NSTX PPPL Princeton Plasma Physics Laboratory

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Characterization of chirping TAE modes on NSTX

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- *U Quebec*

Abstract

The interaction of multiple TAE modes with a background population of fast ions can lead to large losses of fast ions from the core plasma. For future reactors such as ITER, this may result in a decreased fusion efficiency and potential damage to in-vessel components. A deeper understanding of the physics of TAEs can be gathered from NB-driven plasmas of NSTX, where large (up to 30%) fast ion losses are associated with bursting, chirping TAE activity. This work investigates the main features of the bursting/chirping TAE regime on NSTX. On a time scale greater than the inverse rate of bursts (0.5-1ms), TAEs behave as a set of modes characterized by a similar frequency in the plasma frame and similar spatial localization. The detailed dynamics on shorter time scales can be different for each mode. Chirps are usually not synchronized among all the modes, except for the larger bursts. Typical frequency excursion during a chirp is O(10%) of the mode frequency. In general, the modes exhibit increasing amplitude and frequency excursions when the drive for TAEs, e.g. parametrized through the injected NB power, is increased. Higher plasma densities for a fixed injected NB power lead to a reduction of mode activity for all the modes. Recent results from NSTX will be presented and discussed.

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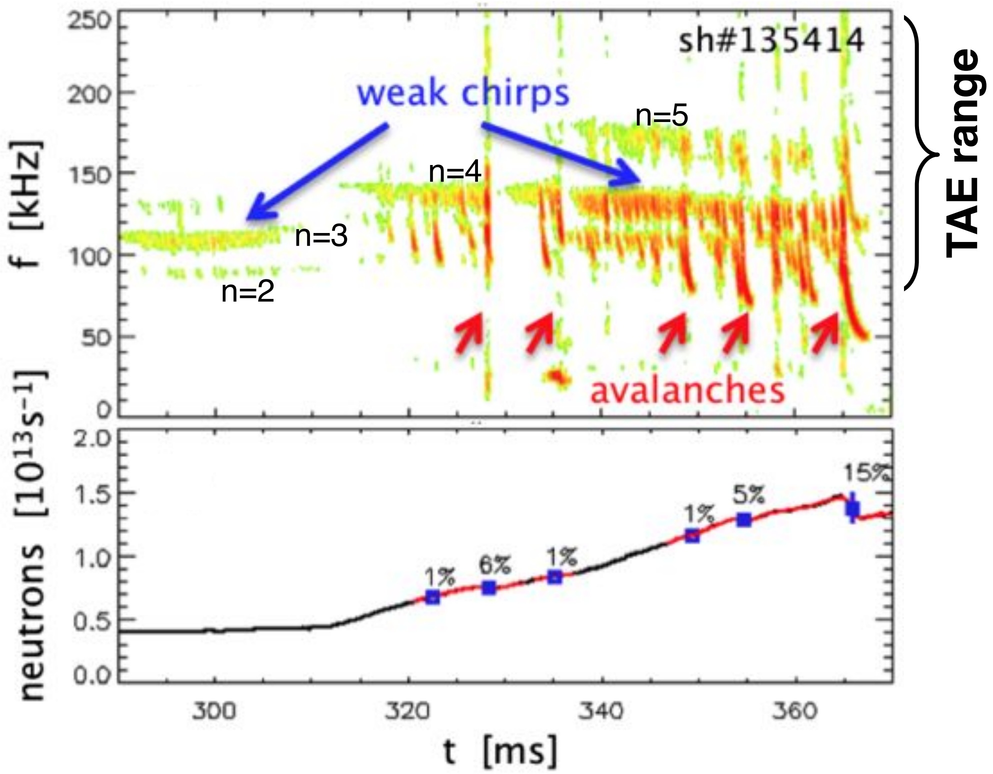
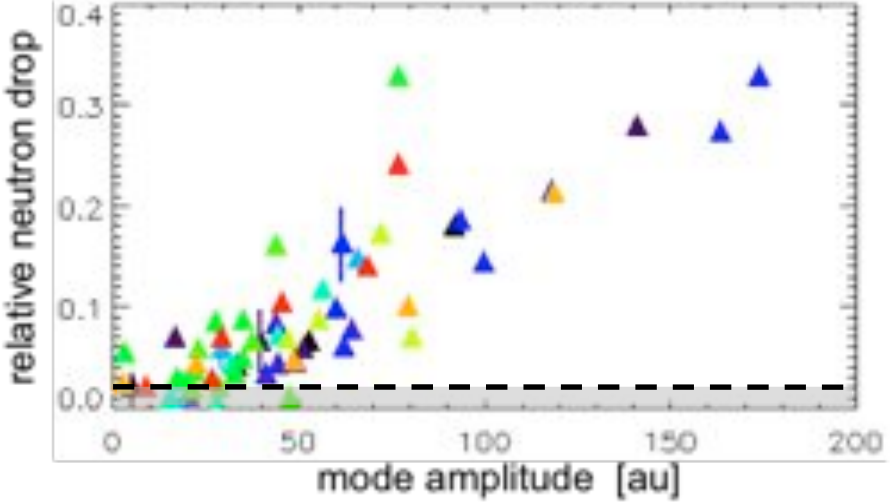
Bursting toroidicity-induced Alfvén eigenmodes (TAEs) can lead to enhanced fast-ion transport

- Multiple TAEs can be simultaneously destabilized
  - Possible overlap of many resonances in phase space
  - Non-linear development into “TAE ***avalanches***” -> fast ion losses

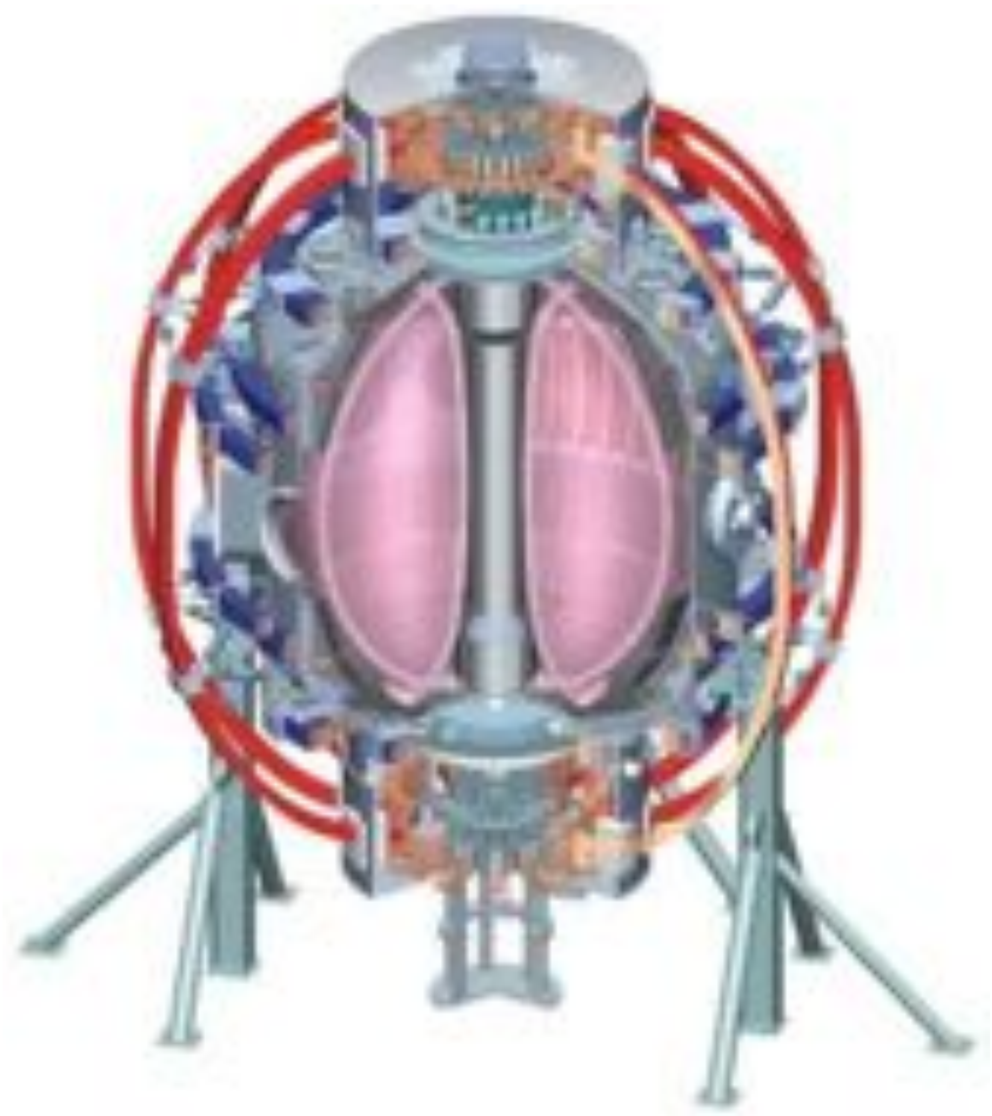


NSTX data (Colors indicate different shots)



Need to understand the physics of bursting TAEs, improve predictive capability

NSTX parameters



Major radius	0.85 m
Aspect ratio	1.3
Elongation	2.7
Triangularity	0.8
Plasma current	~1 MA
Toroidal field	<0.55 T
Pulse length	<2 s

3 Neutral Beam sources

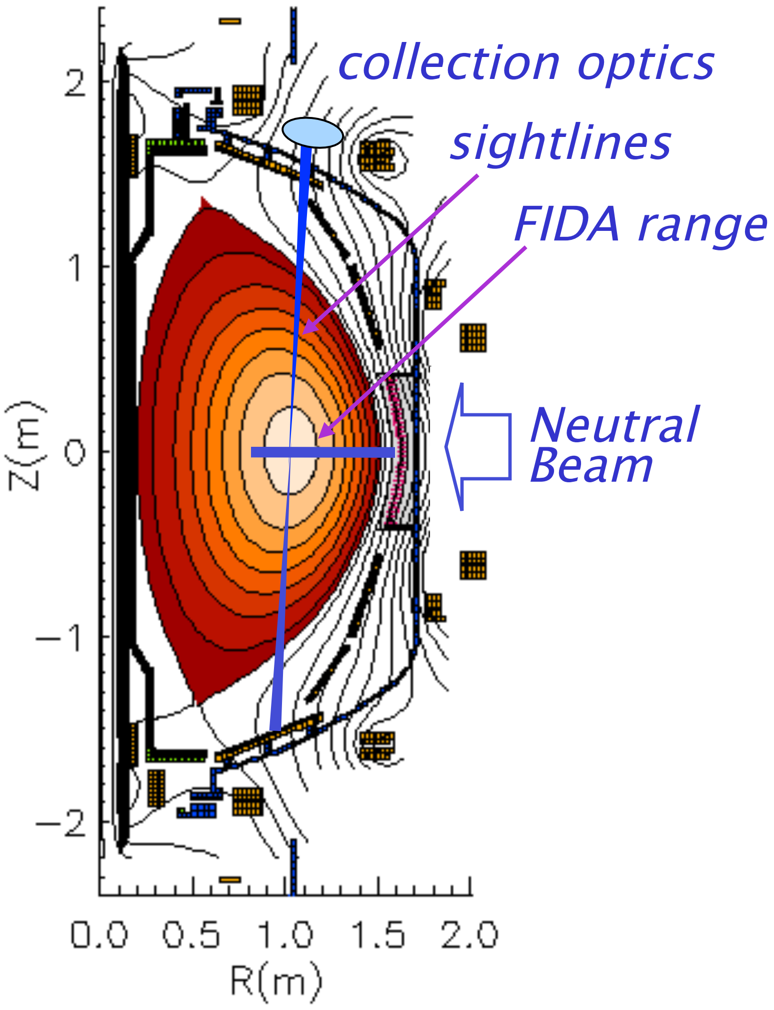
$P_{NBI} \leq 6$ MW, $E_{injection} \leq 95$ keV

⇨ $1 < v_{fast}/v_{Alfvén} < 5$

This work:
Focus on TAEs in L-mode plasma
Center-stack limited
Deuterium plasma
B_{tor}=0.55 T, I_p=0.7-0.9 MA

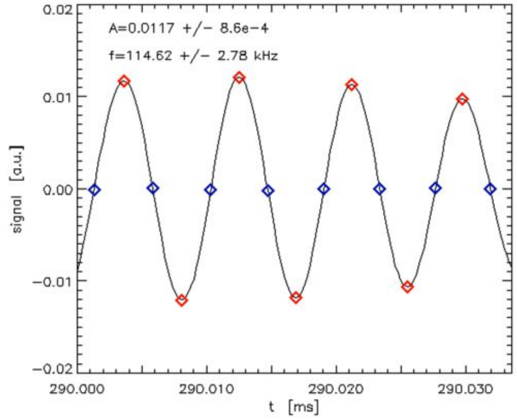
Mode activity and fast ion diagnostics on NSTX

shot#135404, t=320 ms



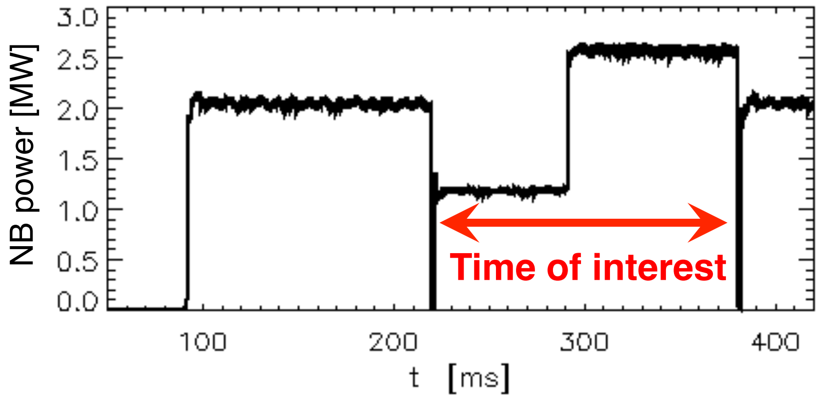
- Mirnov coils
  - Magnetic fluctuations up to 2.5 MHz
- Multi-channel reflectometer
  - Mode structure (L-mode)

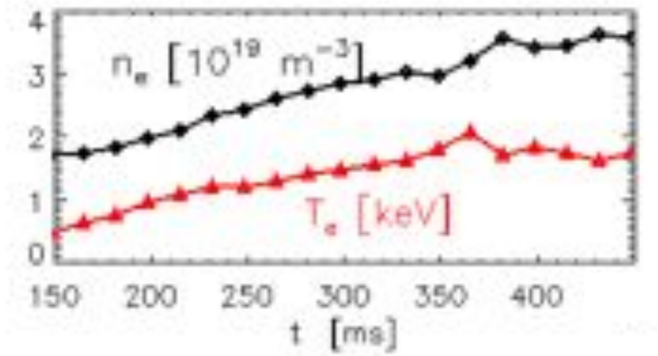
FFT analysis complemented by analysis in time domain to study mode dynamics over short time scale

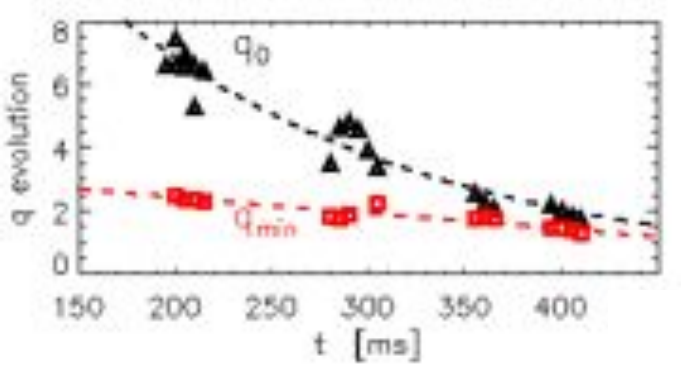


- Fast Ion D-Alpha (FIDA) system
  - Fast ion profile and spectrum through active charge-exchange recombination spectroscopy
  - Weighted toward small pitch (perp. component)
- Neutron rate, NPA, sFLIP

Experimental scenario : $P_{NB}<3MW$, $n_e \sim 3x10^{19} m^{-3}$, $T_i \sim T_e = 1-1.5keV$

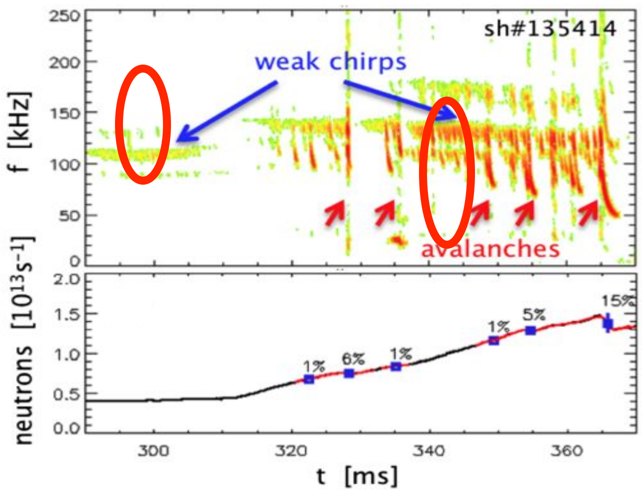


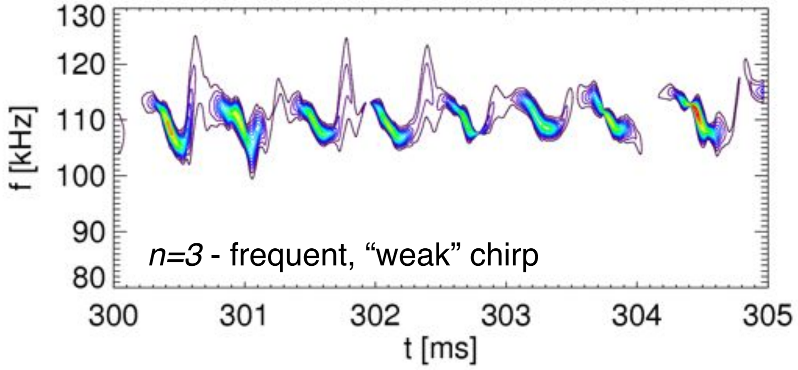


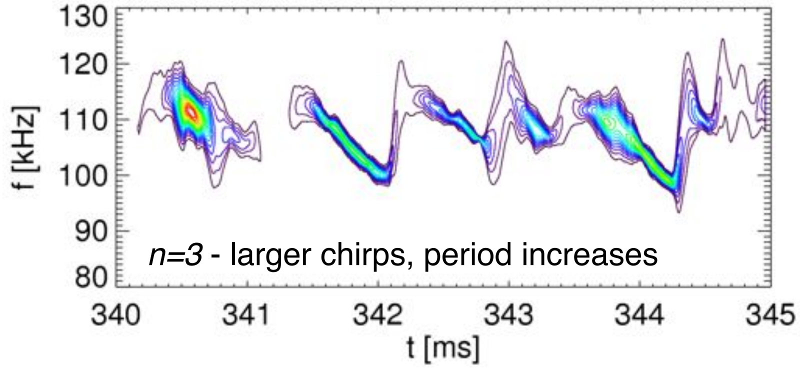


- NB-heated, L-mode plasmas
  - Plasma limited on center-stack
  - NB power and timing varied to affect mode stability
  - Plasma profiles evolving in time
  - Reversed-shear *q* profile
  - Safety factor evolution reconstructed through LRDFIT code constrained by MSE data

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

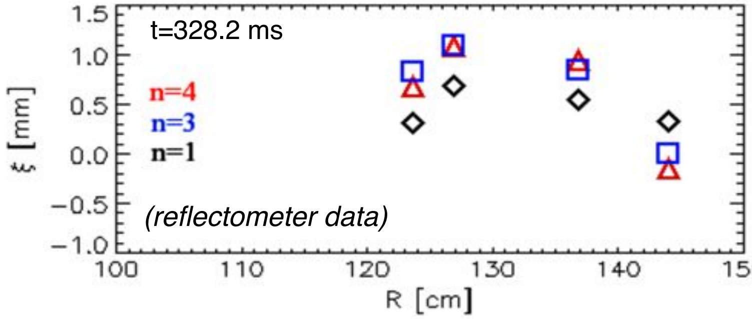






- Modes show more bursting character as discharge evolves
  - NB power increases, fast ion population builds up
- Usually, each mode chirps independently of the others...
- ... but, eventually, *avalanches* occur:
  - Modes lock on similar dynamic, multiple TAEs involved
  - Drop in neutron rate, FIDA

modes have broad radial structure



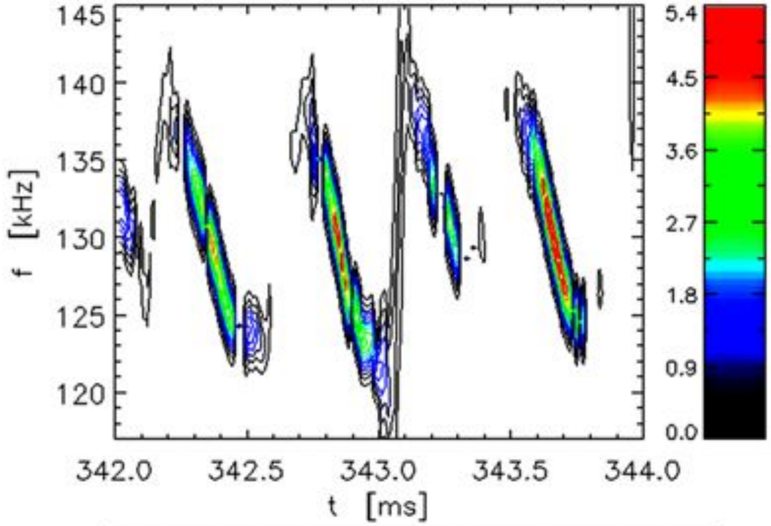
Can TAEs frequency, amplitude evolution be modeled as response of non-linear system?

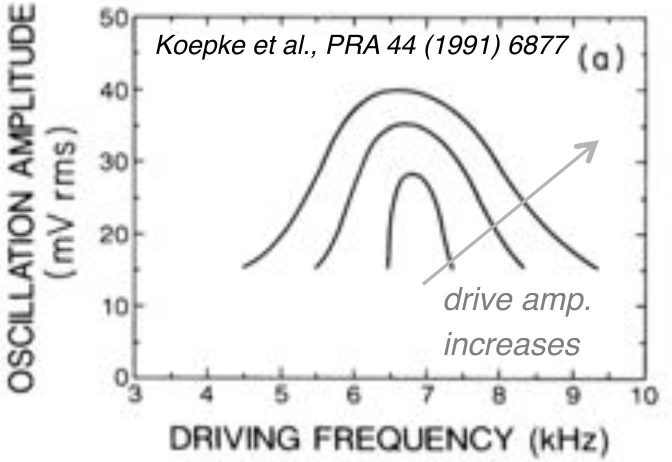
- Evolution of frequency, amplitude reminiscent of *driven oscillator*
- E.g., non-linear Van der Pol oscillator:

$$\ddot{x}-\epsilon(1-\beta x^2)\omega_0\dot{x}+(\omega_0^2+\eta x^2)x=M\omega_0^2\sin(\omega_D t)$$

damping ‘non-linearity’ factor ‘restoring’ term driving force

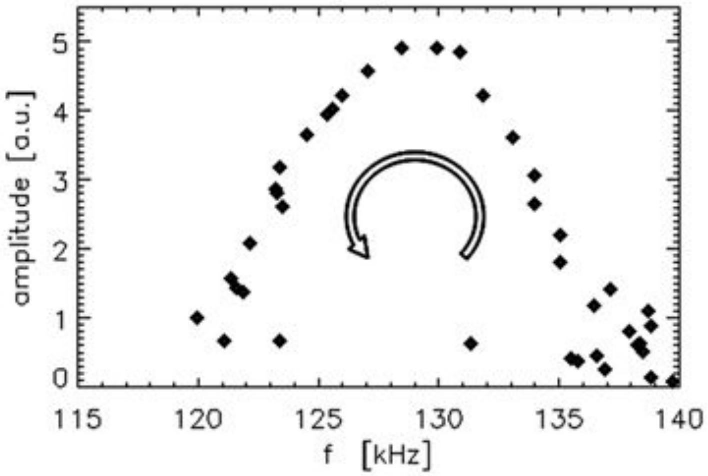
- Can get info on damping, drive (resonant) frequency and their temporal variations?
- Comparison with chirping TAE data under way



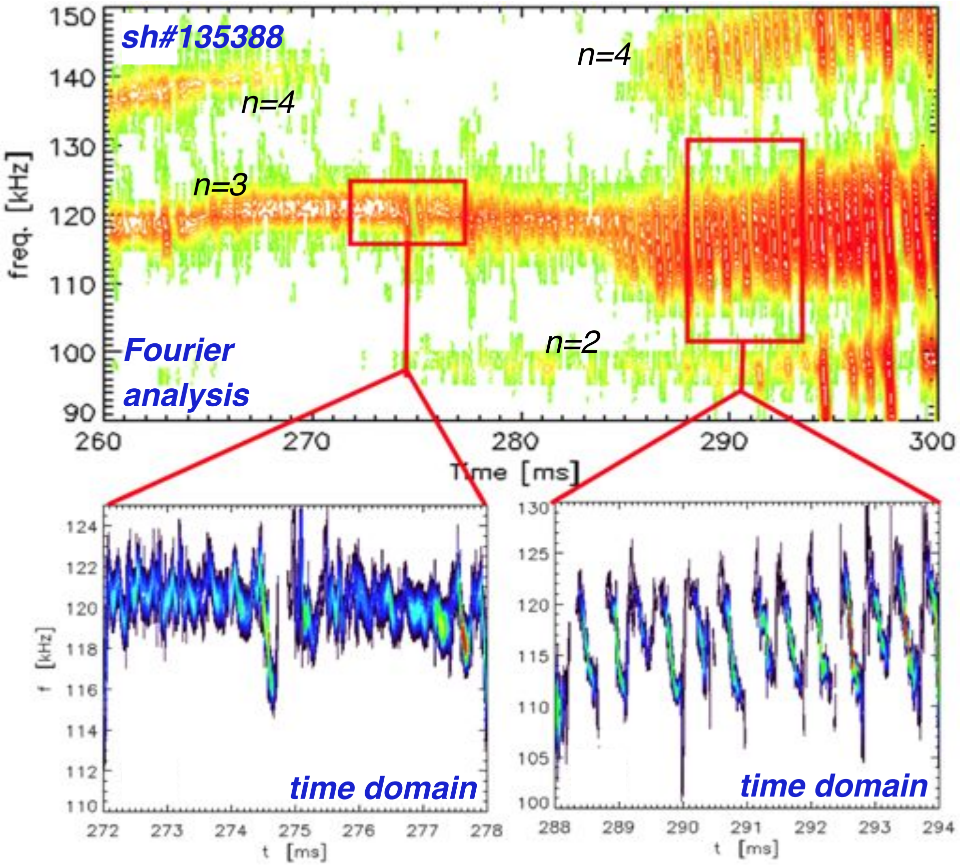

Koepke et al., PRA 44 (1991) 6877

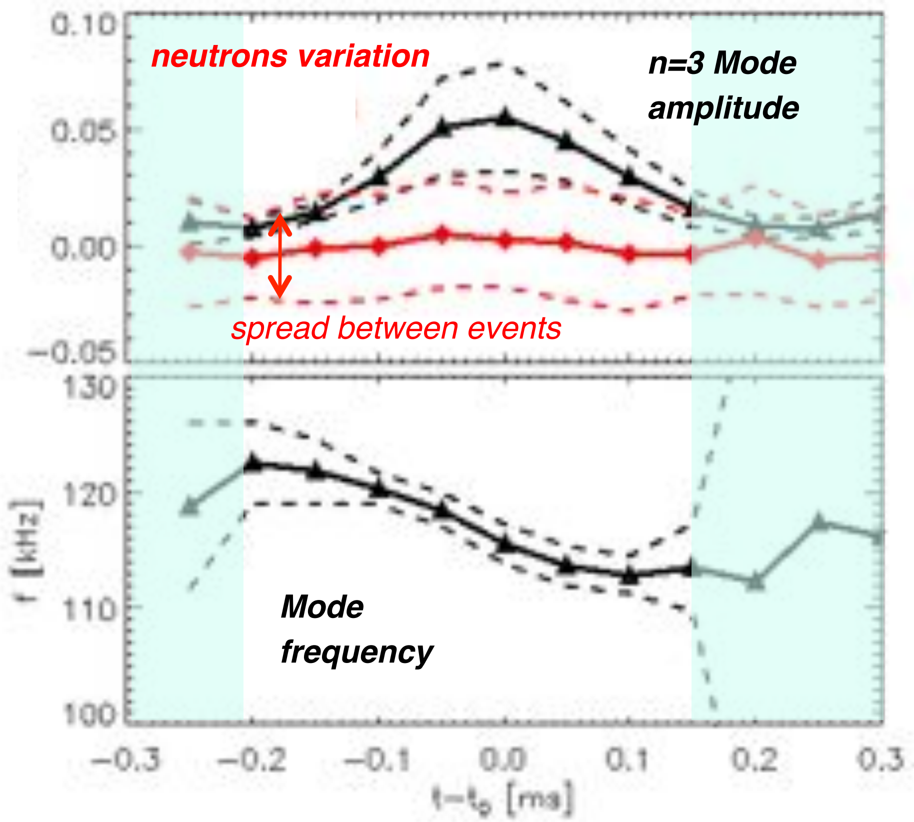
drive amp. increases

⟷



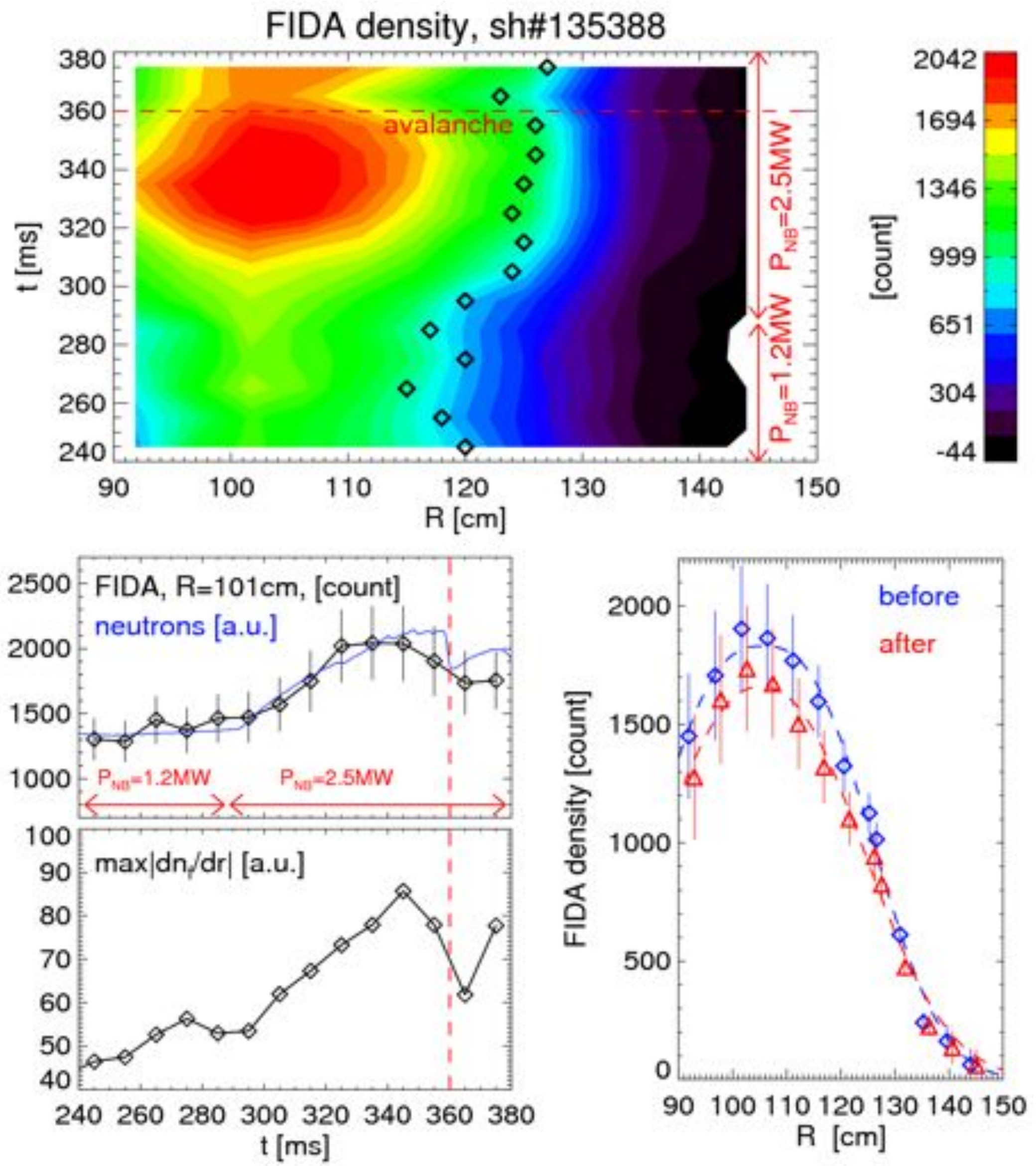
No detectable fast ion losses are observed during weakly bursting/chirping phase





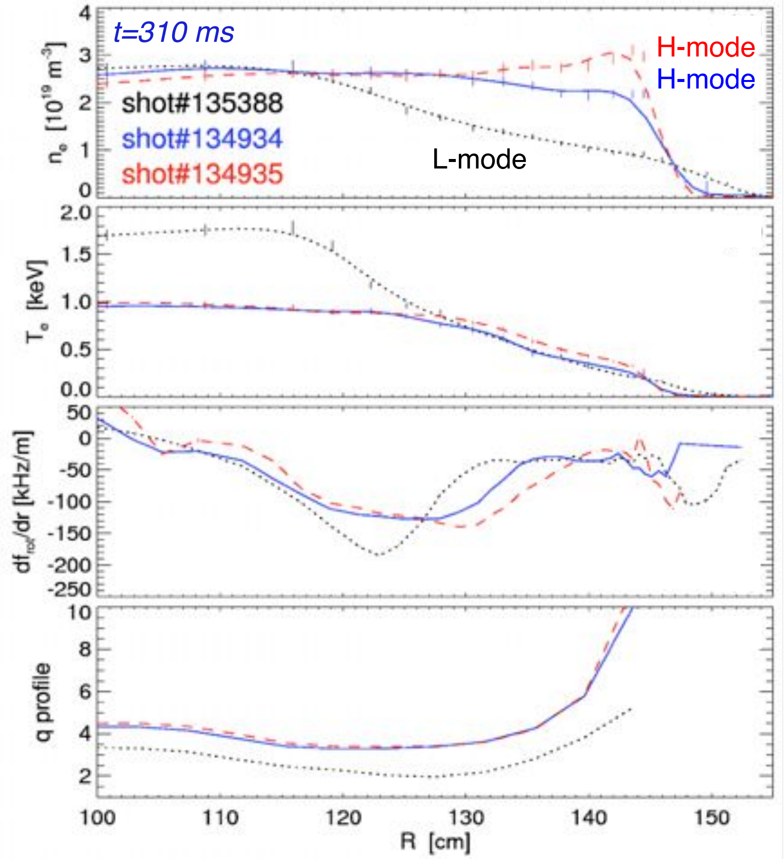
- Statistical average over ~20 events (~10ms)
- No clear evidence of losses from neutrons, FIDA
  - *Does not exclude "continuous" (non-bursting) losses*

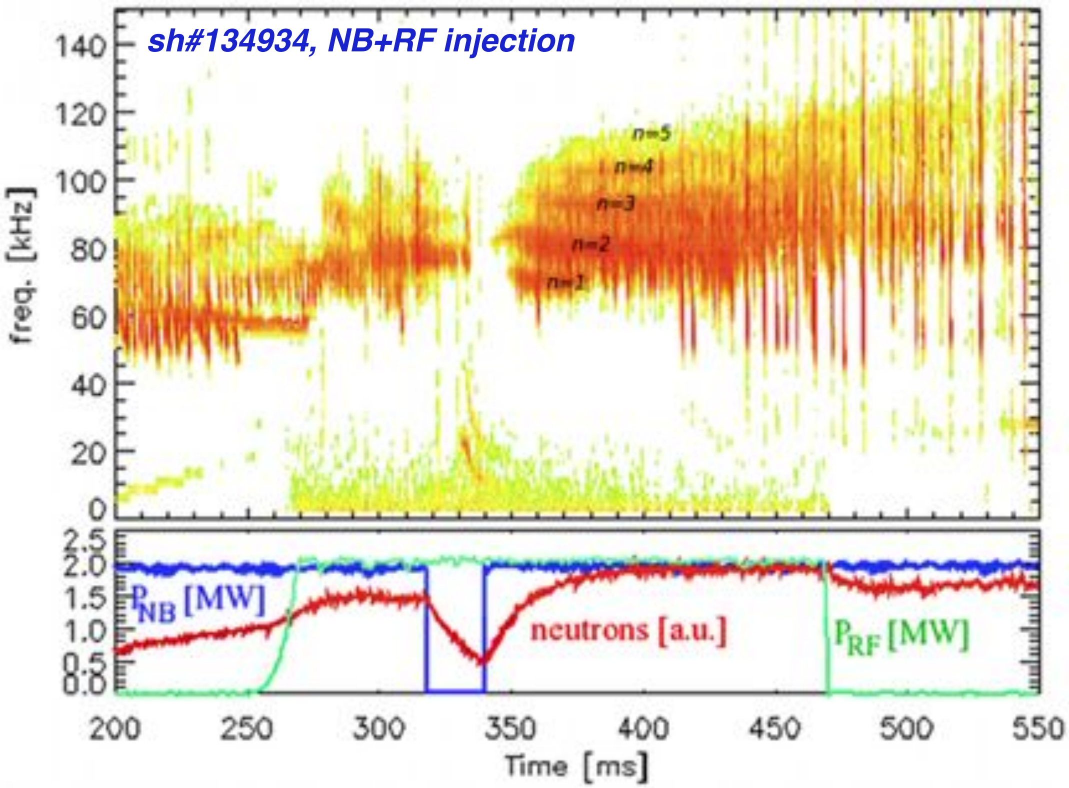
Up to ~30% of fast ions can be lost during a single TAE avalanche



- 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 estimated from FIDA and neutron rate
  - Large portion of phase space affected
- Losses increase with (total) mode amplitude

Similar features are observed in L- and H-mode plasmas and during combined NB+RF : robust dynamics





- Example: H-mode discharges with NB and NB+RF heating
  - Different profiles with respect to L-mode
  - Higher safety factor than for L-mode discharges
  - Reversed shear in both L- and H-mode

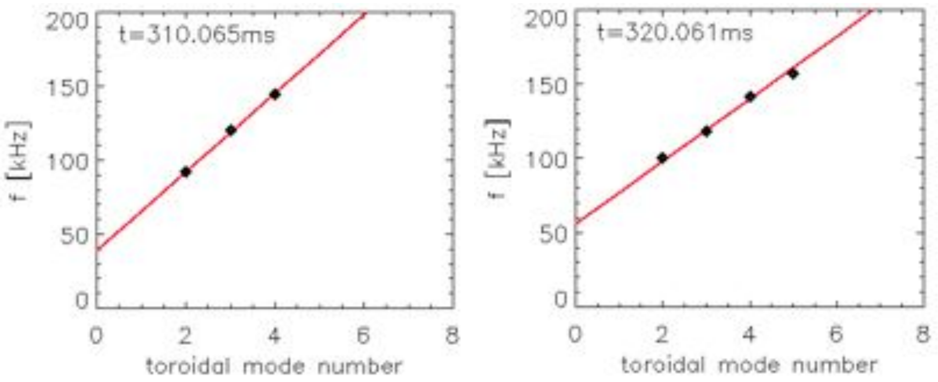
On average, TAE frequencies are consistent with a common frequency *in the plasma frame*

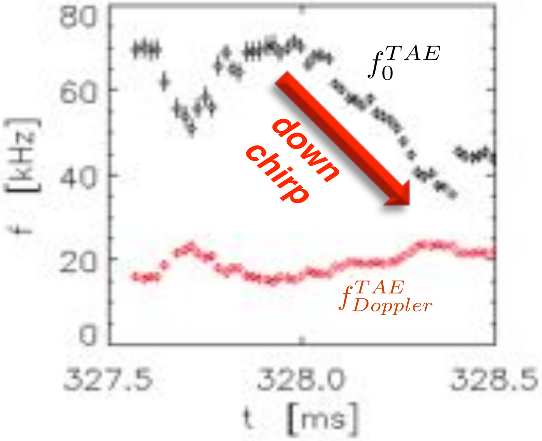
- Measured frequency consistent with:

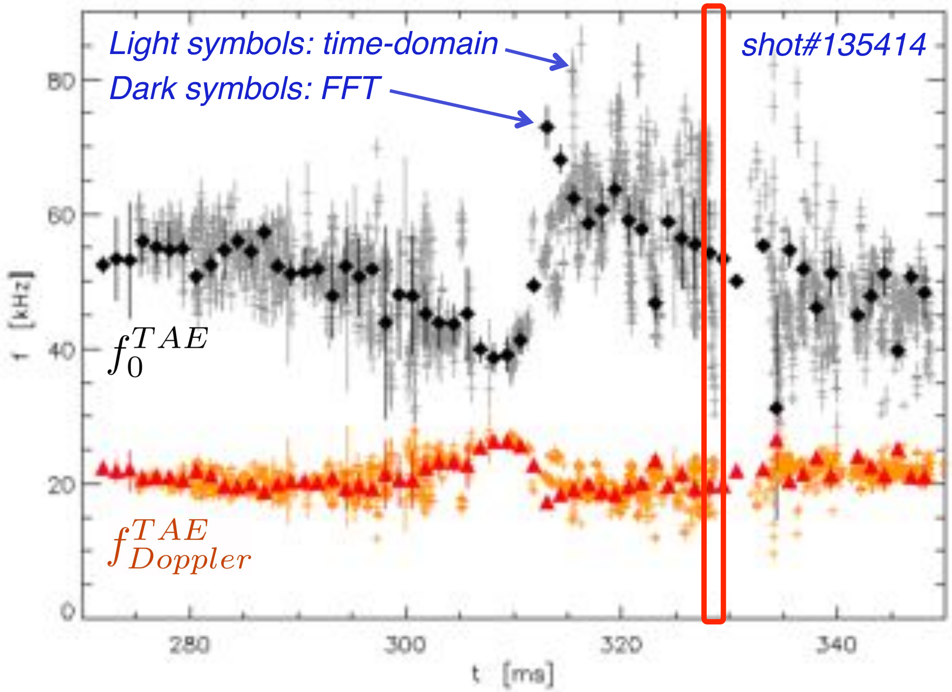
$$\underset{\substack{\downarrow\\ \text{lab frame}}}{f^{TAE}_{lab,n}} = \underset{\substack{\downarrow\\ \text{plasma frame}}}{f^{TAE}_{0}} + n\, \underset{\substack{\downarrow\\ \text{shift from}\\ \text{plasma rotation}}}{f^{TAE}_{Doppler}}$$

- Valid for time scales >1 ms
- In general, each mode shows a different sub-millisecond dynamic...
- ...except during large bursts:
  - Doppler shift only slightly changed here
  - Chirp mainly due to decrease in f^{TAE}_{0}

FFT window 1.3ms







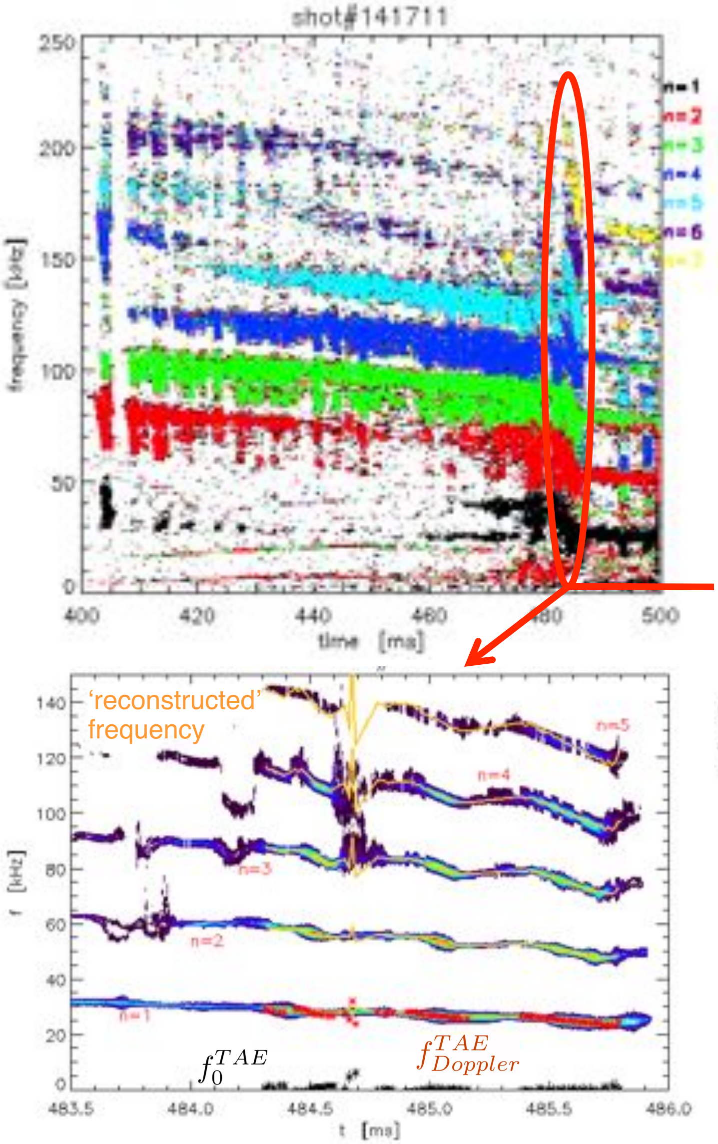
Light symbols: time-domain

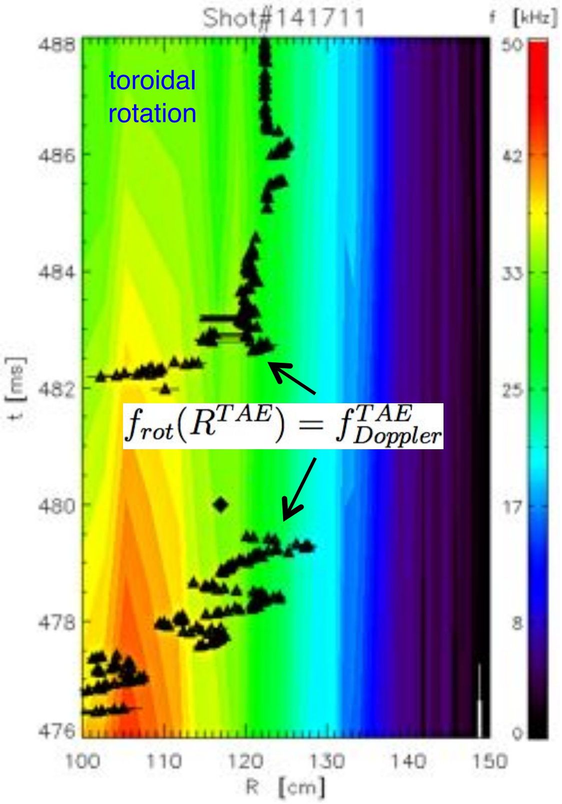
Dark symbols: FFT

shot#135414

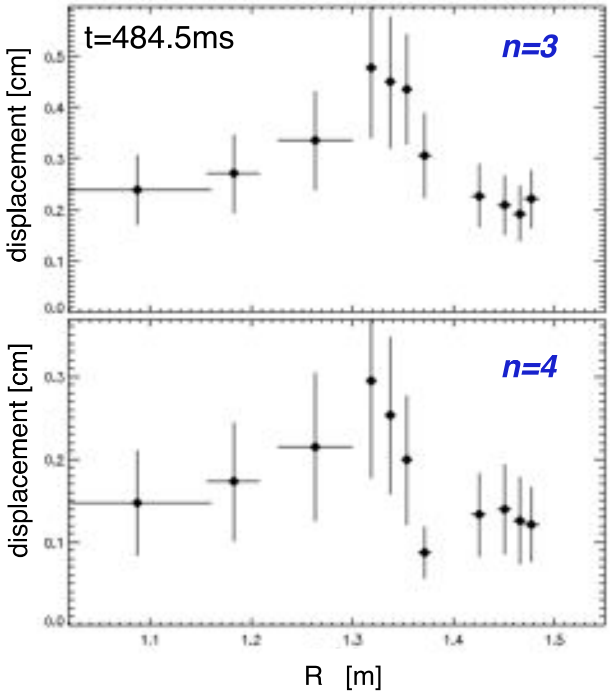
TAE avalanches can drive f_0^{TAE} close to zero frequency (plasma frame) -> coupling with MHD

- Strong burst of TAEs at t~485ms
- Kink-like modes destabilized afterward
- Reconstructed $f_0^{TAE} \longrightarrow 0$
- TAE mode structure ~maintained
- Doppler shift radius R^{TAE} sweeps from plasma center out in ~2 ms



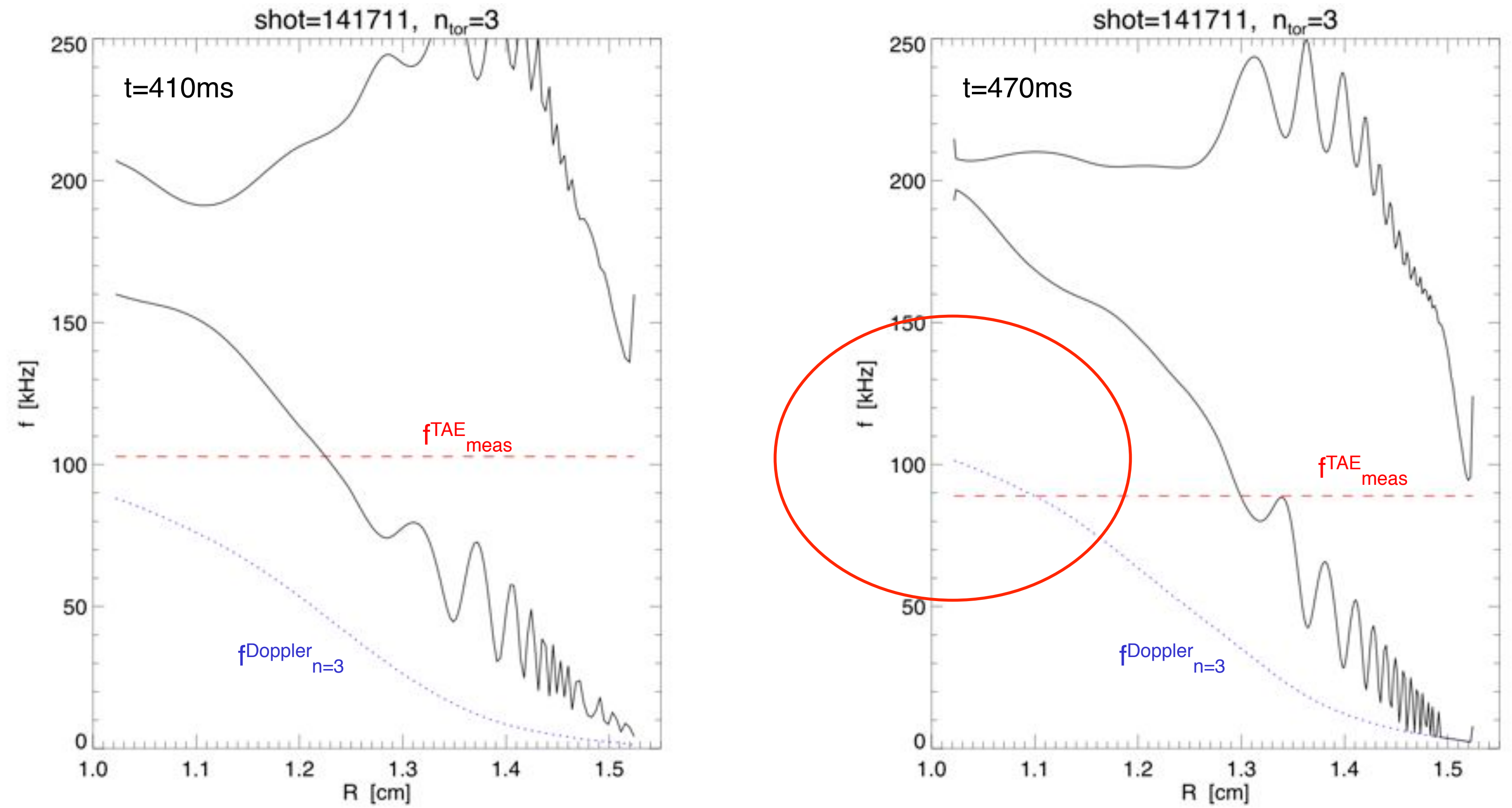


Measured displacement, UCLA reflectometers



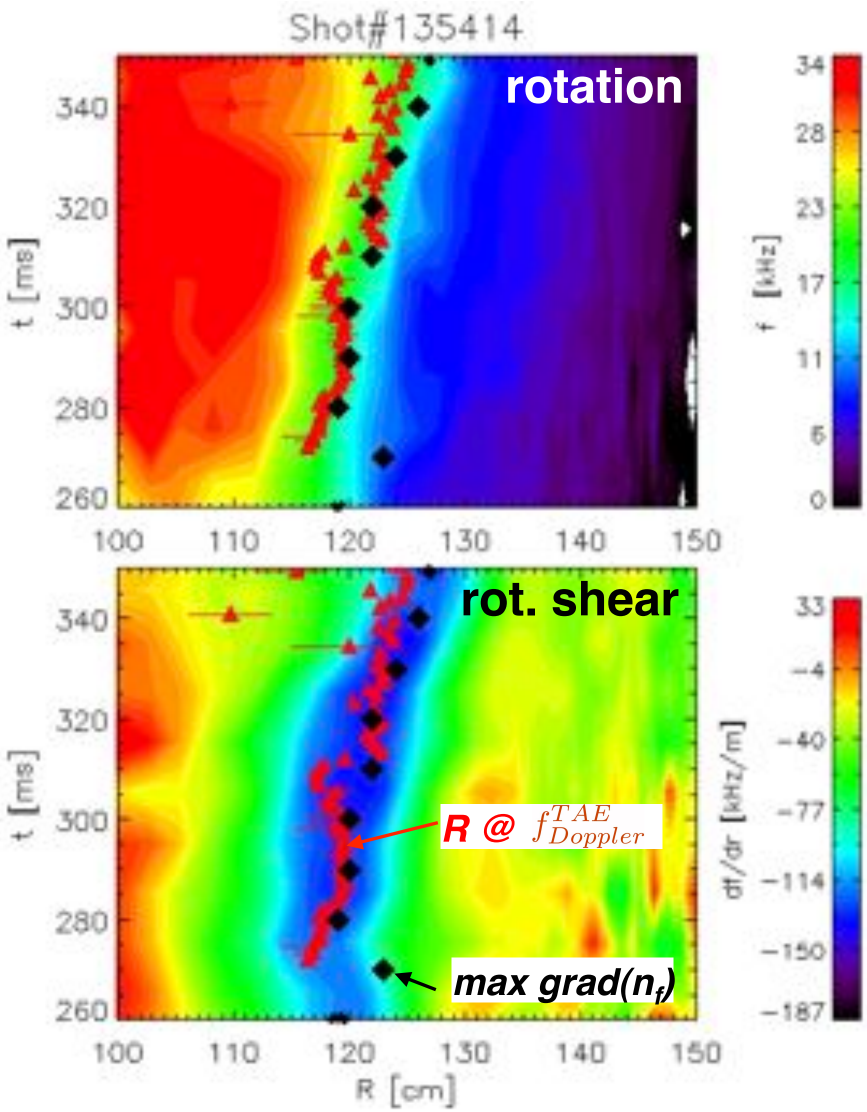
f_0^{TAE} and Doppler shift frequencies overlap at the plasma center when strong bursts occur

TAE continuum from NOVA-K



- Plasma rotation, density increase in time
- Coupling with kinks/fishbones favored when $n_{tor} \times f_{rot}$ on axis ~ f^{TAE} ?

Understanding TAE dynamic requires detailed knowledge of fast ion drive

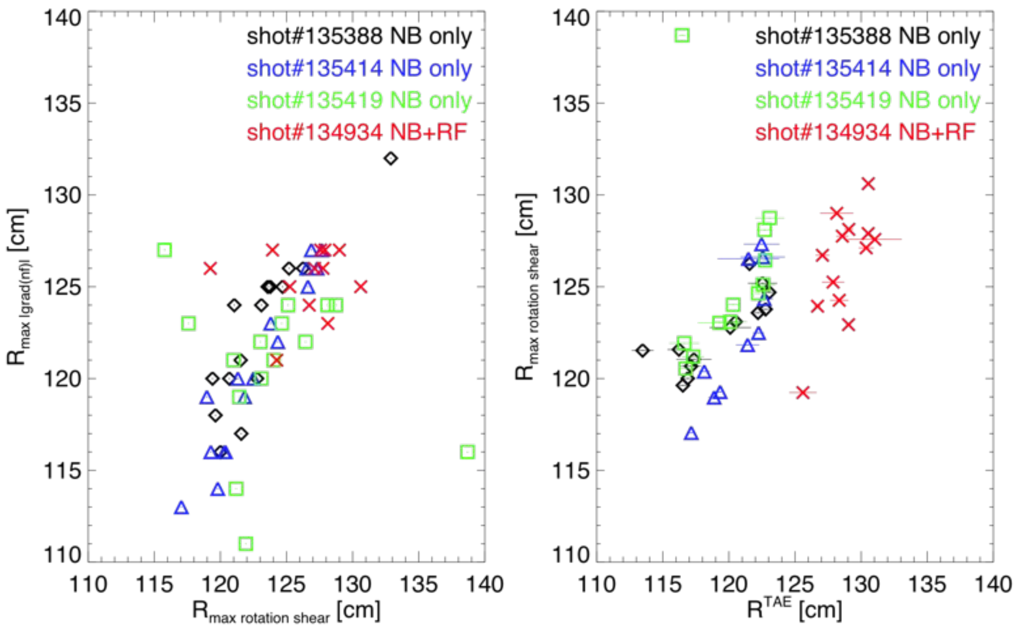


- Modes' *location*, R^{TAE}, obtained by matching with measured rotation profile:

$$f_{rot}(R^{TAE}) = f_{Doppler}^{TAE}$$

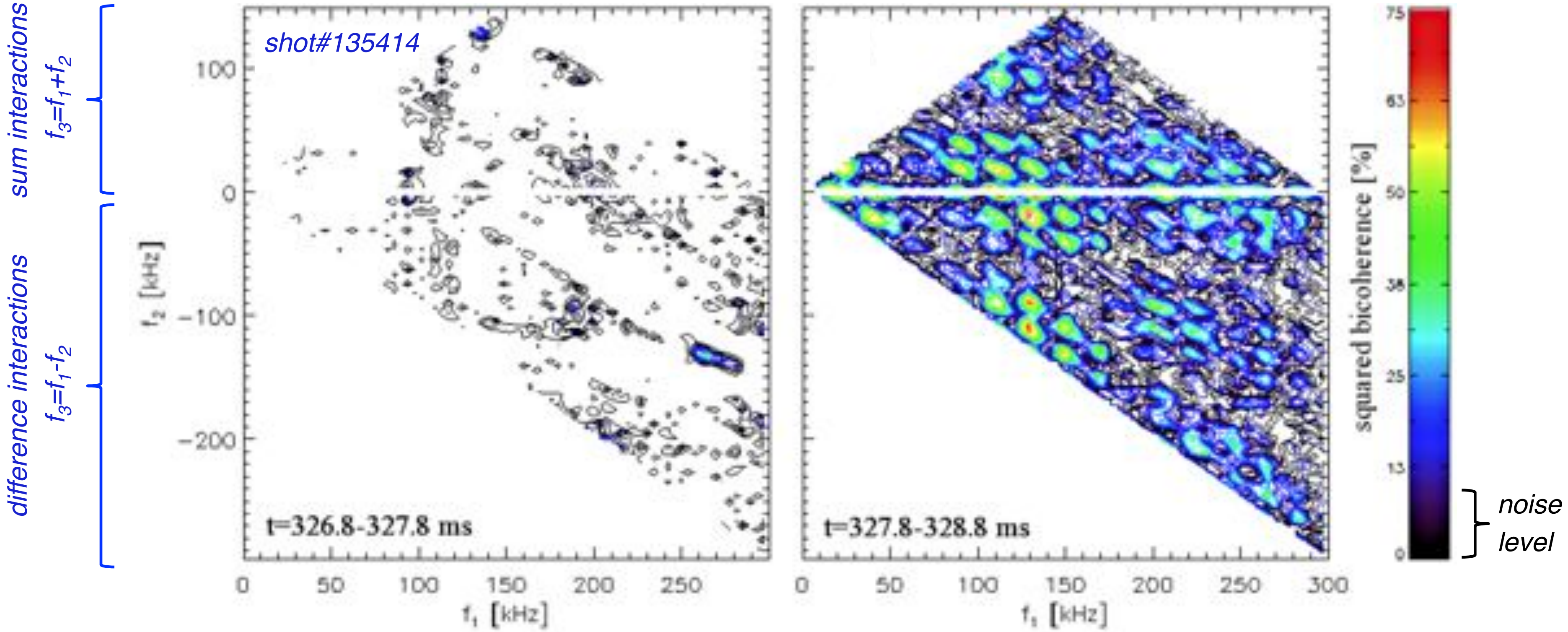
- Correlation between
  - *Mode location*
  - Max rotation shear
  - Steepest fast ion gradient

Coupling through common "source term", i.e. NB injection



Bicoherence suggests coupling between modes at play during large bursts

- High bicoherence >70% measured during burst
  - Average over 11 Mirnov coils distributed toroidally over 360º
  - Indicative of sum/difference interactions between modes
  - Both TAEs and low-frequency modes participate



Simple model based on quadratic interactions can be used to investigate coupling between TAEs

$$\dot{s}_{n3} = < c_{(n_1,n_2)}\, s_{n_1} s_{n_2} >_{f_{n3}}$$

$s_{n2} \rightarrow s_{n2}^*$ (complex conjugate) for difference interaction

Right-hand side filtered around frequency f_{n_3}

Modes must satisfy matching conditions $\begin{cases} n_3 = n_1 \pm n_2 \\ f_{n_3} = f_{n_1} \pm f_{n_2} \end{cases}$

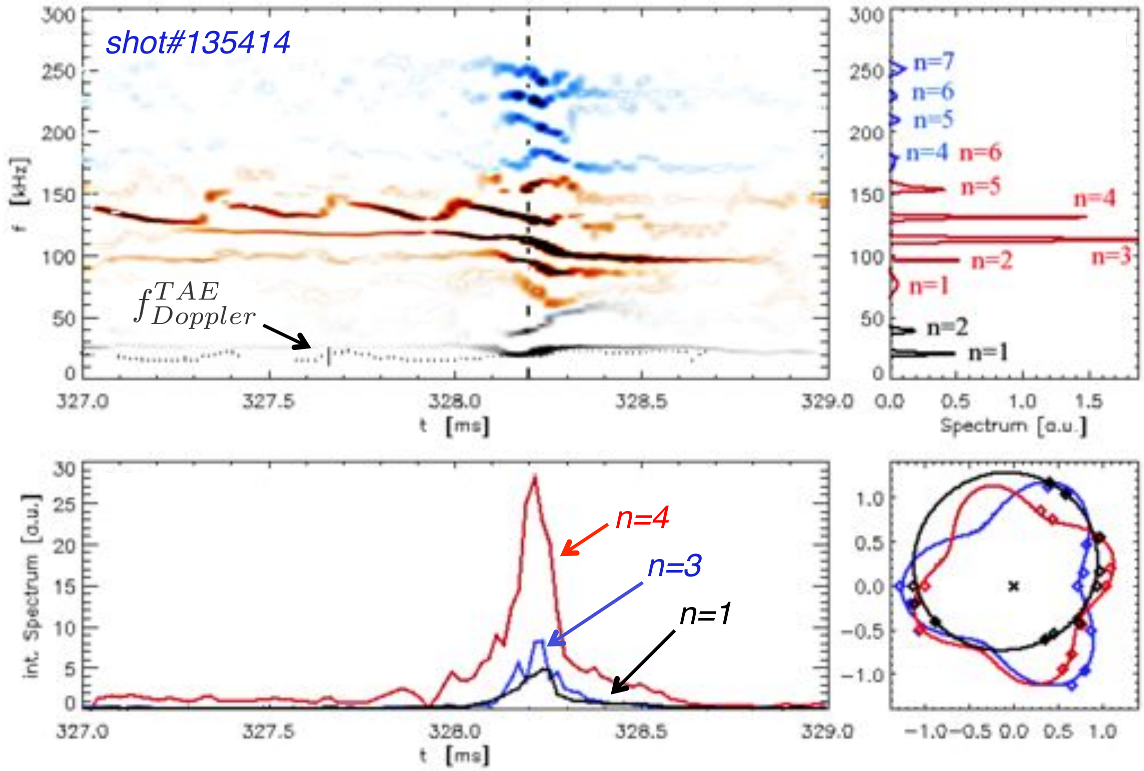
$c(n_1, n_2)$ is the coupling coefficient

In practice:

- Real signals s_{n1}, s_{n2}, s_{n3} measured for each possible triplet, e.g. from Mirnov coils
- "Reconstruct" $\dot{s}_{n3} \rightarrow \dot{s}_{n3,rec}$ from measured s_{n1}, s_{n2}
- Compare measured and reconstructed $\dot{s}_{n3}$
- *Frequency match must be verified in the plasma frame:*
  - Rotation profile and location of each mode must be accurately known

‘New’ modes appear in the spectrum above/ below TAE range during large bursts

- Modes can be classified into three groups
  - *Discriminant: frequency, temporal evolution*



High-frequency *band; only appears during bursts*

“Primary” TAEs*; observed during most of the time interval of interest*

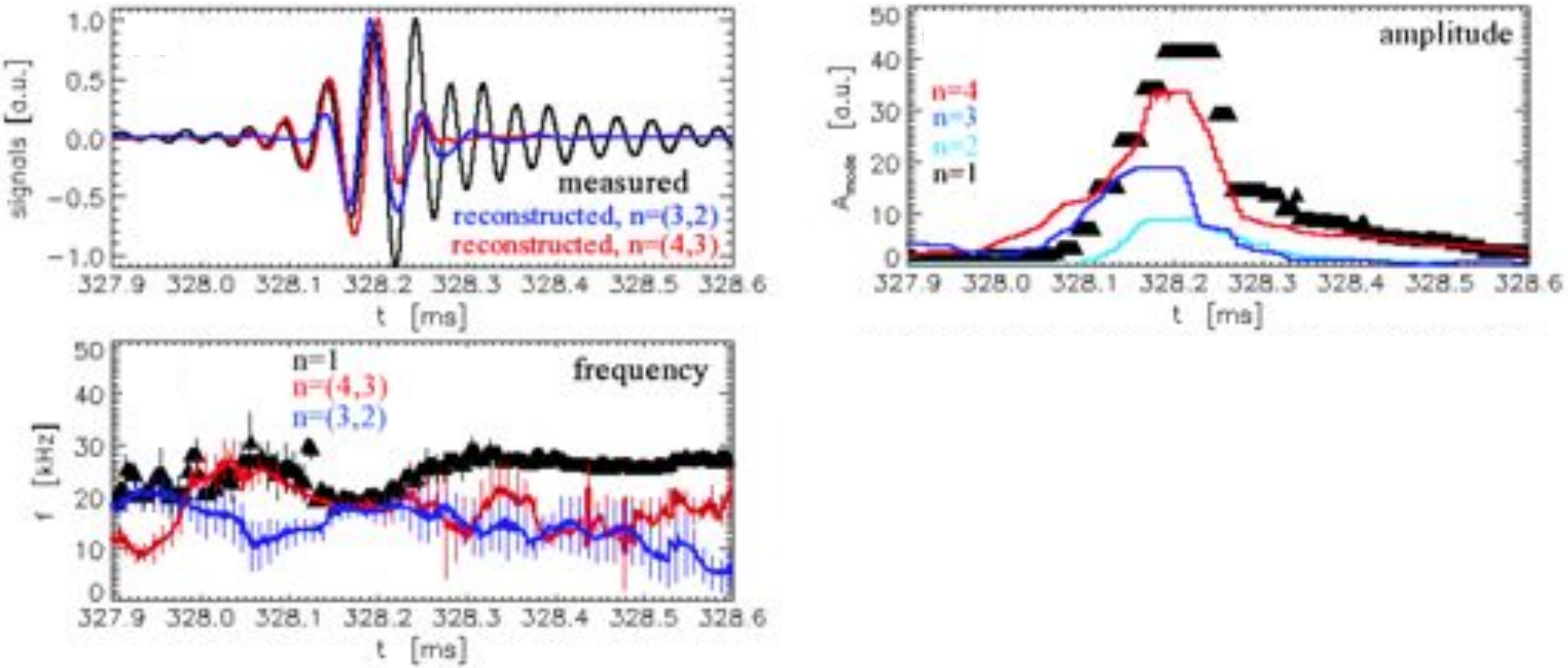
Low-frequency *band; appears during large bursts only? Masked by other MHD modes?*

Toroidal mode structure vs. time and mode number from 11 Mirnov coils

- *Note regions of constructive/ destructive overlap between “primary” TAEs*
- Shown are *n=1*, *n=3*, *n=4*

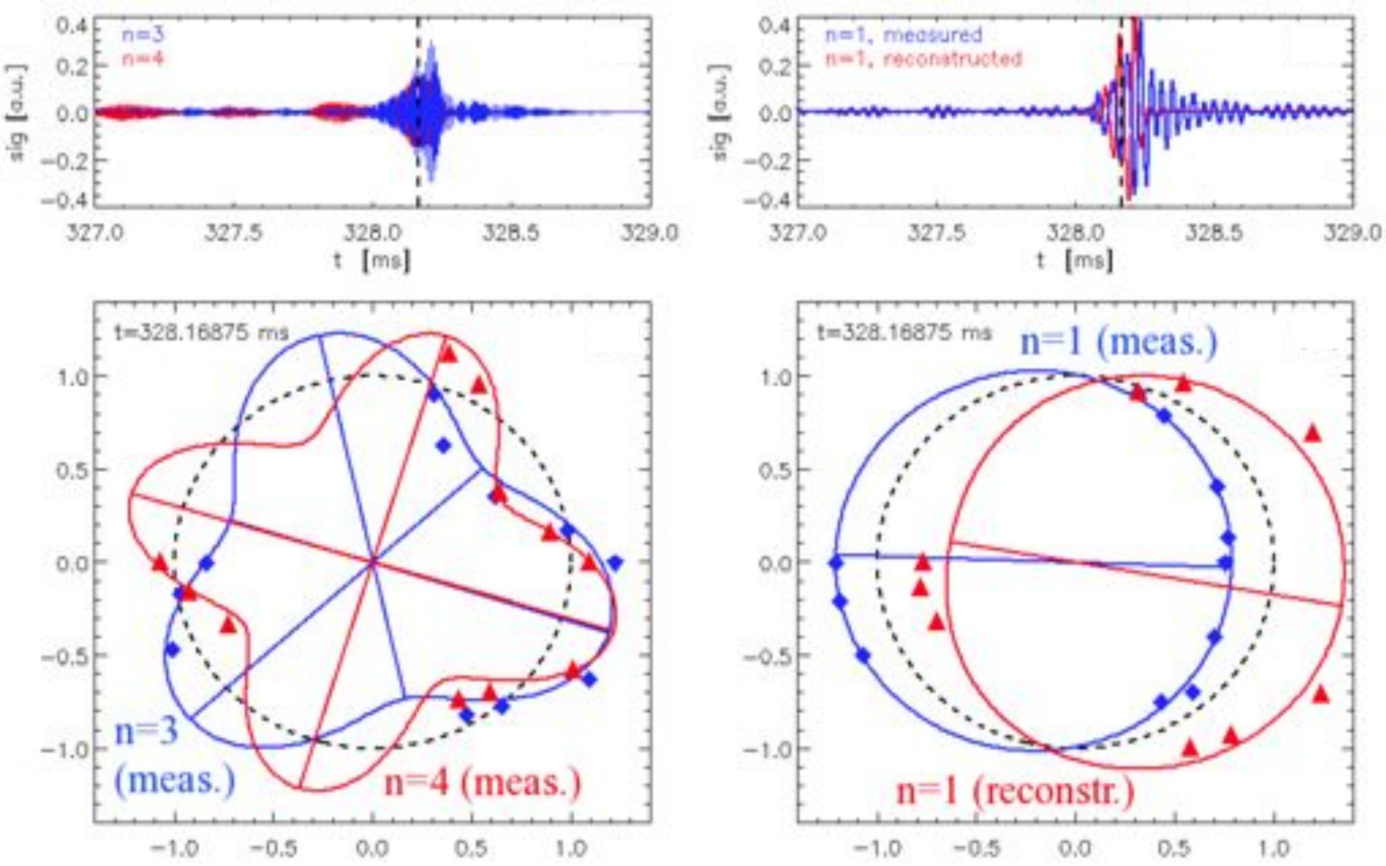
- Picture consistent with primary TAEs
  - coupling to each other
  - generating *secondary* modes through sum/difference with $\Delta n=1$

Good agreement with quadratic interactions' model: amplitude evolution and frequency matching



- "Reconstructed" *n=1* mode agrees with measured one
  - *n=1 mode fades away when either amplitude or frequency matching vanishes*

Mode number matching condition verified



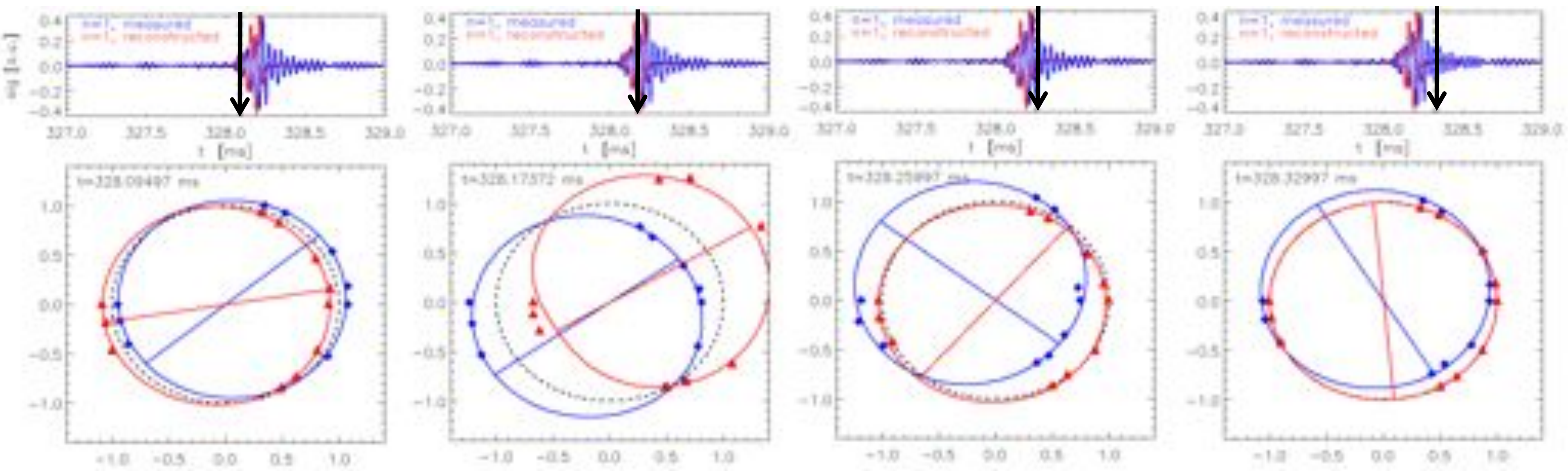
-*Symbols: rms mode amplitude data from 11 Mirnov coils*

- *Solid lines: fit for a given n (n=1 here)*

- *Dashed line: unit circle (zero-amplitude reference)*

- “Reconstructed” toroidal structure of n=1 mode also agrees with measured one
  - *Phase shift of 180 degrees*
  - sdfsdfsdf

Phase matching condition is *transiently* verified during large bursts



- Phase resulting from quadratic interaction is important!
  - *n=1 mode fades away ⇔ phase deviates from 180 degrees, or changes rapidly in time*
  - "Single mode" dynamic, with each mode following its own chirp/burst cycle, is effective in reducing efficiency of quadratic interactions
  - The result is a "semi-cahotic" scenario, with small bursts (single mode) and occasional large bursts (multi-mode avalanches)

Summary

- TAE bursts can cause large, intermittent fast ion transport
- Bursting TAE regime is “robust” against small variations of plasma parameters
  - L-mode *vs.* H-mode, NB only, NB+RF, ... : all show similar features
- Non-linearities occur in both single-mode and multi-mode (avalanching) TAE dynamic
  - But only avalanches seem to cause significant fast ion losses
- More experiments planned for near term
  - Systematic study of TAEs (and *avalanches*) in H-mode
  - Comparison with M3D-K code started; plasma rotation included
  - Extending to paricle-following code SPIRAL
  - Improve “linear” analysis (NOVA-K + ORBIT)