NSTX PPPL Princeton Plasma Physics Laboratory

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

Mario Podestà

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and the NSTX Research Team

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Sep. 7-10, 2011

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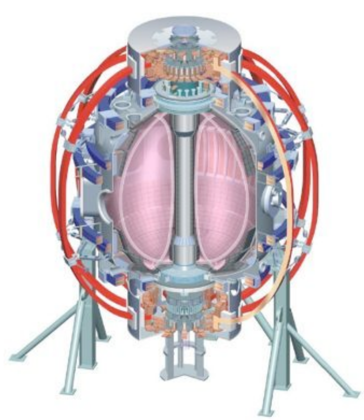
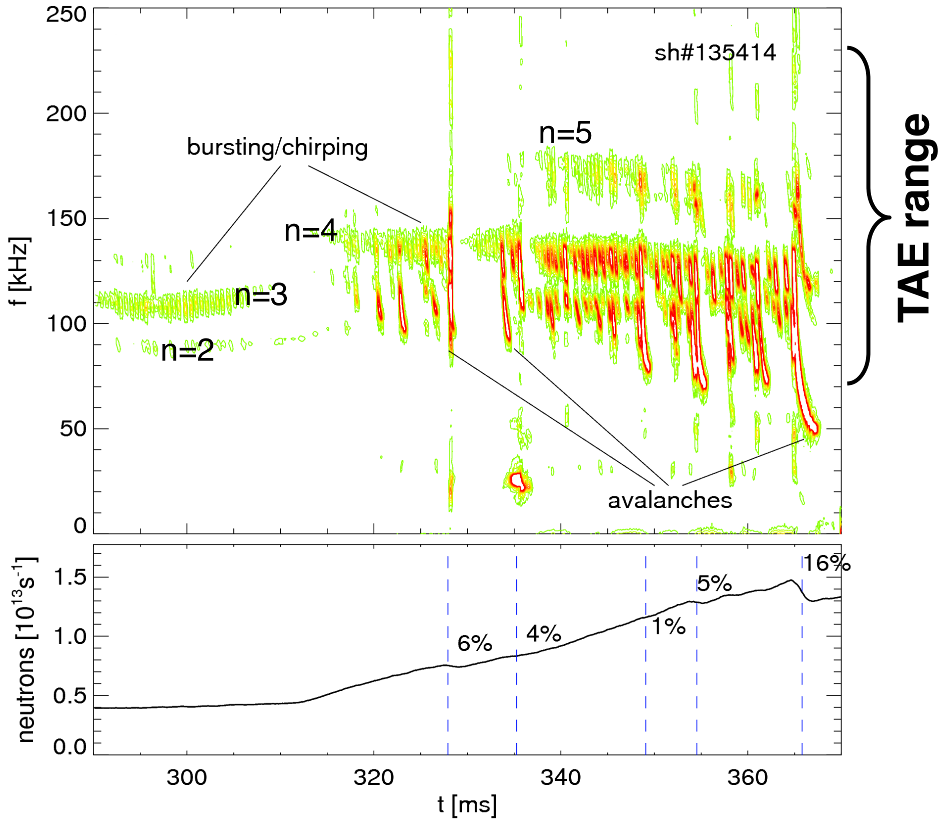


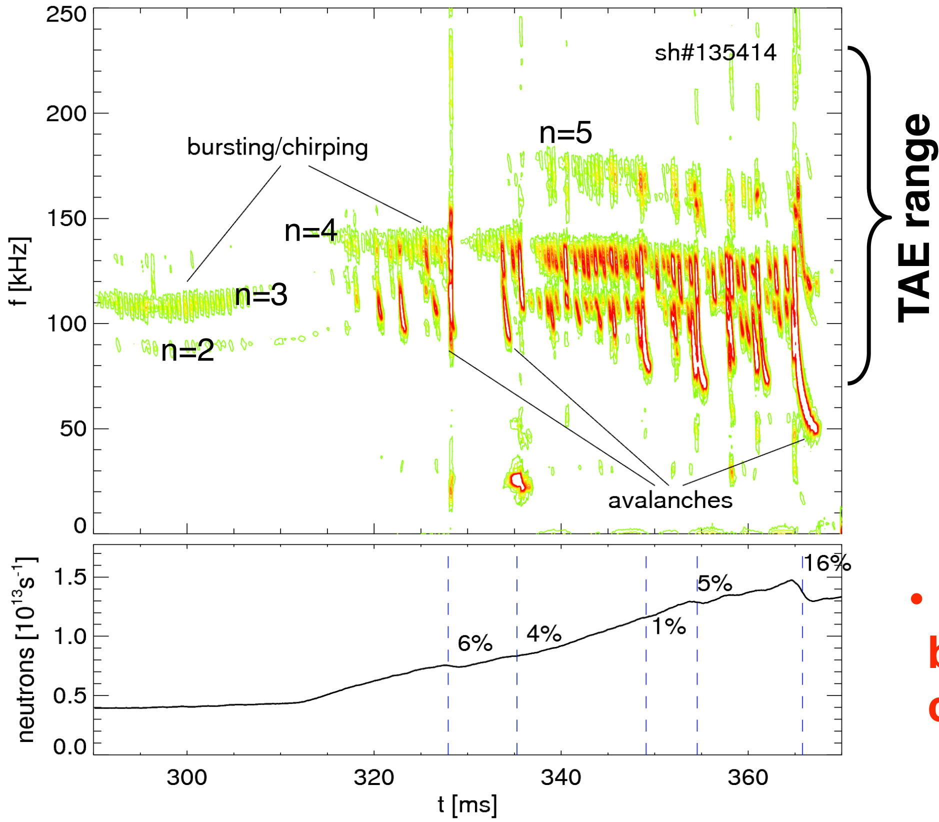
Bursting toroidicity-induced Alfvén eigenmodes (TAEs) can lead to enhanced fast-ion transport

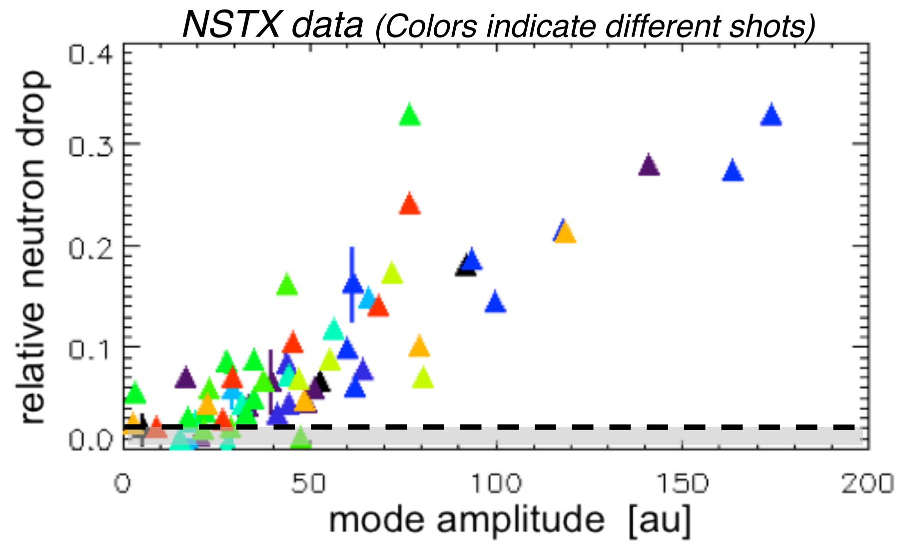
- Multiple TAEs can be simultaneously destabilized
  - Possible overlap of many resonances in phase space
  - Non-linear development into "TAE ***avalanches***"



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
- Summary and open issues

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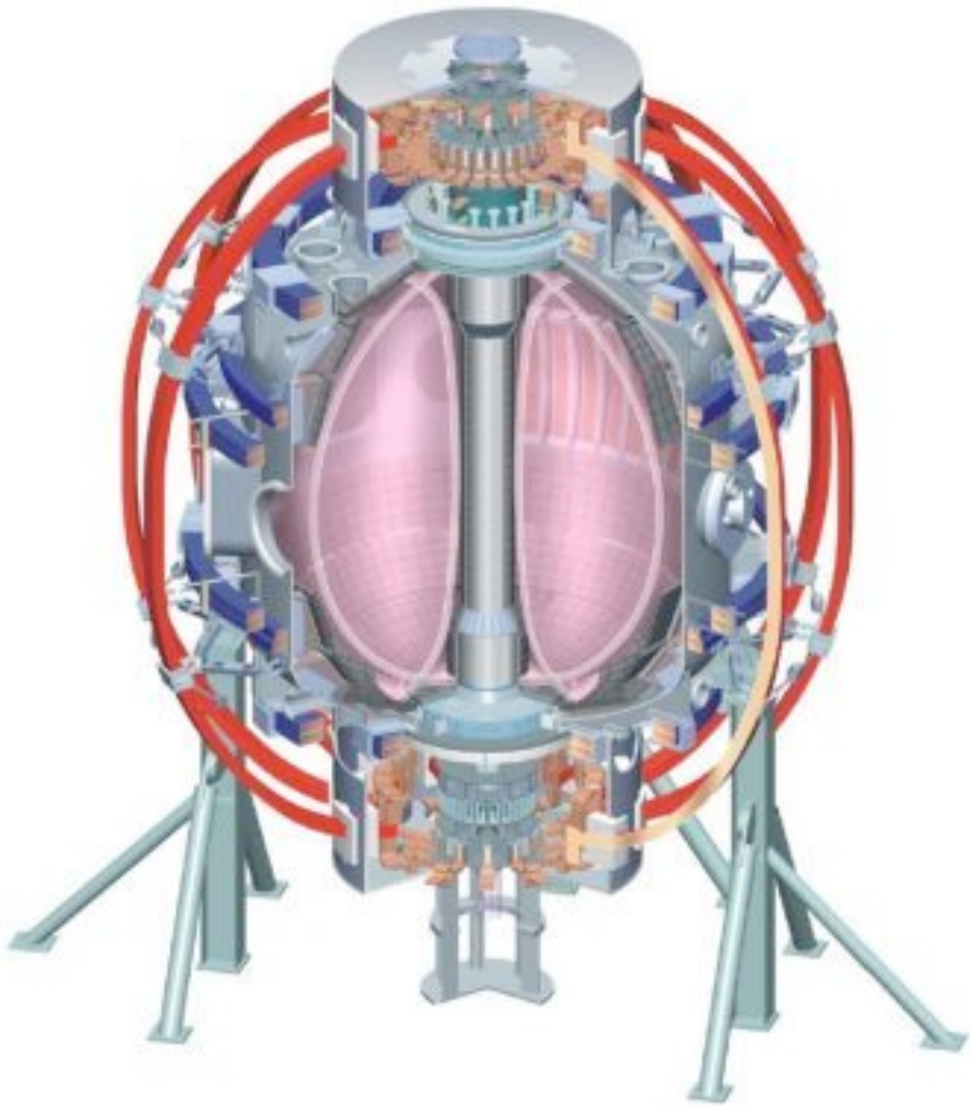
NSTX parameters



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

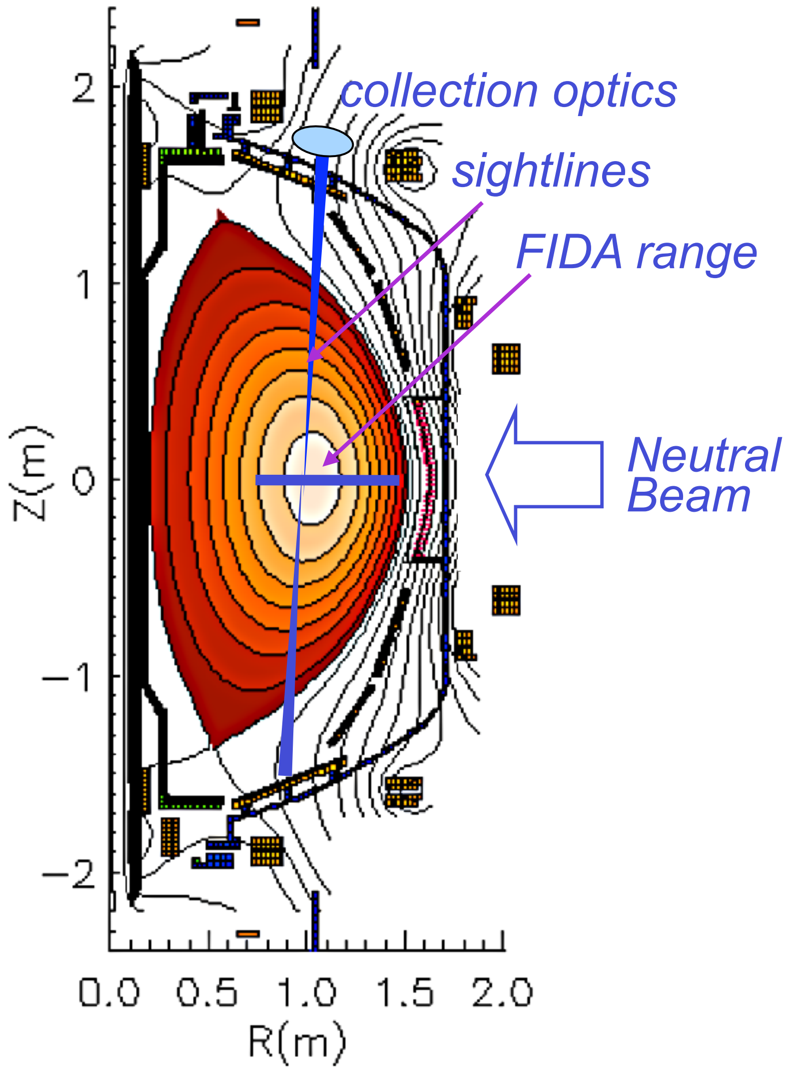
$P_{NBI} \leq$ 6 MW, $E_{injection} \leq$ 95 keV

⇨ $1 < v_{fast}/v_{Alfvén} < 5$

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

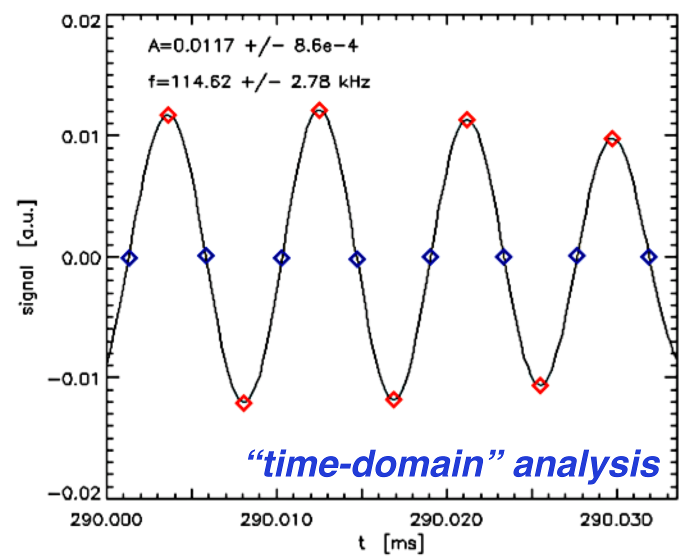
Mode activity and fast ion diagnostics on NSTX

shot#135404, t=320 ms



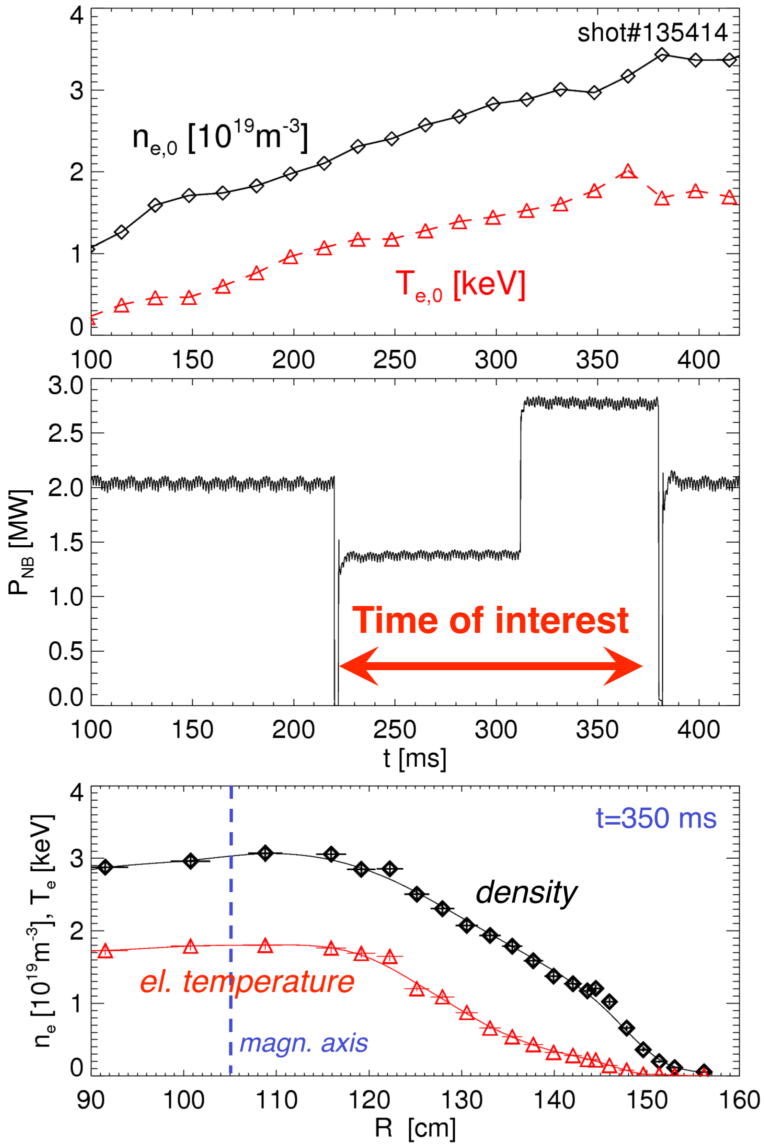
- Mirnov coils
  - Magnetic fluctuations up to 2.5 MHz
- Multi-channel reflectometer
  - Mode structure (monotonic profiles) UCLA

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



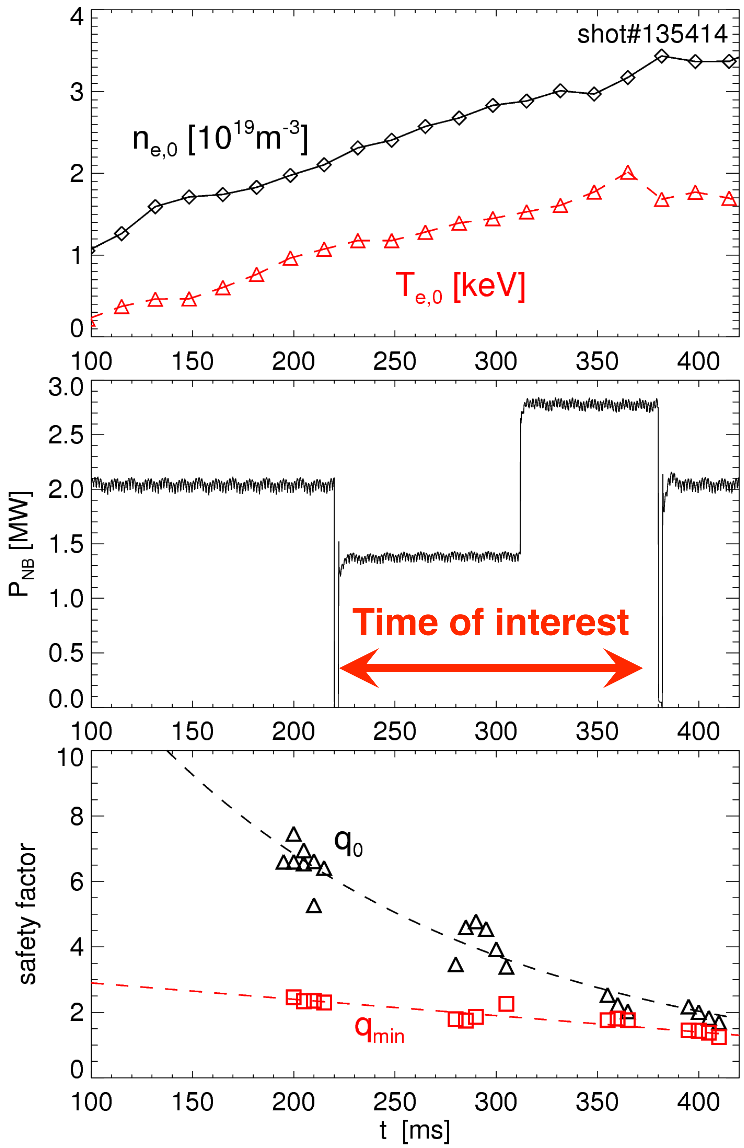
- Fast Ion diagnostics UCIrvine University of California, Irvine
  - Fast Ion D-Alpha systems (fast ion radial profile and spectrum)
  - Neutral Particle Analyzers, Fast Ion Loss probe, neutron rate

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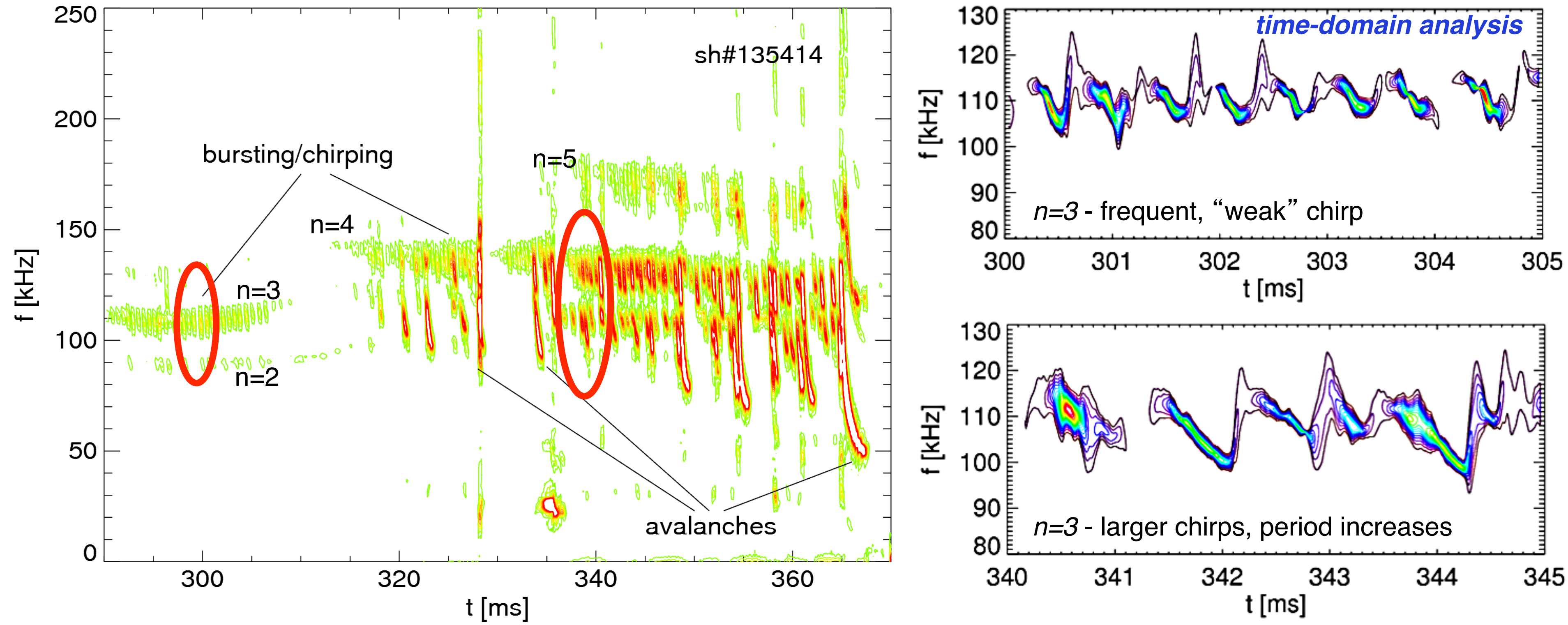
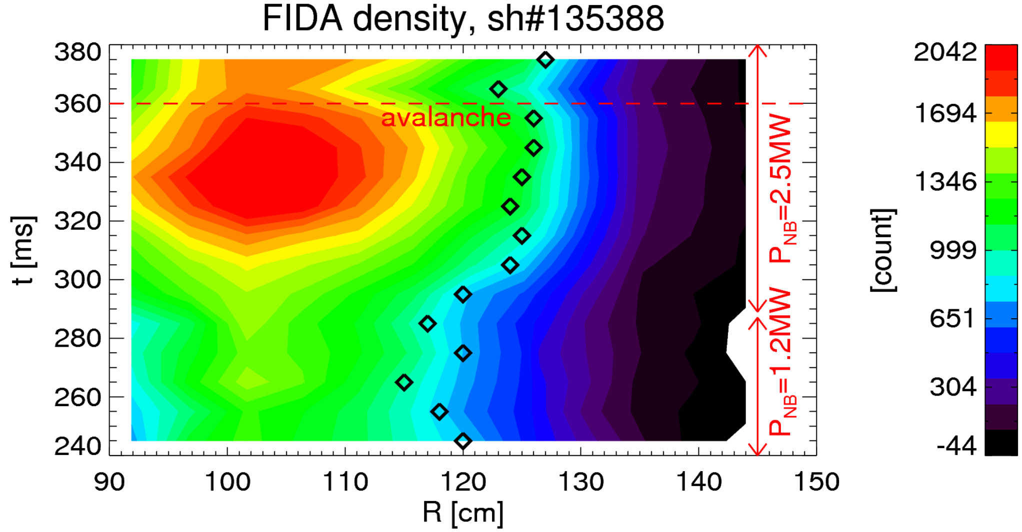
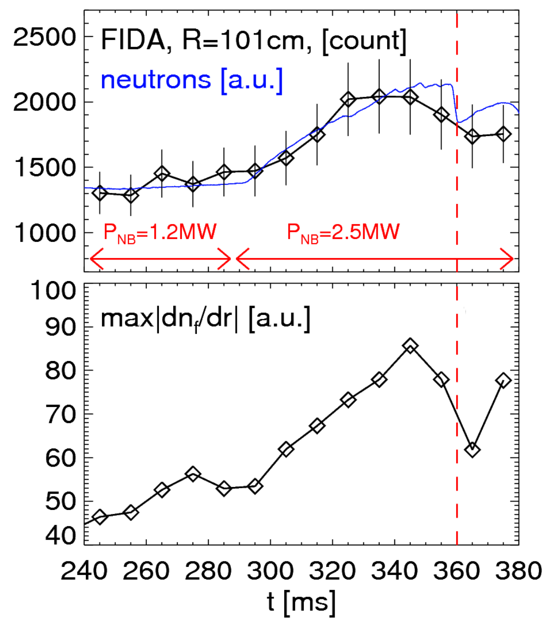
TAEs with low-intermediate toroidal mode number (n=2→7) are observed, with dominant n=2-4 modes

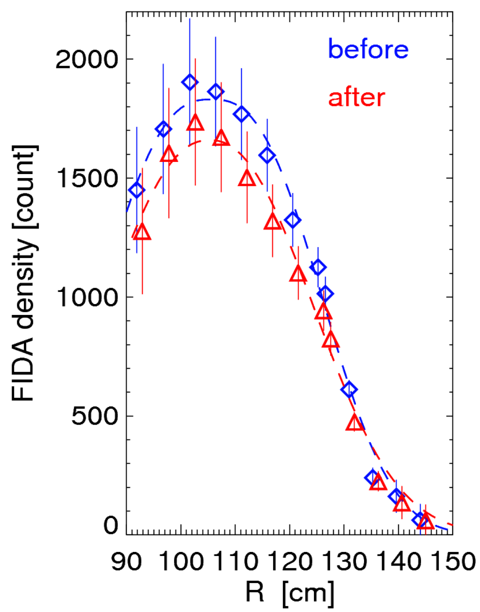


- Burst separation 0.5 – 2 ms
  - No systematic variation with n_e, T_e, P_{NB}, …
  - Frequency evolution does not follow unique patter (e.g. $t^{-1/2}$, linear, exponential)
- Usually, each mode chirps independently of the others...
- ... but, eventually, *avalanches* occur:
  - Drop in neutron rate, 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?

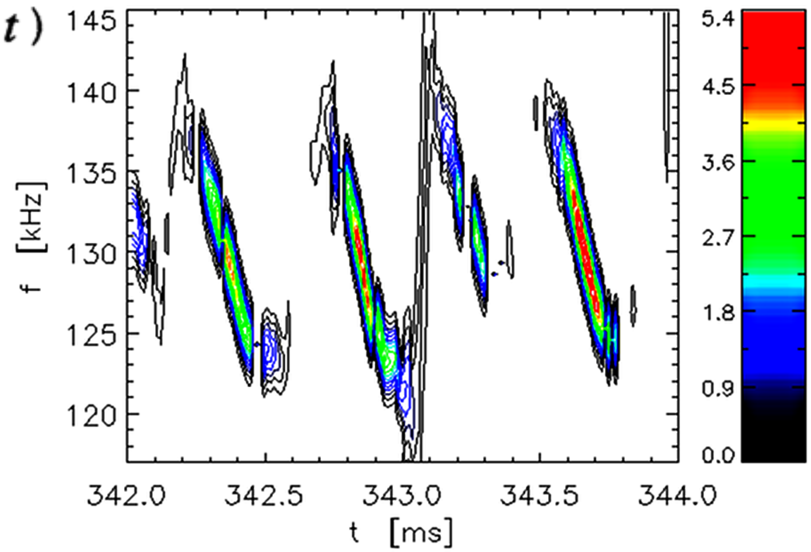
Frequency *vs.* amplitude are correlated; reminiscent of driven, non-linear system

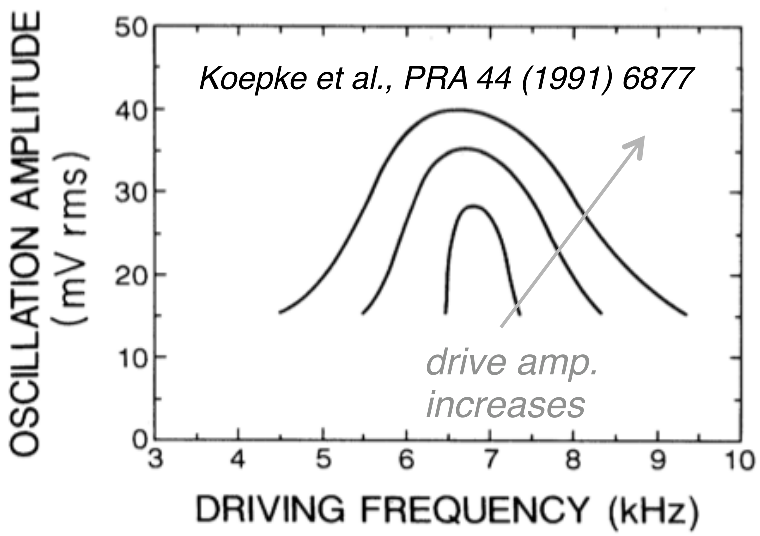
- E.g., non-linear Van der Pol oscillator:

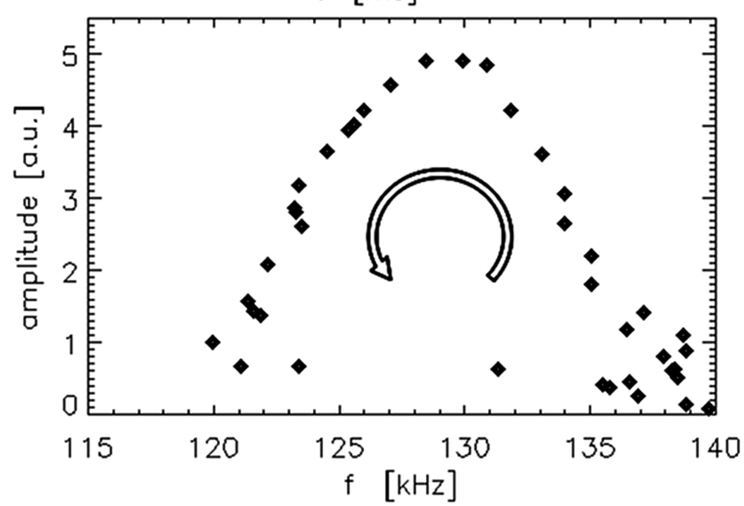
$$\ddot{x} - \epsilon(1-\beta x^2)\omega_0\dot{x} + (\omega_0^2+\eta x^2)x = M\omega_0^2\sin(\omega_D t)$$

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*

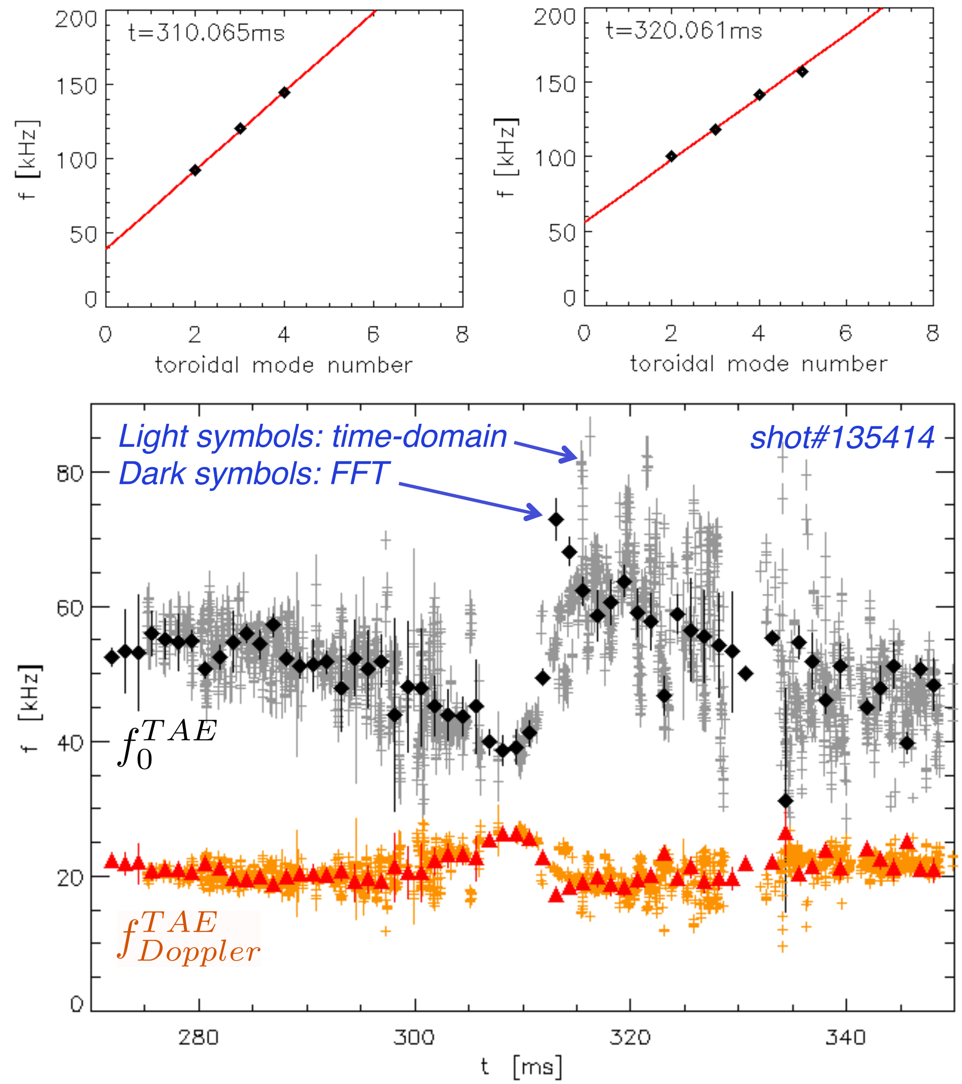
Measured frequency consistent with:

$$f^{TAE}_{lab,n} = f^{TAE}_{0} + n\, f^{TAE}_{Doppler}$$

lab frame — plasma frame — shift from plasma rotation

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

FFT window 1.3ms

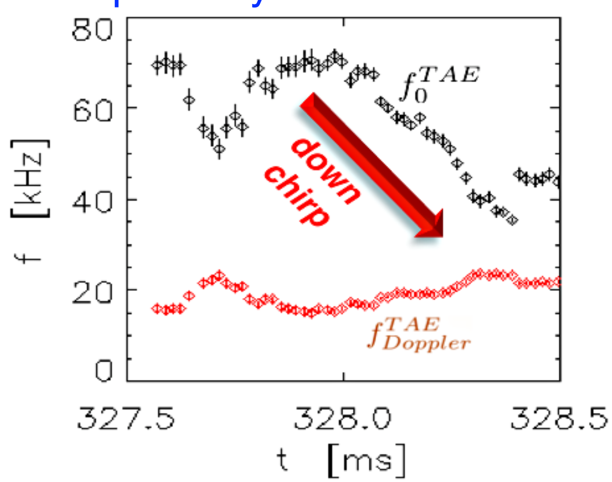


On average, TAE frequencies are consistent with a common frequency *in the plasma frame*

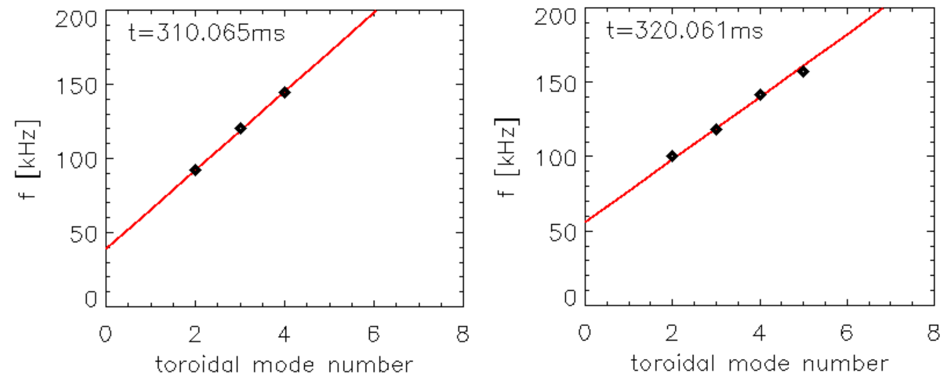
Measured frequency consistent with:

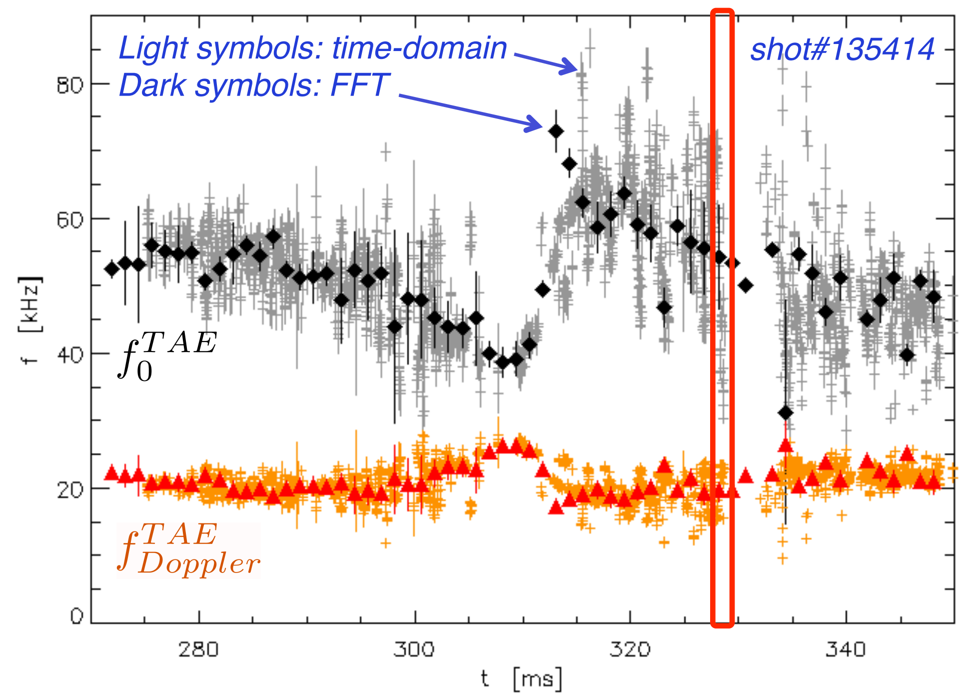
$$\underbrace{f_{lab,n}^{TAE}}_{\text{lab frame}} = \underbrace{f_0^{TAE}}_{\text{plasma frame}} + n\,\underbrace{f_{Doppler}^{TAE}}_{\text{shift from plasma rotation}}$$

- 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_0^{TAE}



FFT window 1.3ms





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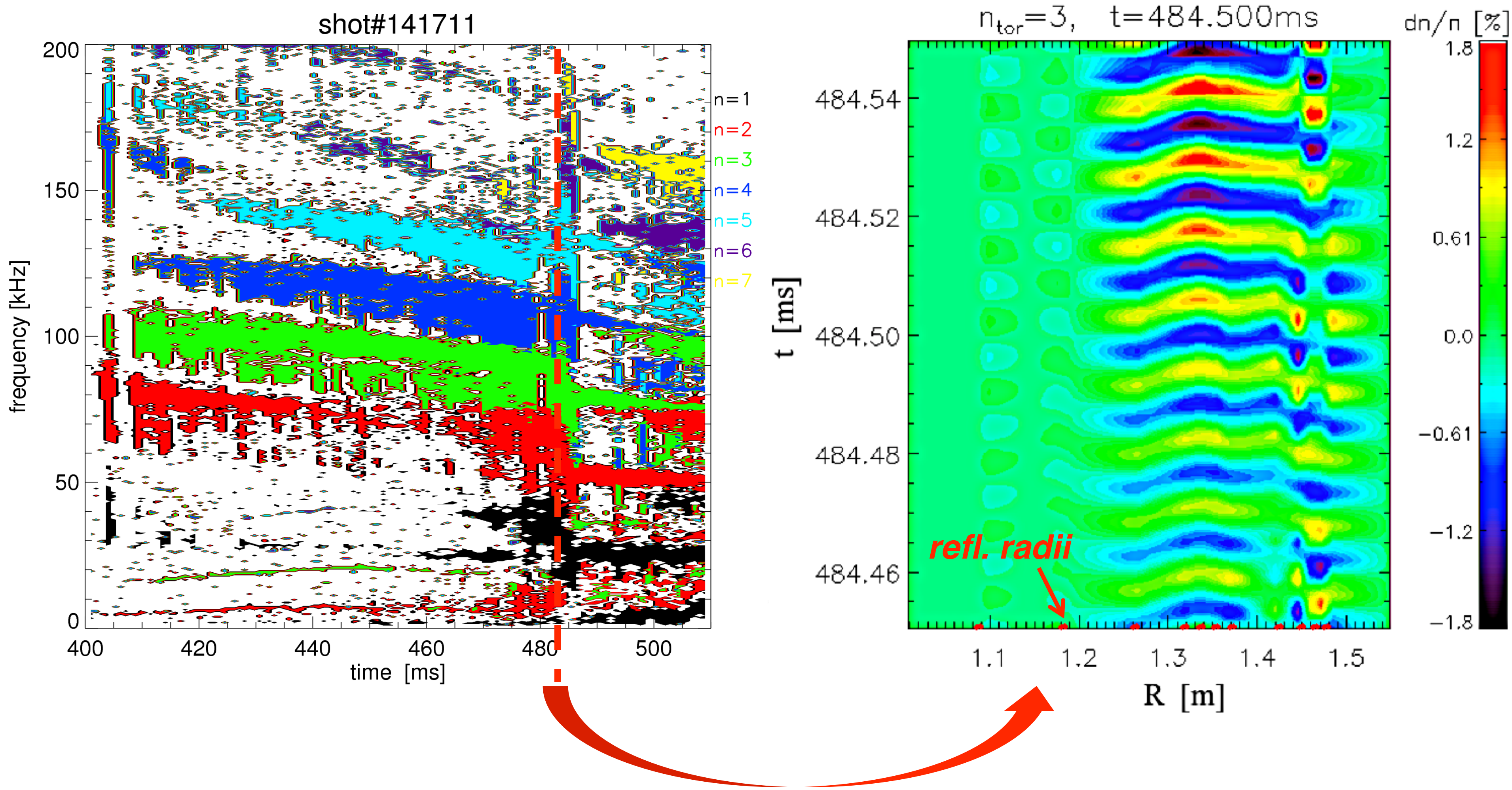
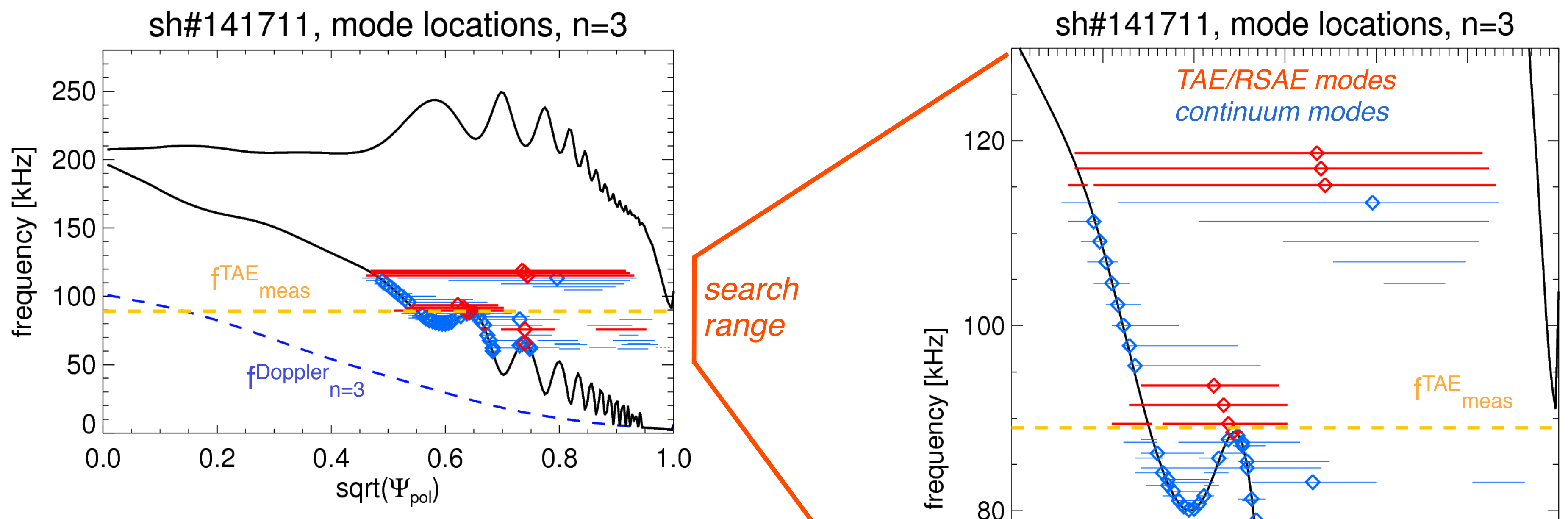
Multi-channel reflectometer is main tool to unravel details of mode structure evolution

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

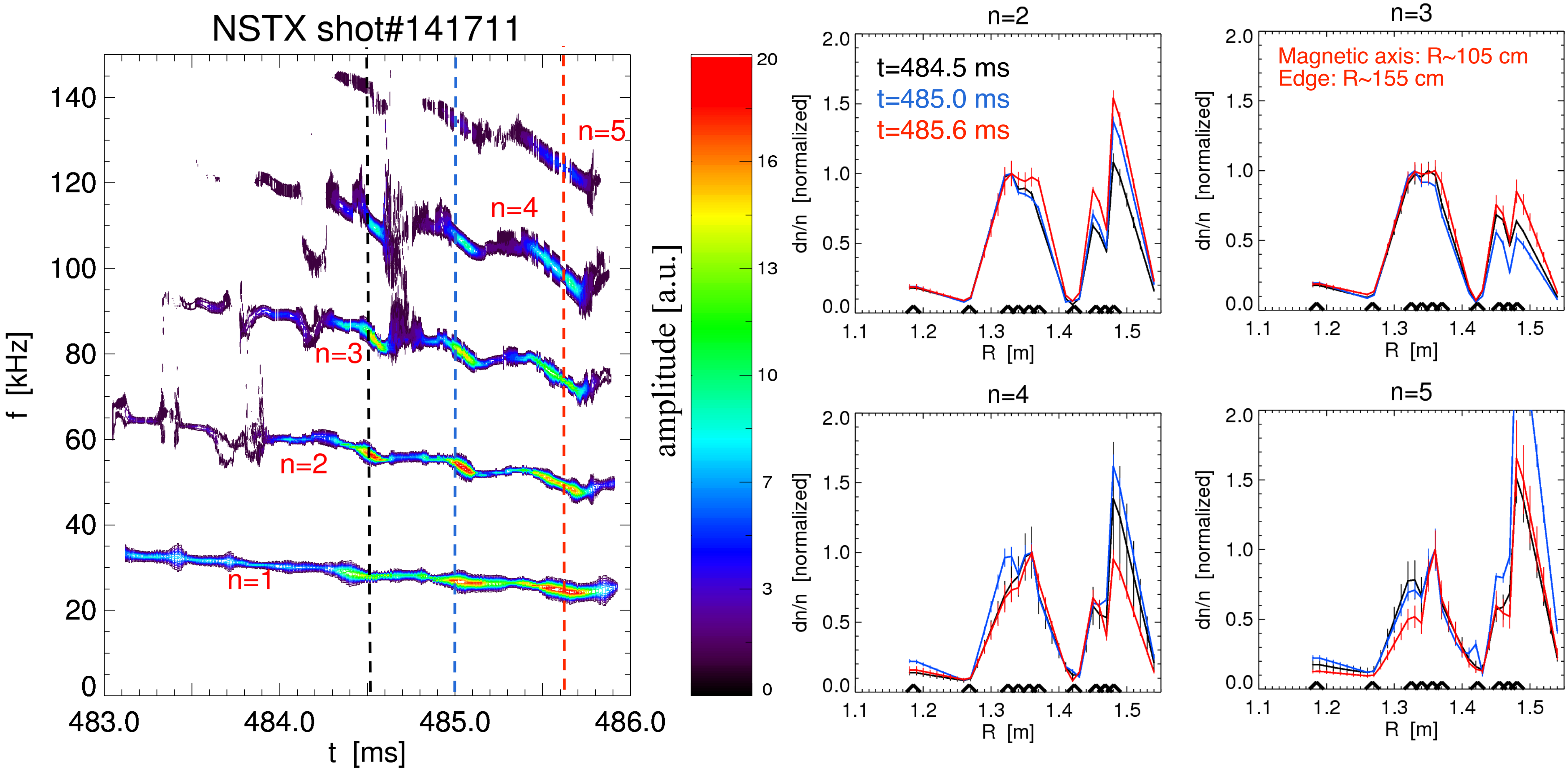


- NOVA provides *all, ideal* eigenmodes in a given frequency range
- Match mode structure (dn/n) from reflectometer to NOVA solutions
- Select 'observed' mode; re-scale NOVA solution according to measured dn/n

Fredrickson et al., PoP 2009

Fredrickson, P1.7

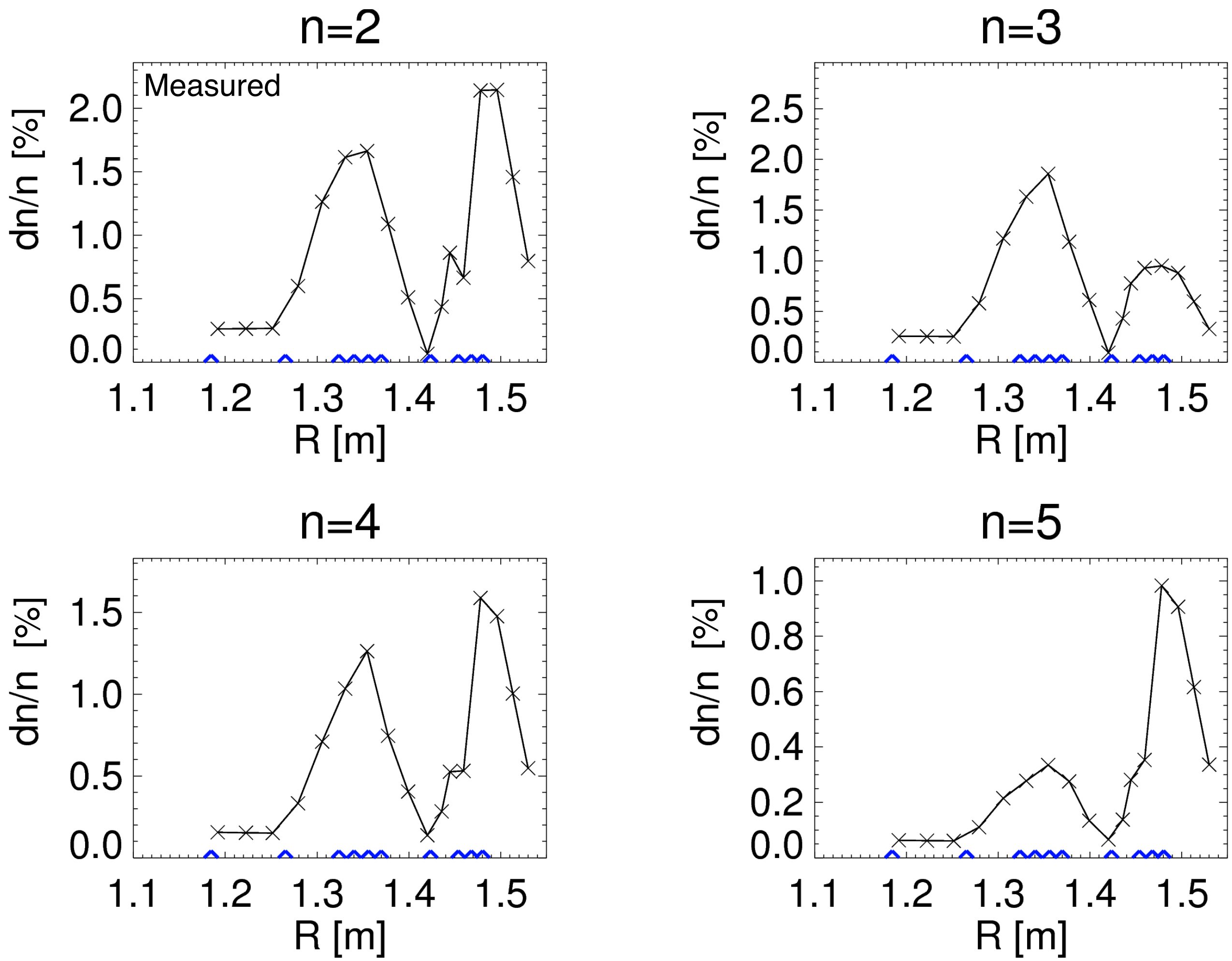
Mode structure maintains its shape even during strong, *multi-step* avalanches



- 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?

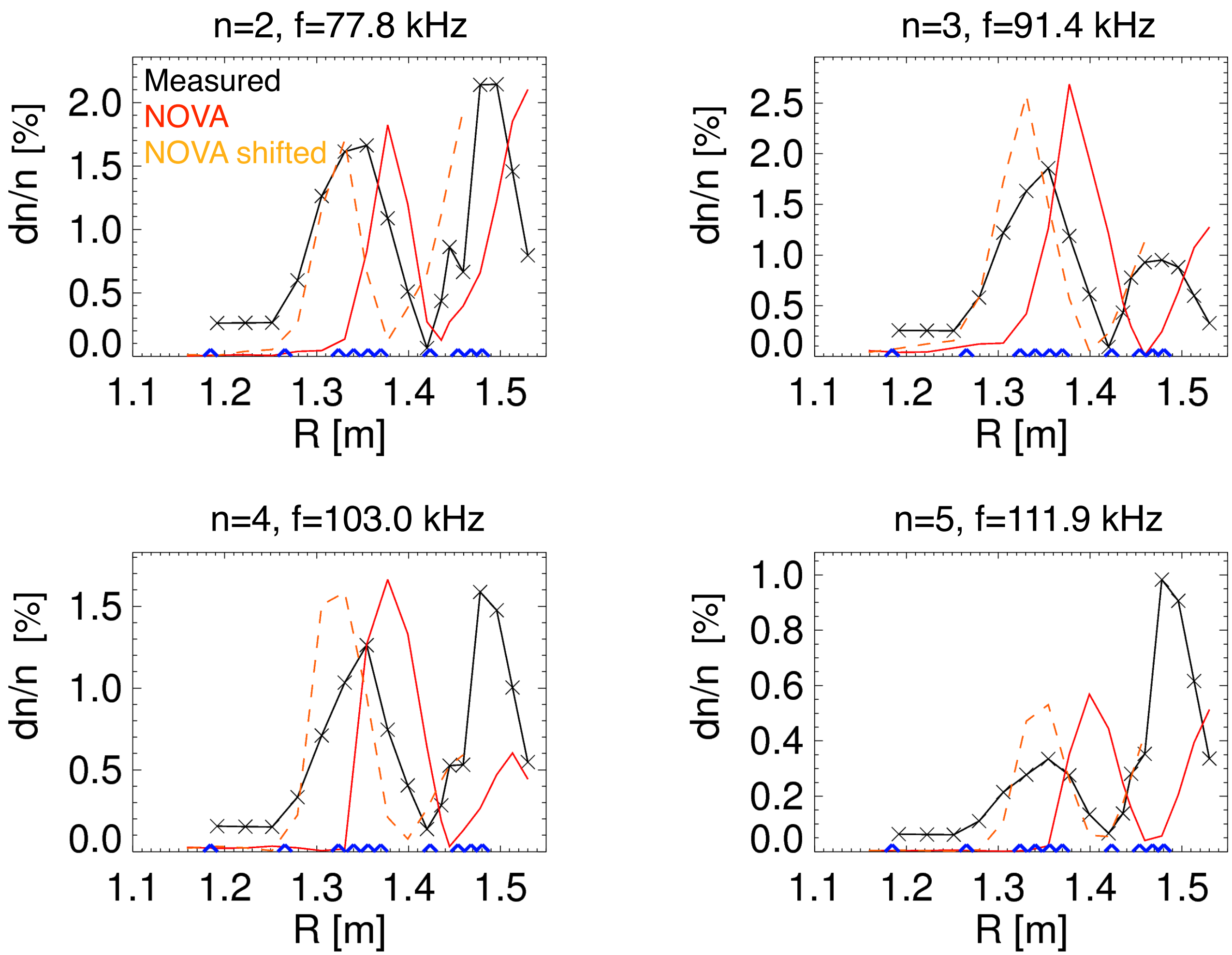
Zonca et al., NF 2005

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'

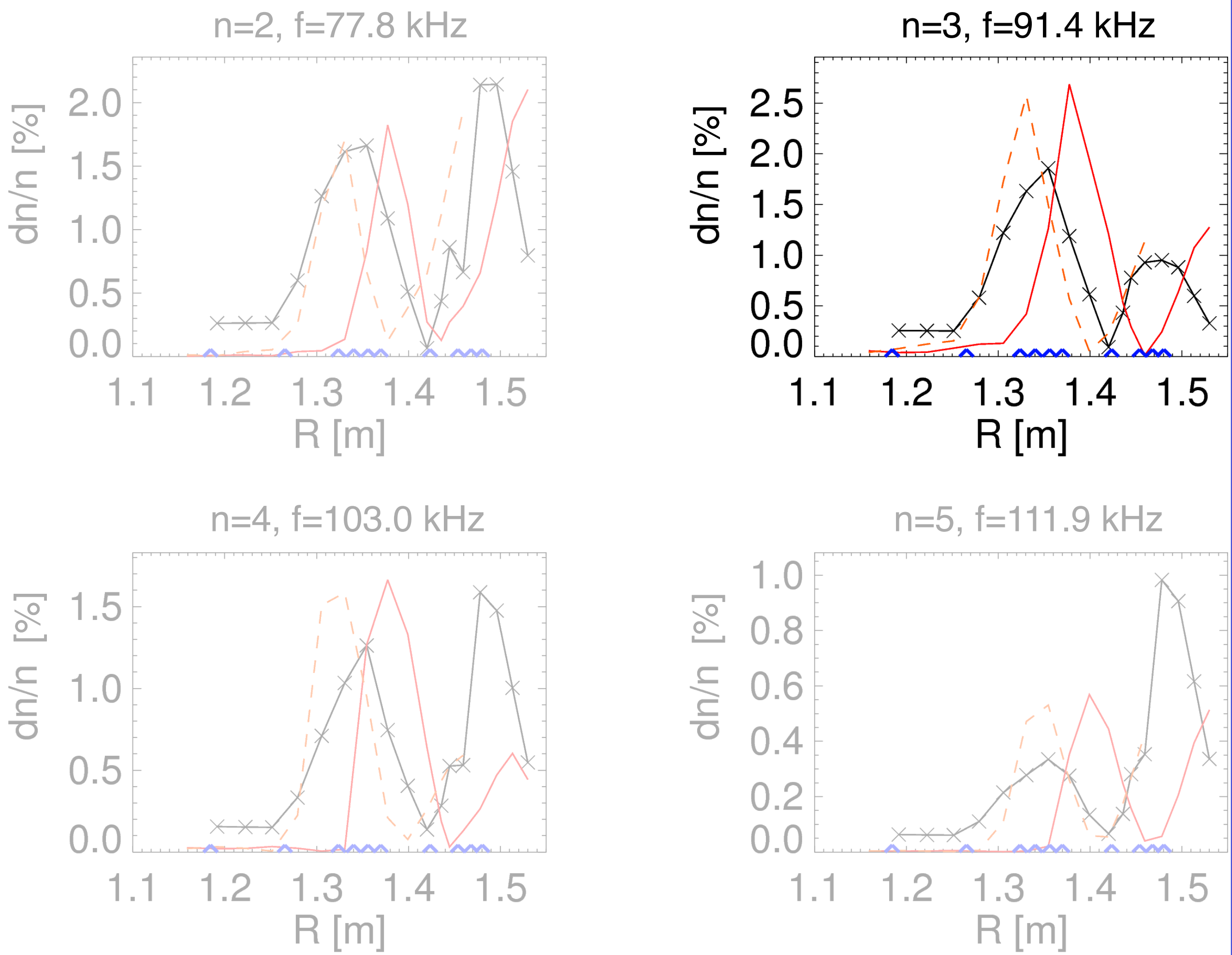


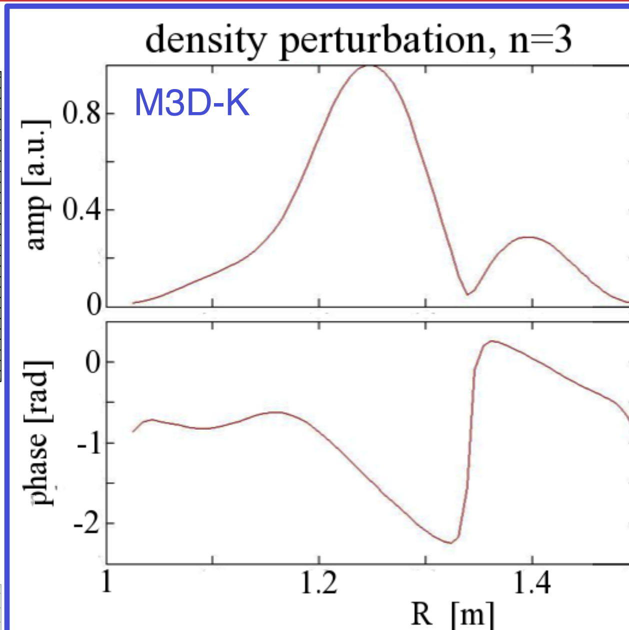
- Frequency from NOVA ~ consistent with experiment
- Doppler shift is included
- But: radial shift of 2-5 cm between measured and simulated dn/n

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*

Initial results from [non-linear, self-consistent] code M3D-K consistent with experiments, too





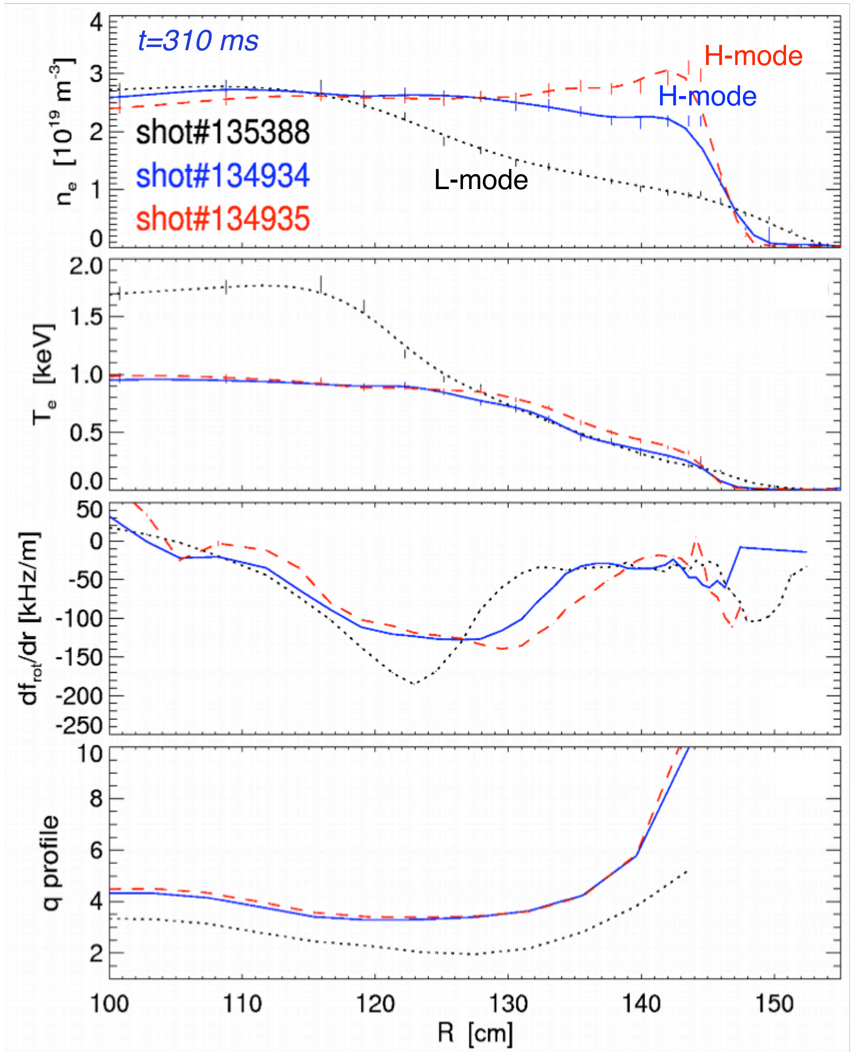
Preliminary M3D-K simulations:

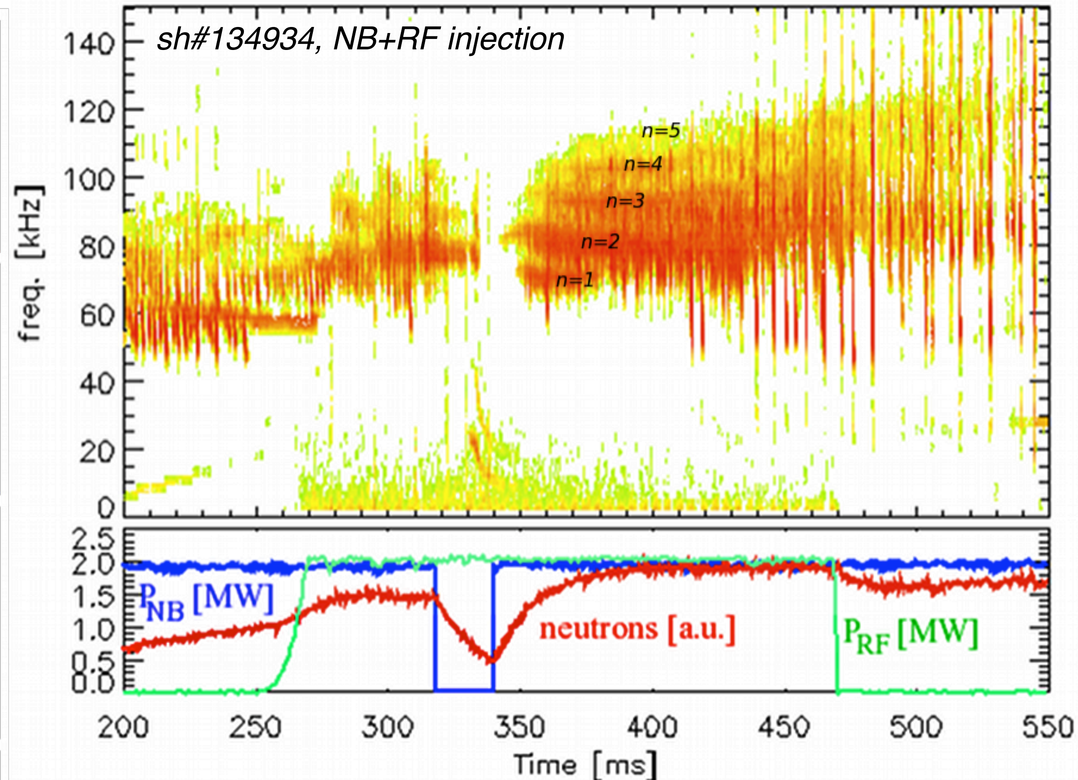
- *Linear; no fast ion effects here*
- *Peak just inside intersection with continuum (from NOVA)*
- *Radial phase variation observed*
- *Mode shifted inward w.r.t. measurements*

Fu, TTF 2011

- 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 ... and M3D-K*

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





Fredrickson, P1.7

- 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

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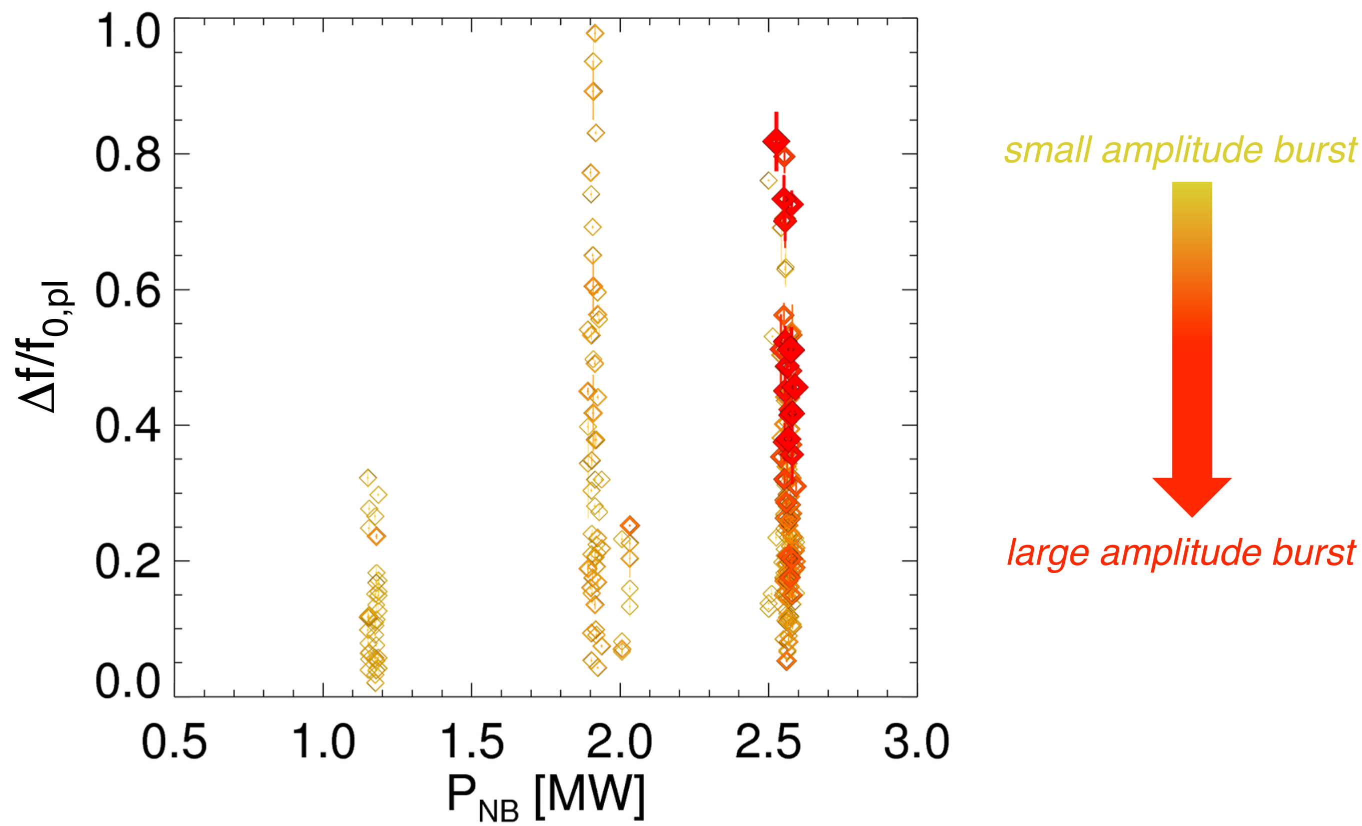
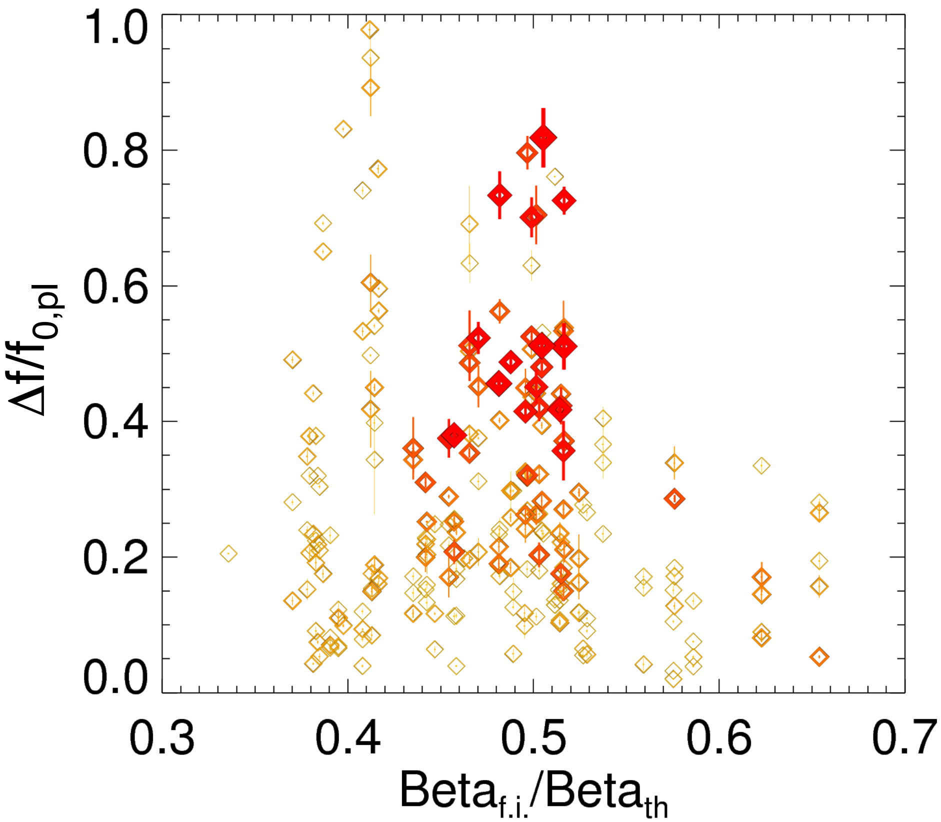
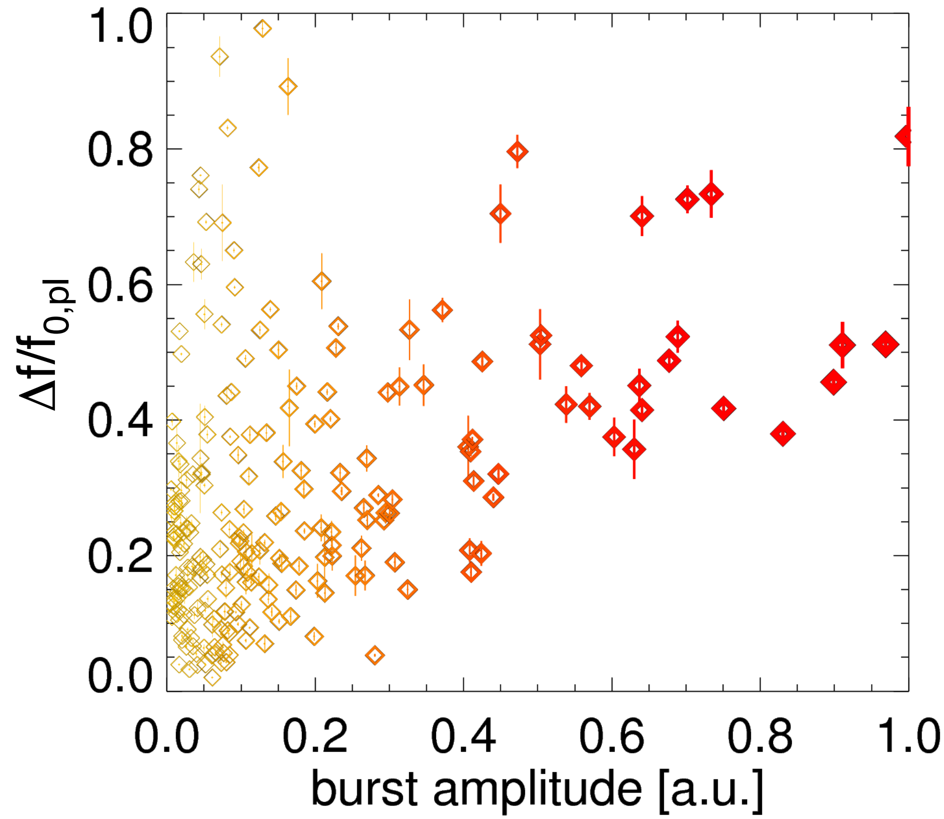
Onset of bursting/chirping regime strongly dependent on injected NB (and RF) power

- 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



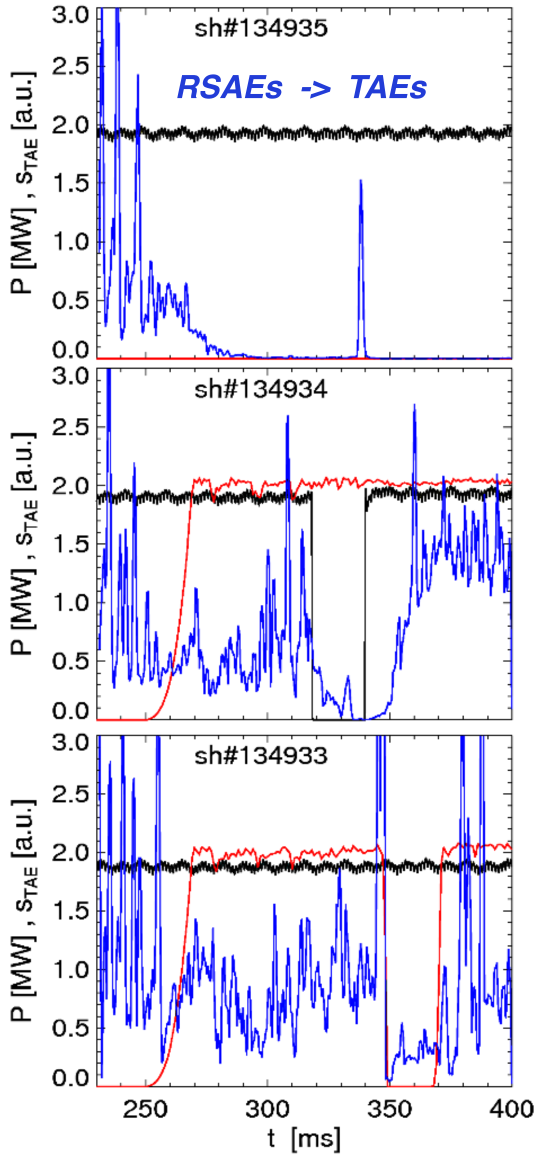
High ratio of fast ion to thermal β leads to bursts/chirps – but other factors determine mode dynamics



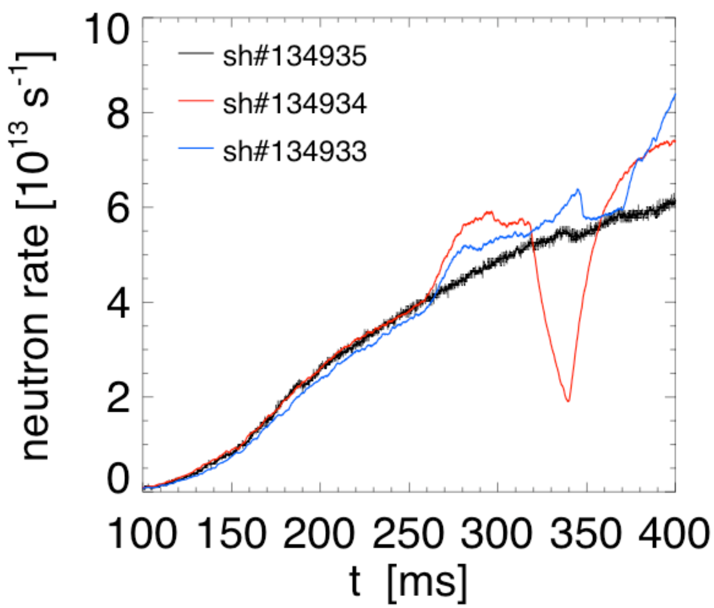


- Modes show more bursting character as discharge evolves
  - NB power increases, fast ion population and $\beta_{f.i.}$ builds up
  - Typical bursts have *edge* $\delta B/B \sim 10^{-4}$ (from Mirnov coils)
    - > Can increase more than x10 during avalanches

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

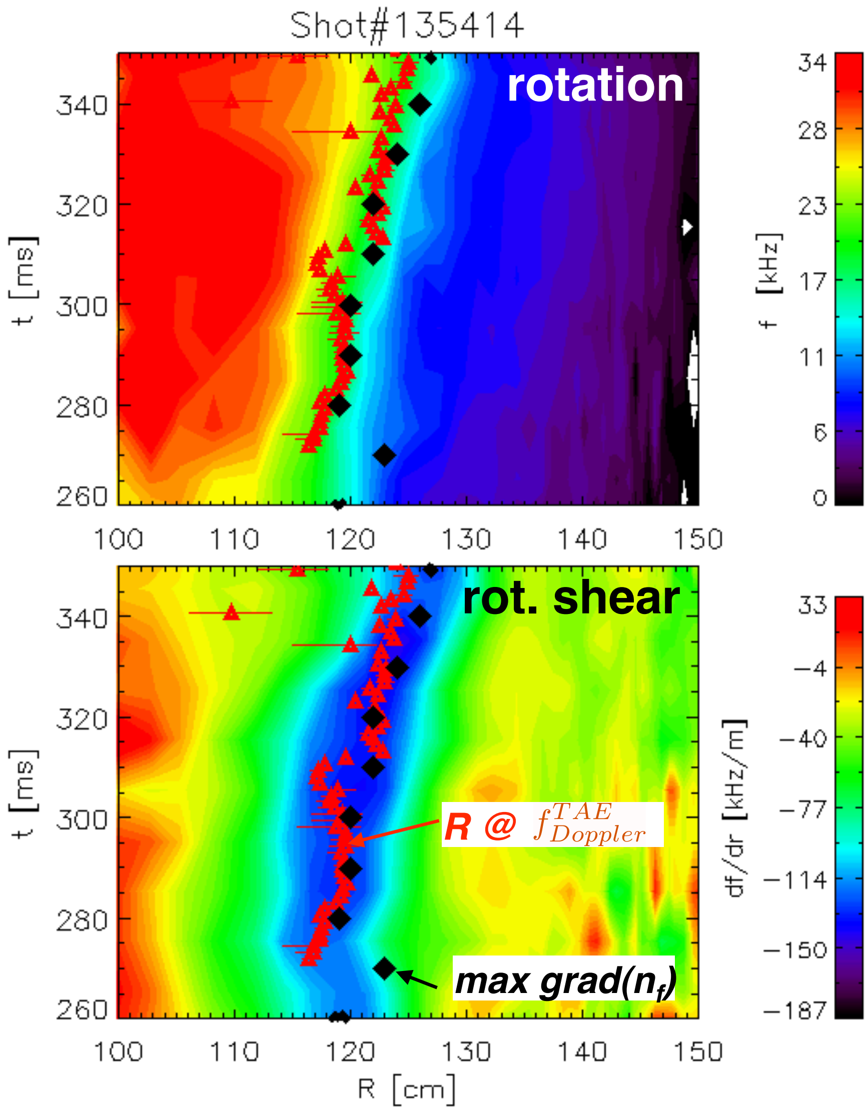


- Example: H-mode discharges with NB and NB+RF heating
  - Different profiles with respect to L-mode (e.g. higher safety factor)
  - Reversed shear in both L- and H-mode



- 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

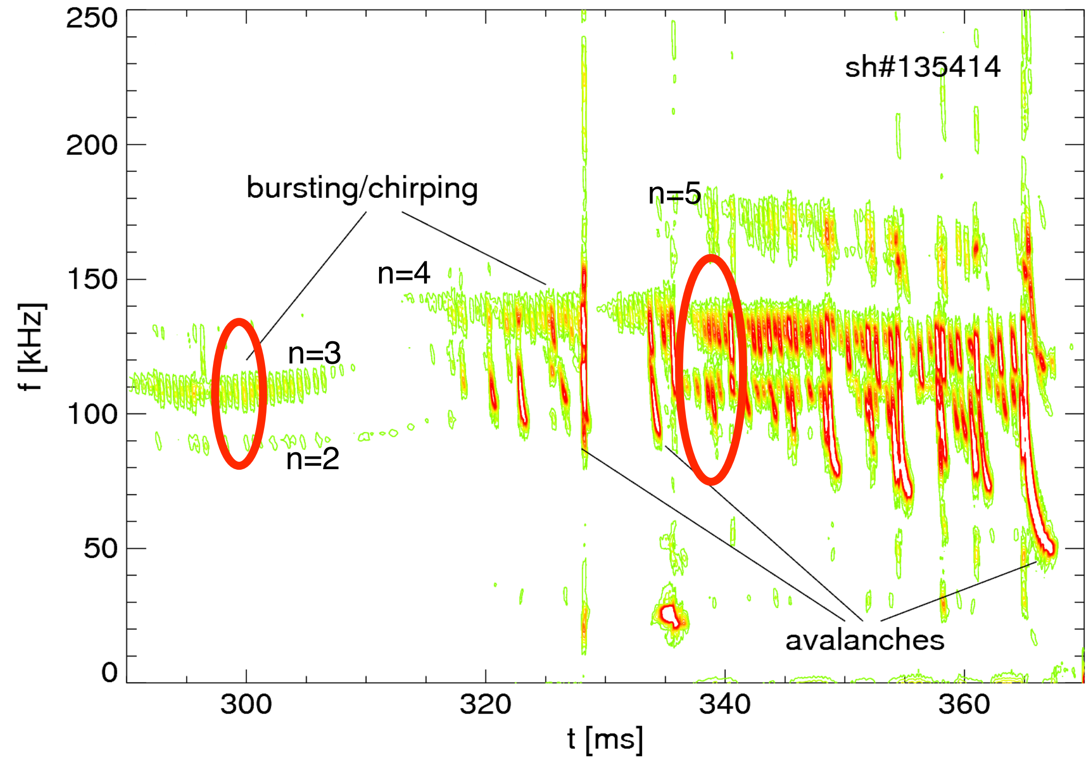
Coupling through common "source term", i.e. **NB injection**

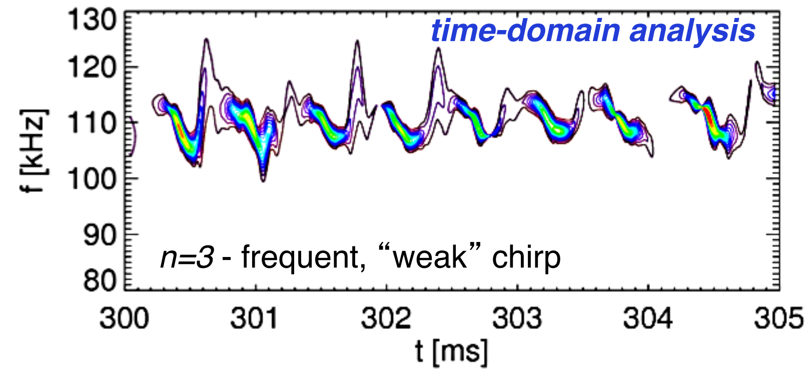
⇩

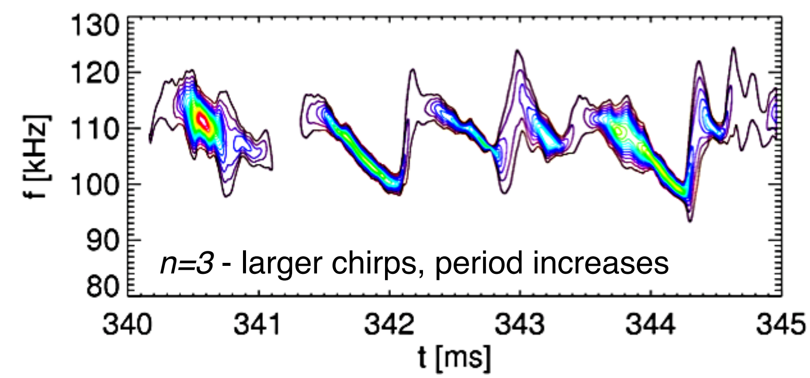
Modes cluster at similar radius: may enhance coupling

Podestà et al., PoP 2010

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







- 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:
  - **Multiple modes lock on similar dynamic, mode-mode coupling**

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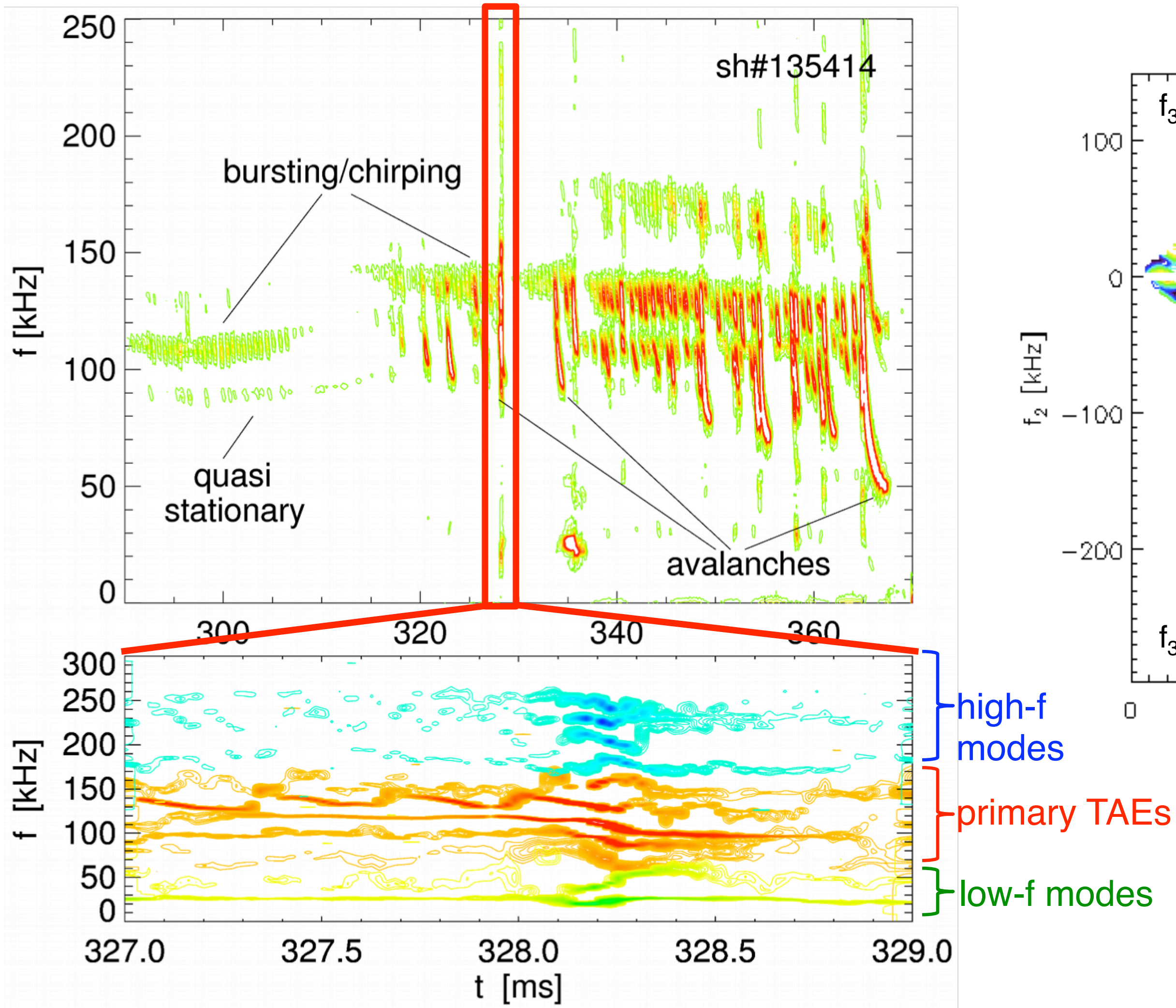
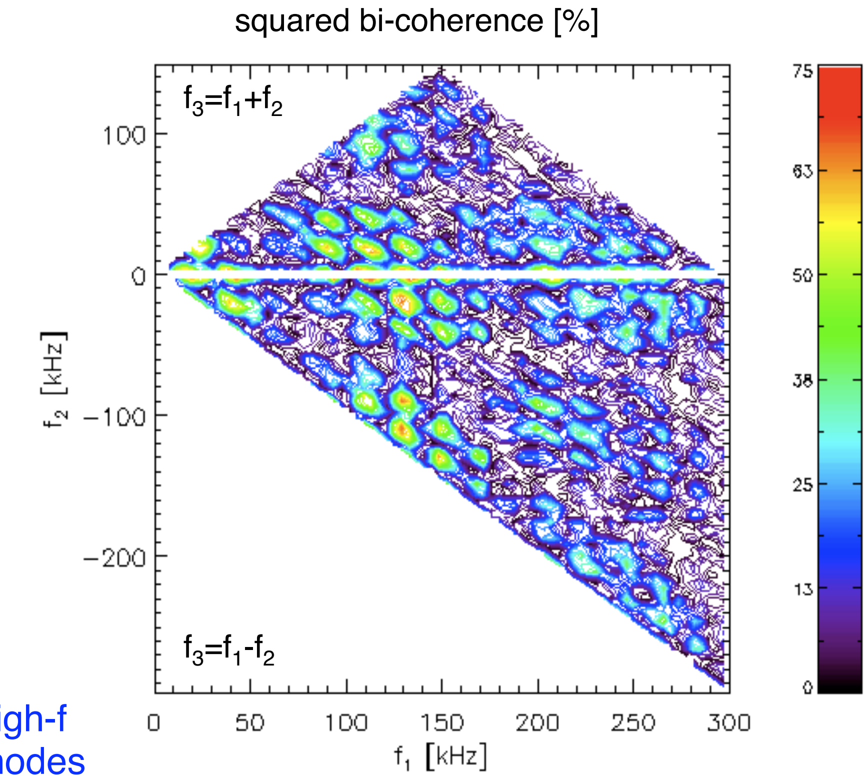
Coupling between multiple TAEs with Δn_{tor}=1, enhanced losses observed during explosive modes' growth





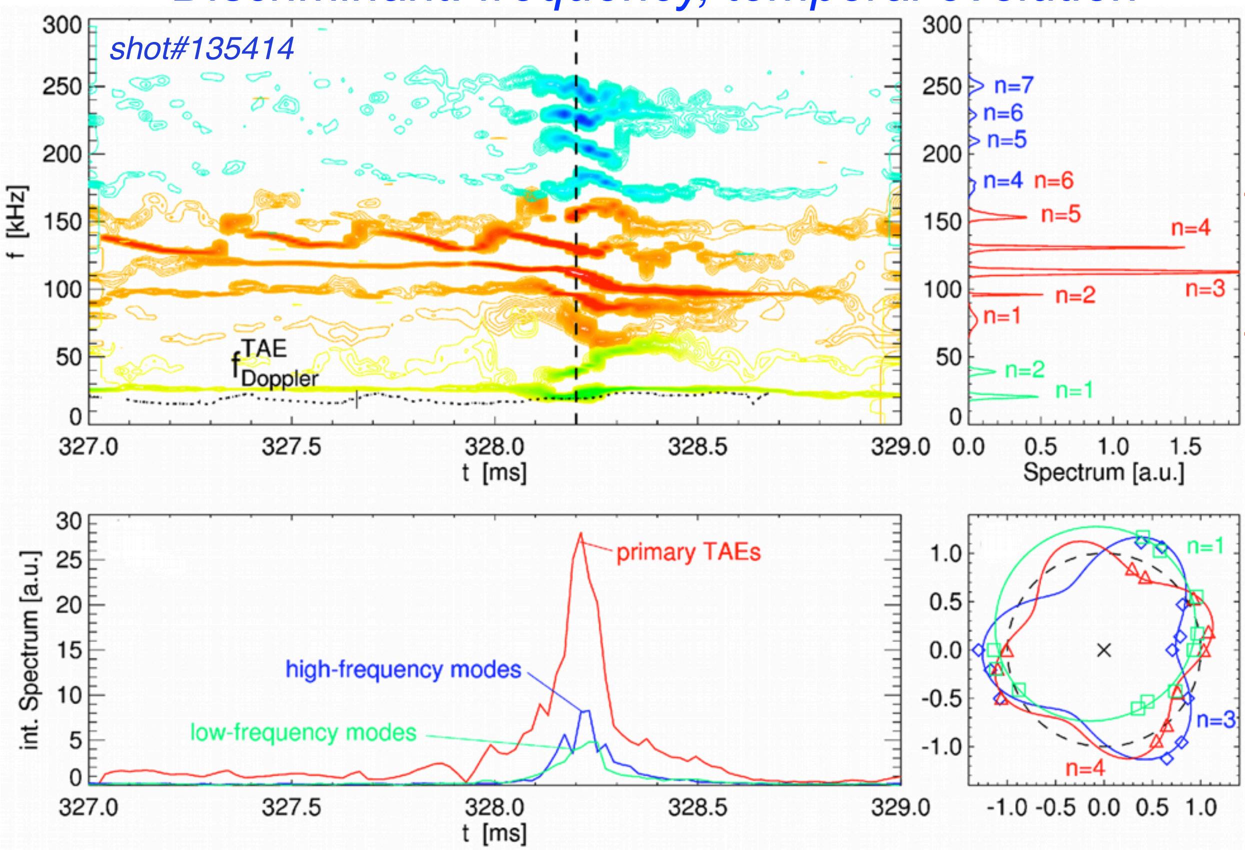
- Coupling generates higher/lower frequency modes

- 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 $\Delta n=1$

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}

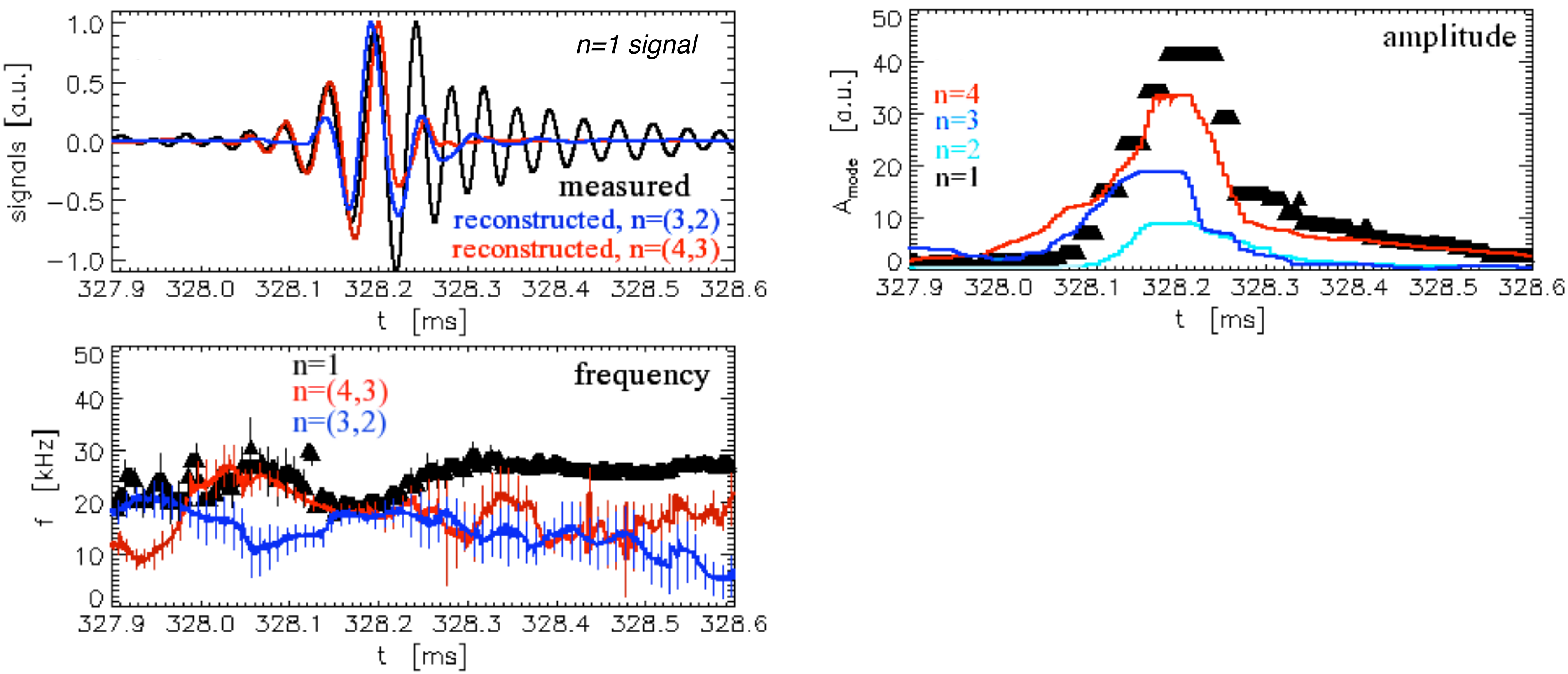
Modes must satisfy matching conditions $\begin{cases} n_3 = n_1 \pm n_2 \\ f_{n_3} = f_{n_1} \pm f_{n_2} \end{cases}$

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

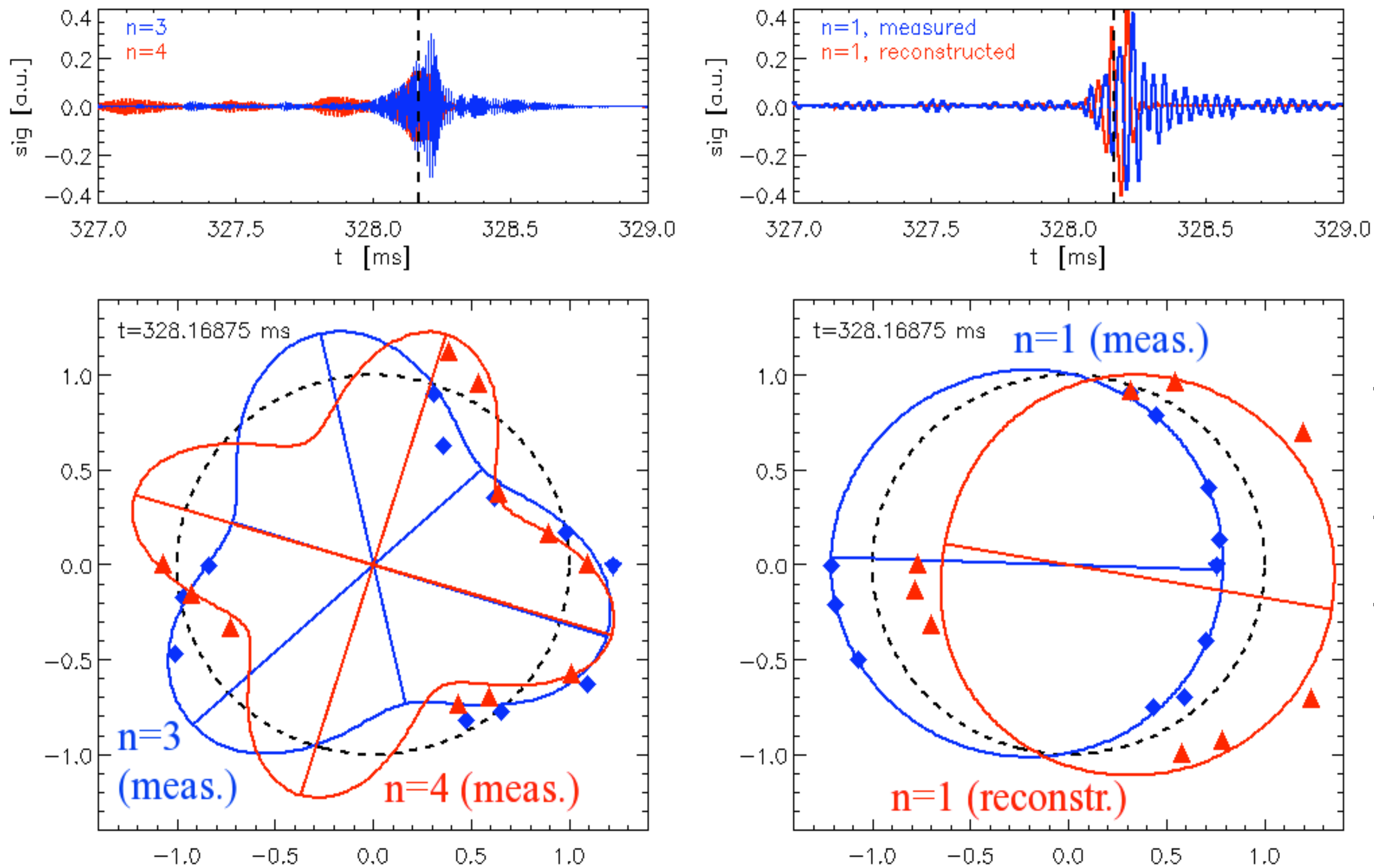
Good agreement with quadratic interactions' model: amplitude evolution and frequency matching



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

Podestà et al., NF 2011

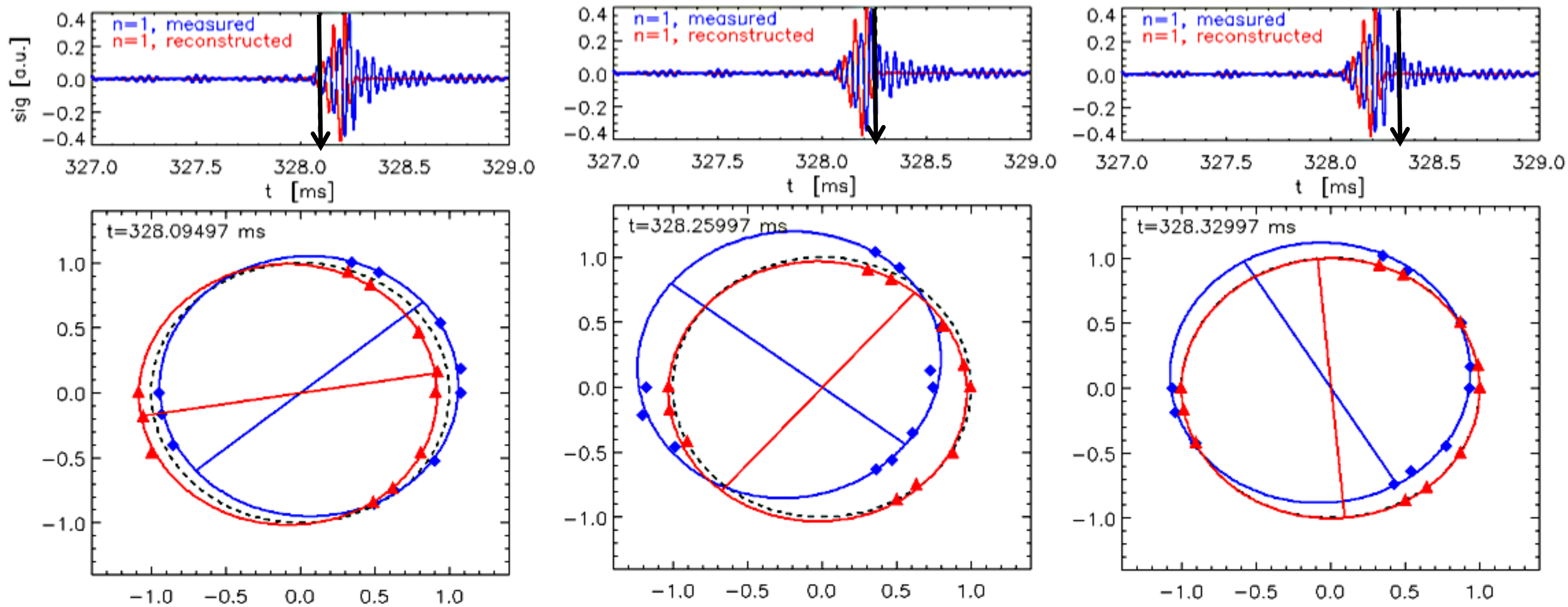
Mode number matching condition verified



-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)

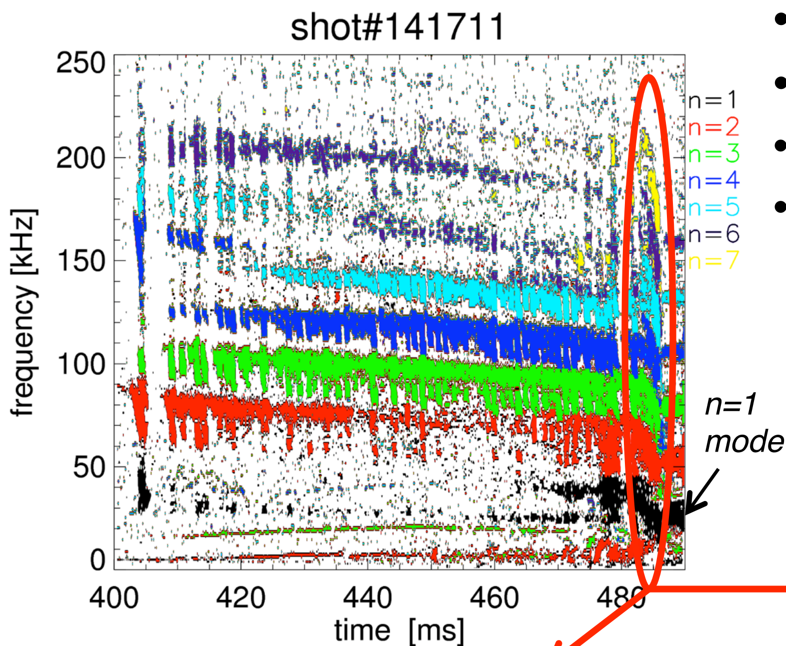
- "Reconstructed" toroidal structure of *n=1* mode also agrees with measured one
  - *Phase shift of ~180 degrees during strongest mode activity*

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

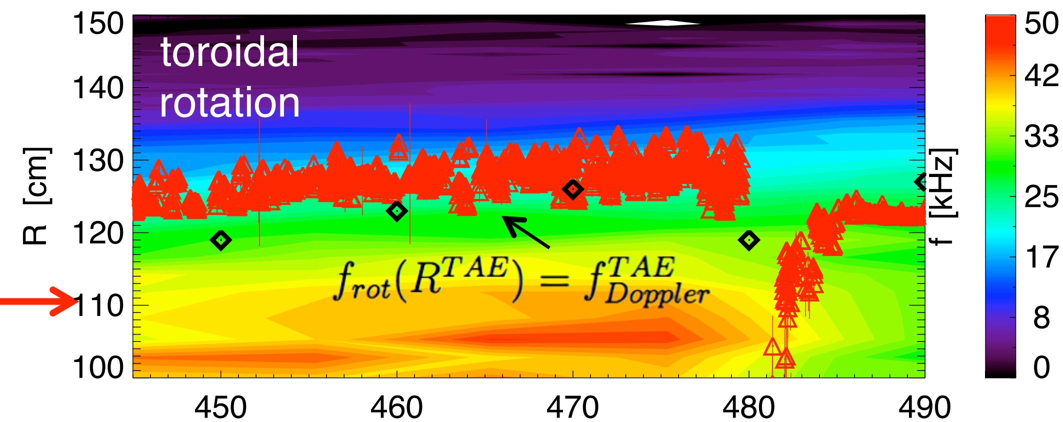


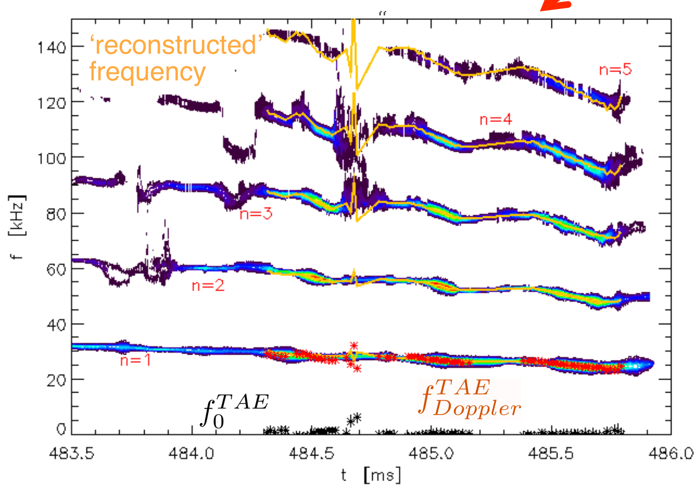
- Stationary phase during quadratic interaction is important!
  - *n=1 mode fades away ⇔ phase changes rapidly in time*
  - "Single mode" dynamic, with each mode following its own chirp/burst cycle, is effective in reducing efficiency of quadratic interactions
  - Result: small bursts (single mode),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

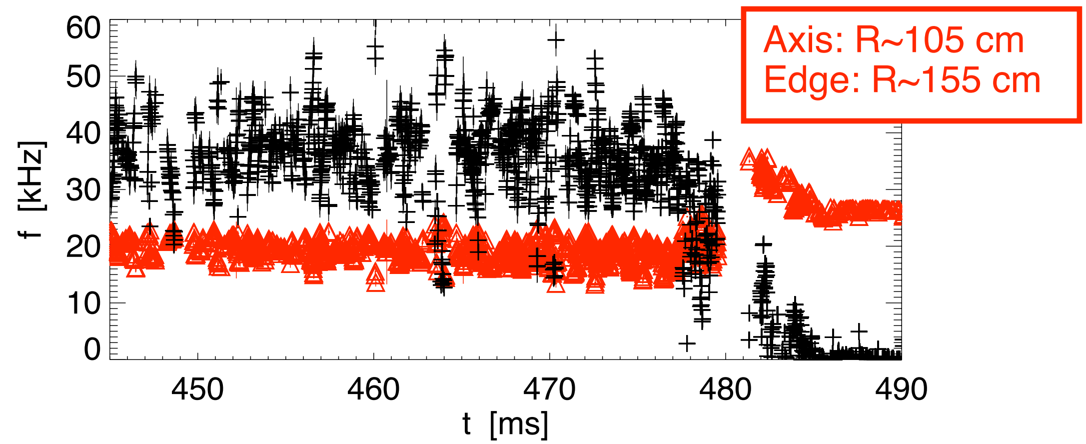
$f_{n=1}$ consistent with central plasma rotation: avalanches drive f_0^{TAE} -> 0 (plasma frame), cause coupling to 'kinks'?



- Kink-like modes destabilized during avalanche
- <u>*Sustained fast ion losses*</u> **Bortolon, O-12**
- TAE mode structure ~ maintained
- Doppler shift radius R^{TAE} sweeps from plasma center out in ~2 ms

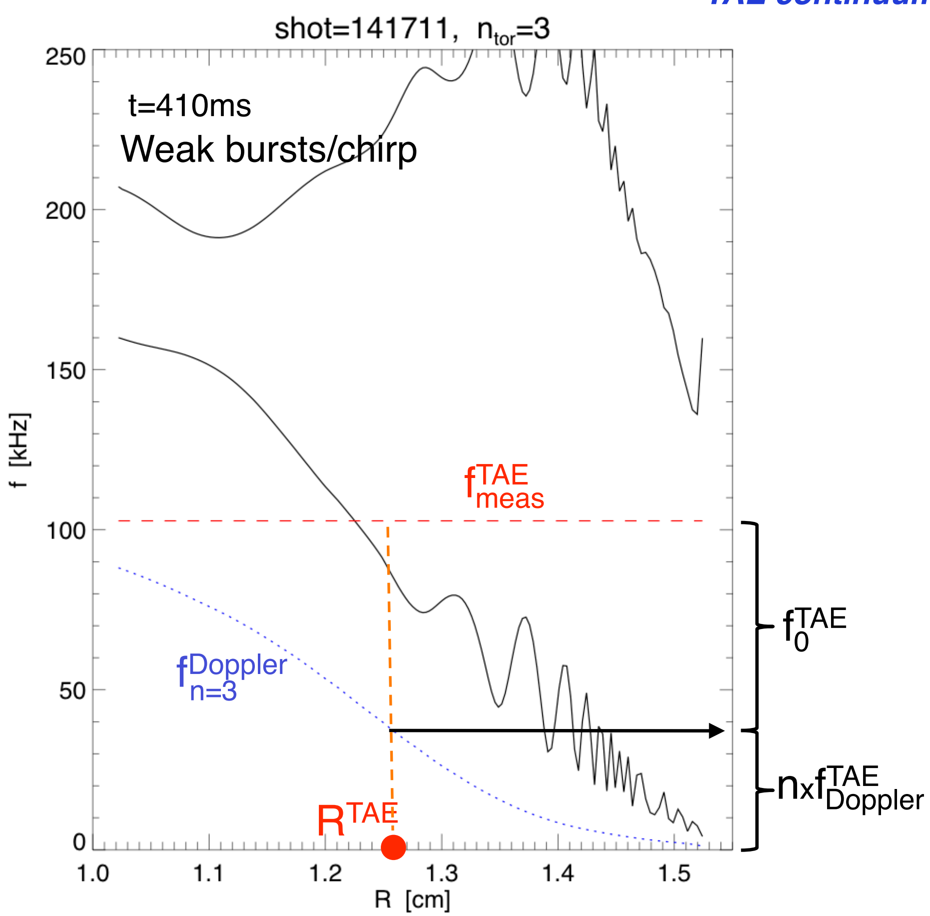






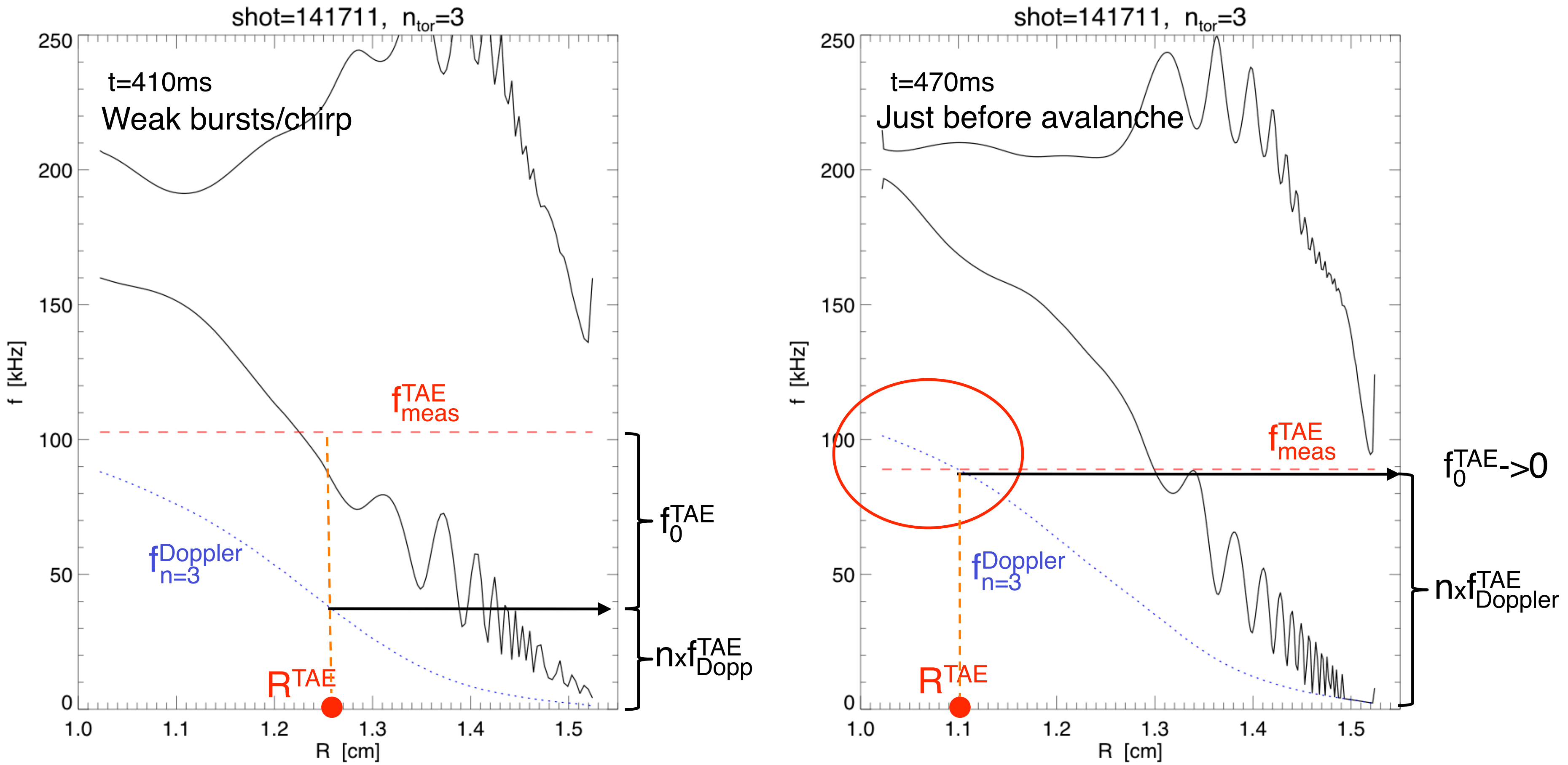
Meaning of f_0^{TAE}: mode frequency at the mode location R^{TAE}, i.e. where drive is maximum

TAE continuum from NOVA-K



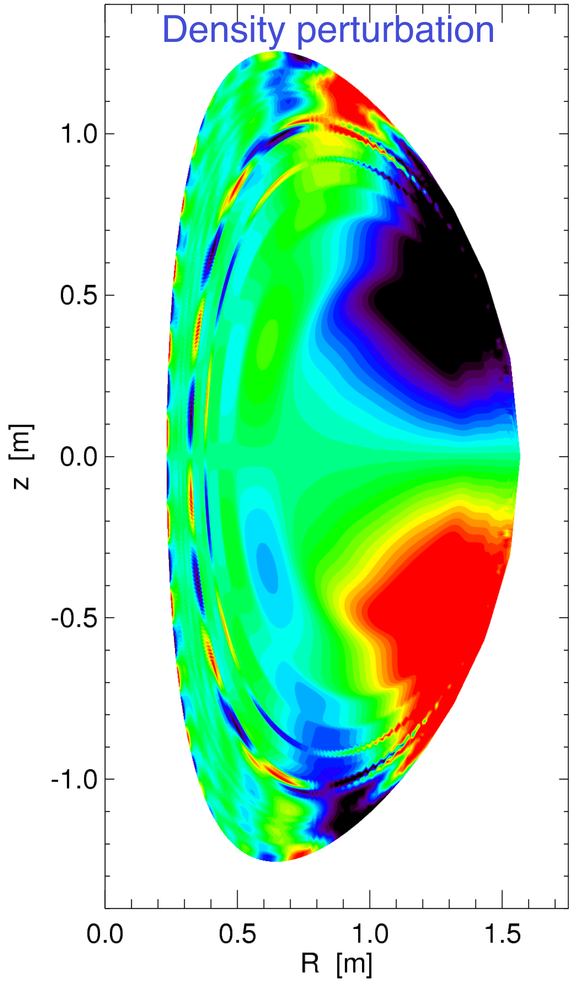
Meaning of f_0^{TAE}->0: f^{TAE} beats with *n* x rotation frequency at the plasma center

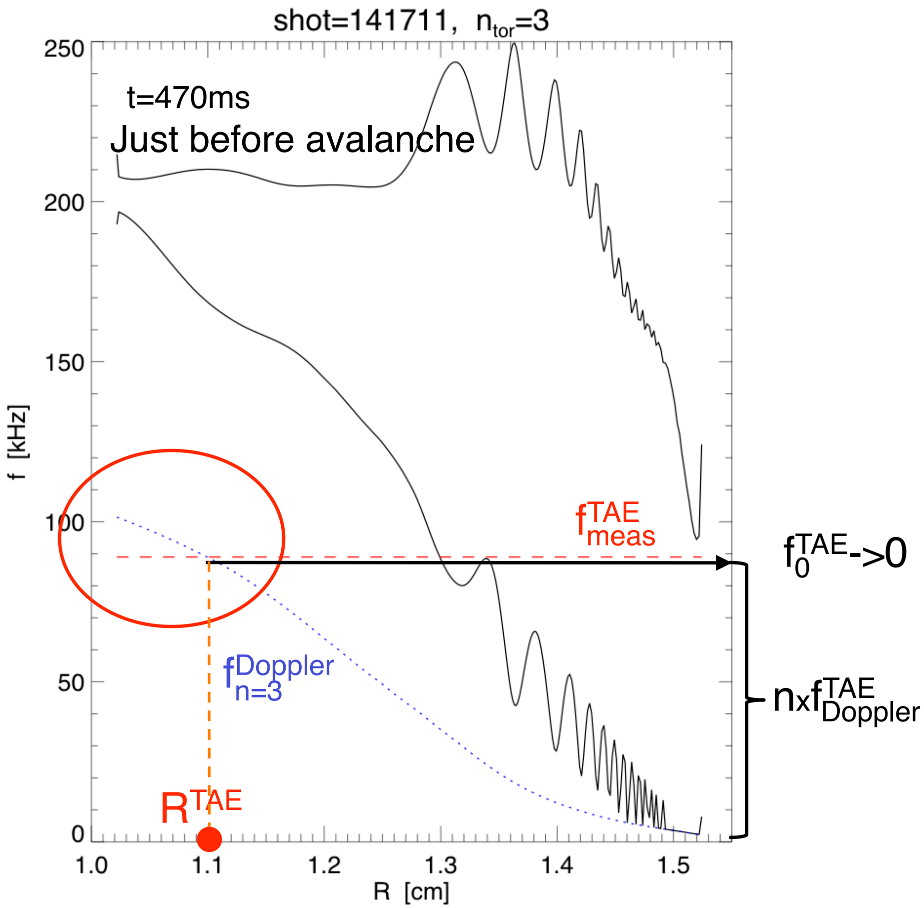
TAE continuum from NOVA-K



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

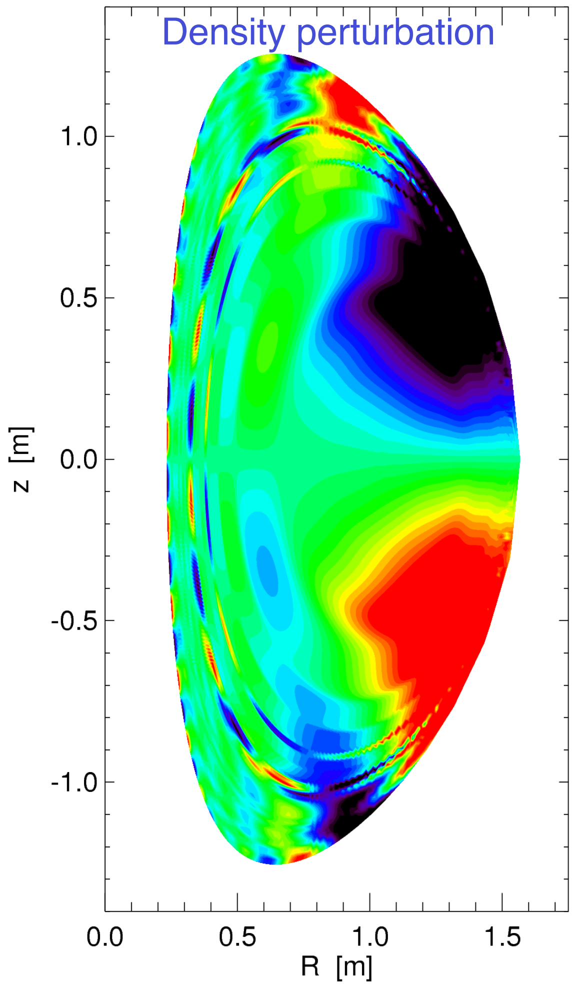
n=1, m=-2, ..., +2 kink found through ideal MHD code NOVA with no rotation, *free boundaries*

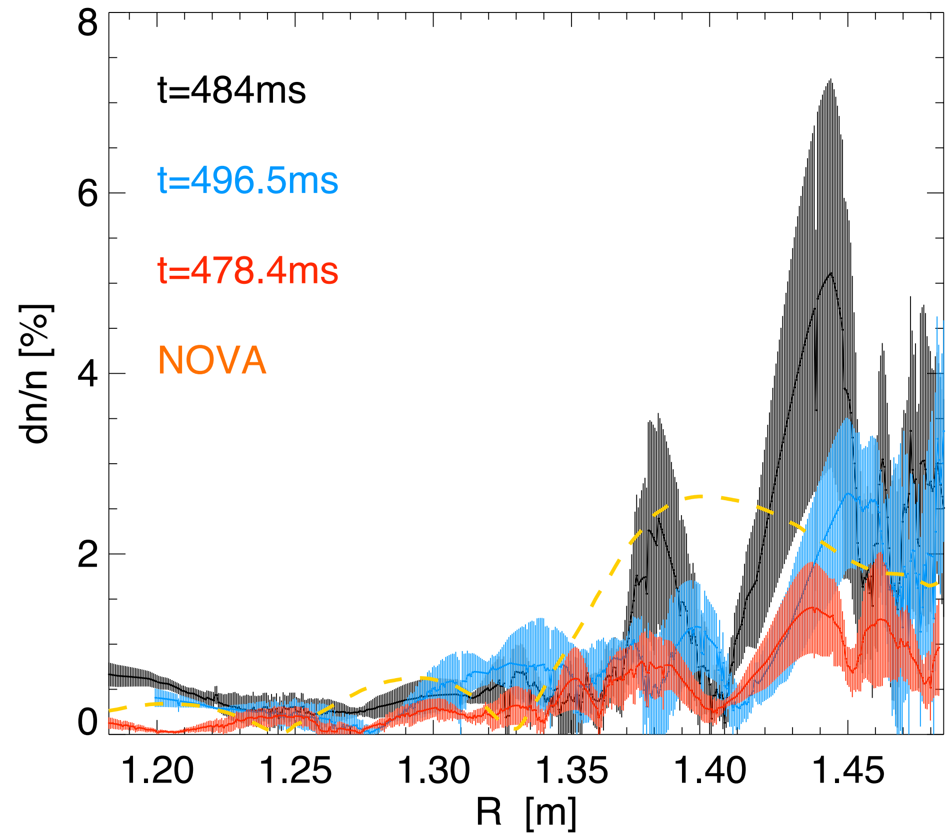




- Large edge perturbation, consistent with reflectometer's data

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





- Data from inversion of multi-channel reflectometer signals
- Assume 'linear' model for reflectometer, pure O-mode propagation, fixed $n_{0,el}$
- Roughly consistent with (ideal) NOVA solution

Outline

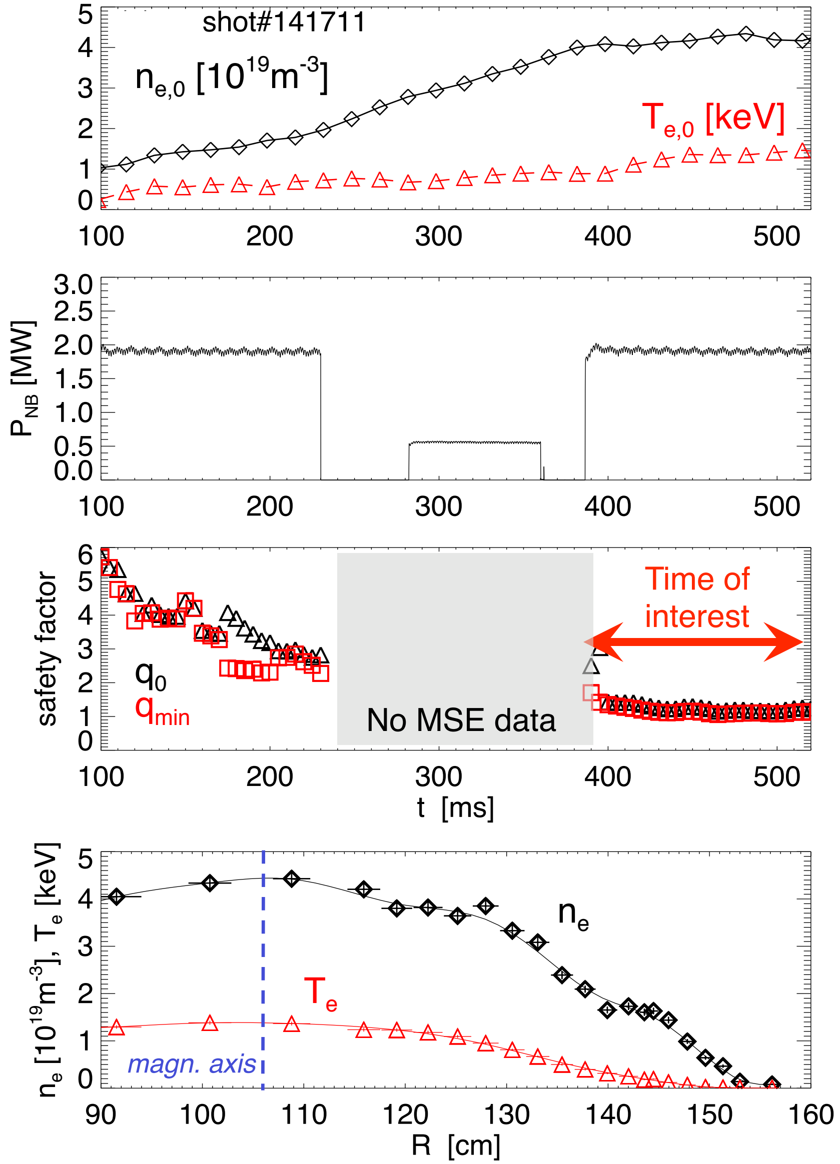
- Experimental scenario, diagnostics
- General features of TAEs on NSTX
  - Frequency, amplitude dynamics
  - Mode structure
  - Role of fast ion drive
- Non-linear dynamics, mode-mode coupling
- Summary and open issues

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

Backup slides

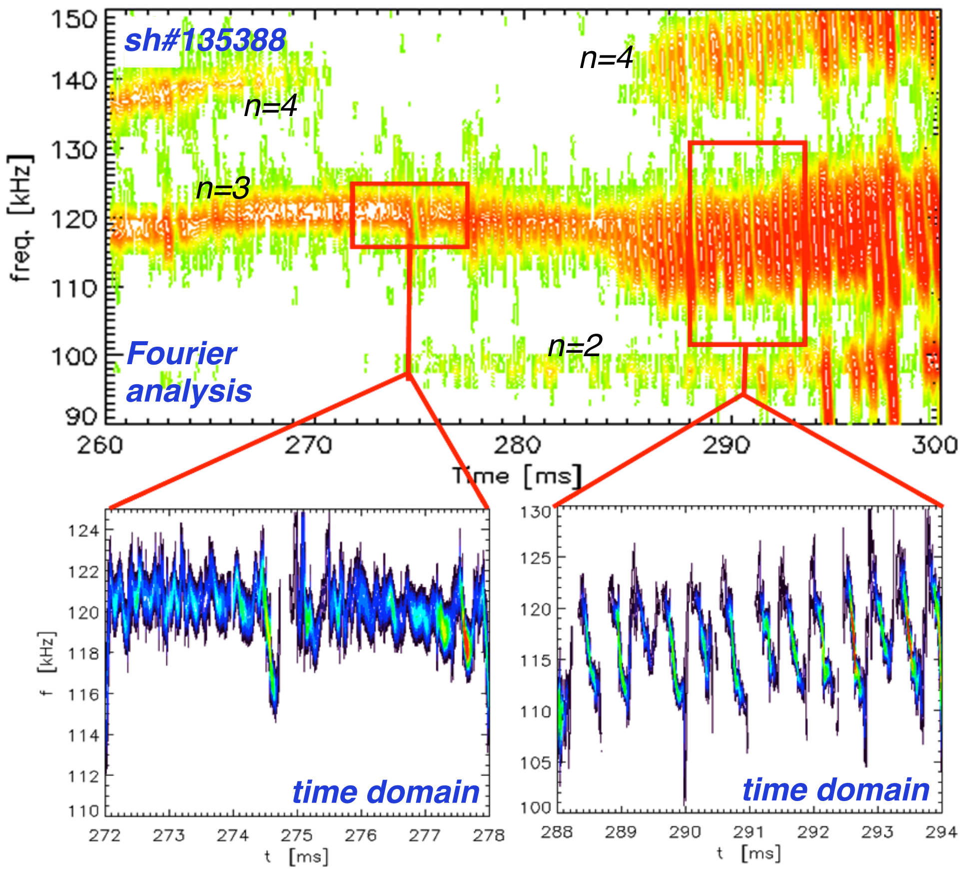
Experimental scenario : P_{NB}<3MW, n_e~3-4x$10^{19}m^{-3}$, T_i~T_e=1-1.5keV

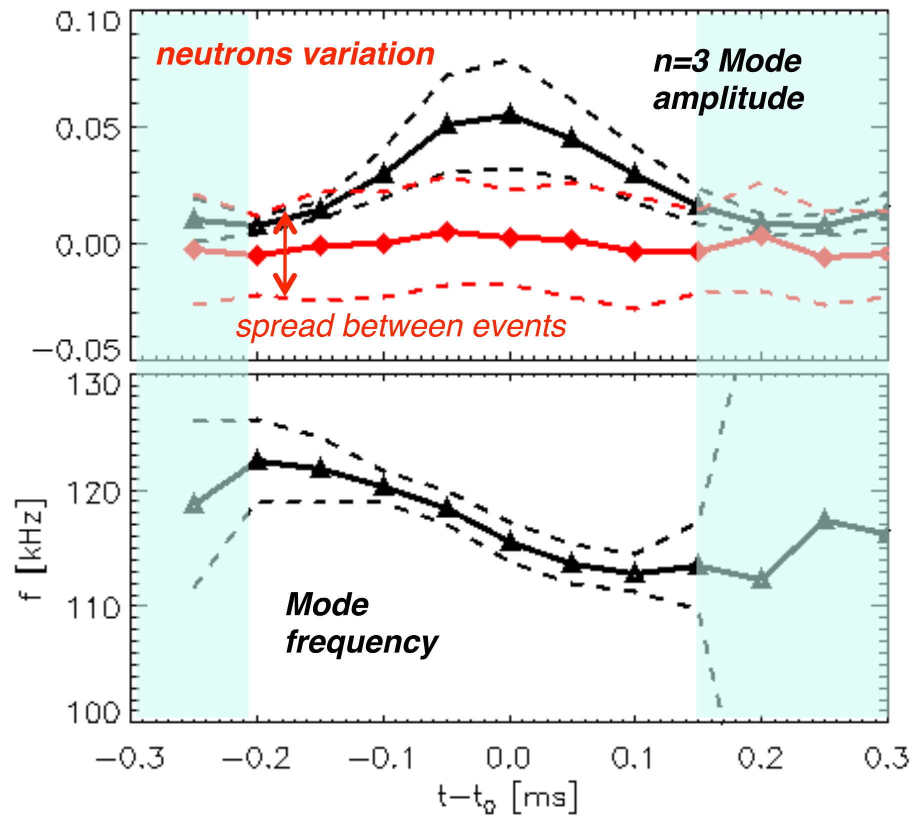


NB-heated, L-mode plasmas

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

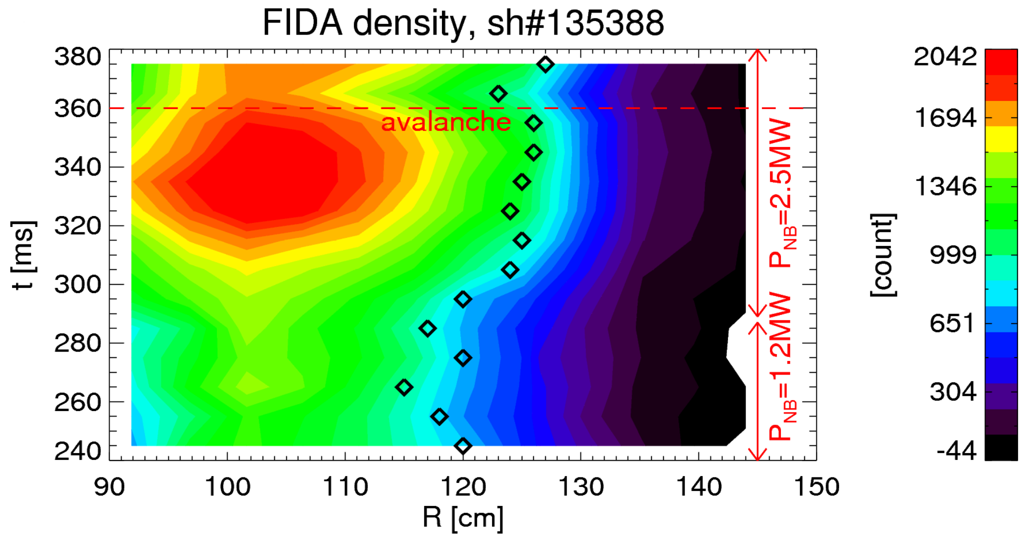
No detectable fast ion losses are observed during weakly bursting/chirping phase

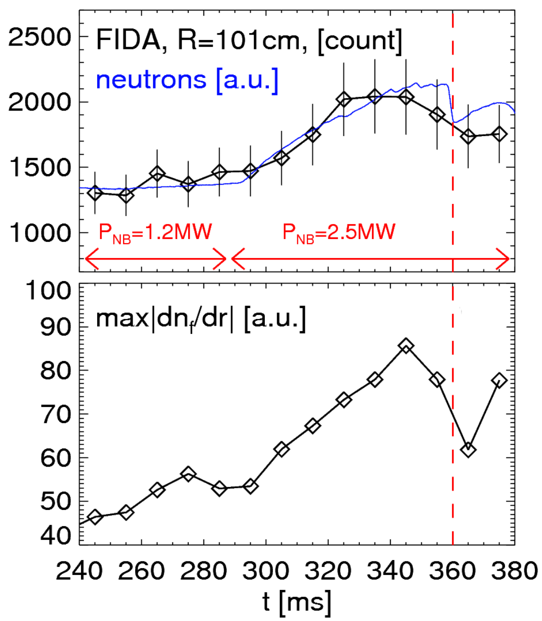


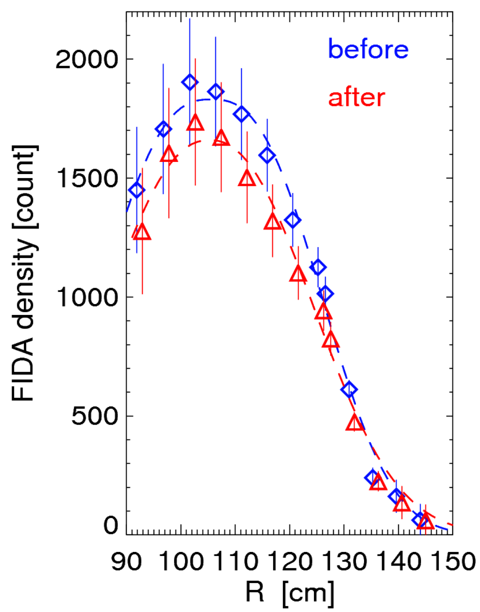


- Statistical average over ~20 events (~10ms)
- No clear evidence of losses from neutrons, FIDA
  - ***Does not exclude "continuous" (non-bursting) losses***

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



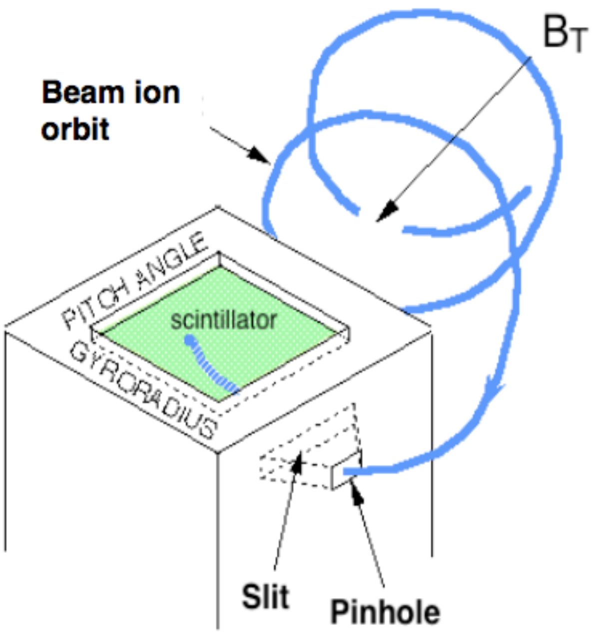




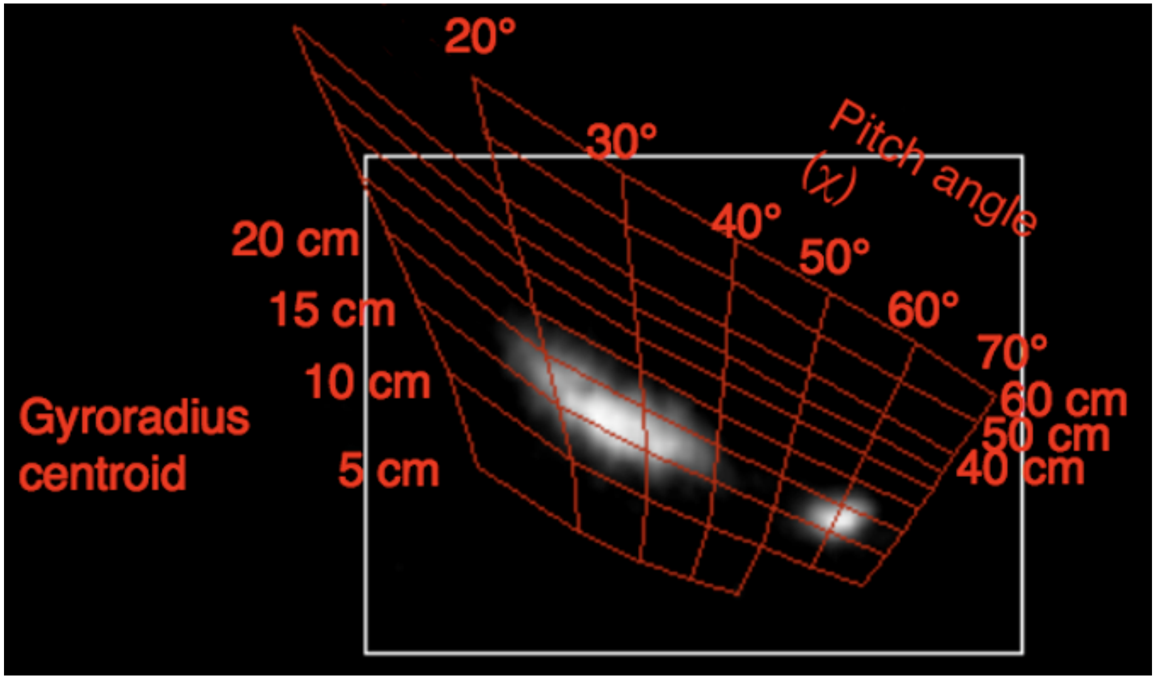
- Fast ion density (FIDA) drops over most of minor radius
- Loss results in a relaxation of the radial gradient → drive for TAEs is reduced
- Comparable losses estimated from FIDA and neutron rate
  - Large portion of phase space affected
- Losses increase with (total) mode amplitude
  - Linear? Quadratic?

Fast ion loss probe at vessel wall captures transient loss, provides details of affected phase space region

Scintillator probe, sFLIP:



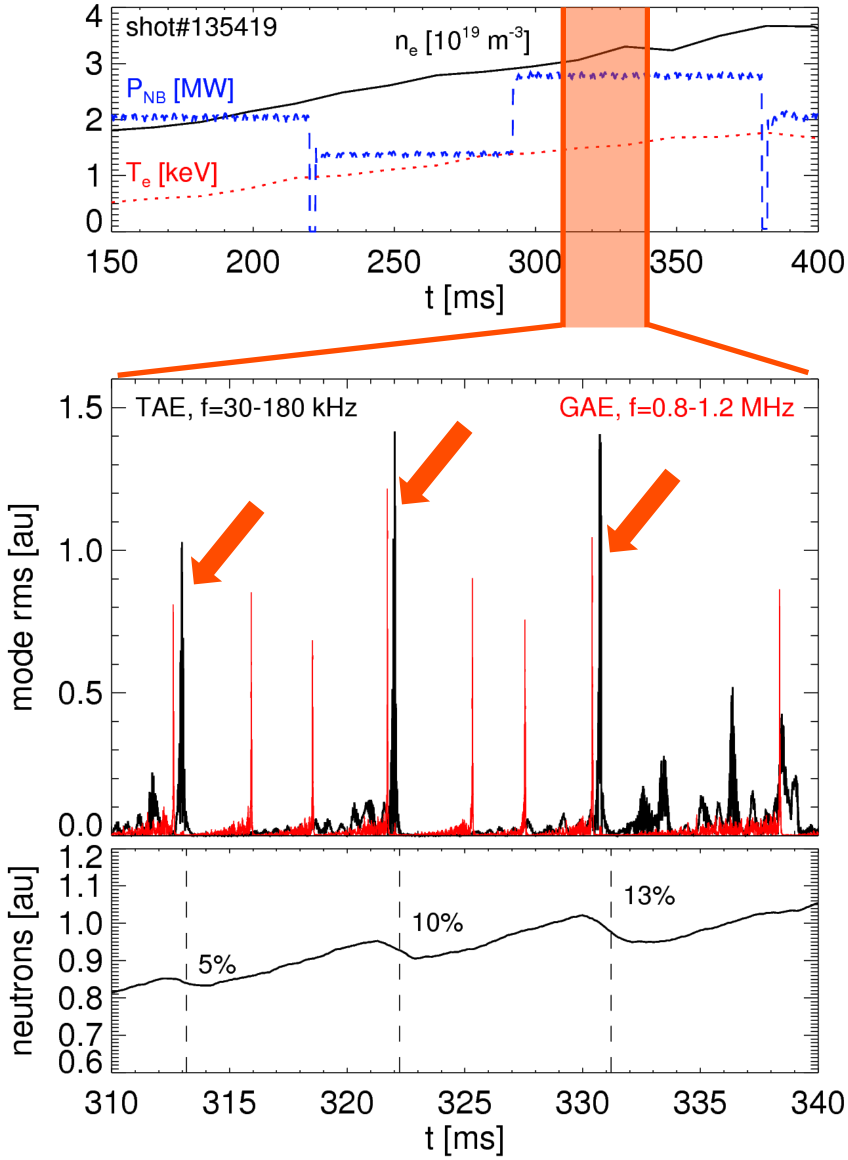
- 'Magnetic spectrometer'
- Provides $\Gamma_{loss}(\rho,\chi,t)$
- $5cm \leq r \leq 60cm$
- $15^o \leq \chi \leq 80^o$
- f_{sampl} = 30 kHz



- Observed losses at $E \sim E_{inj}$, wide pitch range
  - Possible signature of phase space stochastization
- Phase space model help understand loss process, measurements
- Simulations with ORBIT code under way

Darrow, O-1

Evidence of redistribution at play – multiple frequency scales can be involved



- Bursting GAEs sometimes observed at f ~ 1 MHz during TAE activity
- GAE bursts precede TAE avalanches
  - But not all TAE avalanches are preceded by GAE burst
- Indication of fast ion redistribution by GAEs?
  - Different mode localization with respect to TAEs
- Losses only observed after TAE avalanches

Fredrickson, IAEA 2010

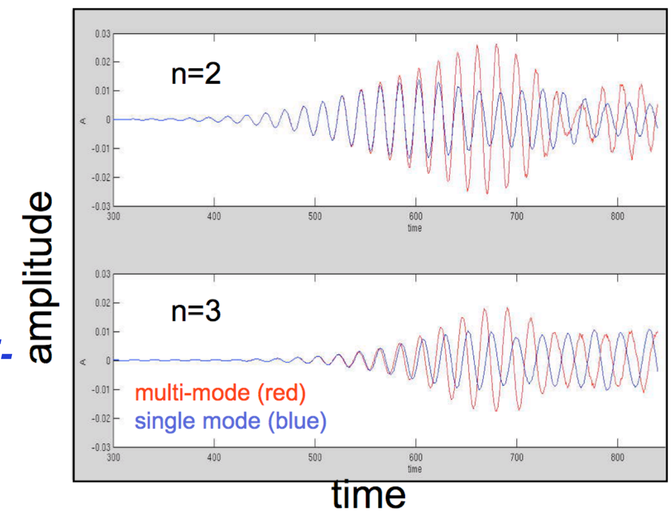
M3D-K – non-linear, self-consistent Hybrid/MHD code

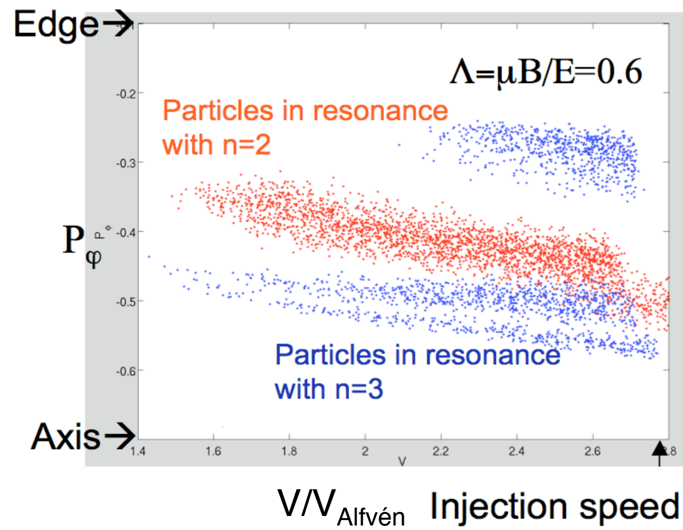
*G.-Y. Fu et al., Phys. Plasmas **13**, 052517 (2006)*

M3D-K code developed at PPPL and used to investigate fast-ion driven Alfvénic modes and MHD

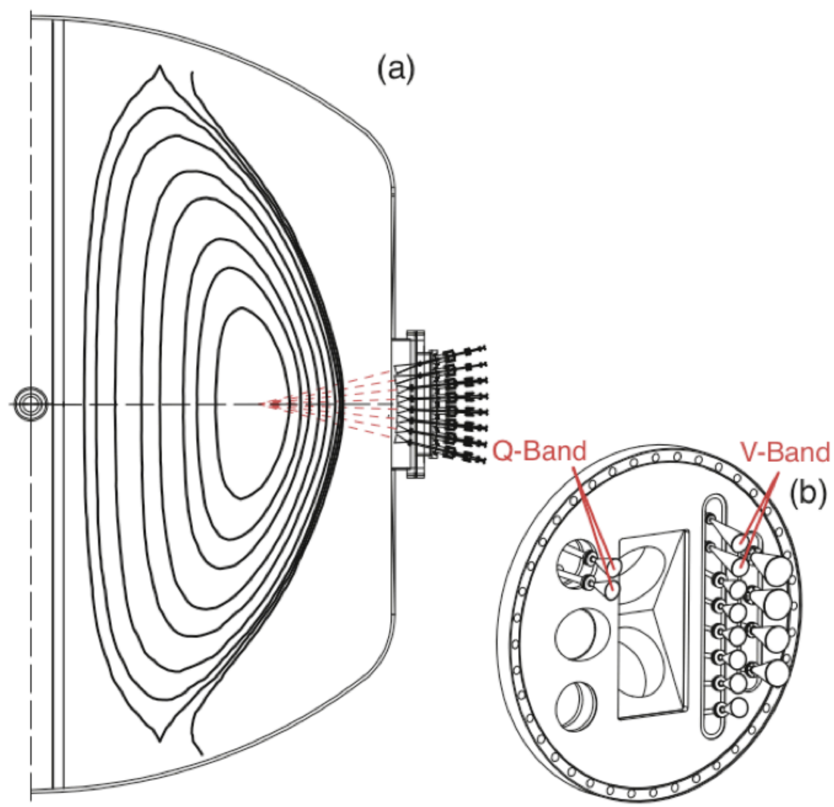
- ***3-D nonlinear.***
- ***Several different physical models:***
  - ***Resistive MHD.***
  - ***Hybrid (fluid electrons, particle ions).***
  - ***MHD/particle (one-fluid thermal plasma, + energetic particle ions).***
- ***Full-orbit kinetic ions.***
- ***Drift-kinetic electrons.***
- ***For particles: Drift-kinetic or gyrokinetic.***

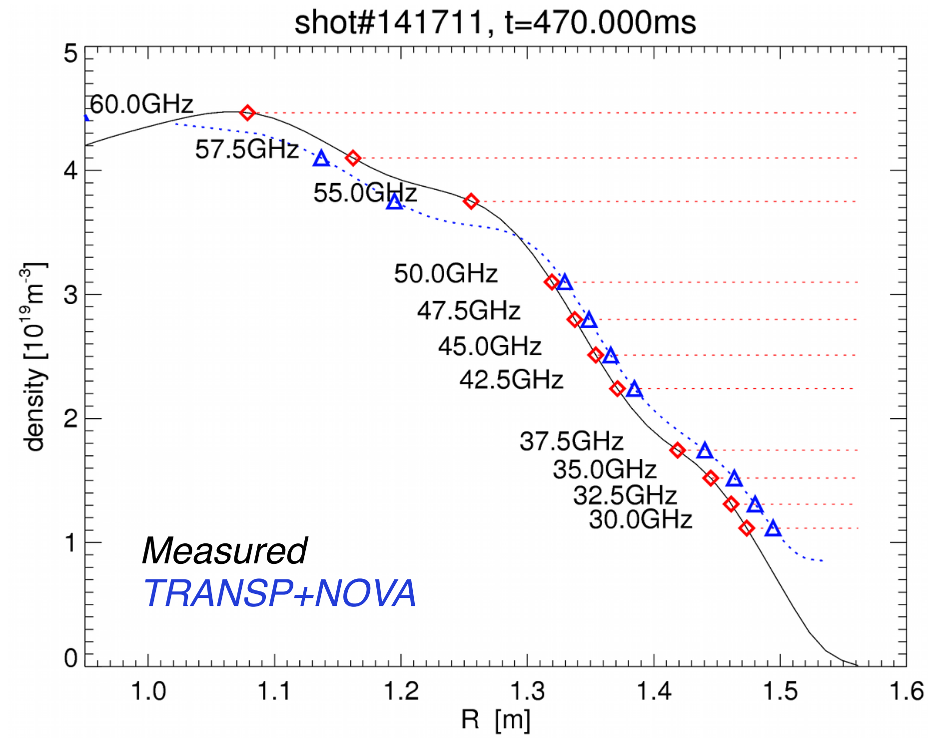
M3D-K simulation of single vs. multi-mode TAE dynamics





NSTX reflectometers are used to measure density fluctuations





- Low-field side launchers/receivers
- Assume pure O-mode propagation

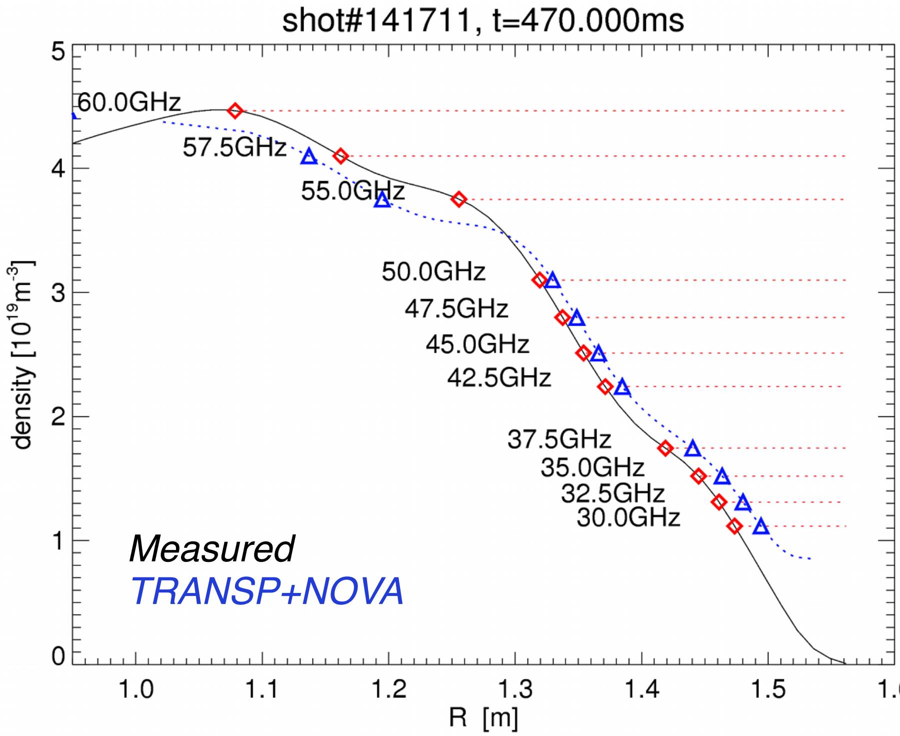
NSTX Multi-channel reflectometer system (UCLA)

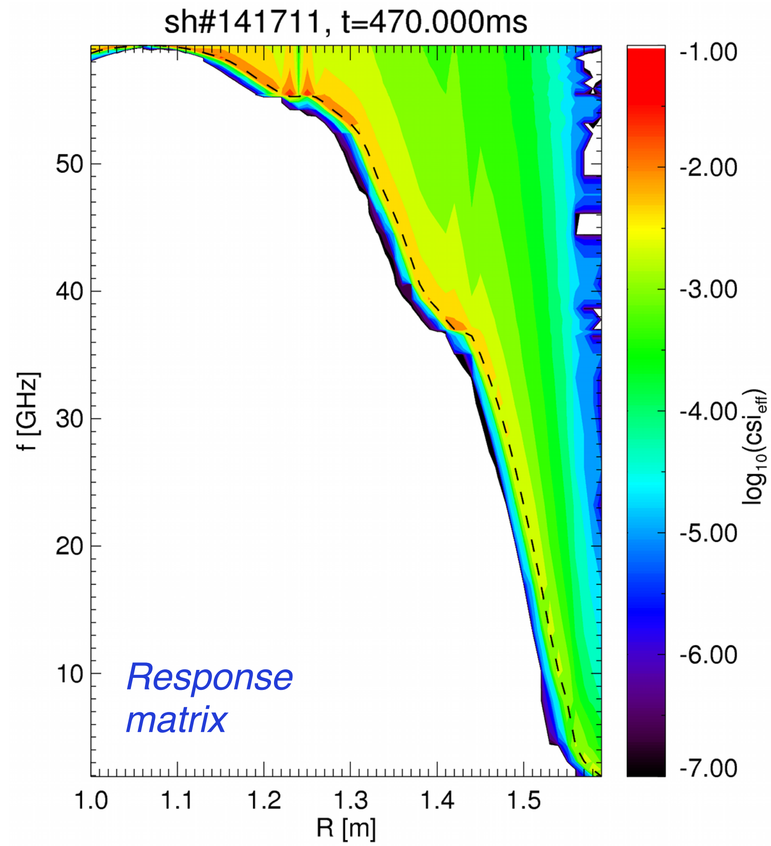
- N. Crocker et al., PPCF 2011 (in press)

$$\Delta\Phi = \frac{2\omega}{c}\int_{x_{c.o.}}^{x_{inj}} N dx$$

$$N^2 = \frac{k^2c^2}{\omega^2} = \frac{c^2}{\omega^2}k_{inj}^2\left[1 - \frac{n(x)}{n_c.o.}\right]$$

Analysis of reflectometer's data





- Low-field side launchers/receivers
- Assume pure O-mode propagation

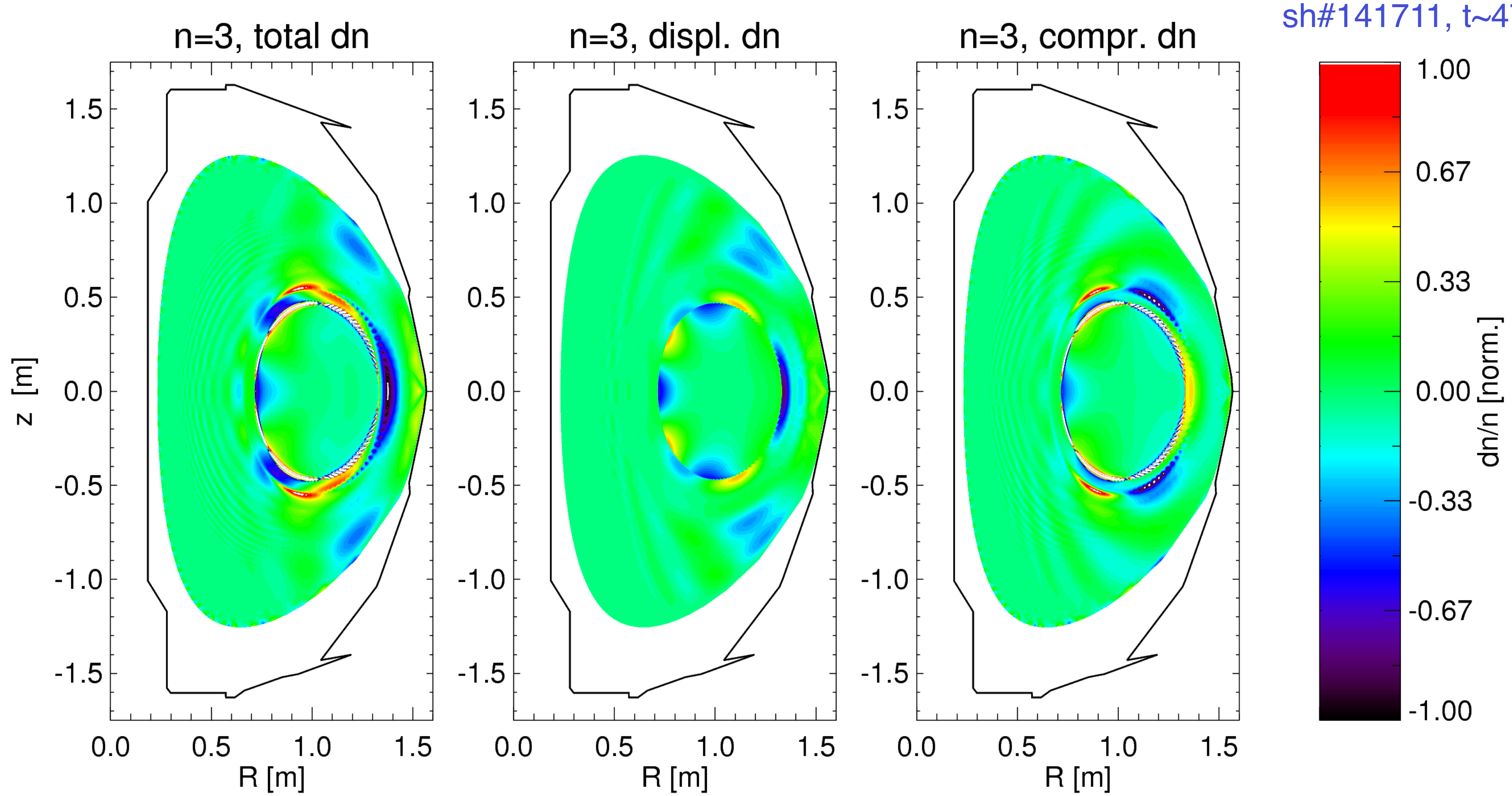
$$\Delta\Phi = \frac{2\omega}{c}\int_{x_{c.o.}}^{x_{inj}} N dx$$

$$N^2 = \frac{k^2c^2}{\omega^2} = \frac{c^2}{\omega^2}\, k_{inj}^2 \left[1 - \frac{n(x)}{n_{c.o.}}\right]$$

- Invert data by using *response matrix*, M : $\Delta\Phi_i = M_{ij}\,\delta n_j$
- Find total δn, *then* filter around each mode's frequency
- OK for small (<3%) δn
- *Assumptions (pure O-mode, linear, ...) likely to break down for large perturbations*

NOVA analysis reveals significant contribution to density perturbation from compressional term

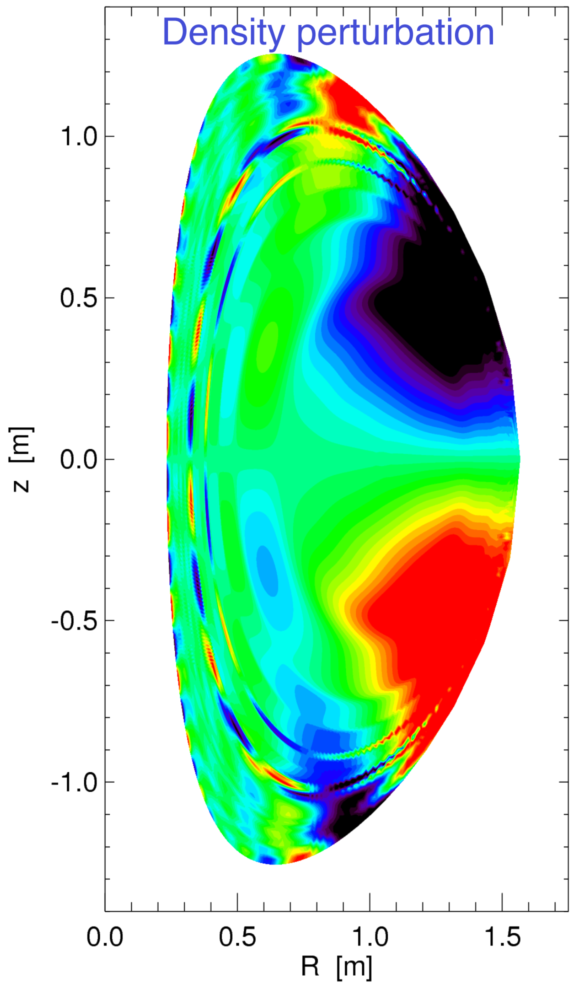
sh#141711, t~470 ms, n=3

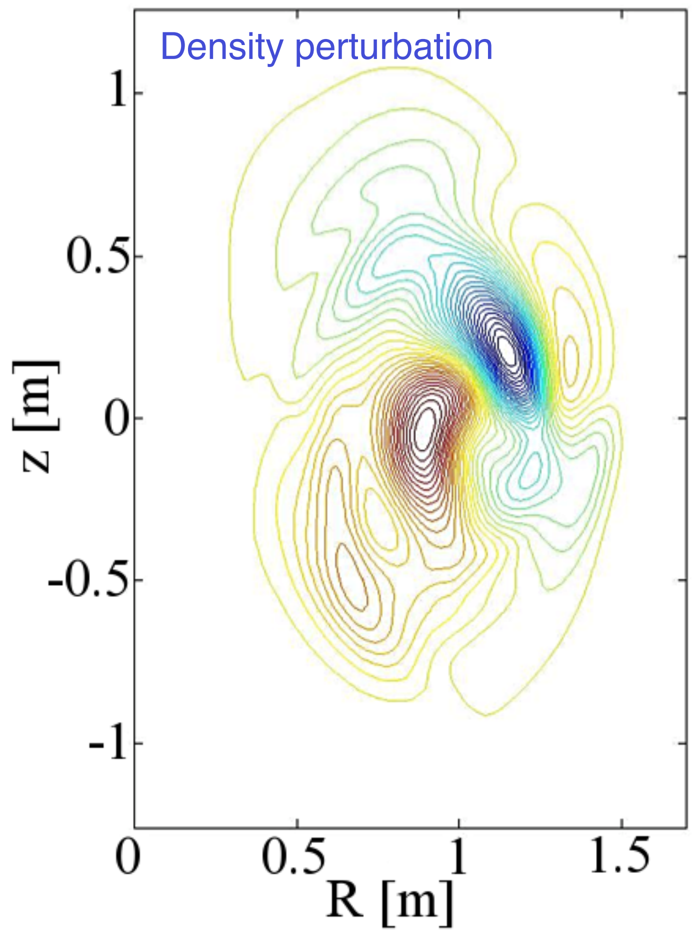


- Compressional term is significant
- Impact interpretation of reflectometer's data, etc.

$$\frac{\delta n}{n} = \nabla \underline{\xi} - \underline{\xi} \cdot \frac{\nabla n}{n}$$

MHD unstable *n=1* kink also found through self-consistent M3D-K code





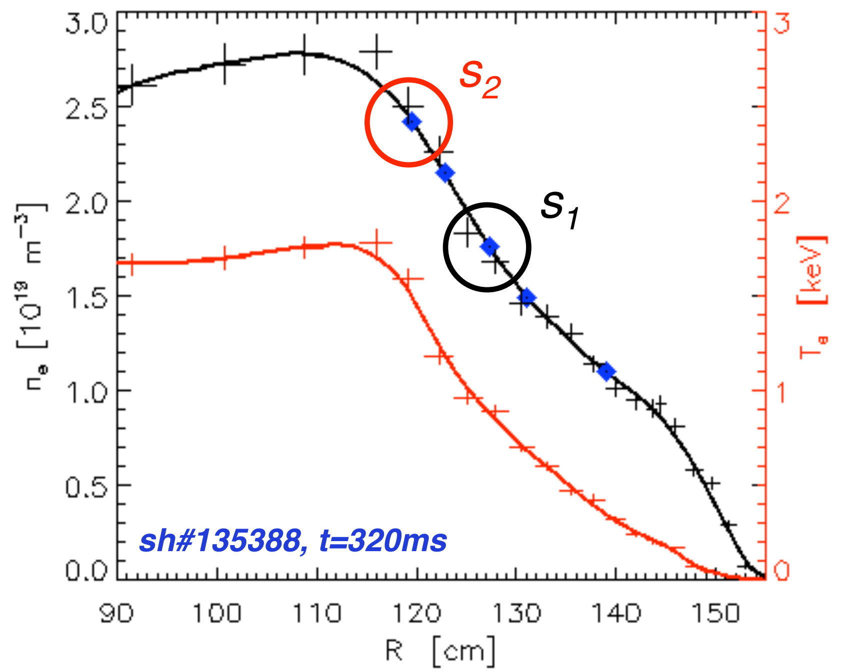
M3D-K:

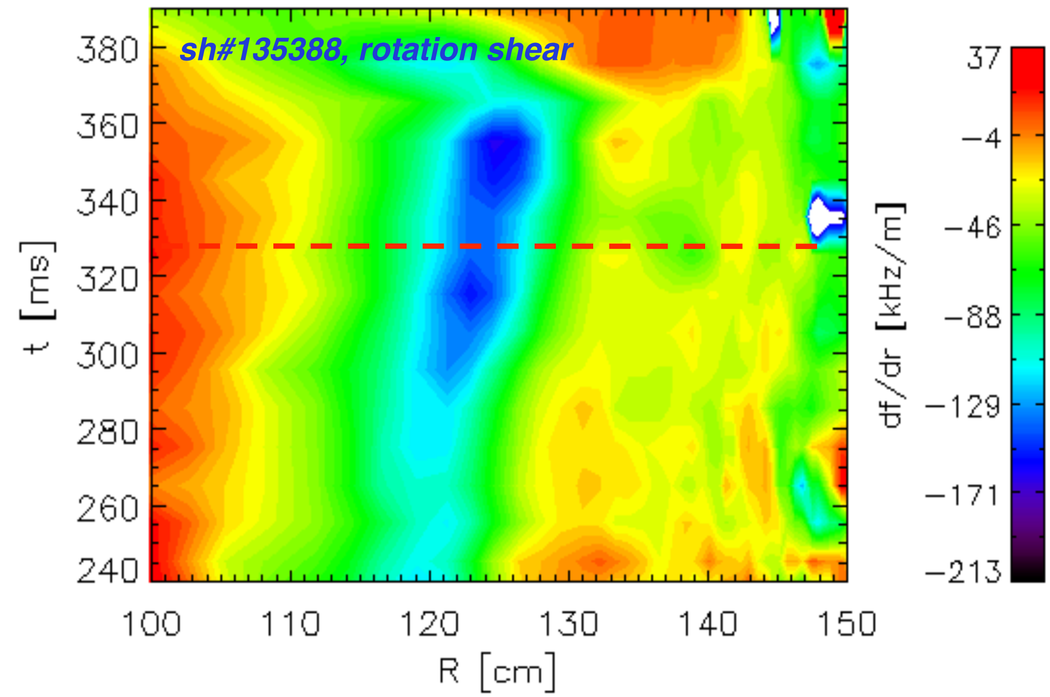
•Realistic geometry (spherical tokamak)
•Experimental parameters and profiles (interface with TRANSP)
•Global; linear/nonlinear
•Non-perturbative fast ion effects (i.e., can model EPM) – <u>not used here</u>
•Plasma rotation is included

Fu, TTF 2011

- Structure is different between NOVA and M3D-K
- Support hypothesis of marginally stable 'kink', destabilized during avalanche

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



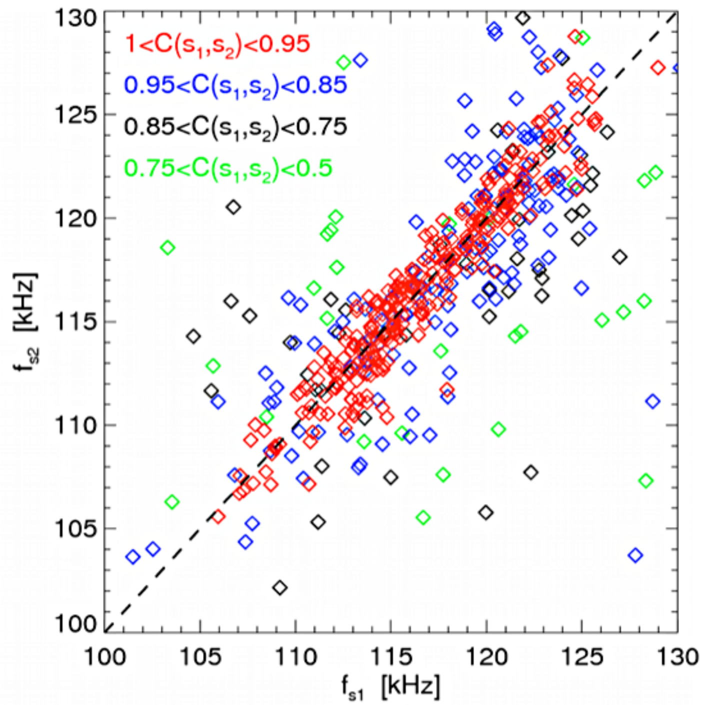


Procedure:

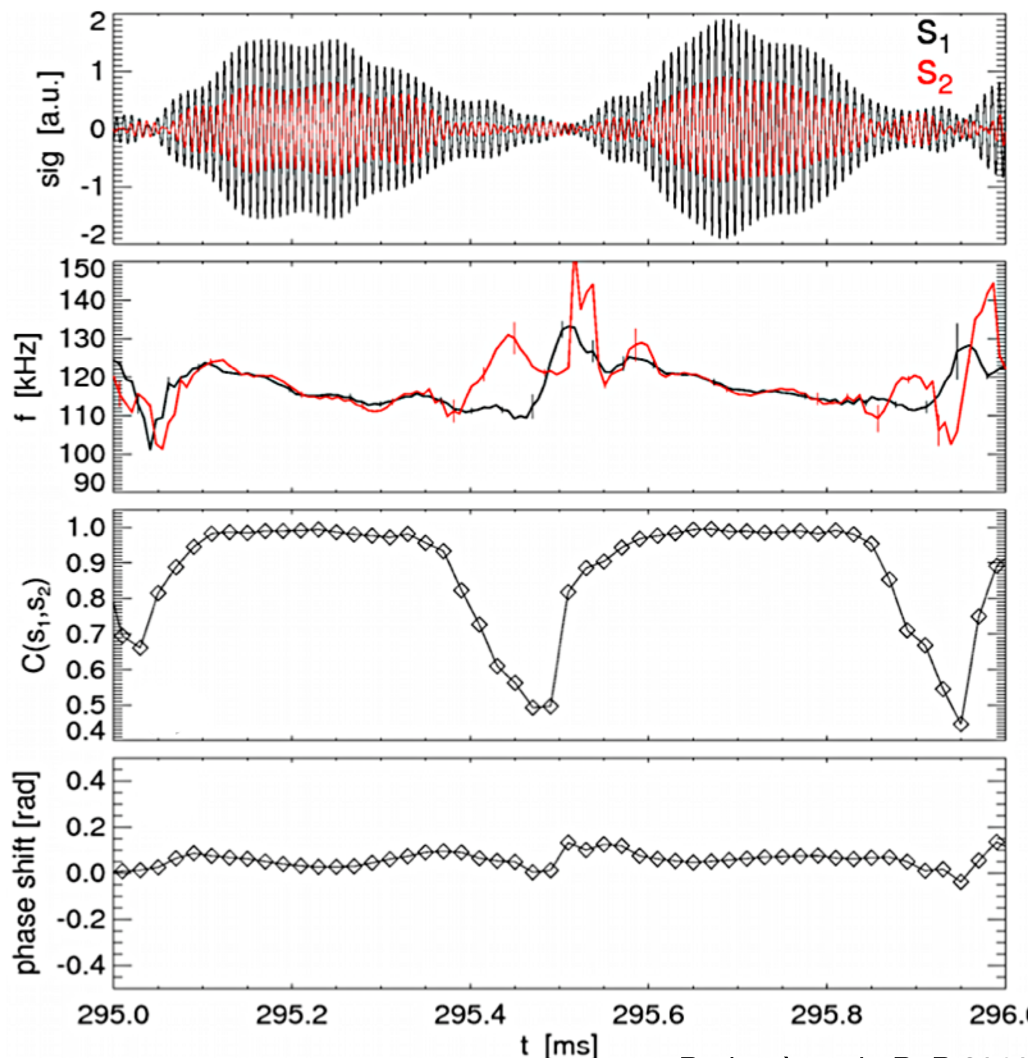
- Band-pass filter signals around mode frequency (ex. *n=3*)
- Reconstruct frequency, amplitude evolution
- Get cross-correlation
- Obtain cross-phase between channels from time delay

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

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



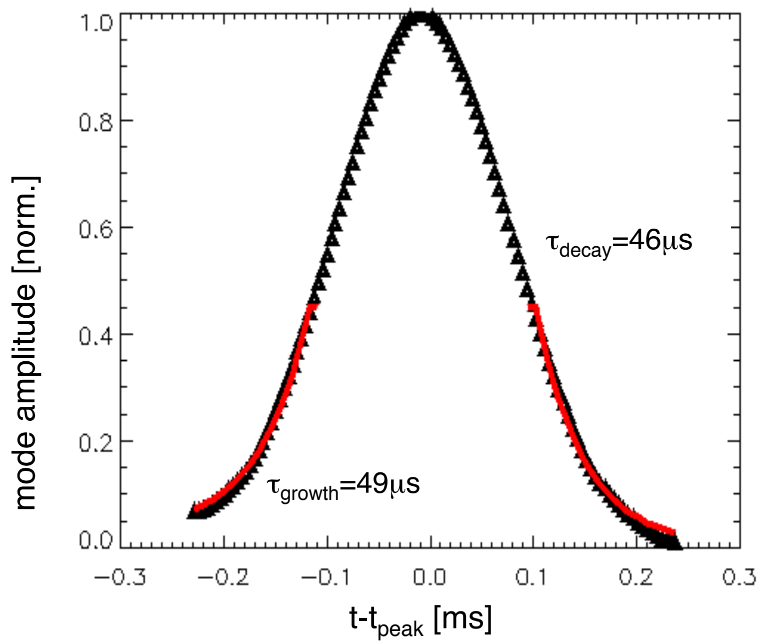
sh#135388, band-pass filtered *n*=3 signals



Podestà et al., PoP 2010

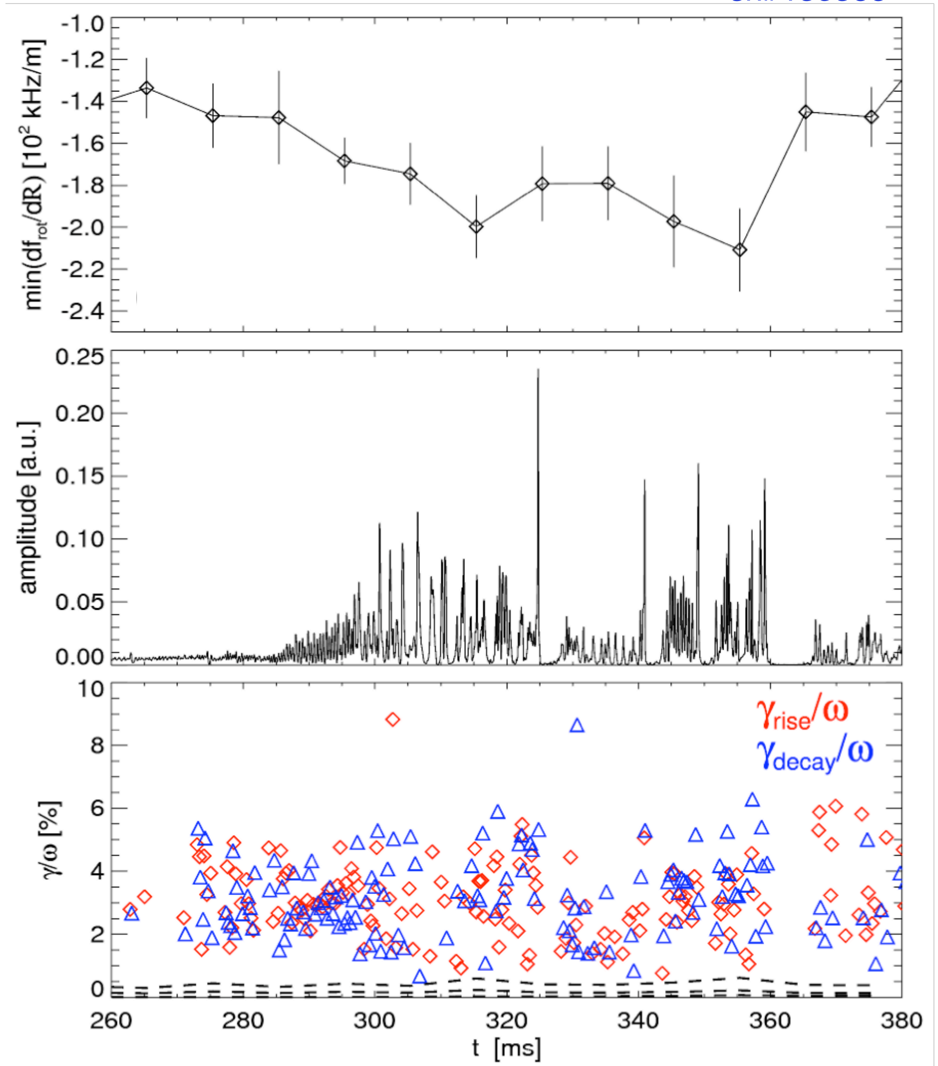
No temporal correlation is observed between rotation shear evolution and mode amplitude rise/decay rates

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

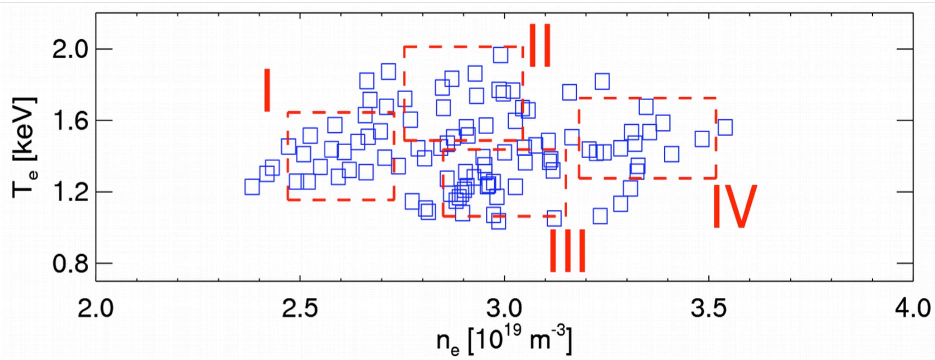


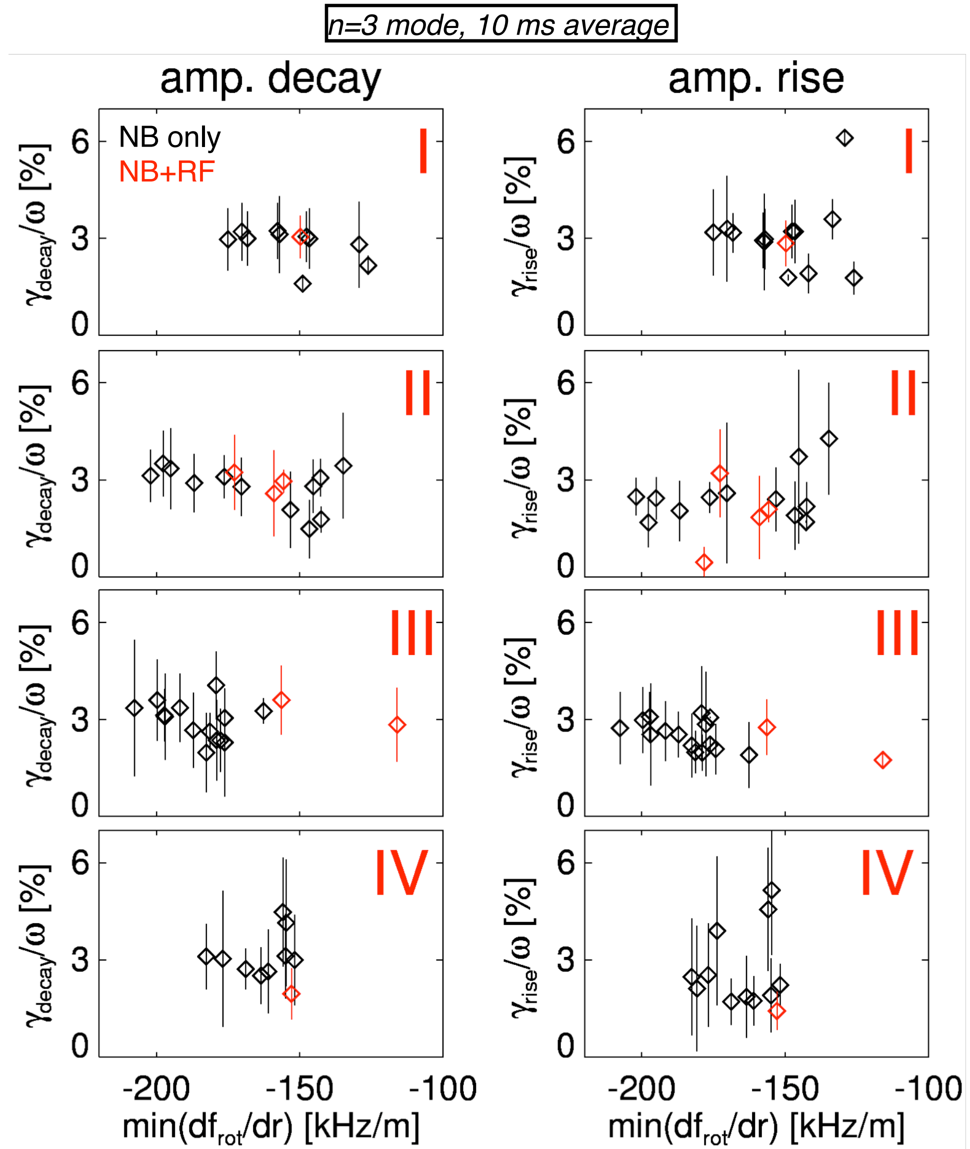
- Shear increases in time
- No correlation with inferred rates

sh#135388



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

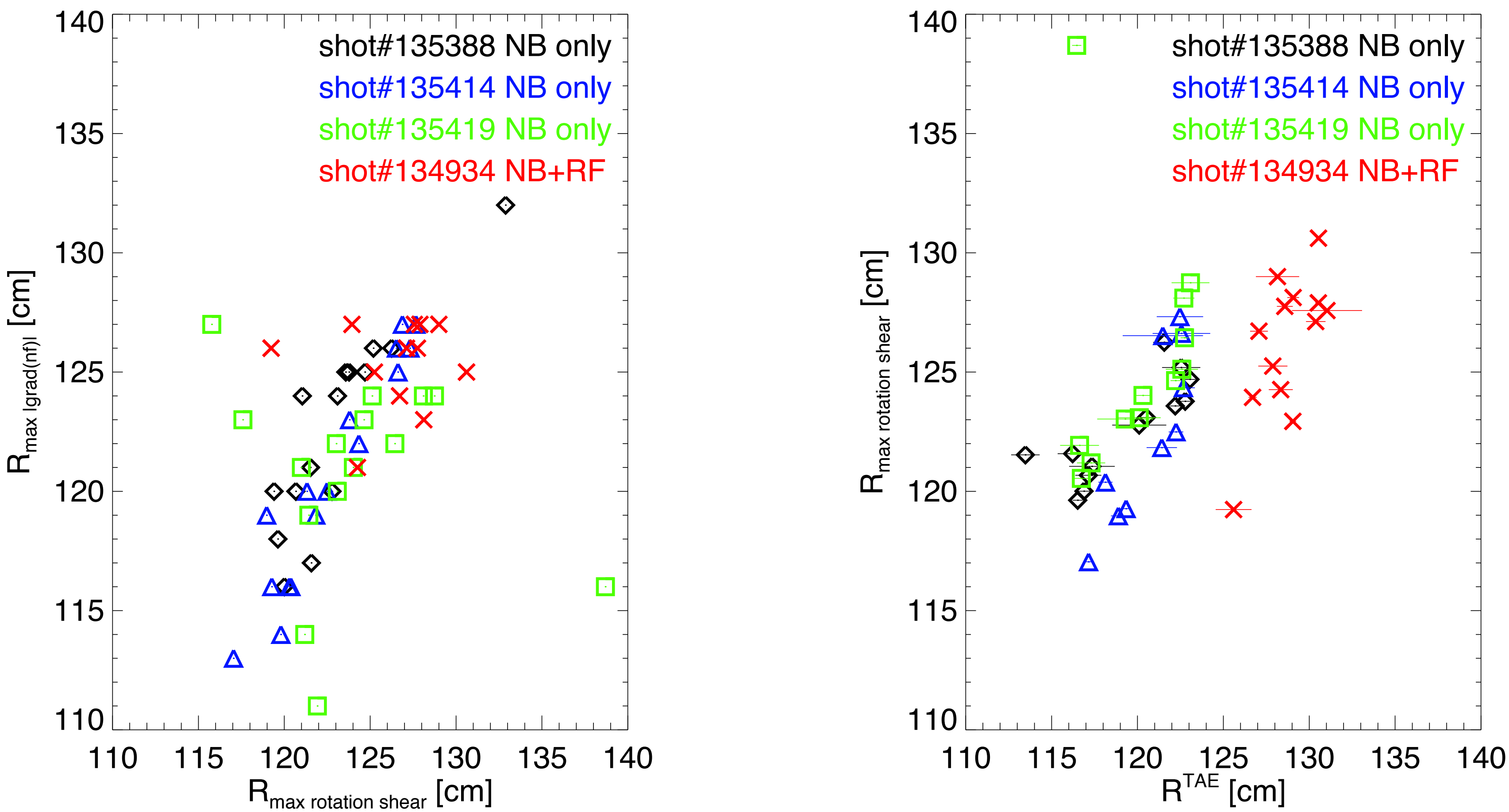




- Database of 10 discharges
- Group data with similar n_e, T_e
  - Similar damping on thermal plasma

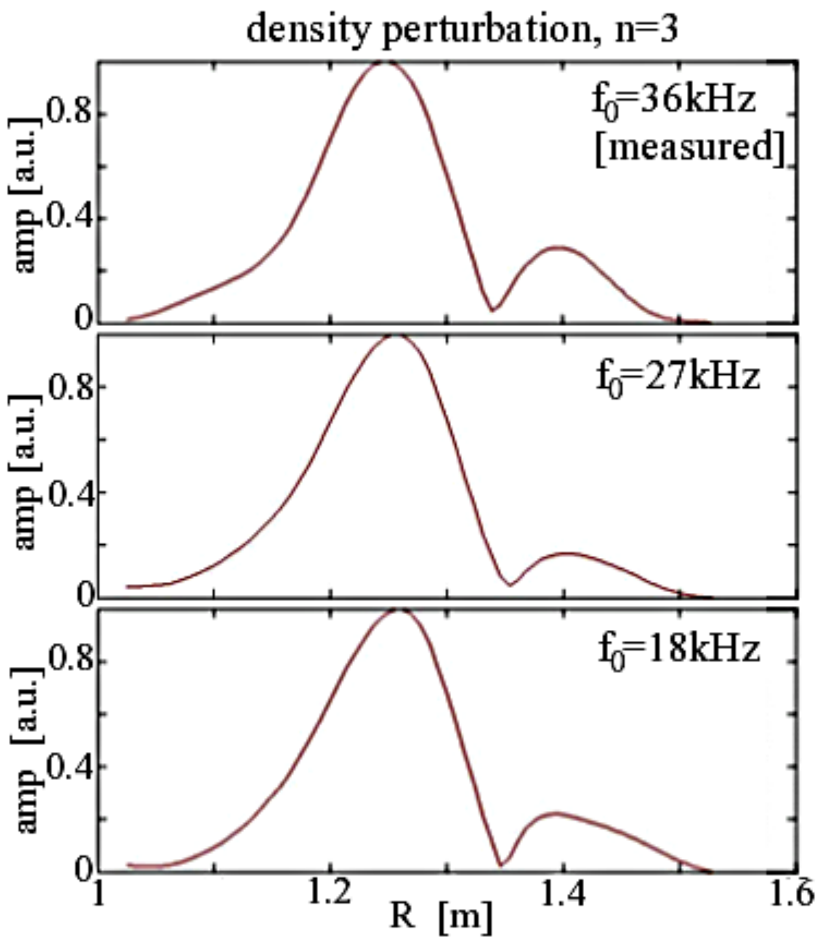
- No simple dependence on injected NB power, T_e, n_e, ...
- Trends hidden by changes in *q* profile, gap structure, ... ?

Additional RF power marginally successful in decoupling fast ion, TAE and thermal plasma dynamics



- May explain slight differences between NB-only and NB+RF

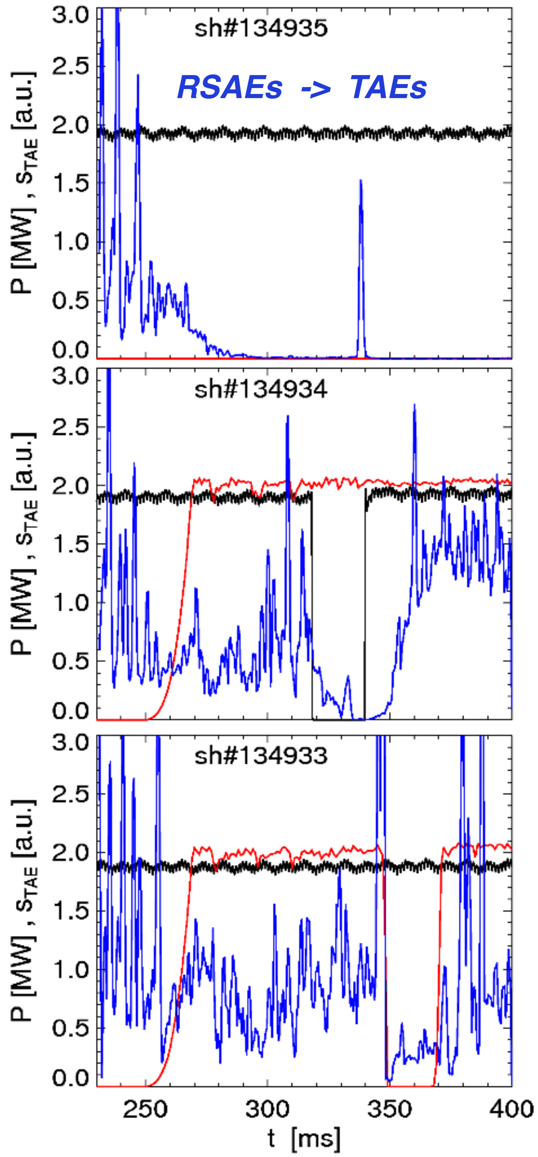
Preliminary results from M3D-K also show little effects of rotation on TAE structure



- No fast ion effects included
- Scale rotation profile from measured f_0=36 kHz down to f_0=18 kHz (50% reduction)
- Mode peak location, structure do not change substantially

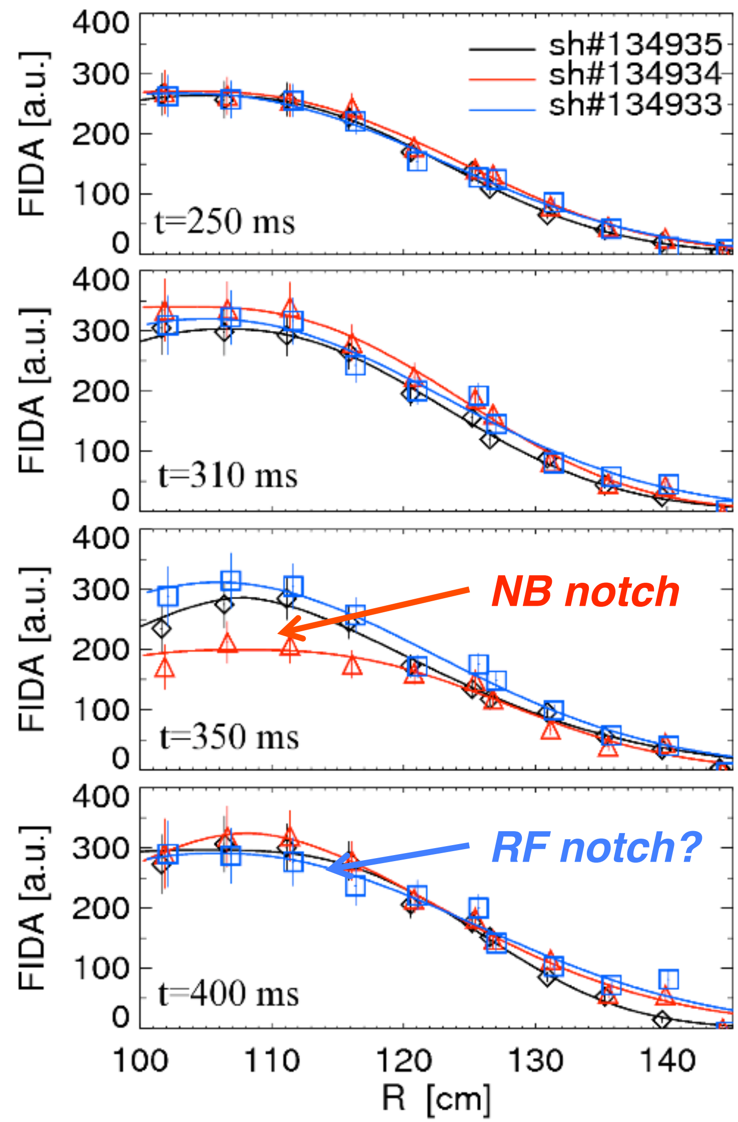
Fu, TTF 2011

Fast ion population is key parameter to destabilize TAEs; subtle details hard to get experimentally…



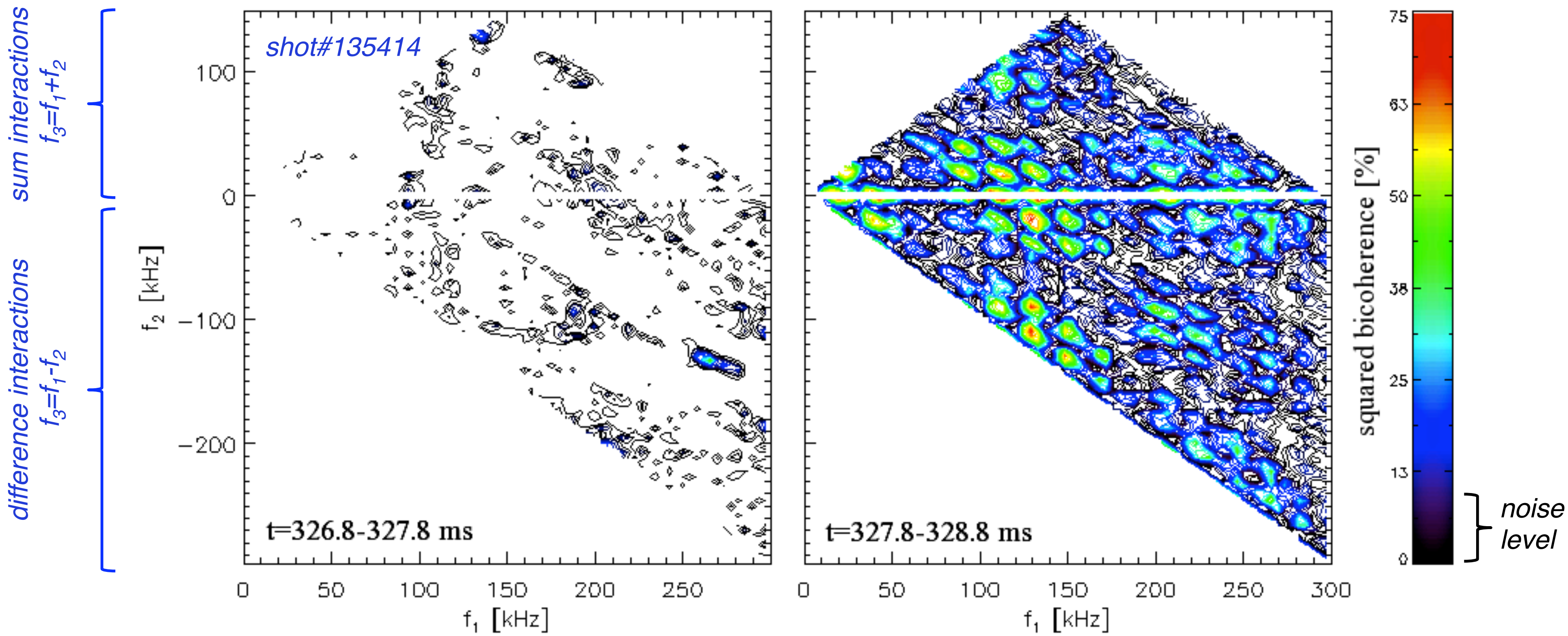
NB only
NB+RF, NB notch
NB+RF, RF notch

- Marginal variations in $n_f(R)$, grad(n_f) from FIDA, except for 100% change in source
- Can not differentiate between role of $\beta_{f.i.}$ and radial gradient
- OK to look at trends

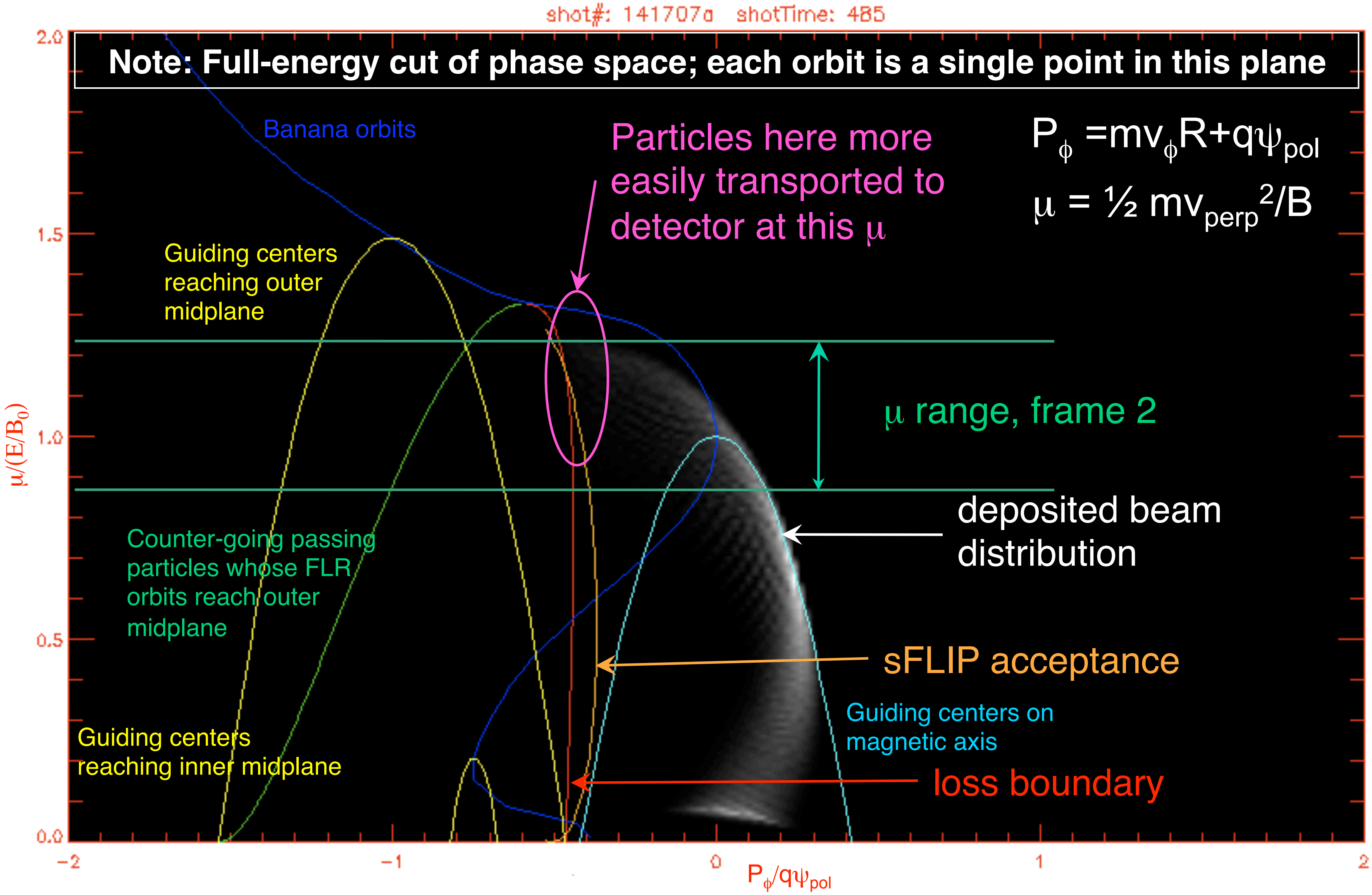


Bicoherence suggests coupling between modes at play during large bursts

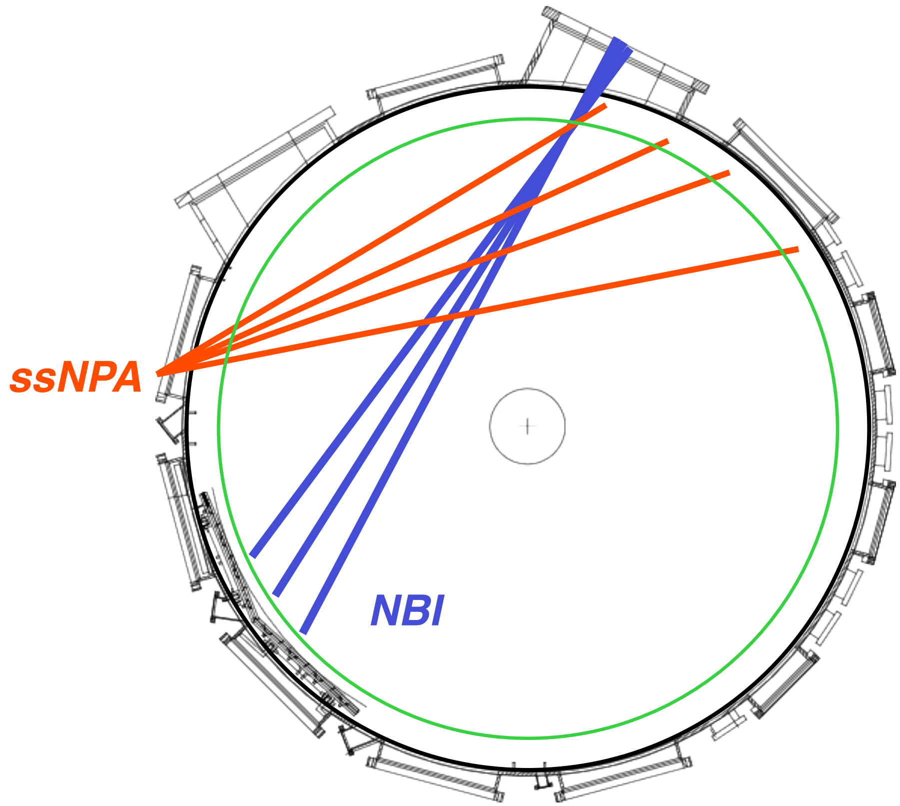
- High bicoherence >70% measured during burst
  - Average over 11 Mirnov coils distributed toroidally over 360°
  - Indicative of sum/difference interactions between modes
  - Both TAEs and low-frequency modes participate



Proximity of beam ions to sFLIP detector at high χ (i.e. high μ) indicates why loss appears there first

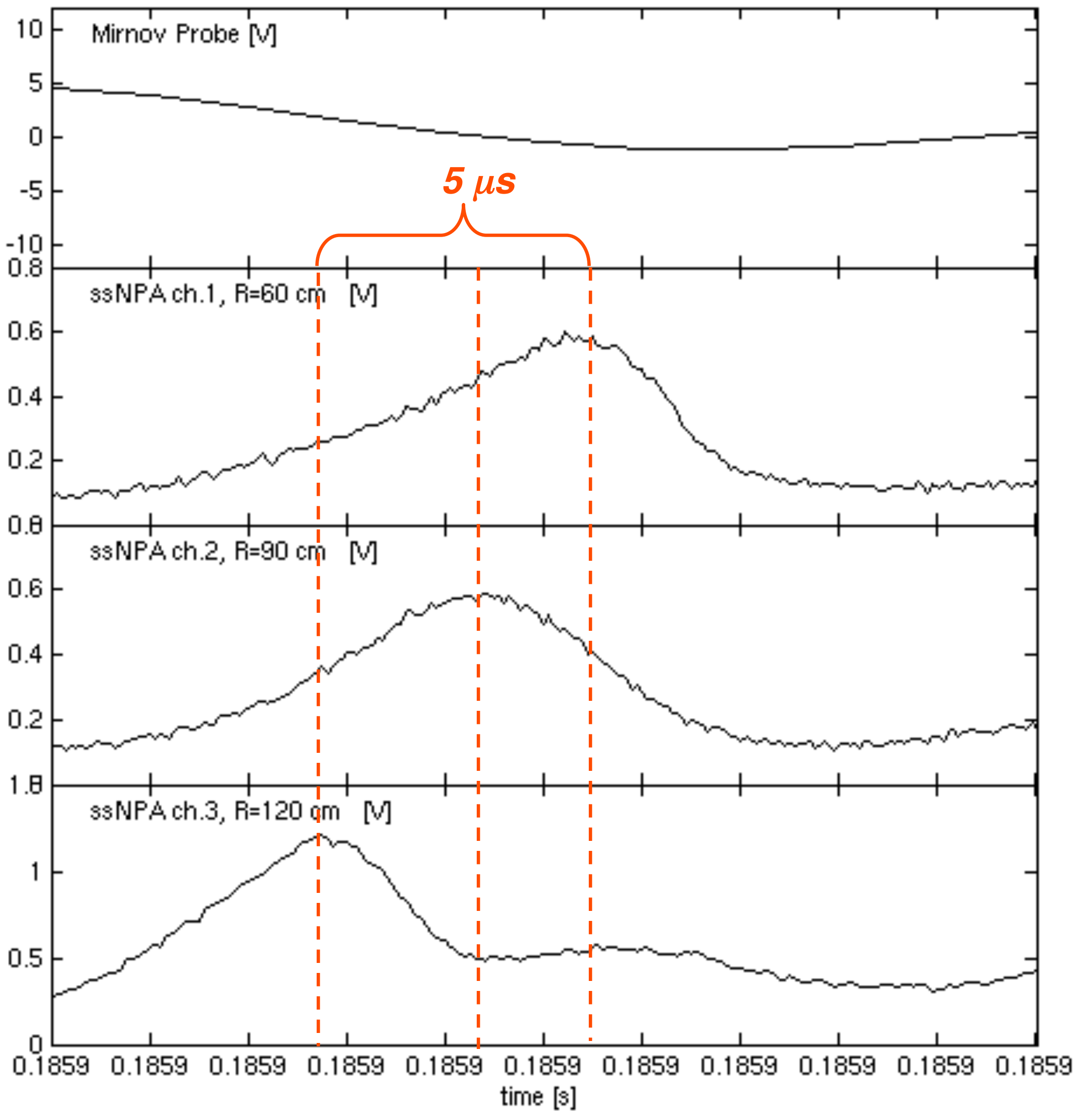


Solid State NPA diagnostic on NSTX operated in “current mode” during FY-10 for high temporal resolution data on mode-induced fast ion losses



- Measurement of flux of energetic neutrals
- 4 lines of sight on the NBI
  - R_{tan} = 60, 90, 100, 120 cm
- Pinhole & Silicon photodiode detector (AXUV)
- Aluminum foil (150nm) blocks light, SXR, low energy neutrals (<10 keV)
- Detected neutrals generated by Charge Exchange of fast ions with **beam** and/or **edge** neutrals

'Fishbone beacon' observed during transient fast-ion losses associated with chirping modes



- Fast frequency chirping instabilities (e.g. TAE) accompanied by periodic bursts in ssNPA signals

- Fast ion loss cone, rotating in phase with the mode, is inferred based on time delay between ssNPA channels

- Burst appear at different phases in different channels

Open Issues

- How to scale present experiments to future devices (ITER), burning plasmas?
  - Code validation, multi-machine comparison are the key
    - > Linear codes (NOVA)
    - > Quasi-linear models, self-consistent codes (M3D-K)
    - > Investigate wave-fast ion interaction (ORBIT, SPIRAL)
    - > *Improve stability calculations*
  - But: conditions will be very different, e.g. $F_{f.i.}(\underline{r},\underline{v},t)$ from alpha's (+NB, RF, …)
    - > E.g. need better understanding of role of spatial *vs.* velocity gradients
  - Parallel effort: develop control tools
    - > Act on NB deposition, q-profile? Active antennas?
- Combine different diagnostics/techniques; develop phase-space models to interpret results consistently