

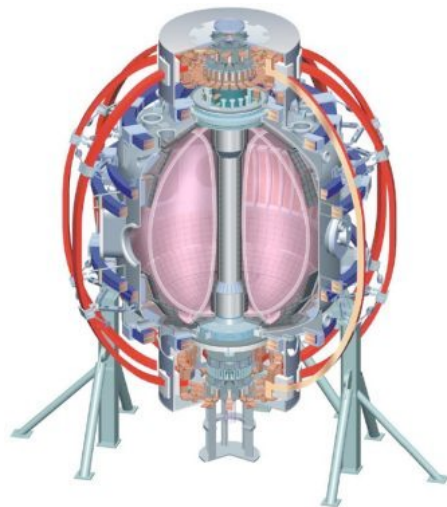
# Energetic particle physics: progress and plans

**E. D. Fredrickson, PPPL**

*For the NSTX Research Team*

**25th NSTX PAC Meeting  
Conference Room LSB-B318, PPPL  
Feb 18-20, 2009**

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# *NSTX is uniquely positioned to study energetic particle physics required for next-step devices*

- NSTX routinely operates with super-Alfvénic fast ions.
  - Fast ion physics studied in all operational regimes, w/full diagnostics.
  - Neutral beam energy at 60 - 100 kV,  $1 < V_{\text{fast}}/V_{\text{Alfvén}} < 5$ 
    - Center stack upgrade extends  $\rho_{\text{fast}}$ ,  $V_{\text{fast}}/V_{\text{Alfvén}}$  toward future devices.
  - Neutral beam power up to 6 (12) MW, strong drive with high  $\beta_{\text{fast}}$ 
    - Fast ion parameters relevant to ITER/future STs
  - Significant fast ion losses with multiple TAE or EPM (avalanches); the predicted loss mechanism for ITER.
- For ITER/future STs, we need the capability to predict:
  - Fast ion confinement; predict impact on ignition conditions
  - Fast ion redistribution; predict beam driven currents.
    - Future STs depend on up to 50% beam driven current.
  - Fast ion losses; predict PFC heat loading, damage by energetic  $\alpha$ 's.

# Outline/Overview of Near Term Research (2009-2011)

- TAE/EPM Avalanche benchmarking is highest priority
  - (In this talk will describe progress on TAE avalanche as benchmark)
  - 1. Identify modes, frequencies, internal structure.
  - 2. Simulate eigenmodes and eigenfrequencies with NOVA
  - 3. Simulate fast ion losses with ORBIT, benchmark FIDA/FLIP/NPA/...
  - 4. Self-consistent modeling with M3D-k.
- Broader research program includes important physics topics
  - Physics of mode drive, damping and saturation amplitudes
  - Physics of frequency chirping (role of HHFW fast ion heating)
    - Importance for fast ion transport with resonance sweeping
  - *Direct* non-linear mode interactions
- Important new diagnostics available in short term
  - BES: extend range of studies to high/low density, H-modes
  - Additional reflectometers improve spatial resolution, density range.
  - pFIDA will measure confined fast ions w/small pitch (important NBCD)
  - Neutron collimator adds constraint on reconstructed confined fast ion profile
  - MSE-LIF to measure q-profile without 90 kV heating beam
    - Improved equilibrium reconstruction with mod(B) to get fast ion pressure

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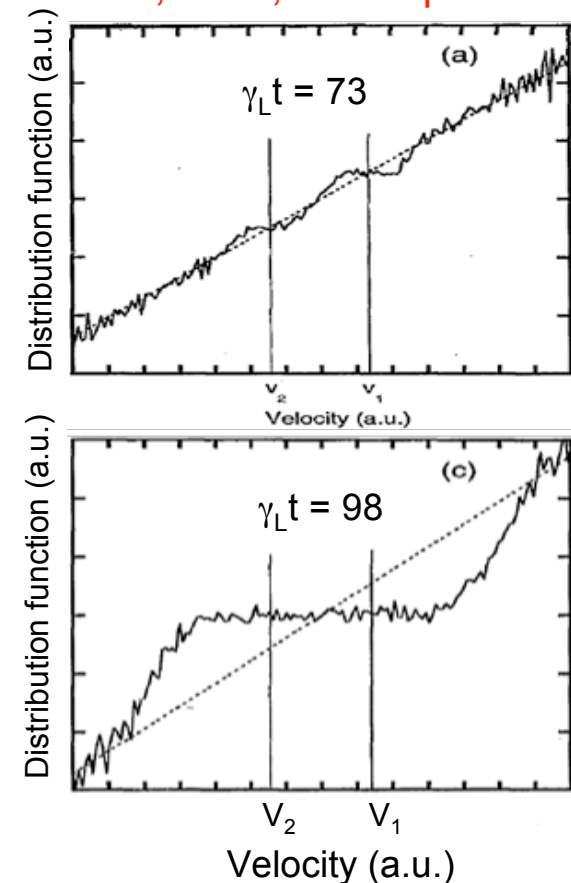
# "Avalanches" are non-linear (stochastic) overlap of particle resonances in phase space

- Avalanches greatly enhance fast ion transport above a sharp threshold in mode amplitude.
- Modifications to fast ion distribution can increase mode drive, excite additional modes.
- Even a single mode in a toroidal system may have multiple resonances that overlap non-linearly.
- Fast ion transport on NSTX for both TAE and EPs is believed due to avalanches.

– It's the transport mechanism expected on ITER

- Measurement of mode amplitude, frequency, fast ion loss/transport.
- Benchmark NOVA/M3D on mode structure, ORBIT/M3D-k on fast ion transport.

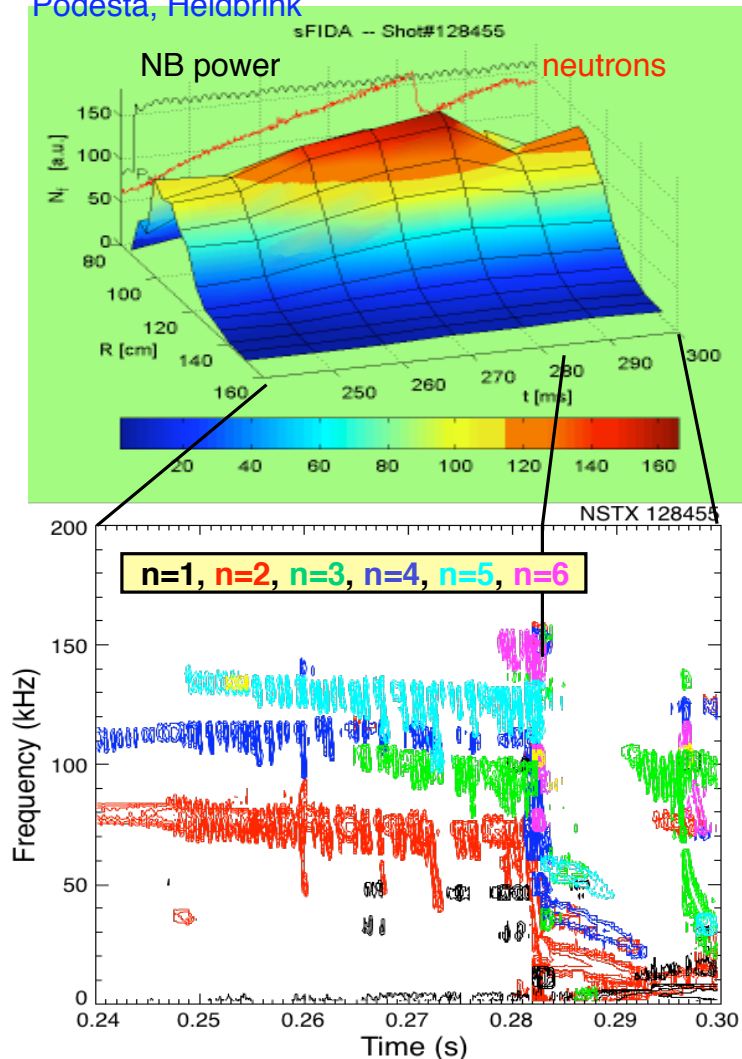
Berk, et al., PoP 2 p 3007



# NSTX EP Research Priority on modes demonstrated to cause fast ion losses; TAE avalanches, EPs

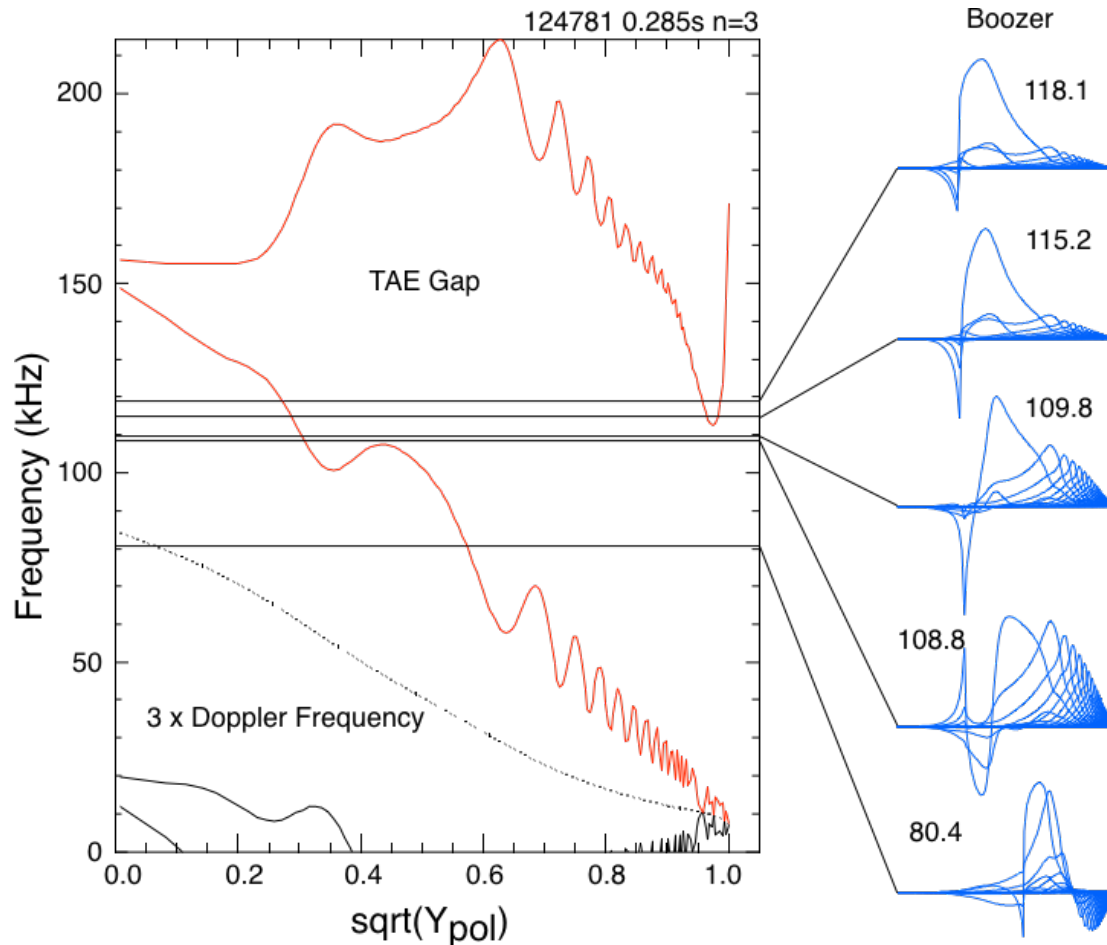
- TAE avalanche, below, has 15% drop in neutrons, drop in core fast ions.

Podesta, Heidbrink



- Mode numbers and frequency spectrum measured with Mirnov array used to guide NOVA calculations.
- Effect on fast ions measured with:
  - Fast neutron rate monitor, FLIP for losses
  - NPAs and FIDA for redistribution
  - Tangential FIDA, neutron collimator, MSE-LIF will improve reconstruction of confined fast ion profile (2010-2011).
- The next slides describe the internal measurements, benchmarking with NOVA and ORBIT.

# Toroidal rotation frequency in NSTX comparable to TAE frequencies

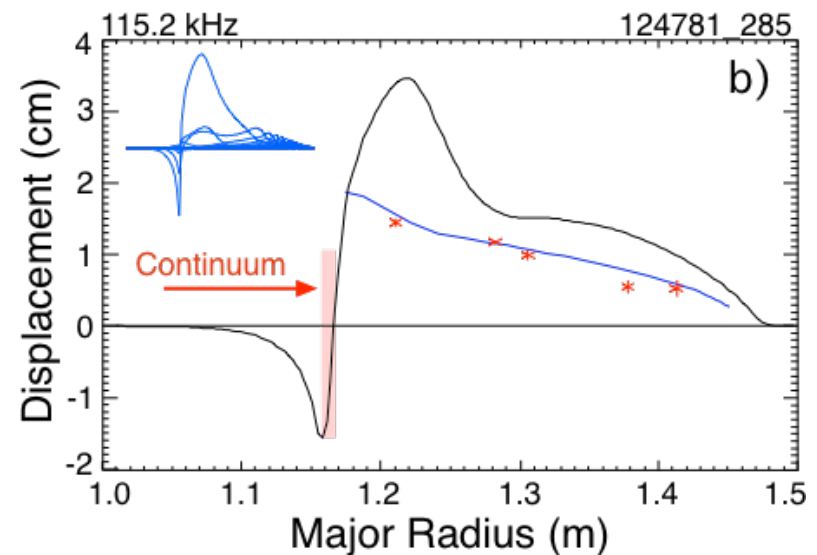
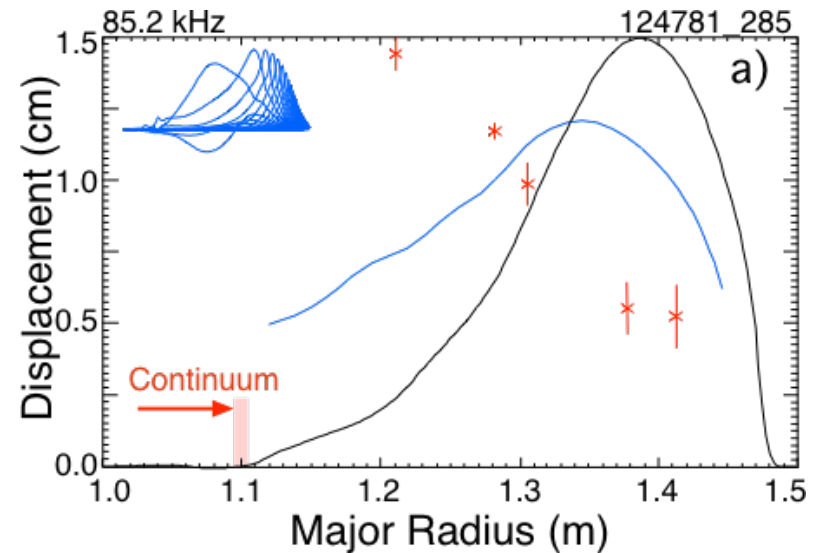


- NOVA simulation including Doppler shift corrections shows sheared rotation significantly distorts TAE gap.
- Gap is "closed", pushing modes outwards.
  - Less sensitive to evolution of  $q$  in core.
  - Non-resonant braking could clarify sheared rotation physics.
- NOVA finds multiple modes; internal measurements needed to select modes.



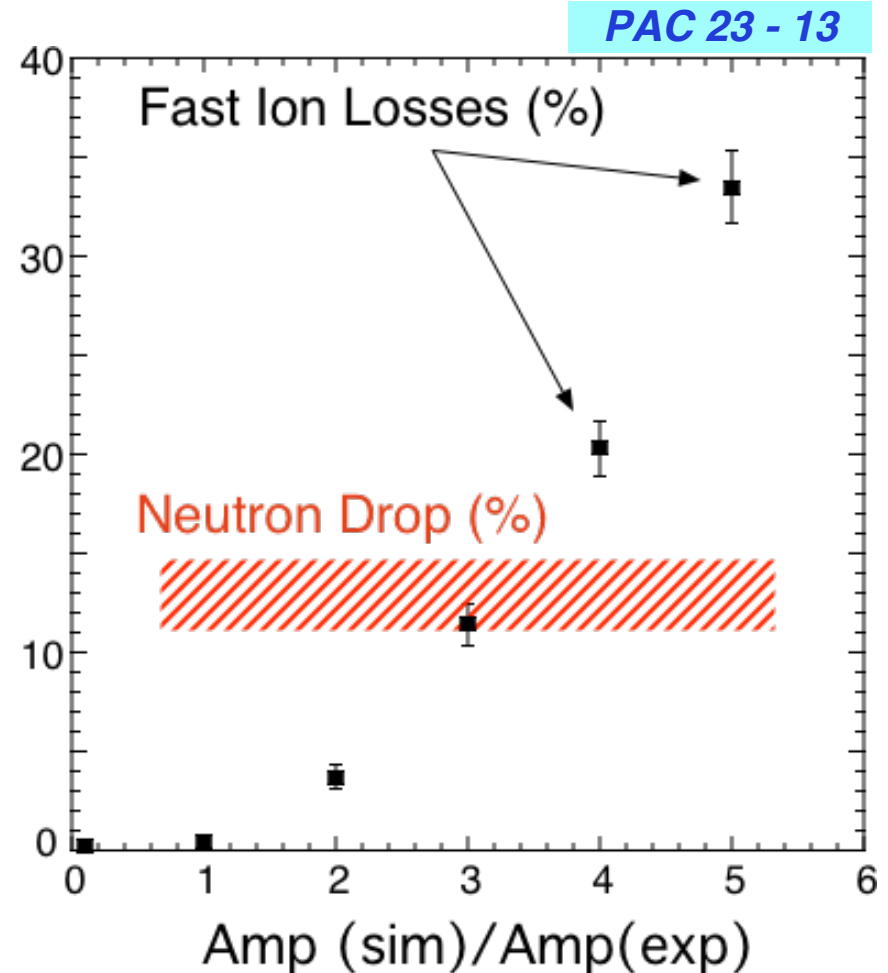
# Reflectometer array measures mode profile, used to scale linear NOVA Eigenmodes to use in ORBIT

- NOVA eigenmode (black curve) fit with "synthetic reflectometer" (blue curve) to reflectometer array data (red points).
- L-mode (peaked density) conditions needed for reflectometers.
- SXI indicates mode extends to core.
- 5-channel reflectometer array to be expanded to > 8 channels,
  - Restricted to peaked (L-mode) density profiles.
- BES will allow us to extend internal studies to H-modes and both higher and lower density plasmas.
  - Higher spatial resolution



# Preliminary ORBIT simulations underestimate fast ion losses

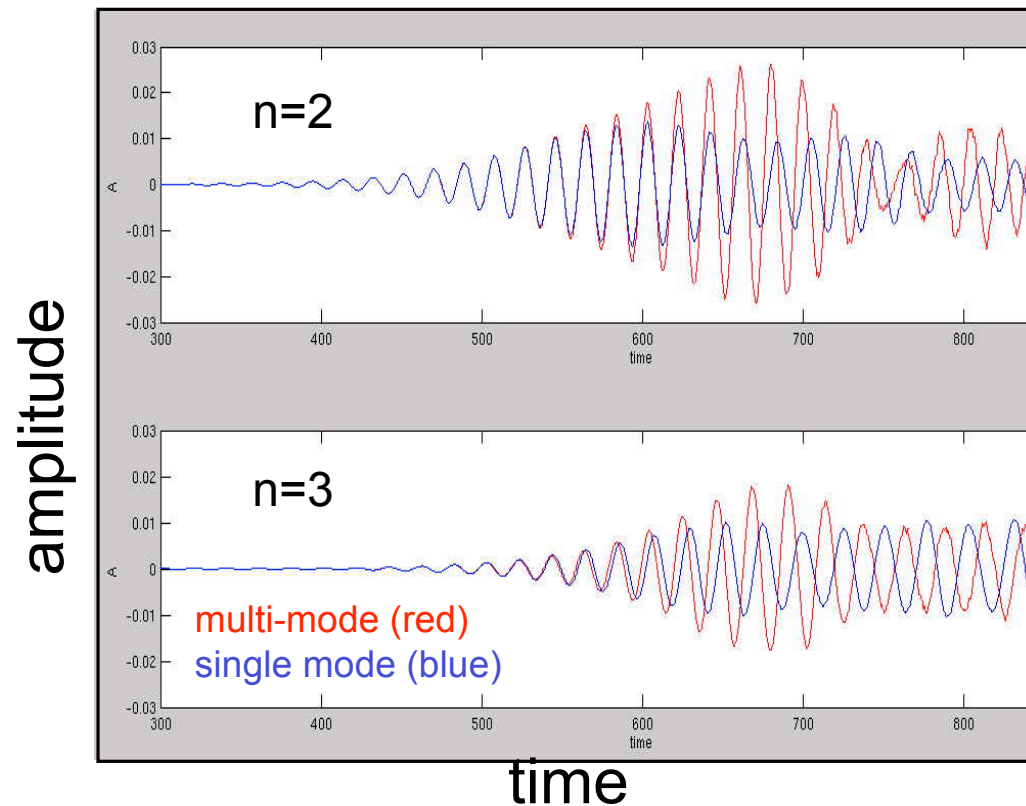
- Mode amplitudes and frequency evolutions from experiment are used in ORBIT simulation.
  - Compressional correction estimated to be  $\approx 2$ .
- Presently, a factor of roughly 3 enhancement in mode amplitude is needed for ORBIT to reproduce experimental losses.
- Adding core mode may help.
  - GRYO-XY may predict more losses
- Simulation is not self-consistent
  - Mode frequency and amplitude evolution from experiment
- Similar experiments on DIII-D found factor of five discrepancy between measured and mode amplitude needed to reproduce losses.





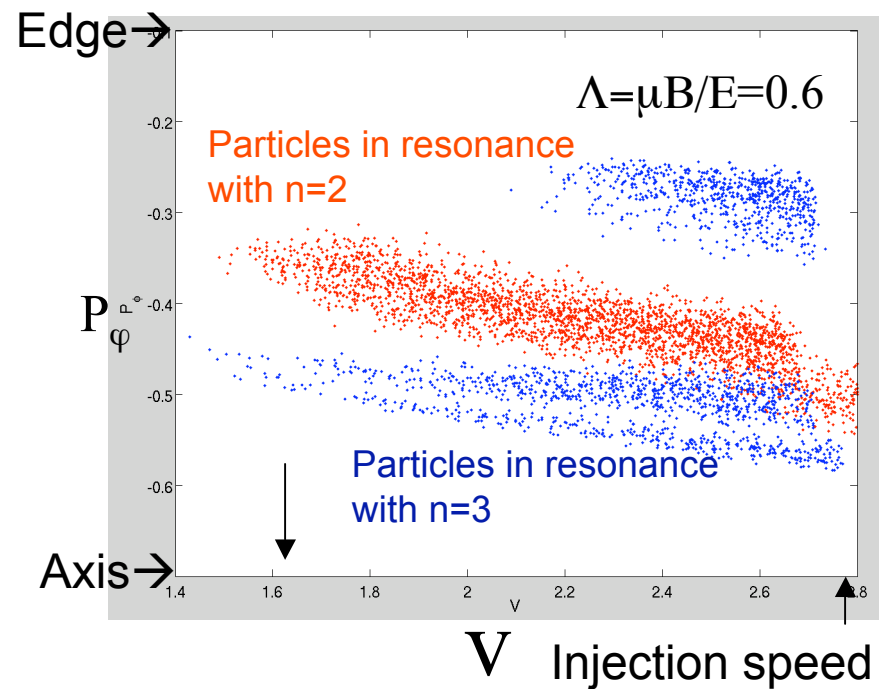
# M3D-K self-consistently models multi-mode TAE

- Mode amplitude larger in multi-mode simulation (red).
- Individual modes saturate at lower amplitude.
- Simulation also reproduces frequency chirping.

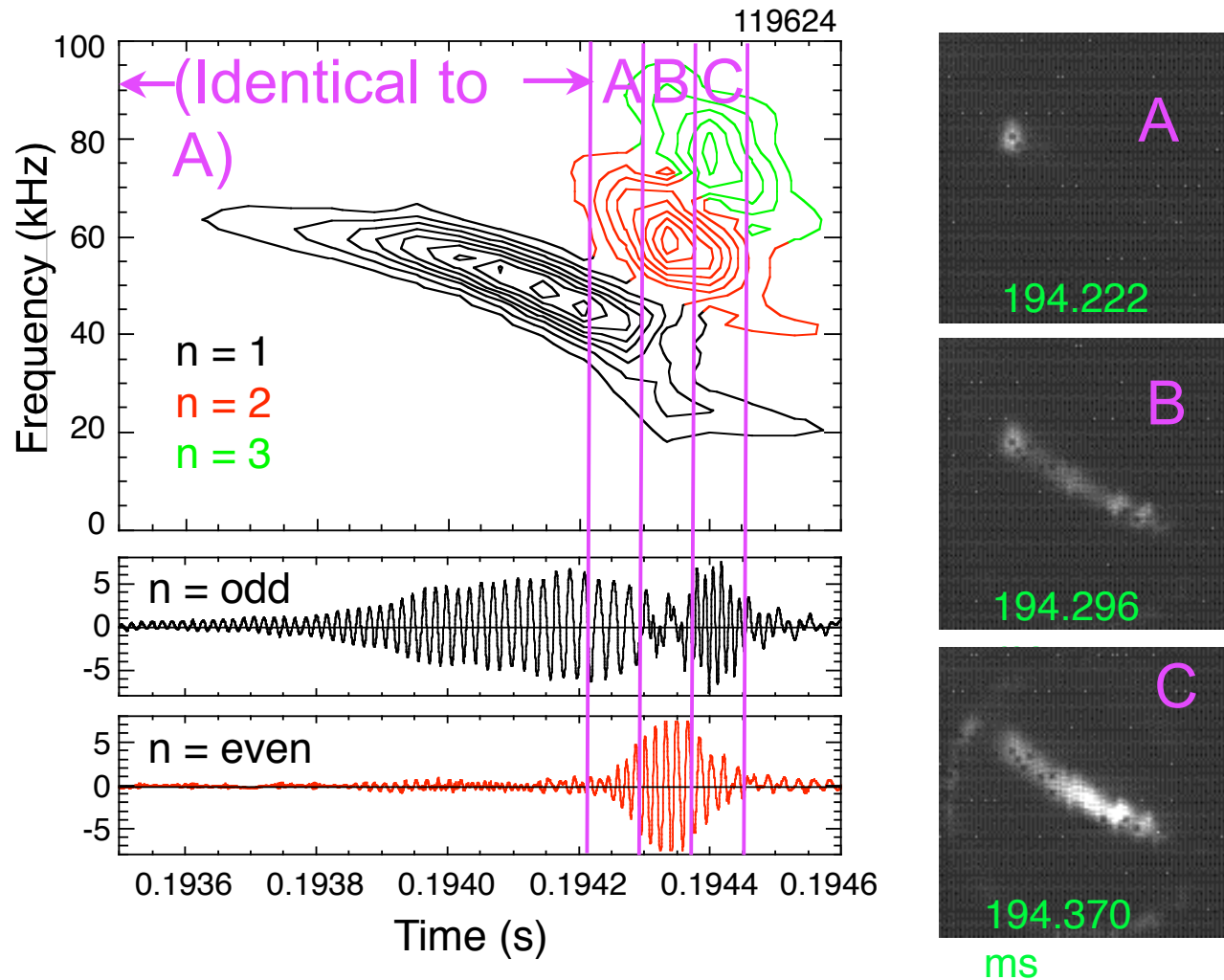


# M3D-k simulation captures physics of avalanche

- Modes interact with broad range of fast ion energies; consistent with NPA measurements.
- Fast-ion resonances from single mode simulations show that resonances can (do) overlap.
- Multiple resonances are seen for  $n=3$  mode.
- Simulation is for "generic" NSTX equilibrium; benchmarking for same equilibrium between NOVA and M3D is underway.



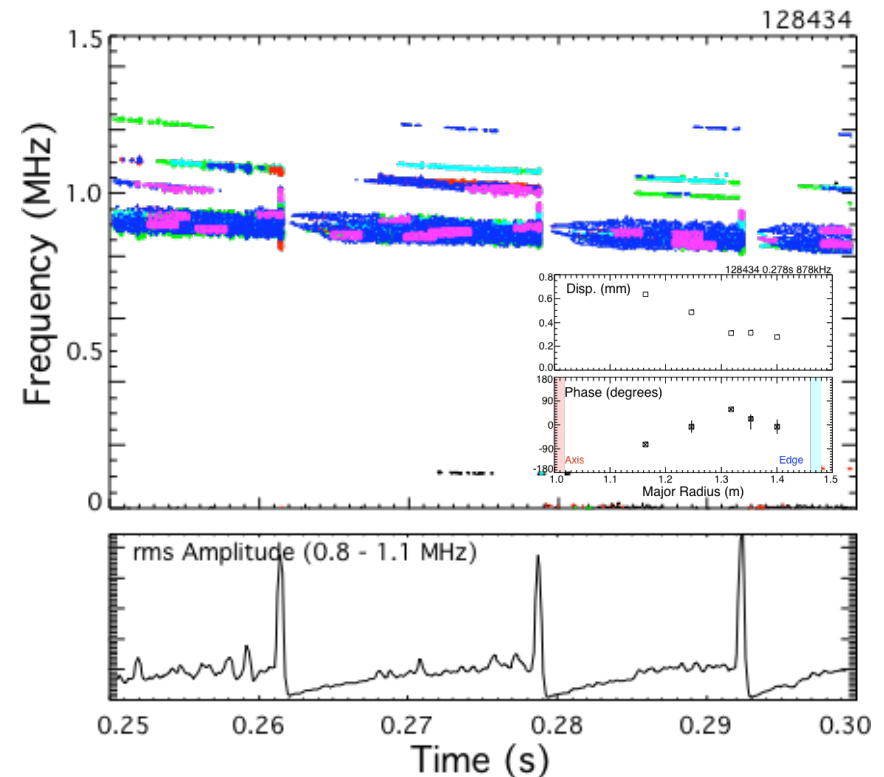
# Avalanche behavior seen for GAE and EPM, also



- Peak in fast ion losses correlated with multi-mode period.

# Global and Compressional Alfvén Eigenmodes are ubiquitous in present NSTX plasmas, higher field may suppress

- GAE exhibit avalanche-like behavior.
  - Slow growth of multiple modes, ending in large, multi-mode burst and quiescent period.
  - Evidence that they have significant impact on fast ion distribution.
  - Doppler-shifted cyclotron resonance would take mostly perpendicular energy; fast ions would end up better confined.
- Can be correlated with low frequency EPs
- Trapped electron precession frequency resonant with CAE/GAE
  - Multi-mode interaction can cause electron transport (ORBIT simulations)
- External excitation of multiple modes could heat thermal ions
  - Stochastic heating predicted and experimentally observed (not on NSTX).
- Diagnostic of fast-ion diffusivity in fast-ion distribution function



# Summary of Plans for 2009 - 2011 and beyond

- Near-term goals
  - Effect on NBI current will be investigated during TAE avalanches with:
    - FIDA(s), vertically scanned NPA, ssNPA, MSE-LIF(?) and sFLIP diagnostics.
    - Benchmark NOVA-ORBIT and M3D-k
  - Scaling of Avalanche onset threshold with  $V_{fast}/V_{Alfvén}$ , and q-profile variations.
  - Extend avalanche studies to H-modes w/BES for internal structure
  - EPM effect on fast ions, measure internal mode structure, ORBIT simulations
  - Beatwave HHFW excitation of TAE (other modes)
  - HHFW suppression of chirping modes (TAE, GAE-Angels, EPM?)
  - Internal structure of GAE/CAE; benchmark HYM code
- With new diagnostics, center-stack capabilities & beam line:
  - Avalanche scaling for wider range of  $\rho_{fast}^*$  and  $V_{fast}/V_{Alfvén}$ .
  - Pitch-angle, radial fast ion profile studies with 2nd NB (incremental)
  - Neutron collimator, pFIDA complement fast-ion redistribution diagnostics.
  - BES extends \*AE studies to H-mode plasmas, higher/lower densities.
  - MSE-LIF frees q-profile measurements from 90 kV beam, adds mod(B)

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# Back-up Slides

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# *NSTX has comprehensive diagnostic set for energetic particle driven mode studies*

- Diagnostics to measure mode structure:
  - High frequency Mirnov arrays;  $\approx 10$  MHz bandwidth
  - Multi-channel reflectometer array; internal mode structure/amplitude
  - Multiple view soft x-ray cameras ( $\approx 100$  kHz bandwidth)
  - High-k scattering; Kinetic Alfvén Waves
  - Firetip 2MHz; internal mode amplitude/structure
  - BES; higher spatial resolution, mode structure at higher/lower density
- Fast particle diagnostics:
  - Fast neutron rate monitors
  - Neutron collimator; spatial profiles of fastest ion populations
  - Scanning NPA; high energy resolution, vertical and radial scan
  - ssNPA; 5-channel midplane radial array
  - sFLIP; scintillator lost ion probe, energy/pitch angle resolved (fast PMT)
  - iFLIP; Faraday cup lost ion probes
  - Tangential/perpendicular FIDA; spatial profile, energy resolved
  - MSE-LIF to measure pressure profile, q-profile with low voltage beams

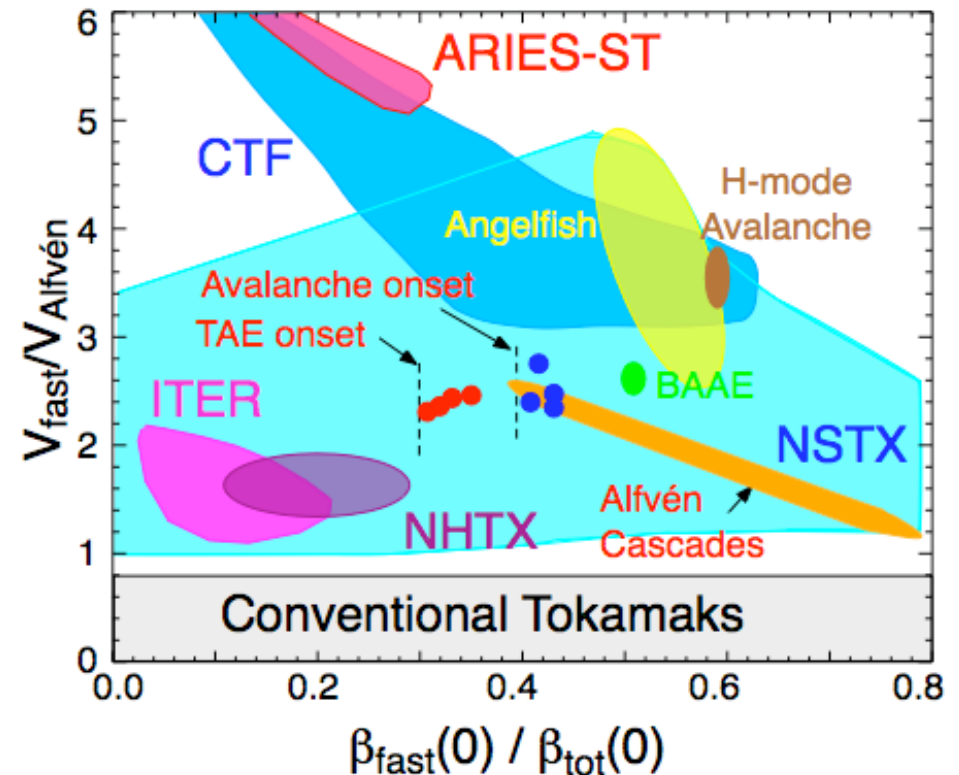
Pre-2009
2009-2010
2011+

# Experimental program strongly coupled to EP theory & modeling community

- Strong analytic and numerical modeling support
  - Strong connection between PPPL and UT theory groups
  - TRANSP; equilibrium and classical fast ion distributions
  - NOVA-k; linear mode structure/stability
  - HINST; local, fully kinetic, stability modeling
  - ORBIT; fast ion redistribution - linear mode structure
  - M3D-k; linear/non-linear mode stability structure and evolution
    - M3D upgrade (GKM) will provide full FLR effects, .e.g., coupling to KAW.
  - HYM; non-linear shear *and* compressional Alfvén waves
  - TORIC and GTC/GYRO/GEM code adaptation to EP physics
- NSTX experiments address energetic particle physics issues important for developing predictive capability.
  - Non-linear, multi-mode transport (ITER/NHTX/ST-CTF)
  - Coupling to KAW at continuum (ITER/NHTX/ST-CTF)
  - Rotational shear effects on mode stability/structure (NHTX, ST-CTF)
  - Phase-space engineering; HHFW modification of fast ion profile

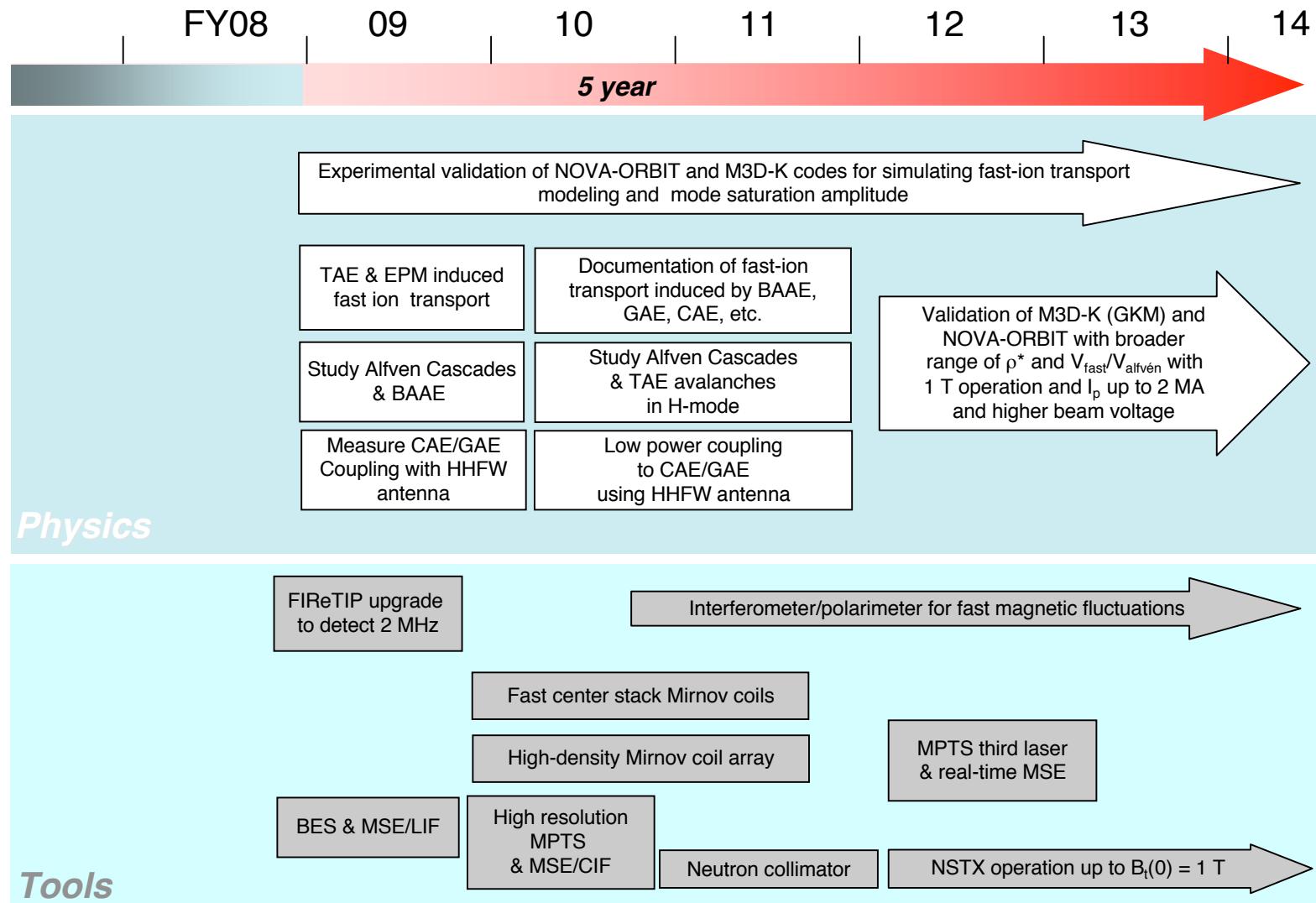
# *NSTX accesses broad range of fast ion parameters, broad range of fast particle modes*

- Cartoon at right illustrates NSTX operational space, as well as projected operational regimes for **ITER, ST-CTF and ARIES-ST**.
- Also shown are parameters where typical fast particle modes (FPMs) have been studied.
- Conventional beam heated tokamaks typically operate with  $V_{fast}/V_{Alfven} < 1$ .
- CTF in avalanche regime motivates studies of fast ion redistribution.
- Higher  $\rho^*$  of NSTX compensated by higher beam beta



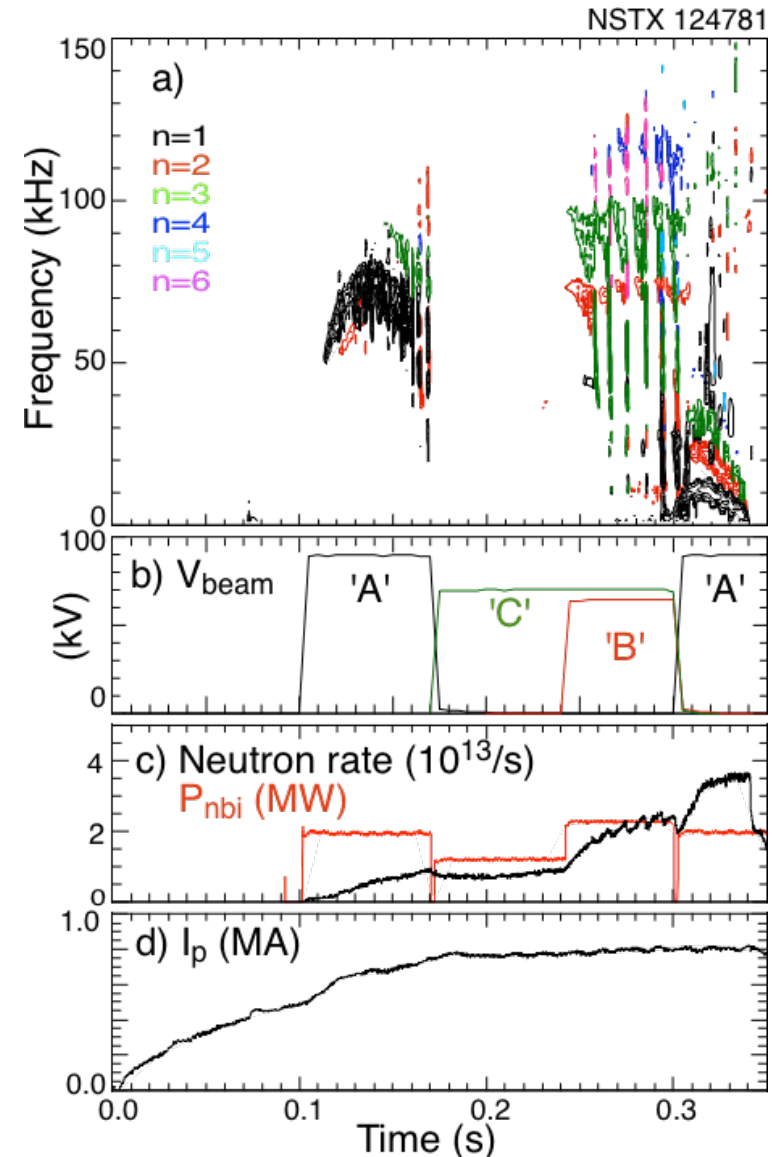
Cartoon is over-simplification and there are other dependences.

# 2009-13 Energetic Particle Research Timeline



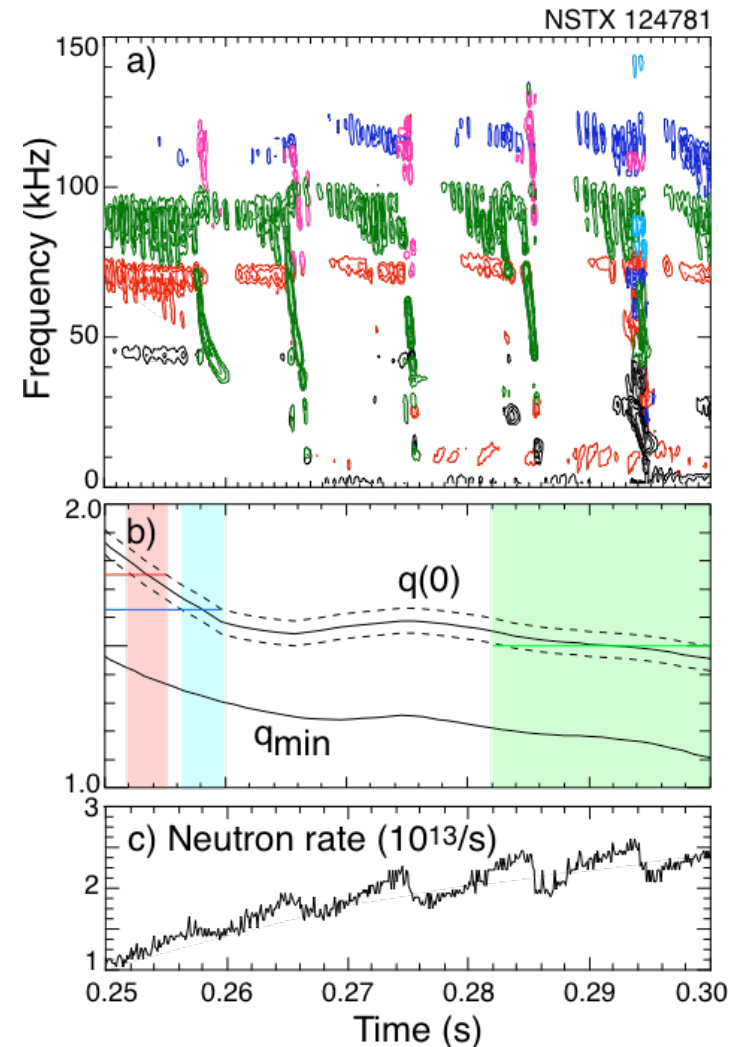
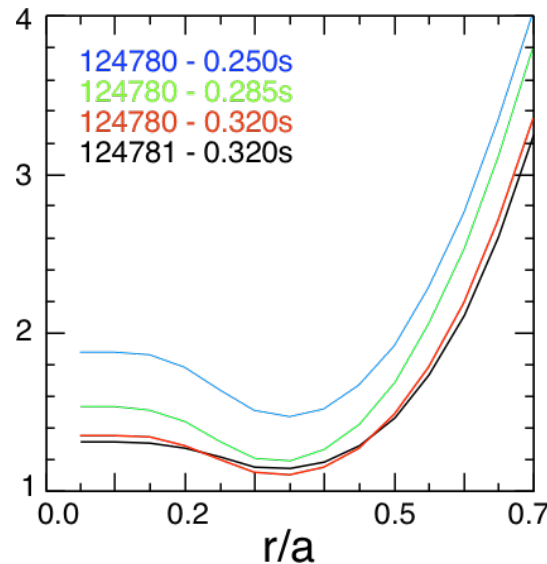
# Shot evolution carefully tailored to optimize studies of TAE avalanches

- Plasma kept in L-mode with Helium puffing to provide reflectometer access.
- Low voltage beams more efficiently excite TAE avalanches
- q-profile measurements with MSE require 90 kV heating beam; interferes with mode drive.
  - Source A injected early to get initial q-profile and shortly after time-of-interest for later profile.
  - Companion shots with extended source A injection provide q-evolution in gap; benchmarked before and after.



# Mode structure insensitive to $q$ evolution in core

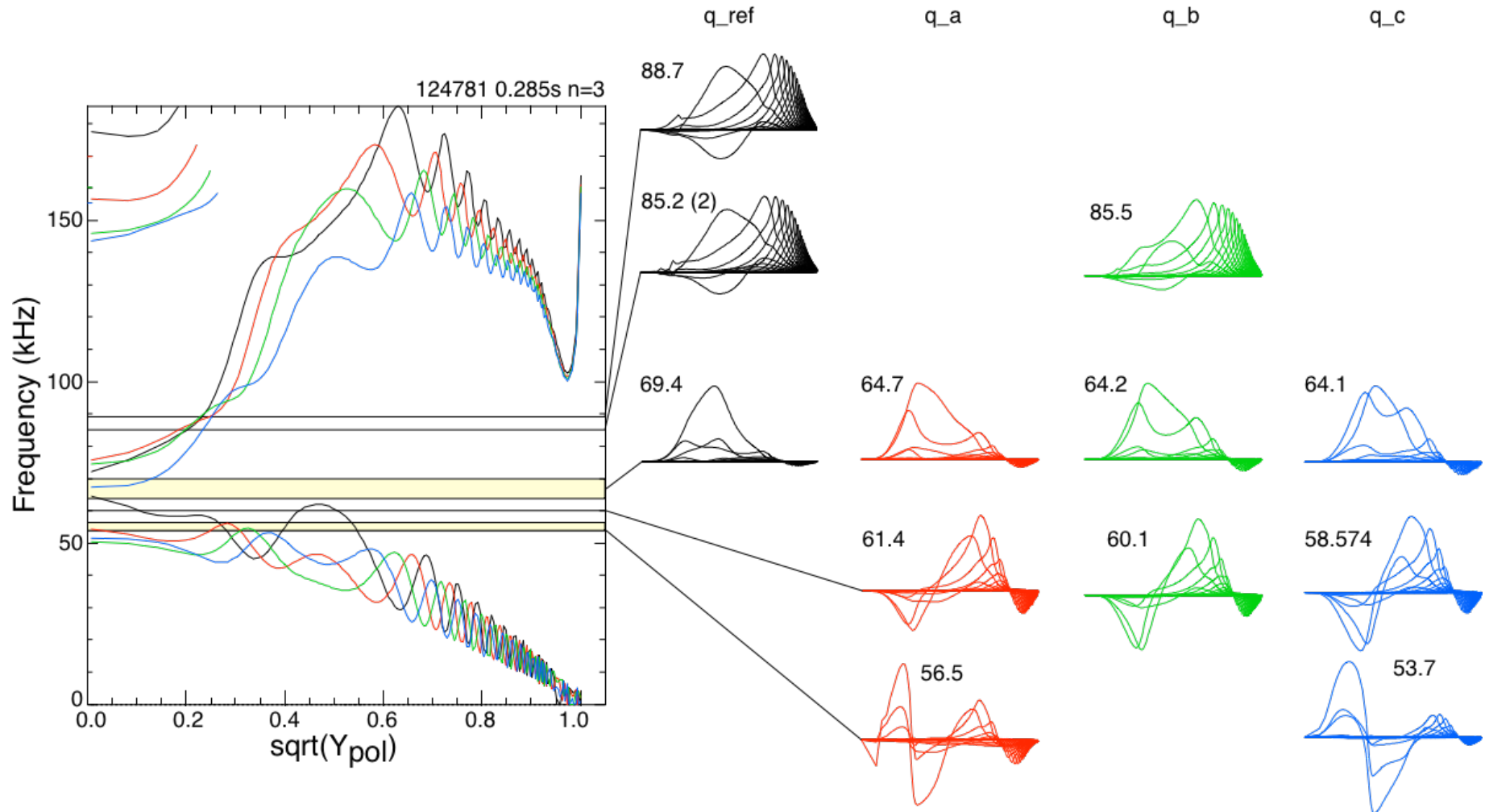
- TAE gaps on axis should open and close as  $q(0)$  drops in core.
- Time evolution depends on toroidal mode number, that is when  $q(0) = \text{rational}$  ( $m/n$ ).
- Could be explained if sheared rotation closed gap access to core region.





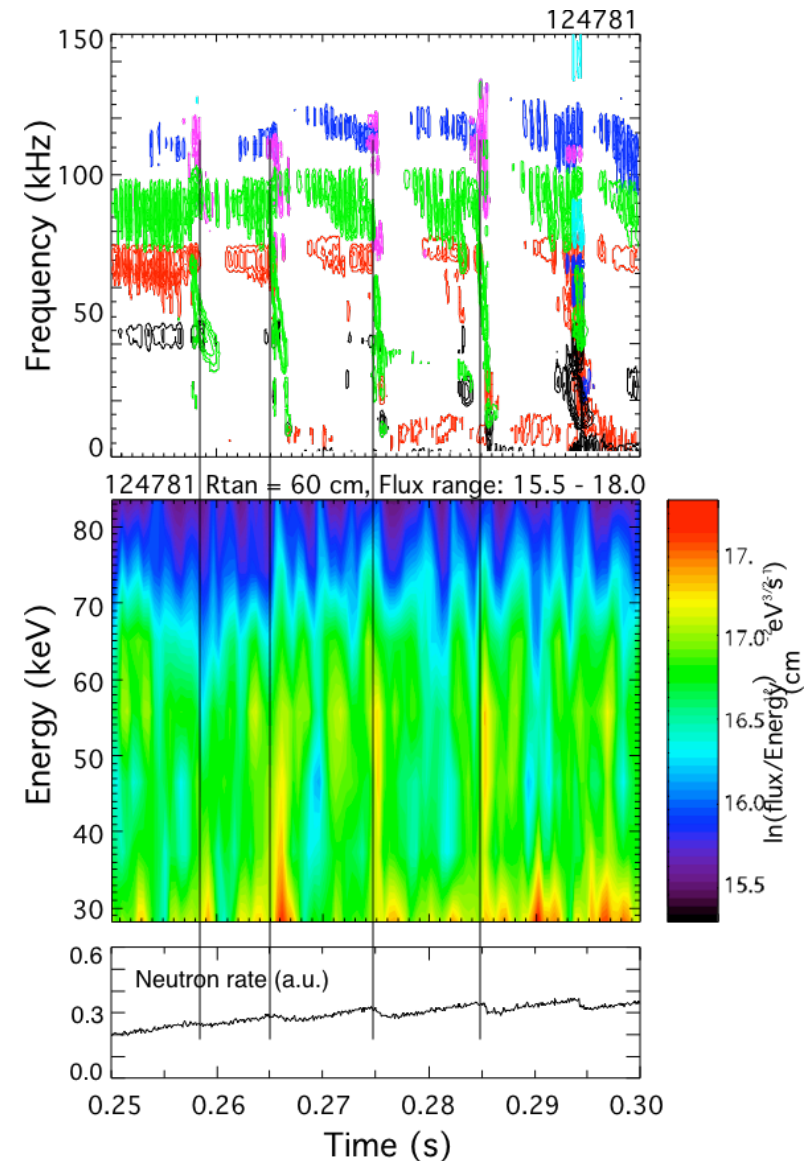
# *$n=3$ Gap closes as $q(0)$ approaches 1.5*

- Sheared rotation correction not included here.

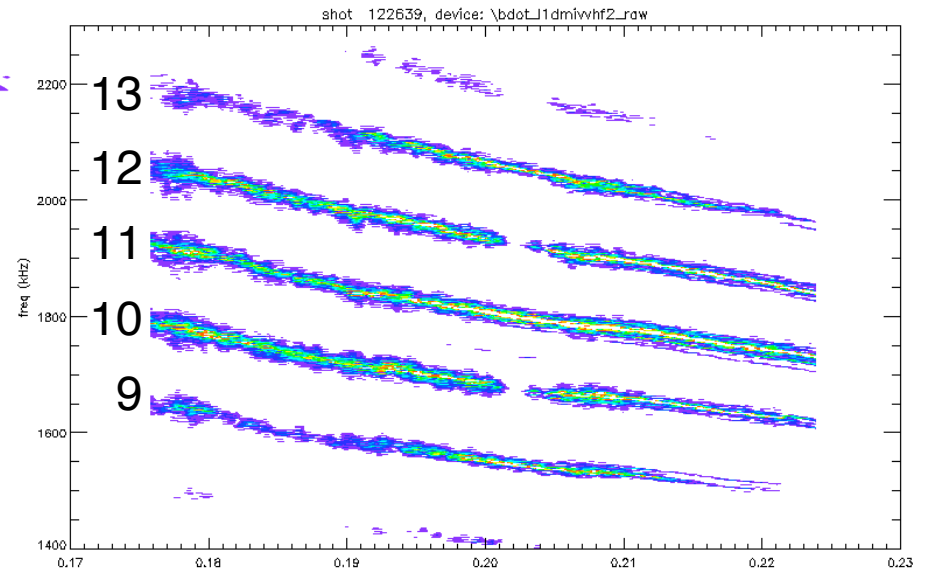
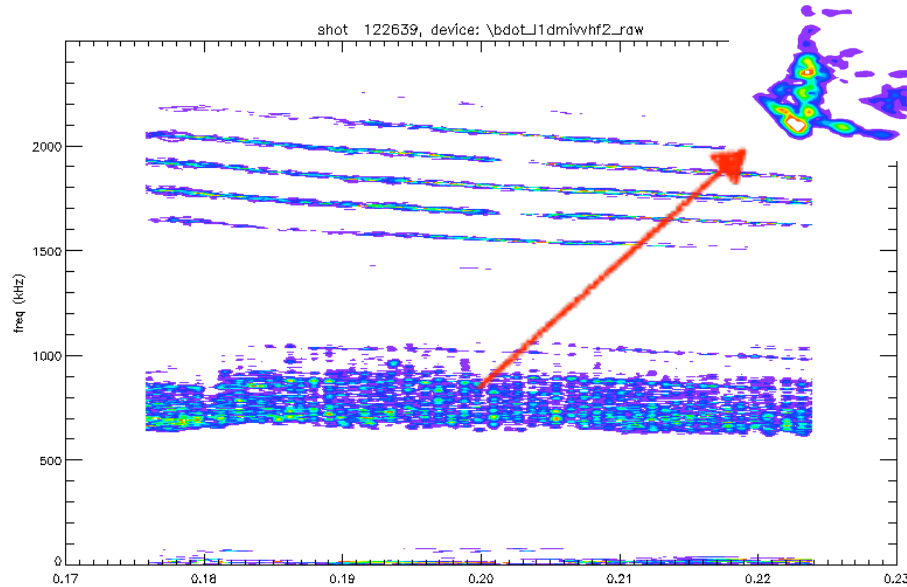


# Documentation of fast ion transport, code validation, highest priority goal for EP group

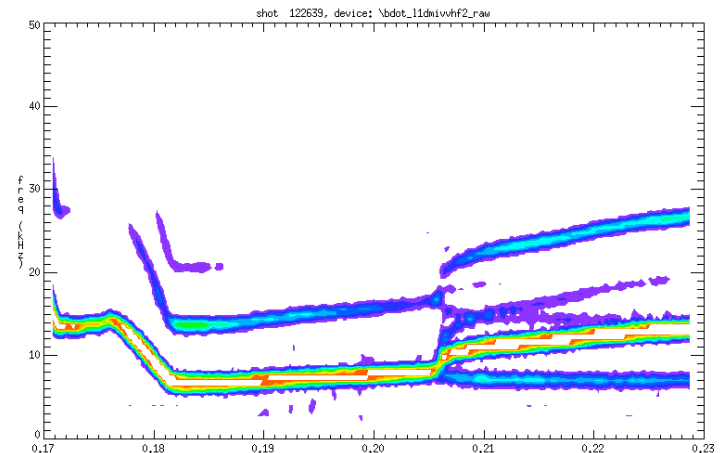
- Fast ion redistribution indicated by neutron drops and in ssNPA and NPA data.
- Lower energy ions ( $v_{\text{fast}}/v_{\text{Alfven}} > 1$ ) seem most strongly affected.
  - Additional experiments needed for quantitative measurements, identification of fast ions involved.
- Lost fast ions also seen on sFLIP detector



# CAE at higher frequencies (1.5 - 2.5 MHz)

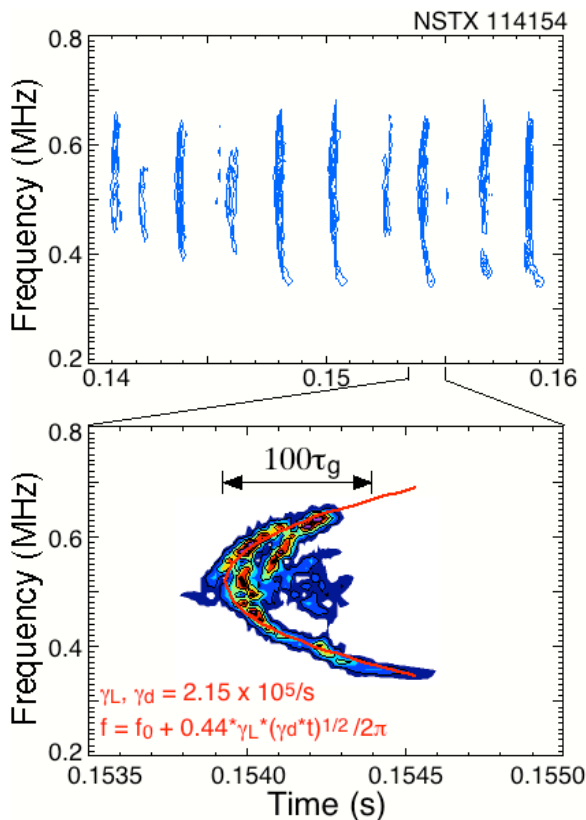


- Good fit to CAE dispersion relation and fast ion resonance condition.
- Only present with low frequency kink.
- So far, only seen in H-mode, but most plasmas are H-mode by this time.
- Reflectometer data would be nice...

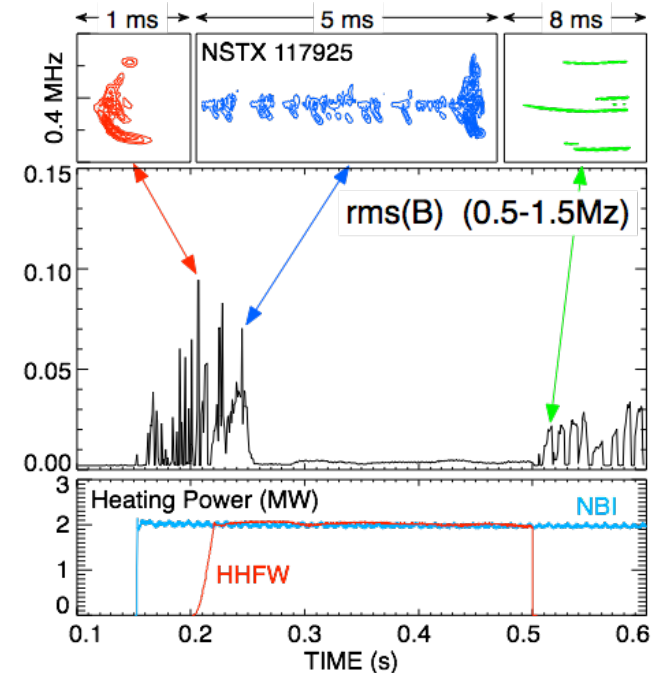


# Studies of Angelfish (hole-clumps) illuminate physics of fast ion phase space structures

- Efforts have continued to develop theoretical and experimental understanding of CAE/GAE hole-clumps.

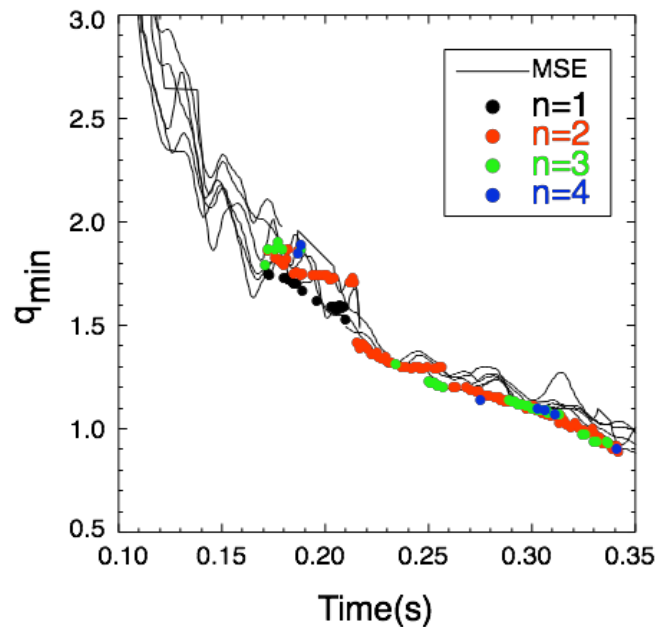


- Linear growth rate in good agreement with analytical estimates



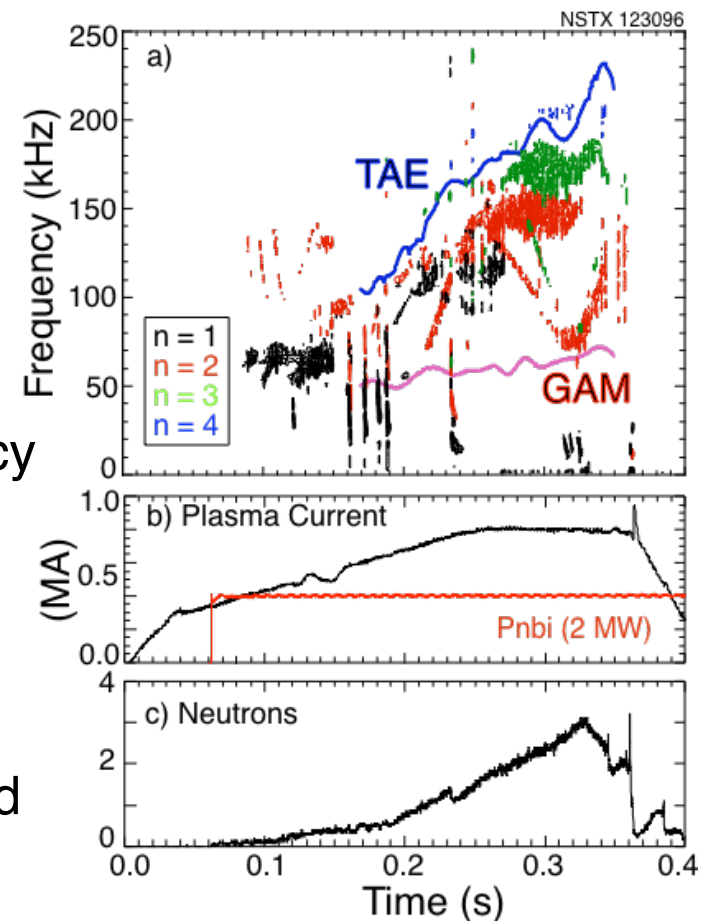
- Suppression power threshold in qualitative agreement with predictions
- Understanding phase-space structures could lead to methods of TAE control

# rsAE, GAM offers multiple opportunities for "MHD Spectroscopy"



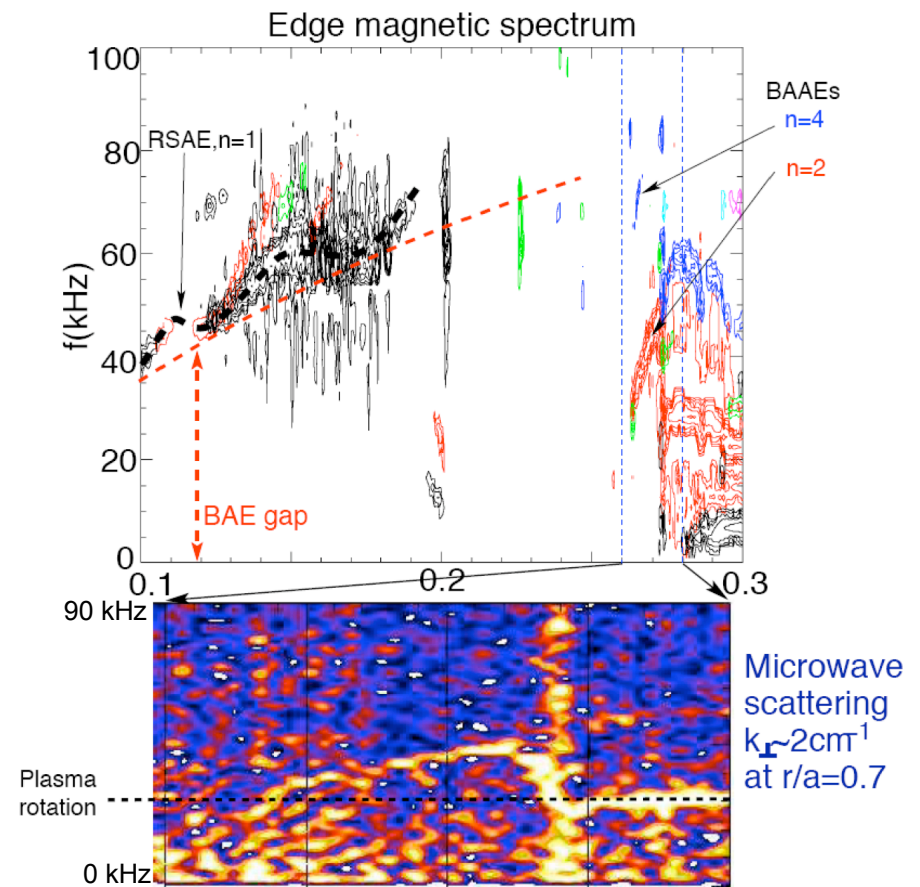
- MSE measurements (at low field) confirm interpretation of modes as rsAE; data used to validate NOVA modeling of rsAE.

- Frequency minimums are at the GAM frequency
  - Scaling studies of  $f_{\text{GAM}}$  measure  $\gamma$  of thermal, energetic plasma components.
- Sheared rotation affects stability, frequency; studied with non-resonant braking.
- Mode structure will be measured with BES, and reflectometers and higher field.



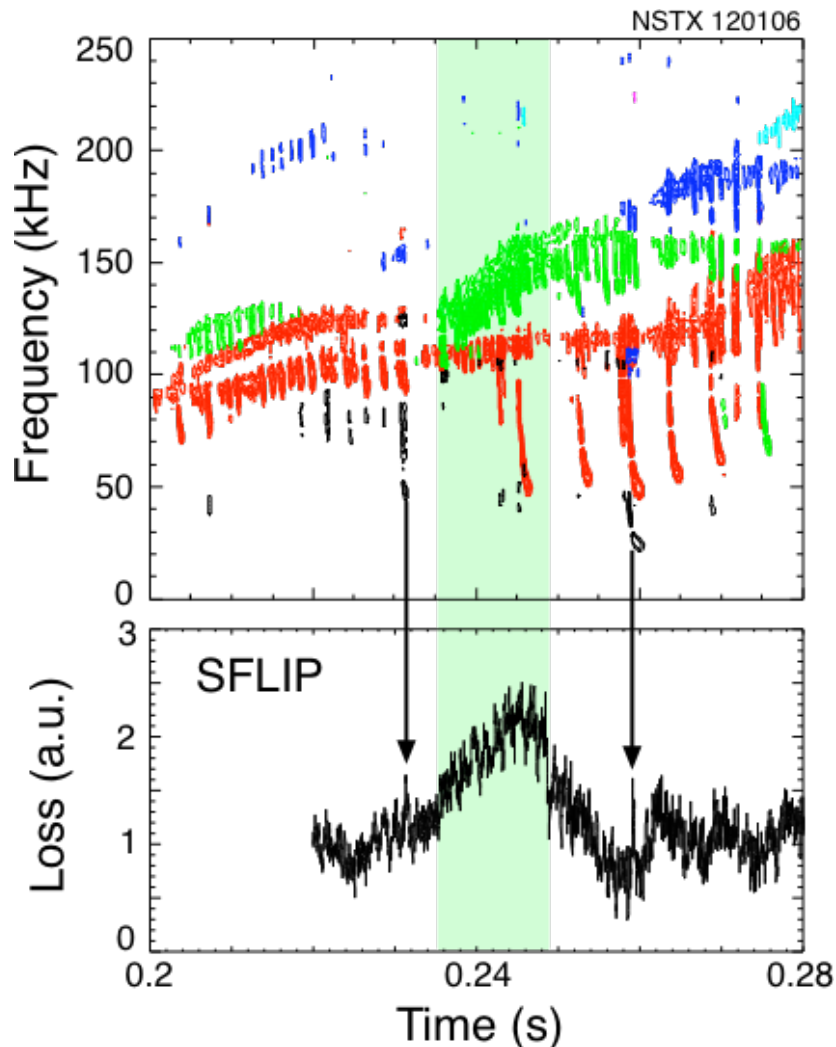
# Coupling of Alfvén and Acoustic branches at high $\beta$ introduce a new 'gap', modes; BAAE

- $\beta$ -induced Alfvén-Acoustic modes (BAAE) exist in gap opened by coupling of the Alfvén and acoustic branches.
- Frequency sweep can be used for MHD spectroscopy, as with rsAE.
- Where Alfvén waves enter continuum, mode-convert to short wavelength Kinetic Alfvén Waves (KAW).
  - This is an important damping mechanism for many Alfvén waves, including TAE.
- Coupling to Kinetic Alfvén Waves detected with High-k scattering diagnostic;
  - KAW wavenumber spectrum, amplitude and locality can be measured.
  - Data will be valuable for validating gyrokinetic upgrade to M3D-K (GKM).





# *rsAE in ST plasmas offer multiple opportunities for unique physics studies*



- For higher  $\beta$ ,  $f_{\text{GAM}}/f_{\text{TAE}}$  larger; rsAE eventually become stable
- Modes only seen at low to very low  $\beta$  (density) for low field NSTX operation; 1 T will expand range of density.
- BES, reflectometer and low field MSE measurements will be used to validate NOVA and M3D for:
  - Coupling of rsAE to TAE; GAM to rsAE
  - Coupling of global modes to Kinetic Alfvén Waves in continuum
- Losses during  $n = 3$  frequency sweep seen on sFLIP diagnostic.
- NSTX rsAE studies will address mystery of fast ion redistribution on DIII-D.