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Energetic Particle Physics Progress and Plans

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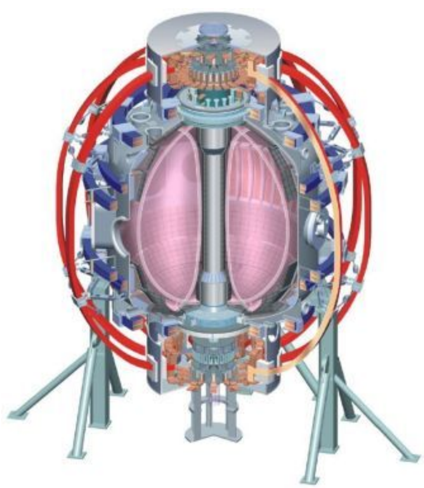
Mario Podestà, PPPL

for the NSTX Research Team

27th NSTX PAC Meeting
Conference Room LSB-B318, PPPL
Feb. 3-5, 2010



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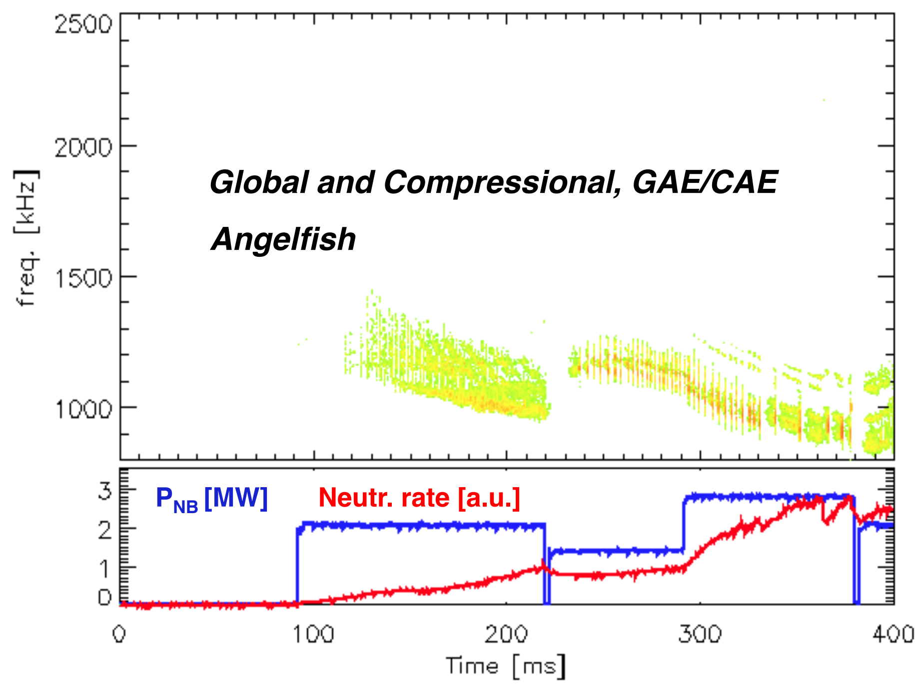
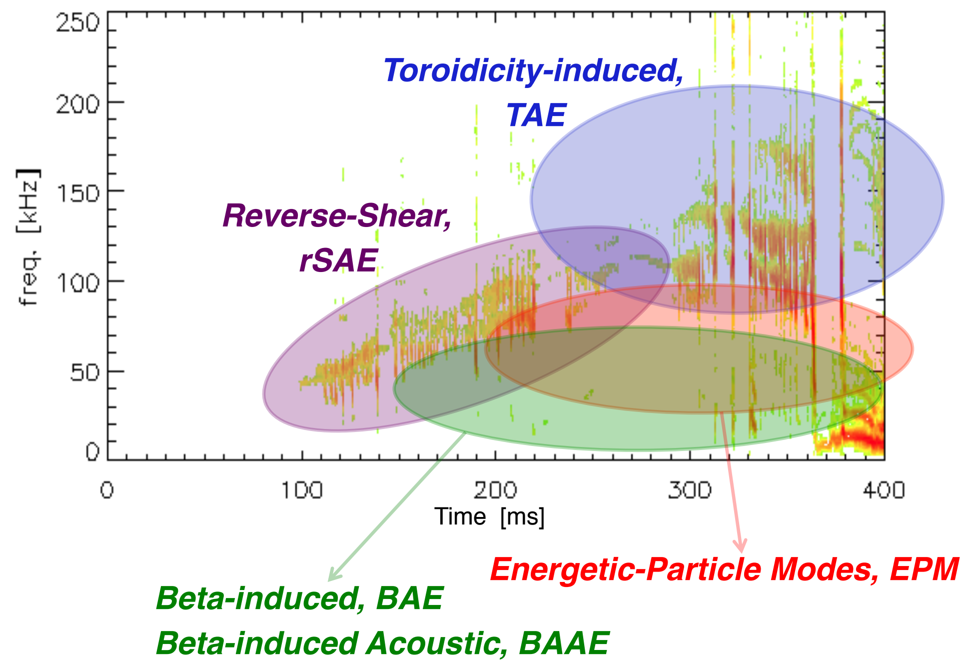
NSTX operates in a unique regime for Energetic Particle physics

ITPA EP-2

- NSTX operation routinely involves Neutral Beam (NB) injection
  - Source of super-Alfvénic ions: injection energy 60-100keV, $1<V_{fast}/V_{Alfvén}<5$
  - Strong drive for fast-ion-driven Alfvén eigenmodes (*AEs) over wide range of frequencies





Center-stack and NB system upgrade will further expand the range of achievable parameters toward ITER and future STs conditions

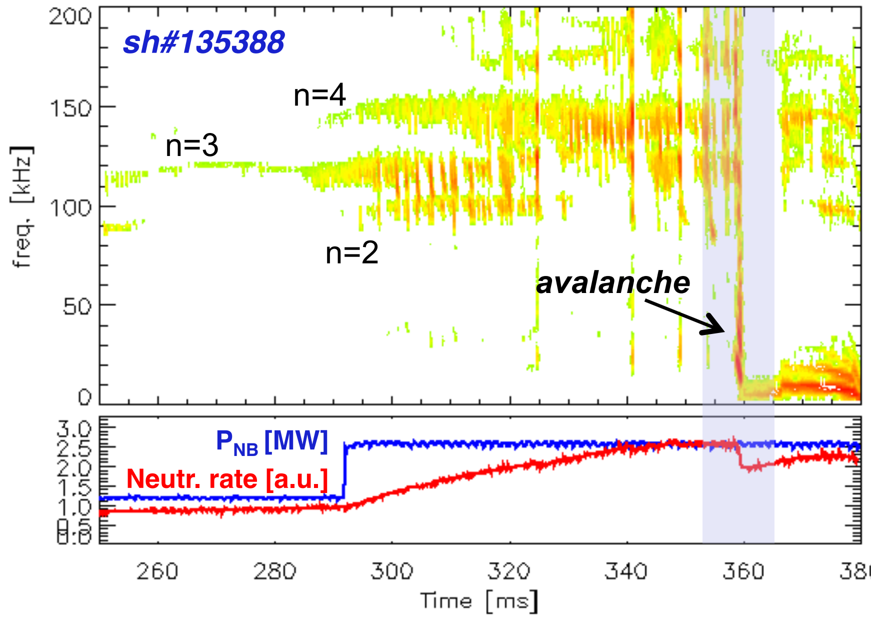
Outline

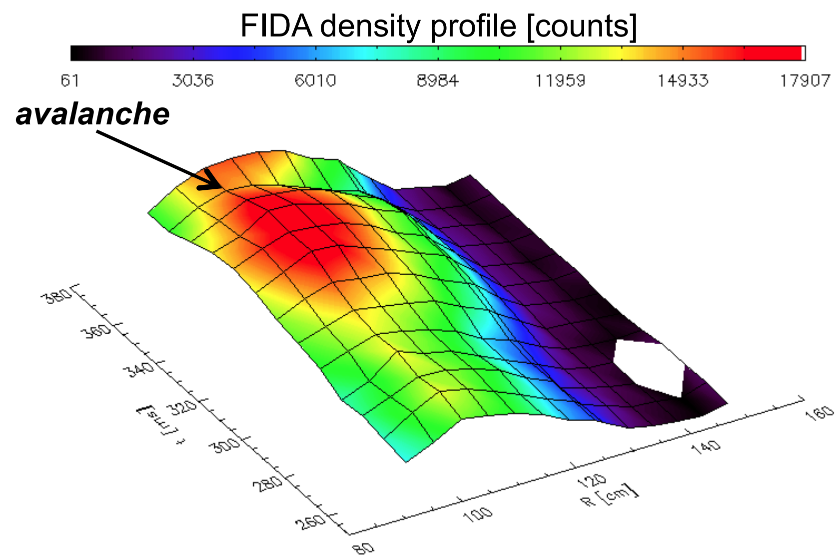
- Physics of multi-mode TAE/EPM *avalanches* and induced fast ion losses
- Study of other *AEs below/above TAE gap frequency
- Validation of linear and non-linear theory/codes
- Support cross-cutting research on other topics

Non-linear evolution of multiple TAE modes into *avalanches* causes large fast ion losses

ITPA EP-2

- Multiple TAEs are simultaneously destabilized by NB injection
  - No (detectable) losses caused by weakly chirping modes, but…
  - Eventually, modes undergo strong frequency sweep with increasing amplitude: ***avalanche***
    - Neutron rate drops up to 30-35%
    - Expected loss mechanism in ITER
- TAE studies will be extended to H-mode plasmas in 2010-2011
  - Mode structure from BES, interferometer
  - Use BES/high-K to search for kinetic effects, e.g. continuum damping through kinetic Alfvén waves (KAWs)

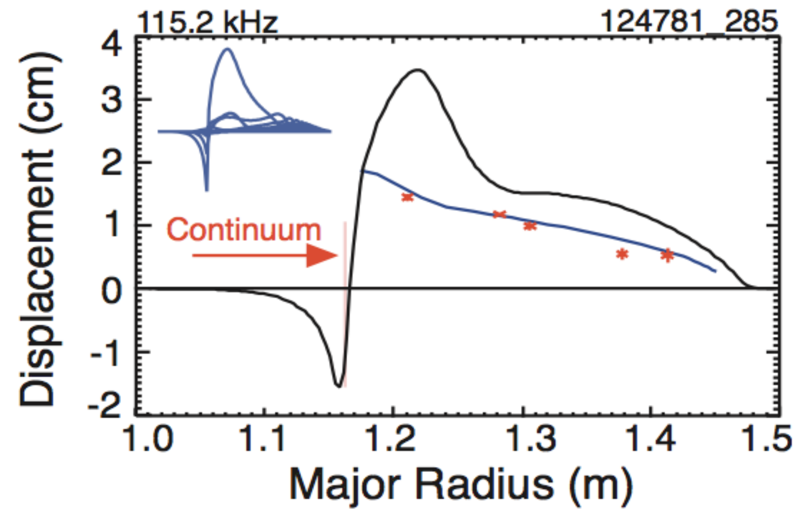


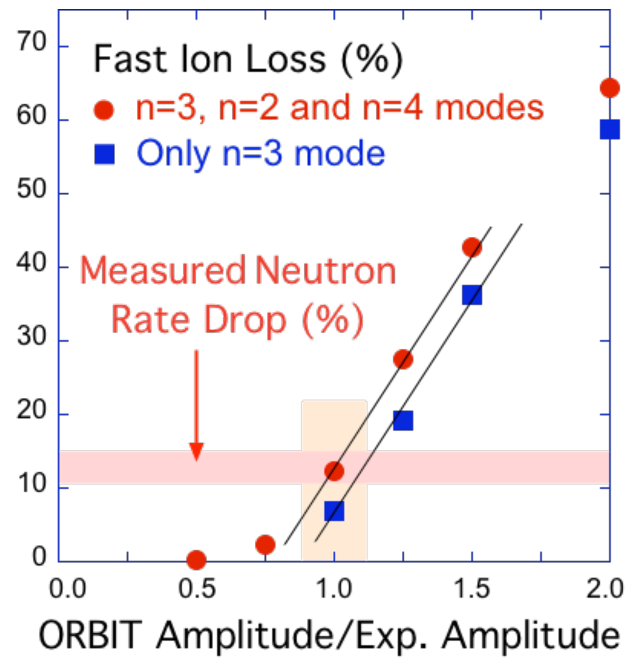


Modeling TAE avalanches with linear codes (NOVA-K, ORBIT) can reproduce measured level of fast ion losses

- Procedure:
  - Calculate linear eigenmodes with NOVA-K
  - Match and select “observed” modes based on measured mode structure (reflectometer)
  - Rescale amplitude according to measured displacement
    - 2x mode amplitude is needed when compressibility is included (2009)
  - Calculate fast ion loss with ORBIT
    - Including potential fluctuations enhances losses (2009)
- Simulated losses agree with experiment
  - Comparable mode amplitude
    - All dominant modes must be retained
    - No simple (linear) dependence of losses upon mode amplitude
- Main limitations:
  - *Linear*; *not self-consistent*; mode amplitude/ frequency in ORBIT adjusted to mimic data

PAC25-24



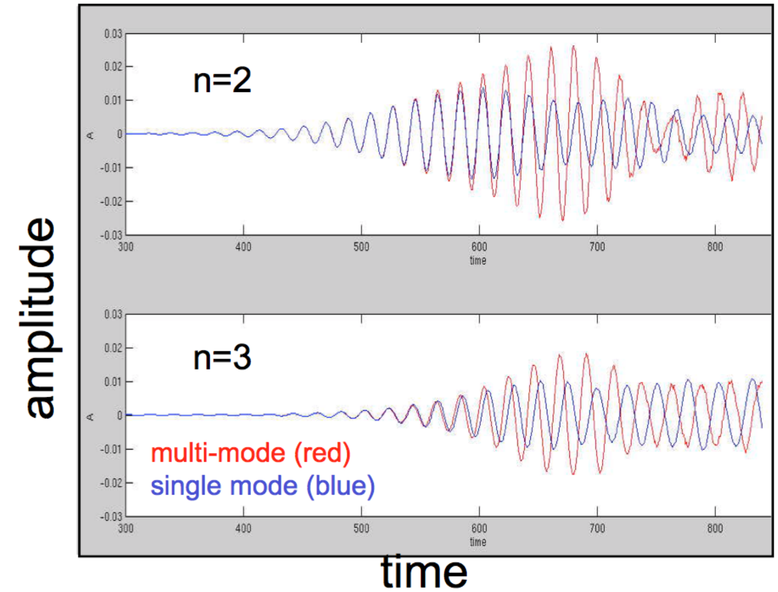


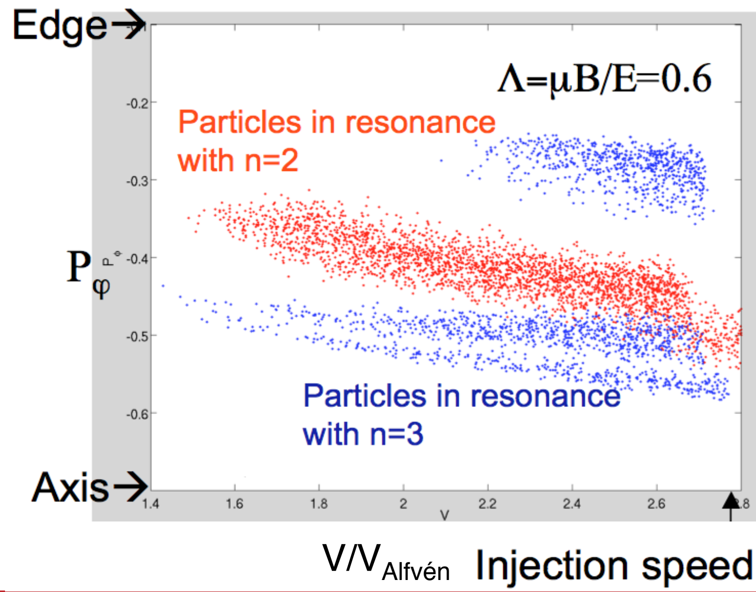
Phys. Plasmas **16**, 122505 (2009)

Benchmarking non-linear, self-consistent code M3D-K is planned to improve predictive capability

- Past results highlight importance of multi-mode dynamics
  - Enhanced saturation level is larger in multi-mode simulation
  - Broad, overlapping resonance regions in phase space

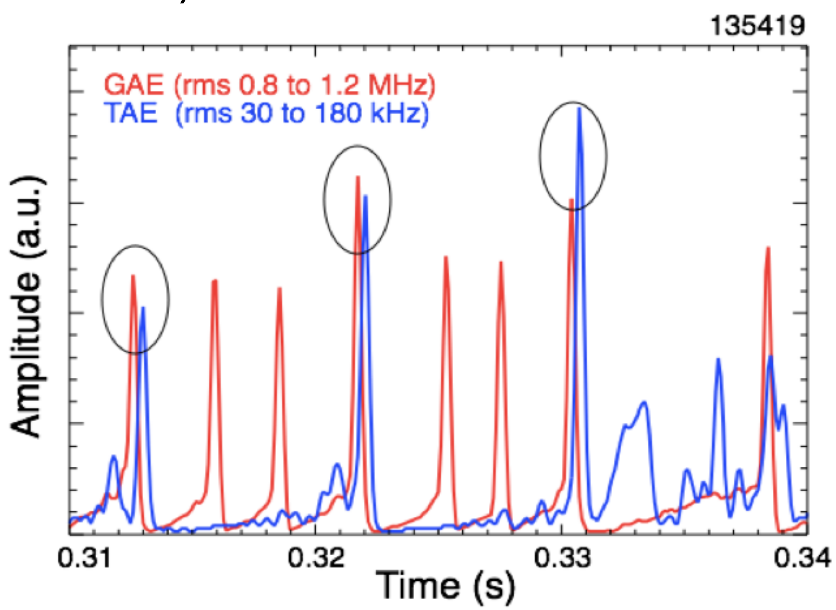
- 2010-2011: dedicated experiments planned for validating the M3D-K code
  - Optimize measurements of mode structure (BES, reflectometer)
  - Initial focus on L-mode plasmas with weakly turbulent TAE activity
  - Use stability predictions (growth, damping rates) from linear analysis
    - Self-consistent stability calculation would require additional code development
  - Compare predicted mode structure and multi-mode (non-linear) dynamics of TAEs with experiment

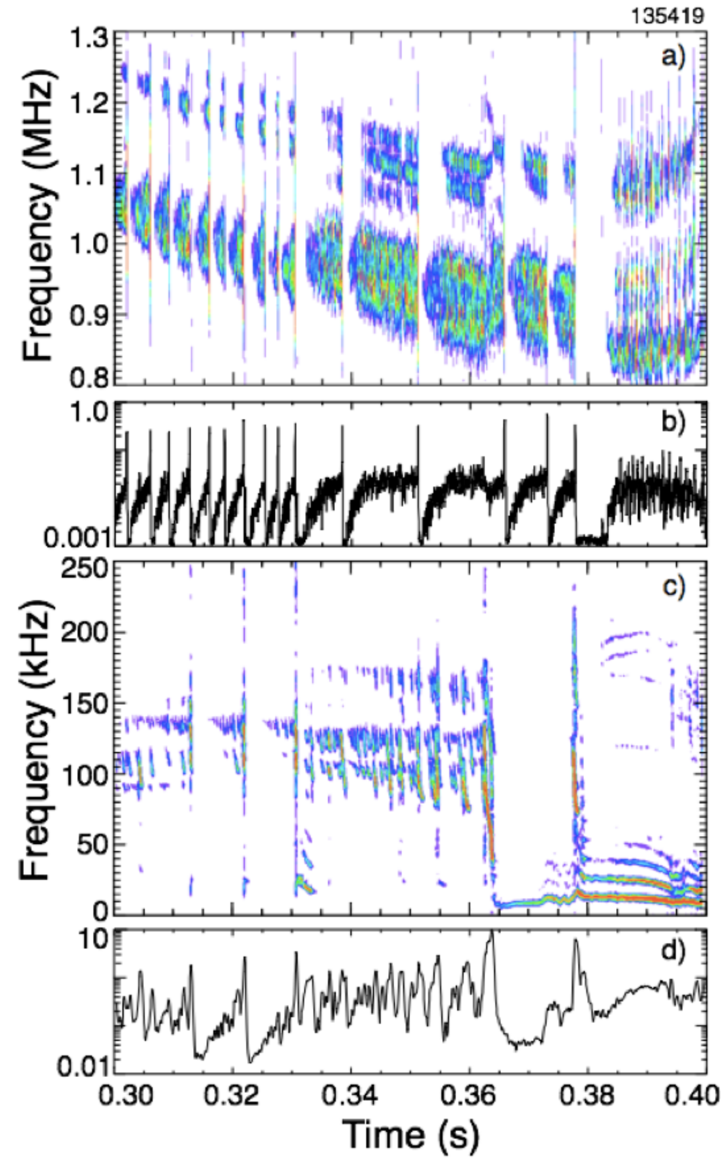




GAEs/CAEs show avalanching behavior that correlates with TAE avalanches at lower frequency

- Bursts can trigger TAE/EPM avalanches
- Implies significant fast ion redistribution
  - Effects on fast ion confinement might be masked by dominant TAEs/EPMs
- Extend study to H-mode in 2010-2011
- Codes (HYM, M3D-K) may reveal underlying non-linear physics of mode-mode coupling (2011-2012)





Energetic Particles research plans for 2010

- Study physics of Alfvénic modes and their effect on fast ion transport
  - H-mode TAE avalanches [0.5] EP-2
  - *Angelfish* instability and effects of HHFW on chirping modes [0.5] EP-2
  - GAE induced electron transport [0.5 *(0.5)*] EP-2, TC-12
  - EPM effects on fast ion transport and NB-driven current profile *(0.5)* EP-2
    - Complement analysis with modeling to separate inductive/NB-driven currents
  - Conversion of *AEs to Kinetic Alfvén waves *(0.5)* EP-1

- Validate linear & non-linear codes and theory to simulate *AEs
  - ➢ Close collaboration with PPPL theory group
  - Validation of M3D-K code [0.5] EP-2
  - Develop and validate model for fast ion distribution function

[ ] priority 1 run days *( ) priority 2 run days* ITPA

Energetic Particles research plans for 2011-2012

- **2011:**
  - Continue study of H-mode TAE avalanches
    - Whole BES system allows to measure mode structure and search for kinetic effects
  - Revisit EPM effects on NB-driven current profile
    - New tangential FIDA directly looks at co-going fast ions
    - MSE-LIF adds information on q-profile evolution and mod(B)
  - Extend modeling with M3D-K to avalanches
  - Investigate stability threshold calculations with NOVA-K; compare with experiments

- **2012:**
  - NSTX Milestone (incremental): "*Assess predictive capability of mode-induced fast ion transport*"
  - Study effects of rotation and rotation shear on *AEs stability

Energetic Particle research plan is well supported by diagnostics/hardware upgrades in 2010-2012

- **Planned diagnostic upgrades**
  - Improve mode structure measurements: BES, reflectometers, interferometer
  - Higher temporal resolution of Fast Ion Loss Probe (sFLIP)

  } **2010**

  - Complete BES installation, full 32-channel system
  - "Tangential" FIDA system, more sensitive to co-going fast ions
  - Collimated neutron detector
  - MSE-LIF for q-profile measurements w/o constraints on NB source A

  } **2011/ 2012**

- **Additional tools:**
  - Lithium/LLD for better density control
  - Upgraded HHFW antenna to affect fast ion phase space

  } **2010**

  - Non-resonant n=3 braking and real-time plasma rotation control
    - Controlled experiments on rotation/rotation shear impact on mode stability and structure

  } **2011/ 2012**

Summary of Energetic Particle research plan 2010-2012

- 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

- Validation of linear and non-linear theory/codes is highest priority

- Will support other high-priority research activities related to fast ions

Backup viewgraphs

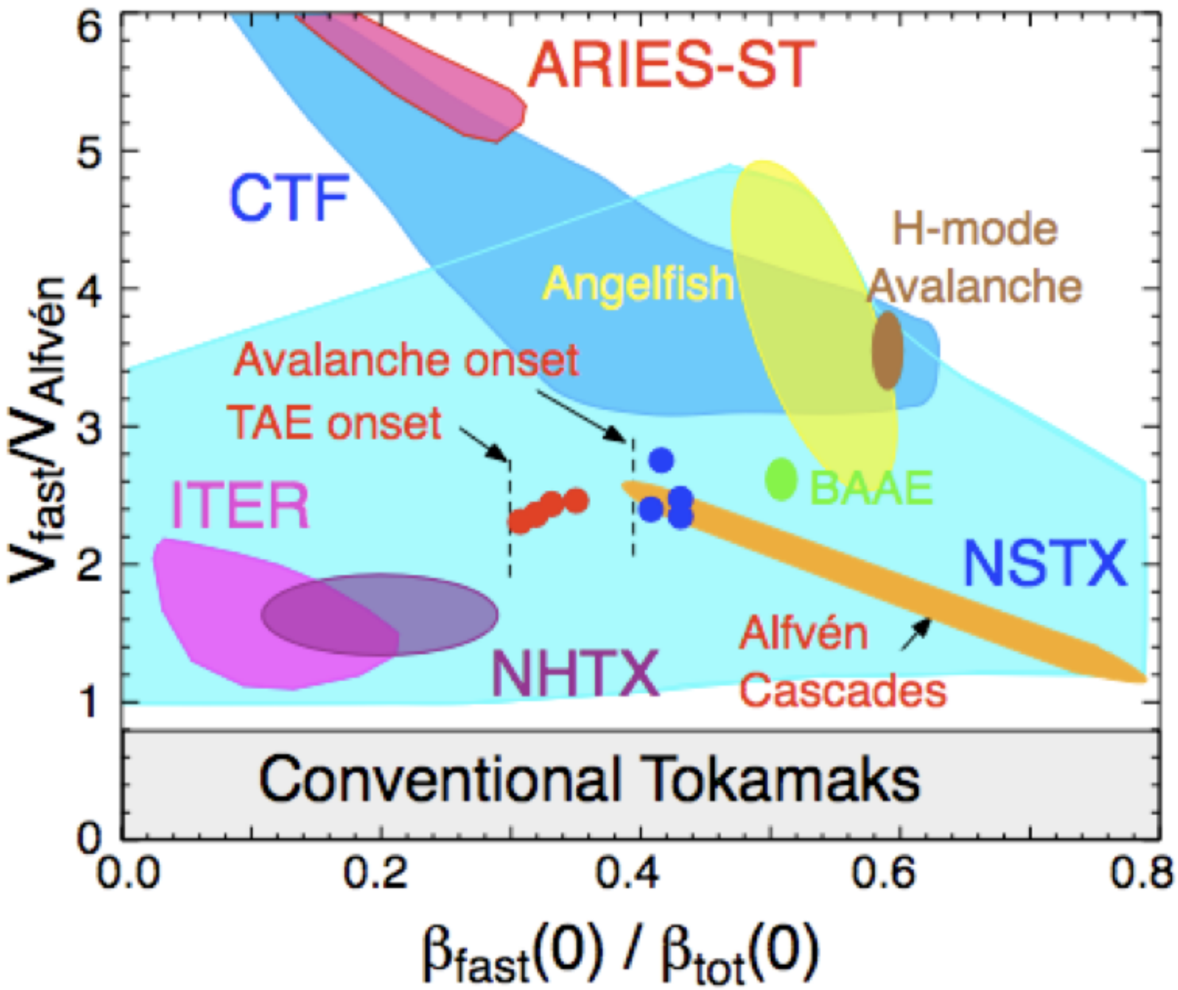
NSTX milestones, ITPA tasks, PAC-25 recommendations and ReNeW themes

- 2012 NSTX milestone (incremental): *"Assess predictive capability of mode-induced fast ion transport"*
- ITPA EP-2: *"Fast ion losses and redistribution from localized Alfvén Eigenmodes"*
- PAC 25-24 : *"… emphasis on resolving the discrepancy between measured and simulated mode amplitudes to reproduce fast ion losses"*
- ReNew thrust #3: *"**Understand the role of alpha particles in burning plasmas.** Key actions would be developing diagnostics to measure alpha particle properties and alpha-induced fluctuations, incorporating validated theories for alpha particle behavior into integrated burning-plasma simulation tools, and expanding the operating regime of burning plasma devices through the development of control techniques for alpha-driven instabilities."*
- ReNeW thrust #6: *"**Develop predictive models for fusion plasmas, supported by theory and challenged with experimental measurement.** advances in plasma theory and simulation would be combined with innovative diagnostic methods and experiments to improve and validate models of confined plasma dynamics. assessment of critical model elements would be provided by dedicated analysts, acting as bridges between theorists, code developers and experimentalists."*

WPI FY2012 NSTX Research Milestone (incremental)

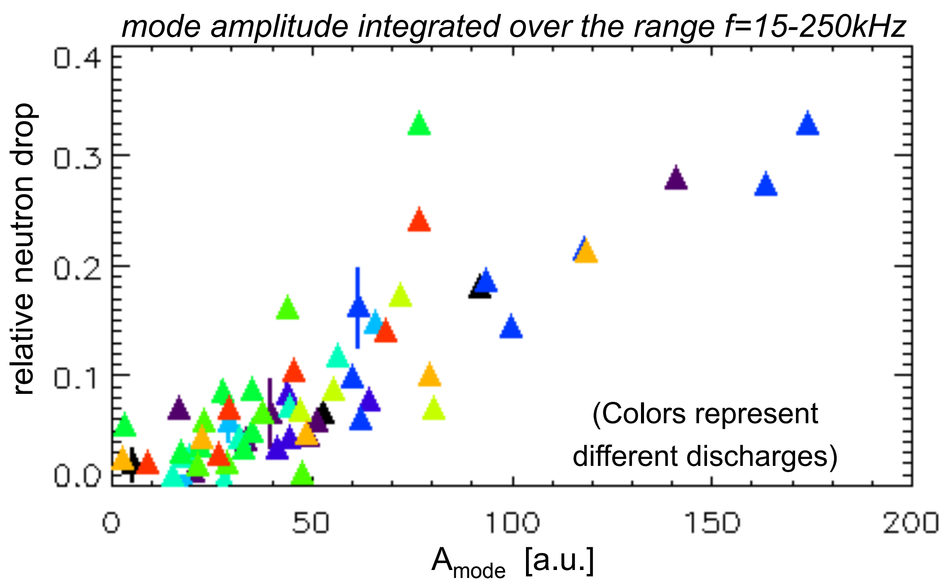
- **IR(12-1) Assess predictive capability of mode-induced fast-ion transport.**
  Good confinement of fast-ions from neutral beam injection and thermonuclear fusion reactions is essential for the successful operation of ST-CTF, ITER, and future reactors. Significant progress has been made in identifying 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 Far-Infrared Reflectometer. NSTX will also make new measurements of the internal magnetic field structure of AEs using far-infrared polarimetry (if available) and improved measurements of the fast-ion distribution function 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 and spatial structure. Both linear (e.g., NOVA-K, ORBIT) and non-linear (e.g., M3D-K, HYM) codes will be used in the analysis.

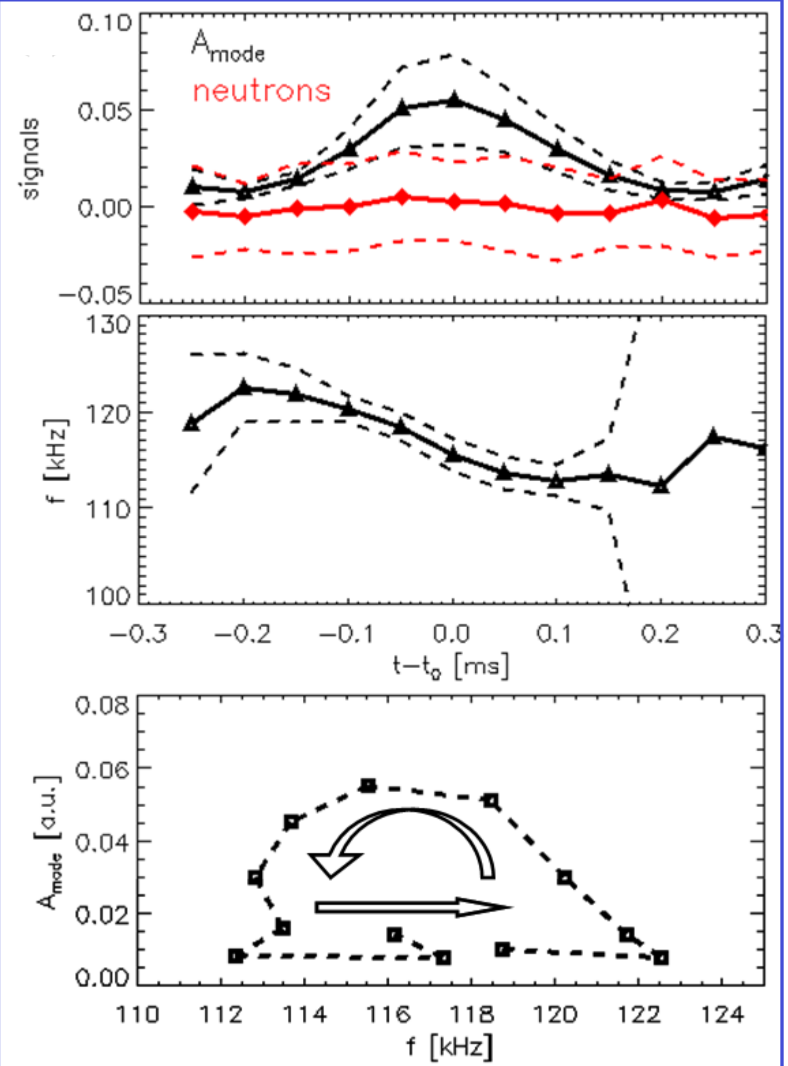
NSTX plasmas encompass a broad range of achievable regimes for Energetic Particle research



Mode-induced losses greatly deteriorate fast ion confinement for sufficiently large mode amplitude

- No (detectable) losses caused by weakly chirping modes
  - Need more modeling effort to investigate “steady”, weak losses
- Large losses associated with avalanches
  - Clear dependence upon mode amplitude

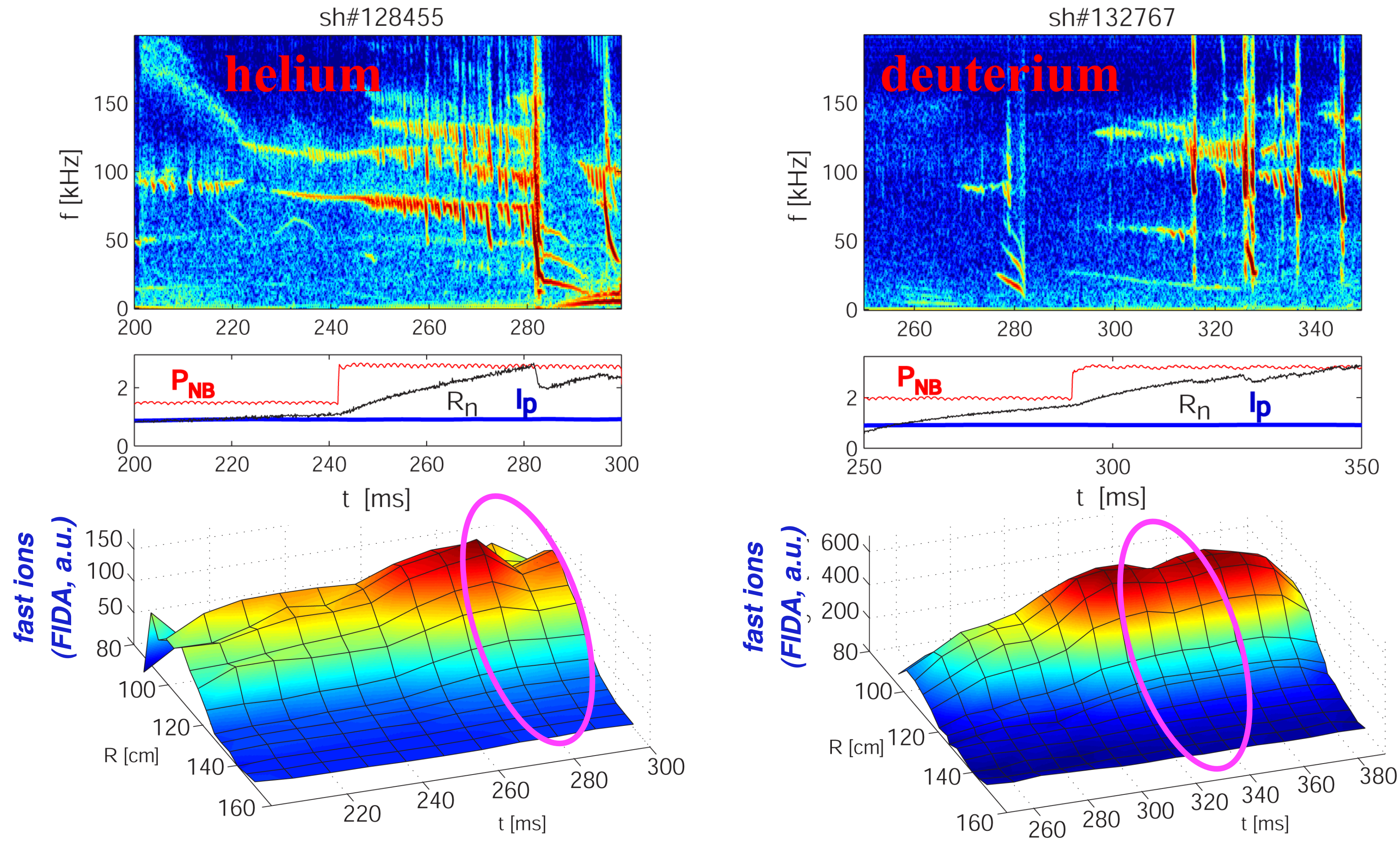




Statistically-averaged (~10ms) mode behavior and neutron response to weakly chirping TAE activity

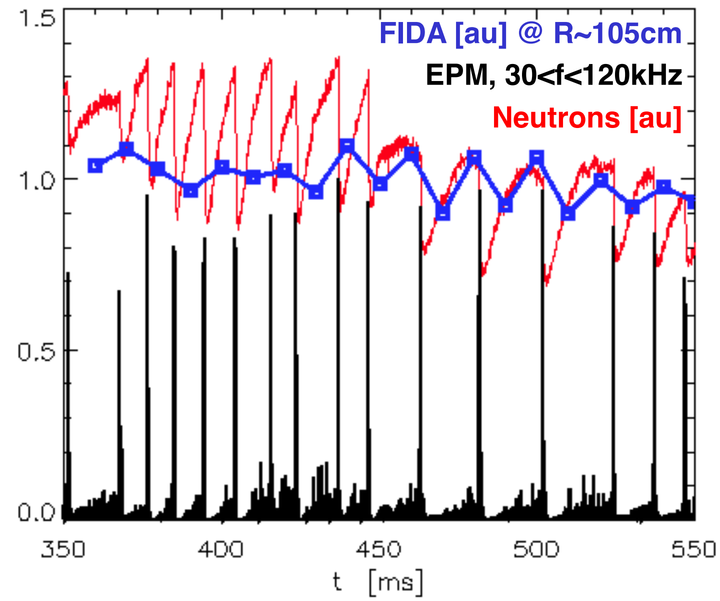
Similar TAE and TAE avalanches' behavior observed in Helium and Deuterium plasmas

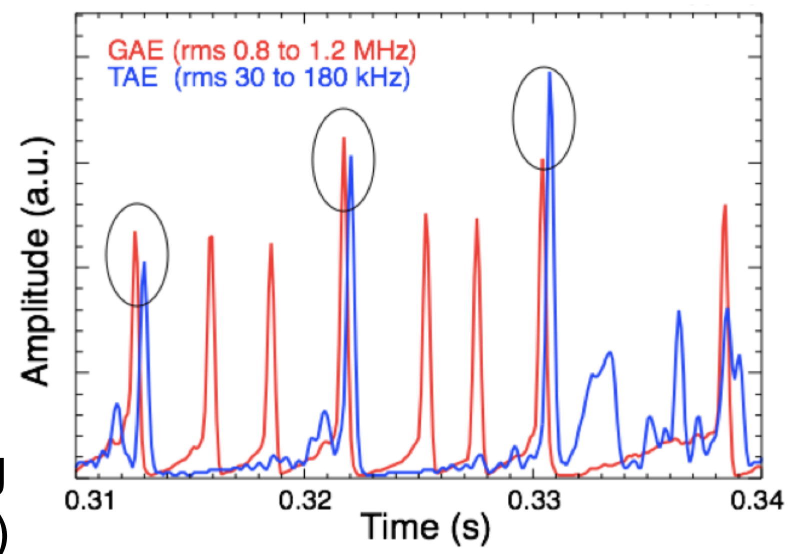
- Low-*n*, quasi-stationary TAEs evolve into bursty behavior & *avalanches*
- Fast ion losses ≤30% observed (e.g. FIDA, neutrons) during avalanches
- Similar $n_{e,i}$, $T_{e,i}$, I_p, B_{tor}, P_{NB} (but different plasma shape: LSN *vs* limiter)



Energetic-Particle modes (EPMs) and GAEs/CAEs show avalanching behavior, too

- Chirping **EPMs** cause fast ion losses
  - Drops up to 30% in < 1 ms observed in neutrons, FIDA, sFLIP
- Variations in current profile from MSE comparable with those from other modes
  - Analysis (TRANSP) will continue in 2010
    - Separate effects on Ohmic/NB-driven currents
  - "Tangential" FIDA (2011) will measure co-going fast ions – more relevant for current drive.
- **GAE** bursts can trigger TAE/EPM avalanches
  - Implies significant fast ion redistribution
  - Effects on fast ion confinement might be masked by dominant TAEs/EPMs
- Extend study to H-mode in 2010
- Codes (HYM, M3D-K) may reveal underlying physics of mode-mode coupling (2011-2012)

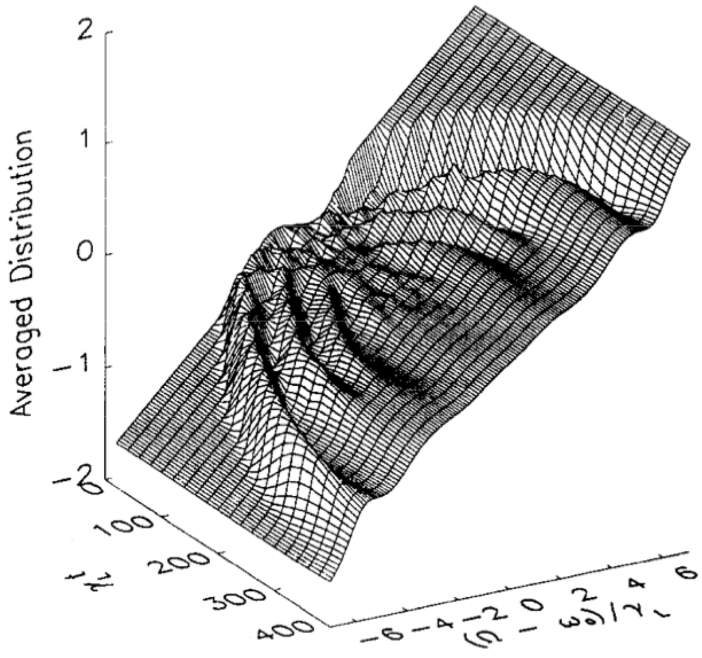




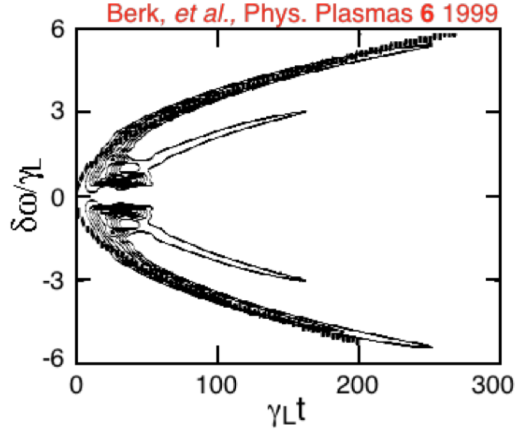
Physics of chirping modes will be also investigated for other classes of *AEs: *Angelfish*

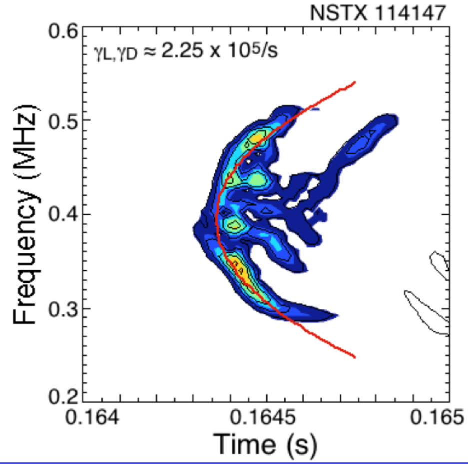
- Berk & Breizman "hole-clump" model predicts up/down frequency chirps
  - Chirp results from mode overlap in phase space and modification of fast ion distribution
  - Competition of drive, damping and off-resonance particle scattering rate can set up a cyclic behavior
- Observed features of GAE/CAE *Angelfish* are consistent with the B&B model

Phys. Lett. A **234**, 213 (1997)



Berk, *et al.*, Phys. Plasmas **6** 1999





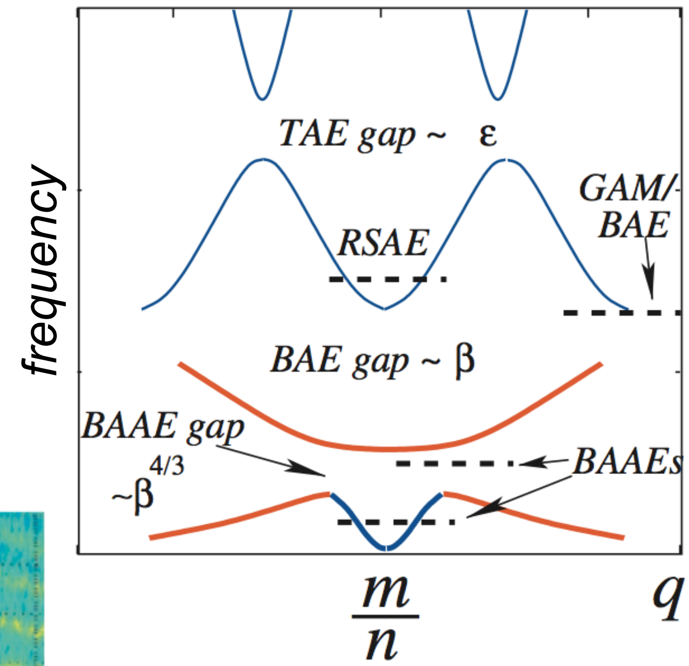
  - First experiments on GAE/CAE *Angelfish* showed weak suppression of chirps by HHFW – but limited dataset & diagnostic coverage
  - Will revisit in 2010, with enhanced diagnostic capability
    - Use HHFW to affect phase space diffusivity
  - CAEs or GAEs? Use BES to measure details of mode structure

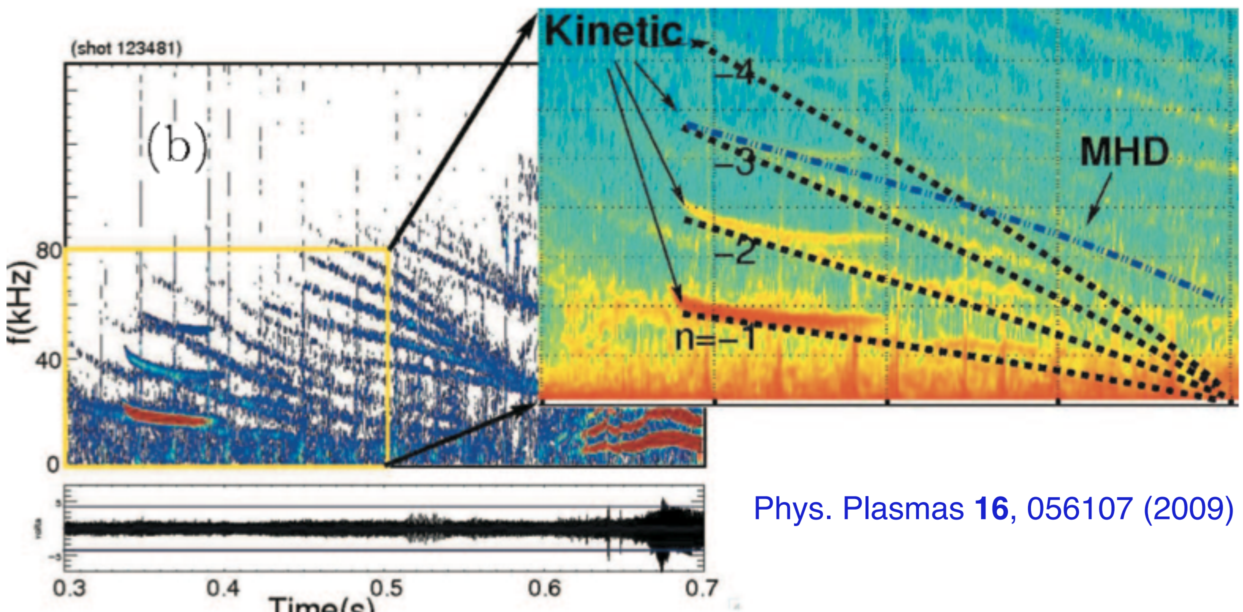
Good progress has been made to compare kinetic theory with measurements for BAAE modes

- Low frequency Alfvén continuum is modified by interaction with acoustic branch

  Beta-induced Alfvén Acoustic Eigenmodes

- Kinetic theory of BAAEs can explain measured spectra and their temporal evolution
  - Mode frequency follows q-profile evolution

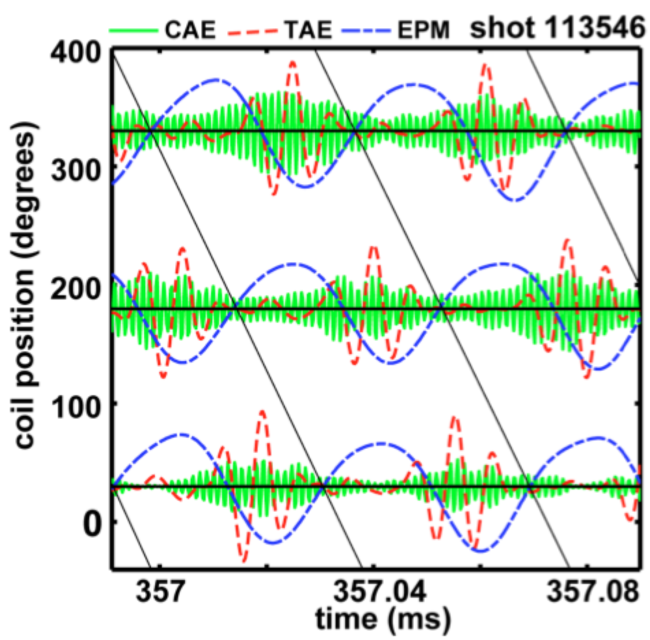


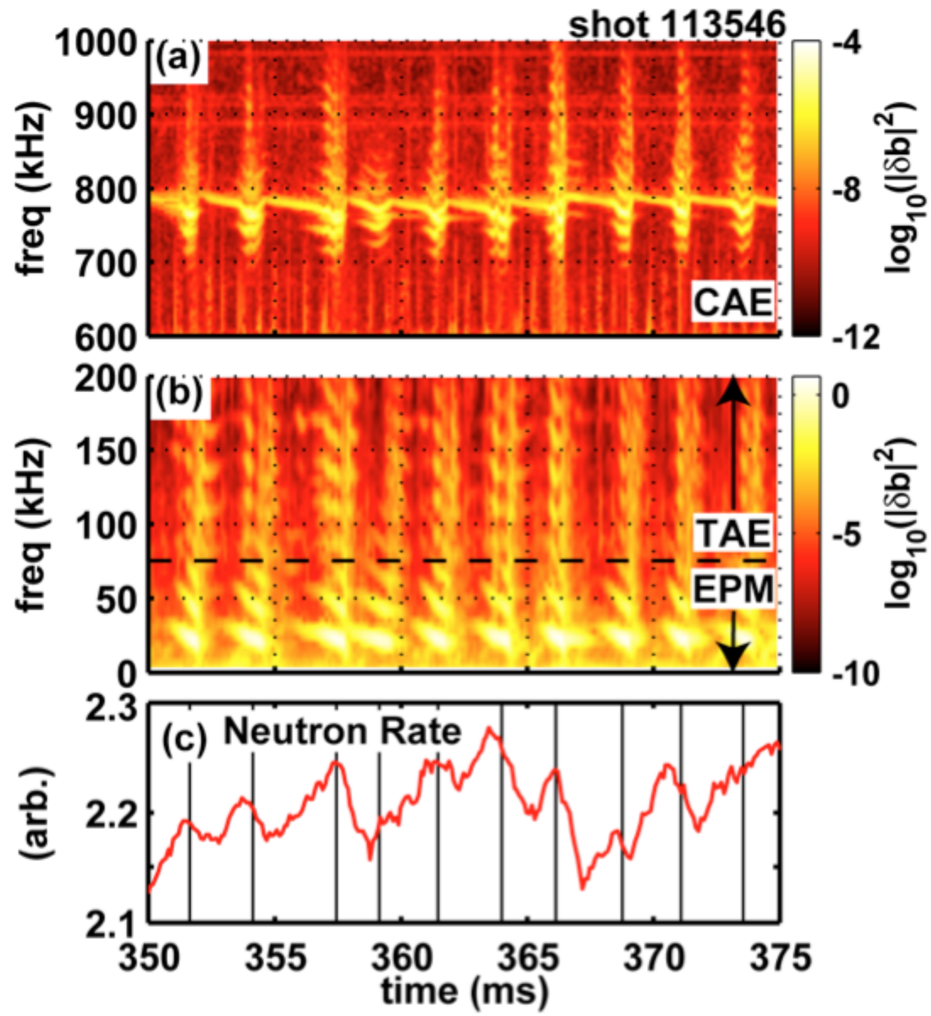


Phys. Plasmas **16**, 056107 (2009)

Three-wave coupling between different *AEs has been documented

- Coupling between TAEs and EPMs documented since 2006
- EPMs determine low-frequency modulation (toroidally) of mode amplitude
- Study is being extended to high-frequency modes, e.g. CAEs
  - Evidence for three-wave coupling between TAEs and CAEs





Phys. Rev. Lett. **97**, 045002 (2006)