Effects of toroidal rotation shear on TAE dynamics in NSTX

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Abstract

The effects of a sheared toroidal rotation on the dynamics of bursting toroidicity-induced Alfvén eigenmodes (TAEs) are investigated experimentally in neutral beam heated plasmas on the National Spherical Torus Experiment. The modes extend over most of the minor radius across a region where a strong toroidal rotation shear of up to 200 kHz/m is measured. However, no clear evidence of increased decorrelation of the modes is found. Instead, experiments indicate a strong correlation between the TAE dynamics and the instability drive. For instance, the amplitude of the bursts increases as the fast ion population builds up and otherwise stable TAEs can be promptly destabilized by auxiliary RF heating, due to modifications of the fast ion distribution. It is argued that kinetic effects involving changes in the mode drive and damping mechanisms other than rotation shear, such as continuum damping, are mostly responsible for the bursting dynamics of the modes observed in NSTX.

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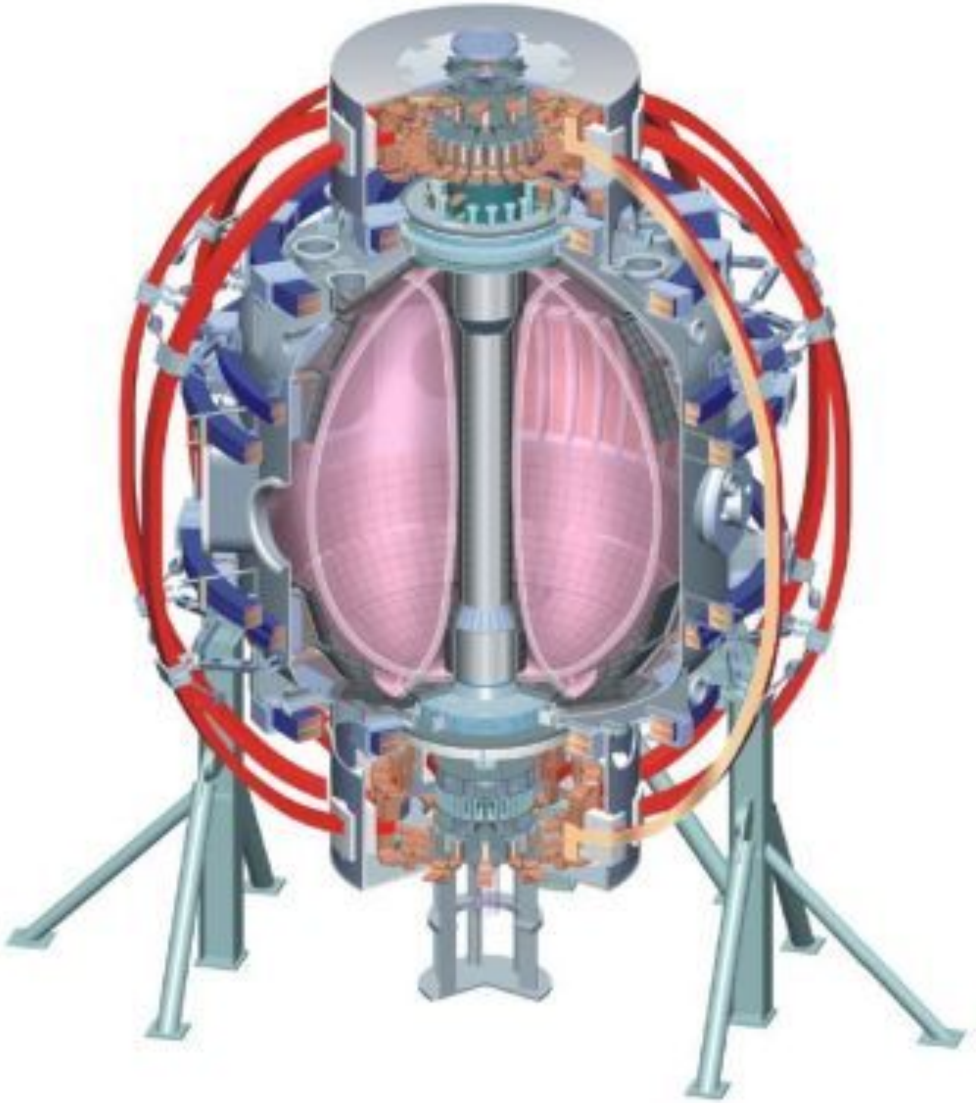
NSTX parameters



Major radius	0.85 m
Aspect ratio	1.3
Elongation	<3
Triangularity	0.8
Plasma current	<1.4 MA
Toroidal field	<0.6 T
Pulse length	<1.5 s

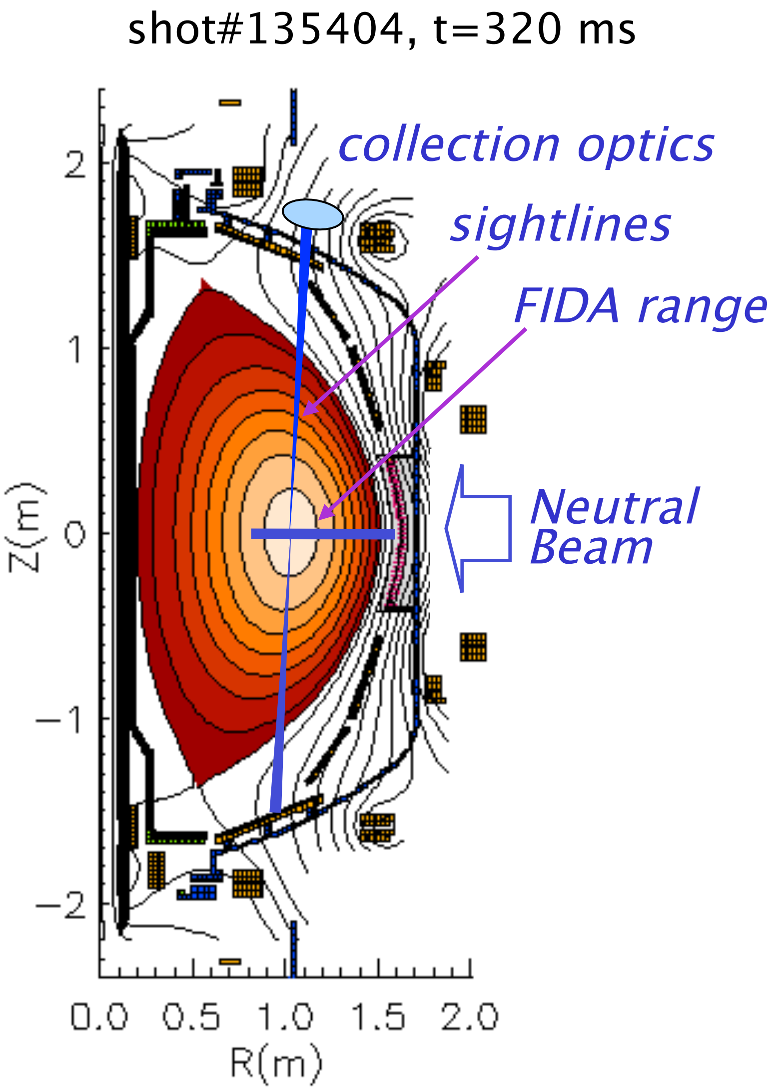
3 Neutral Beam sources

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

⇨ $1 < v_{fast}/v_{Alfven} < 5$

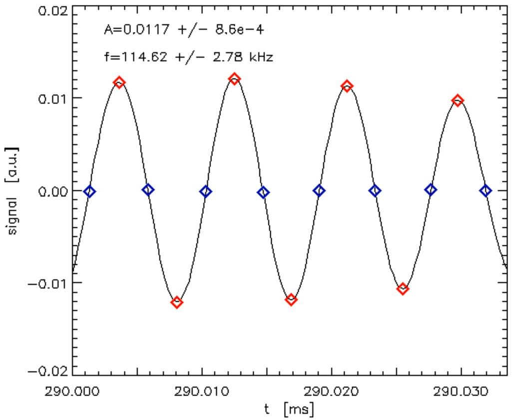
This work:
Focus on TAEs in L-mode plasma
Center-stack limited
Deuterium plasma
B_{tor}=0.55 T, I_p=0.7-0.9 MA

Mode activity and fast ion diagnostics on NSTX



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

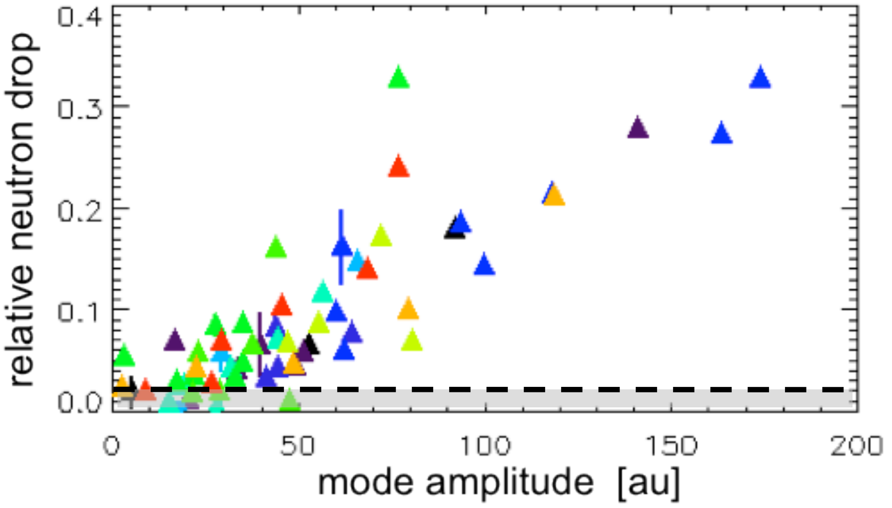
FFT analysis complemented by analysis in time domain to study mode dynamics over short time scale



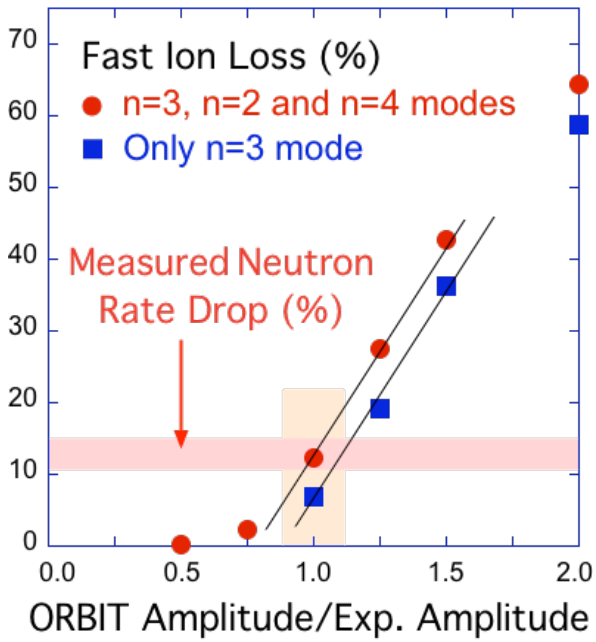
- Fast Io ystem
  - Fast ion profile and spectrum through active charge-exchange recombination spectroscopy
  - Weighted toward small pitch (perp. component)
- Neutron rate, NPA, sFLIP

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)*

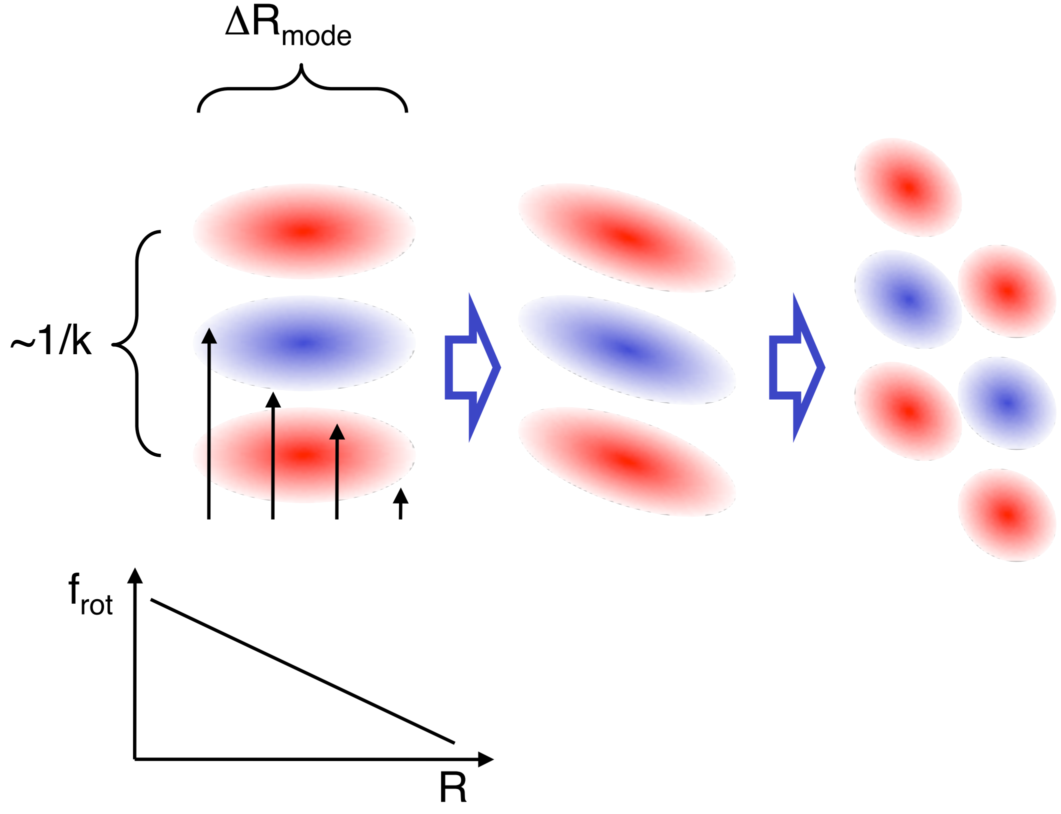


NOVA + ORBIT simulation

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

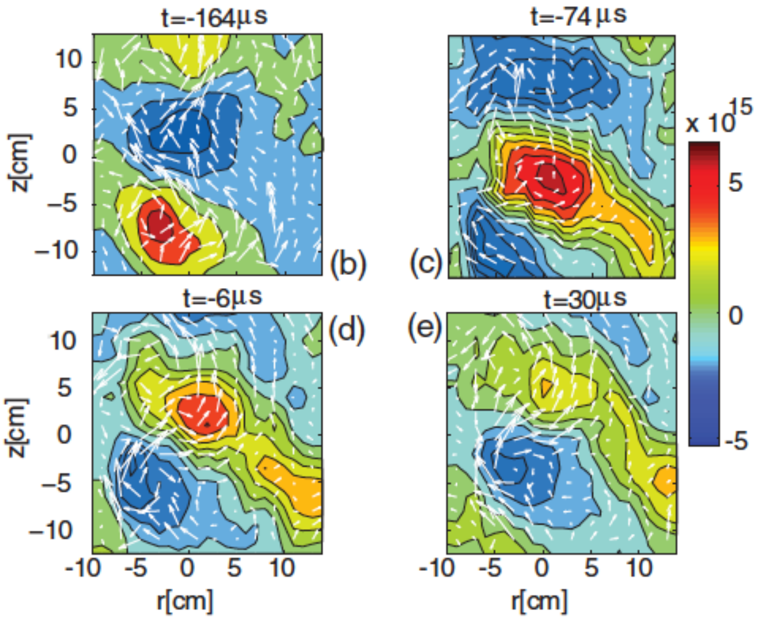
- Need to understand the causes of bursting TAE behavior
- Need to develop tools to control/limit TAEs in future reactors (ITER, STs)

Sheared velocity profile can *shear-off* mode structure, leading to decorrelation → effective damping



Example: *interchange mode in a sheared ExB flow,* $k \rightarrow k_{perp}$

(Density fluctuations from conditionally-sampled Langmuir probe data)

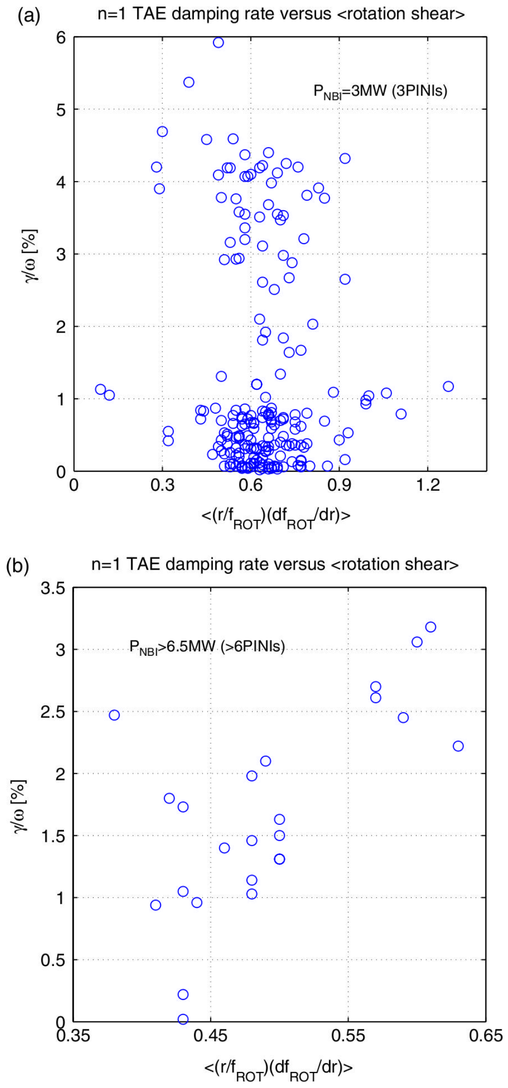


*I. Furno et al., PRL **100** 055004 (2008)*

- If effective for TAEs ($k \rightarrow k_{//}$), it may allow “external” control of mode amplitude
  - e.g.: through magnetic braking, tailored NB/RF deposition, ...

Damping of TAEs by rotation shear explained results from JET, JT60-U

*D. Testa et al., NF **45** 907 (2005)*



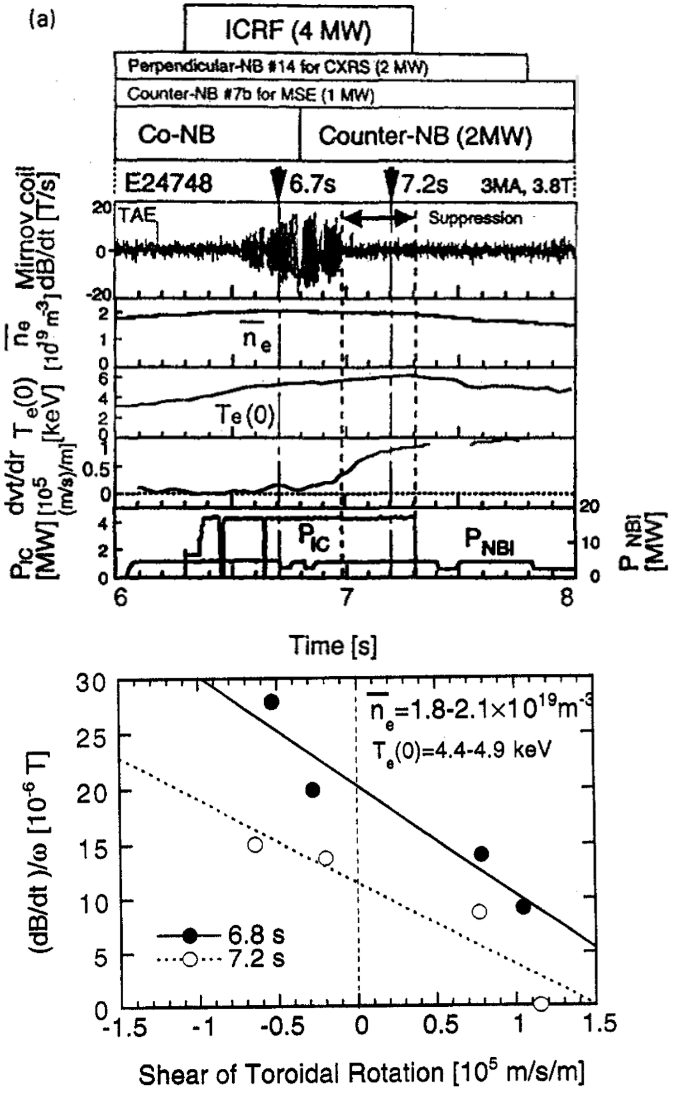
JET

direct measurements of linear damping rate through saddle coils

JT60-U

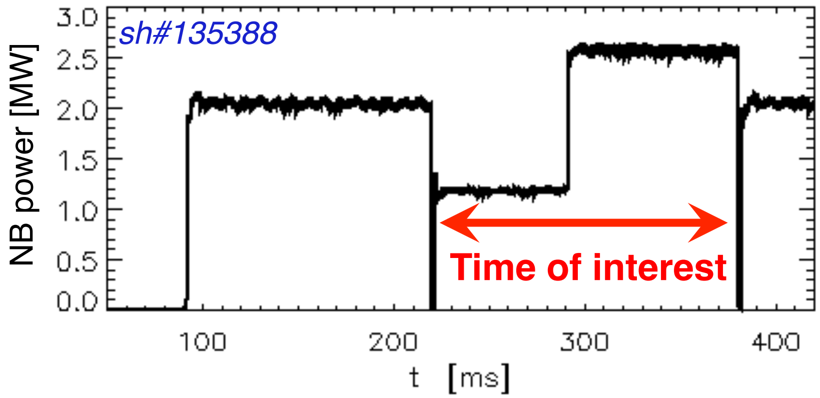
measurements of unstable TAE with different NB/RF injection

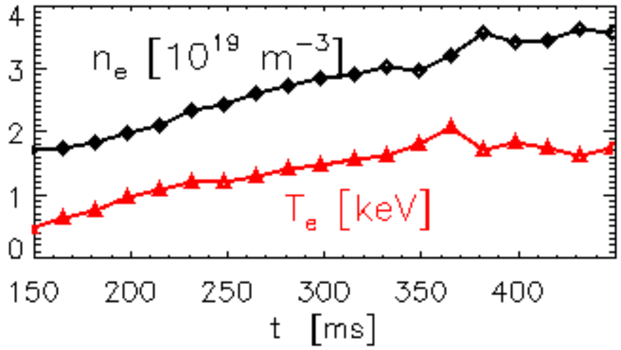
*M. Saigusa et al., NF **37** 1559 (1997)*

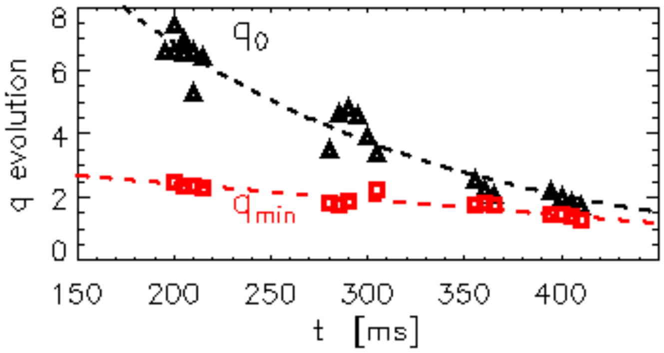


NSTX ?

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

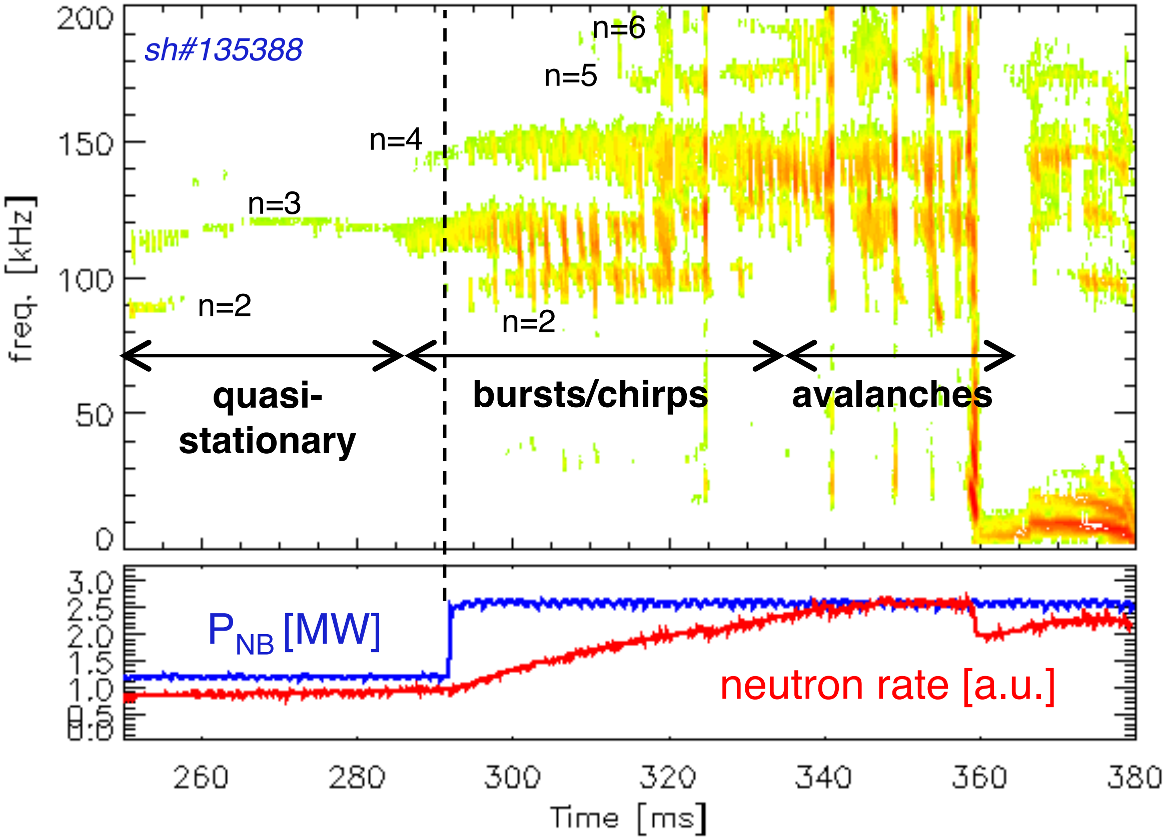






- NB-heated, L-mode plasmas
  - Plasma limited on center-stack
  - NB power and timing varied to affect mode stability
  - Plasma profiles evolving in time
  - Reversed-shear *q* profile
  - Safety factor evolution reconstructed from similar discharges through `LRDFIT` code constrained by MSE data

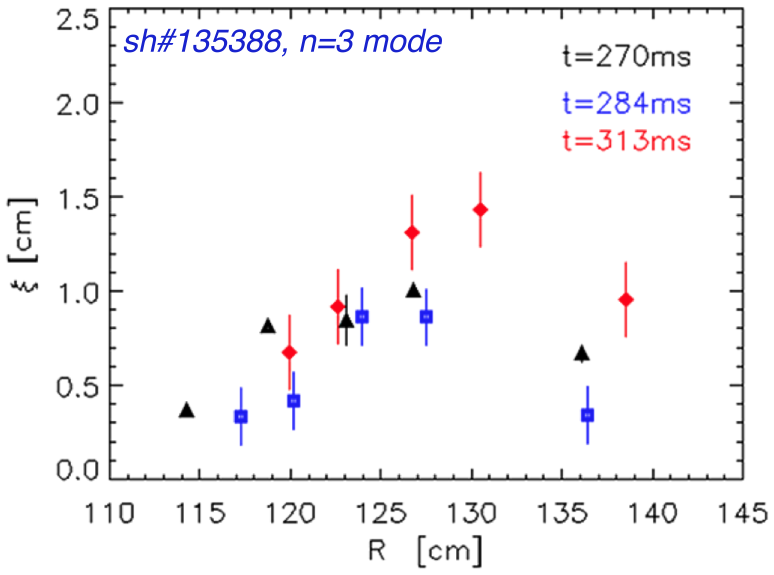
TAEs with low toroidal mode number (n=2→7) are observed, with dominant n=2-4 modes



- Three TAE “regimes” are (qualitatively) identified, with gradual transition from one to the other
  - Classification based on amplitude of bursts/chirps
  - Focus on phase before avalanches

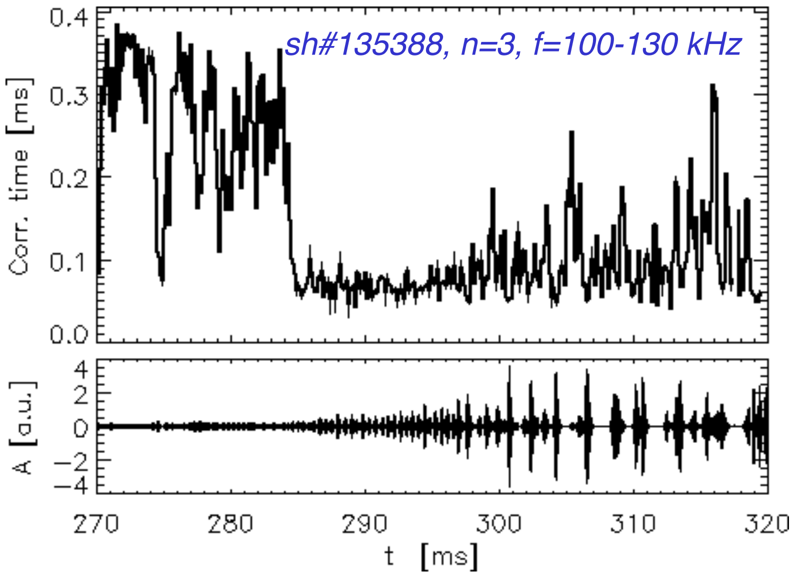
Modes extend over broad region and remain "coherent" over ~0.5 ms

- Magnetic axis: R~105 cm
- LCFS: R~145 cm
- Measured displacement of *n=3* mode:



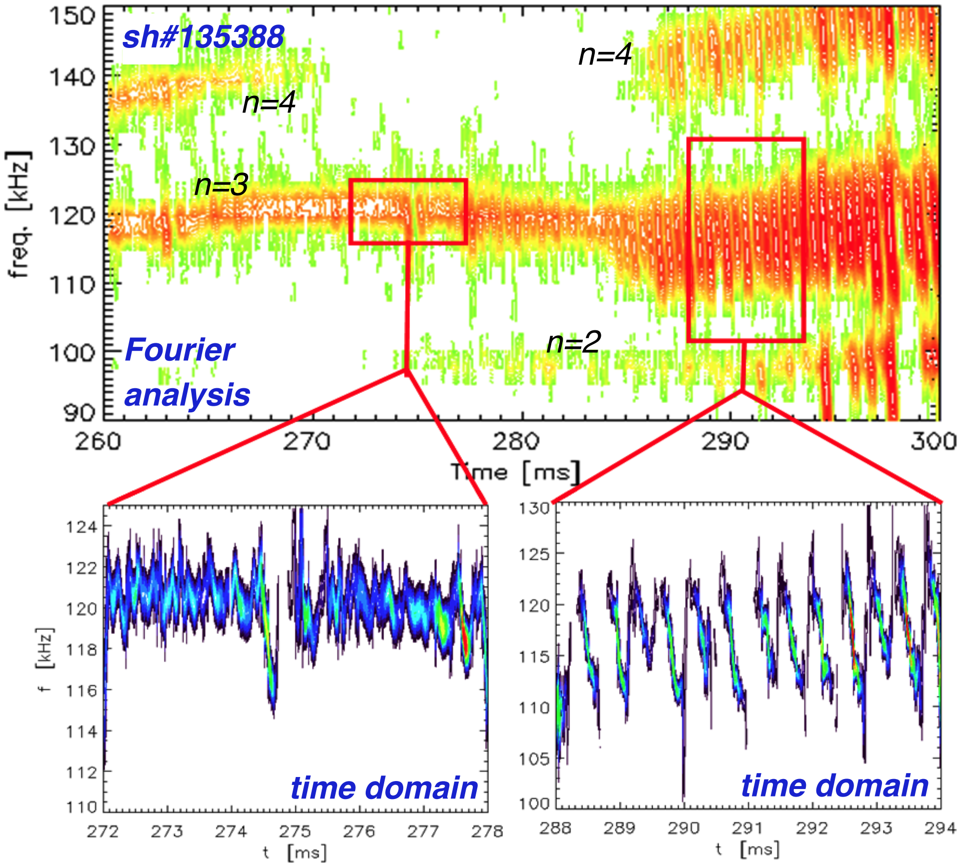
- Auto-correlation time:

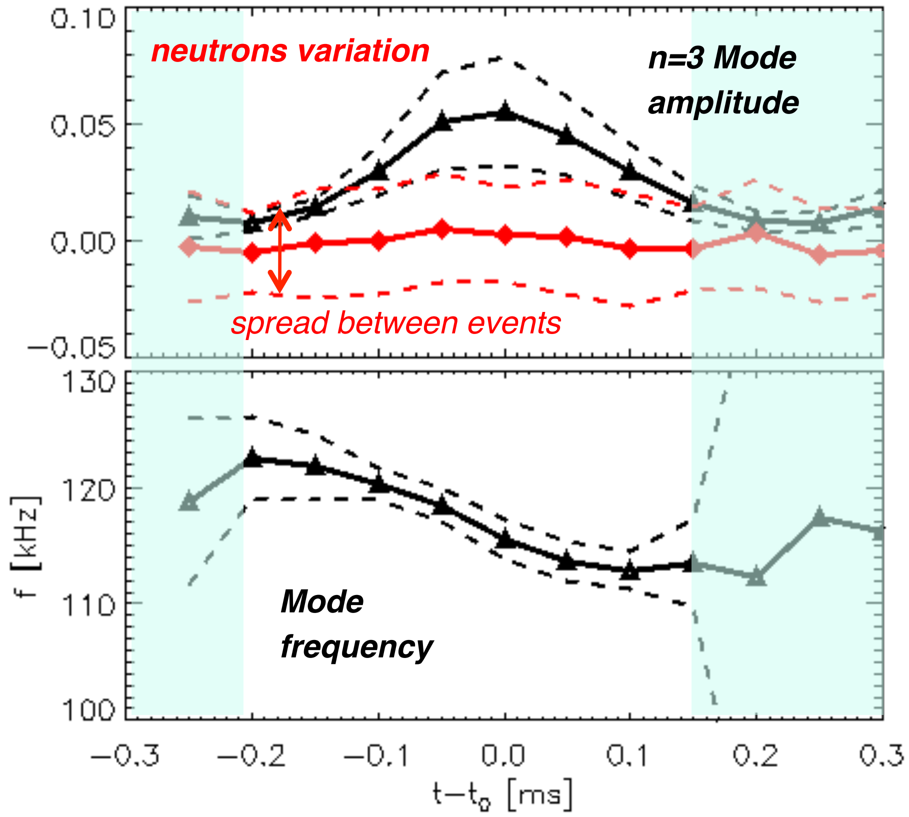
$$\tau_{corr}^{-1} = \tau_{phase}^{-1} + \tau_{freq}^{-1}$$



- Dominated by frequency chirp rate for bursting modes

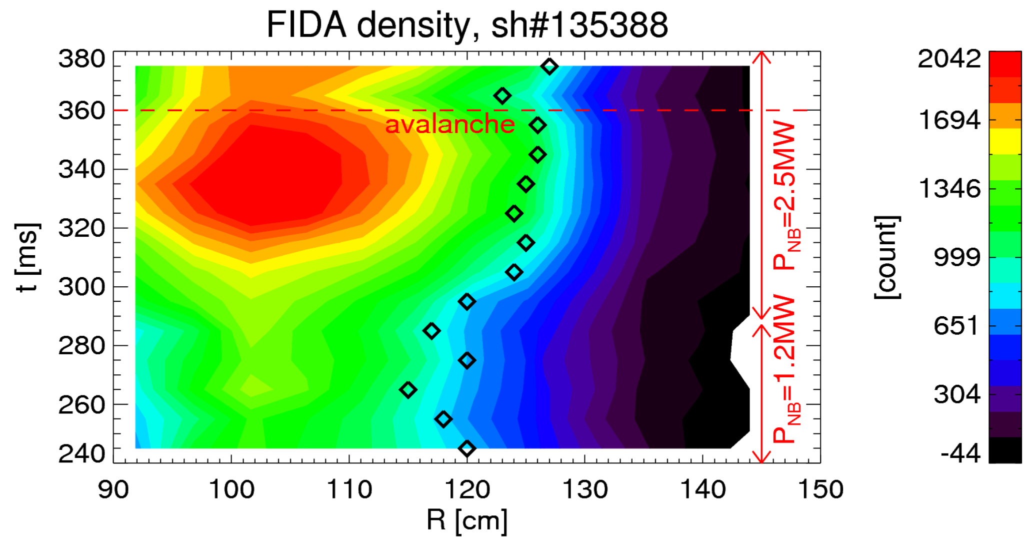
No detectable fast ion losses are observed during weakly bursting/chirping phase

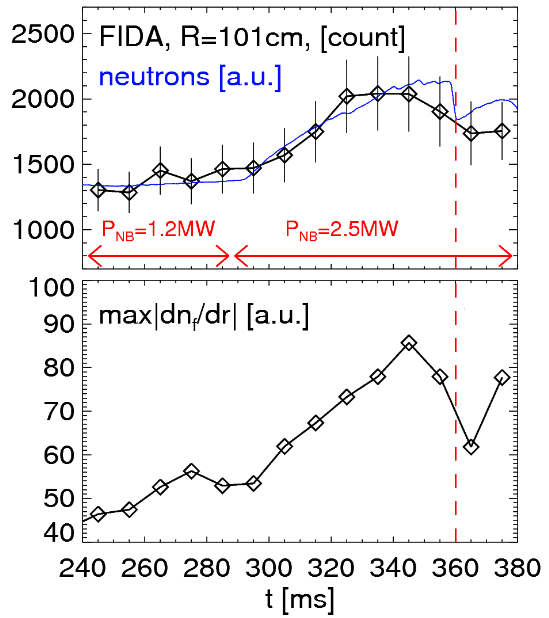


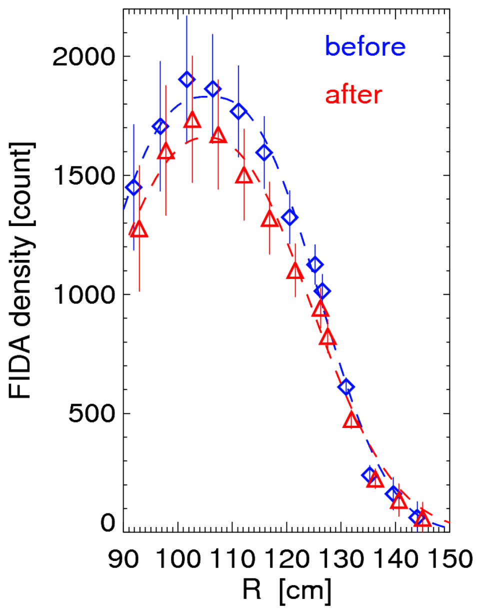


- Statistical average over ~20 events (~10ms)
- No clear evidence of losses from neutrons, FIDA
  - *Does not exclude "continuous" (non-bursting) losses*

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

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

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

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

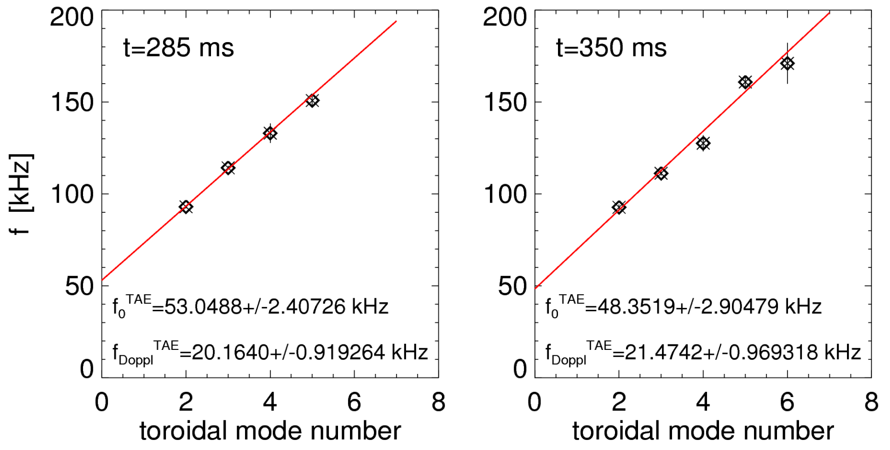
lab frame

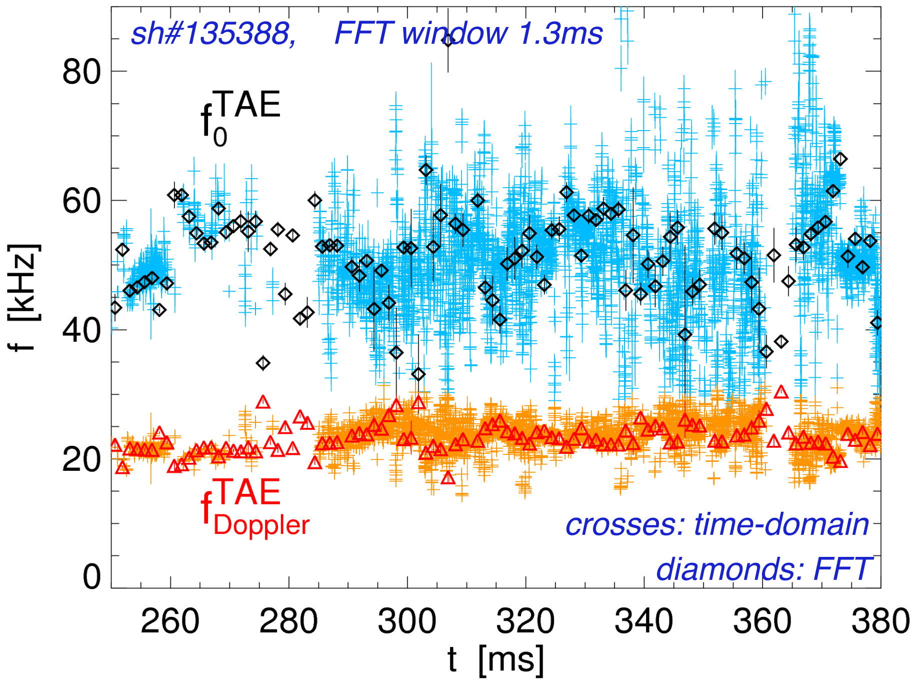
plasma frame

shift from plasma rotation

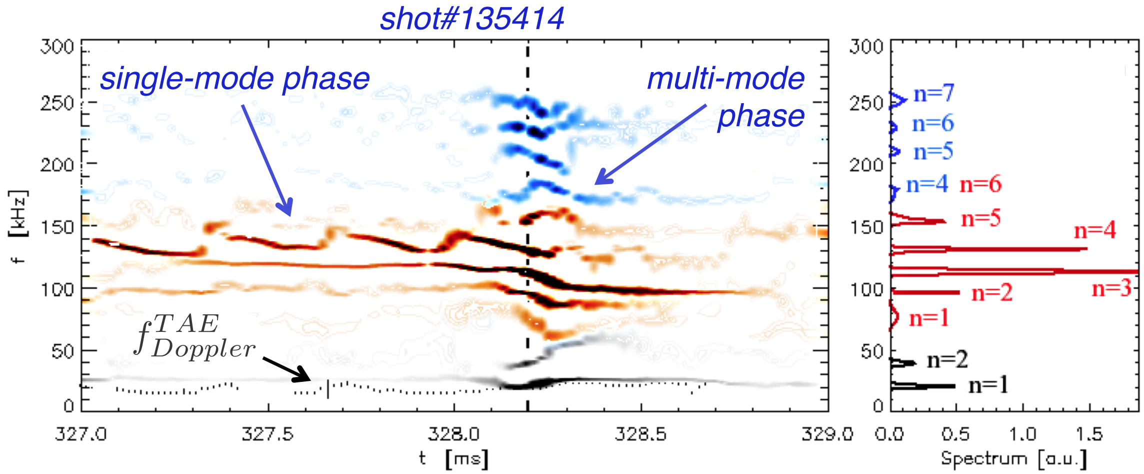
- Valid for time scales >1 ms

- TAEs are not simple harmonics of a fundamental mode
- Not caused by “locking” on stationary mode





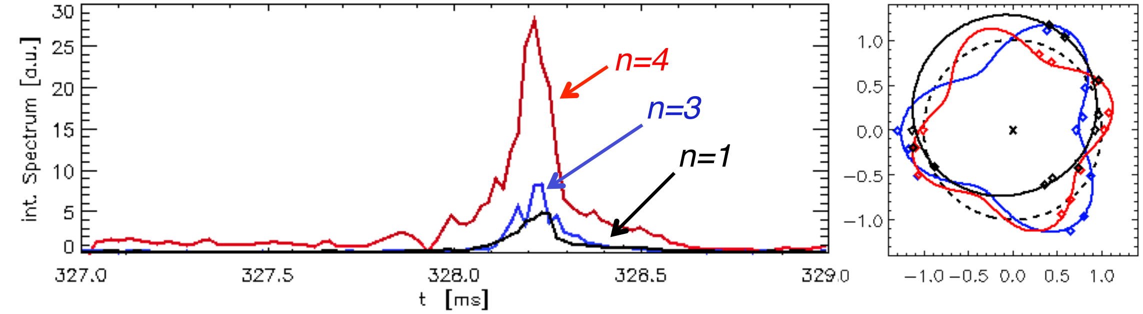
Sub-millisecond dynamic may be different for each mode, *except during large bursts*



High-frequency band; only appears during bursts

"Primary" TAEs; observed during most of the time interval of interest

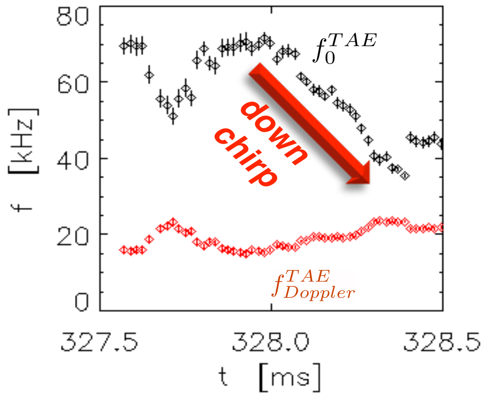
Low-frequency band; appears during large bursts only? Masked by other MHD modes?



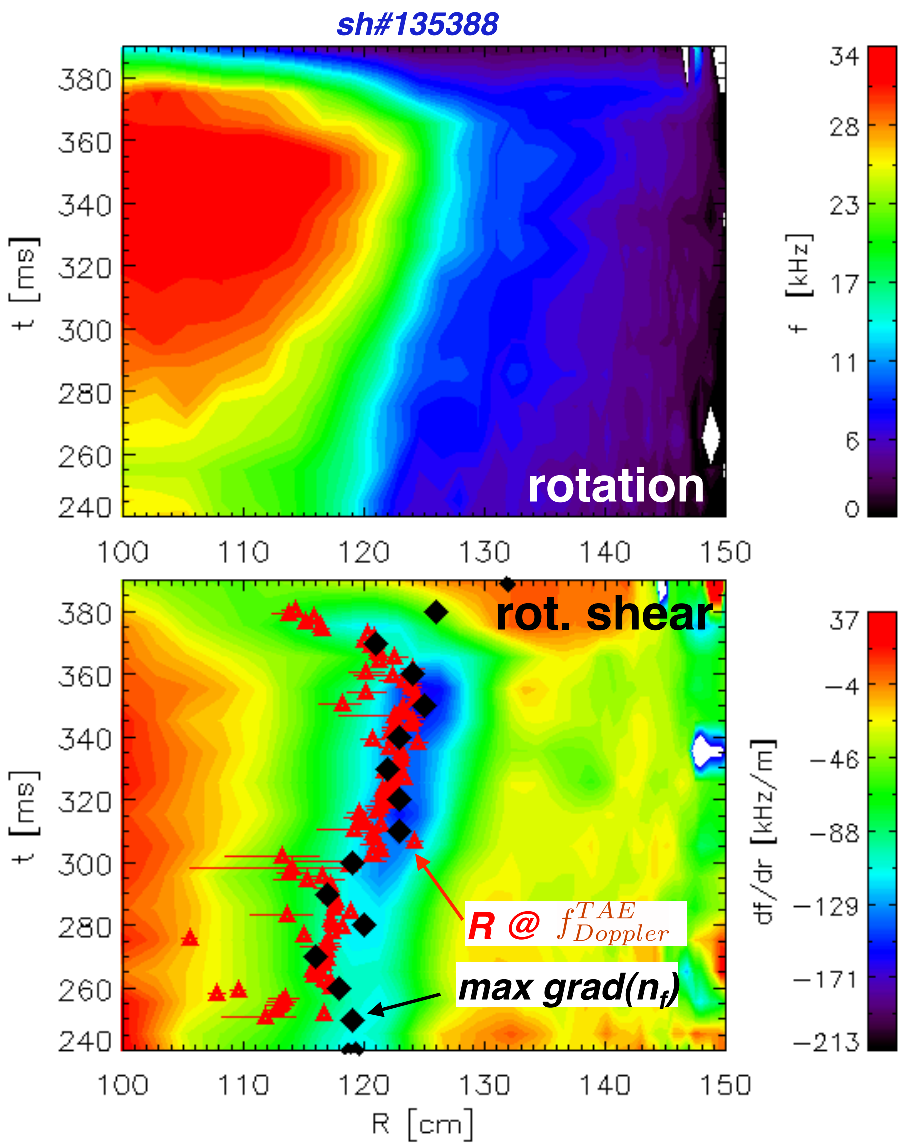
Toroidal mode structure vs. time and mode number from 11 Mirnov coils

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

- Multiple modes chirp down in frequency
  - Observed chirp mostly due to decreasing f_0^{TAE}
- Picture consistent with primary TAEs
  - coupling to each other during bursts
  - generating *secondary* modes through sum/ difference quadratic interactions with *Δn=1*



Understanding TAE dynamic requires detailed knowledge of fast ion drive



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

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

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

Coupling through "source term" (NB injection)

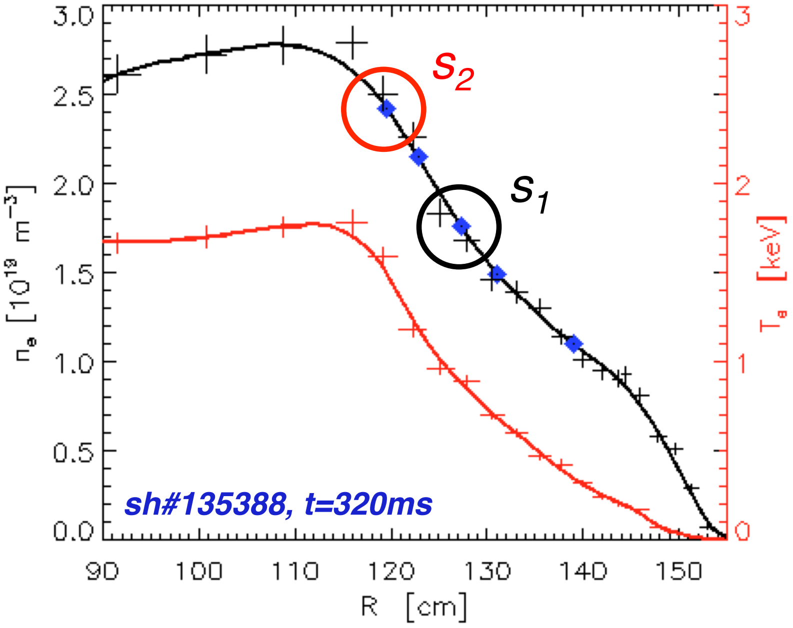
- De-correlation rate:

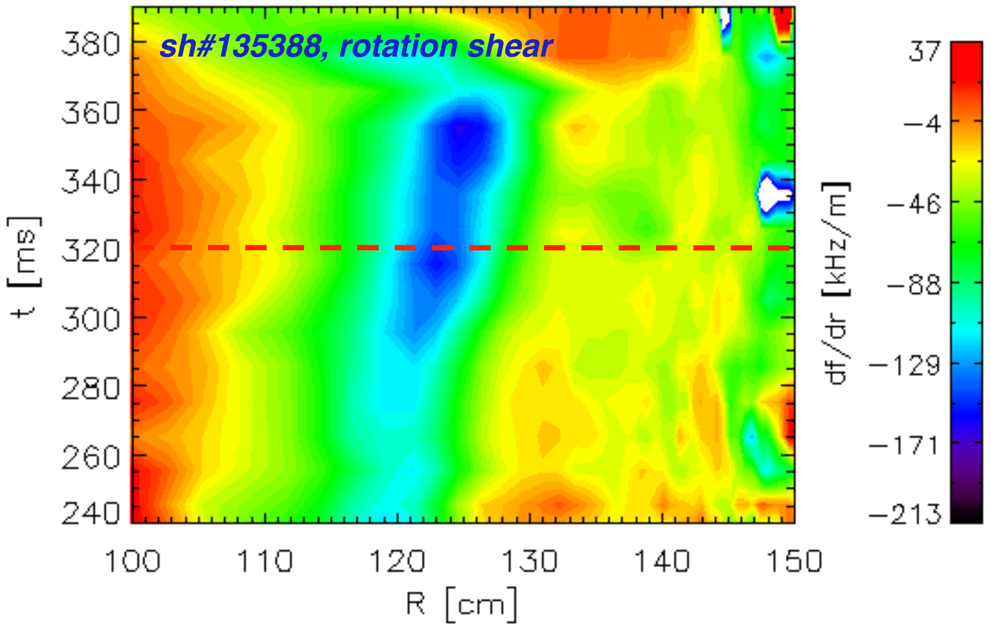
$$\tau_{dec}^{-1} = k_{\|} \Delta R_{mode}\, 2\pi R_{mode} \frac{\partial f_{rot}(r)}{\partial R}$$

$$k_{\|} \quad \approx \quad |n - m/q_{min}| \, / R_{mode} \,, \ \Delta R_{mode} \sim 20 \text{ cm}$$

- τ_{dec}~500μs, comparable with
  - Time scale of frequency sweep
  - Auto-correlation time for TAEs

Multi-channel reflectometer is used to look for decorrelation of TAE across shear layer

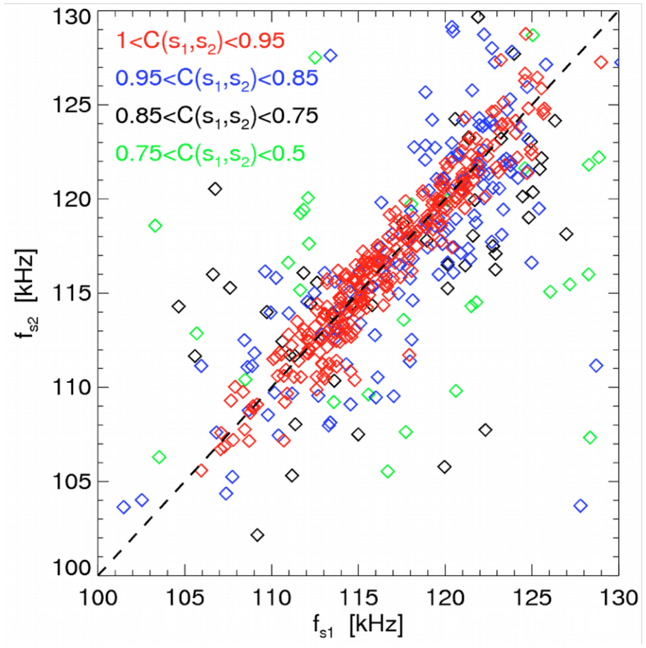




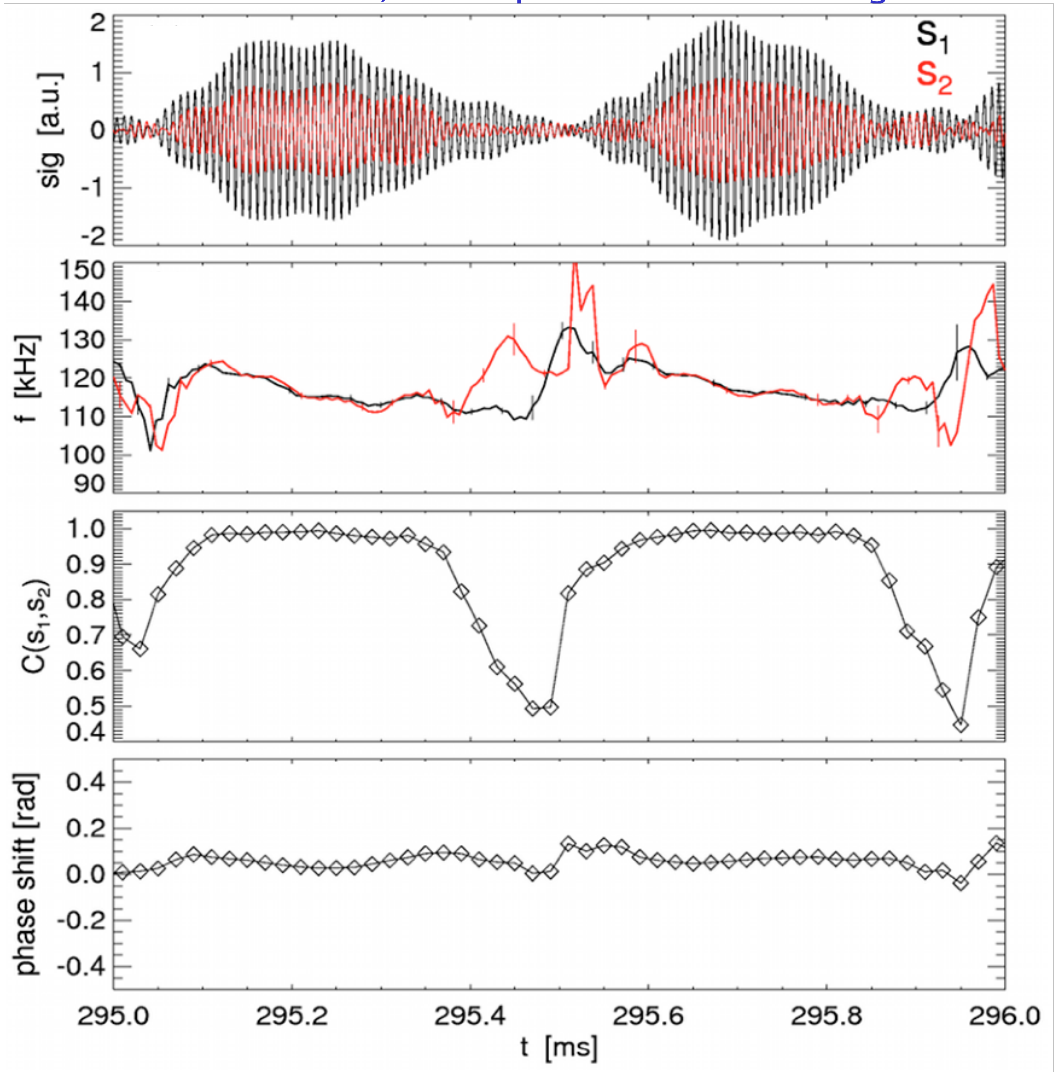
- Band-pass filter signals around mode frequency (ex. $n=3$)
- Reconstruct frequency, amplitude evolution
- Get cross-correlation
- Obtain cross-phase between channels from time delay

Results from reflectometer show no evidence for spatial decorrelation of the modes

- No difference in measured frequency
- Mode starts decaying when cross-correlation is still ~1
- No systematic cross-phase variation

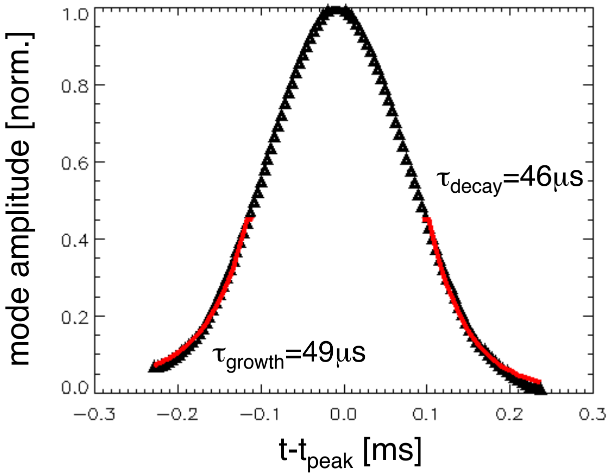


sh#135388, band-pass filtered *n=3* signals

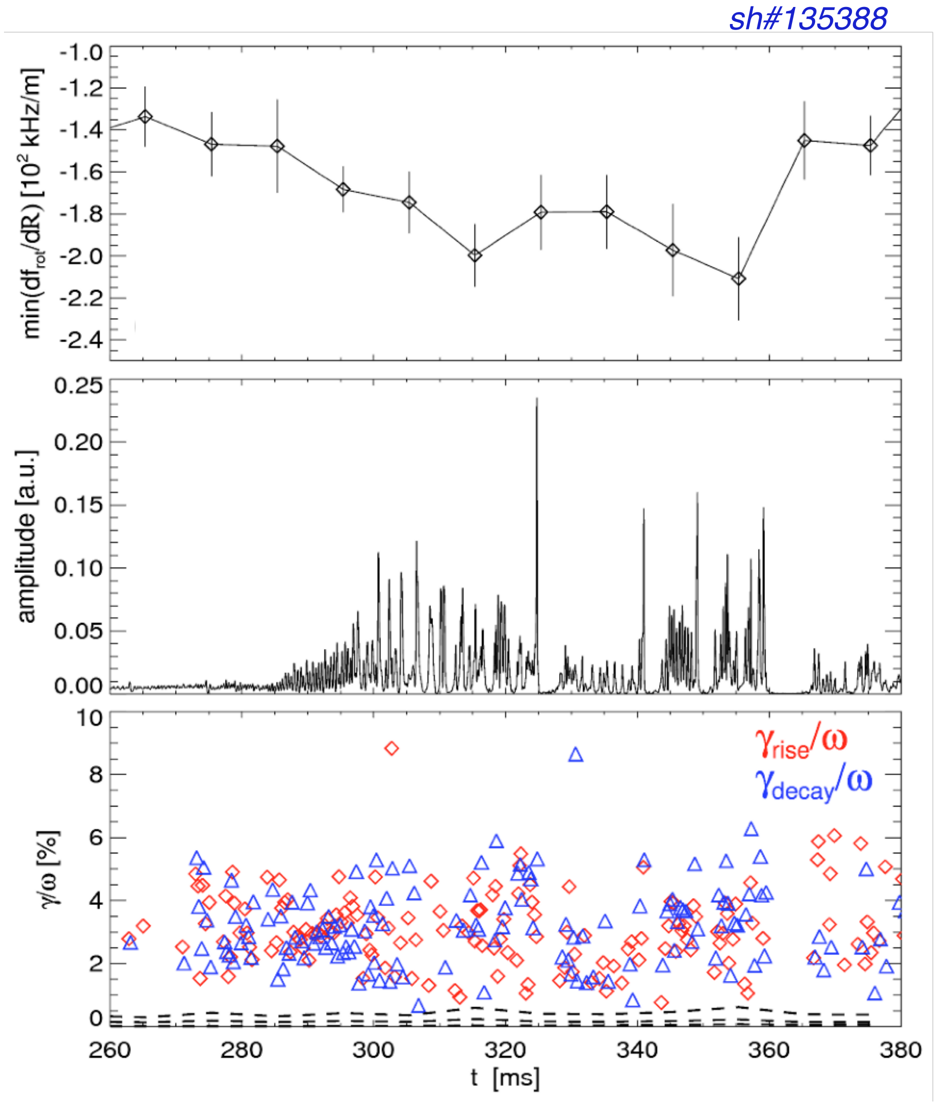


No temporal correlation is observed between shear evolution and mode amplitude rise/decay rates

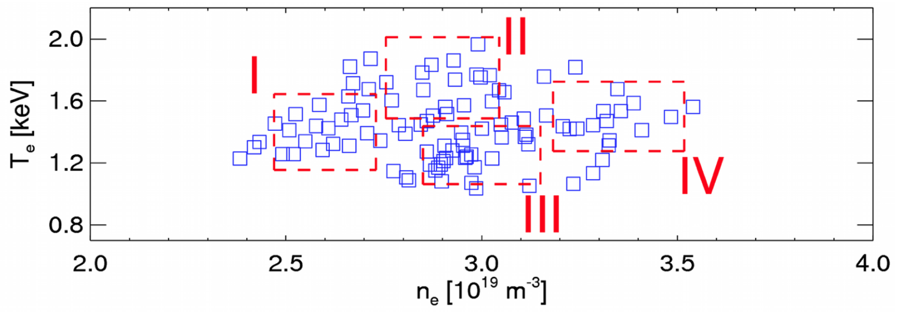
- Effective growth/decay rates calculated from exponential fit (B-dot data)



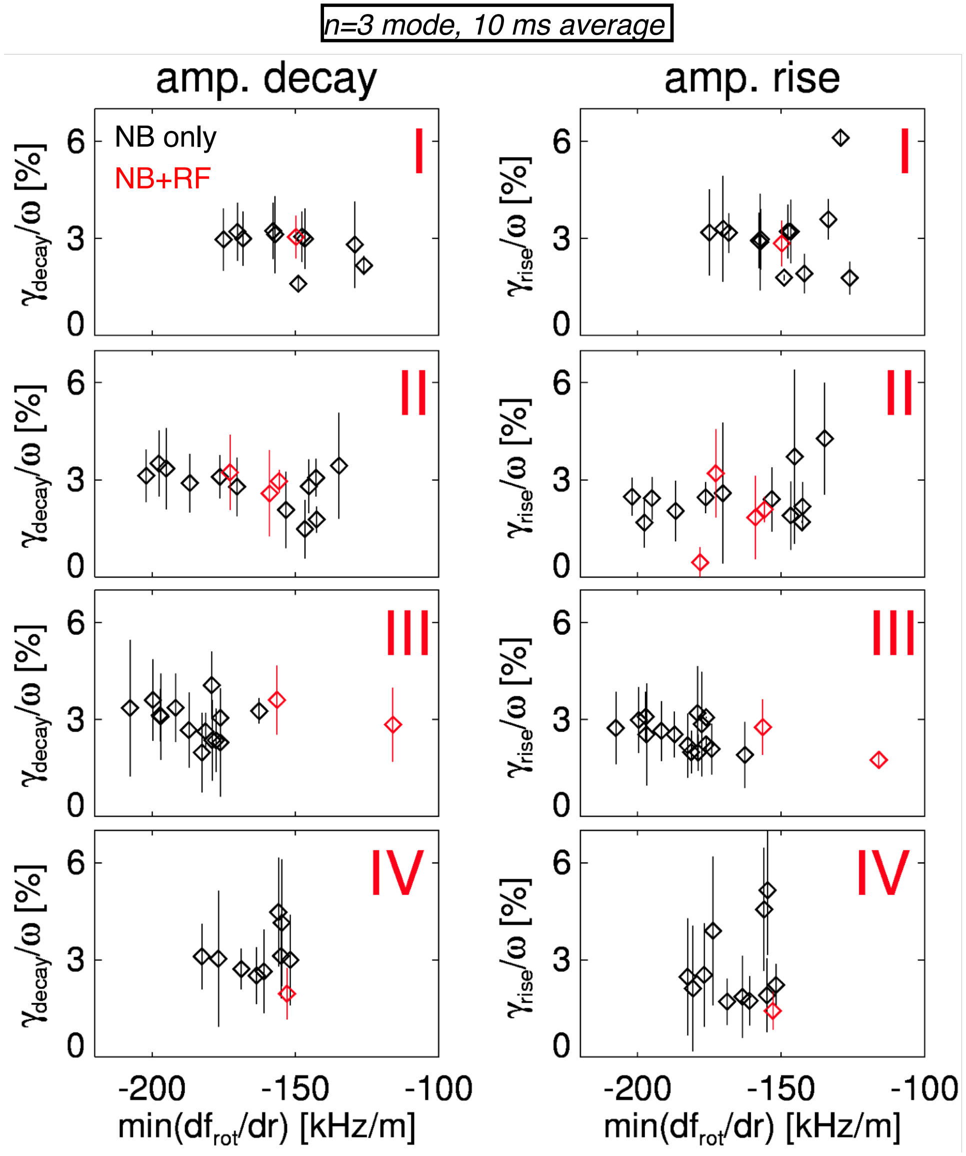
- Shear increases in time
- No correlation with inferred rates



Statistically significant ensemble does not show any clear trend of rise/decay rates on rotation shear



- Database of 10 discharges
- Group data with similar n_e, T_e
  - Similar damping on thermal plasma
- No simple dependence on injected NB power, T_e, n_e, ...
- Trends hidden by changes in *q* profile, gap structure, ... ?

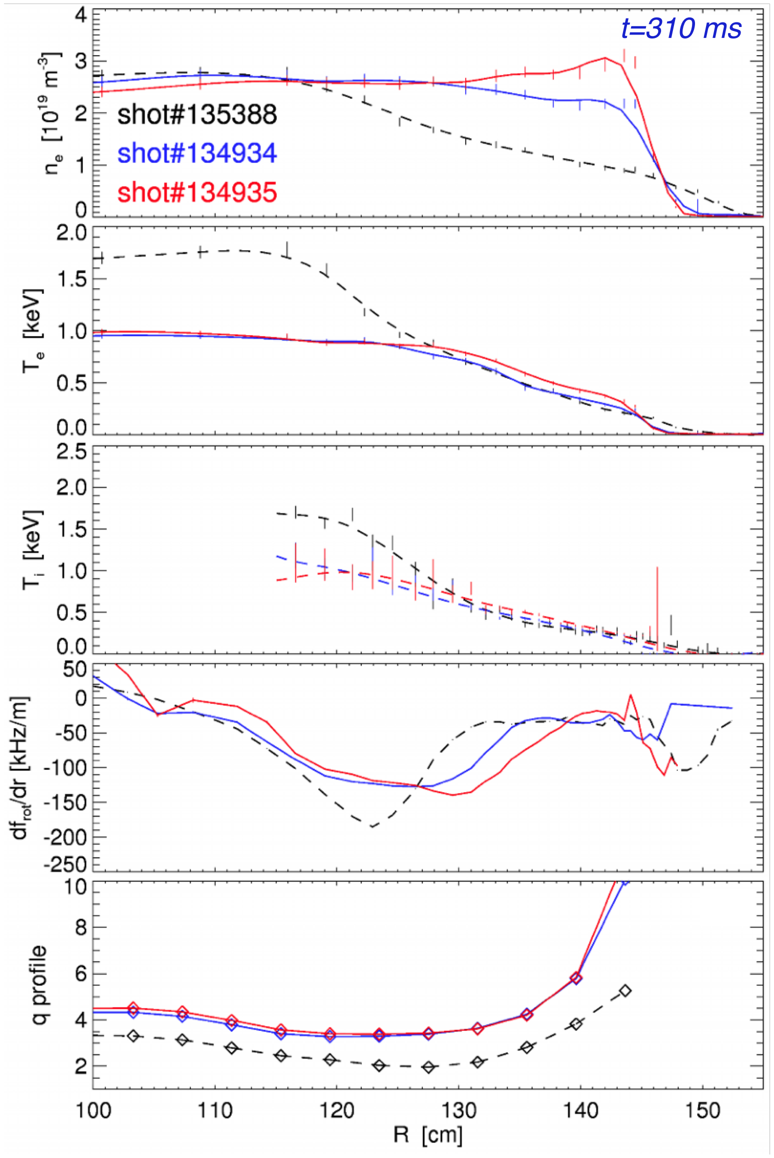


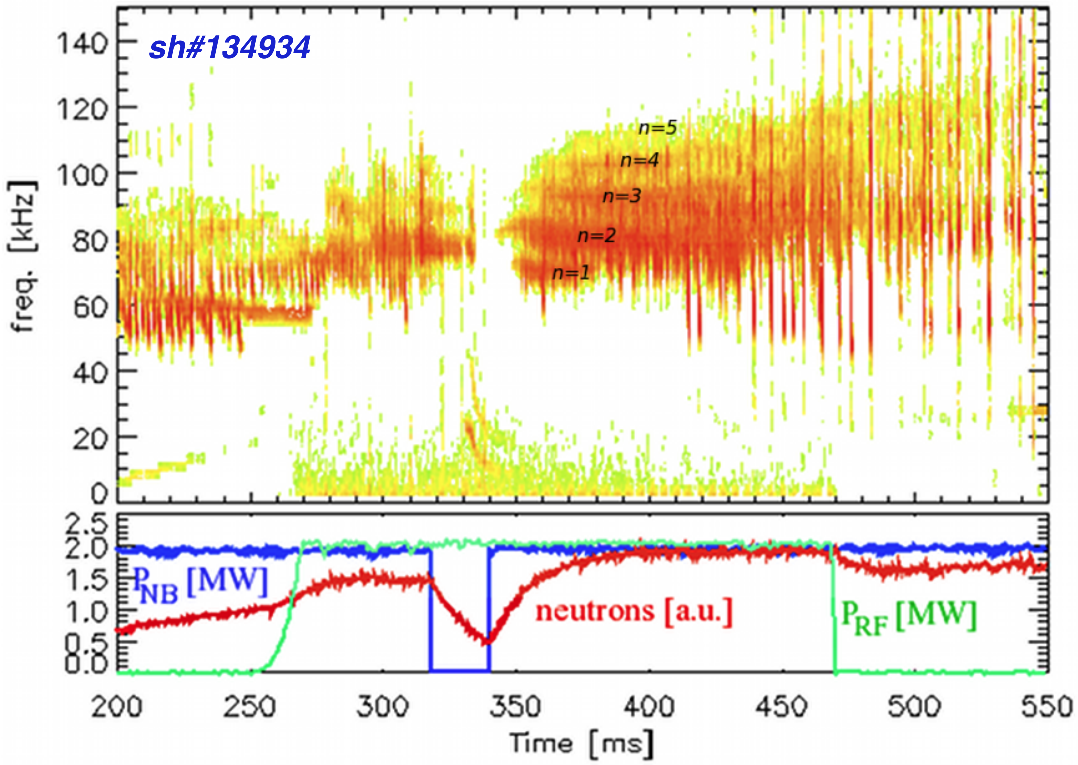
For the discharges analyzed so far, rotation shear plays little (or no) role in the dynamics of bursting TAEs

- NSTX rotation profile usually characterized by strong shear, ~200 kHz/m
- Correlation observed between position of max shear, fast ion gradient, radius where $f_{rot} = f^{TAE}_{Doppler}$
  - NB injection determines both rotation and fast ion profile
- However, no clear impact of sheared rotation is observed
  - No hints of spatial decorrelation (from reflectometer)
  - No correlation between shear evolution and effective growth/decay rates

What determines the bursting TAE behavior?

H-mode, NB+RF discharges: TAE dynamic is similar to L-mode scenario discussed previously

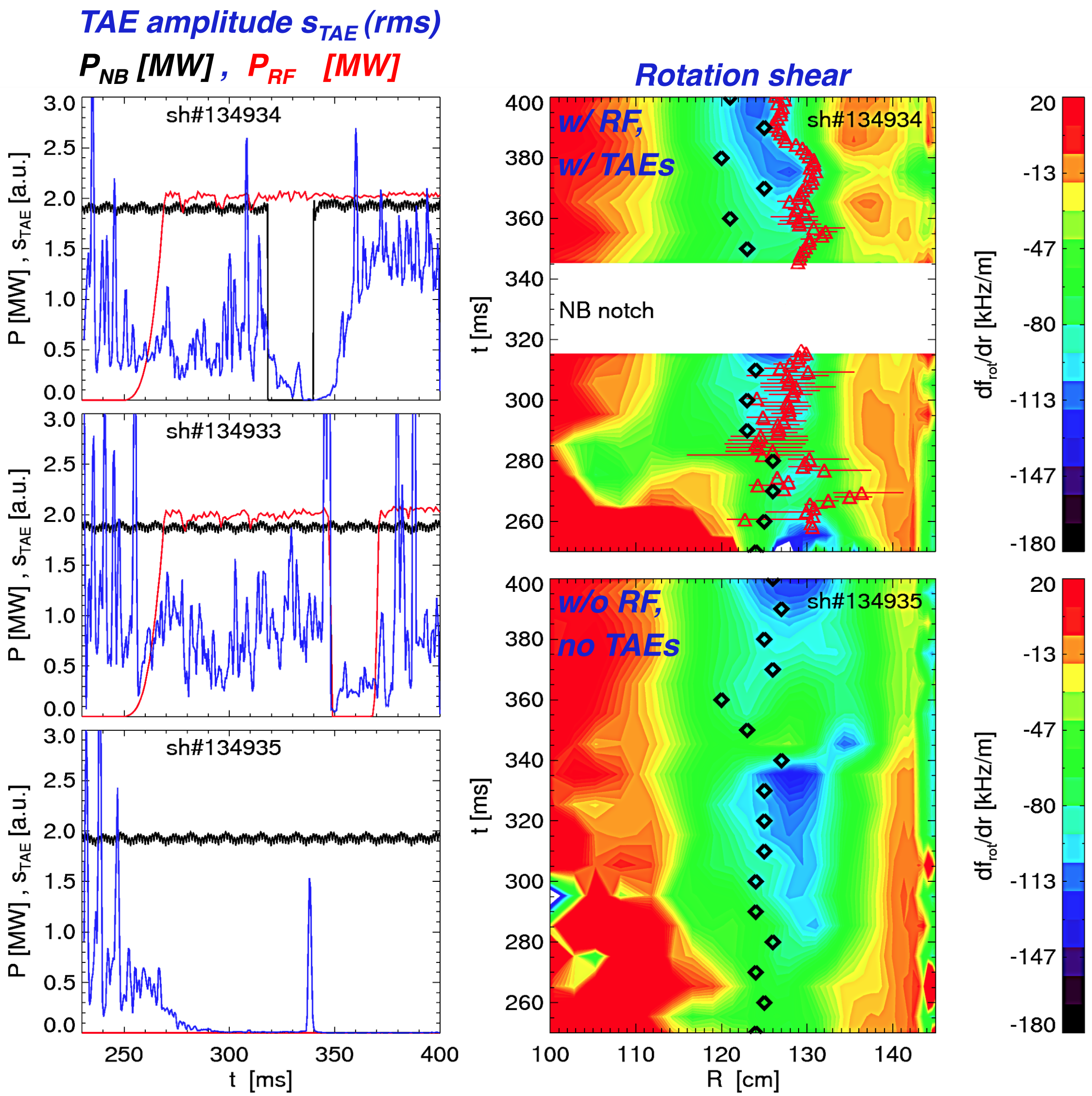




- Move to H-mode discharges with NB and RF heating:
  - Different profiles; shear rate is comparable
  - Similar TAE dynamic as for L-mode

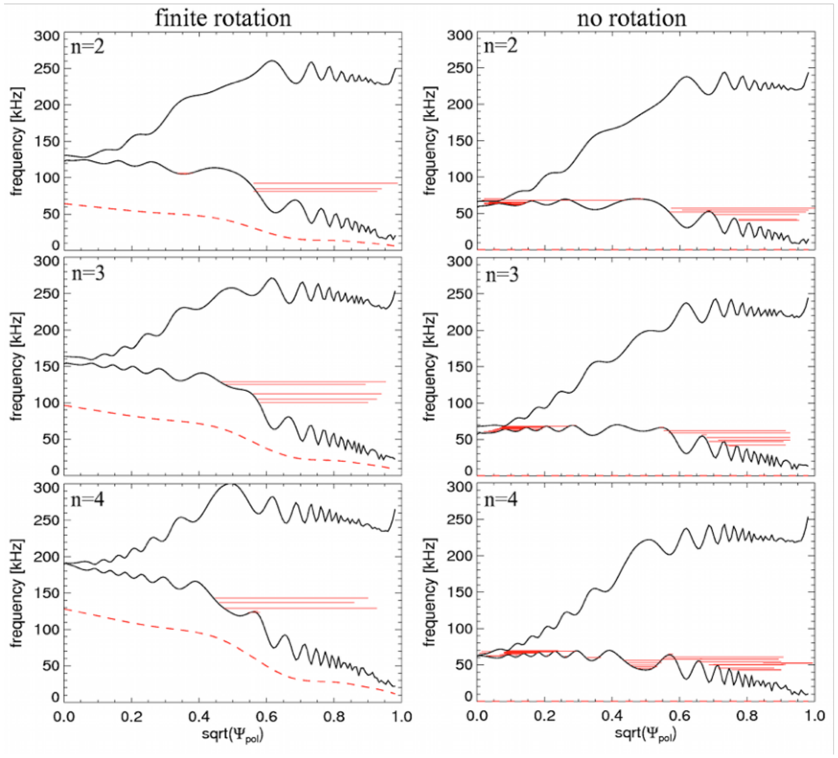
Effects of TAE drive are key factor in determining the observed bursting dynamics

- Bursting dynamic 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



Summary

- Rotation shear seems to have marginal effects on TAE dynamic in NSTX plasmas
  - Experiments suggest that TAEs are mainly affected by other mechanisms: TAE drive, details of fast ion distribution, ...
  - Consistent with Berk&Breizman model for bursting/chirping modes
  - Rotation profile may play an important role
- Bursting TAE regime is “robust” against small variations of plasma parameters
  - Effective amplitude growth/decay rates fairly insensitive to n_e, T_e, P_{NB}, ...



- More experiments planned for near term
  - Perform systematic study of TAEs (and *avalanches*) in H-mode
  - Comparison with M3D-K code planned; plasma rotation included
  - Will continue “linear” analysis (NOVA-K + ORBIT)

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