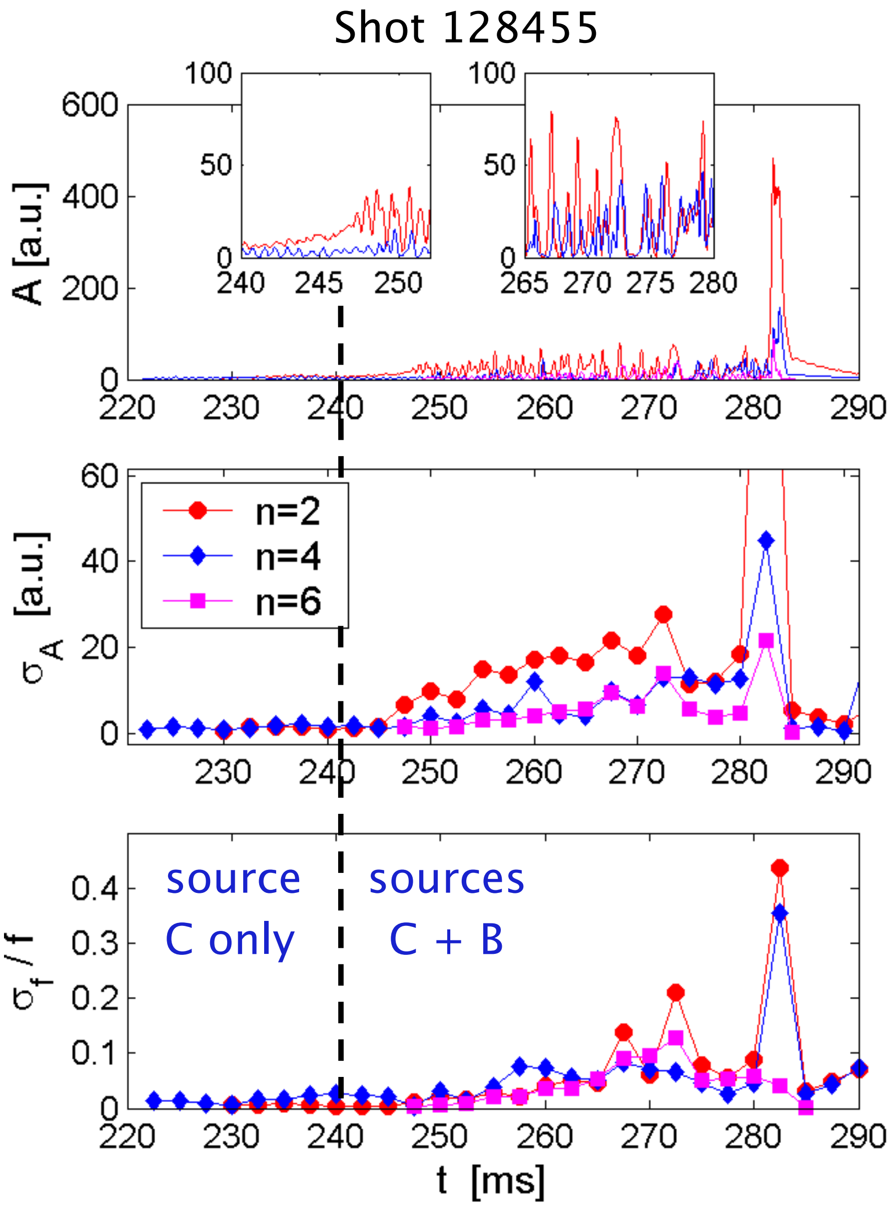
Dynamics of modes suggests transition between turbulent regimes before avalanches

- Track amplitude and *rms* value of fluctuations in *A* and *f*
  - Data binned over 2.5 ms

- As source B turns on, drive for TAEs increases
  - First, amplitude increases but σ_A, σ_f remain small (t < 248ms)
  - Then, quasi-periodic variations of *A* and *f* (248 ms< t <275 ms)

⇒ onset of weekly turbulent regime

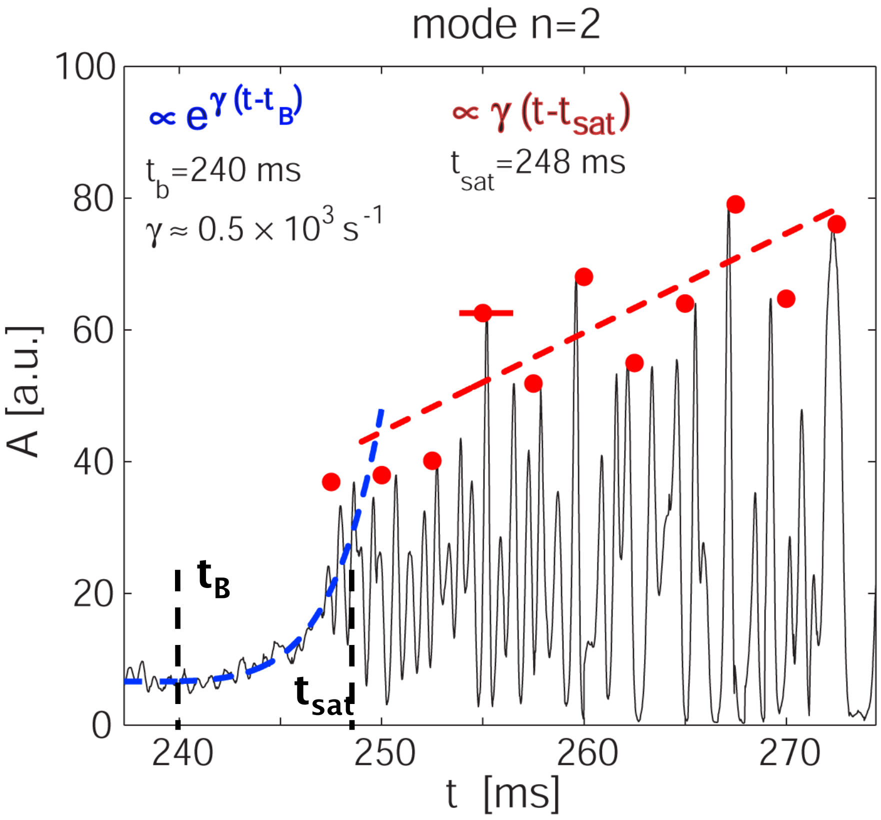
  - Finally, bursty *A* and *f* just before avalanche (t >275 ms)


Shot 128455

Initial growth consistent with increase of drive, then more turbulent dynamics develops

- Exponential growth for t< 250 ms
- Complex dynamics for t > 250 ms

- Competition between drive, damping and off-the-resonance scattering rate may explain this dynamics
  - Time scales:
    - slowing down of beam ions ~30ms
    - linear drive and damping γ_L, γ_D



Can obtain quantitative comparison with theory ?

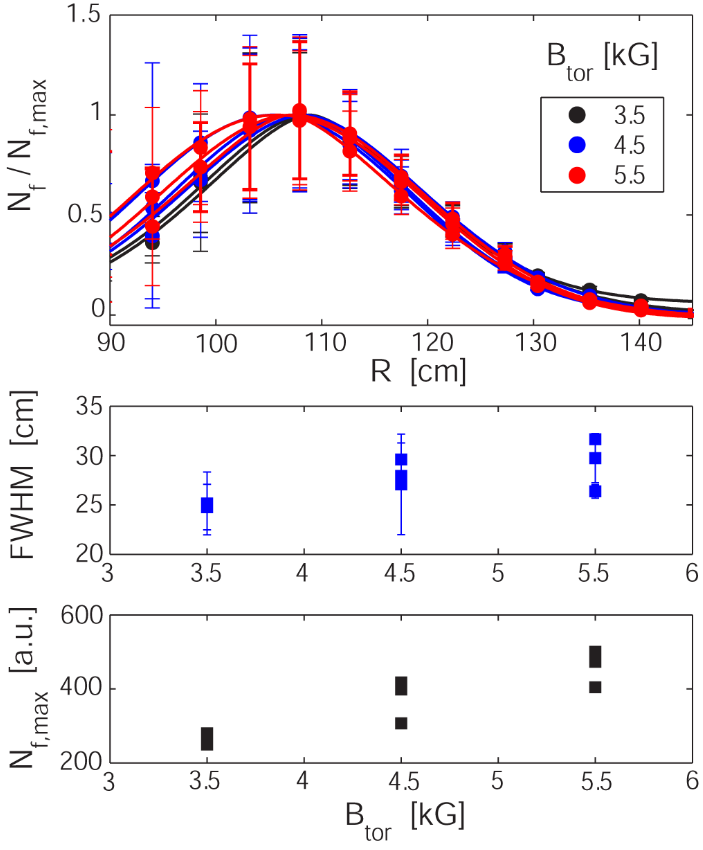
TAEs and avalanches more easily destabilized for higher magnetic field

- Fast-ion density profile broadens, maximum level increases

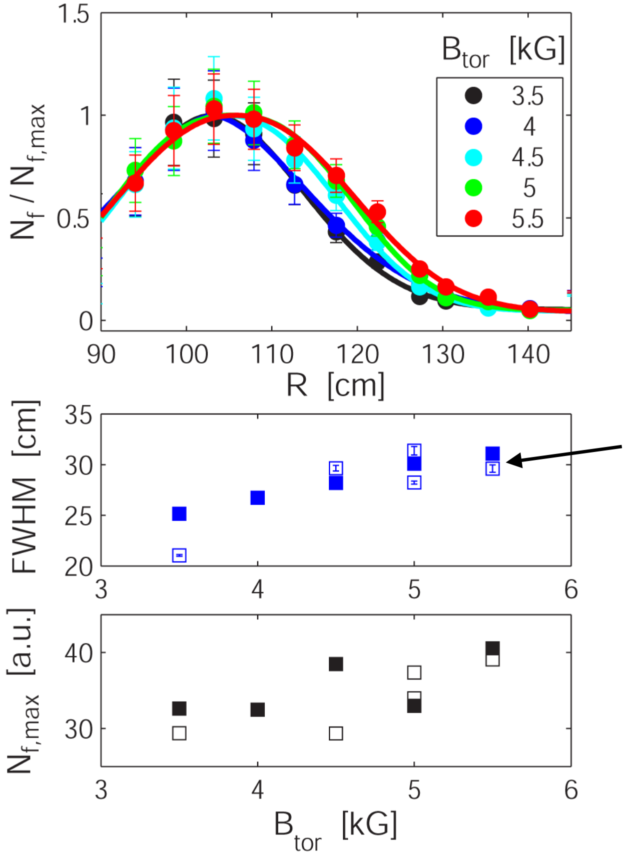
  ⇒ N_f can provide stronger drive for TAEs

Helium plasma, L-mode

(TAE avalanches scenario)



Deuterium plasma, H-mode



Open symbols: different density

Abstract

Toroidicity-induced Alfvén eigenmodes (TAEs) can redistribute fast ions in velocity and real space, thus degrading fusion and current drive efficiency in devices such as ITER. TAEs naturally occur in beam-heated NSTX plasmas, making it a suitable environment for fast ion studies. Space and energy resolved measurements of fast-ion dynamics during TAE activity are presented. Modest changes in the radial fast ion profile, $n_f(R)$, correlate with TAEs for multiple quasi-stationary modes. As the injected neutral beam power is increased above a critical threshold, TAEs start interacting non-linearly, and eventually terminate in *avalanches*. A decrease in $n_f(R)$ is observed. A depletion of fast ions with energy >20keV, leading to drops of up to ~40% in the neutron rate over ~1ms during such avalanche events, is measured. The conditions that lead to TAE avalanches are investigated. Properties of the unstable modes (mode structure, linear growth/damping rates) are calculated via the NOVA-k code, and benchmarked against the temporal evolution of TAE structure and amplitude measured by reflectometers and Mirnov coils. Growth and damping rates are calculated on the basis of the fast ion profile, as predicted by the TRANSP equilibrium code. Space, time and energy resolved measurements from FIDA are complemented by data from neutral particle analyzers, a scintillator-based fast-ion loss diagnostic and neutron detectors.

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