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

Study of chirping Toroidicity-induced Alfvén Eigenmodes in the National Spherical Torus Experiment

Mario Podestà

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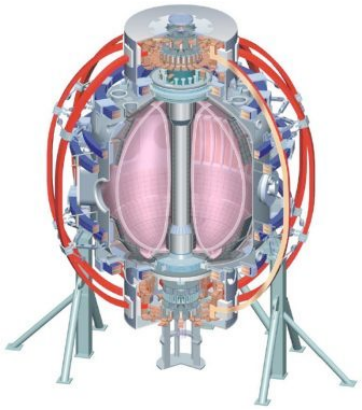
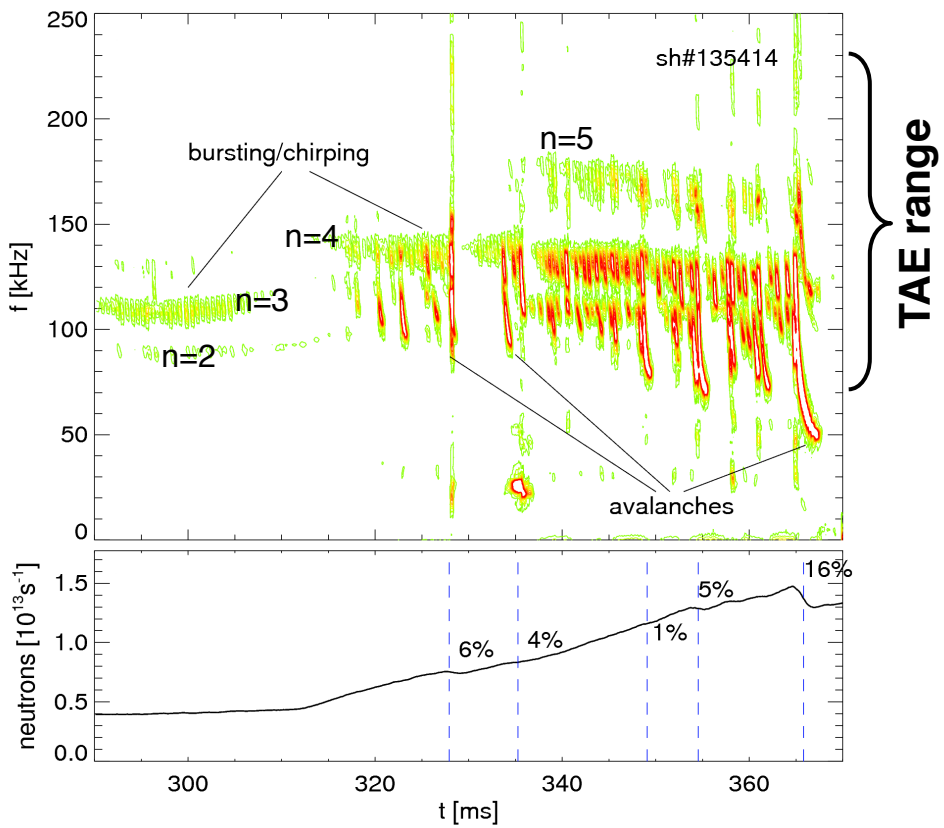
12th IAEA technical meeting on Energetic Particles in magnetic confinement systems
Austin, TX
Sep. 7-10, 2011



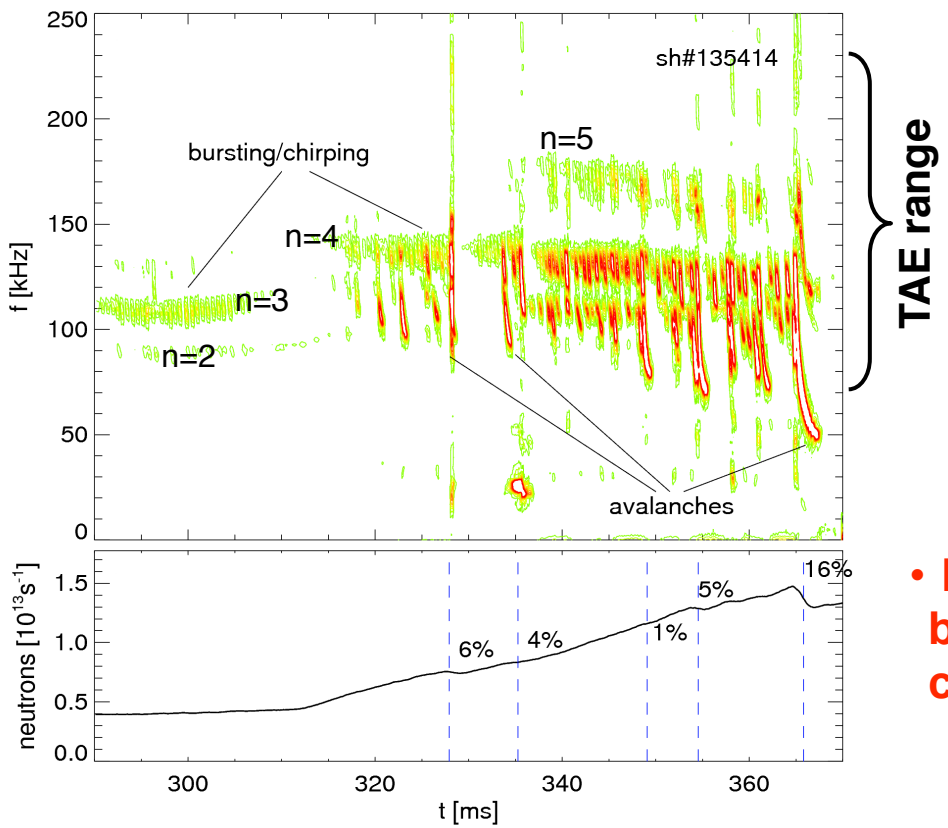
Bursting toroidicity-induced Alfvén eigenmodes (TAEs) can lead to enhanced fast-ion transport

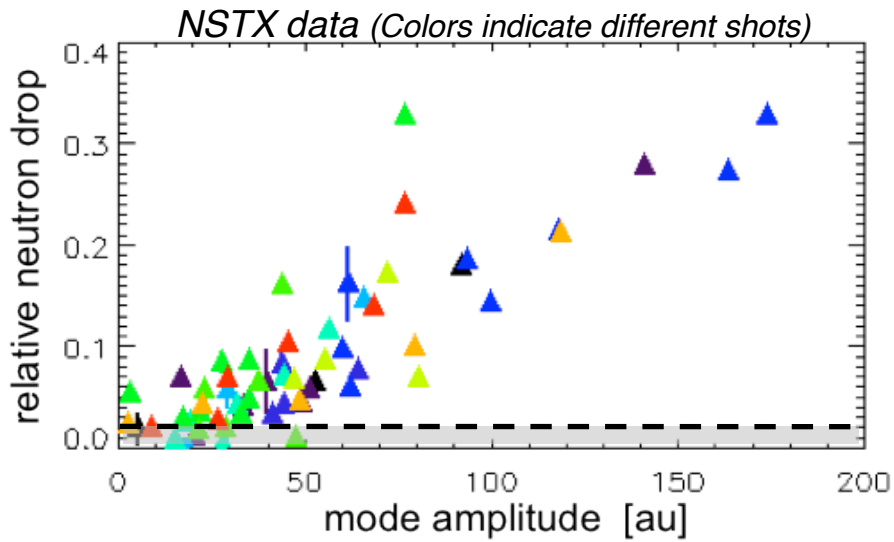
- Multiple TAEs can be simultaneously destabilized
  - Possible overlap of many resonances in phase space
  - Non-linear development into "TAE ***avalanches***"



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





- **Need to understand the physics of bursting TAEs, improve predictive capability for future devices (ITER)**

Spherical tokamaks such as NSTX provide excellent test-bed

Outline

- Experimental scenario, diagnostics
- General features of TAEs on NSTX
  - Frequency, amplitude dynamics
  - Mode structure
  - Role of fast ion drive
- Non-linear dynamics, mode-mode coupling
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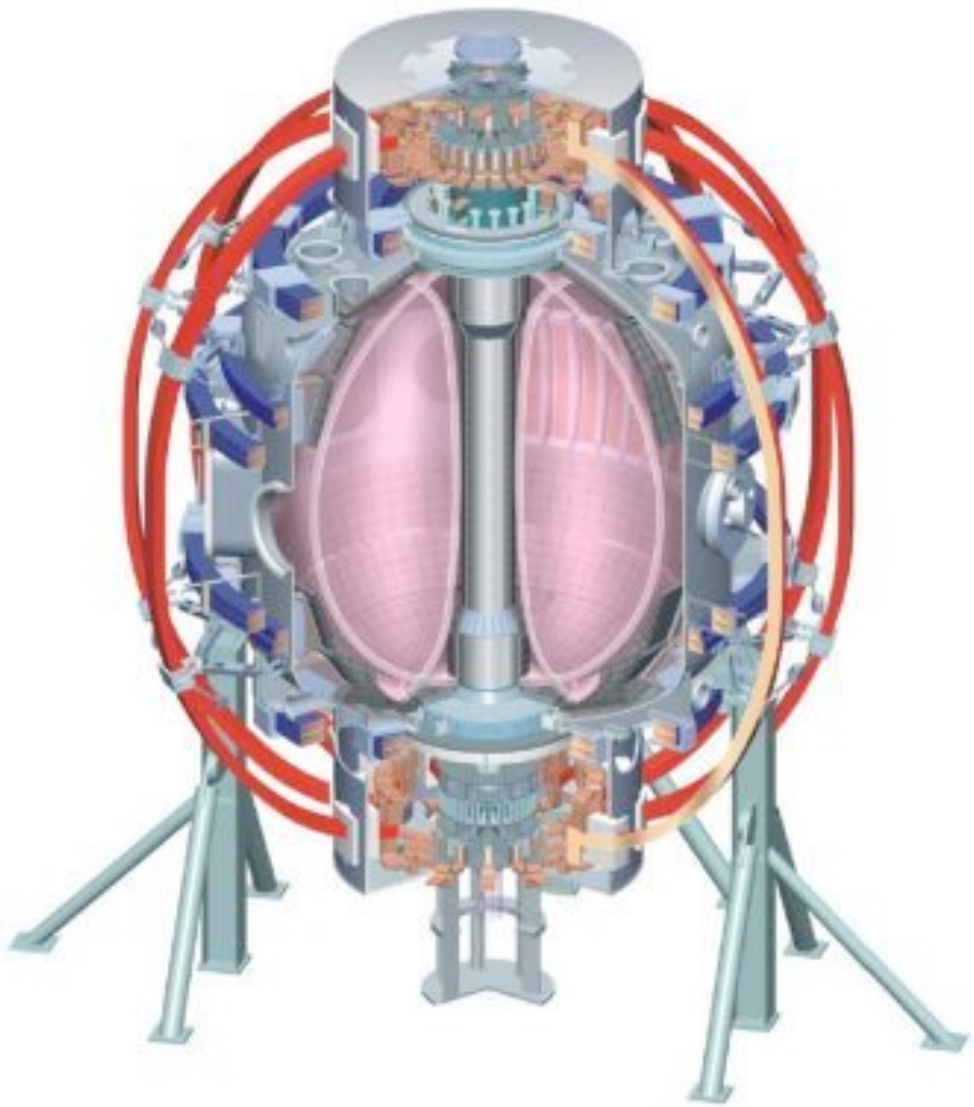
NSTX parameters



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

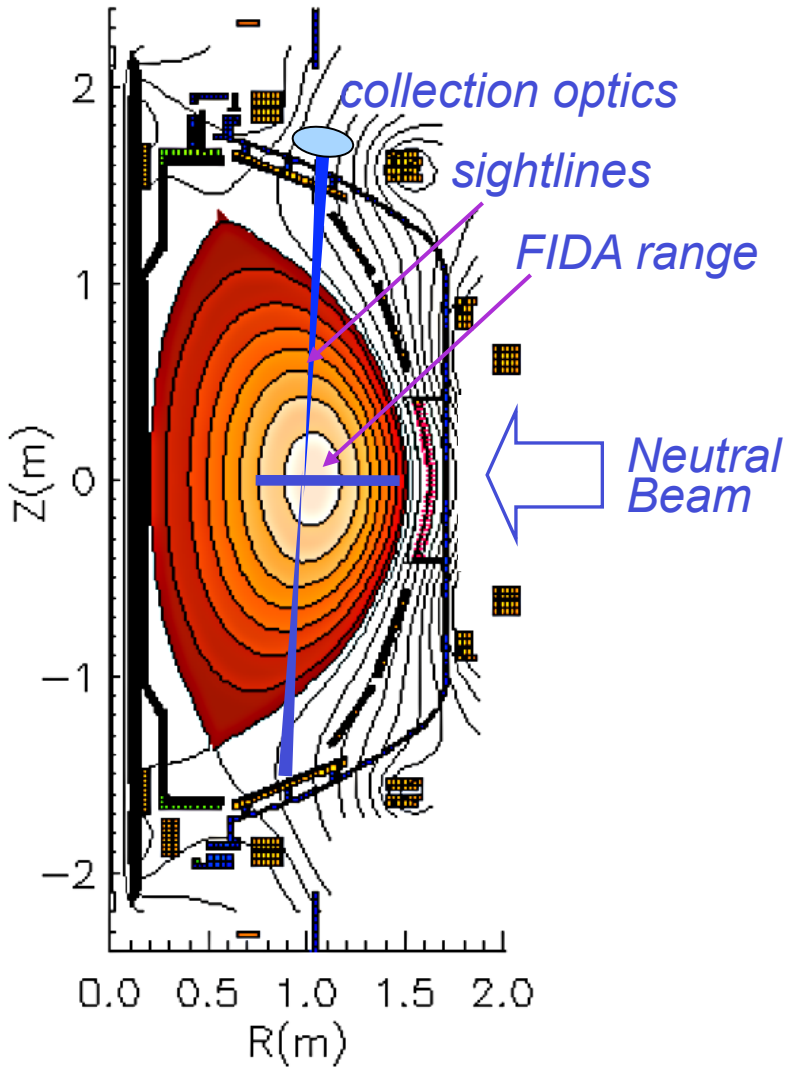
$P_{NBI} \leq 6$ MW, $E_{injection} \leq 95$ keV

⇨ **$1 < v_{fast}/v_{Alfvén} < 5$**

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

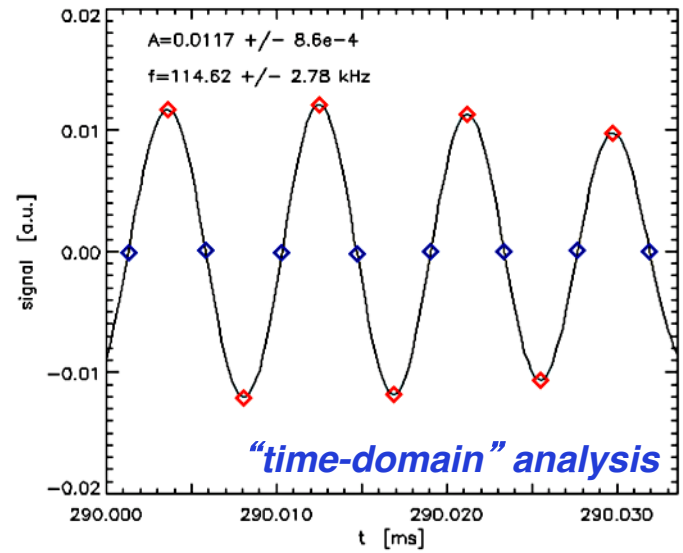
Mode activity and fast ion diagnostics on NSTX

shot#135404, t=320 ms



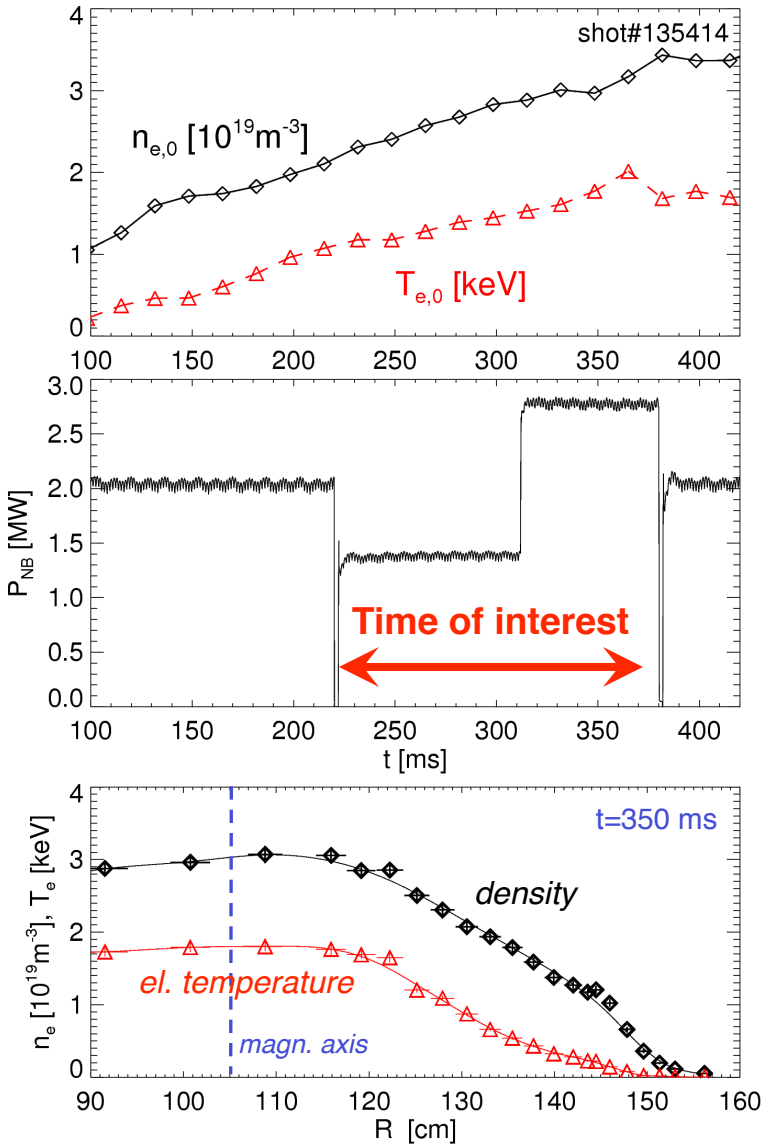
- Mirnov coils
  - Magnetic fluctuations up to 2.5 MHz
- Multi-channel reflectometer
  - Mode structure (monotonic profiles) UCLA

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



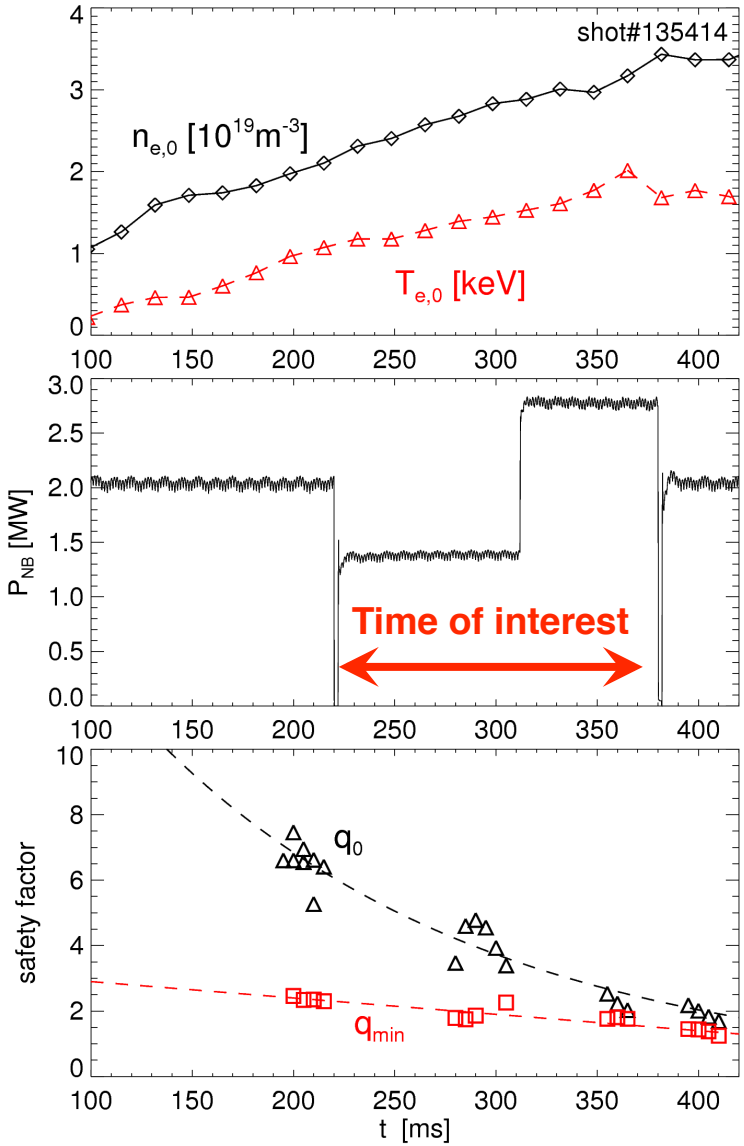
- Fast Ion diagnostics UCIrvine University of California, Irvine
  - Fast Ion D-Alpha systems (fast ion radial profile and spectrum)
  - Neutral Particle Analyzers, Fast Ion Loss probe, neutron rate

Experimental scenario : P_{NB}<3MW, n_e~3-4x$10^{19}m^{-3}$, T_i~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
    - > Monotonic, centrally peaked: OK for reflectometer measurements
  - Central plasma rotation up to 40kHz
    - > Large Doppler shift of mode frequency

Safety factor profile evolves from strongly to slightly-reversed shear



- 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
    - > q_{min}~1 toward end of discharge
  - Safety factor evolution reconstructed through LRDFIT code constrained by MSE data

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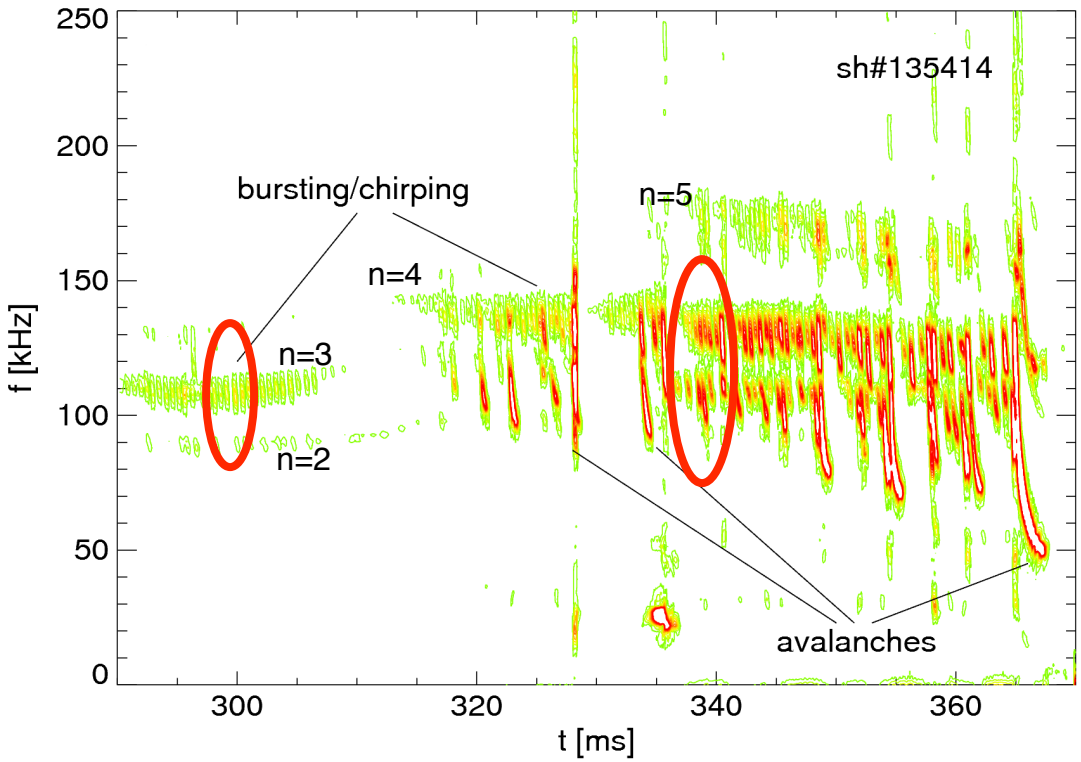
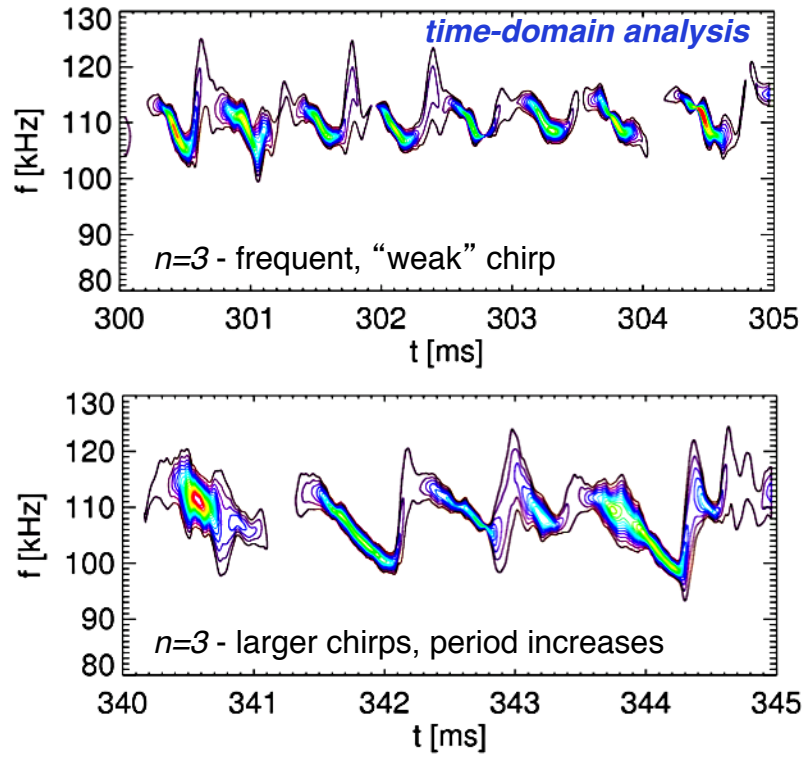
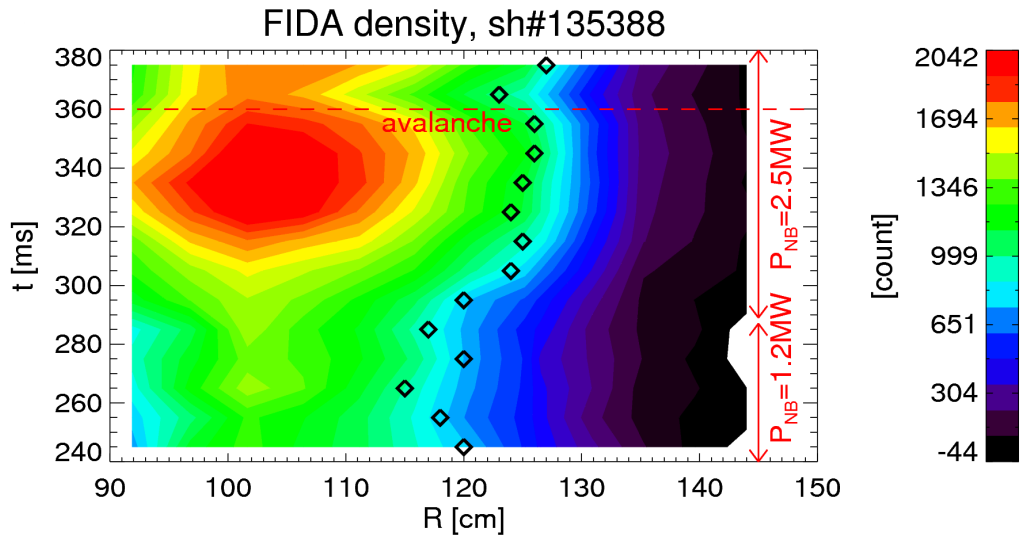
TAEs with low-intermediate toroidal mode number (*n*=2→7) are observed, with dominant *n*=2-4 modes

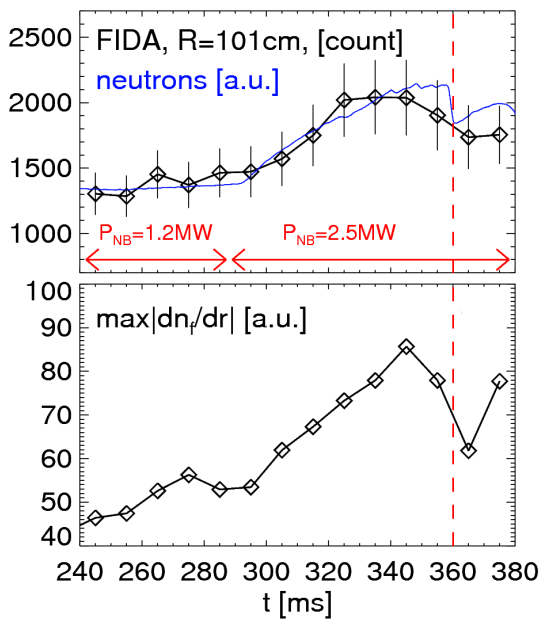


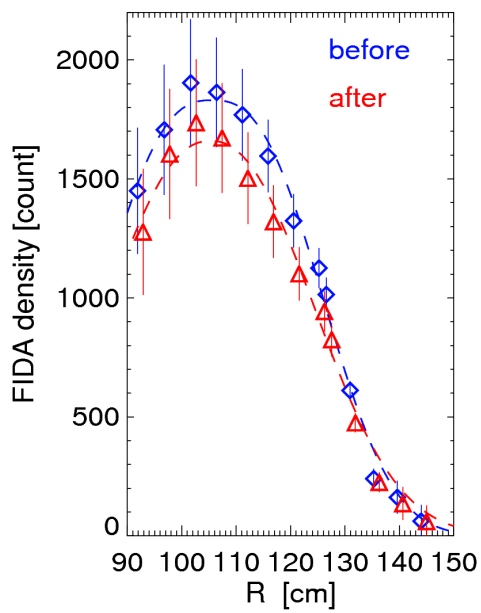


- Burst separation 0.5 – 2 ms
  - No systematic variation with n_e, T_e, P_{NB}, …
  - Frequency evolution does not follow unique patter (e.g. $t^{-1/2}$, linear, exponential)
- Usually, each mode chirps independently of the others...
- ... but, eventually, *avalanches* occur:
  - Drop in neutron rate, 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 estimated from FIDA and neutron rate
  - Large portion of phase space affected
- Losses increase with (total) mode amplitude
  - Linear+threshold? Quadratic?

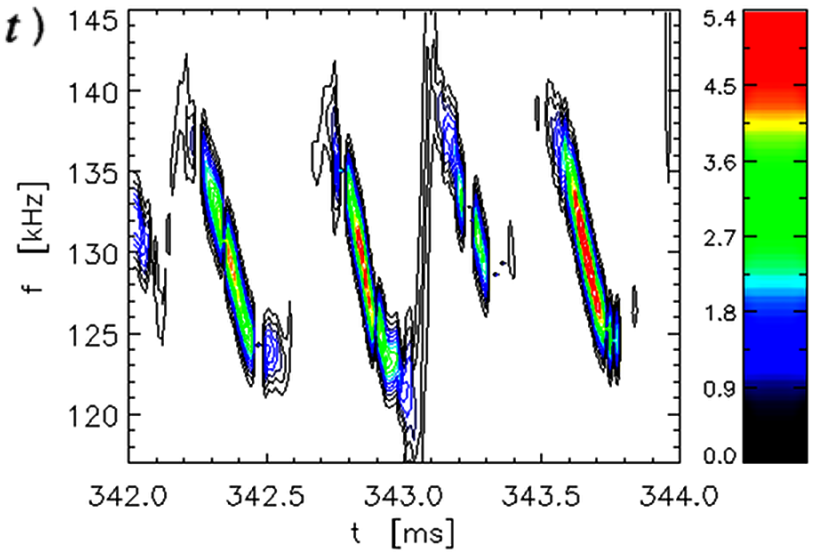
Frequency *vs.* amplitude are correlated; reminiscent of driven, non-linear system

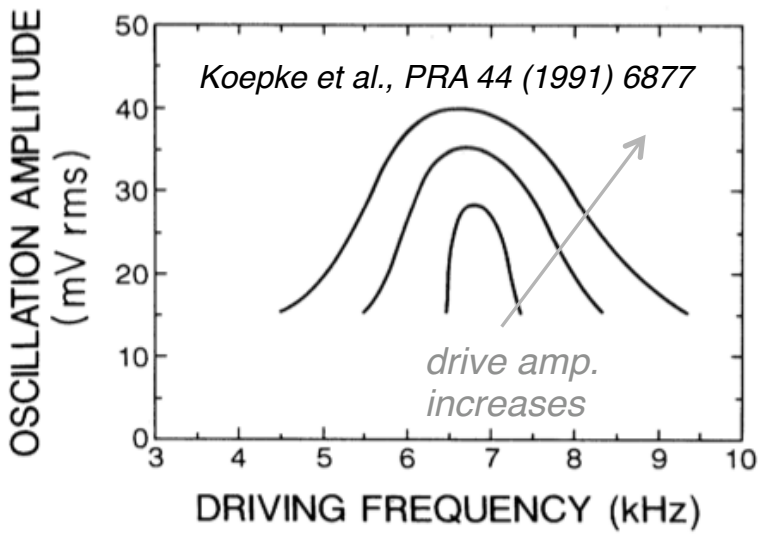
- E.g., non-linear Van der Pol oscillator:

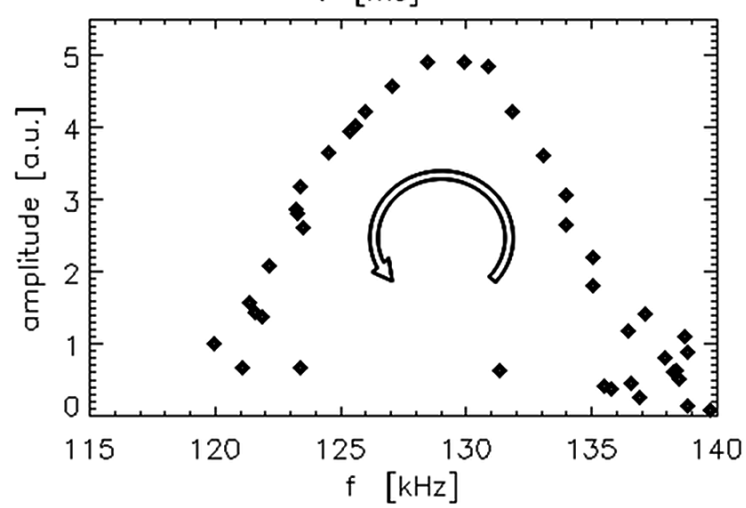
$$\ddot{x} - \epsilon(1-\beta x^2)\omega_0\dot{x} + (\omega_0^2 + \eta x^2)x = M\omega_0^2 \sin(\omega_D t)$$

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







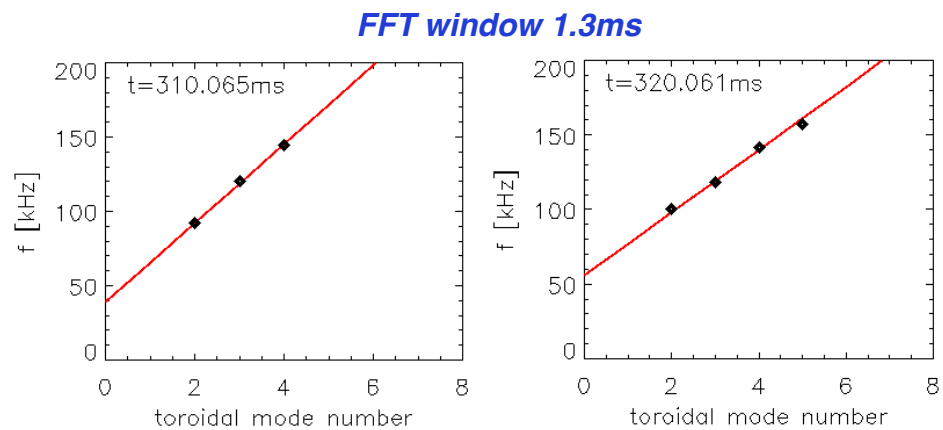
On average, TAE frequencies are consistent with a common frequency *in the plasma frame*

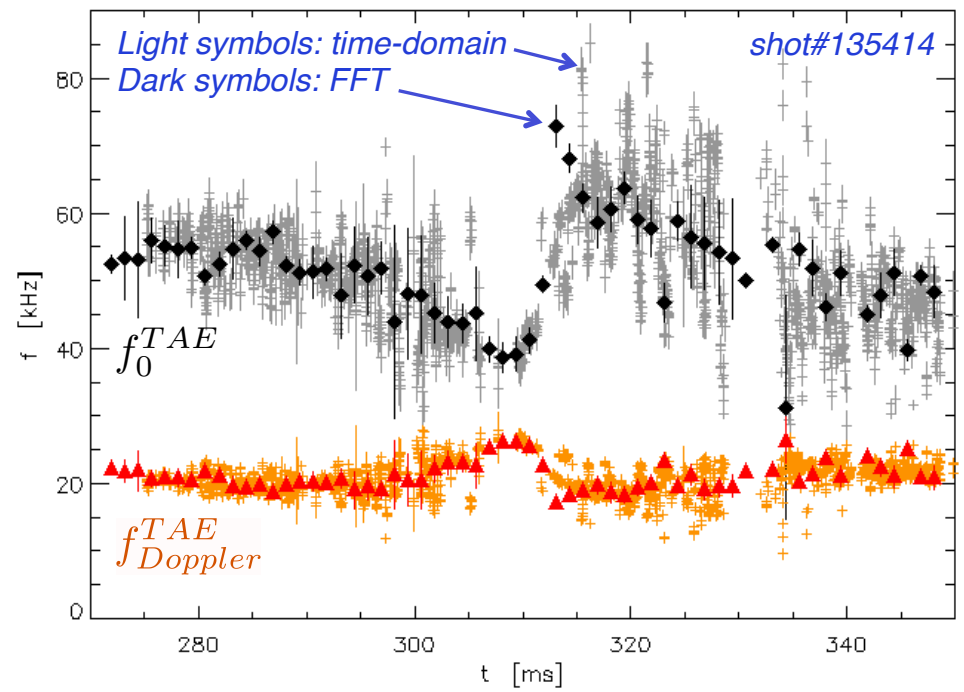
Measured frequency consistent with:

$$f_{lab,n}^{TAE} = f_0^{TAE} + n\, f_{Doppler}^{TAE}$$

lab frame — plasma frame — shift from plasma rotation

- Valid for time scales >1 ms
- In general, each mode shows a different sub-millisecond dynamic





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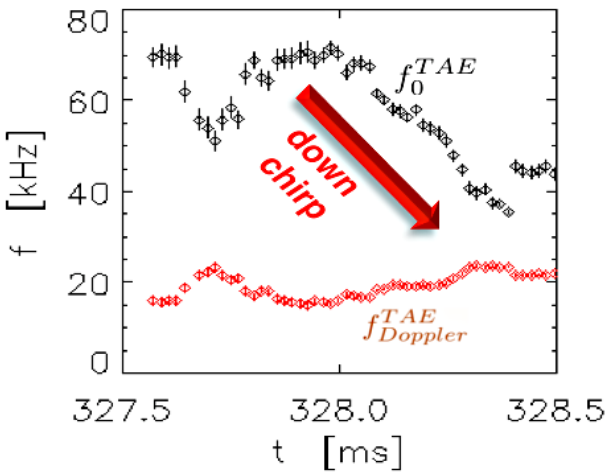
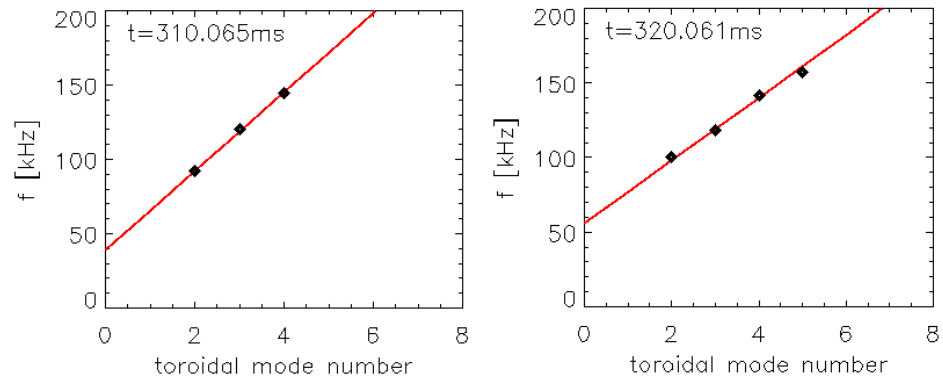
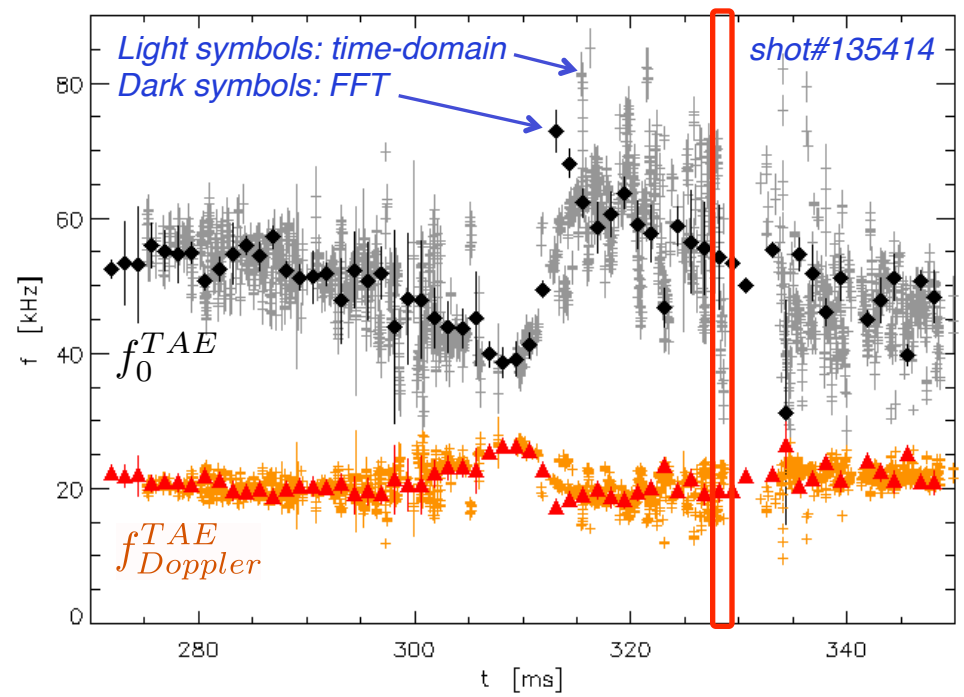
- In general, each mode shows a different sub-millisecond dynamic...
- ...except during large bursts:
  - Doppler shift only slightly changed here
  - Chirp mainly due to decrease in f_0^{TAE}



FFT window 1.3ms





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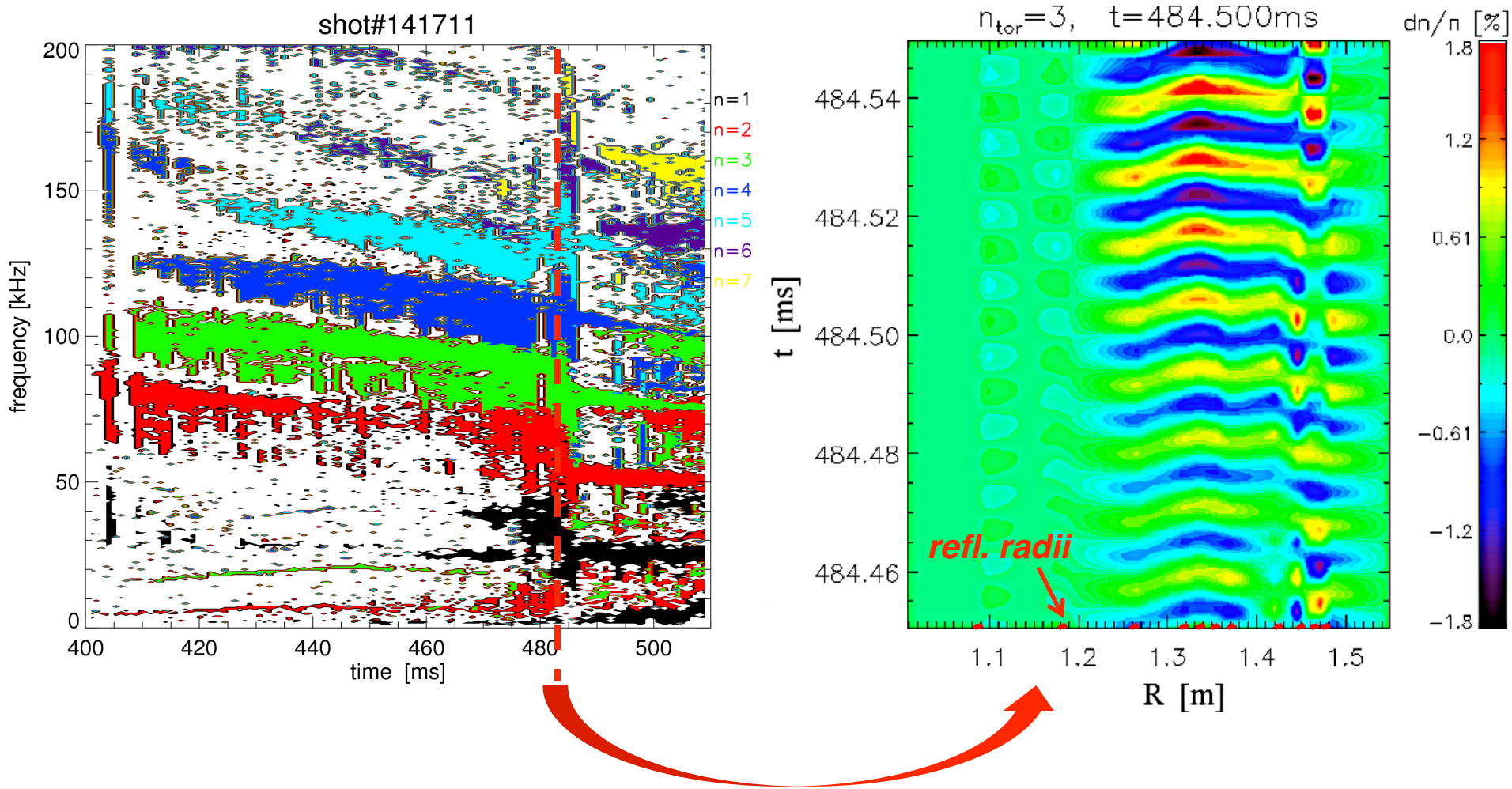
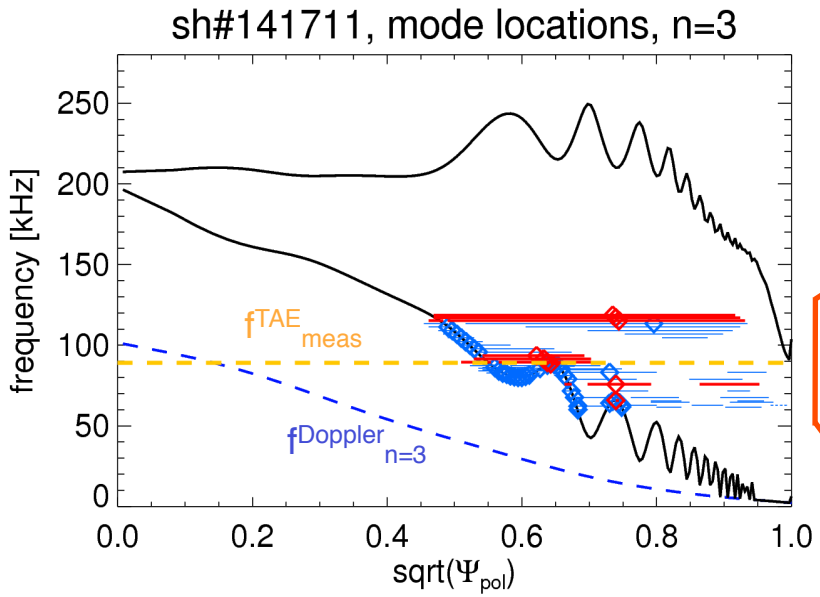
Multi-channel reflectometer is main tool to unravel details of mode structure

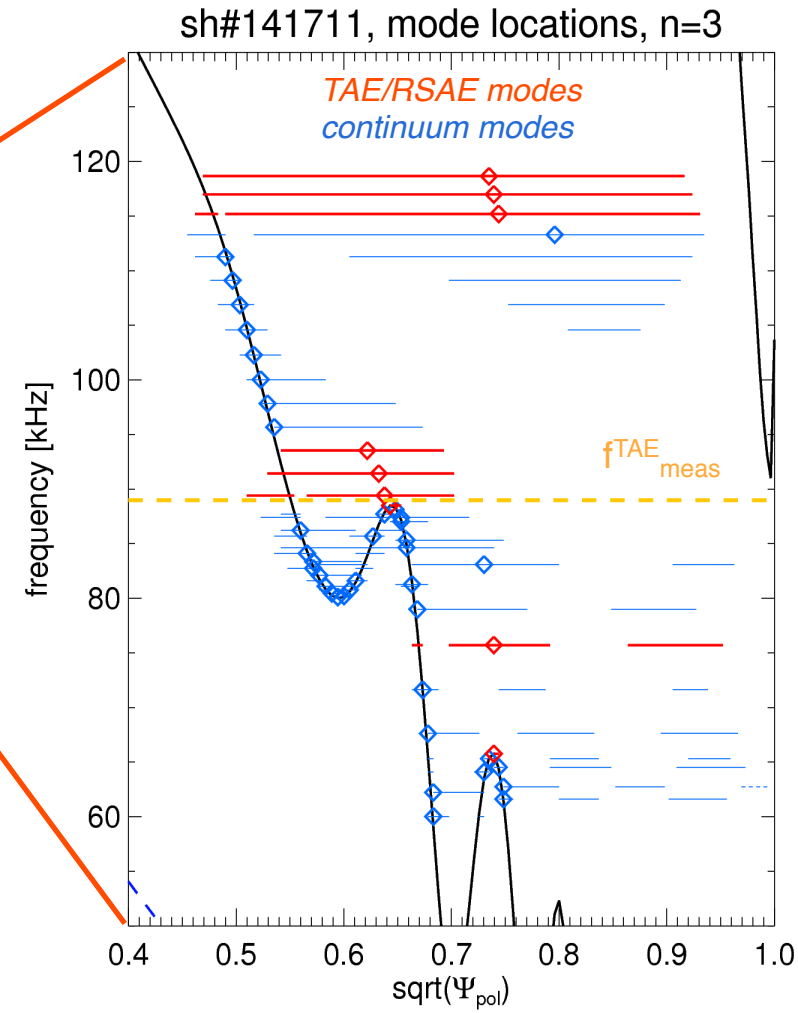
Crocker et al., PPCF 2011



- Makes it possible comparison with codes – e.g. NOVA – in terms of dn/n

NOVA eigenmodes selected from matching with measured frequency, mode number, structure





search range

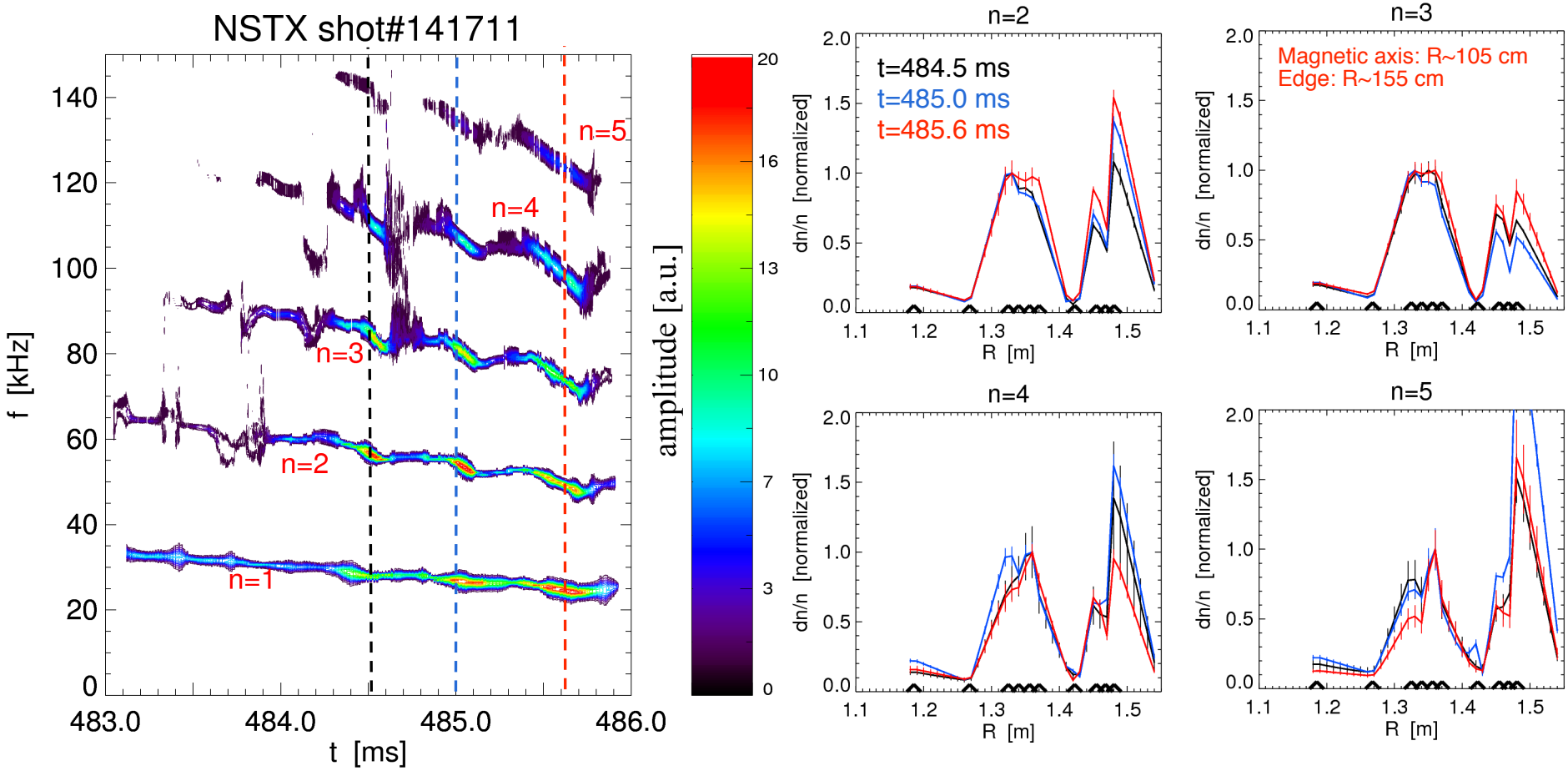
- NOVA provides *ideal* eigenmodes in a given frequency range
- Match mode structure (dn/n) from reflectometer to NOVA solutions
- Select 'observed' mode; re-scale NOVA solution according to measured *dn/n*
- [Use as input for ORBIT, calculate fast ion transport]

Fredrickson et al., PoP 2009

Fredrickson, P1.7

Darrow, O1

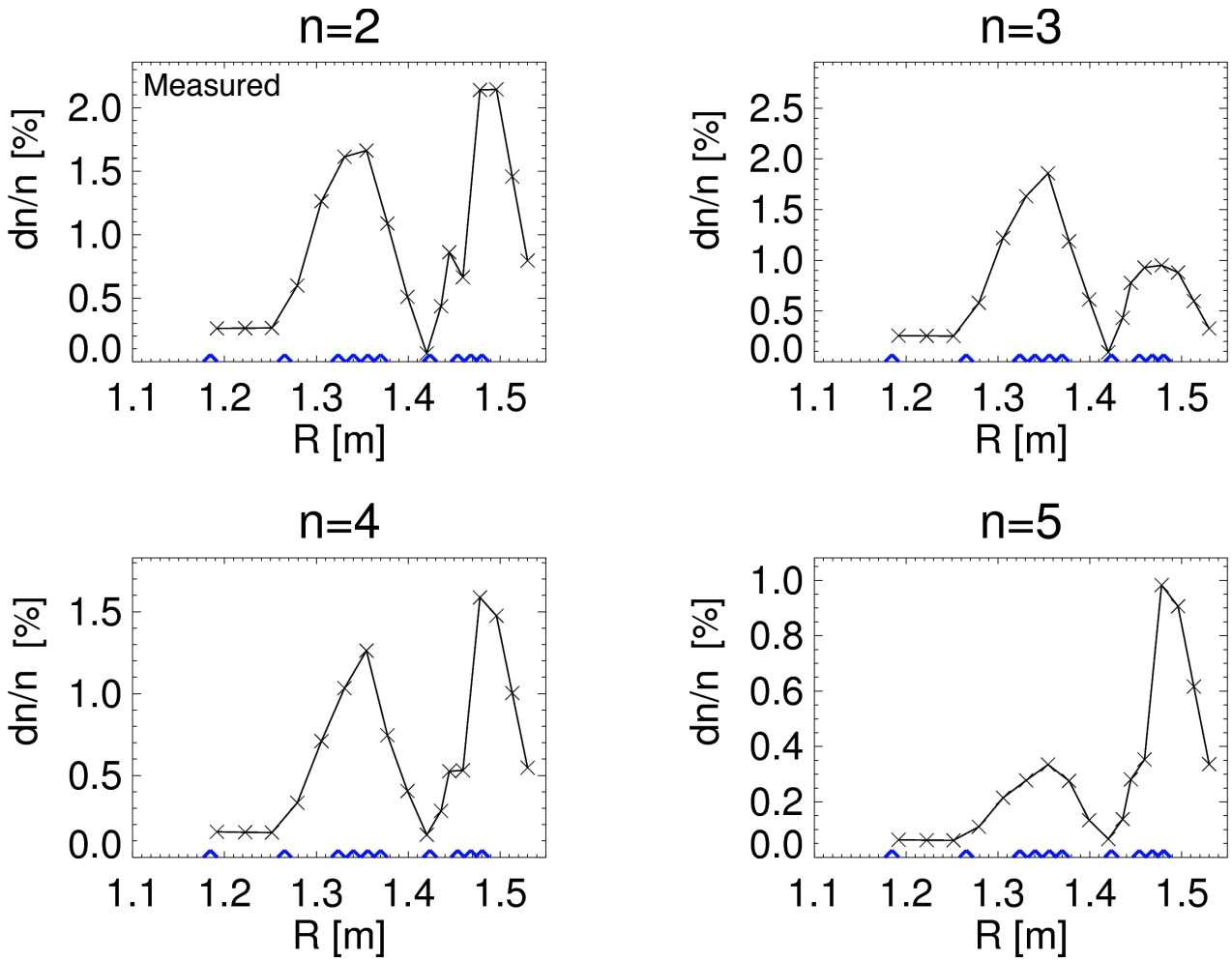
Mode structure maintains its shape even during strong, *multi-step* avalanches



- Re-scaled dn/n shown (compare radial structure, not amplitude)
- Outward propagation of *unstable front* during burst not observed
  - Broad mode structure, ~ minor radius
  - Incomplete transition TAE → EPM?

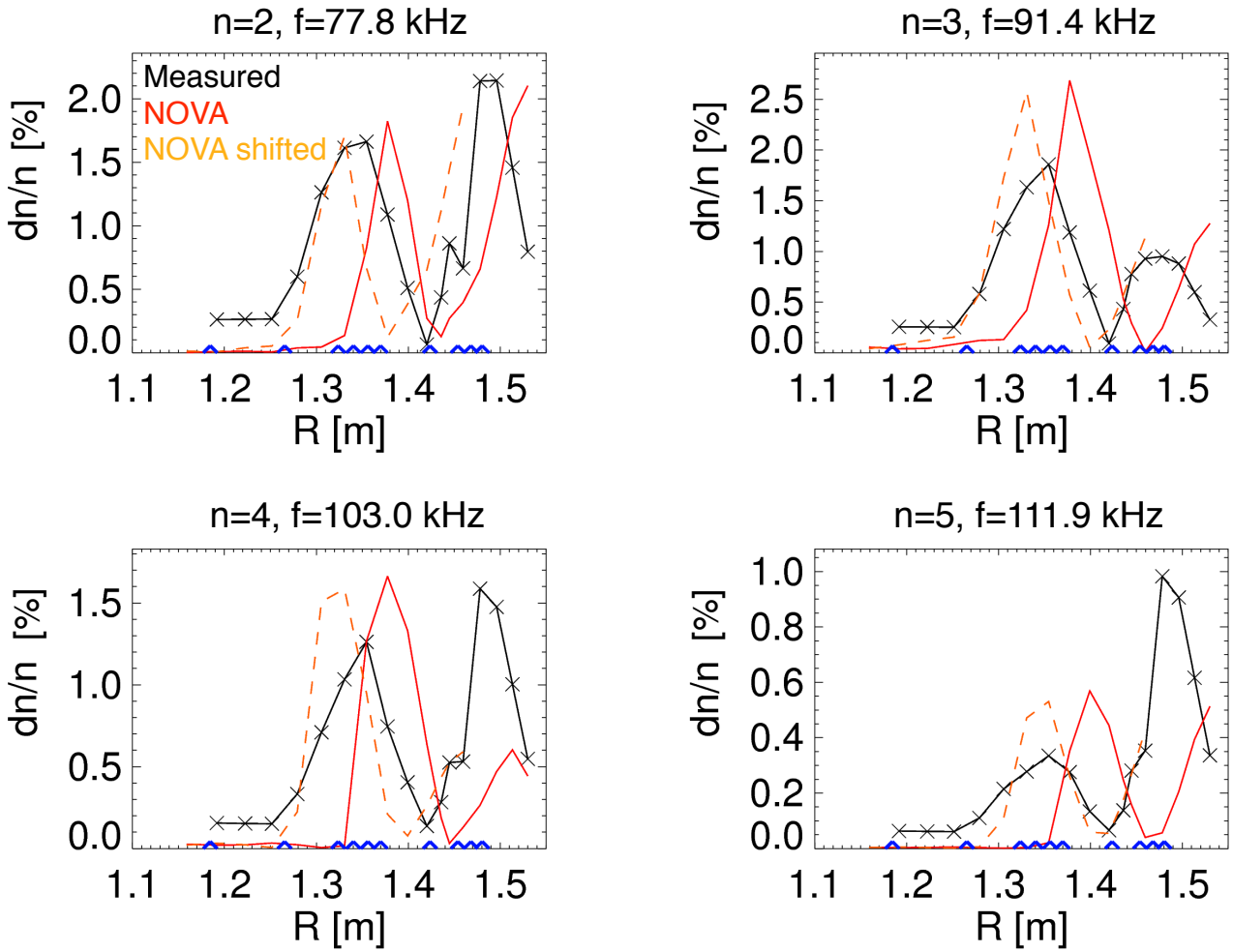
Zonca et al., NF 2005

Modes have broad mode structure, extending over good fraction of minor radius; peak at mid-radius



- sh#141711
- t=470ms
- Magnetic axis: R~105 cm
- Edge: R~155 cm

Comparison with NOVA (ideal MHD) is satisfactory; however, no good match for *n=1* … if 'TAE'

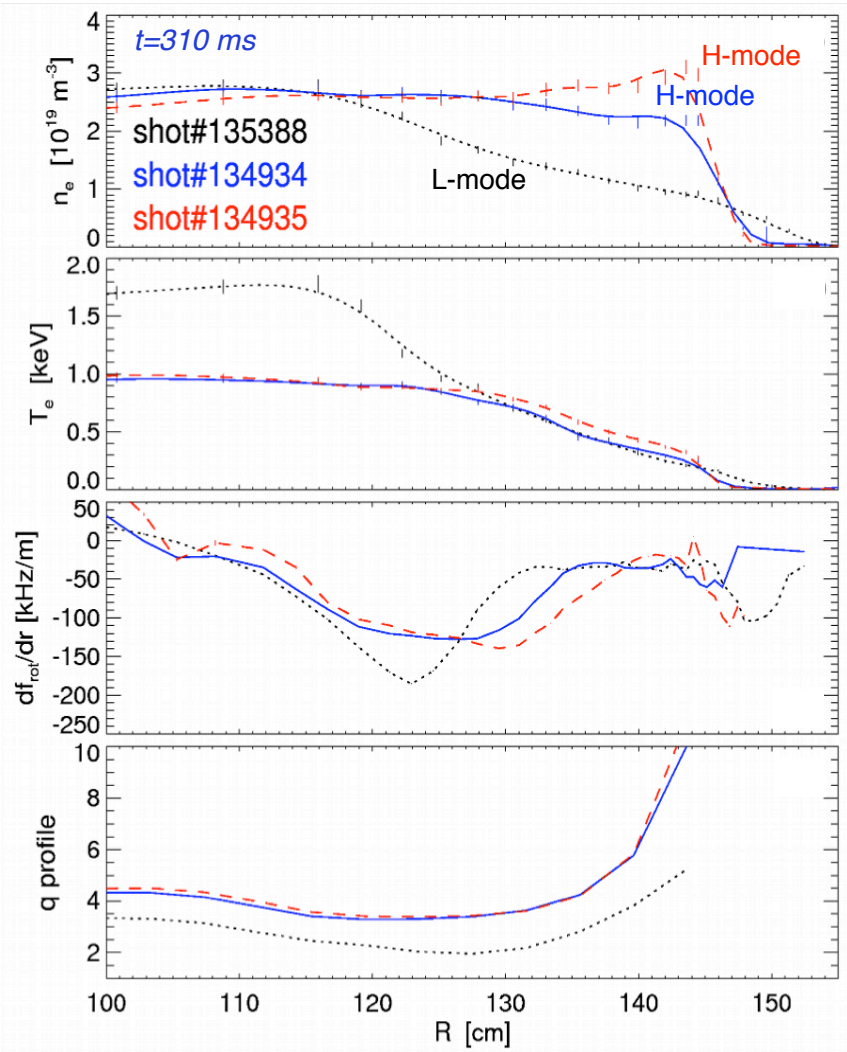


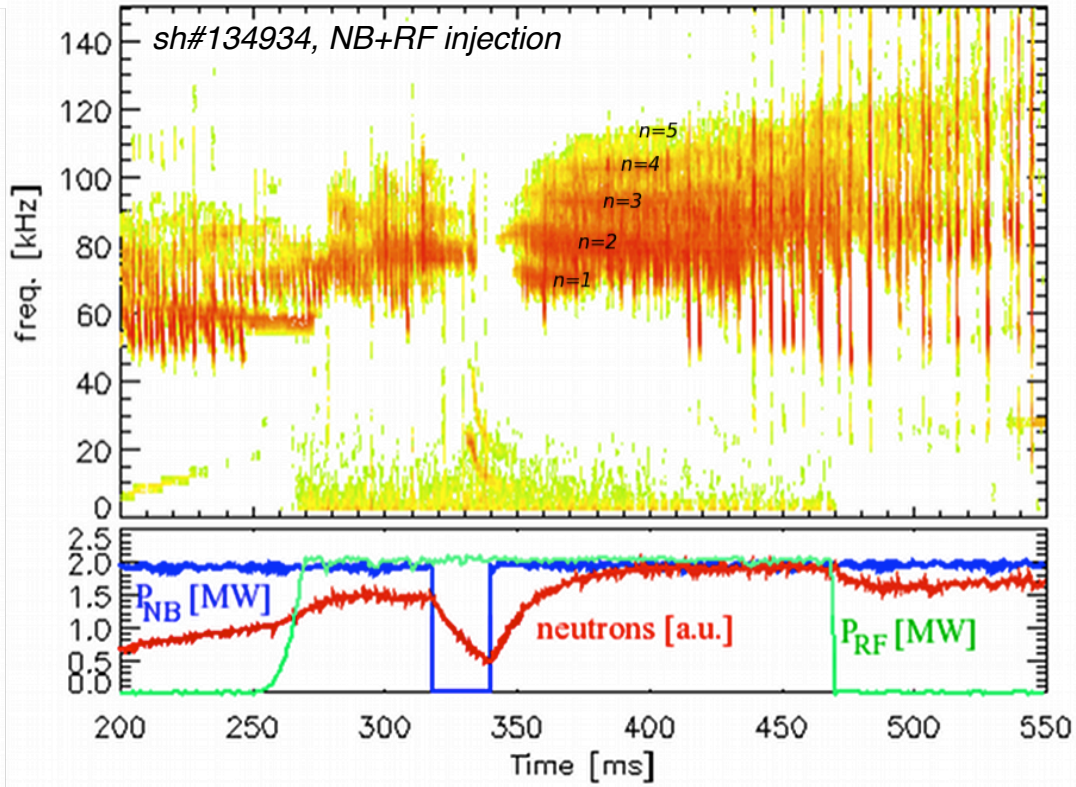
- Frequency from NOVA ~ consistent with experiment
- Doppler shift is included
- But: radial shift of 2-5 cm between measured and simulated dn/n

n_{tor}	f_{meas} [kHz]	f_{NOVA} [kHz]
2	60-80	77.8
3	80-100	91.4
4	110-125	103
5	130-140	111.9

- NOVA results assume ideal MHD, no fast ion effects
- *Need to carefully check profile consistency between experimental data (MPTS, CHERS) and TRANSP output / NOVA input*

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





- Example: H-mode, NB / NB+RF
  - Profiles different from L-mode
  - Higher safety factor than for L-mode discharges
  - Reversed shear in both L- and H-mode

Fredrickson, P1.7

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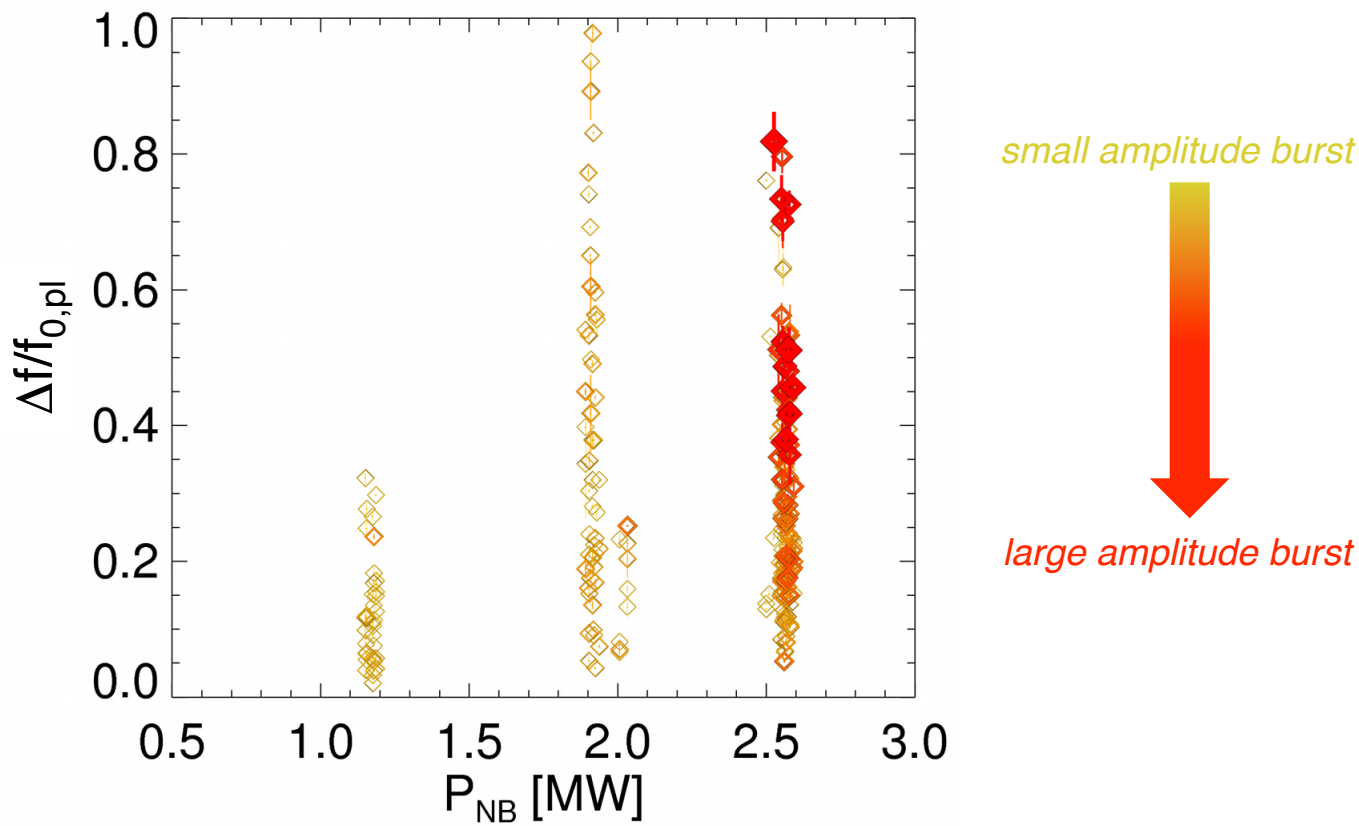
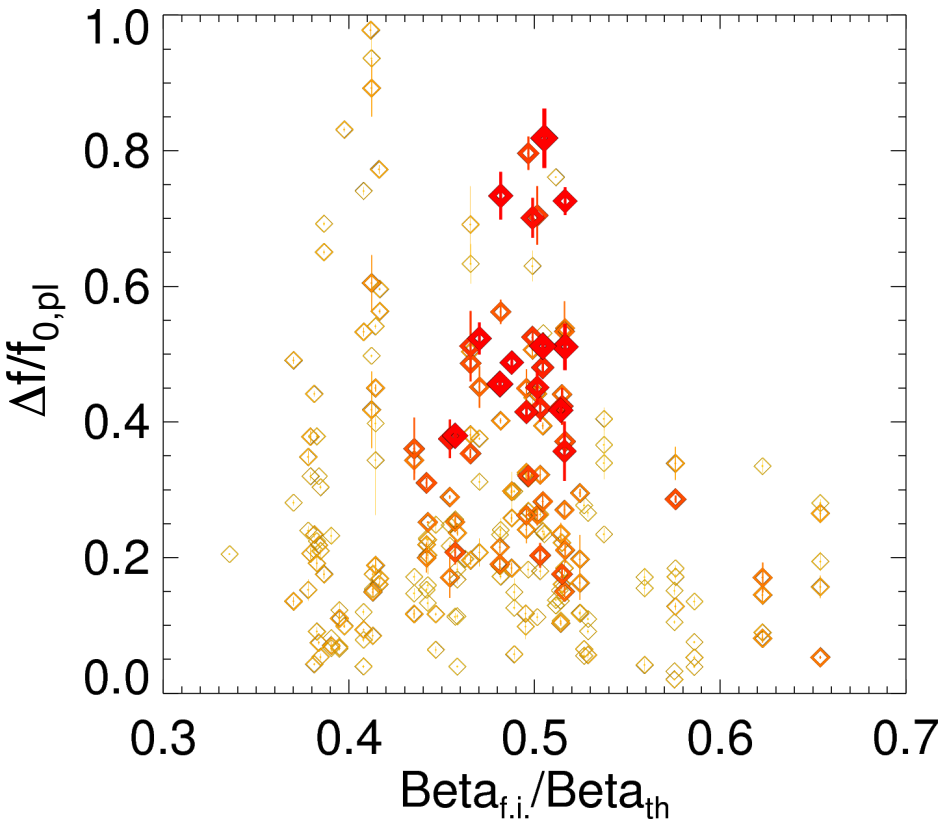
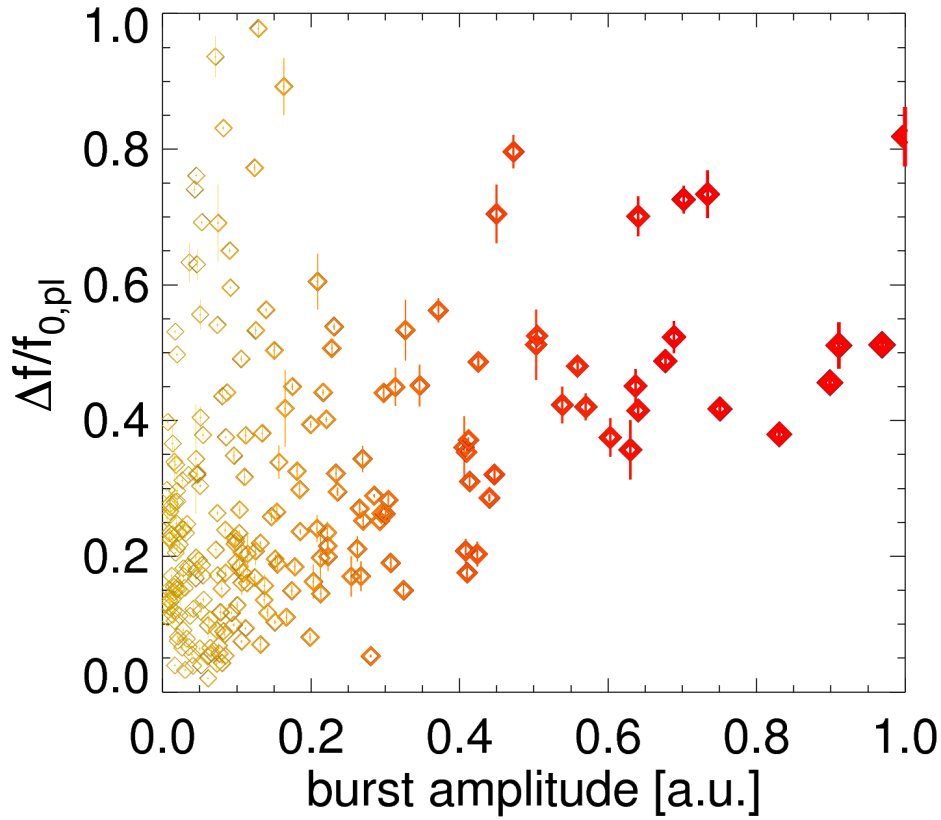
Onset of bursting/chirping regime strongly dependent on injected NB (and RF) power

- Take fractional frequency variation $\Delta f/f_{0,pl}$ as metric for *severity* of bursts
  - $f_{0,pl}$: mode frequency in the plasma frame
- Each symbol represents values for single *n* mode, 5 ms average



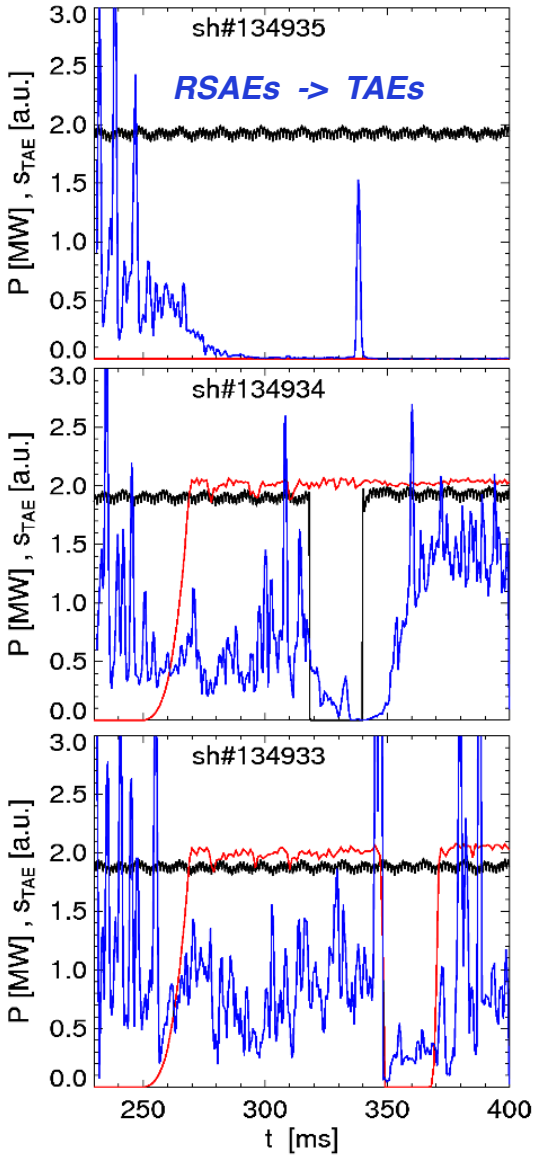
High ratio of fast ion to thermal β leads to bursts/chirps – but other factors determine mode dynamics



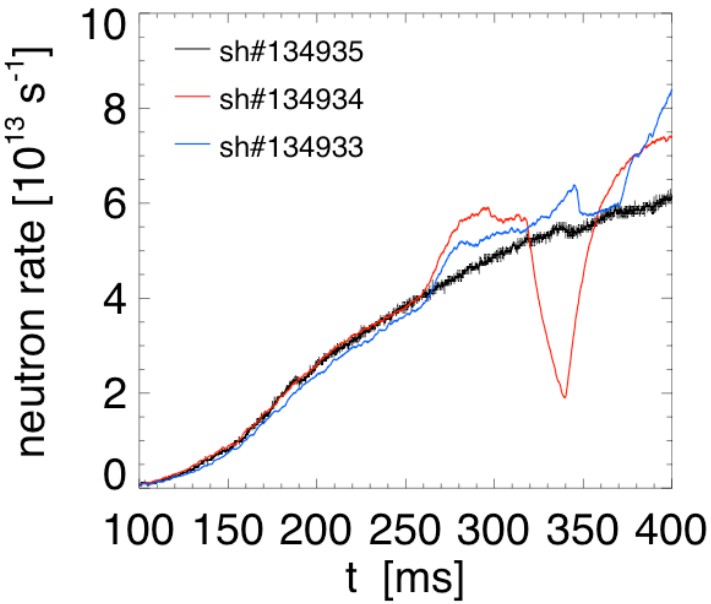


- Modes show more bursting character as discharge evolves
  - NB power increases, fast ion population and $\beta_{f.i.}$ builds up
  - Typical bursts have *edge* $\delta B/B \sim 10^{-4}$ (from Mirnov coils)
    - > Can increase more than x10 during avalanches

Destabilization of TAEs correlates with variations of heating scheme, e.g. NB *vs.* NB+RF



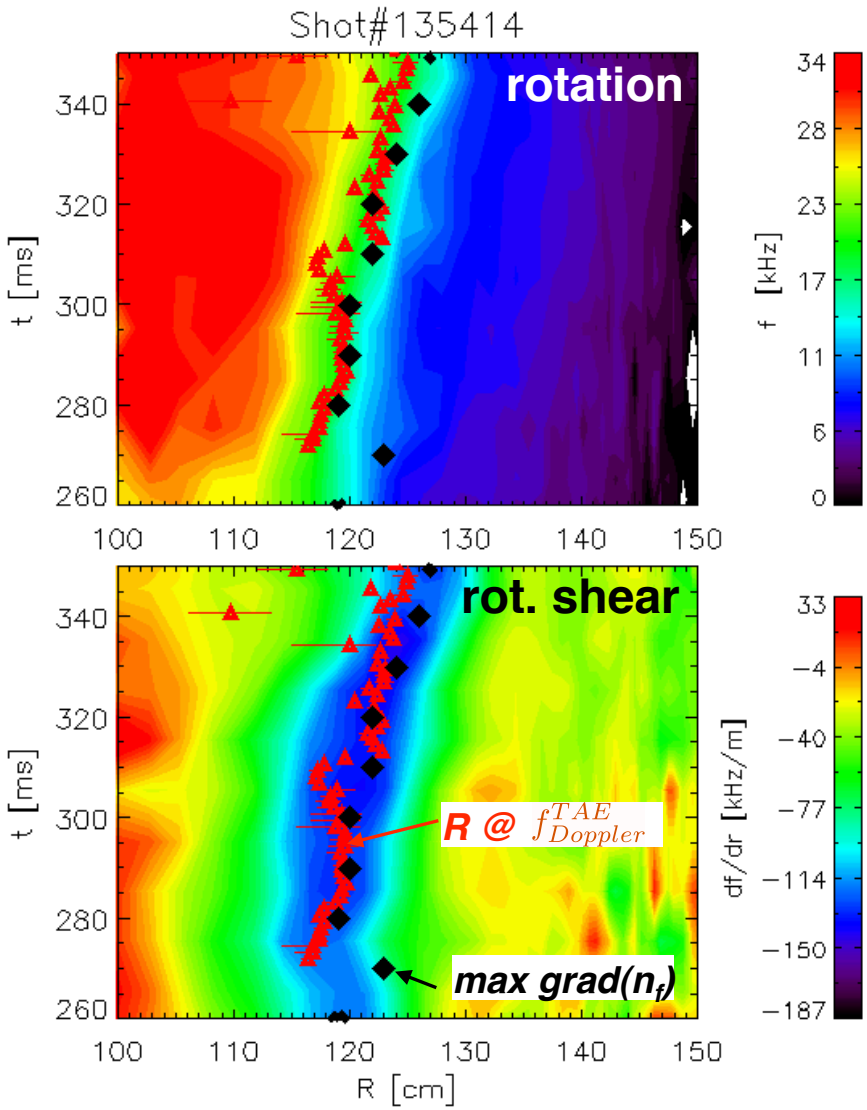
- Example: H-mode discharges with NB and NB+RF heating
  - Different profiles with respect to L-mode (e.g. higher safety factor)
  - Reversed shear in both L- and H-mode



NB only
NB+RF, NB notch
NB+RF, RF notch

- Here NB alone does not drive TAEs
- NB+RF does: increase in fast ions

Strong dependence on NB drive leads to entangled evolution of TAEs, fast ions and thermal plasma



- *Mode location*, R^{TAE}, obtained by matching $f^{TAE}_{Doppler}$ with measured rotation profile:

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

- Correlation between
  - *Mode location* ***R*** @$f^{TAE}_{Doppler}$
  - Max fast ion gradient ***max grad(n_f)***
  - Max rotation shear

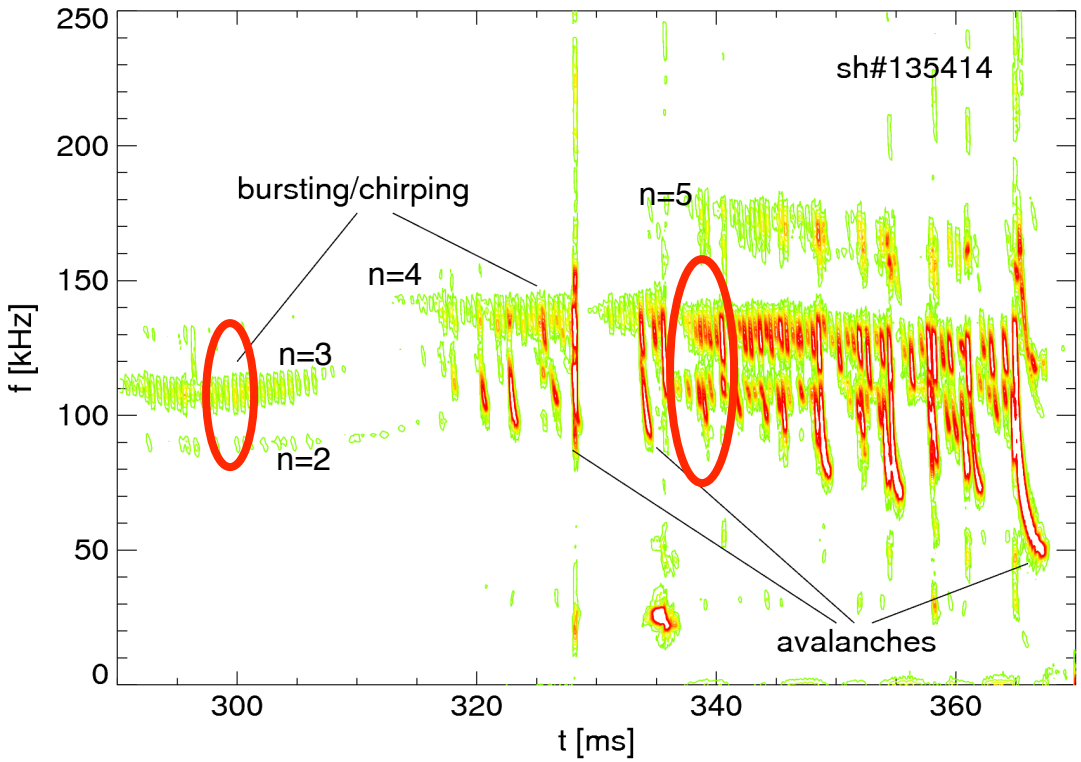
Coupling through common "source term", i.e. **NB injection**

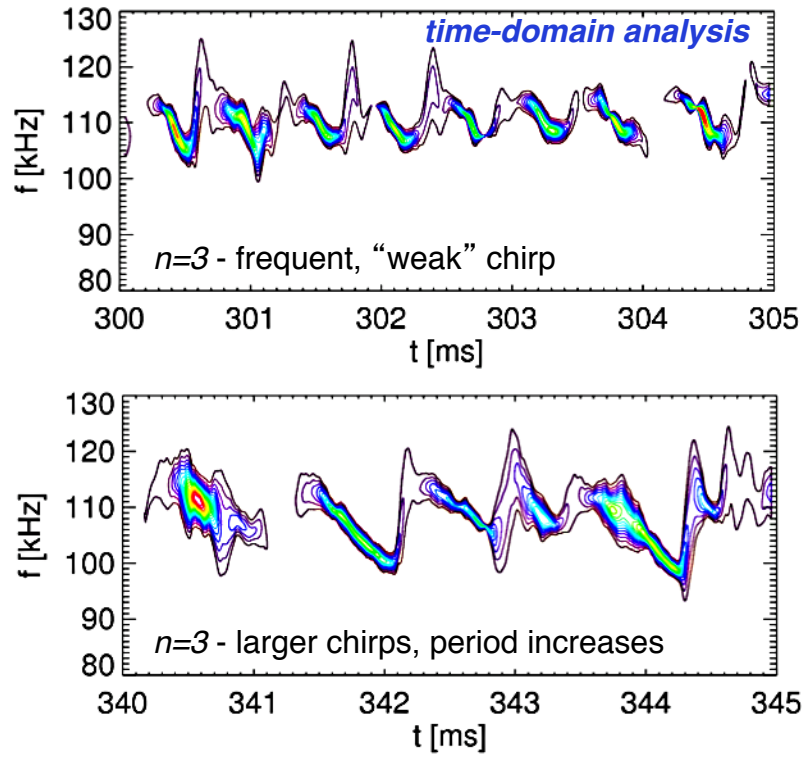
⇩

Modes cluster at similar radius: may enhance coupling

Podestà et al., PoP 2010

Once set up, bursting/chirping TAE regime is rather insensitive to variations in plasma parameters





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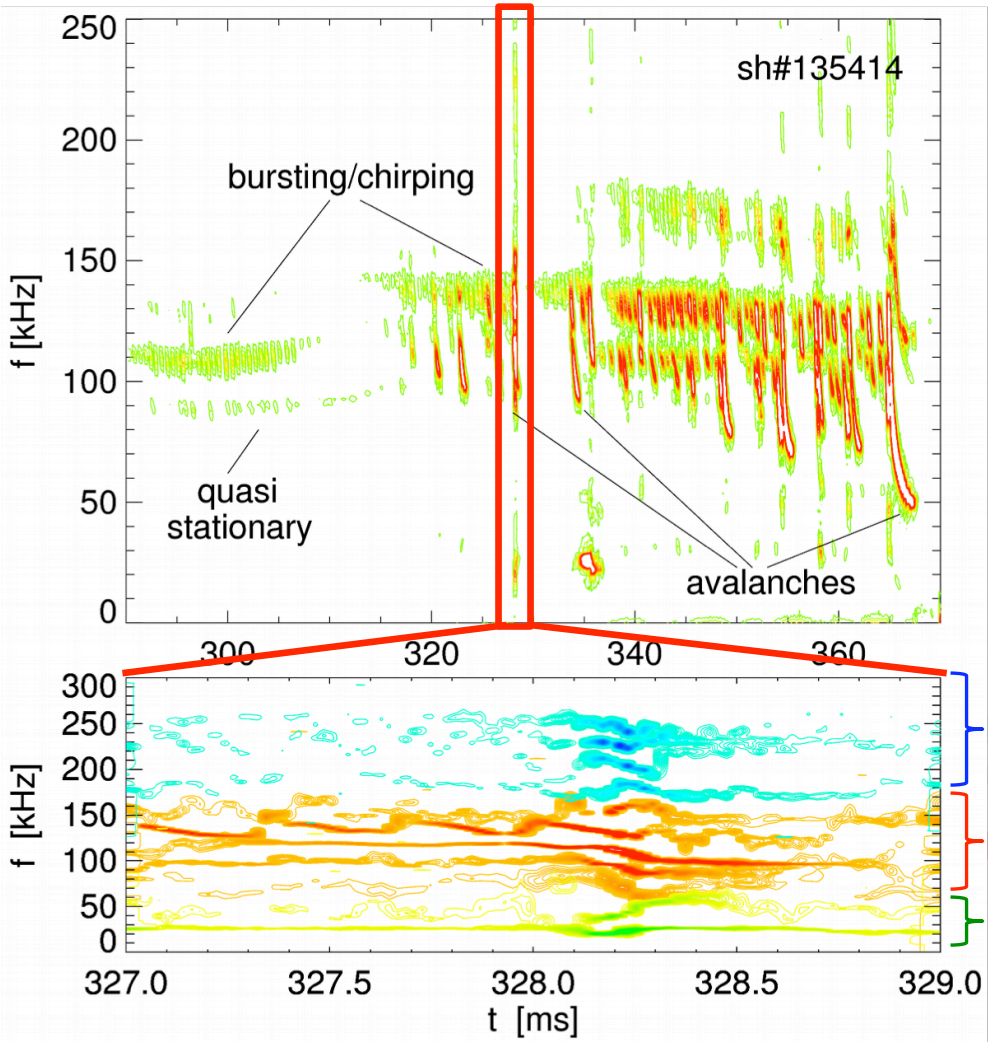
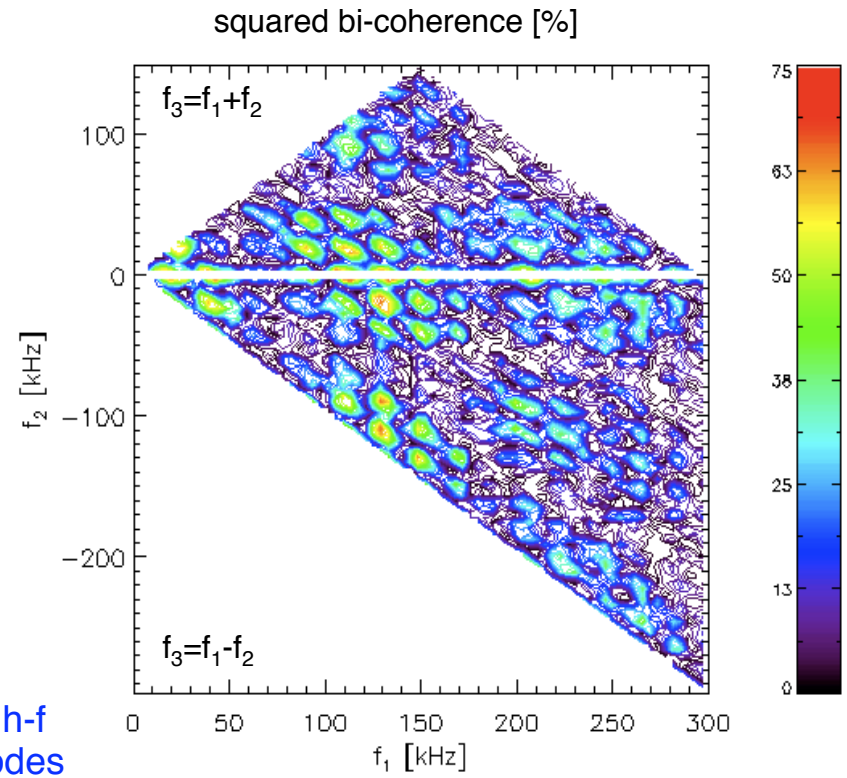
  - Frequency evolution does not follow unique patter (e.g. $t^{-1/2}$, linear, exponential)
- Usually, each mode chirps independently of the others...
- ... but, eventually, *avalanches* occur:
  - **Multiple modes lock on similar dynamic, mode-mode coupling**

Outline

- Experimental scenario, diagnostics
- General features of TAEs on NSTX
  - Frequency, amplitude dynamics
  - Mode structure
  - Role of fast ion drive
- Non-linear dynamics, mode-mode coupling
- Summary

Coupling between multiple TAEs with $\Delta n_{tor}=1$, enhanced losses observed during explosive modes' growth





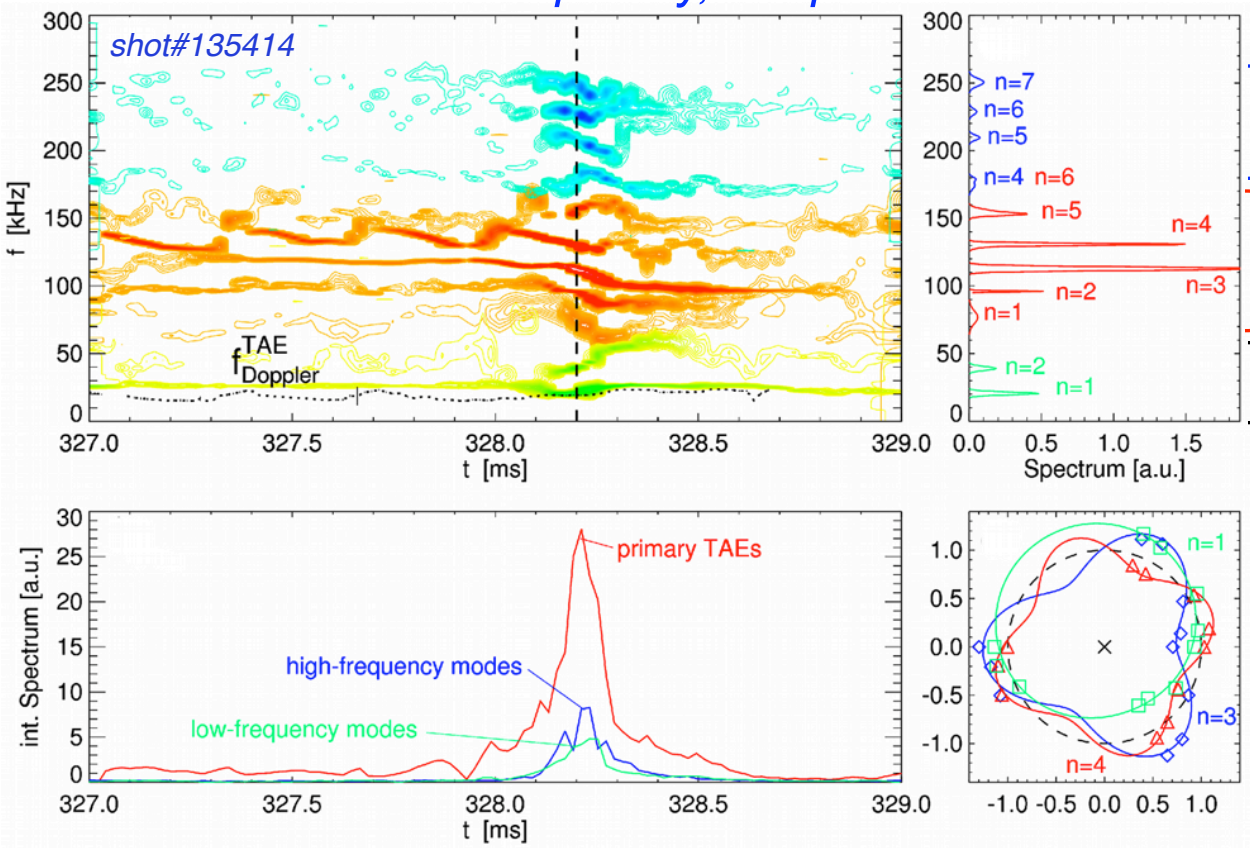
- Coupling generates higher/lower frequency modes

- Multiple modes follow similar dynamic during the burst
  - *Transition* from single- to multi-mode regime

Podestà et al., NF 2011

‘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; 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?*

Poloidal plot: 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/pumping *secondary* modes through sum/difference with *Δn=1*

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

$$\dot{s}_{n_3} = < c_{(n_1,n_2)}\, s_{n_1} s_{n_2} >_{f_{n_3}}$$

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

Right-hand side filtered around frequency f_{n_3}

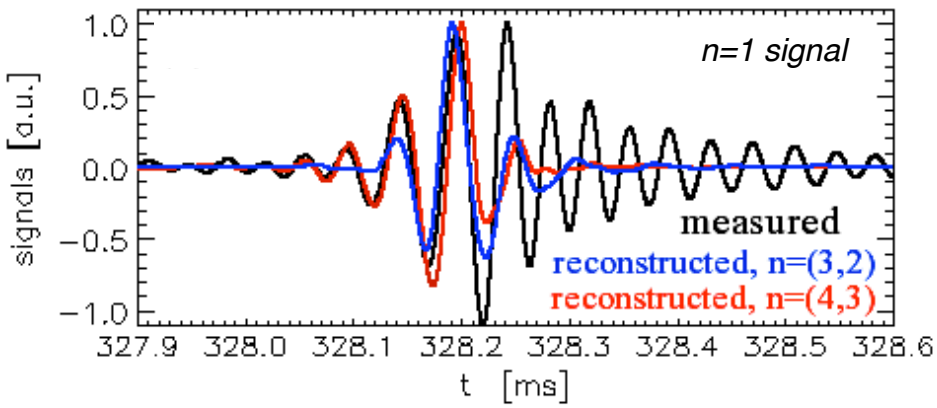
Modes must satisfy matching conditions $\begin{cases} n_3 = n_1 \pm n_2 \\ f_{n_3} = f_{n_1} \pm f_{n_2} \end{cases}$

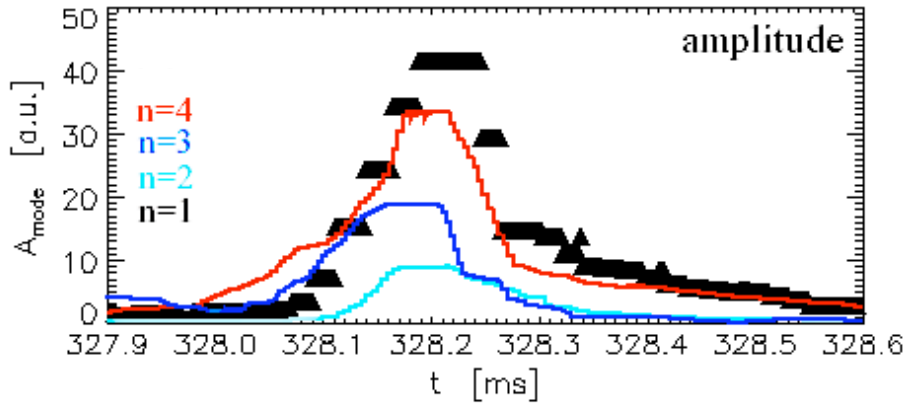
$c(n_1, n_2)$ is the coupling coefficient, here used as 'free scaling parameter'

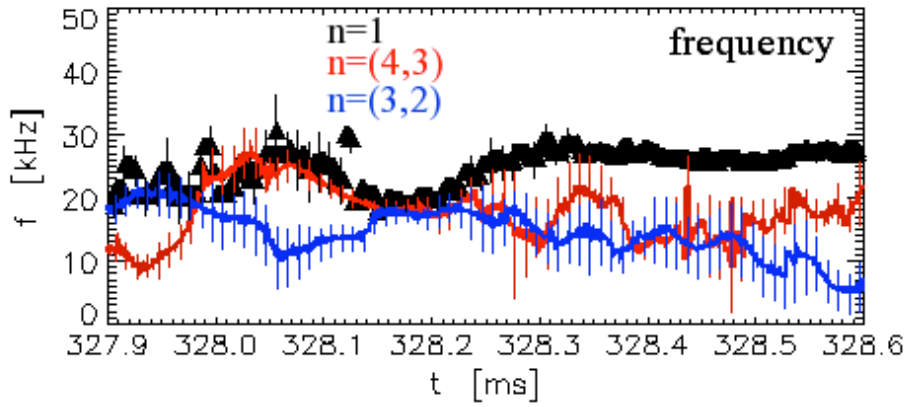
In practice:

- 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

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



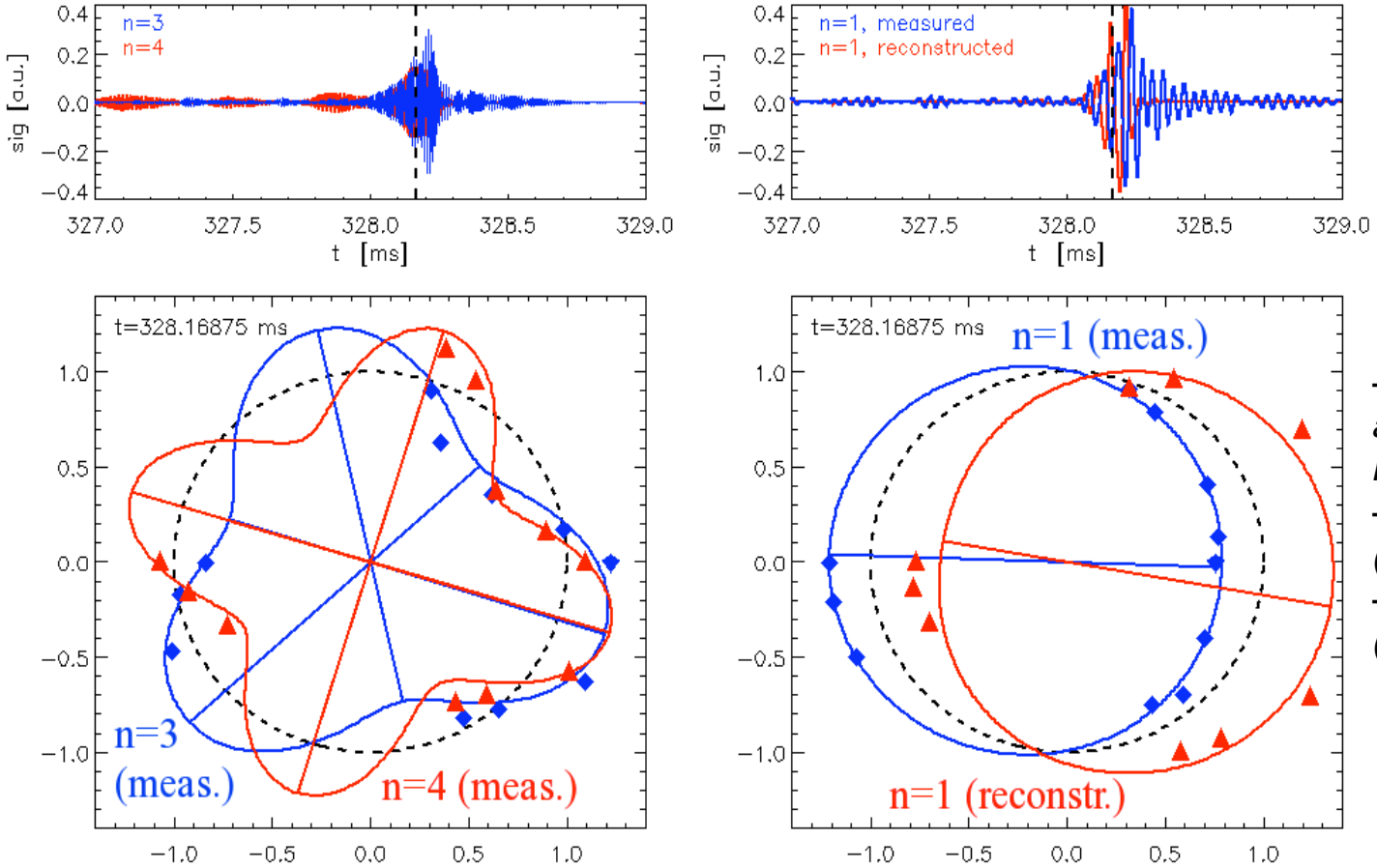




- *n=1* mode fades away when either amplitude of pump modes or frequency matching vanishes

Podestà et al., NF 2011

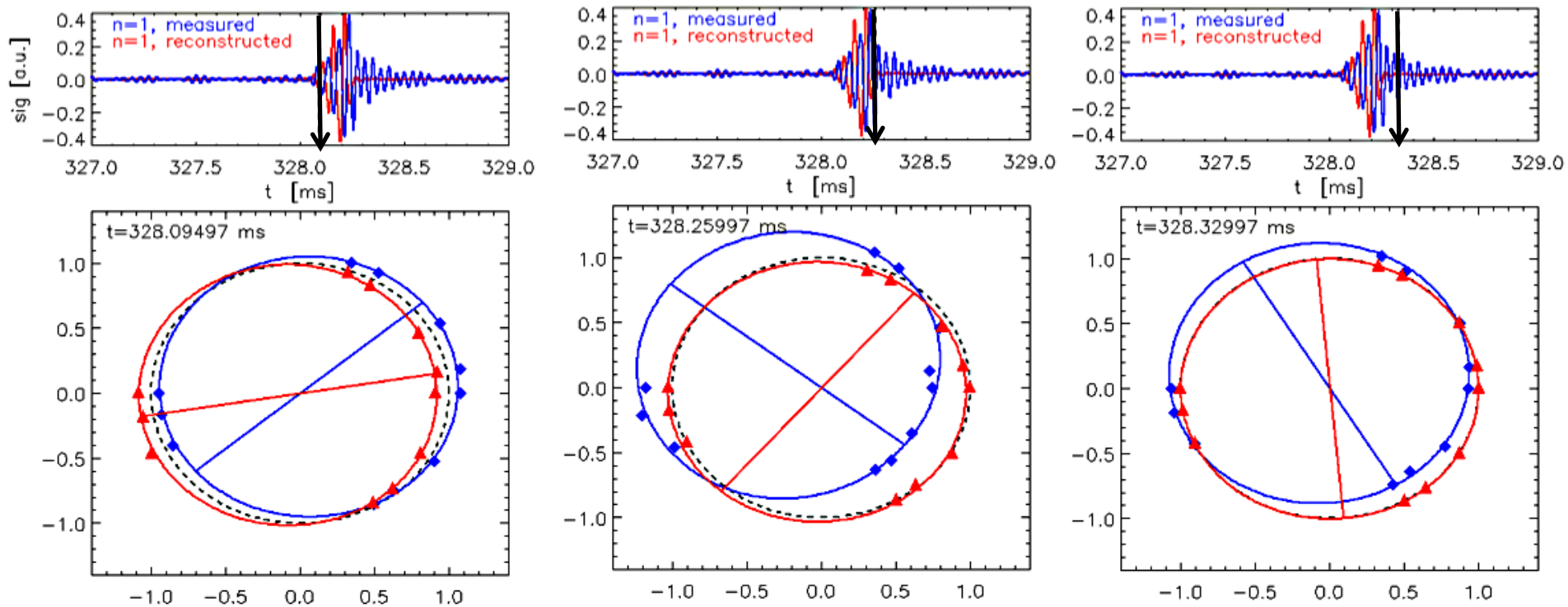
Mode number matching condition verified



-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)

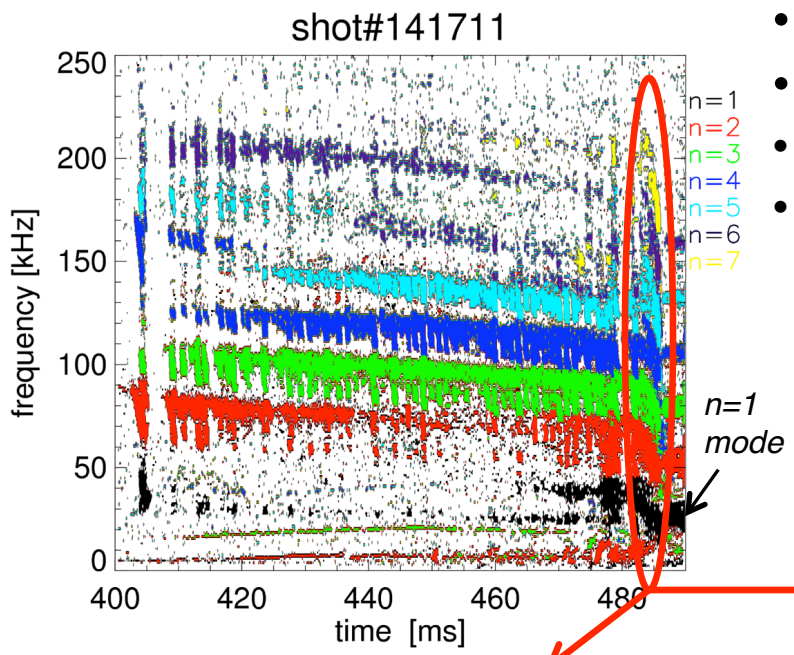
- "Reconstructed" toroidal structure of *n=1* mode also agrees with measured one
  - *Phase shift of ~180 degrees during strongest mode activity*

Phase matching condition is *transiently* verified for tens of (primary) mode cycles during large bursts



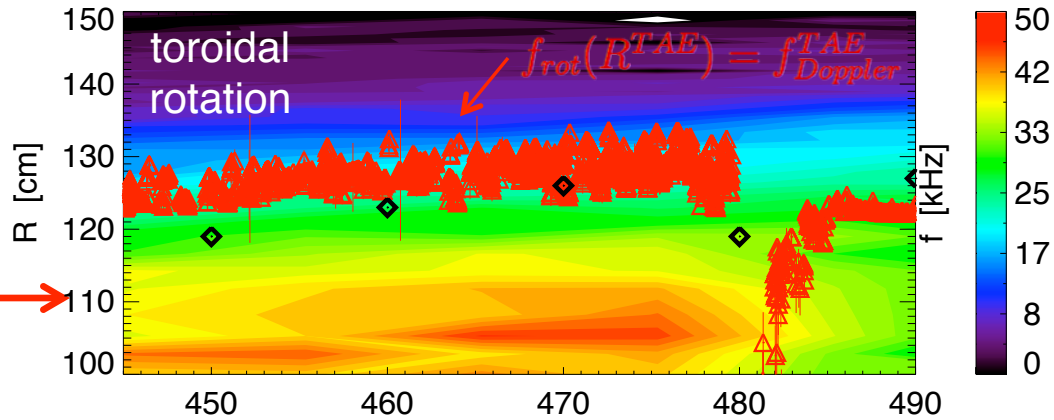
- Stationary phase during quadratic interaction is important!
  - *n=1 mode fades away ⇔ phase changes rapidly in time*
  - "Single mode" dynamic, with each mode following its own chirp/burst cycle, is effective in reducing efficiency of quadratic interactions
  - Result: small bursts (single mode), and occasional multi-mode avalanches
- ***n=1* mode mediates coupling: <u>what is it</u>?**

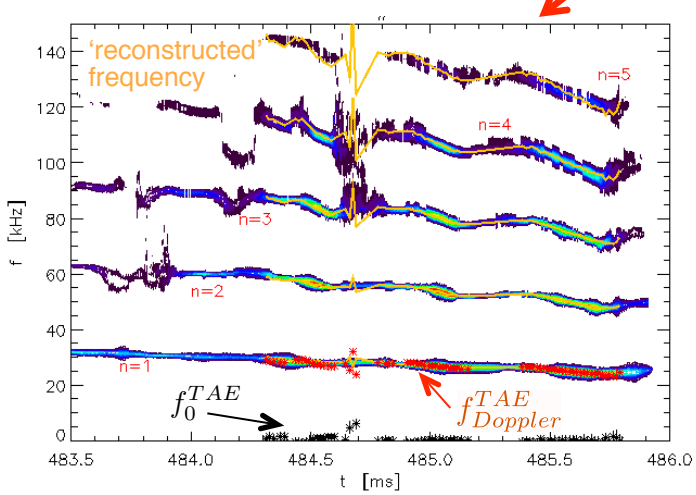
$f_{n=1}$ consistent with central plasma rotation: avalanches drive f_0^{TAE} -> 0 (plasma frame), cause coupling to 'kinks'?

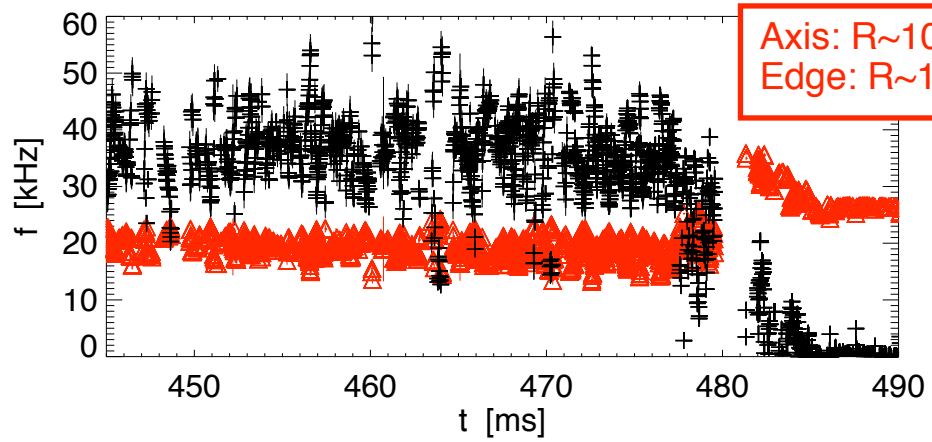


- Kink-like modes destabilized during avalanche
- *Sustained fast ion losses*
- TAE mode structure ~ maintained
- Mode location R^{TAE} sweeps from plasma center out in ~2 ms

Bortolon, O-12



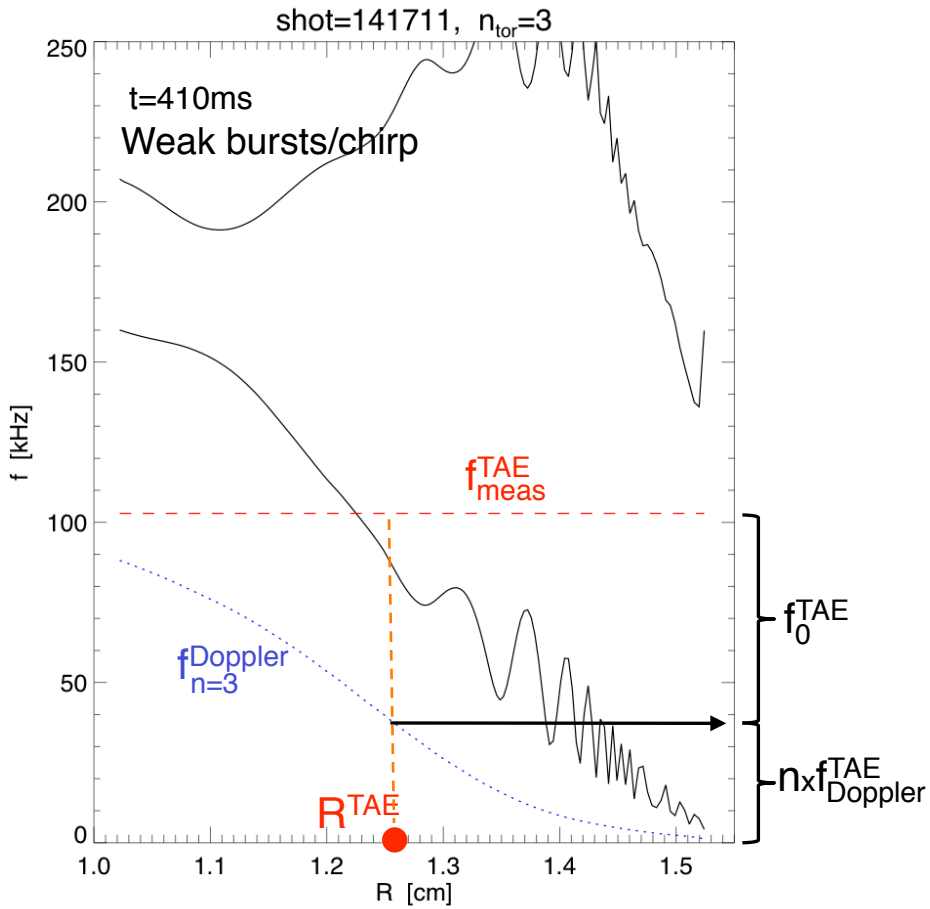




Axis: R~105 cm
Edge: R~155 cm

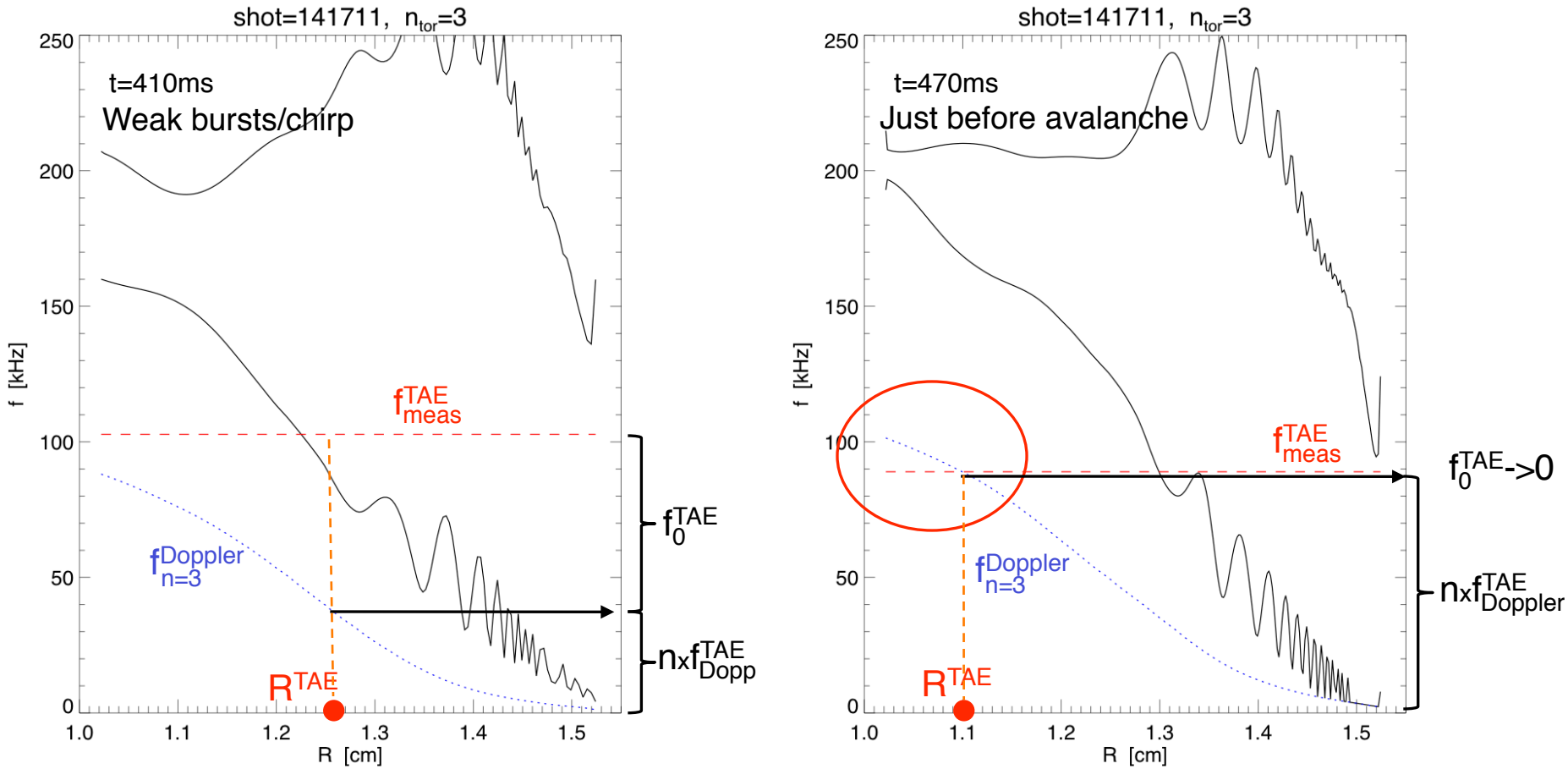
Meaning of f_0^{TAE}: mode frequency at the mode location R^{TAE}, i.e. where drive is maximum

TAE continuum from NOVA-K



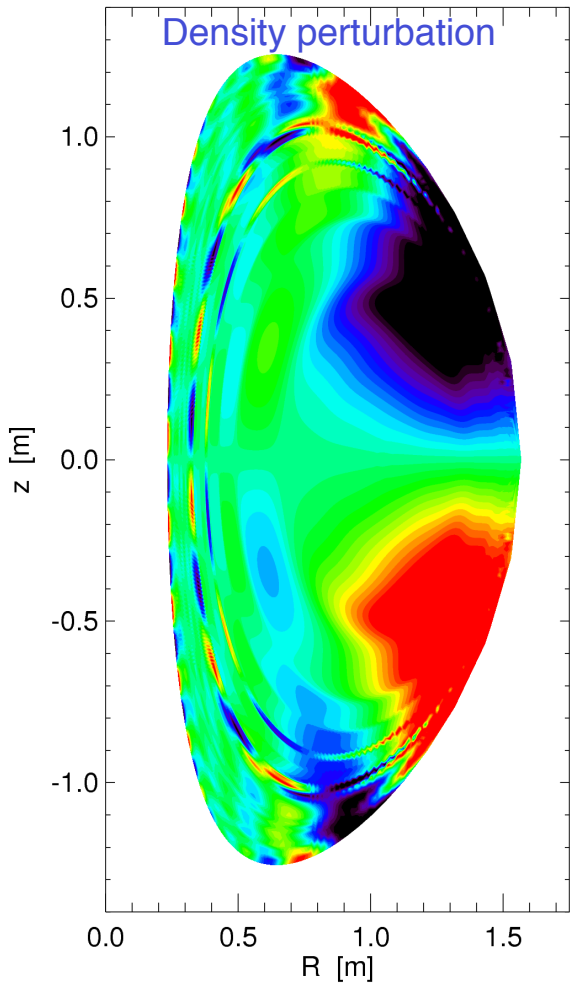
Meaning of f_0^{TAE}->0: f^{TAE} beats with *n* x rotation frequency at the plasma center

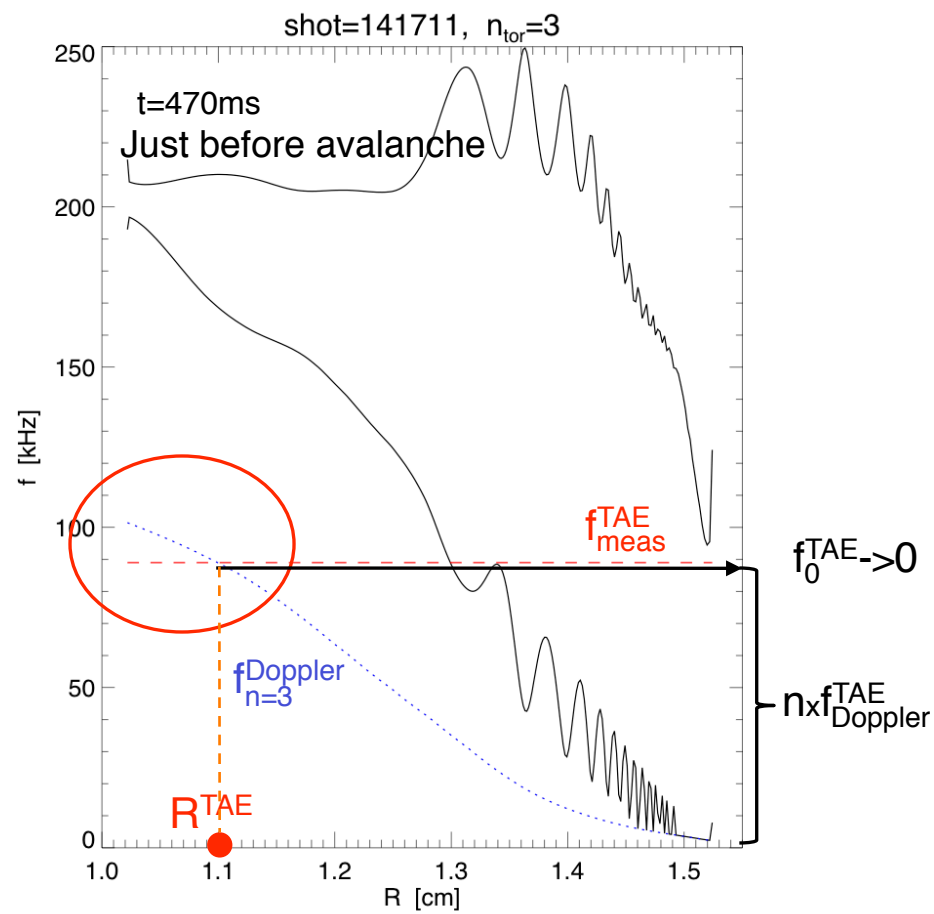
TAE continuum from NOVA-K



- *Coupling with kink-like modes favored when n_{tor} x f_{rot} on axis ~ f^{TAE}*
- *Observed for q>1: fishbone branch involved?*

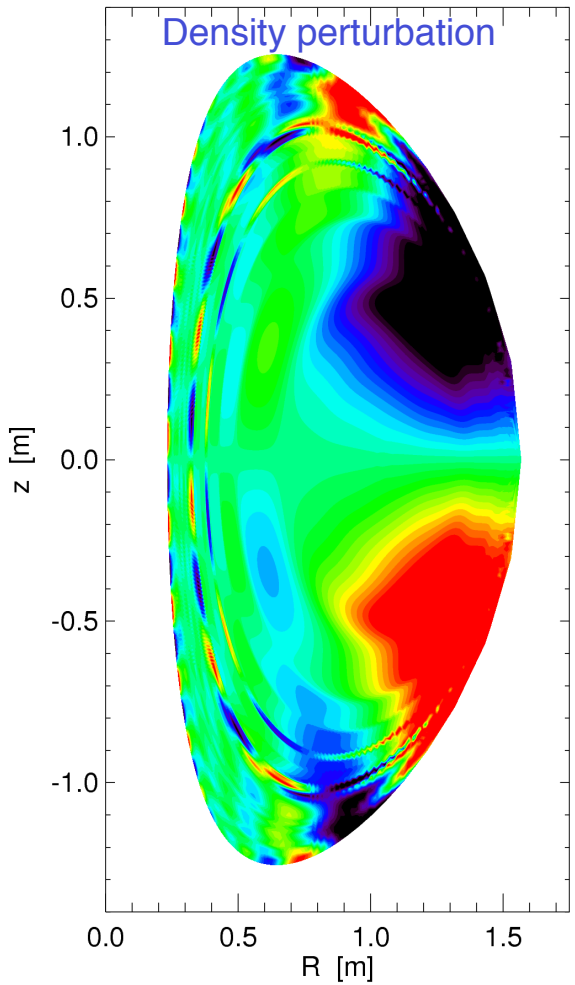
n=1, m=-2, ..., +2 kink found through ideal MHD code NOVA with no rotation, *free boundaries*

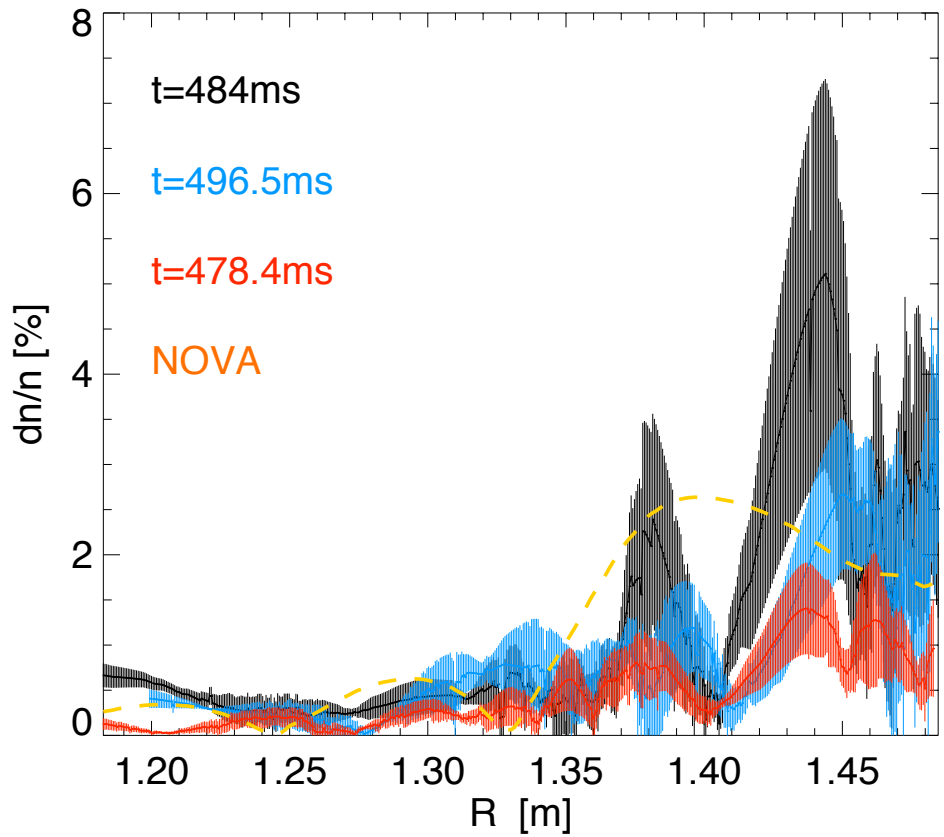




- Large edge perturbation, consistent with reflectometer's data

Measured perturbation evolves during burst; large edge component, dn/n>5%





- Data from inversion of multi-channel reflectometer signals
- Roughly consistent with (ideal) NOVA solution

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Summary

- After onset, bursting/chirping 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 at play in both single-mode and multi-mode (avalanching) TAE dynamics
  - But only avalanches seem to cause significant fast ion losses
  - Coupling manifests as intermittent, chaotic process
  - Coupling can encompass multiple 'scales': TAE, kink/fishbones (, GAE, ...)
  - Dynamics complicated by link between fast ions, TAEs, thermal plasma through NB injection
- Different physics for weak chirps *vs.* avalanches?
  - Single-mode; weak chirps regulated by phase-space, fast ion profile effects
  - Multi-mode; avalanches lock on underlying kink/fishbone ('global')
- Present experiments allow thorough benchmark of codes
  - Linear MHD satisfactory for first-order estimates of mode structure
  - Non-linear, self consistent codes required to capture full dynamics