NSTX

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Supported by U.S. DEPARTMENT OF ENERGY | Office of Science

Non-linear dynamics of toroidicity-induced Alfvén eigenmodes on NSTX

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23rd IAEA Fusion Energy Conference

Daejeon, Rep. of Korea

11-16 October 2010

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Abstract

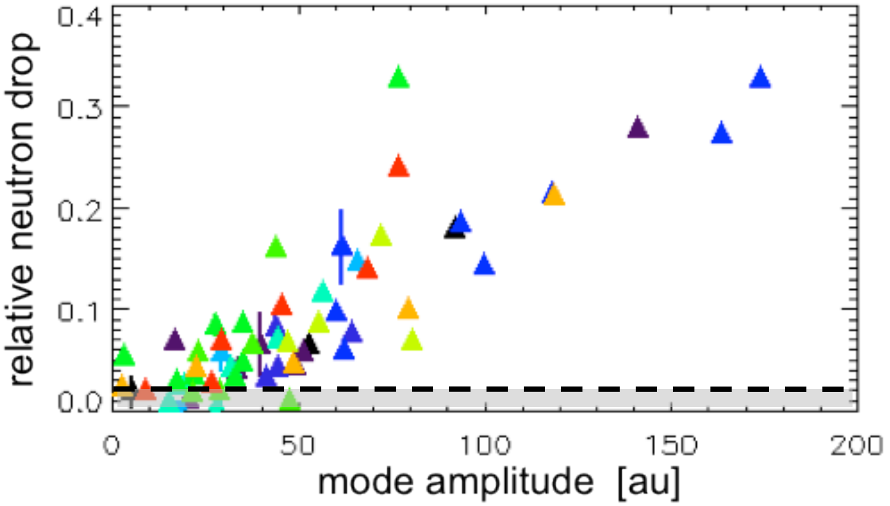
The National Spherical Torus Experiment (NSTX) routinely operates with neutral beam injection as the primary system for heating and current drive. The resulting fast ion population is super-Alfvénic, with velocities $1 < v_{fast}/v_{Alfvén} < 5$ and normalized Larmor radius comparable to that of alphas in future reactors. Fast ions provides a strong drive for toroidicity-induced Alfvén eigenmodes (TAEs) with toroidal mode number $n = 2–8$ and frequency $60 < f < 250$ kHz. As the discharge evolves, the fast ion population builds up and TAEs exhibit increasing bursts in amplitude and down-chirps in frequency, which eventually lead to a so-called TAE *avalanche*. Avalanches cause large (up to ~30%) losses over <1ms, as inferred from the neutron rate and other fast fast ion diagnostics (FIDA, sFLIP, NPA). The increased fast ion losses correlate with a stronger activity in the TAE band. In addition, a $n = 1$ mode with frequency well below the TAE gap appears in the Fourier spectrum of magnetic fluctuations during avalanche events. The non-linear coupling between modes, which correlates with an enhanced fast ion transport during avalanches, is investigated.

Work supported by U.S. DOE contracts DE-AC02-09CH11466, DE-FG02-06ER54867 and DE-FG02-99ER54527

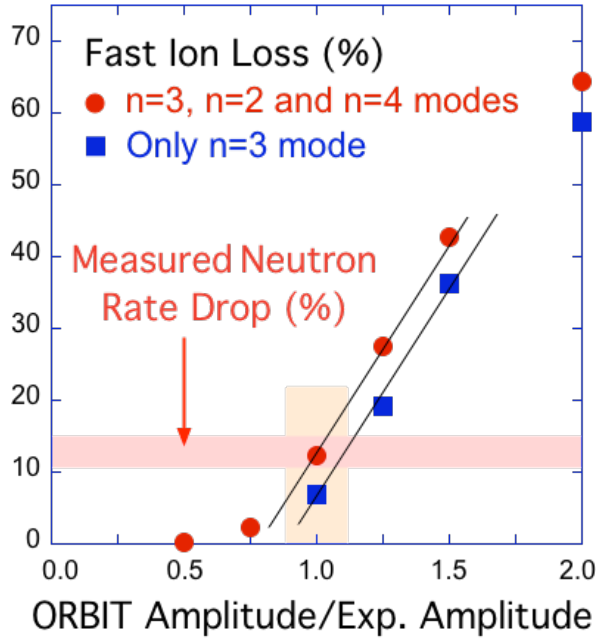
Bursting toroidicity-induced Alfvén eigenmodes (TAEs) can lead to enhanced fast-ion transport

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

NSTX data *(Colors indicate different shots)*



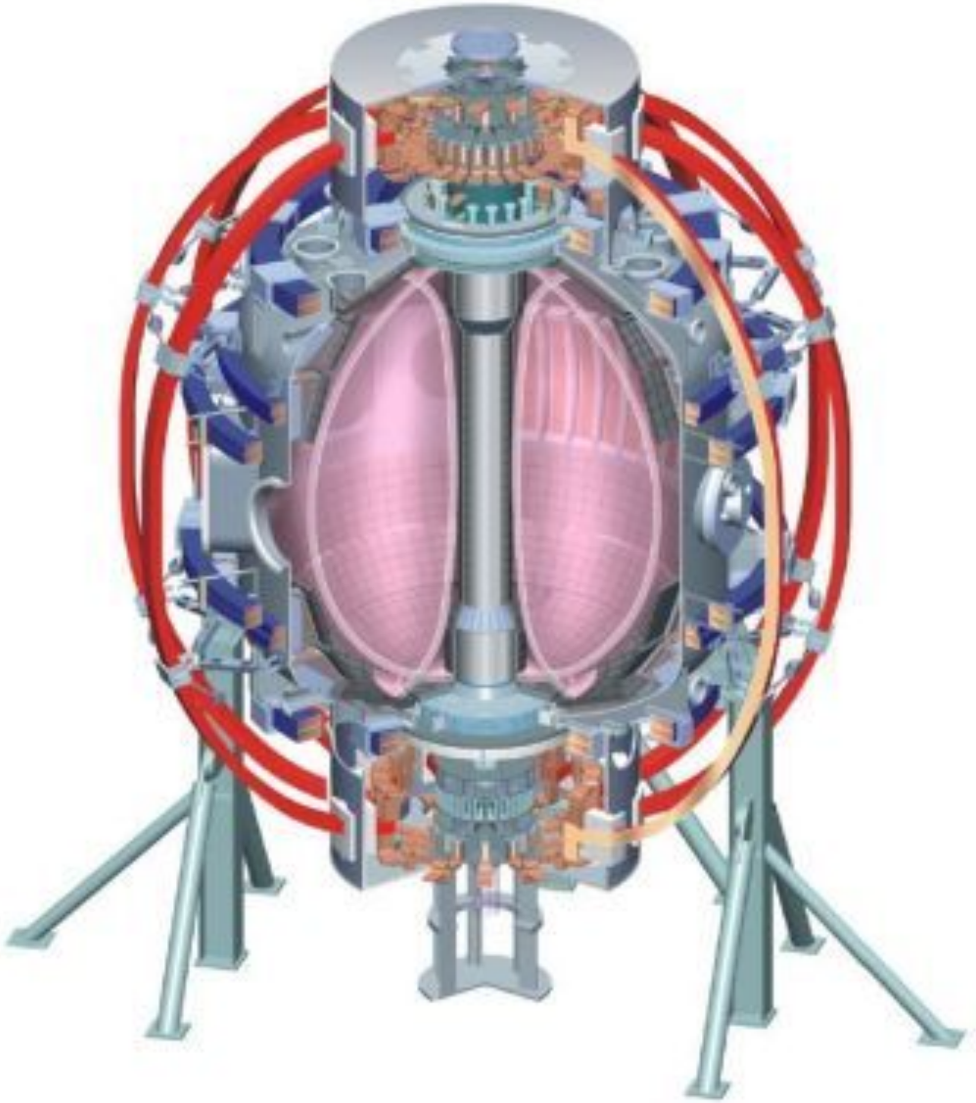
NOVA + ORBIT simulation



E. Fredrickson *et al.*, Phys. Plasmas **16**, 122505 (2009)

- Must control/limit TAEs in future reactors (ITER, STs)
  - Need to understand the causes of bursting TAE behavior
  - Need to 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	<0.6 T
Pulse length	<2 s

3 Neutral Beam sources

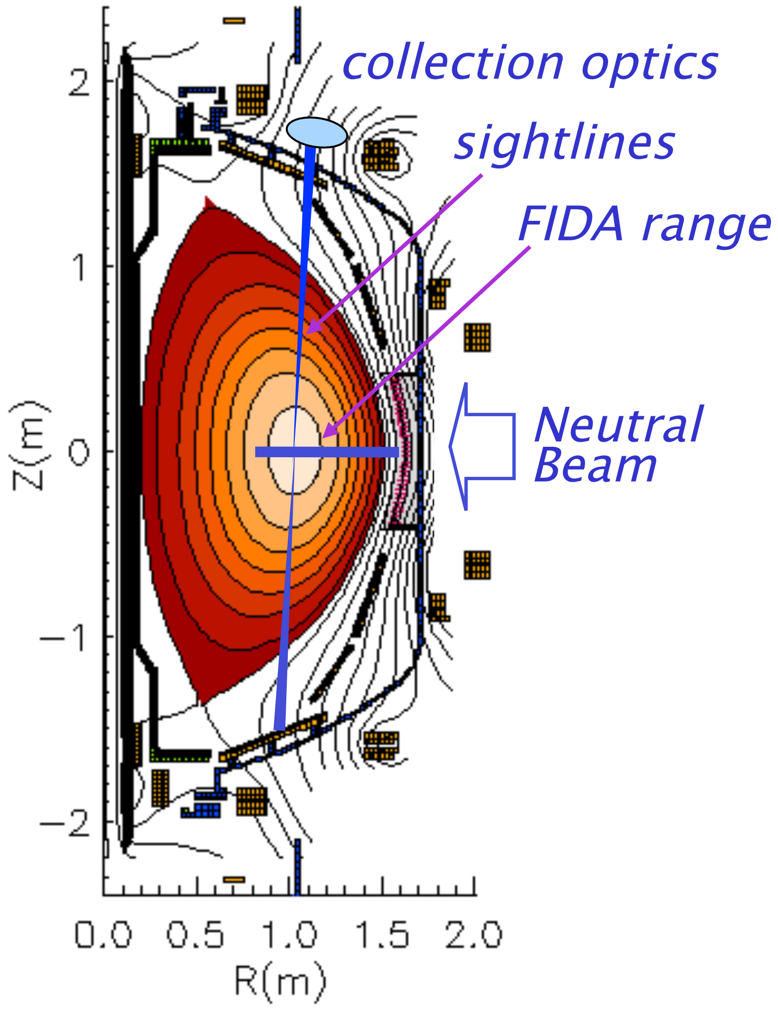
$P_{NBI} \leq 6$ MW, $E_{injection} \leq 95$ keV

⇨ $1 < v_{fast}/v_{Alfven} < 5$

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

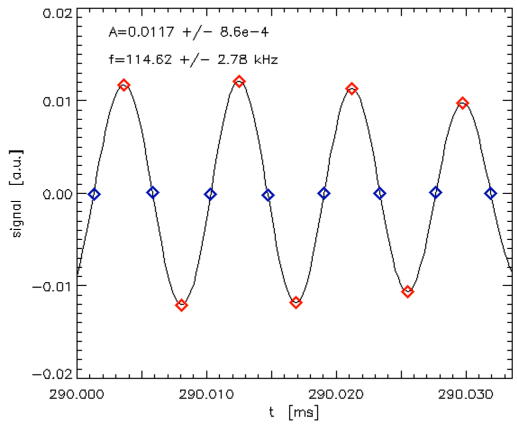
Mode activity and fast ion diagnostics on NSTX

shot#135404, t=320 ms



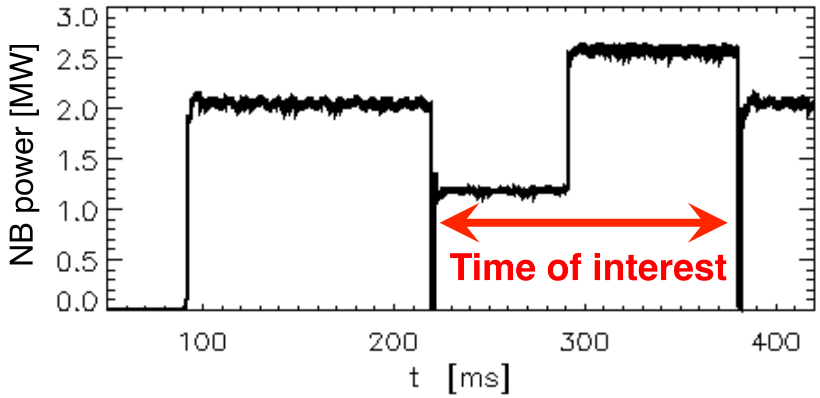
- Mirnov coils
  - Magnetic fluctuations up to 2.5 MHz
- Multi-channel reflectometer
  - Mode structure (L-mode)

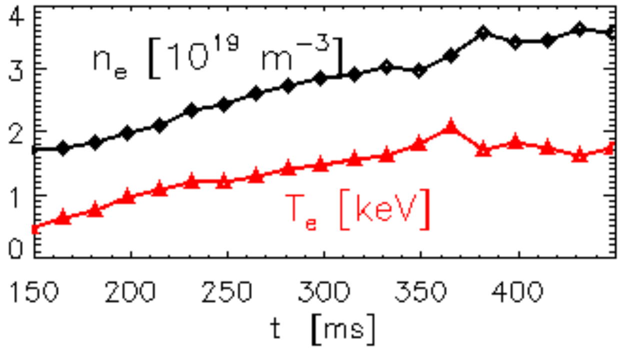
FFT analysis complemented by analysis in time domain to study mode dynamics over short time scale

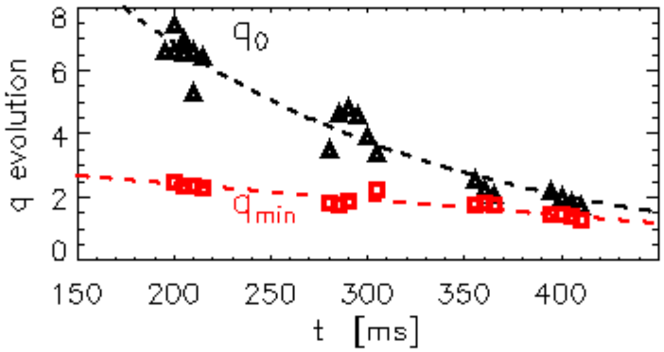


- Fast Ion D-Alpha (FIDA) system
  - Fast ion profile and spectrum through active charge-exchange recombination spectroscopy
  - Weighted toward small pitch (perp. component)
- Neutron rate, NPA, sFLIP

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

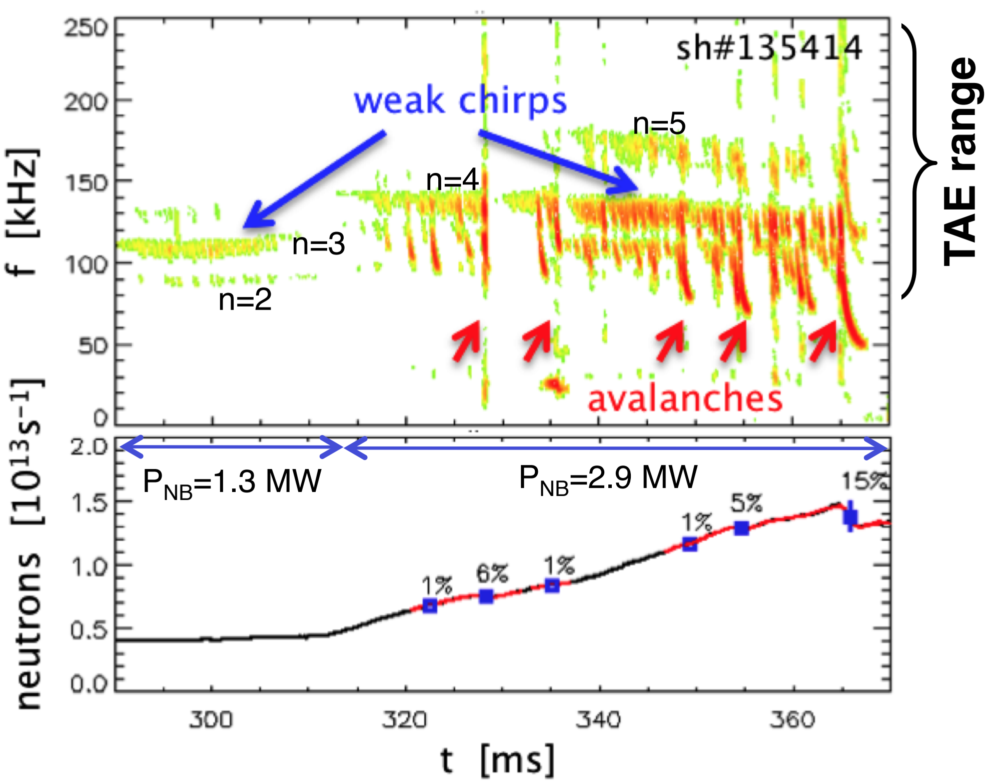


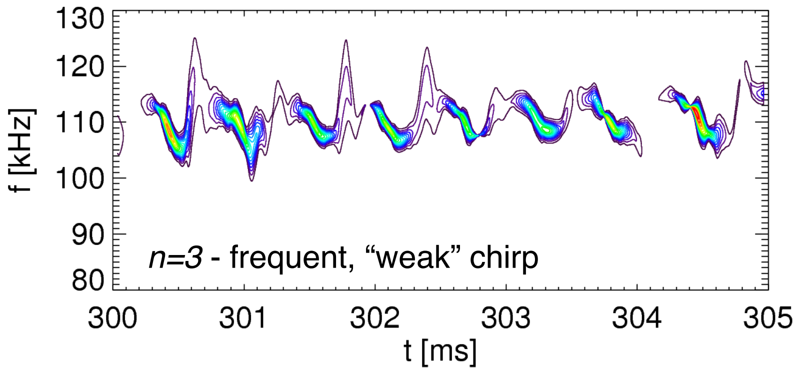


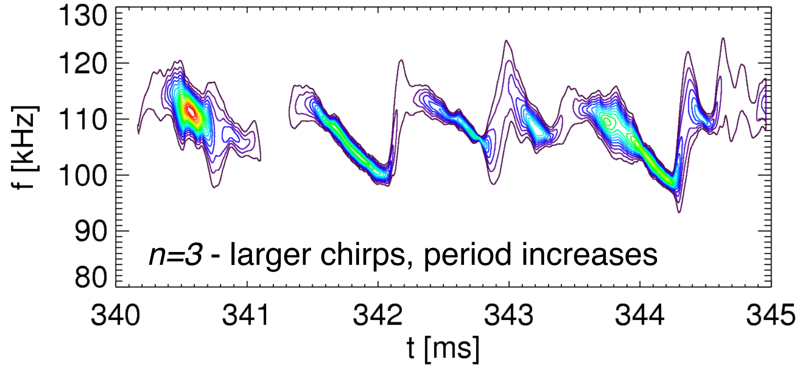


- NB-heated, L-mode plasmas
  - – Plasma limited on center-stack
  - – NB power and timing varied to affect mode stability
  - – Plasma profiles evolving in time
  - – Reversed-shear *q* profile
  - – Safety factor evolution reconstructed from four similar discharges through LRDFIT code constrained by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

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

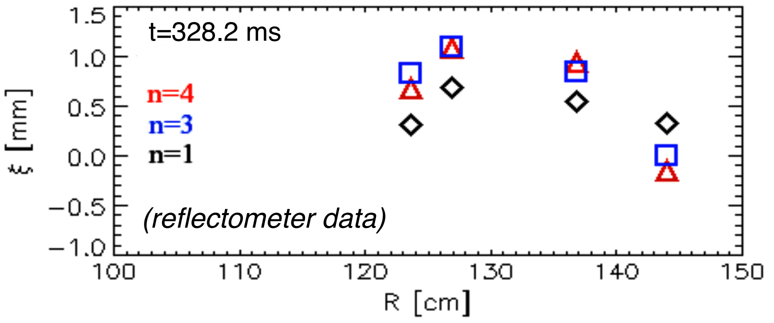




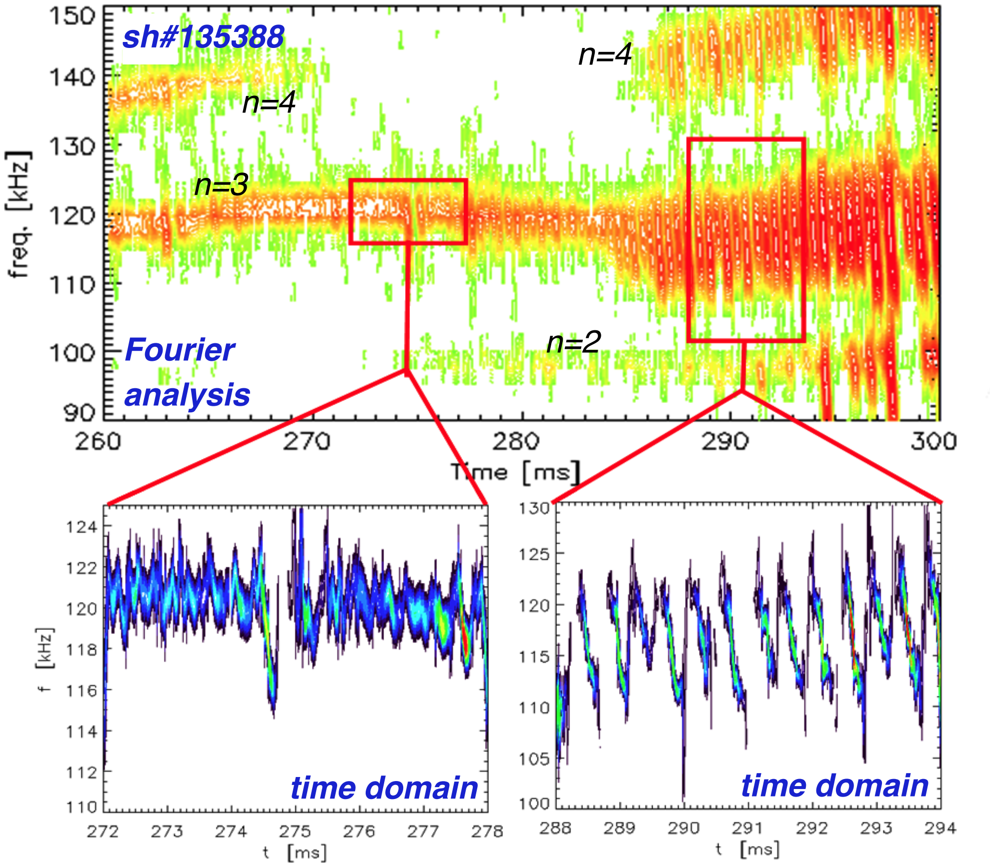


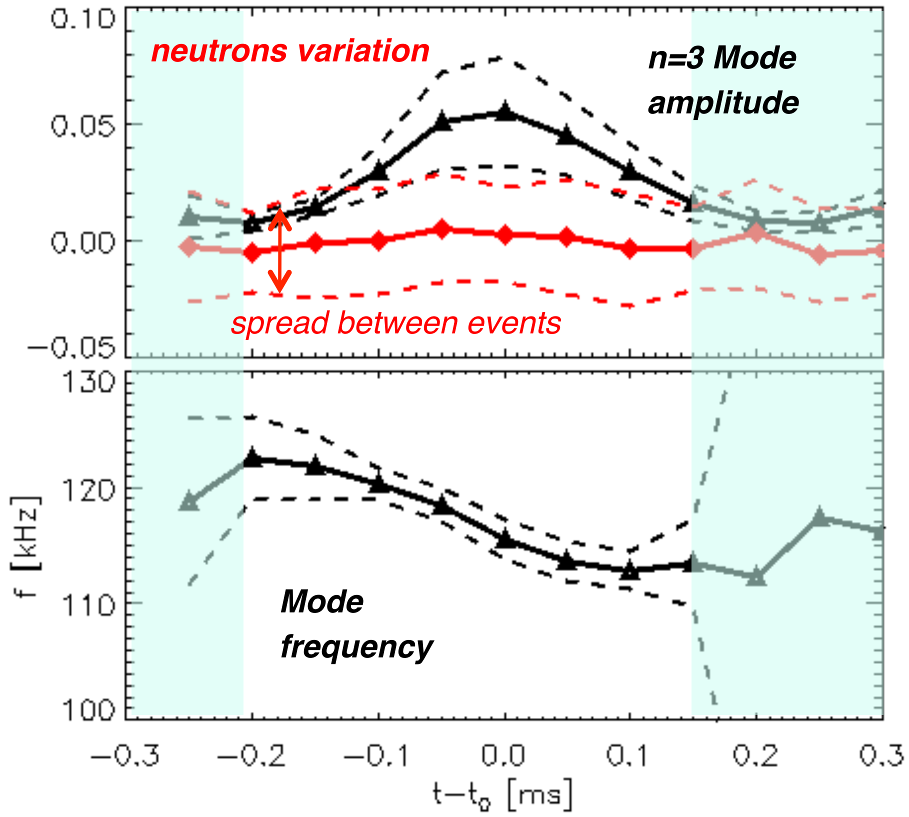
- Modes show more bursting character as discharge evolves
  - NB power increases, fast ion population builds up
- Usually, each mode chirps independently of the others...
- ... but, eventually, *avalanches* occur:
  - Modes lock on similar dynamic, multiple TAEs involved
  - Drop in neutron rate, FIDA

modes have broad radial structure



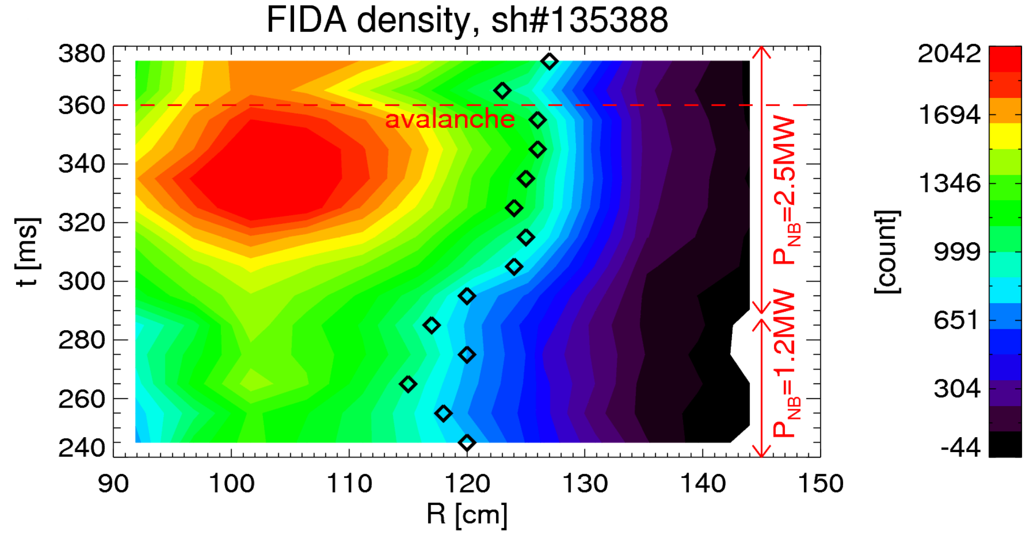
No detectable fast ion losses are observed during weakly bursting/chirping phase

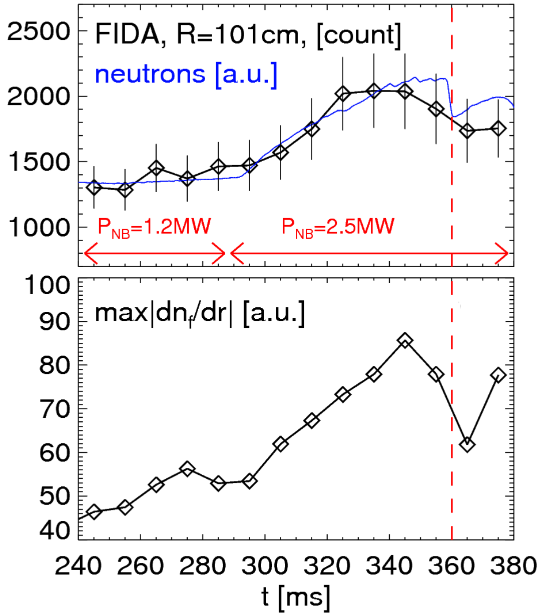


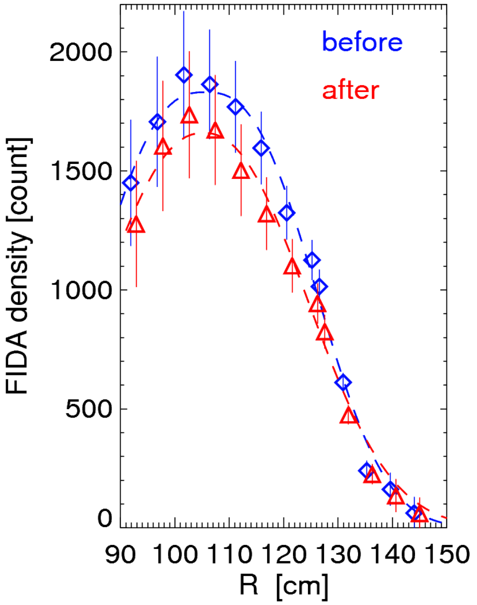


- Statistical average over ~20 events (~10ms)
- No clear evidence of losses from neutrons, FIDA
  - *Does not exclude "continuous" (non-bursting) losses*

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

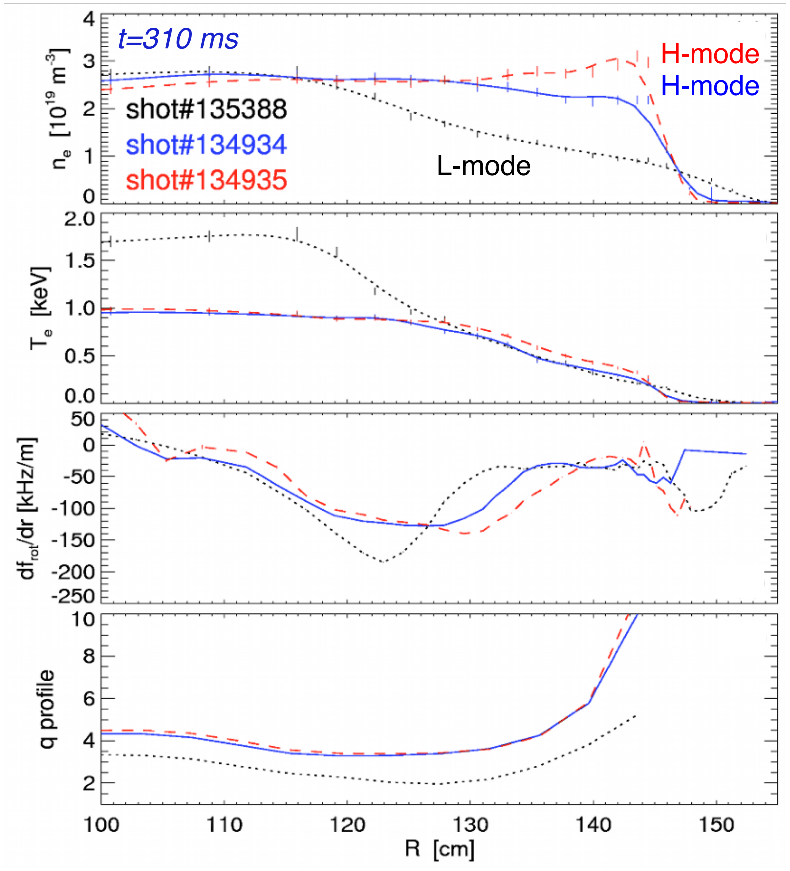


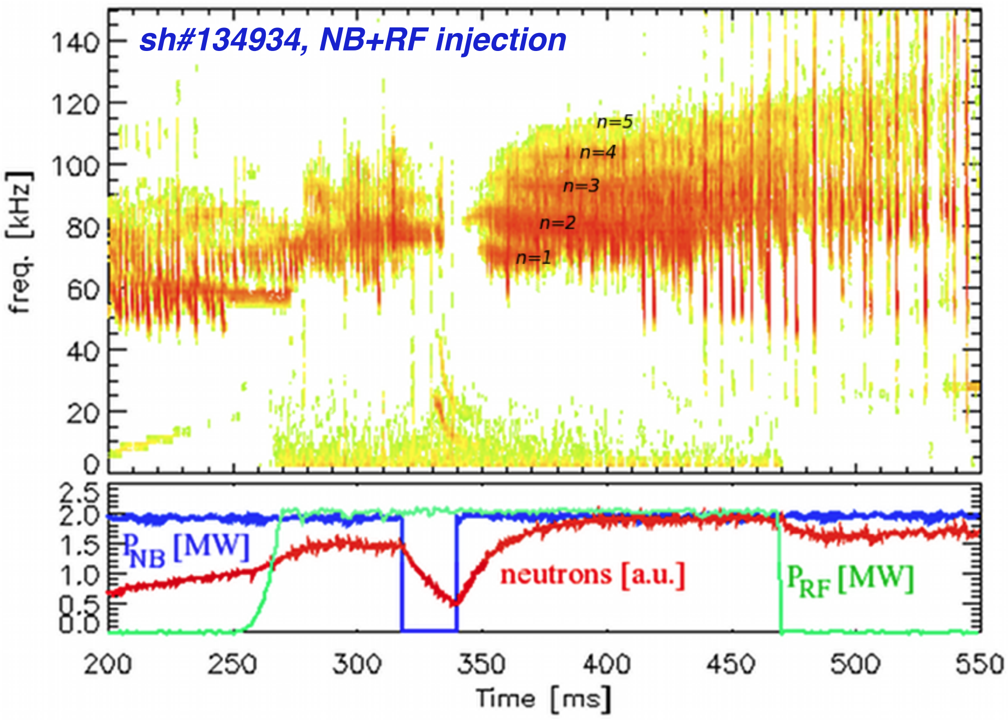




- Fast ion density (FIDA) drops over most of minor radius
- Loss results in a relaxation of the radial gradient → drive for TAEs is reduced
- Comparable losses estimated from FIDA and neutron rate
- Losses increase with (total) mode amplitude

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

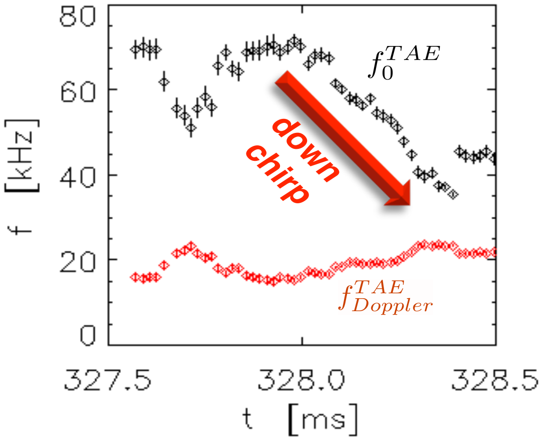
On average, TAE frequencies are consistent with a common frequency *in the plasma frame*

- $f_{n = 2\text{-}6}$ consistent with:

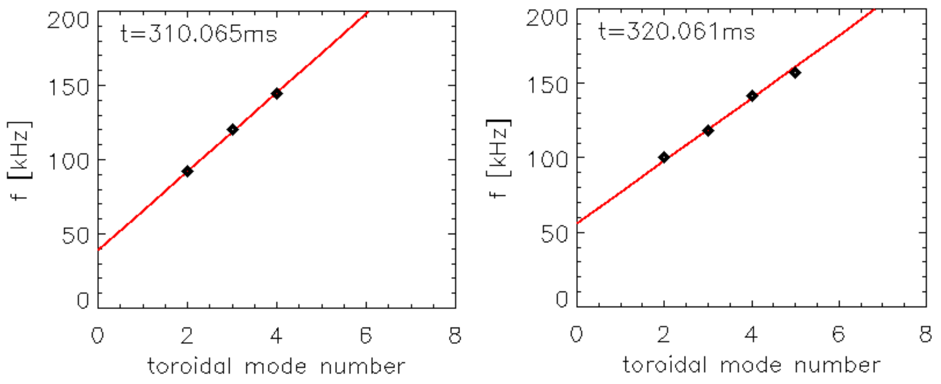
$$f^{TAE}_{lab,n} = f^{TAE}_0 + n\, f^{TAE}_{Doppler}$$

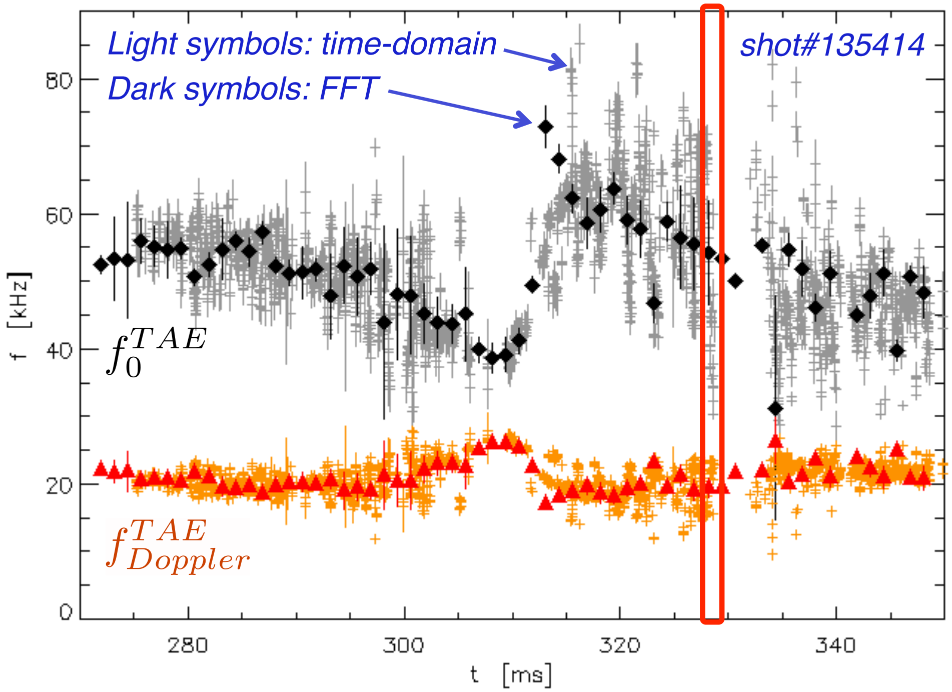
↓ lab frame
↓ plasma frame
↓ shift from plasma rotation

- Valid for time scales >1 ms
- In general, each mode show a different sub-millisecond dynamic...
- ...except during large bursts:
  - Doppler shift only slightly changed
  - Chirp mainly due to decrease in f_0^{TAE}

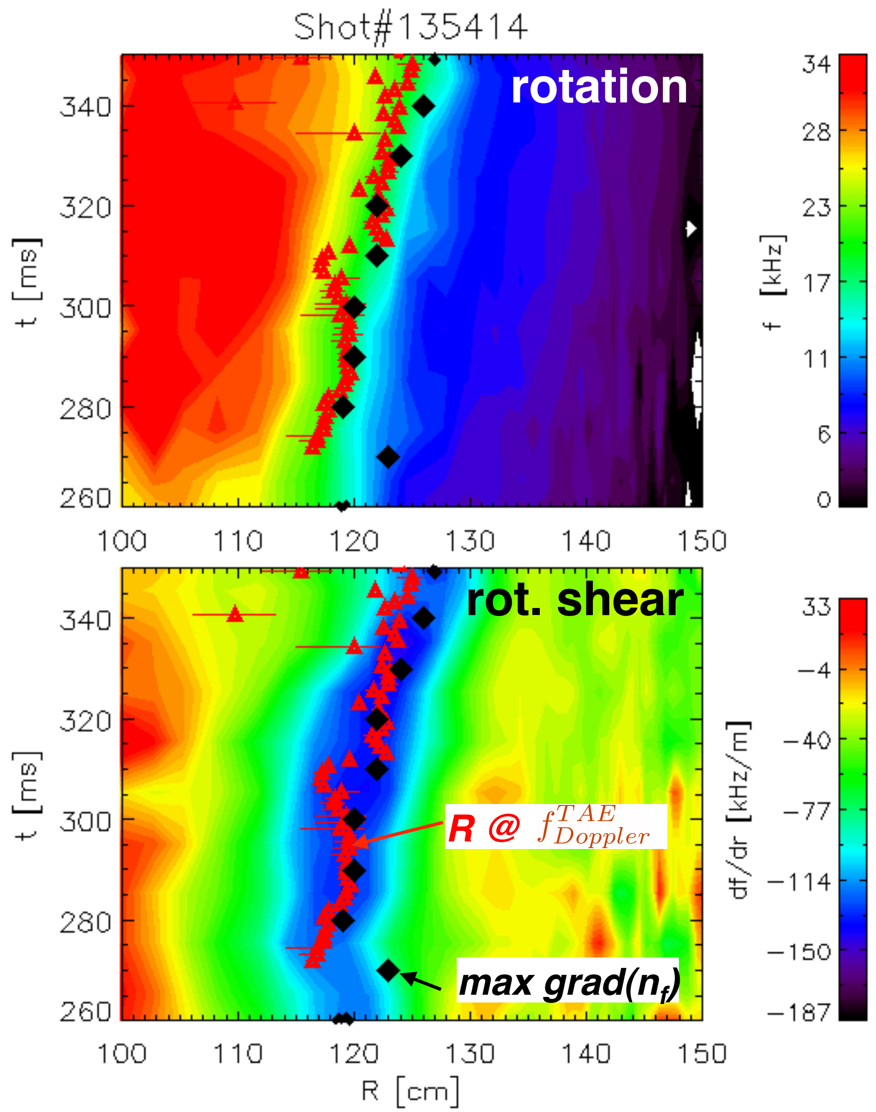


FFT window 1.3ms





Understanding TAE dynamic requires detailed knowledge of fast ion drive

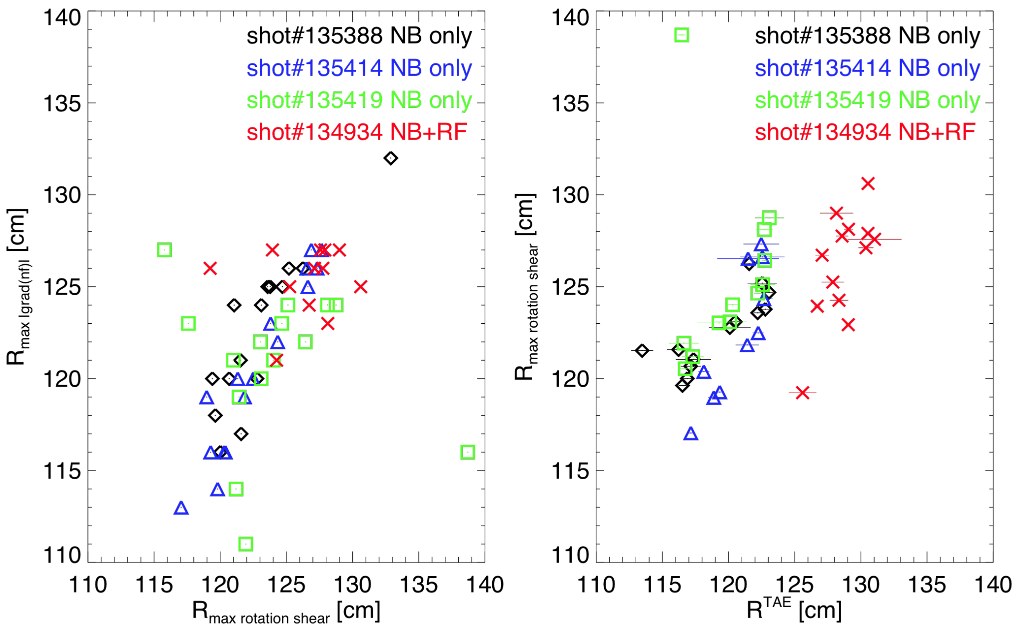


- Modes' *location*, R^{TAE}, obtained by matching with measured rotation profile:

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

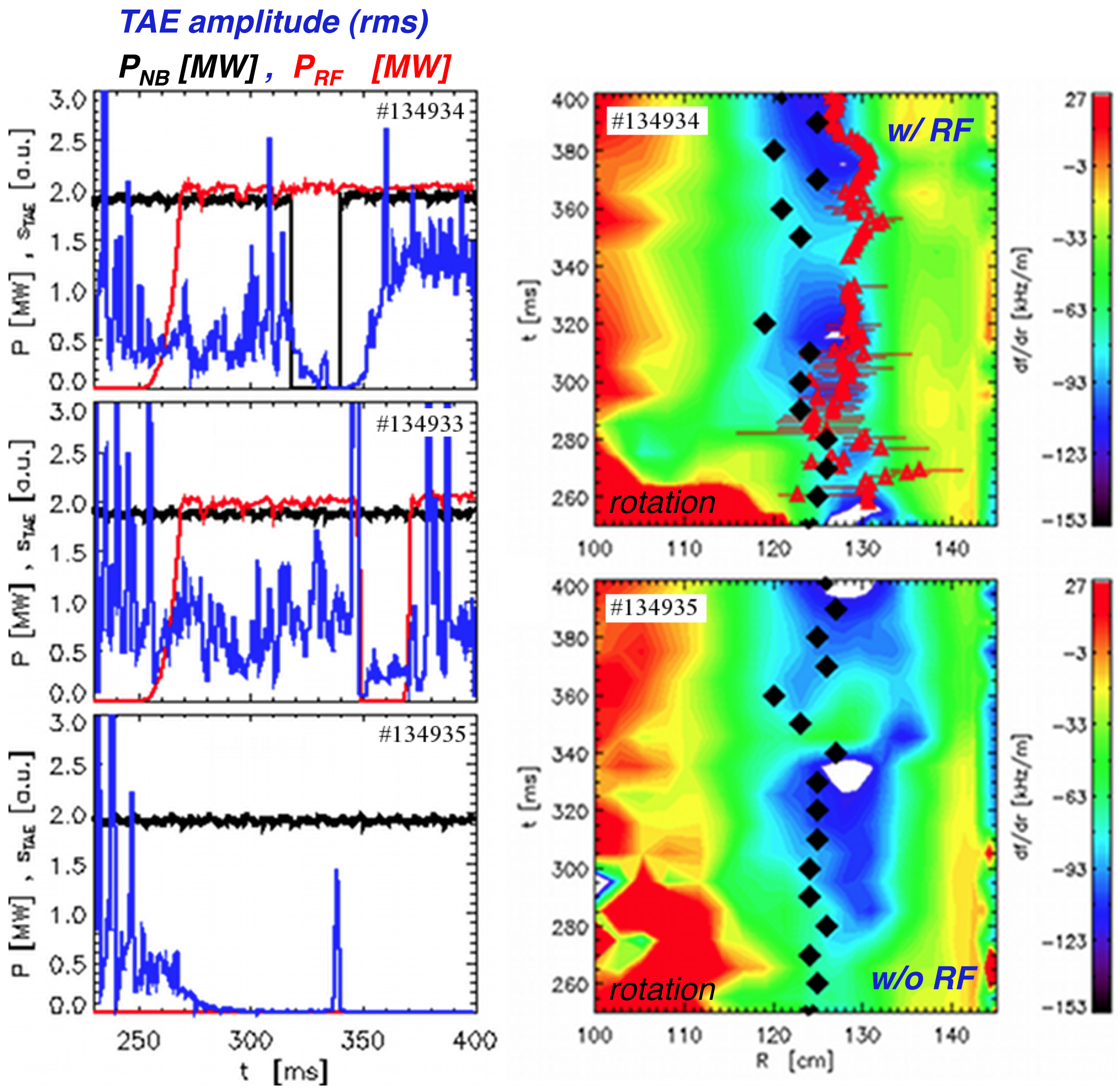
- Correlation between
  - *Mode location*
  - Max rotation shear
  - Steepest fast ion gradient

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



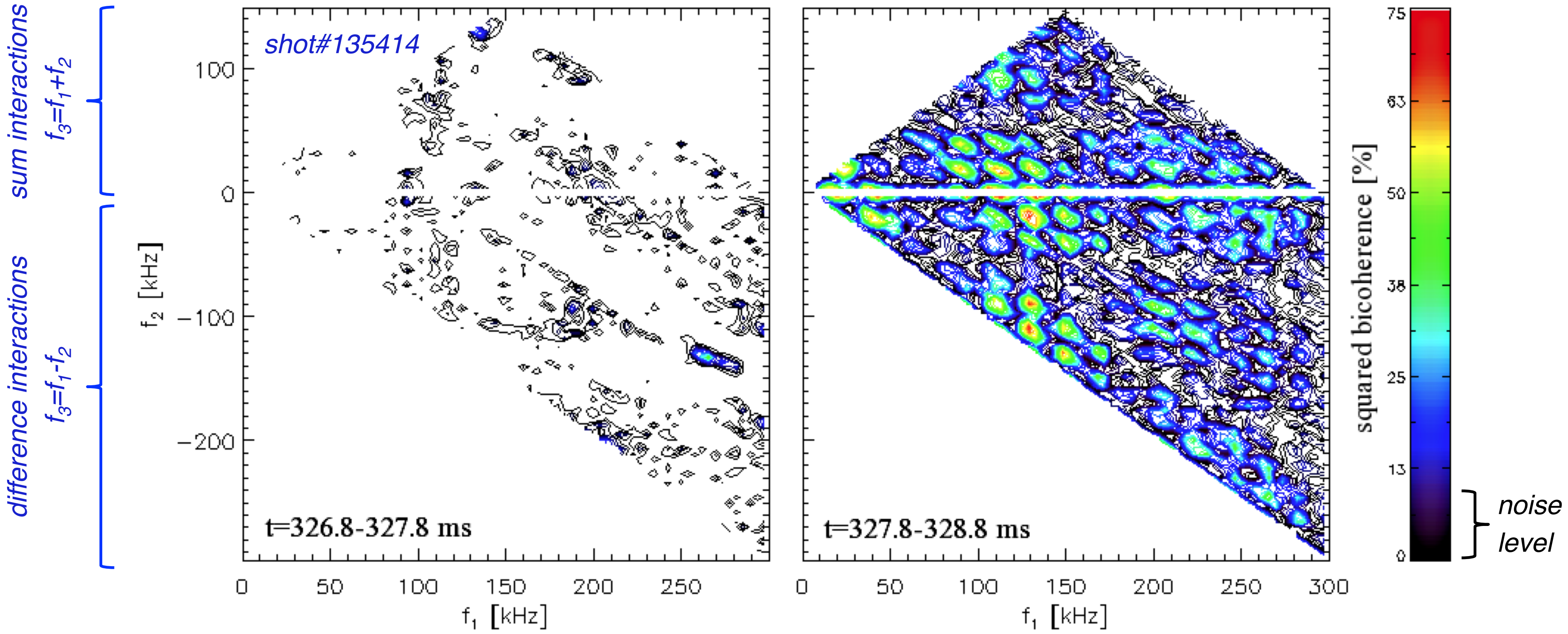
Effects of TAE drive are key factor in determining the observed bursting dynamics

- Bursting dynamics is preserved when drive, $f^{TAE}_{Doppler}$ and shear locations separate
- TAEs respond quickly to notches in NB, RF power
- NB alone is not enough here to drive TAEs unstable



Bicoherence suggests stronger coupling 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 $\begin{cases} n_3 = n_1 \pm n_2 \\ f_{n_3} = f_{n_1} \pm f_{n_2} \end{cases}$

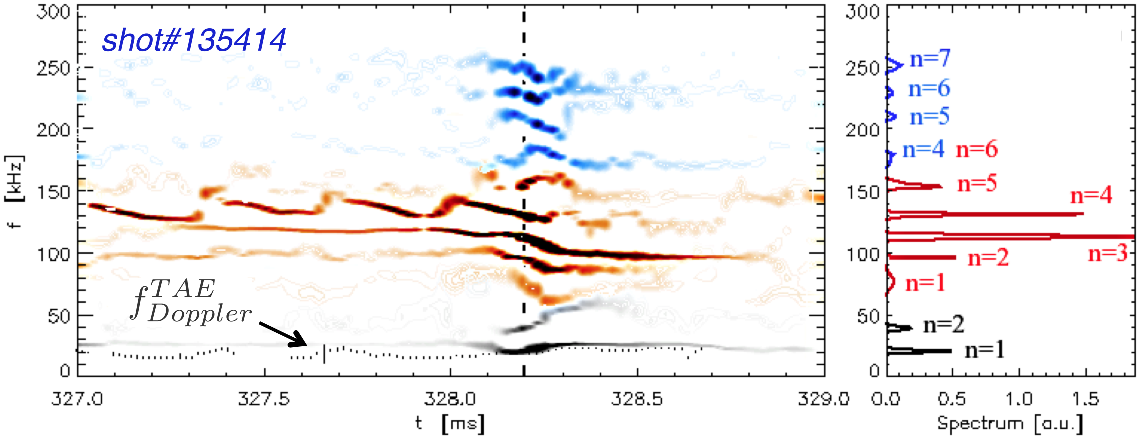
$c(n_1, n_2)$ is the coupling coefficient

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

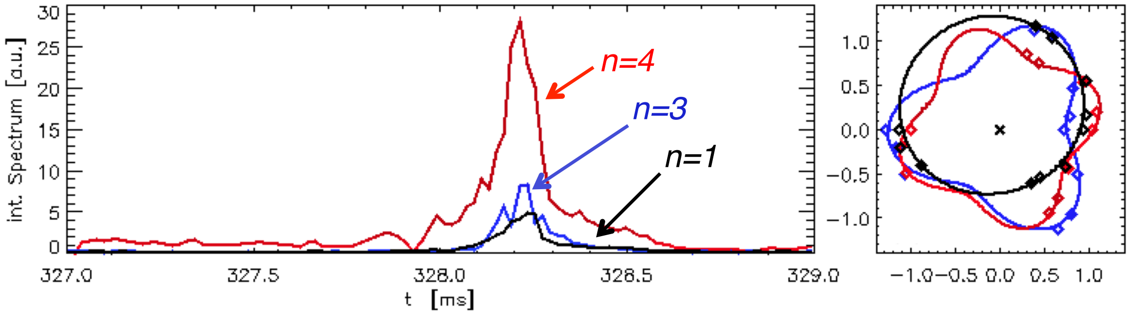
- Modes can be classified into three groups
  - *Discriminants: frequency, temporal evolution*



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?

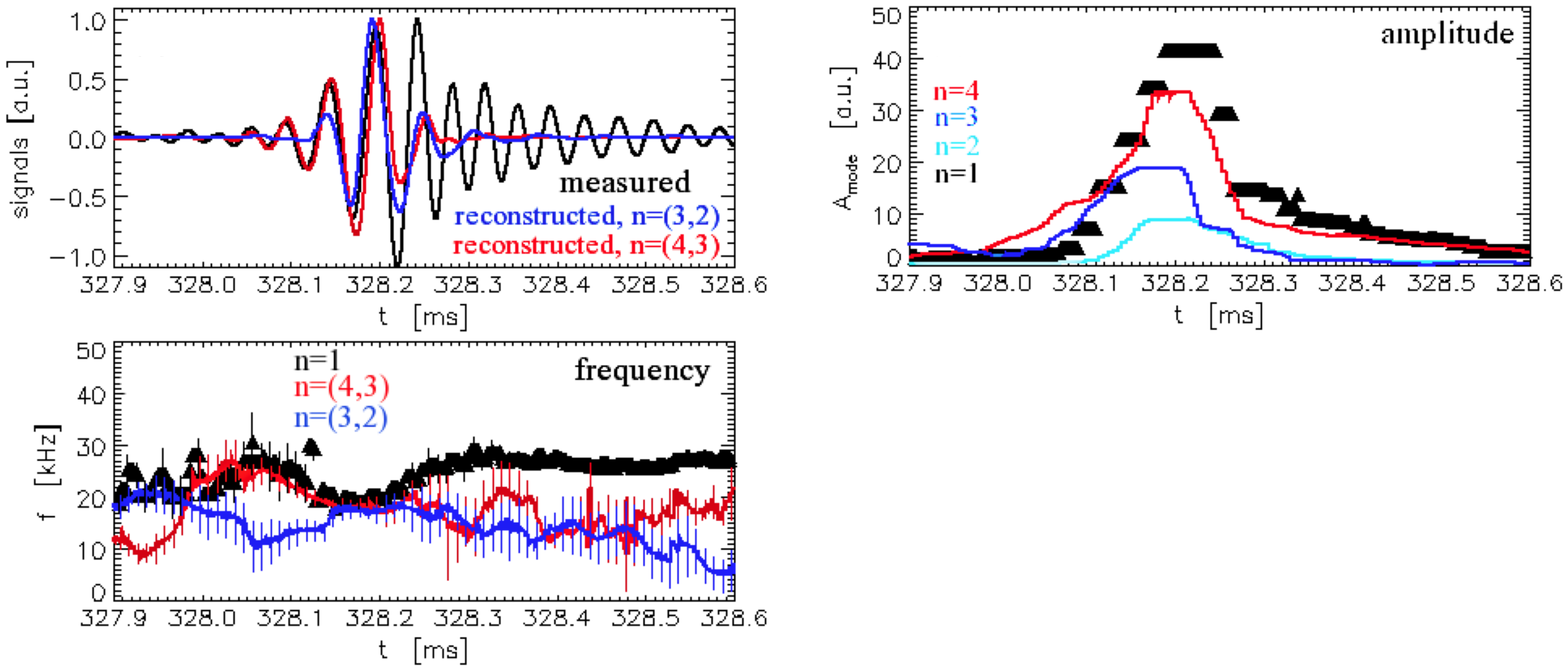


Toroidal mode structure vs. time and mode number from 11 Mirnov coils

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

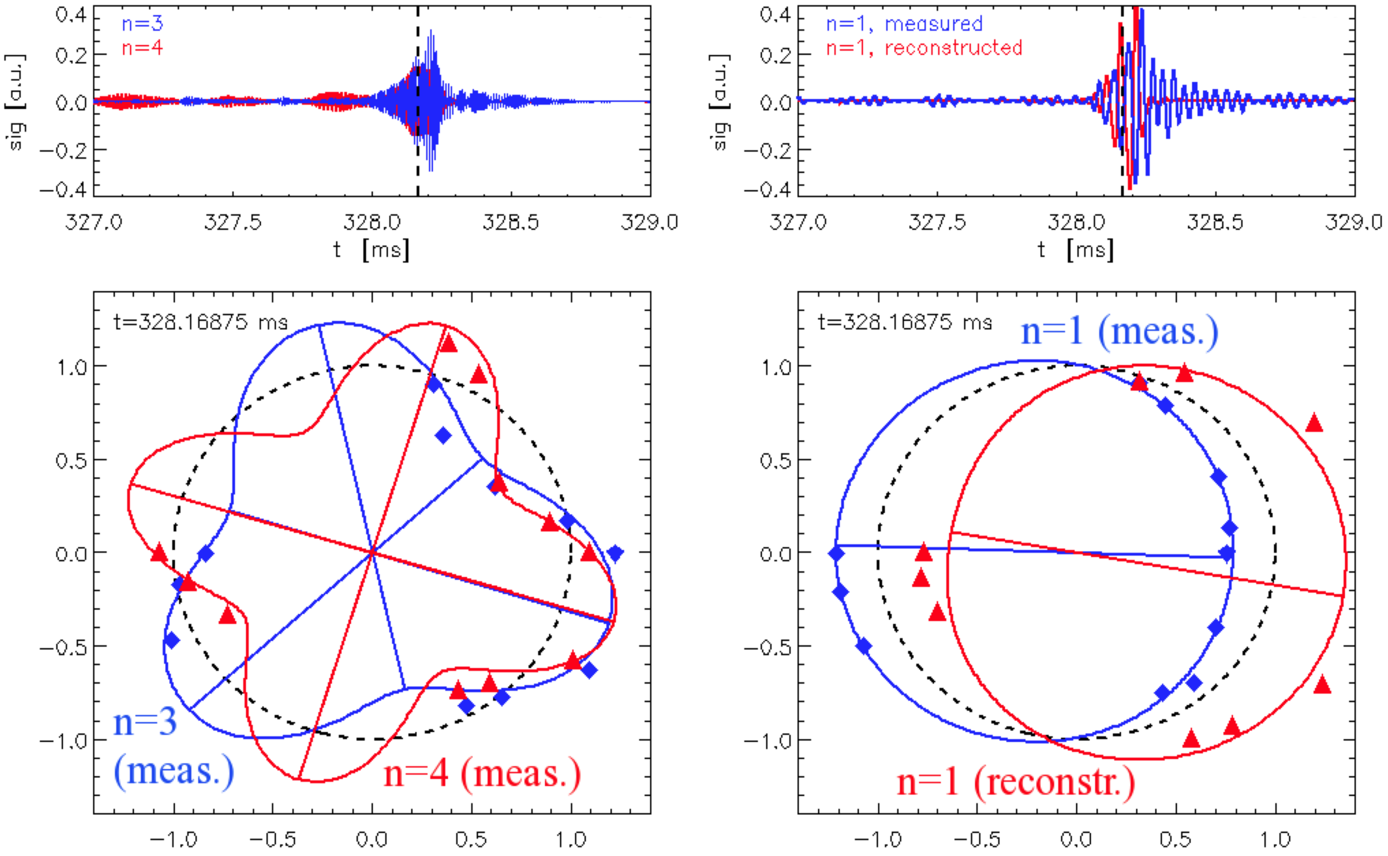
- Picture consistent with primary TAEs
  - coupling to each other
  - generating *secondary* modes through sum/difference with *Δn=1*

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



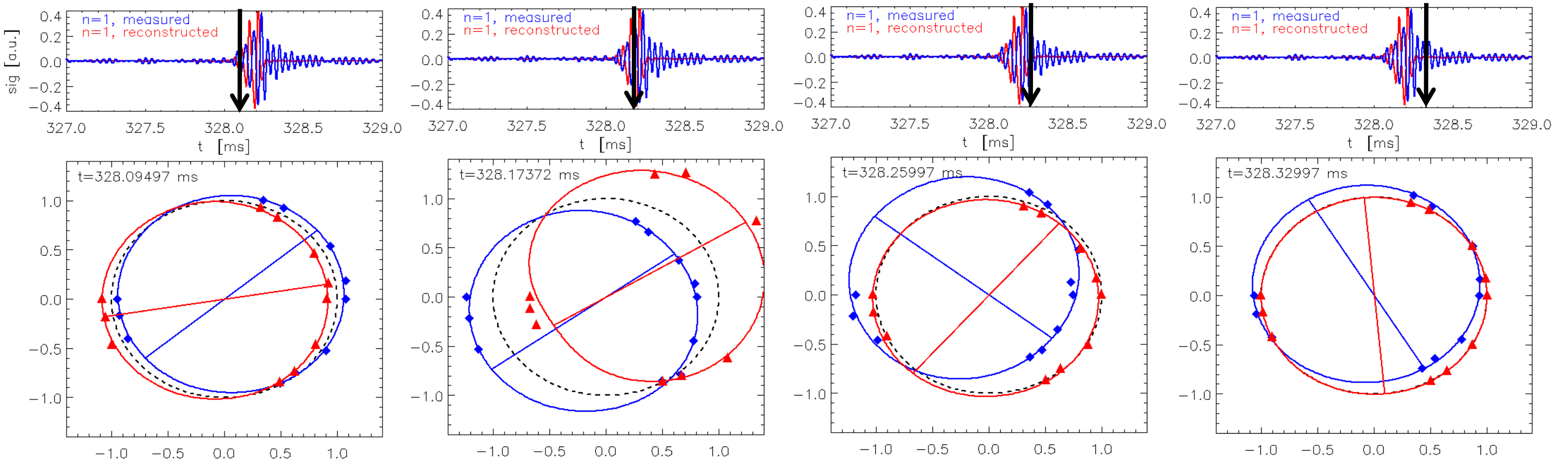
-Symbols: rms mode amplitude data from 11 Mirnov coils

- 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, as expected for “difference” interaction (complex conjugate term)*

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*
  - “Single mode” dynamic, with each mode following its on 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
  - 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 planned; plasma rotation included
  - Improve "linear" analysis (NOVA-K + ORBIT)