Energetic Particles Physics Progress and Plans

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for the NSTX Research Team

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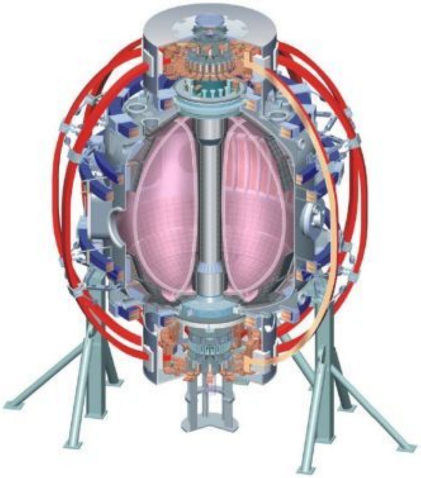

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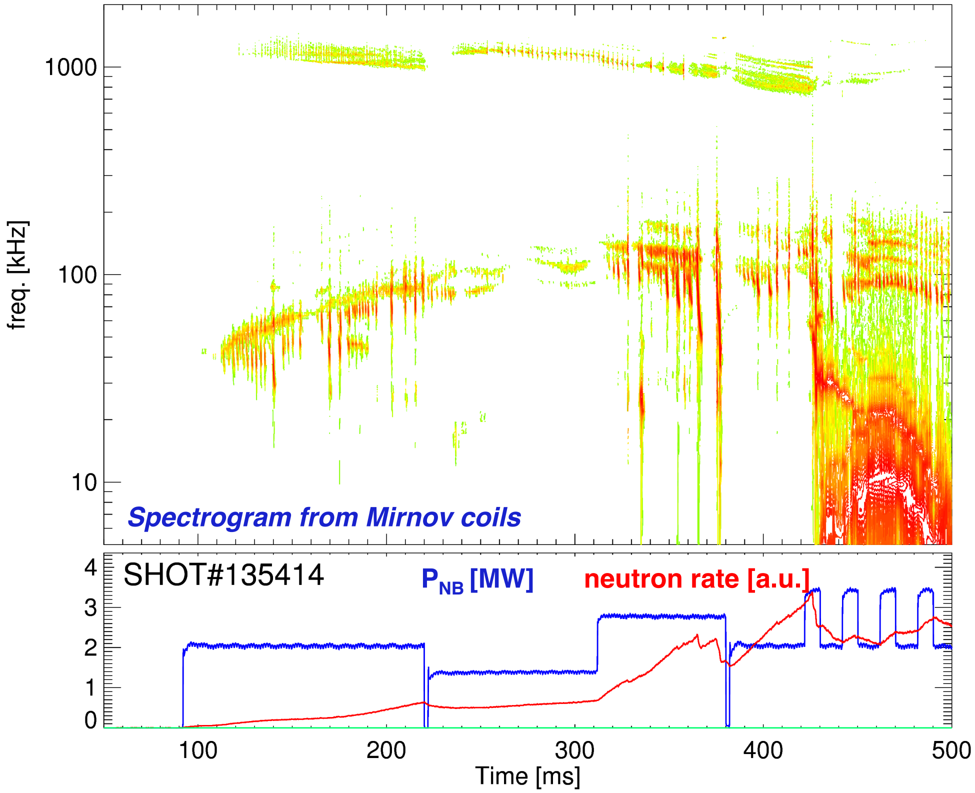
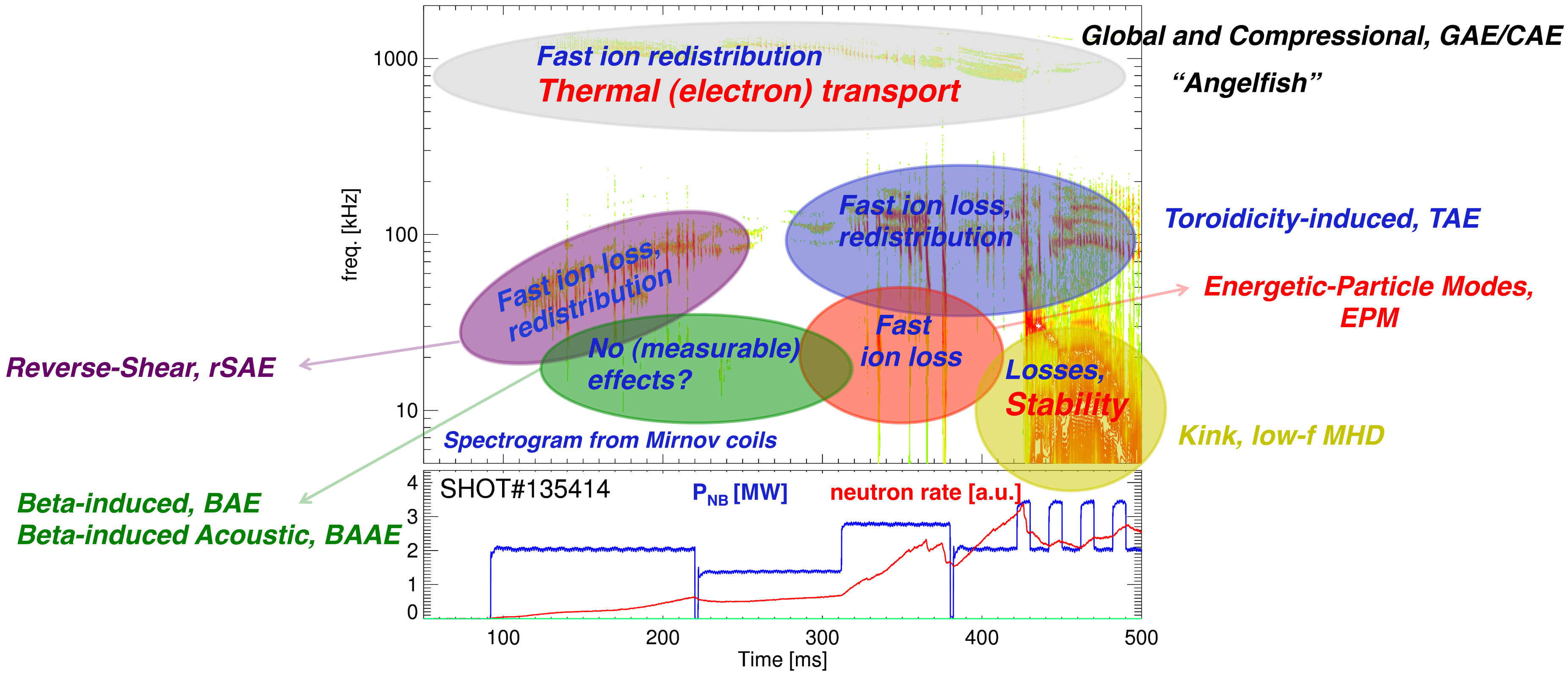
Neutral Beam heated NSTX plasmas provide unique regimes for Energetic Particles studies

- Neutral Beam (NB) injection represents source of super-Alfvénic ions
  - Injection energy 60-100keV, leading to $1<V_{fast}/V_{Alfvén}<5$
  - Strong drive for Alfvén eigenmodes (*AEs) over wide range of frequencies



Wide range of Alfvénic instabilities identified, characterized

- Making good progress on understanding fast-ion transport associated with different modes



Next frontier: acquire predictive capability for mode dynamics, associated fast-ion transport

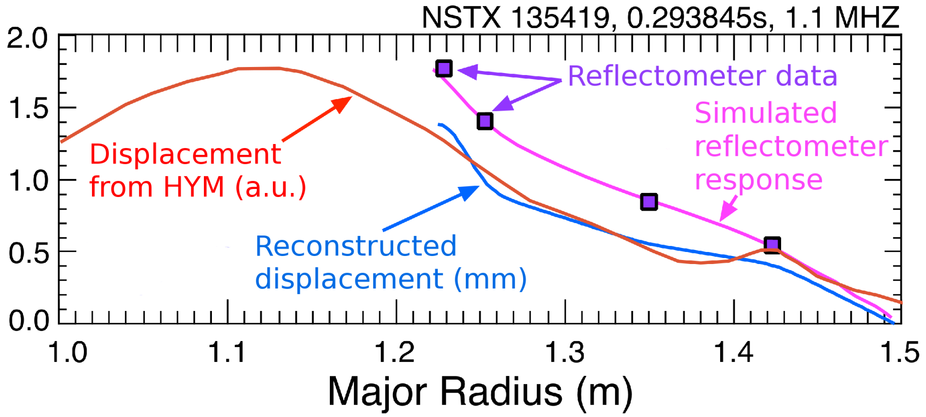
Outline

- Physics of high-frequency *AEs (GAEs/CAEs)
- Physics of TAEs
- *AE-induced fast ion loss/redistribution
- Modeling of Alfvénic modes in tokamaks
- Plans for FY11-12 (and beyond)

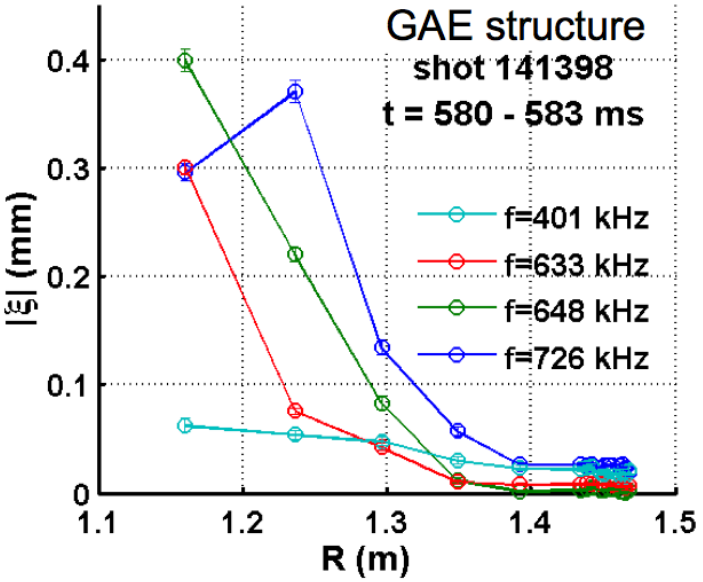
B# = additional material in Backup Slides

Increased emphasis in FY10 on high-frequency *AEs (GAEs/CAEs) which can cause enhanced thermal and fast ion transport

- Electron transport modeled with particle following code ORBIT
  - Transport by GAEs *consistent* with TRANSP estimates (T&T presentation)
  - *Using mode structure from theory*
- Validate eigenfunction modeling (HYM code) for GAEs against experiments in FY11



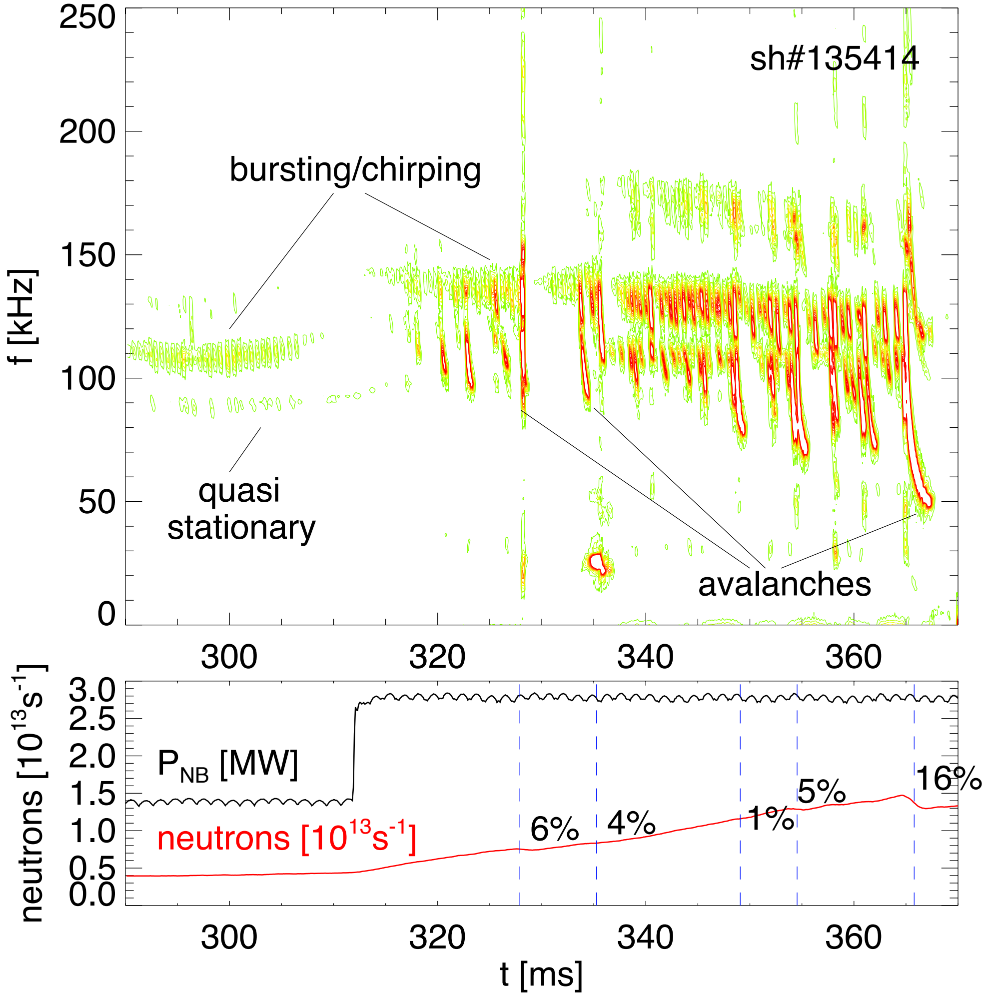
- Progress made in characterizing synergy between high/low frequency *AEs
- Increasing (but still *indirect*) evidence of fast ion redistribution by GAEs
  - E.g., GAE *avalanches* appear to trigger TAE bursts (FY09-10) ***B32***
  - May also explain *anomalies* observed in NPA data ***B15/16***
- Further studies in FY11-12, enabled by upgraded reflectometer, BES + codes



Upgraded reflectometer has
4x more channels (FY10):
spatial resolution/coverage much improved

At lower frequencies, coupling between TAE modes and enhanced losses are observed during large bursts

B17/19

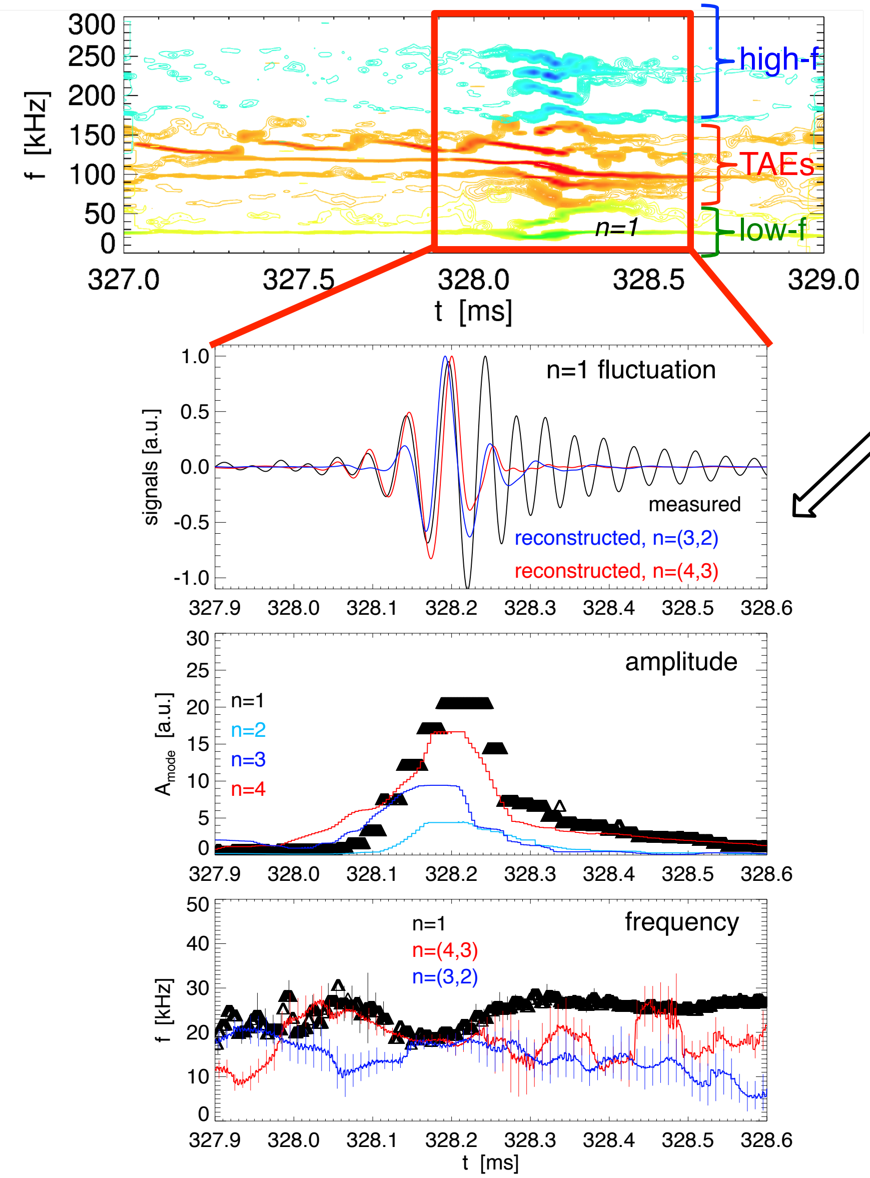


- TAEs usually observed in a *bursting* regime
- Larger bursts (*avalanches*) cause up to 30% losses of confined fast ions
- Bursting character enhanced by adding more NB (fast ion drive)
  - No clear stabilizing effects due to rotation shear, RF, ...
- Single modes usually chirp independently from each other...
- ...except in large bursts

ITPA EP-2

ITPA EP-4

TAE burst data consistent with three-wave coupling, possibly destabilizing otherwise stable kink-like modes



- *Primary* TAEs couple and generate higher/lower frequency modes
  - Analysis from Mirnov coils' data
  - Similar results from reflectometer
- Conditions for three-wave coupling are <u>transiently</u> satisfied:

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

with $n_3 = n_1 \pm n_2$, $f_{n_3} = f_{n_1} \pm f_{n_2}$ **B20/23**

- Simple model breaks down for large avalanches
  - Coupling between large number of modes, need more complete model/simulations

Need to move from linear (e.g. NOVA+ORBIT) to non-linear, self-consistent simulations to improve predictive capability:

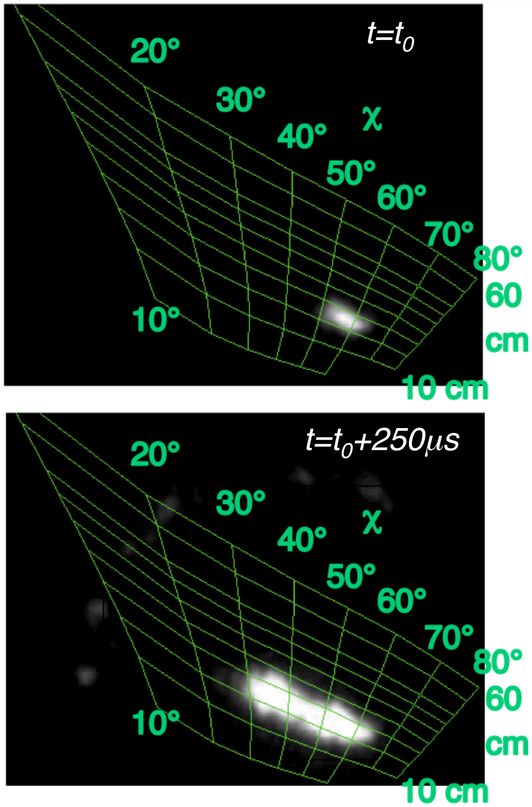
<u>Motivates IR12-2</u> **B34**

ITPA EP-2

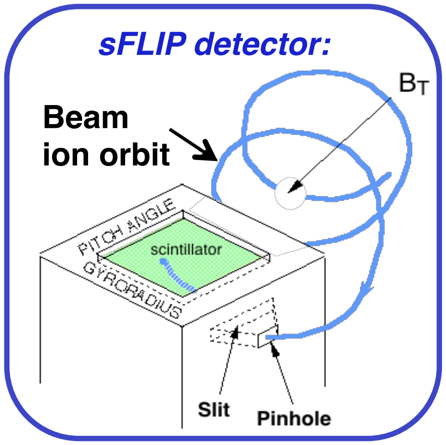
Fast ion losses commonly observed during TAE/EPM bursts *with strong frequency chirps*

- Can degrade fusion, NBI-CD performance (ASC-TSG presentation)
- Clear dependence of lost fraction on *total* mode amplitude
- No simple correlation with number/spectrum of modes
  - Consistent with a fully non-linear system of modes causing transport
- *Scintillator Fast Ion Loss Probe* (sFLIP) shows wide range of pitch involved in loss process, narrow energy range **B26/27**
  - Complements measurements from FIDA,NPA,ssNPA
  - New phase space model of sFLIP helps understand measurements based on sFLIP "acceptance" *vs.* χ, E **B24/25**
  - New t-FIDA (FY11) will help discriminate between loss of parallel *vs.* perpendicular components

sFLIP: lost fast ions vs. χ, E during TAE avalanche.
χ=acos($v_{//}/v_{tot}$) , ρ_i=$E^{1/2}/\Omega_{ci}$



E=90keV ⇔ ρ_i@sFLIP=25cm
E=15keV ⇔ ρ_i@sFLIP=10cm



Link between TAE/EPM dynamic and resulting fast ion losses will be further investigated

ITPA EP-2

Extensive validation of codes modeling TAEs is planned to improve predictive capabilities (NSTX-U and beyond): IR12-2

- Validation of M3D-K *vs.* experiments started

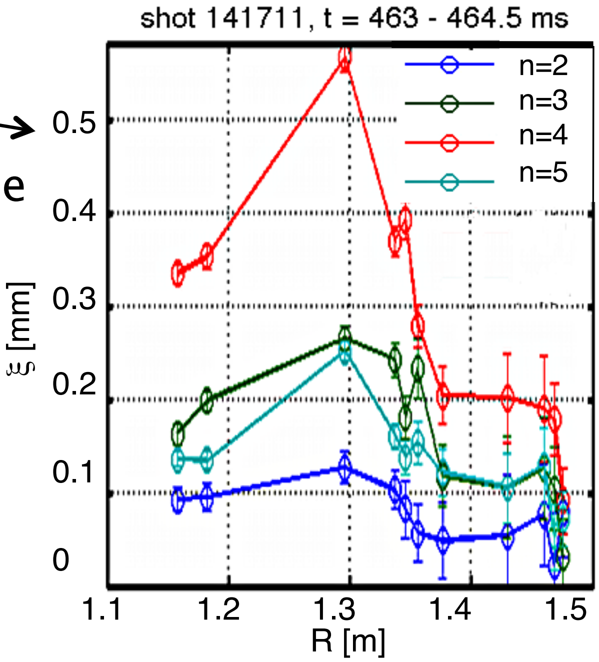
M3D-K: non-linear, self-consistent hybrid MHD/particle w/ sources and sinks

B30

  - Comprehensive set of data collected in FY10
    - Great benefit from improved mode structure measurements: BES, reflectometer
  - Begin studying saturated regime
    - Compare mode spectrum, frequency/amplitude evolution (bursts/chirps)
    - Single *vs.* multi-mode dynamics
  - Compare with linear predictions (NOVA-K)

NOVA-K: linear, perturbative kinetic MHD

  - Extend to stability analysis (FY12)



- Extend the comparison to SPIRAL in FY-11

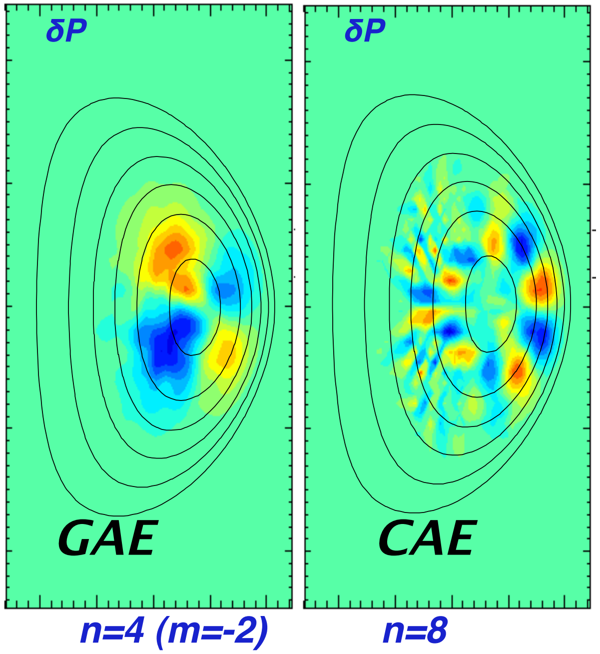
SPIRAL: full-orbit particle-following code

  - Mode structure from measurements, NOVA-K
  - Compare predicted losses with experiments

FY12+, NSTX-U: Assess impact, improve models of fast ion losses on NBI-CD (see ASC-TSG presentation)

PAC27-26

Good progress made in simulating GAEs/CAEs on NSTX with HYM code



n=4 (m=-2) n=8

- Powerful, unique tool to understand and predict fast ion and thermal transport by high-f *AEs

HYM: non-linear, delta-f hybrid MHD/particle **B28/29**

- Predictions compare well with experiments (frequency, mode number, ...)
  - CAEs: edge localized; GAEs: core localized
  - GAE mode have m~1-3; for CAE, m~8-10
  - Both GAE and CAE modes have large compressional magnetic component near the plasma edge
- Plans for FY11-12: complete HYM validation, apply to NSTX and NSTX-Upgrade plasmas
  - Compare mode structure with experimental ones (enabled by BES, upgraded reflectometer and FIReTIP **B31**)
  - Study effects of sub-cyclotron modes on particle confinement
  - Add sources/sinks to study long-time-scale non-linear evolution of unstable modes

Energetic Particles research plans for 2011-2012 and beyond

2011:

- **Continue study of TAEs, high-f *AEs** (including avalanches) in H-mode
  - Revisit *AE effects on NB-driven current profile (ASC-TSG)
- **Benchmark codes**: HYM, M3D-K and SPIRAL; model GAE/CAE and TAE dynamics

2012:

- **Support Milestone R12-2**: *"… heating, ramp-up of CHI start-up plasmas" (SFSU-TSG)*
- **Address (incremental) Milestone IR12-2**: "*Assess predictive capability of mode-induced fast ion transport"*
- **Investigate (linear) stability** threshold calculations with NOVA-K; compare with experiments, M3D-K
- Implement **constraints of fast ion pressure** in TRANSP based on FIDA, neutrons

2013+:

- **Complete data analysis, publish results**
- **Collaborate with other facilities** on Energetic Particles Physics research
- **Prepare for post-upgrade operations**
  - NPA/ssNPA specification; upgrade data acquisition for higher field, longer pulse

Summary of Energetic Particles research plan 2011-2012

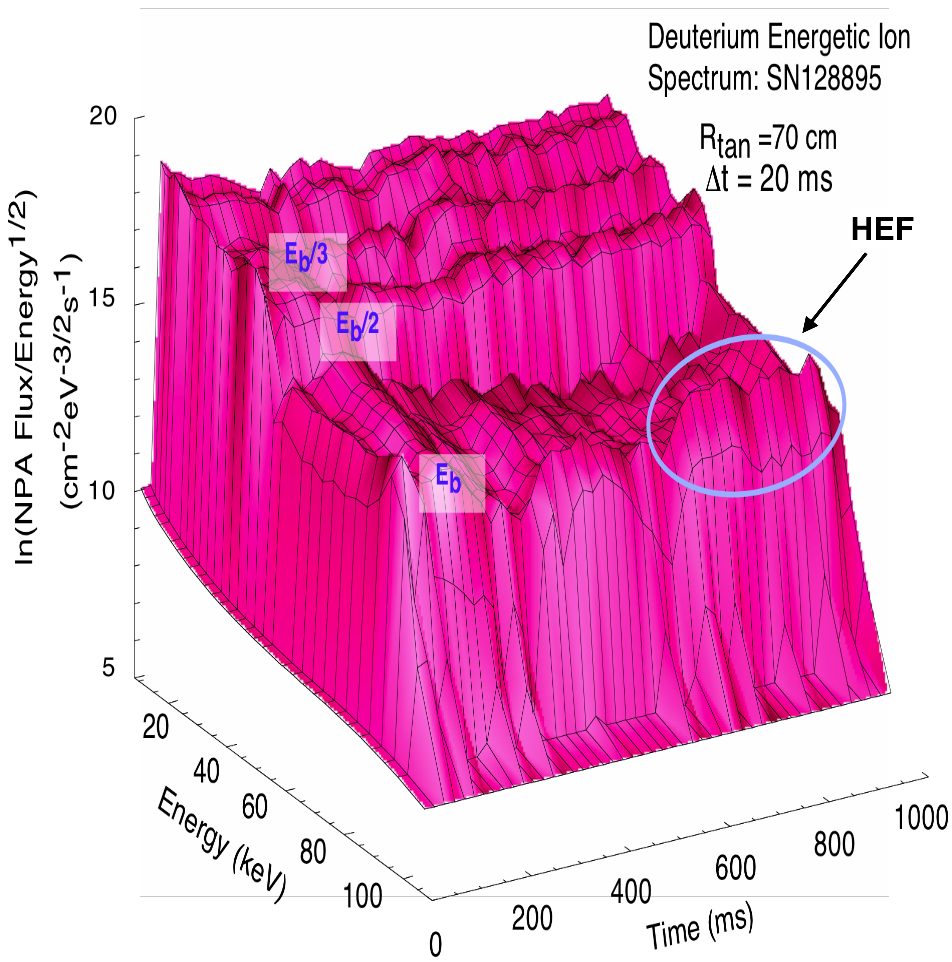
- Study of TAE/EPM *avalanches* and induced fast ion losses will proceed and will be extended to H-mode plasmas

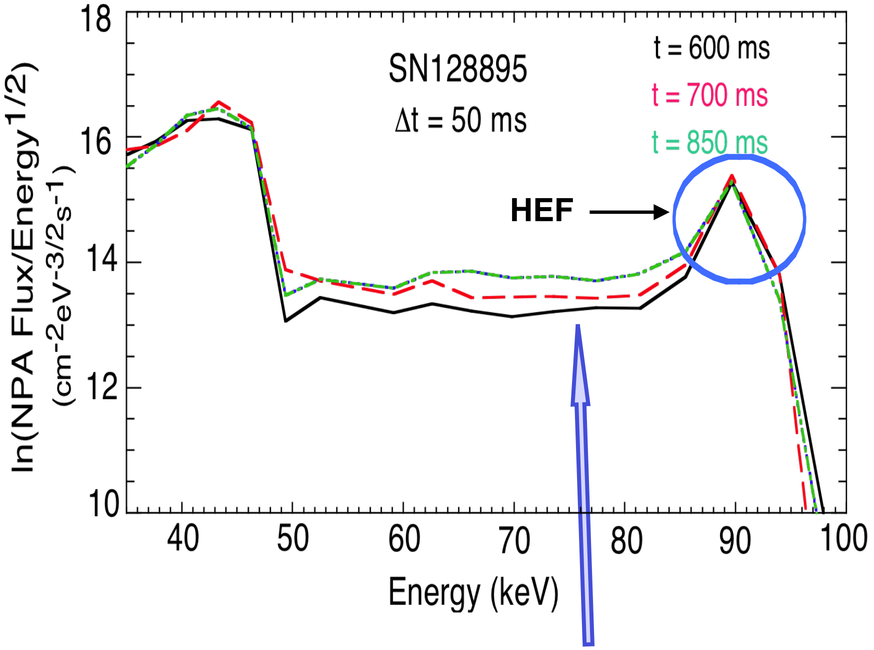
- Understanding of physics behind other *AEs and their effects on fast ion dynamics will progress
  - High frequency modes (GAEs/CAEs)

- Increasing emphasis on validation of linear and non-linear theory/codes
  - Support NBI-CD research for NSTX Upgrade (and next steps)

Backup slides

High-Energy Feature (HEF): a strong increase (~4x) in the E||B NPA Charge Exchange Flux narrowly localized around the NB injection energy



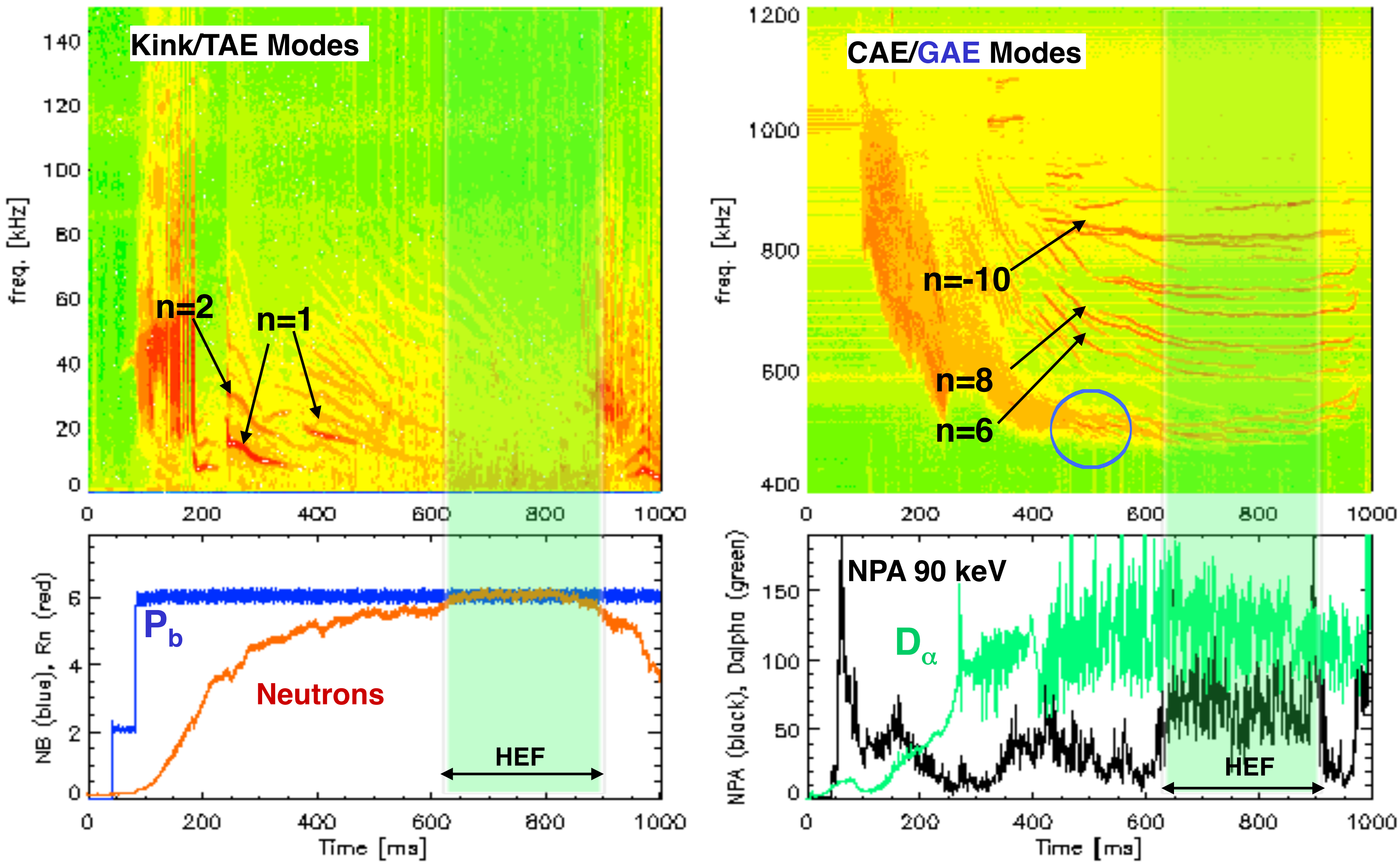


- Spectrum exhibits modest slowing down of fast ions below the HEF energy.
- The slowing down distribution evolves over a period of ~ 300 ms.
- This evolution is ~ 10x longer than the usual NB slowing down time, τ_s ~ 30 ms.

HEF occurs during quiescent kink/TAE MHD

No modulation of the robust CAE/GAE activity is observed during the HEF

SN128895



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

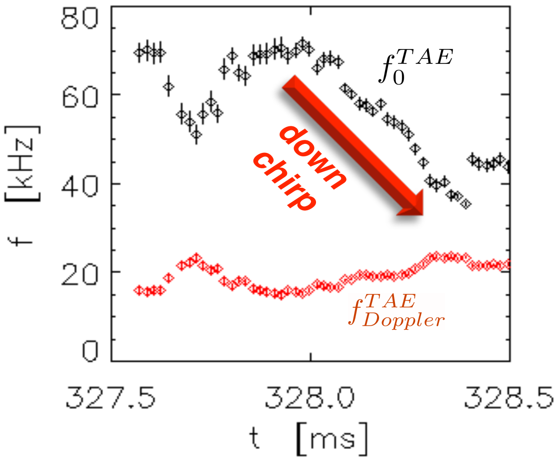
↓ shift from plasma rotation

Valid for time scales >1 ms

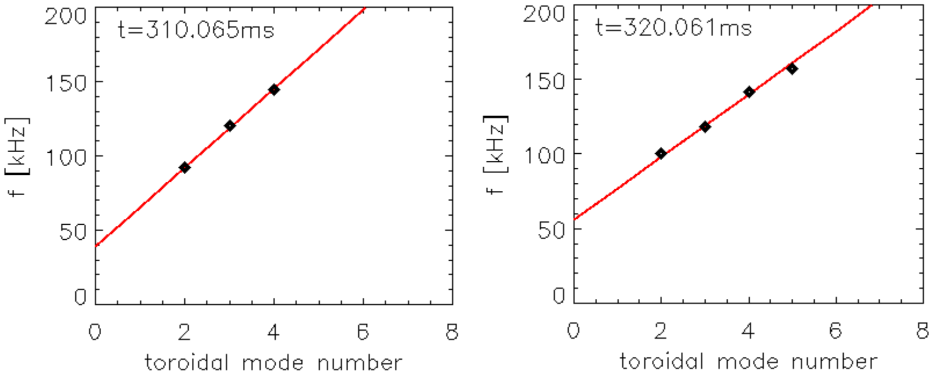
In general, each mode show a different sub-millisecond dynamic...

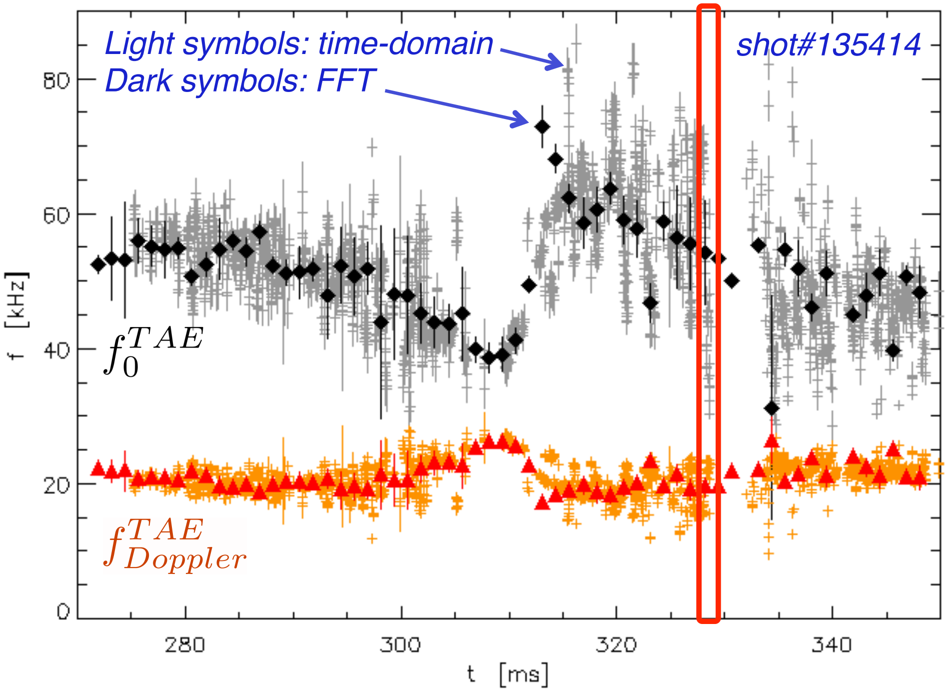
...except during large bursts:

- Doppler shift only slightly changed
- Chirp mainly due to decrease in f^{TAE}_0

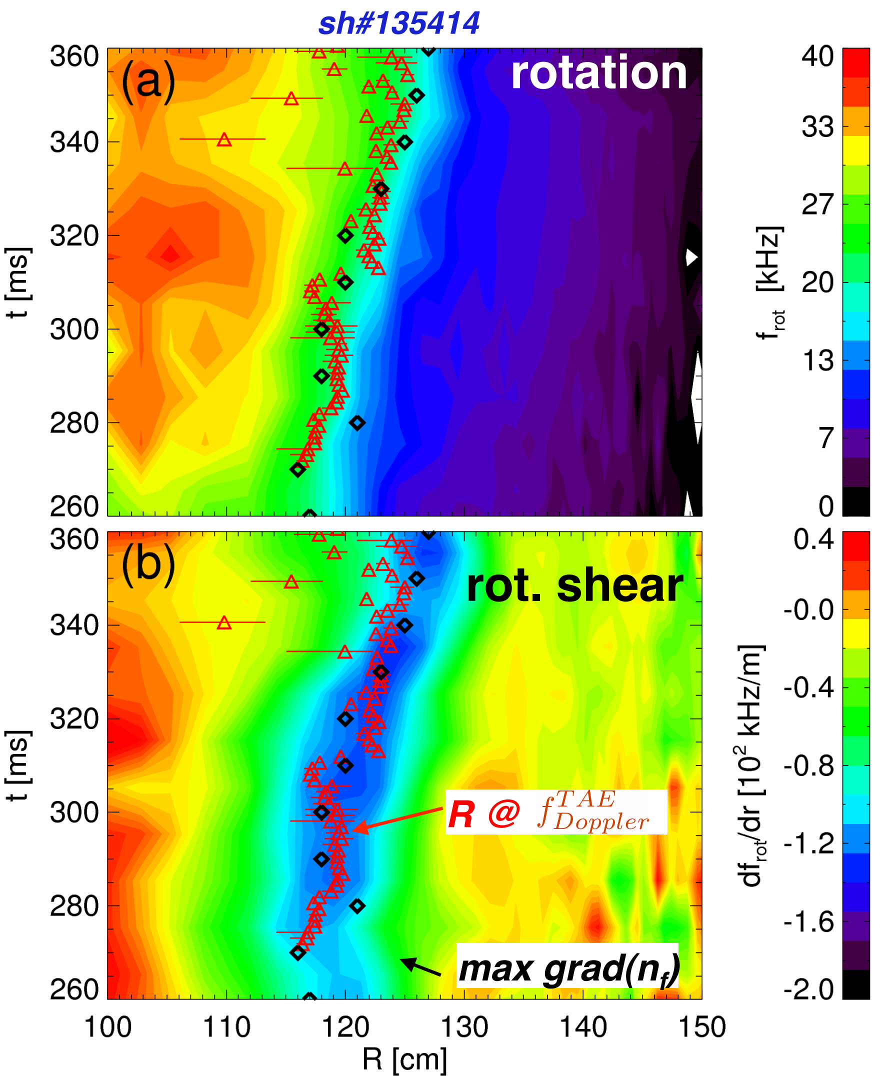


FFT window 1.3ms





Understanding TAE dynamic requires detailed knowledge of fast ion drive



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

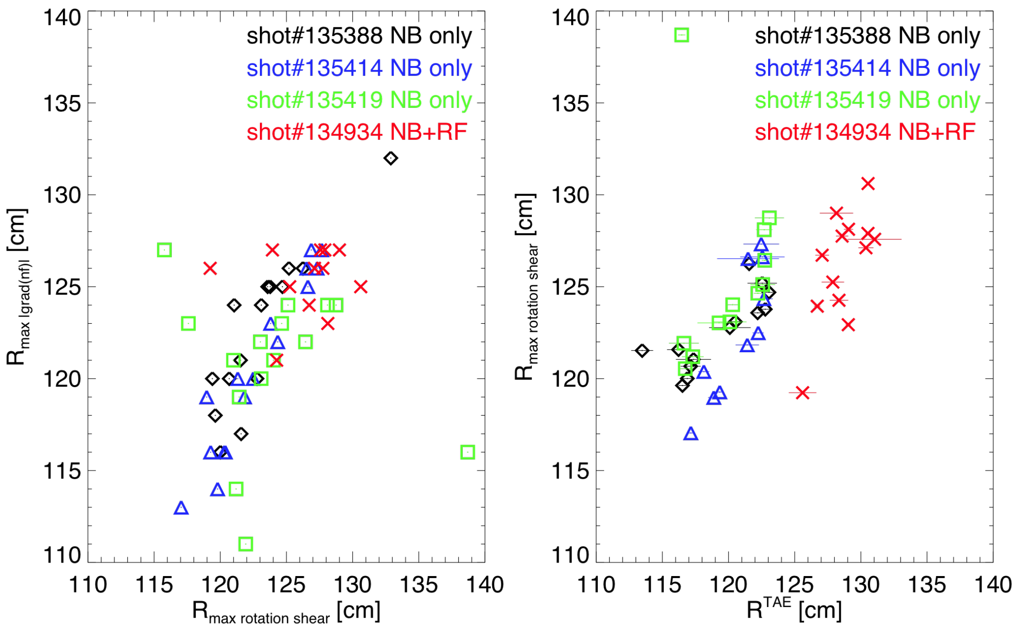
$$f_{rot}(R^{TAE}) = f^{TAE}_{Doppler}$$

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

ITPA EP-2

ITPA EP-4

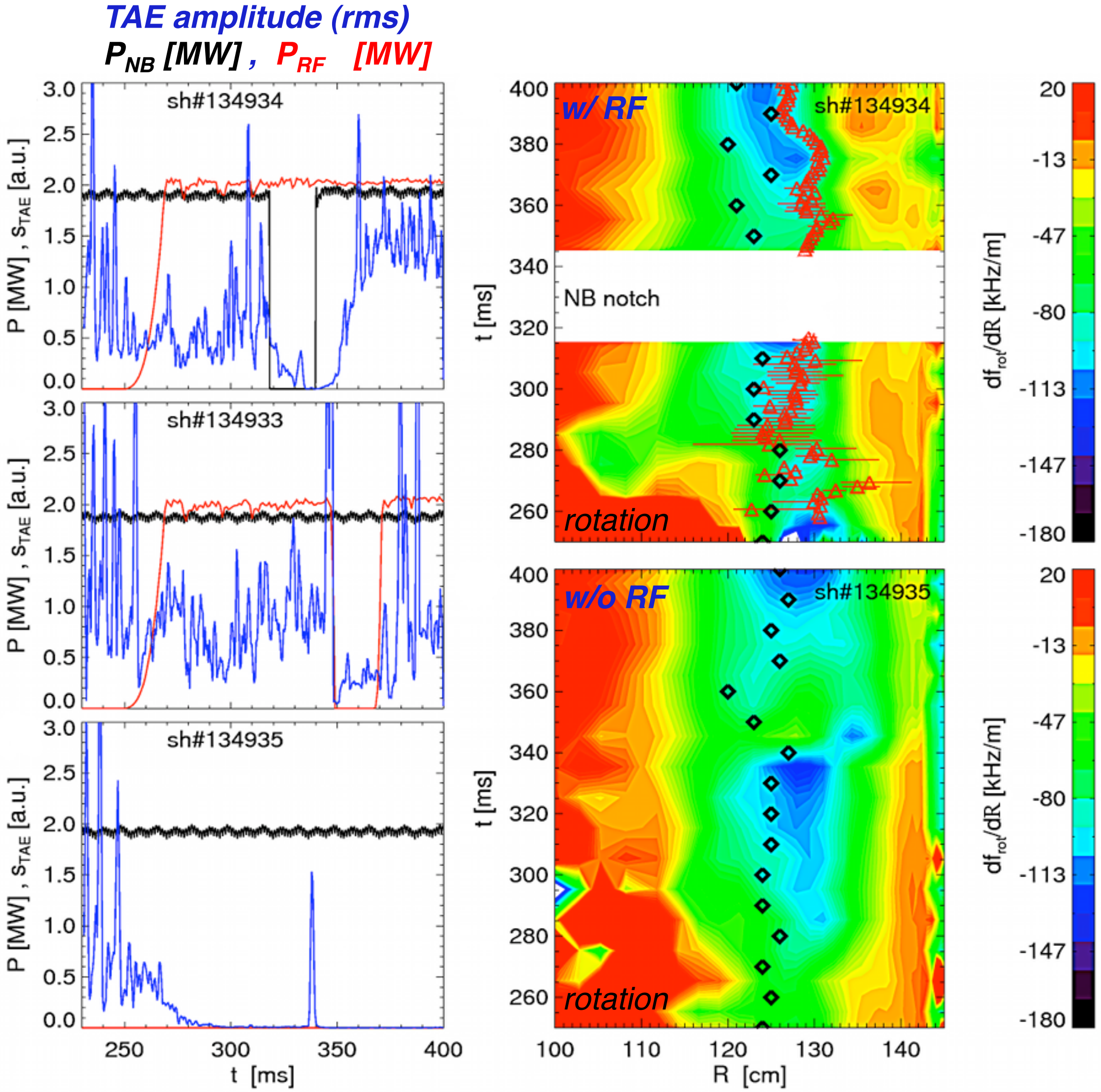
Coupling through common "source term", i.e. NB injection



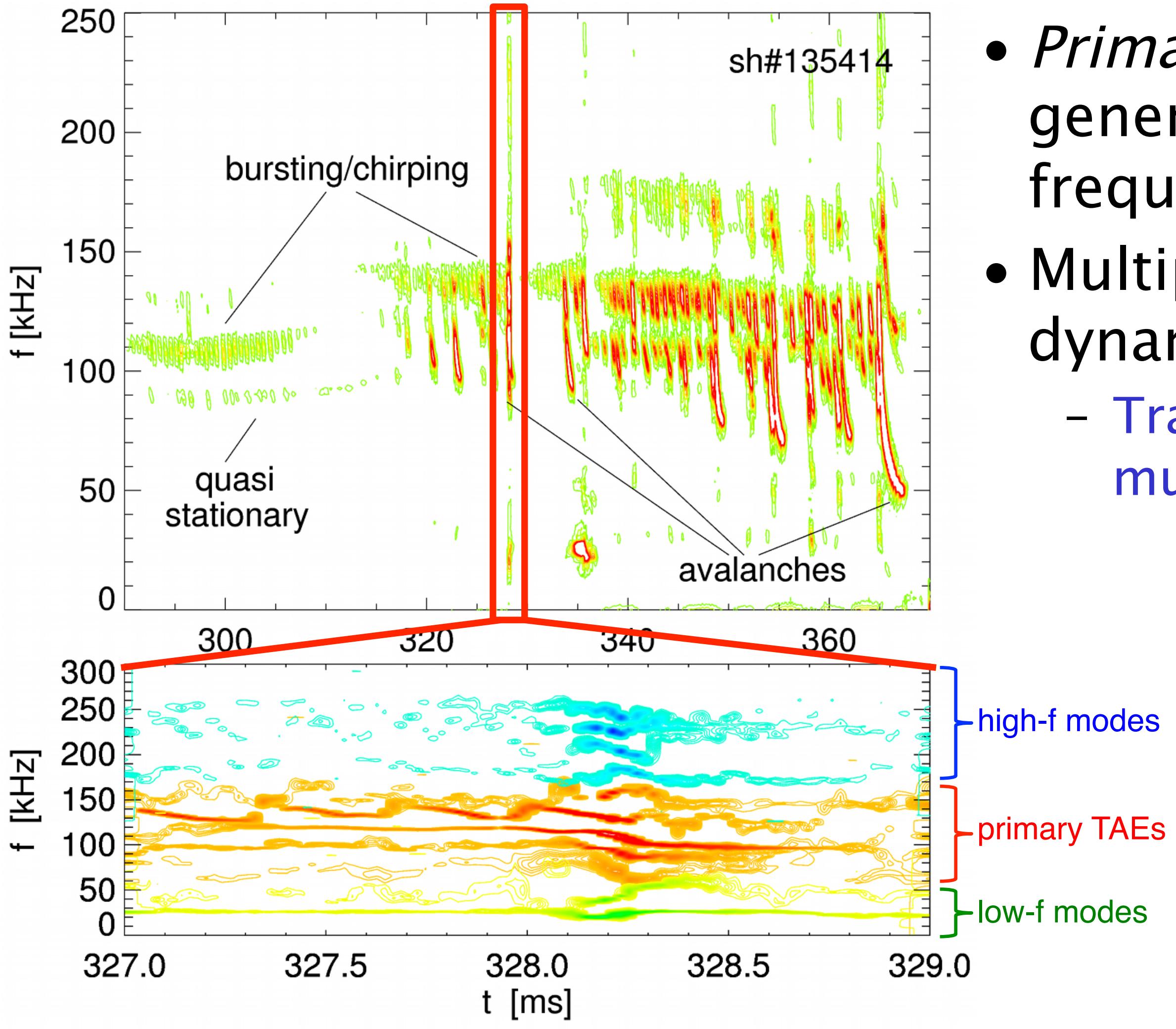
TAE drive is key factor in determining the observed bursting dynamics

ITPA EP-4

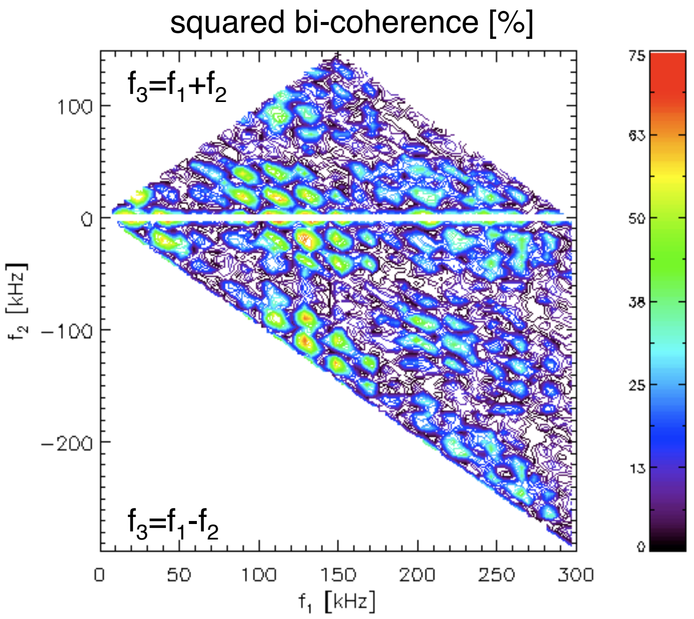
- Bursting dynamics is preserved when drive, $f^{TAE}_{Doppler}$ and shear locations separate
- TAEs respond quickly to notches in NB, RF power
- NB alone is not enough here to drive TAEs unstable



Coupling between multiple TAEs and enhanced losses are observed during explosive modes' growth

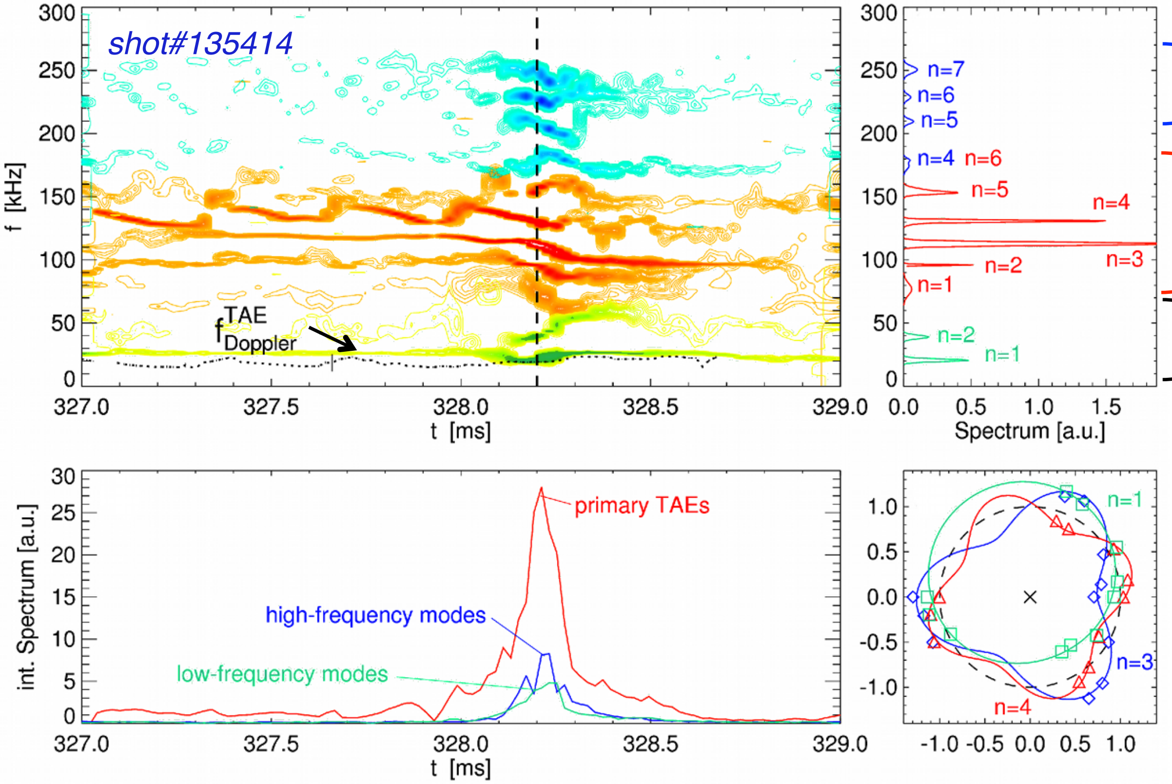


- *Primary* TAEs couple and generate higher/lower frequency modes
- Multiple modes follow similar dynamic during the burst
  - Transition from single- to multi-mode regime



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

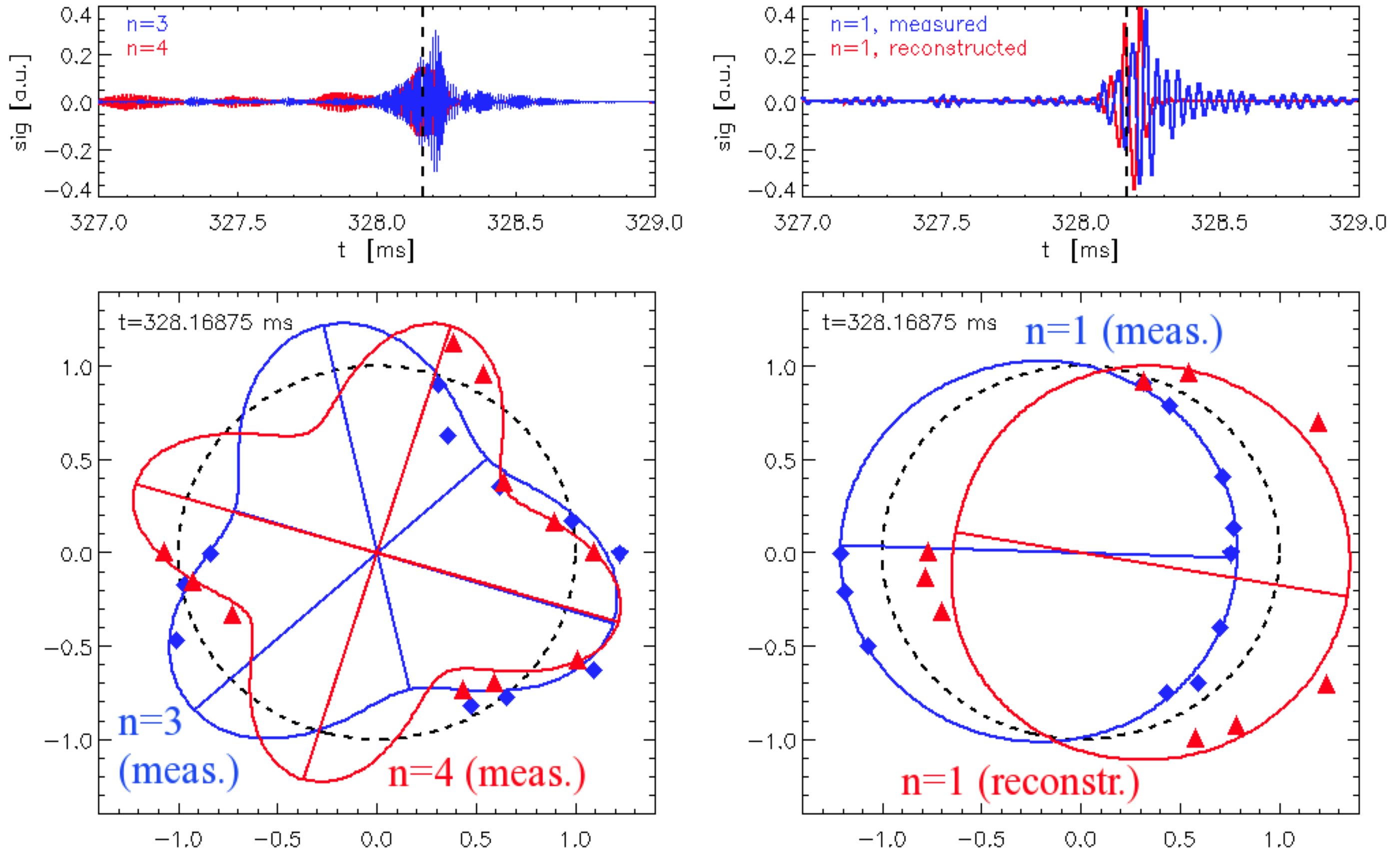
Low-frequency band; appears during large bursts only? Masked by other MHD modes?

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 $\Delta n=1$

Mode number matching condition verified



Polar plot of toroidal mode structure

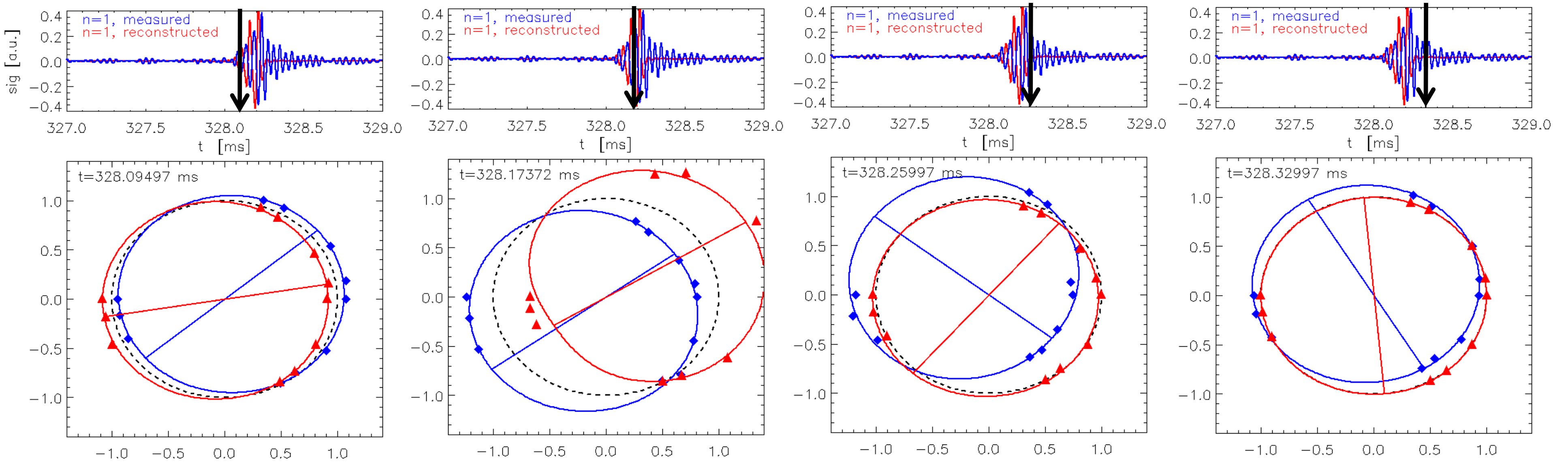
-Symbols: rms mode amplitude data from 11 Mirnov coils

- 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)*

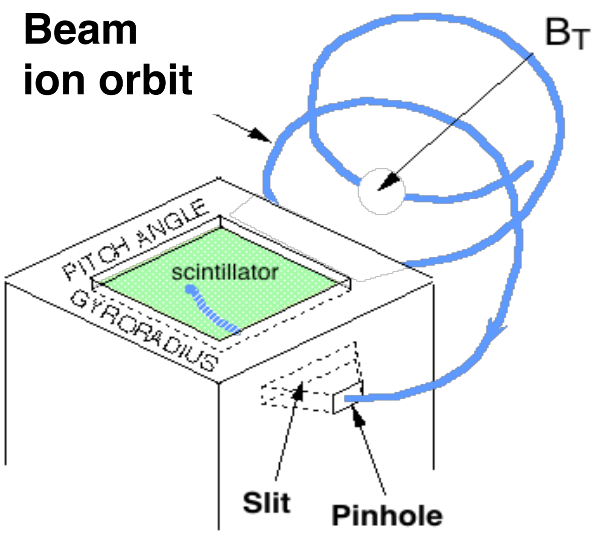
Phase matching condition is <u>transiently</u> verified during large bursts

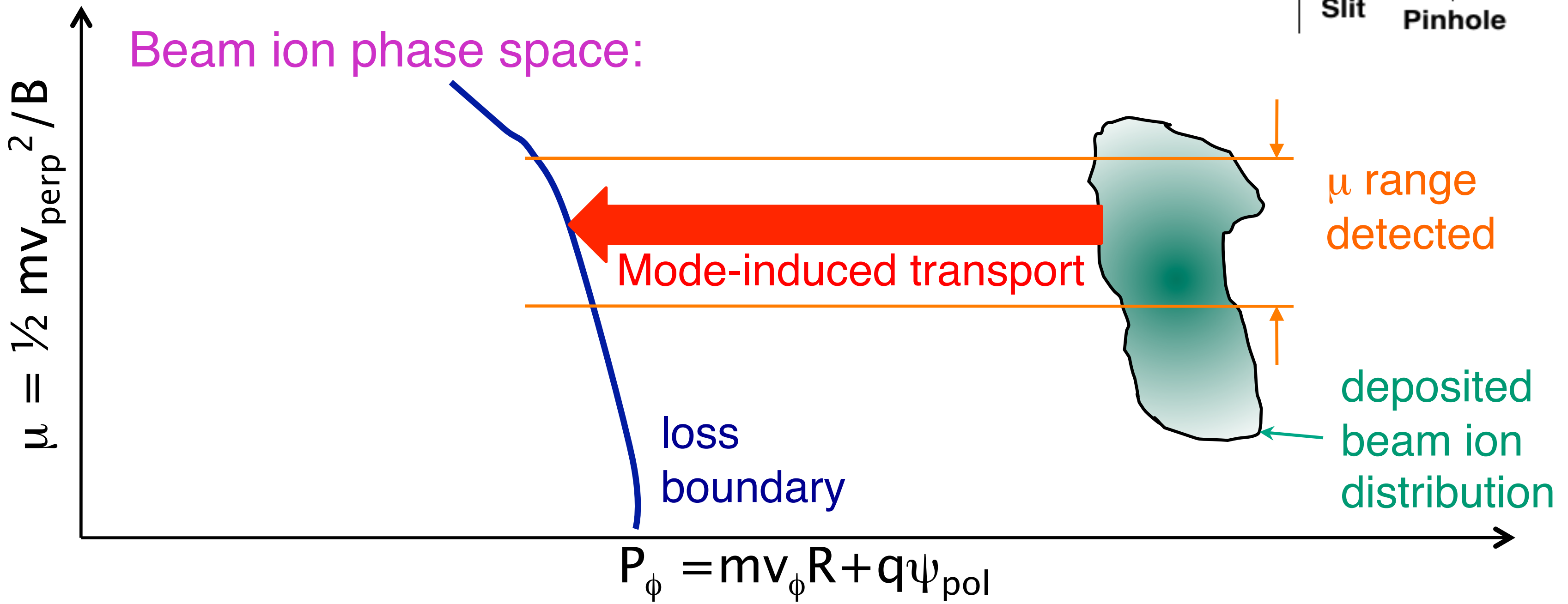


- Phase resulting from quadratic interaction is important!
  - *n=1 mode fades away ⇔ phase deviates from 180 degrees*
  - “Single mode” dynamic, with each mode following its on chirp/burst cycle, is effective in reducing efficiency of quadratic interactions
  - The result is a “semi-cahotic” scenario,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

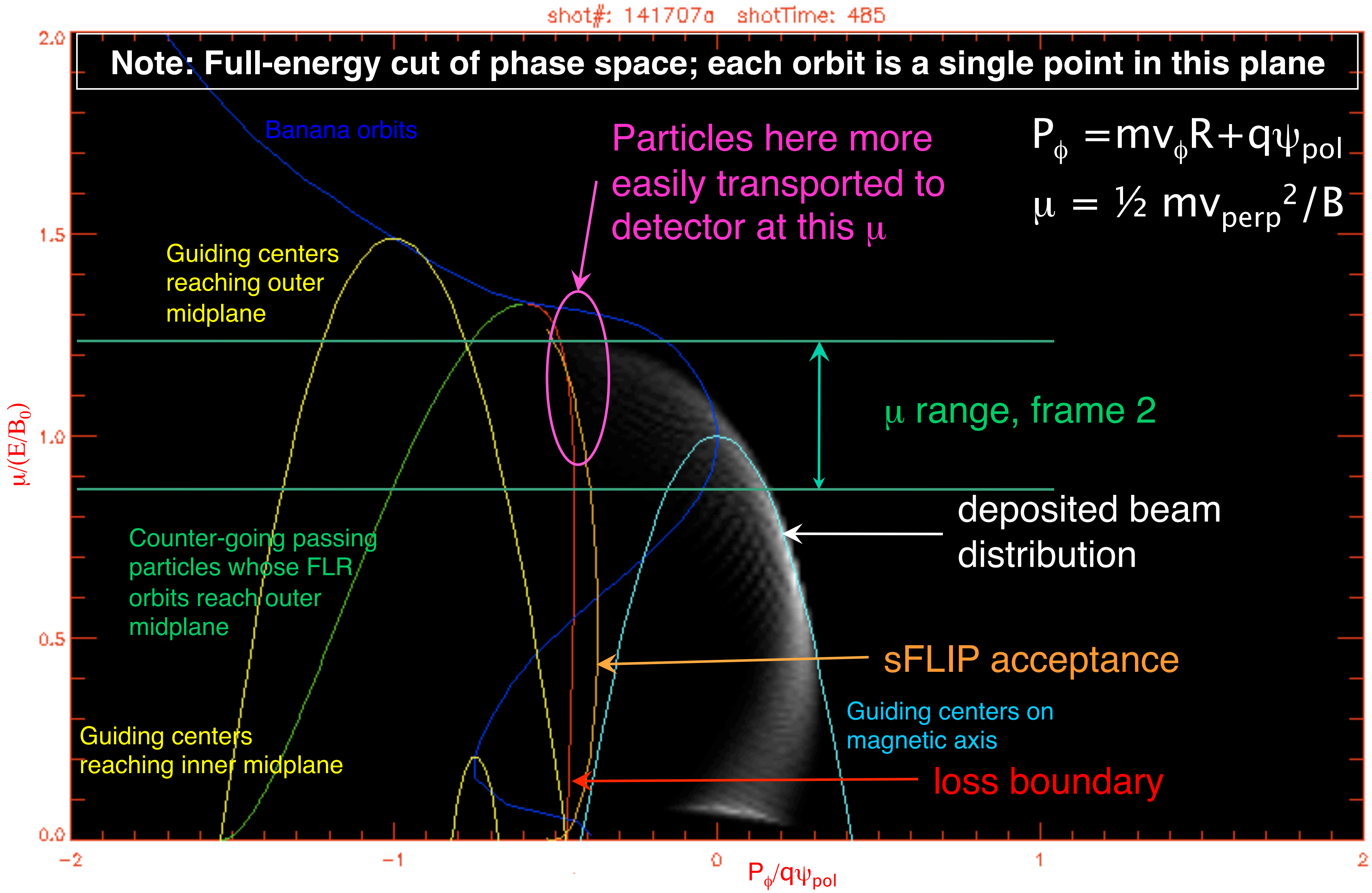
Phase space model of sFLIP diagnostic helps understand features observed during TAE avalanche loss

- Observed TAE frequencies $<<\Omega_{ci}$, so μ will be conserved
- Modes destroy toroidal symmetry, so P_ϕ no longer constant
- From experiments: $E_{loss}=E_{inj}$, so avalanche convects ions at constant μ across loss boundary to detector
- Distance displaced in P_ϕ indicates strength of transport

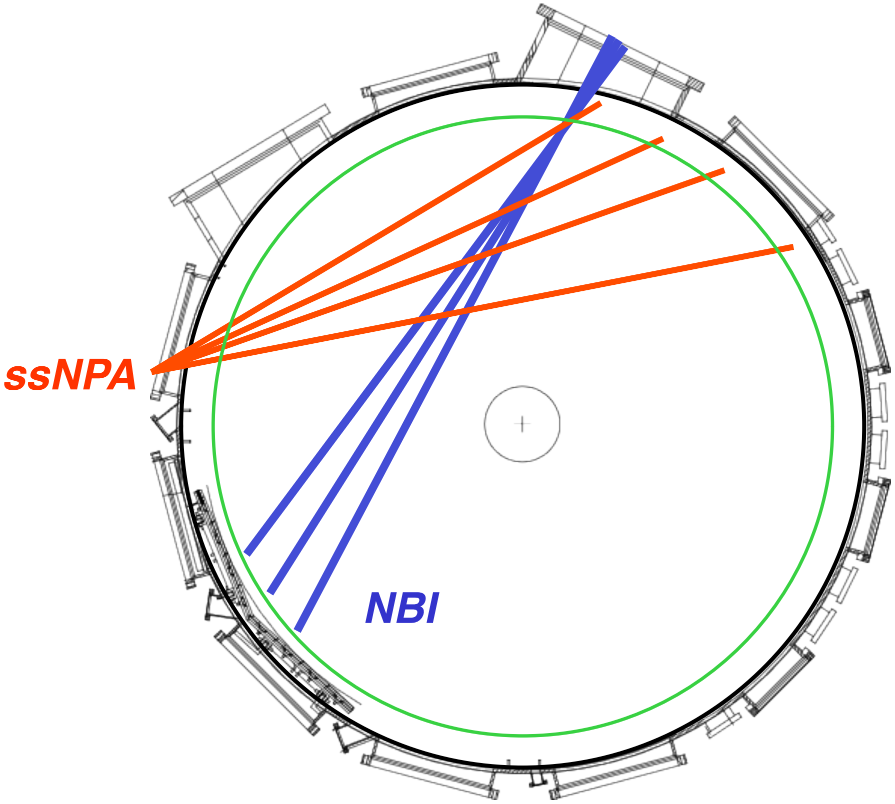




Proximity of beam ions to sFLIP detector at high χ (i.e. high μ) indicates why loss appears there first

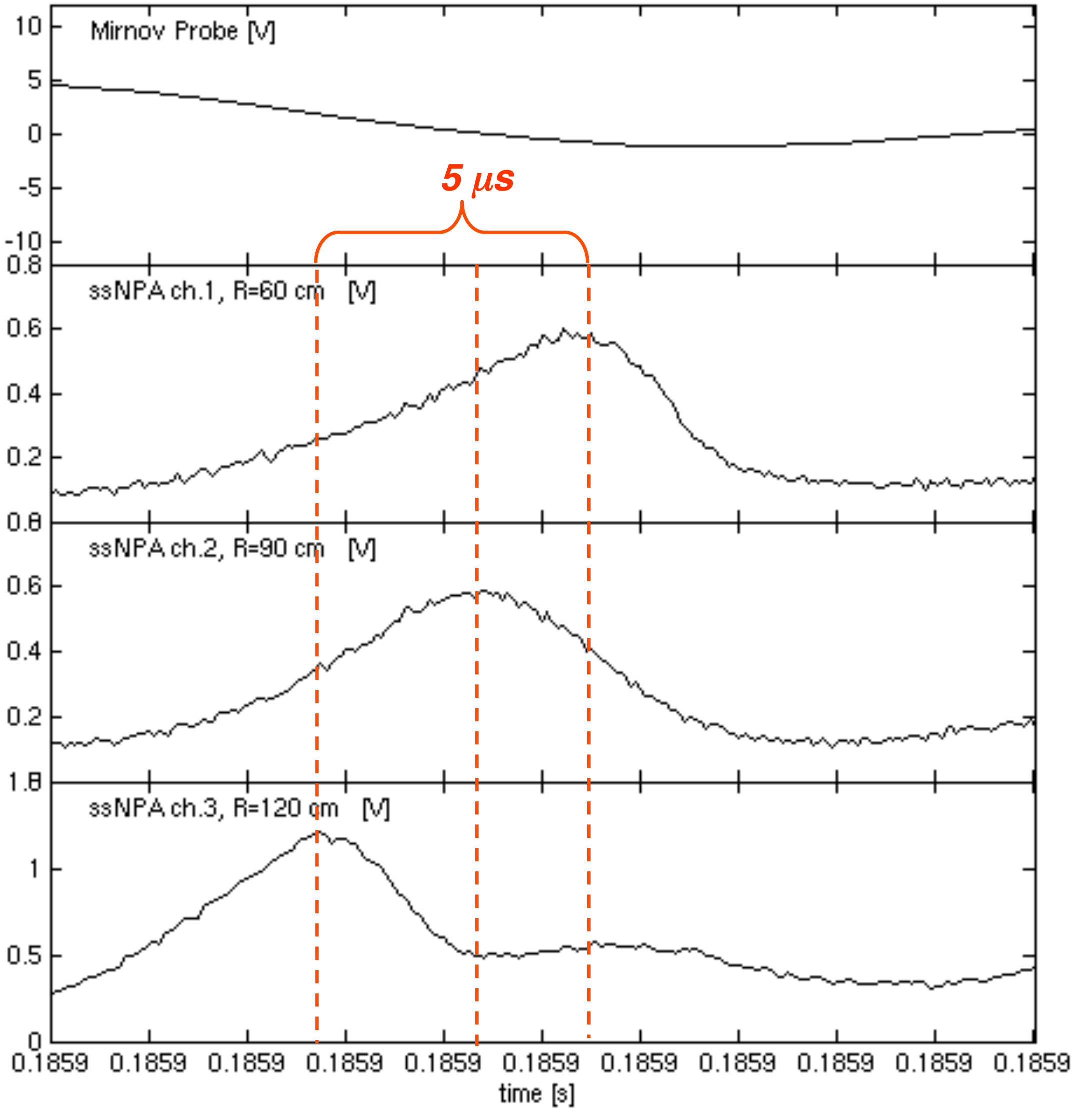


Solid State NPA diagnostic on NSTX operated in “current mode” during FY-10 for high temporal resolution data on mode-induced fast ion losses



- 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



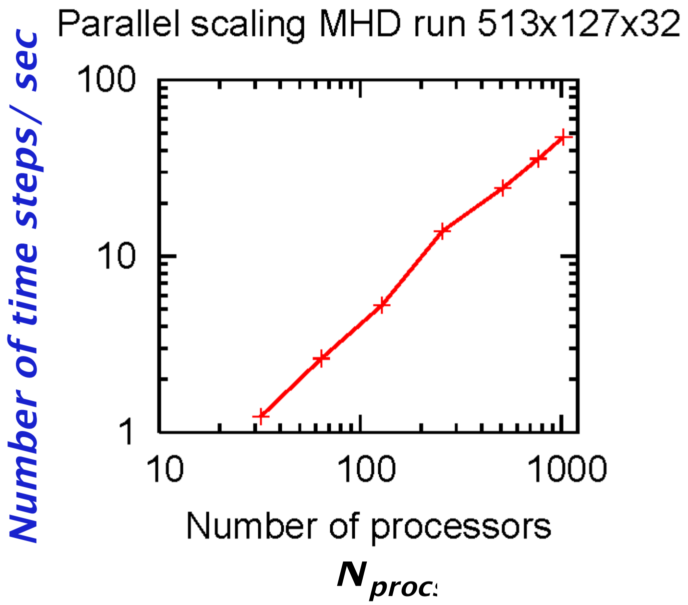
- Fast frequency chirping instabilities (e.g. TAE) accompanied by periodic bursts in ssNPA signals
- Fast ion loss cone, rotating in phase with the mode, is inferred based on time delay between ssNPA channels
- Burst appear at different phases in different channels

HYM – Parallel Hybrid/MHD Code

*E. V. Belova et al., Phys. Plasmas **10**, 3240 (2003)*

HYM code developed at PPPL and used to investigate kinetic effects on MHD modes in toroidal geometry (FRCs and NSTX)

- ***3-D nonlinear.***
- ***Several different physical models:***
    - ***Resistive MHD & Hall-MHD.***
    - ***Hybrid (fluid electrons, particle ions).***
    - ***MHD/particle (one-fluid thermal plasma, + energetic particle ions).***
- ***Full-orbit kinetic ions.***
- ***Drift-kinetic electrons.***
- ***For particles: delta-f / full-f numerical scheme.***
- ***Parallel (3D domain decomposition, MPI)[1].***



MPI version of HYM code shows very good parallel scaling up to 1000 processors for production-size simulation runs, and allows high-resolution nonlinear simulations.

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[1] ***Simulations are performed at NERSC.***

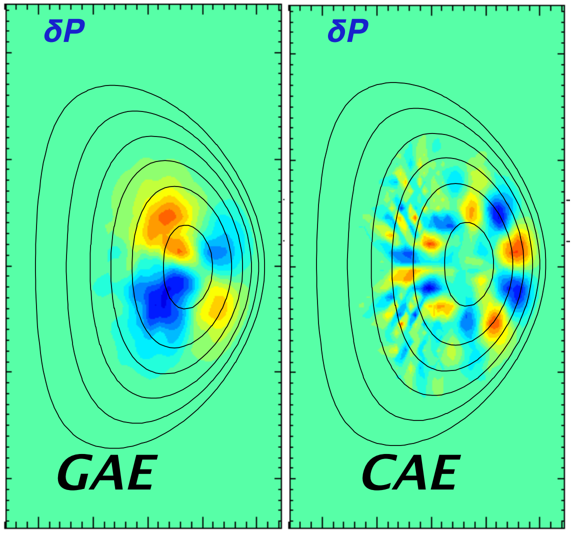
3D simulations of energetic ion-driven instabilities with HYM compare well with NSTX data

Linearized delta-f simulations

- *Low-n simulations show instability of Global Alfven Eigenmode (GAE) with large $k_{||}$ and significant compressional component.*

For n=4-9 : γ= (0.005 -- 0.016)ω_{ci}
and ω= 0.2-0.5 ω_{ci}

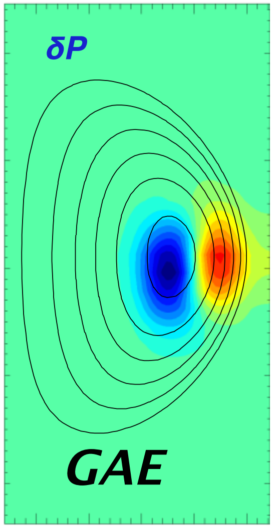
- *Simulation with larger n (n=>8) show weakly unstable CAE mode with ω= 0.4 ω_{ci} and γ~ 0.001 ω_{ci}.*



n=4 (m=-2)   n=8

- *GAE modes are more unstable than CAE (agrees with analytical calculations) with $\gamma/\omega \sim n_b/n_0$.*
- *CAE modes are edge localized, whereas GAE modes are core localized.*
- *GAE mode have small m~1-3; for CAE, m~8-10.*
- *GAE mode propagates counter to beam direction.*

- *Both GAE and CAE modes have large compressional magnetic component near the plasma edge.*



n=6(m=-1)

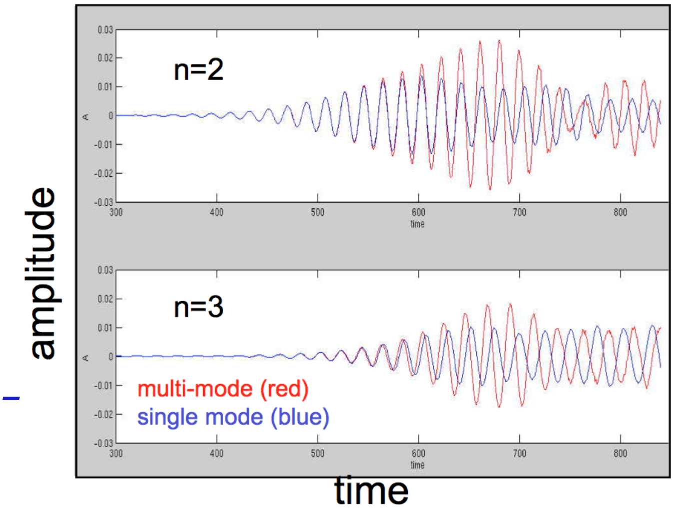
M3D-K – non-linear, self-consistent Hybrid/MHD code

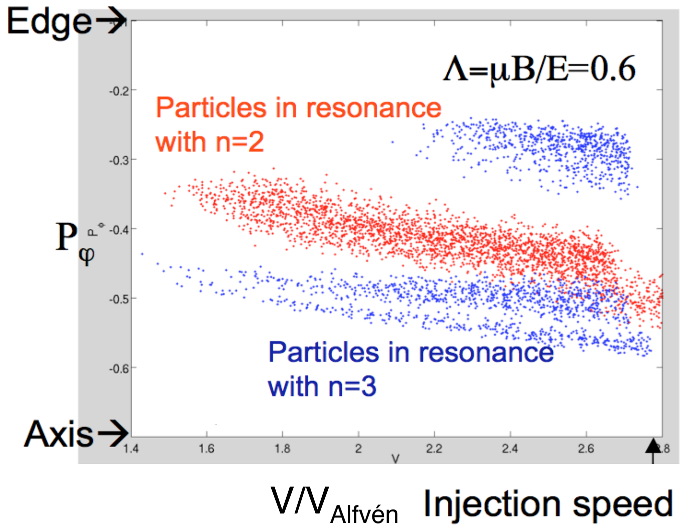
G.-Y. Fu et al., Phys. Plasmas ***13****, 052517 (2006)*

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.***

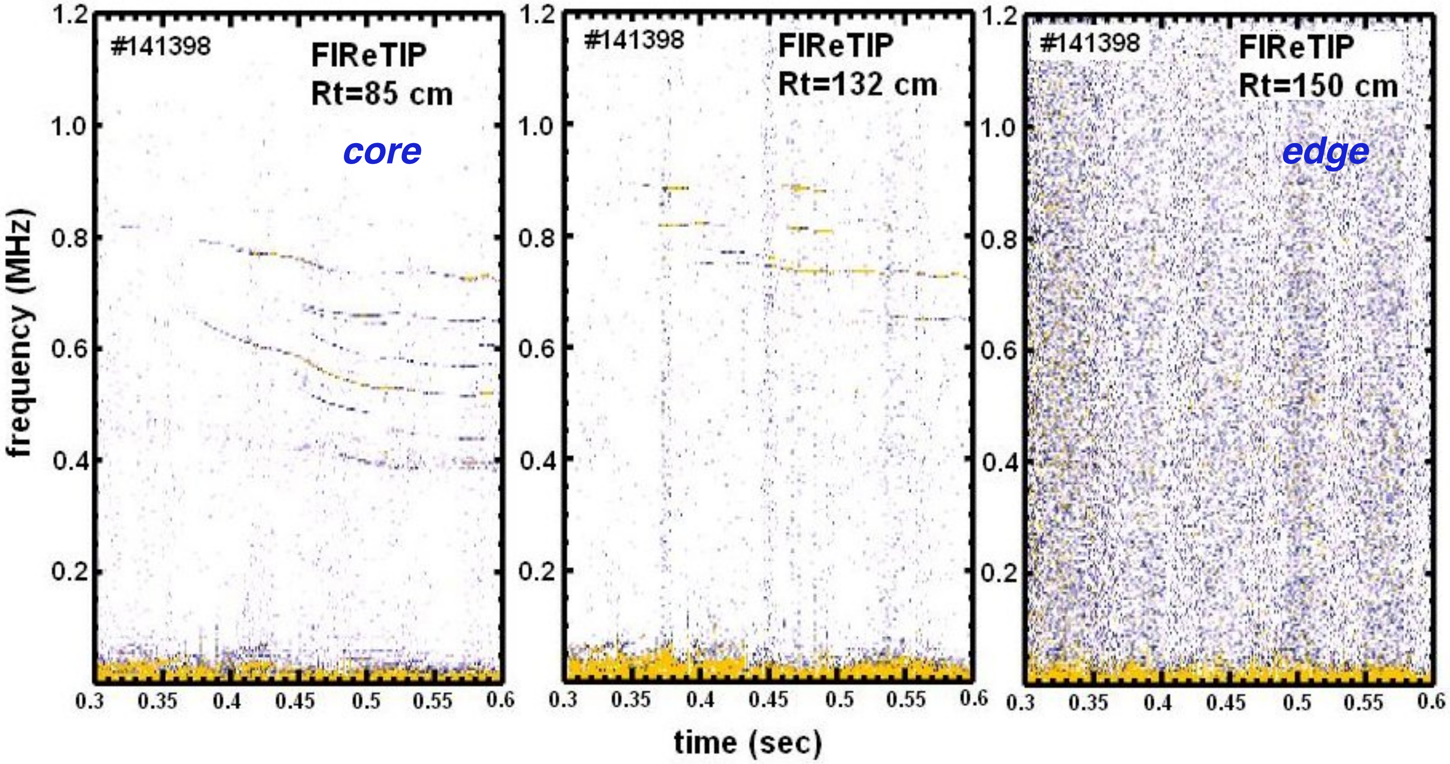
M3D-K simulation of single vs. multi-mode TAE dynamics





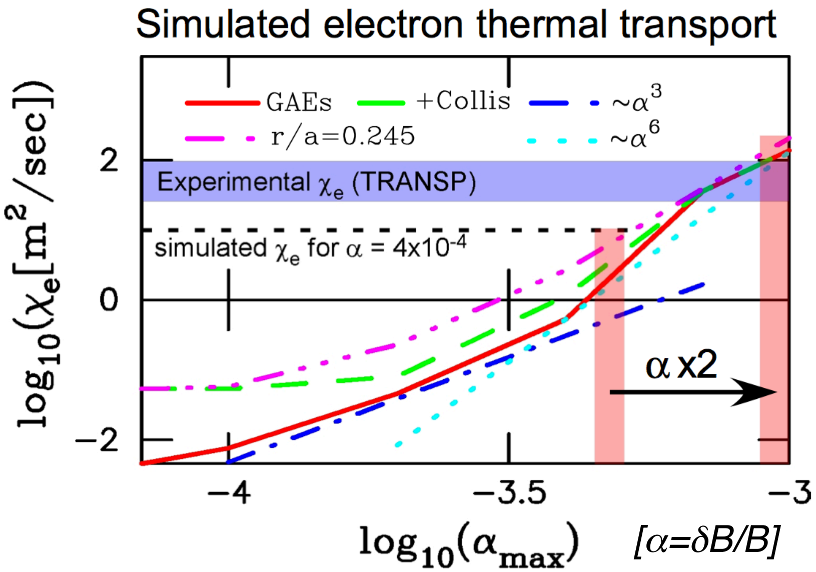
Upgraded Far-Infrared Tangential Interferometer/Polarimeter (FIReTIP) provides line-integrated measurement of Alfvénic modes

- Significant improvements to bandwidth made in FY10
  - Bandwidth extended from 200kHz up to 4MHz
  - Up to five chords available at different tangency radii
  - Example: reduction of GAE amplitude from core to edge confirms core-localized nature of the modes

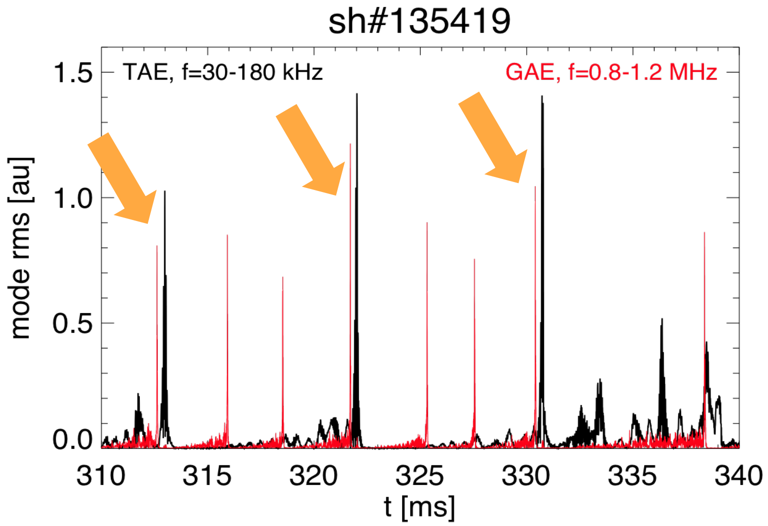


High-frequency *AEs (GAEs/CAEs) can cause enhanced thermal and fast ion transport

- Electron transport modeled with particle following code ORBIT
  - Mode structure from theory
  - Transport by GAEs *consistent* with TRANSP estimates (see T&T presentation)
- Improve GAE modeling in FY-11
  - Mode structure from experiments (BES, reflectometer)
  - Compare with HYM code



- GAE *avalanches* appear to trigger TAE bursts
- First evidence of redistribution of fast ions by GAEs
  - May also explain *anomalies* observed in NPA data
- Synergy between high/low frequency *AEs further explored in FY11-FY12



ITPA tasks 2011, Energetic Particles Physics

Participate in:

- ***EP-2 Fast ion Loss and Redistribution from Localised AEs***
- ***EP-4 Effect of dynamical friction (drag) at resonance on nonlinear AE evolution***

Also considering participation in:

- ***EP-3 Fast ion transport by small scale turbulence***
- ***EP-6 Fast-Ion Losses and Associated Heat Load from Edge Perturbations (ELMs and RMPs)***

IR(12-2): Assess predictive capability of mode-induced fast-ion transport

Good confinement of fast-ions from neutral beam injection and thermonuclear fusion reactions is essential for the successful operation of ST-CTF, ITER, and future reactors. Significant progress has been made in identifying the Alfvénic modes (AEs) driven unstable by fast ions, and in measuring the impact of these modes on the transport of fast ions. However, theories and numerical codes that can quantitatively predict fast ion transport have not yet been validated against a sufficiently broad range of experiments. To assess the capability of existing theories and codes for predicting AE-induced fast ion transport, NSTX experiments will aim at improved measurements of the mode eigenfunction structure utilizing a new Beam Emission Spectroscopy (BES) diagnostic and enhanced spatial resolution of the Multi-Channel Reflectometer. Improved measurements of the fast-ion distribution function will be available utilizing a tangentially viewing Fast-Ion D-alpha (FIDA) diagnostic. In order to broaden the range of discharge conditions studied to those relevant to future devices, experiments will be conducted for both L-mode and H-mode scenarios. Specific targets for the experiment-theory comparison are those between the measured and calculated frequency spectra, spatial structure and induced fast ion transport. Both linear (e.g., NOVA-K, ORBIT) and non-linear (e.g., M3D-K, HYM) codes will be used in the analysis. In addition, the newly developed full-orbit particle-following code SPIRAL will be adapted to the NSTX geometry and used to model fast ion losses by Alfvénic modes.

Energetic Particles experiments will benefit from upgraded diagnostics, additional tools in 2011-2012

- **Planned diagnostic upgrades:**

  - Upgraded reflectometer, 24-channel BES
  - Full 32-channel BES system
  - "Tangential" FIDA system, more sensitive to co-going fast ions
  - Prototype 3-channel 'Fusion source profile' diagnostic (8 channels, FY12)
  - Upgraded Mirnov coils' array
    - Increase number of coils, improve bandwidth
    - Better estimate of (large, >6) mode numbers, high frequency modes
  - MSE-LIF for q-profile, mod(B) measurements w/o constraints on NB source A
- **Additional tools, FY11-12:**
  - Apply HHFW heating to affect fast ion phase space
  - Non-resonant braking (n=2 *vs.* n=3 w/ 2nd SPA unit), real-time rotation (under development)
    - Assess rotation/rotation shear impact on mode stability, structure
  - Numerical codes for *AE simulations:

***HYM**: non-linear, delta-f hybrid MHD/particle*

***M3D-K**: non-linear, self-consistent hybrid MHD/particle with sources and sinks*

***NOVA-K**: linear, perturbative kinetic MHD*

***SPIRAL**: full-orbit particle-following code*

Energetic Particles research plans for 2011-2012 and beyond

2011:

- Continue study of TAEs, high-f *AEs (including avalanches) in H-mode plasmas
  - Fully exploit BES system, upgraded reflectometer (monotonic profiles), FIReTIP
- Revisit *AE effects on NB-driven current profile (ASC-TSG)
  - Exploit new *tangential* FIDA, MSE-LIF
- Benchmark HYM, M3D-K and SPIRAL codes; model GAE/CAE and TAE dynamics

2012:

- Support Milestone R12-2*: "... heating, ramp-up of CHI start-up plasmas" (SFSU-TSG)*
  - NBI and *AE modeling for start-up plasma research
- Address (incremental) Milestone IR12-2: "*Assess predictive capability of mode-induced fast ion transport*"
  - Use improved validation to perform simulations of NSTX Upgrade plasmas: expected unstable *AEs, associated losses and effects on NBI-CD
- Investigate (linear) stability threshold calculations with NOVA-K; compare with experiments, M3D-K
- Implement constraints of fast ion pressure in TRANSP based on FIDA, neutrons

2013+:

- Complete data analysis, publish results
- Collaborate with other facilities on Energetic Particles Physics research
- Prepare for post-upgrade operations
  - NPA/ssNPA specification; upgrade data acquisition for higher field, longer pulse

Papers on Alfvén Eigenmodes in NSTX

EPMs: "*Bounce precession fishbones in the National Spherical Torus Experiment", E. D.* Fredrickson *et al.*, Nucl. Fusion **43** (2003) 1258.

BAAEs: "*Beta-induced Alfvén-acoustic eigenmodes in National Spherical Torus Experiment and DIII-D driven by beam ions",* N. N. Gorelenkov *et al.*, Phys. of Plasmas **16**, 056107 (2009).

rSAEs: *"Alfvén cascade modes at high β in the National Spherical Torus Experiment"*, N. A. Crocker *et al.,* Phys. Plasmas **15**, 102502 (2008)

TAEs: *"Modeling fast-ion transport during toroidal Alfvén eigenmode avalanches in National Spherical Torus Experiment"*, E. D. Fredrickson *et al.*, Phys. Plasmas **16**, 122505 (2009)

GAEs/CAEs: "*Theory and Observations of High Frequency Alfvén Eigenmodes in Low Aspect Ratio Plasmas",* N. N. Gorelenkov *et al.*, Nucl. Fusion, **43** (2003) 228.

"Angelfish" modes: *Weak effect of ion cyclotron acceleration on rapidly chirping beam-driven instabilities in the National Spherical Torus Experiment",* W. W. Heidbrink et al., Plasma Phys. Cont. Fusion **48** (2006) 1347