NSTX

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Energetic particle physics: progress and plans

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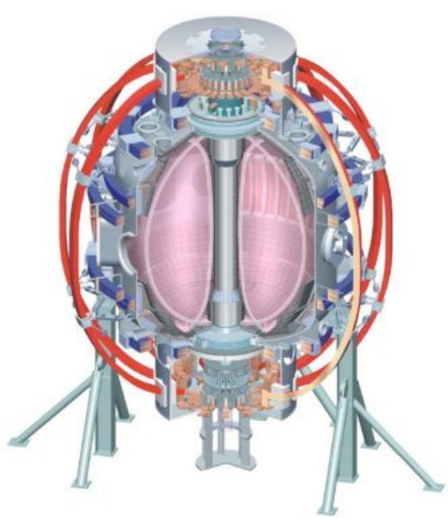
E. D. Fredrickson, PPPL

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 keV, $1 < V_{fast}/V_{Alfvén} < 5$
    - Center stack upgrade extends ρ_{fast}, $V_{fast}/V_{Alfvén}$ toward future devices.
  - Neutral beam power up to 6 (12) MW, strong drive with high β_{fast}
    - Fast ion parameters enable physics studies 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 α'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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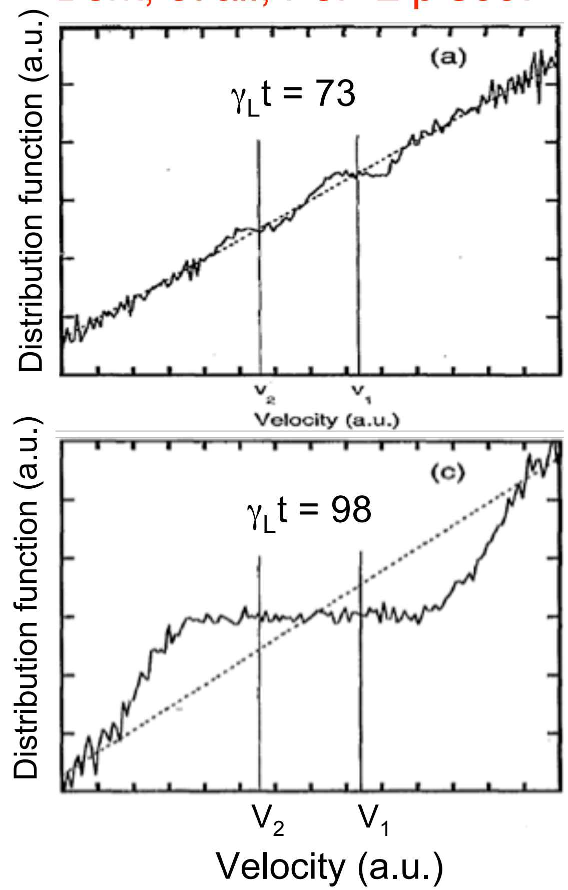
"Avalanches" are non-linear (stochastic) overlap of particle resonances (islands) in phase space

Berk, et al., PoP **2** p 3007



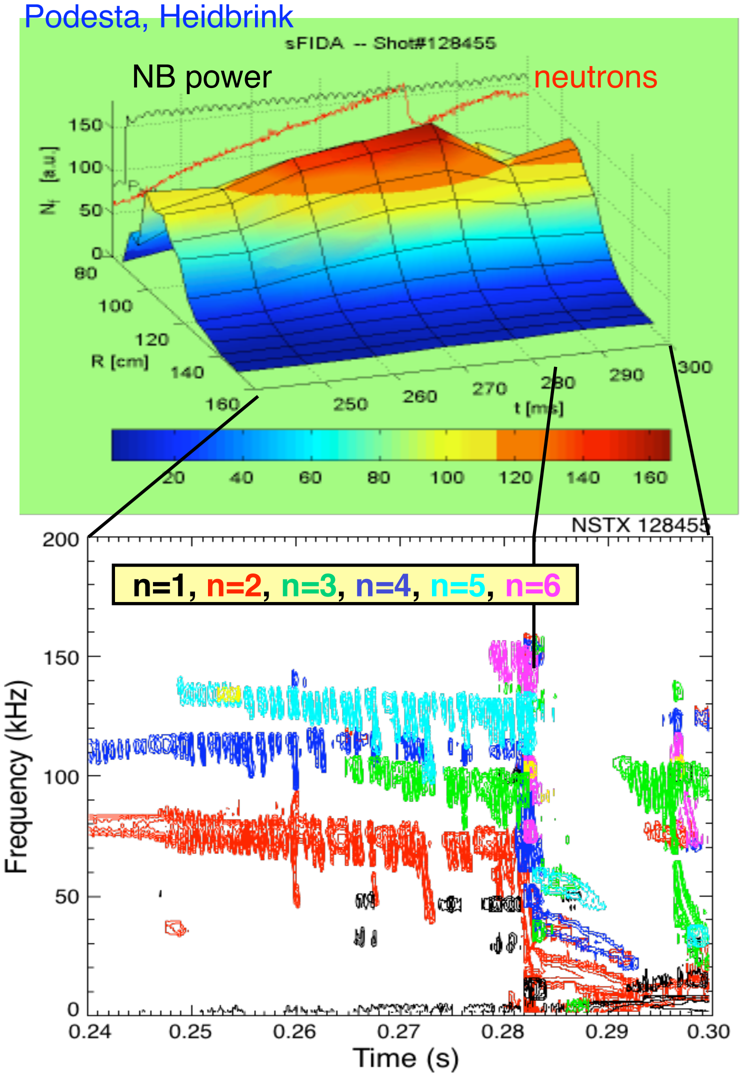
- Avalanches greatly enhance fast ion transport above a sharp threshold in mode amplitude.
- Modifications to fast ion distribution can increase mode drive, excite additional modes.
- Even a single mode in a toroidal system may have multiple resonances that overlap non-linearly.
- Fast ion transport on NSTX for both TAE and EPMs 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-k on mode structure, ORBIT/GYROXY/M3D-k on fast ion transport.

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

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

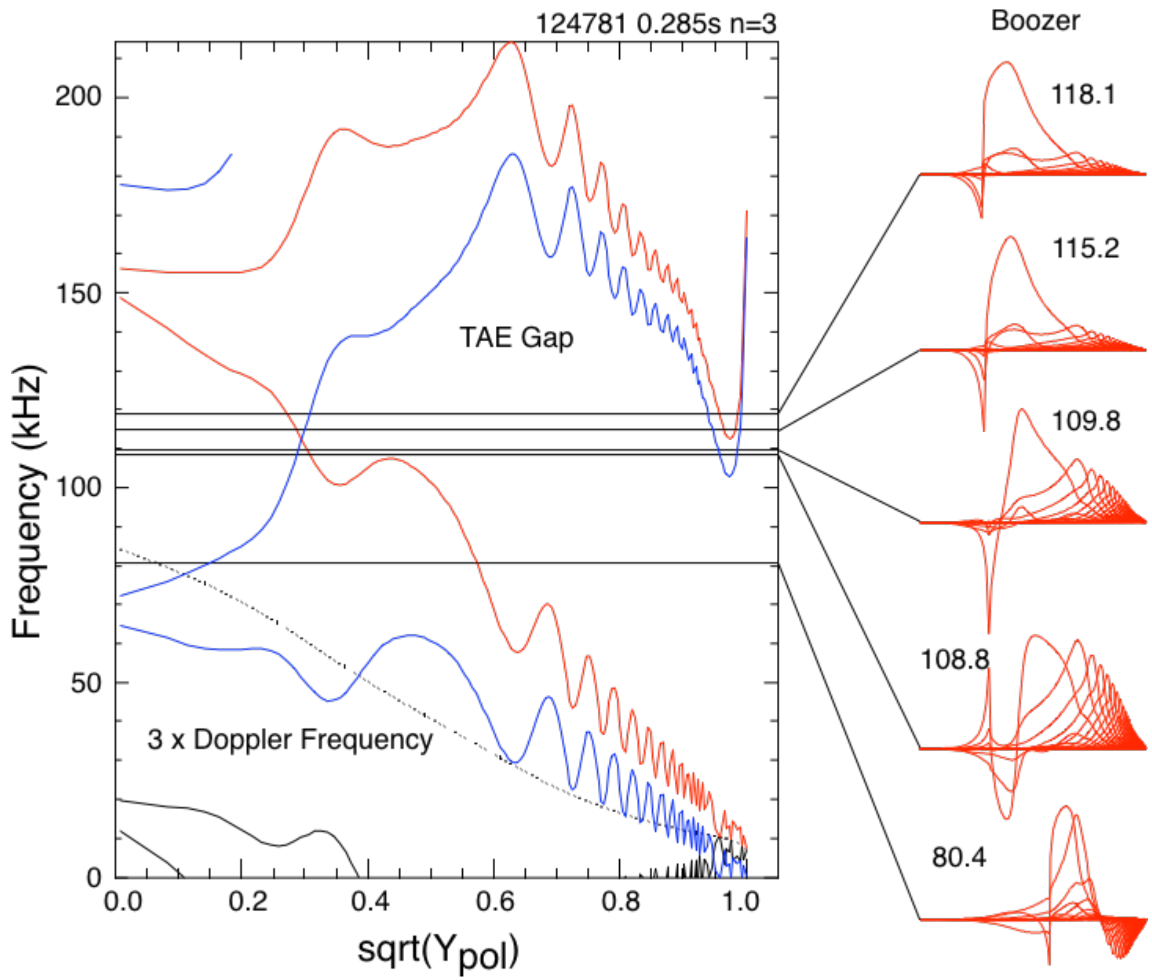
Podesta, Heidbrink



- 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

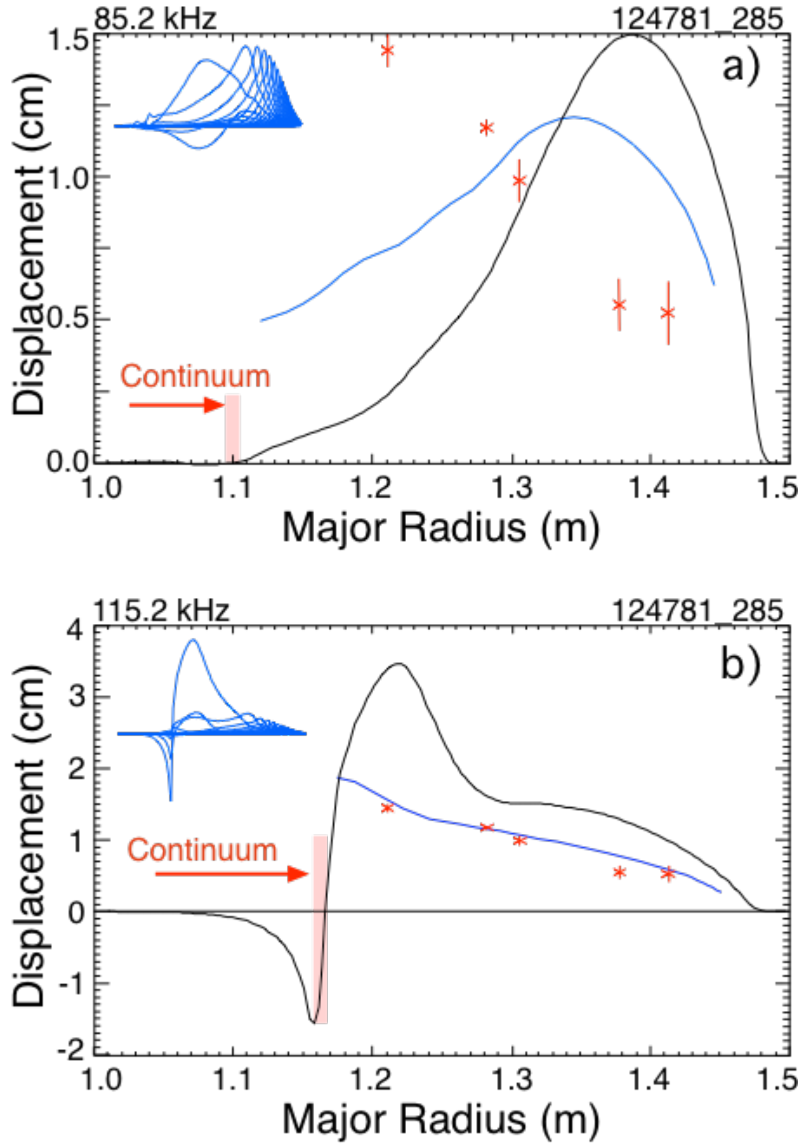


- NOVA simulation including Doppler shift corrections shows sheared rotation significantly distorts TAE gap.
- Gap is "closed", pushing modes outwards.
  - Less sensitive to evolution of q in core.
  - Non-resonant braking could clarify sheared rotation physics.

- 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

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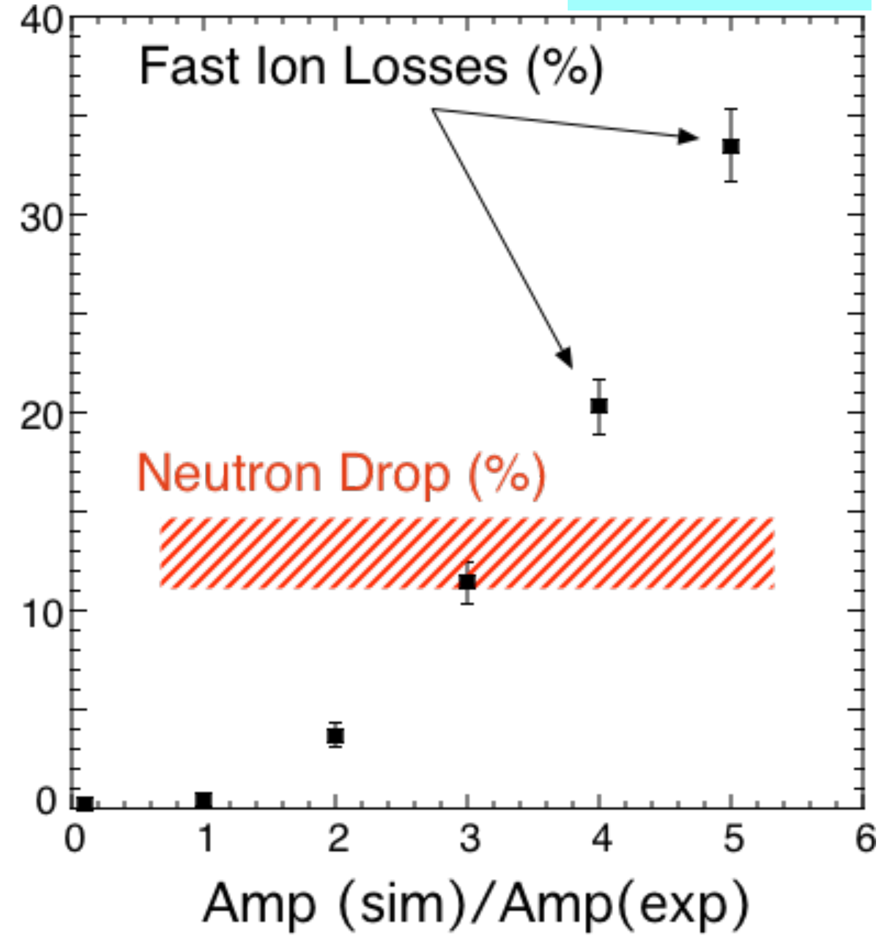
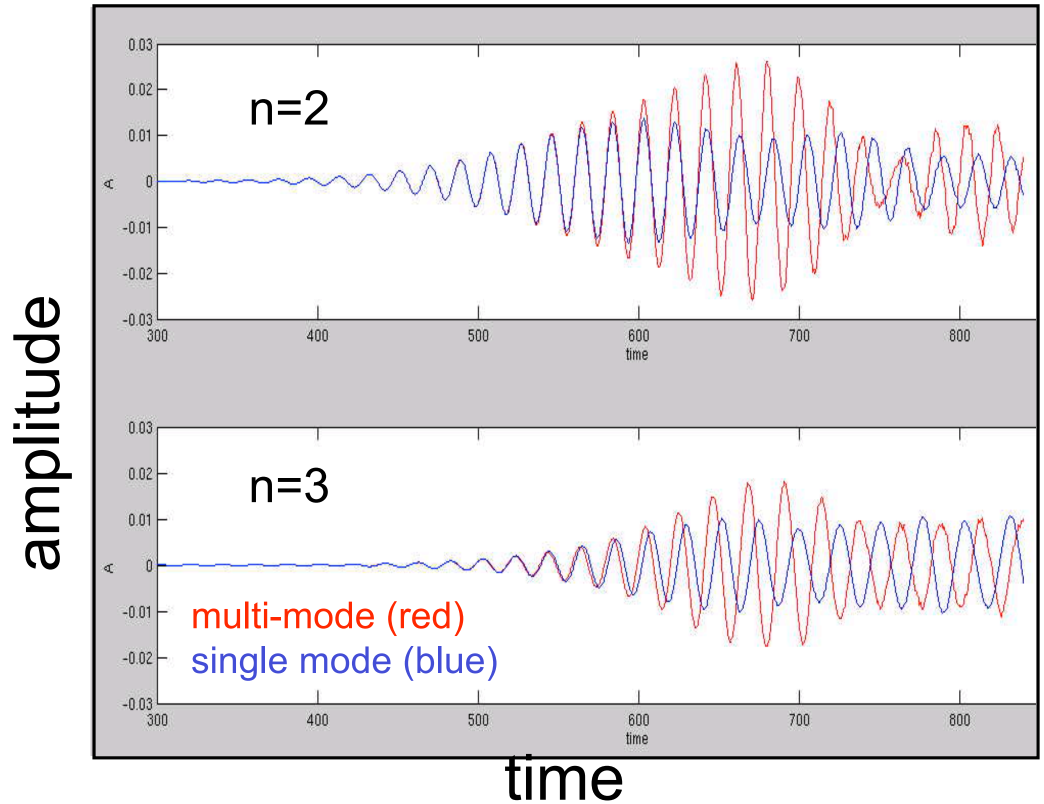
- Mode amplitudes and frequency evolutions from experiment are used in ORBIT simulation.
  - Compressional correction estimated to be ≈2.
- Presently, a factor of roughly 3 enhancement in mode amplitude is needed for ORBIT to reproduce experimental losses.
- Adding core mode may help.
  - GRYO-XY may 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

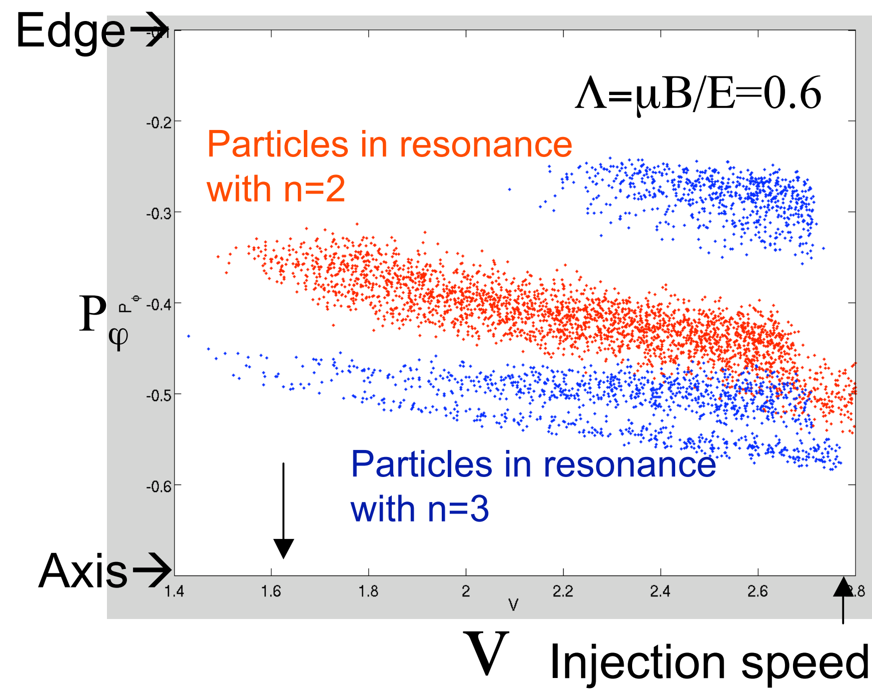
- Mode amplitude larger in multi-mode simulation (red).
- Individual modes saturate at lower amplitude.
- Simulation also reproduces frequency chirping.



M3D-k simulation captures physics of avalanche

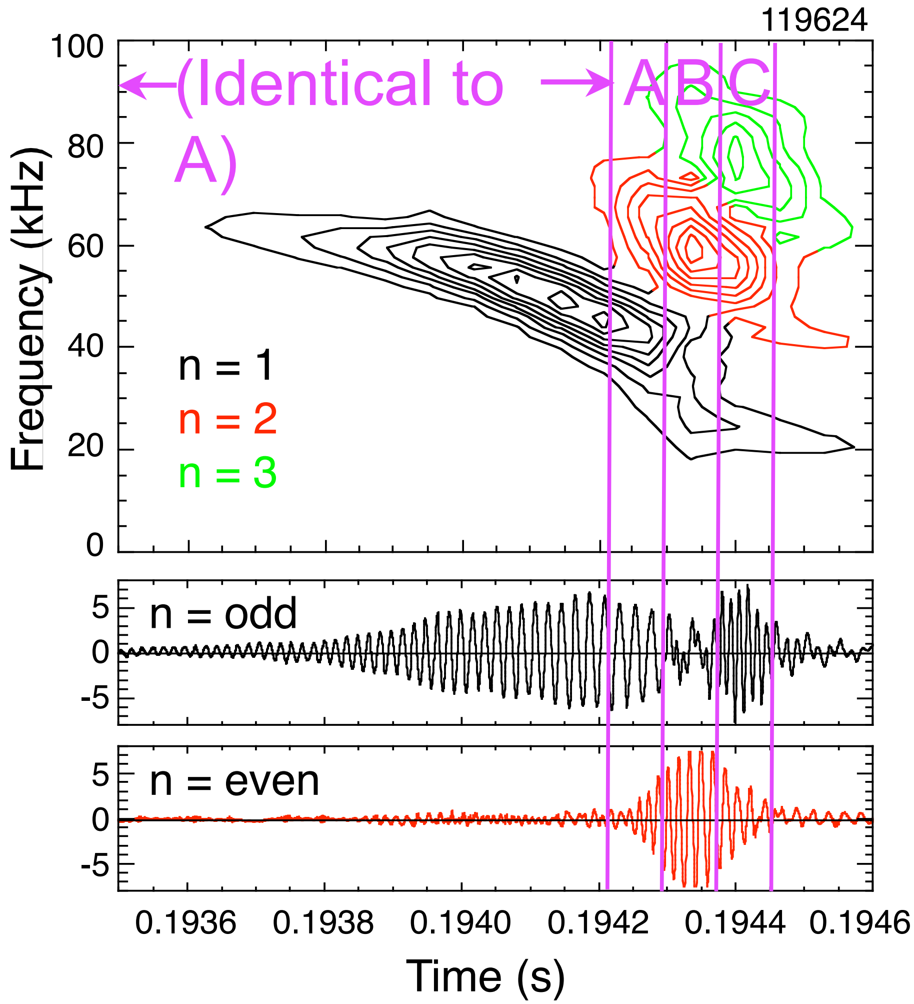
- Modes interact with broad range of fast ion energies; consistent with NPA measurements.

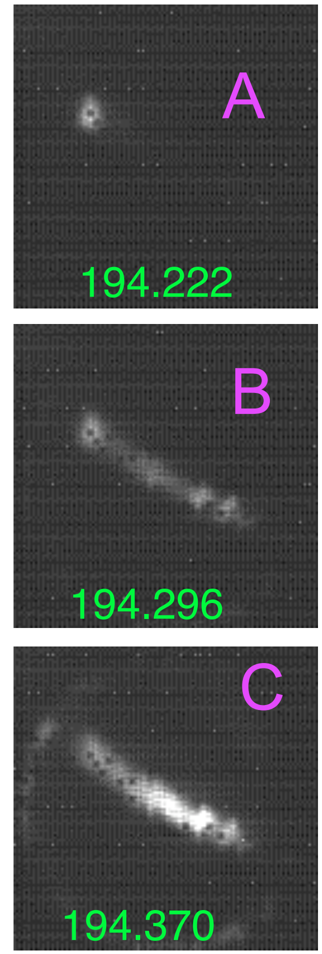
- Fast-ion resonances from single mode simulations show that resonances can (do) overlap.
- Multiple resonances are seen for n=3 mode.



- Simulation is for "generic" NSTX equilibrium; benchmarking for same equlibrium between NOVA and M3D is underway.

Avalanche behavior seen for GAE and EPM, also





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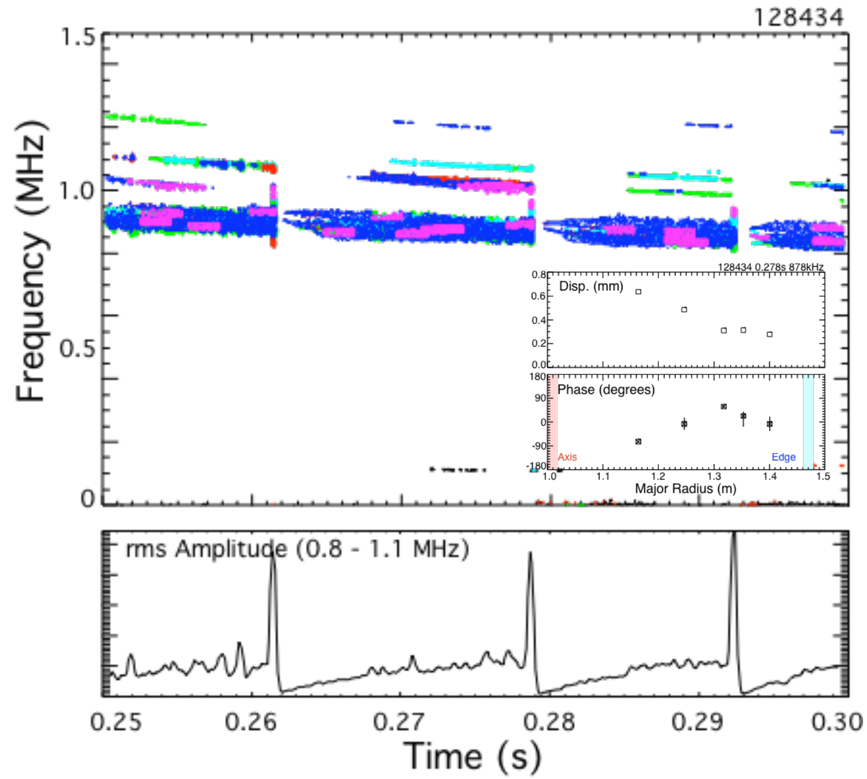
- Peak in fast ion losses correlated with multi-mode period.

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 EPMs



- 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

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- With new diagnostics, center-stack capabilities & beam line:
  - Avalanche scaling for wider range of ρ^*_{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)

Back-up Slides

NSTX has comprehensive diagnostic set for energetic particle driven mode studies

- Diagnostics to measure mode structure:
  - High frequency Mirnov arrays; ≈ 10 MHz bandwidth
  - Multi-channel reflectometer array; internal mode structure/amplitude
  - Multiple view soft x-ray cameras (≈ 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

Pre-2009
2009-2010
2011+

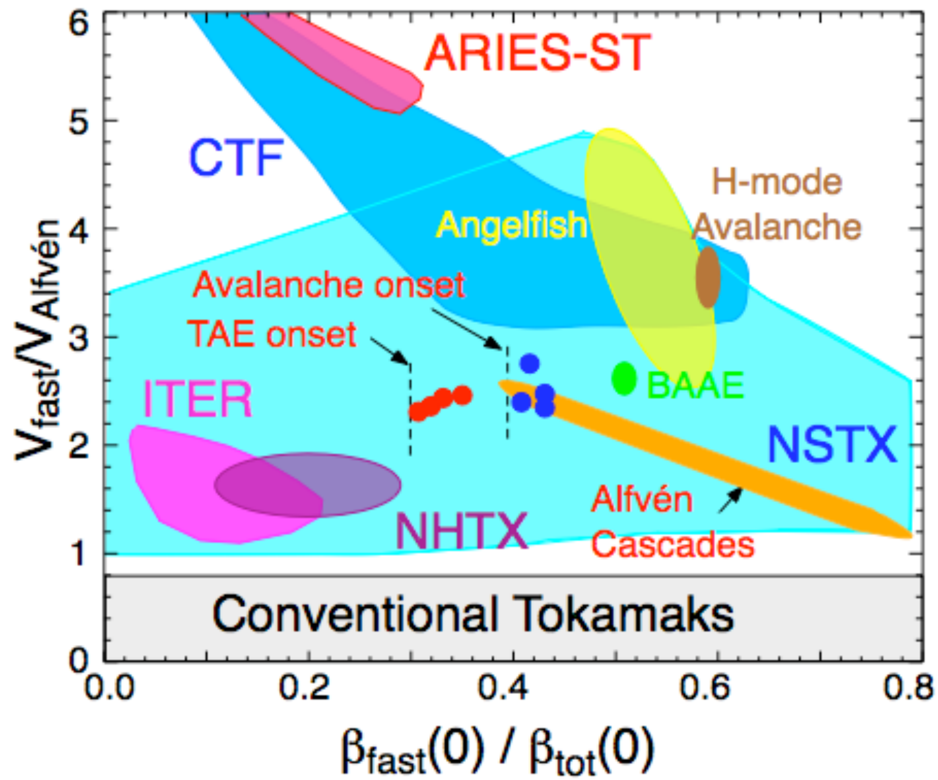
- Fast particle diagnostics:
  - Fast neutron rate monitors
  - Neutron collimator; spatial profiles of fastest ion populations
  - Scanning NPA; high energy resolution, vertical and radial scan
  - ssNPA; 5-channel midplane radial array
  - sFLIP; scintillator lost ion probe, energy/pitch angle resolved (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

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

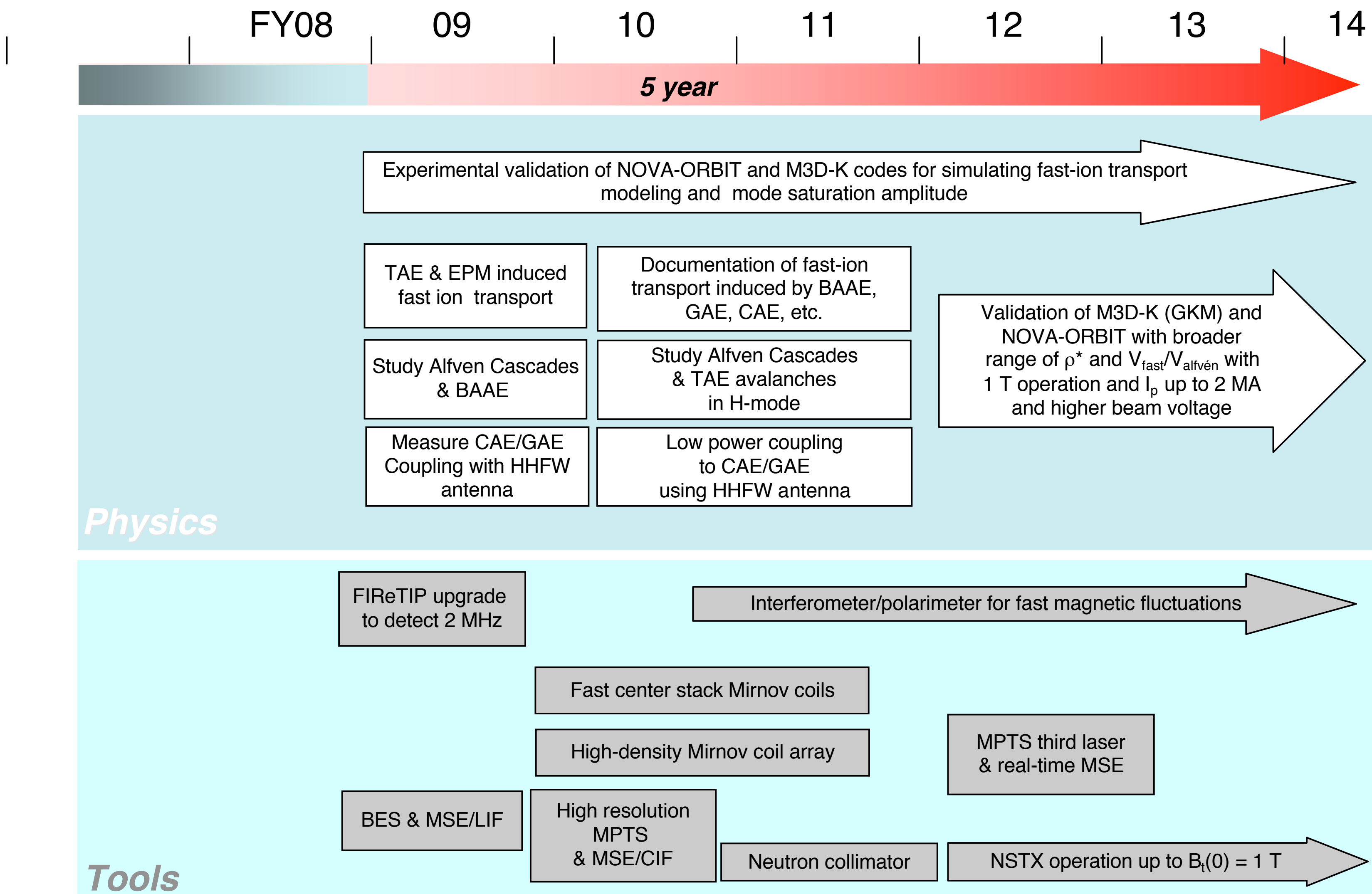
NSTX accesses broad range of fast ion parameters, broad range of fast particle modes

- 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 ρ^* of NSTX compensated by higher beam beta



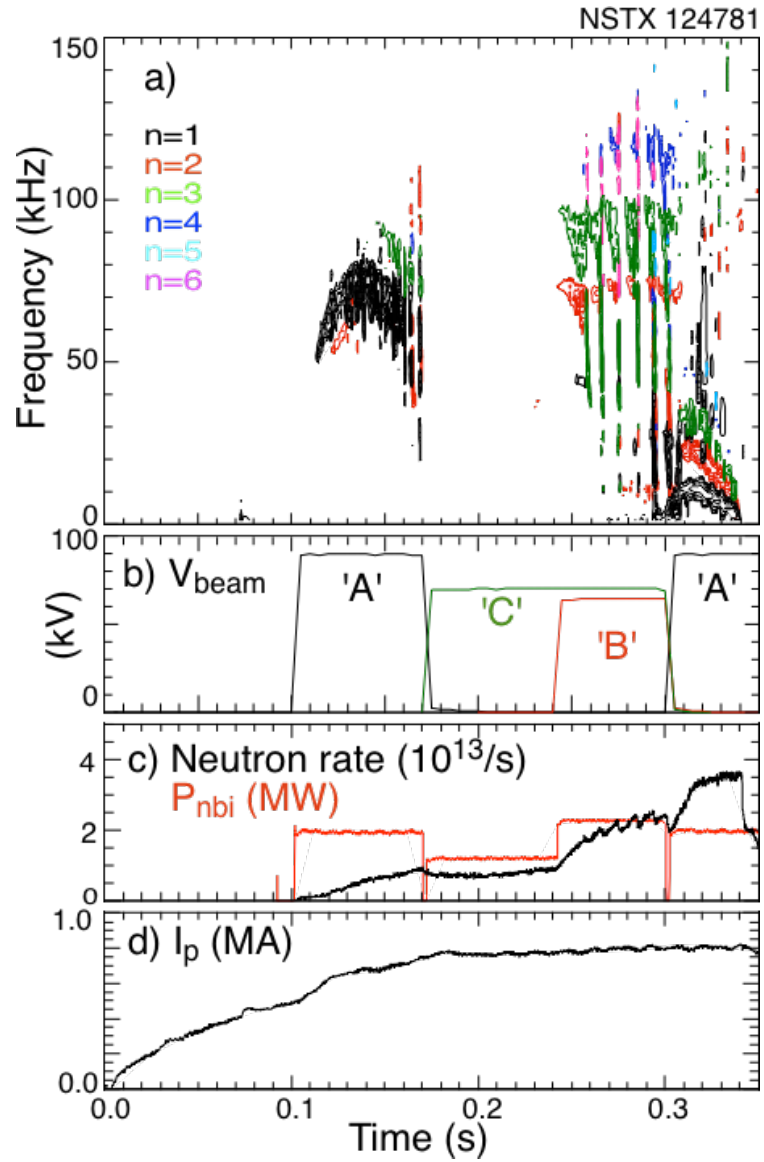
Cartoon is over-simplification and there are other dependences.

2009-13 Energetic Particle Research Timeline



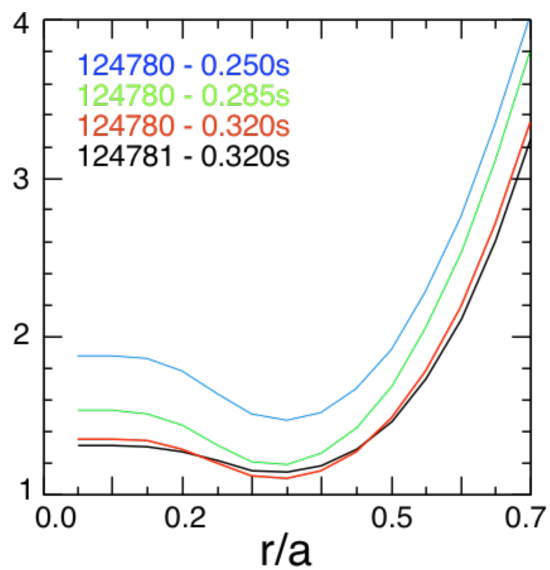
Shot evolution carefully taylored to optimize studies of TAE avalanches

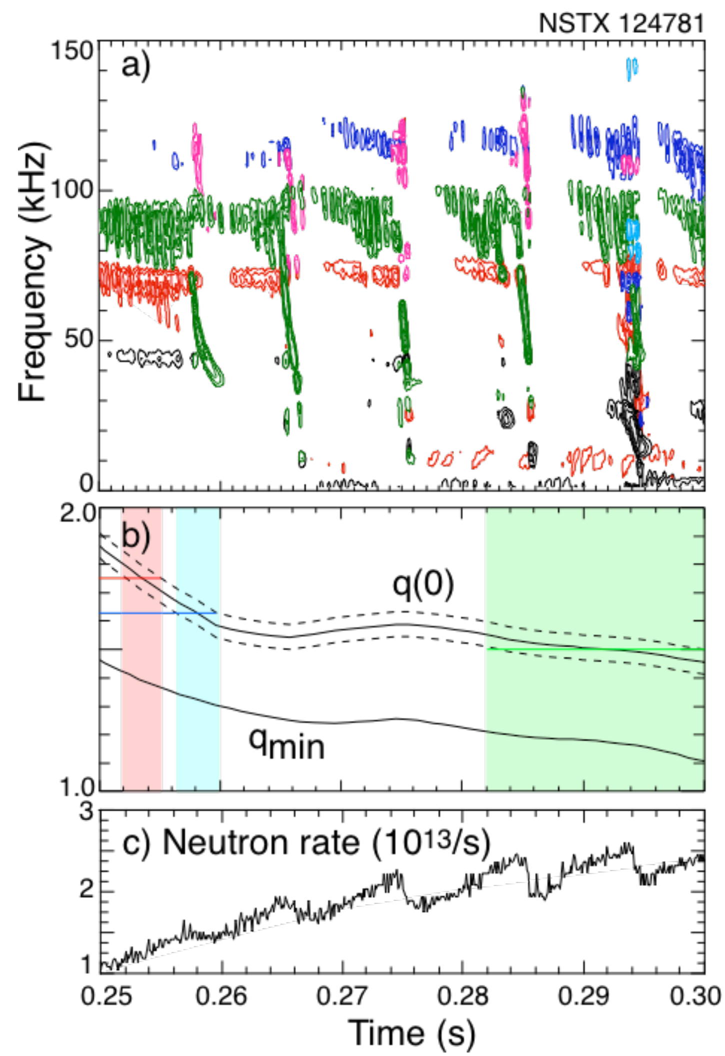
- Plasma kept in L-mode with Helium puffing to provide reflectometer access.
- Low voltage beams more efficiently excite TAE avalanches
- q-profile measurements with MSE require 90 kV heating beam; interferes with mode drive.
  - Source A injected early to get initial q-profile and shortly after time-of-interest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

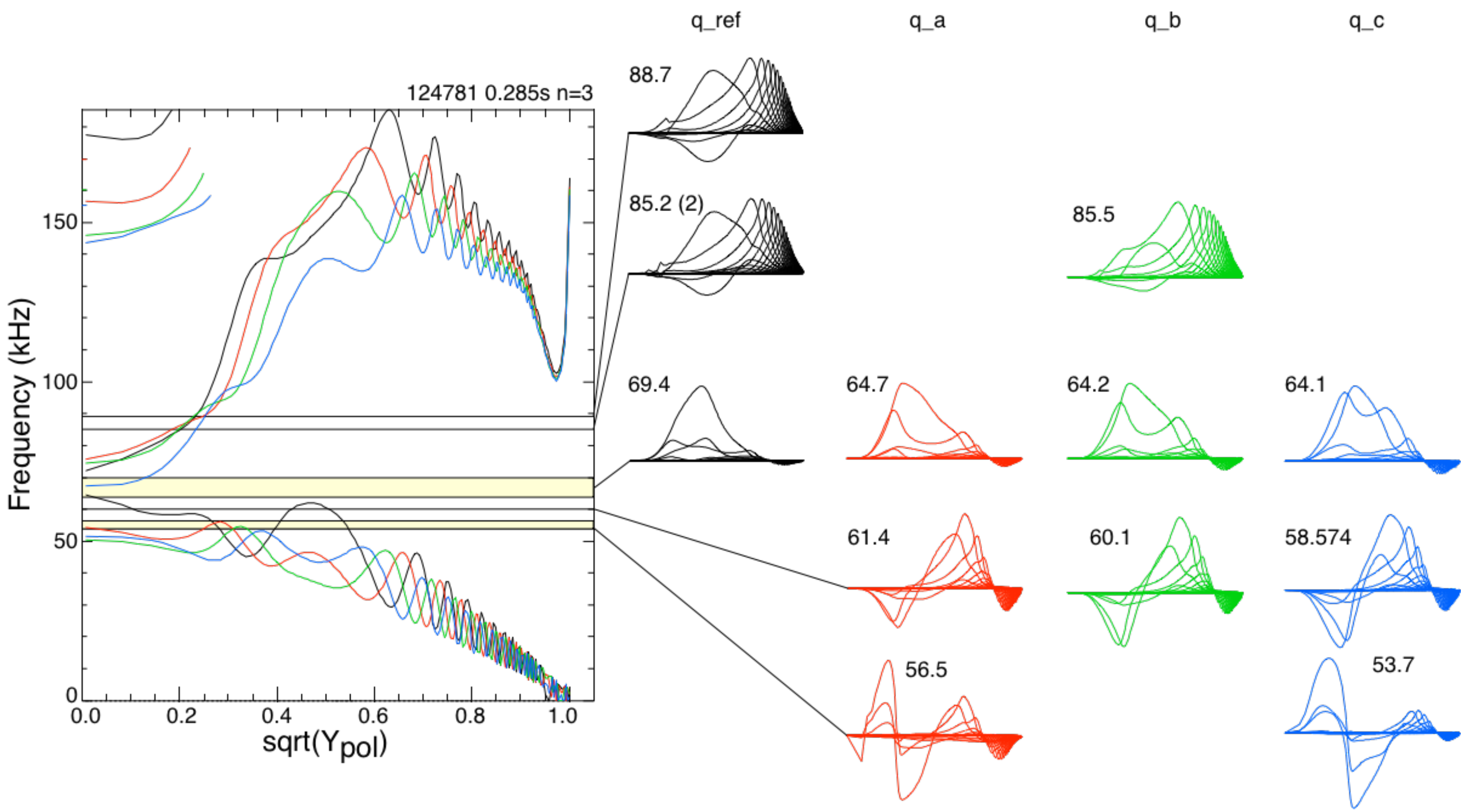
- TAE gaps on axis should open and close as q(0) drops in core.
- Time evolution depends on toroidal mode number, that is when q(0) = rational (m/n).
- Could be explained if sheared rotation closed gap access to core region.





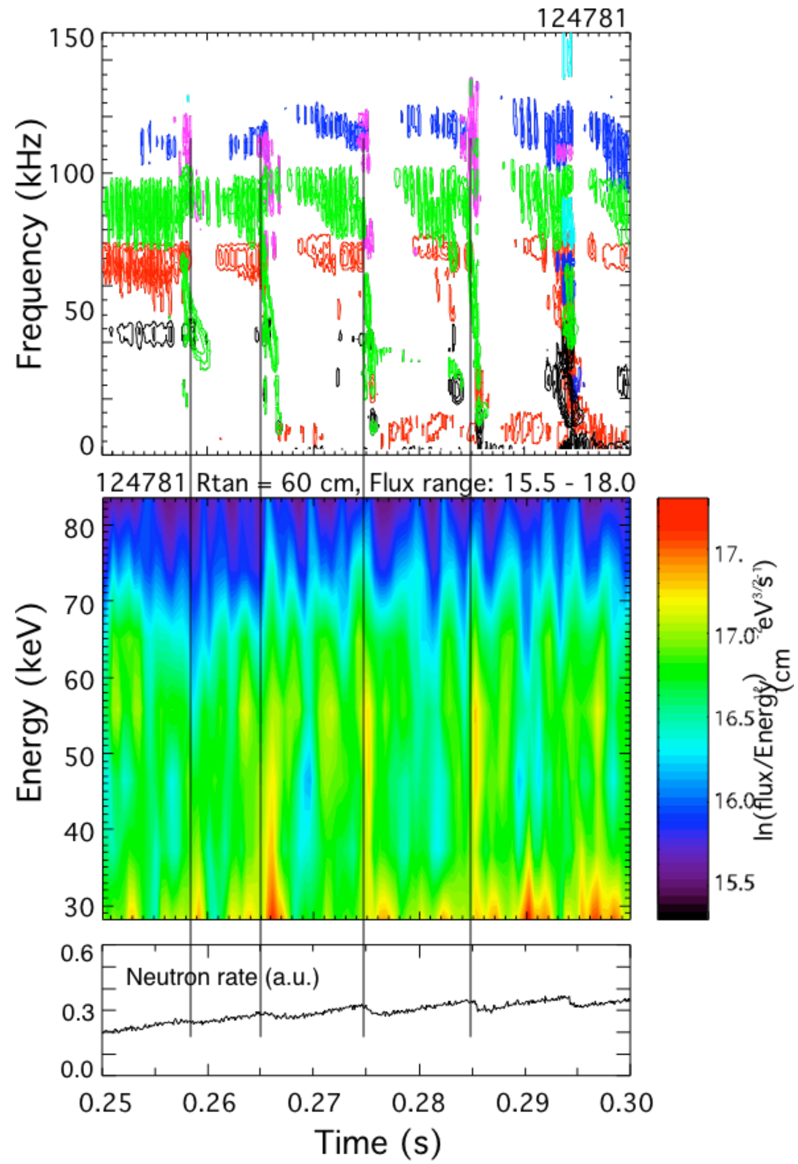
n=3 Gap closes as q(0) approaches 1.5

- Sheared rotation correction not included here.

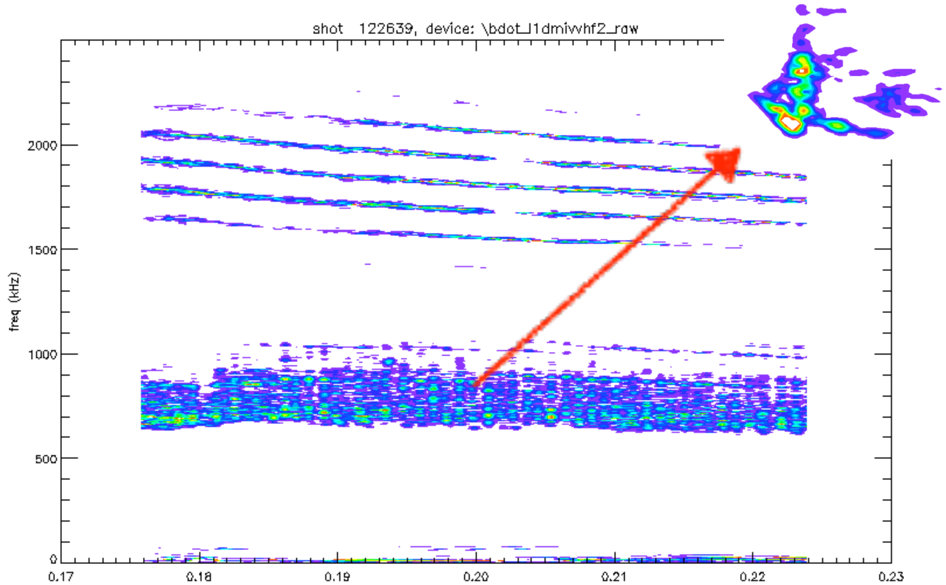


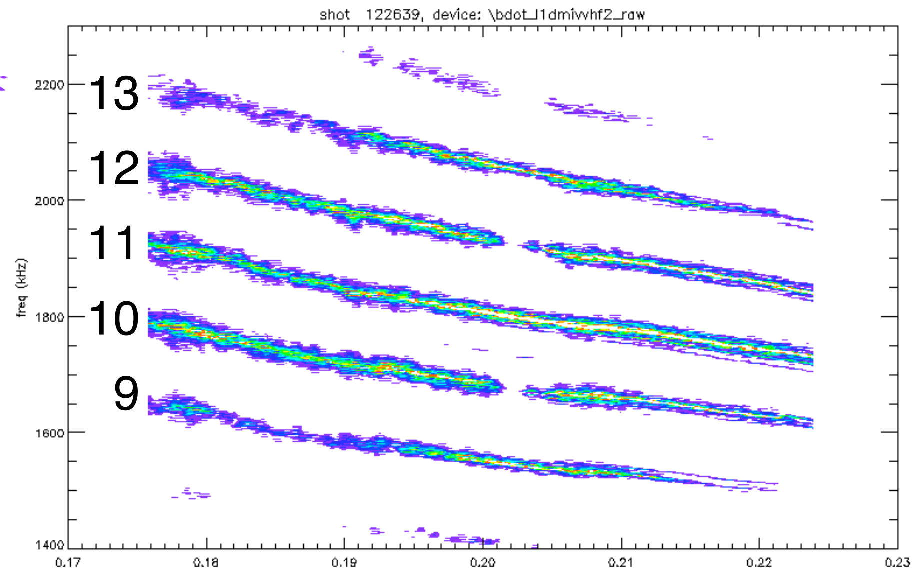
Documentation of fast ion transport, code validation, highest priority goal for EP group

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

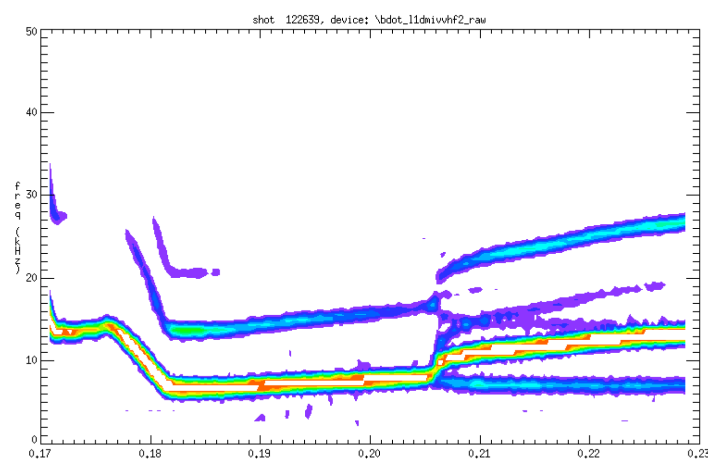


CAE at higher frequencies (1.5 - 2.5 MHz)



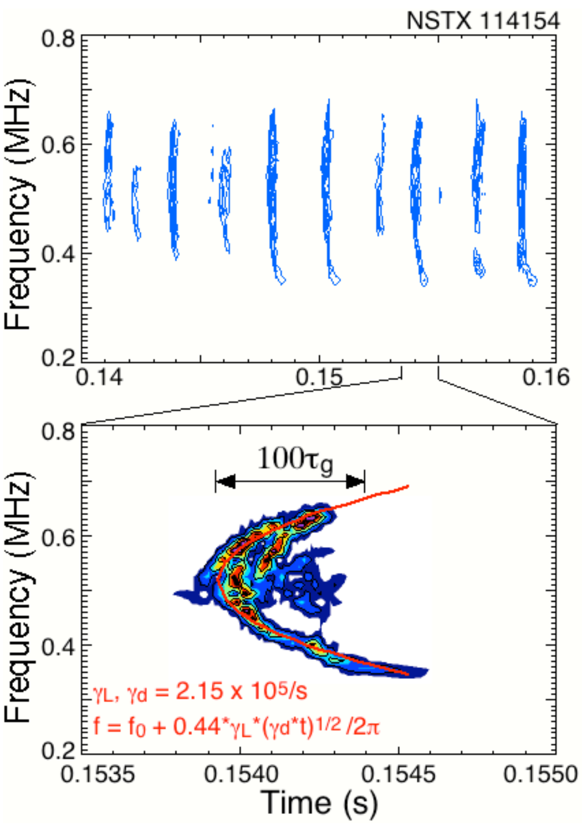


- Good fit to CAE dispersion relation and fast ion resonance condition.
- Only present with low frequency kink.
- So far, only seen in H-mode, but most plasmas are H-mode by this time.
- Reflectometer data would be nice...

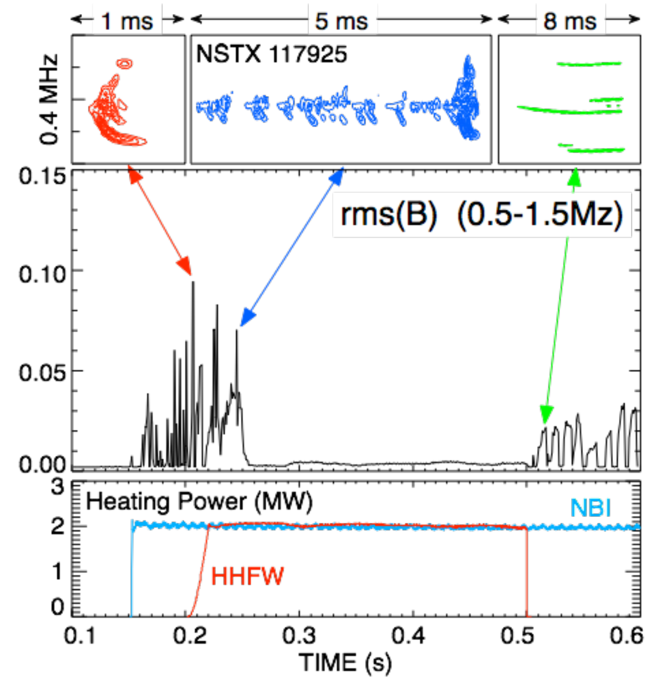


Studies of Angelfish (hole-clumps) illuminate physics of fast ion phase space structures

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

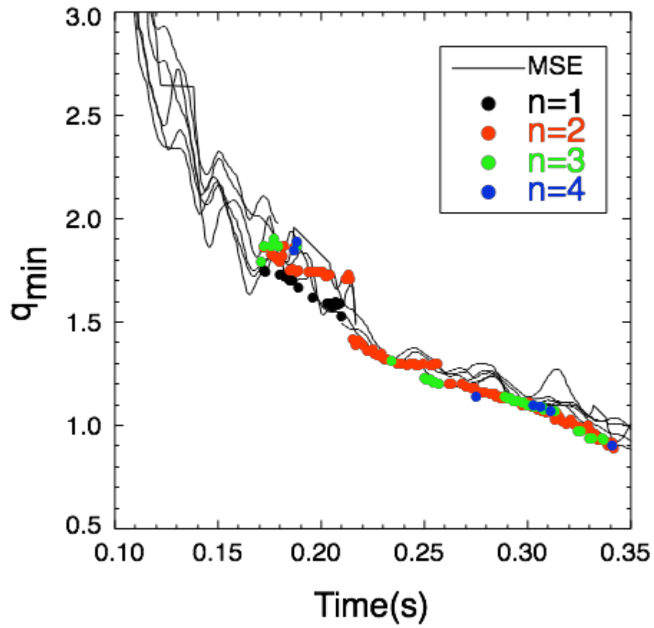


- Linear growth rate in good agreement with analytical estimates

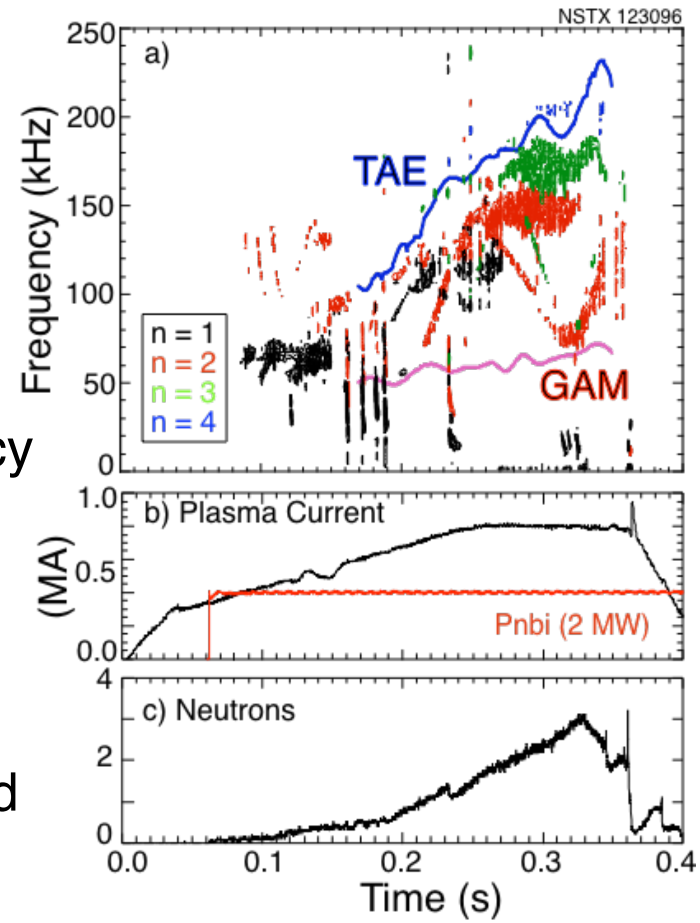


- Suppression power threshold in qualitative agreement with predictions
- Understanding phase-space structures could lead to methods of TAE control

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.

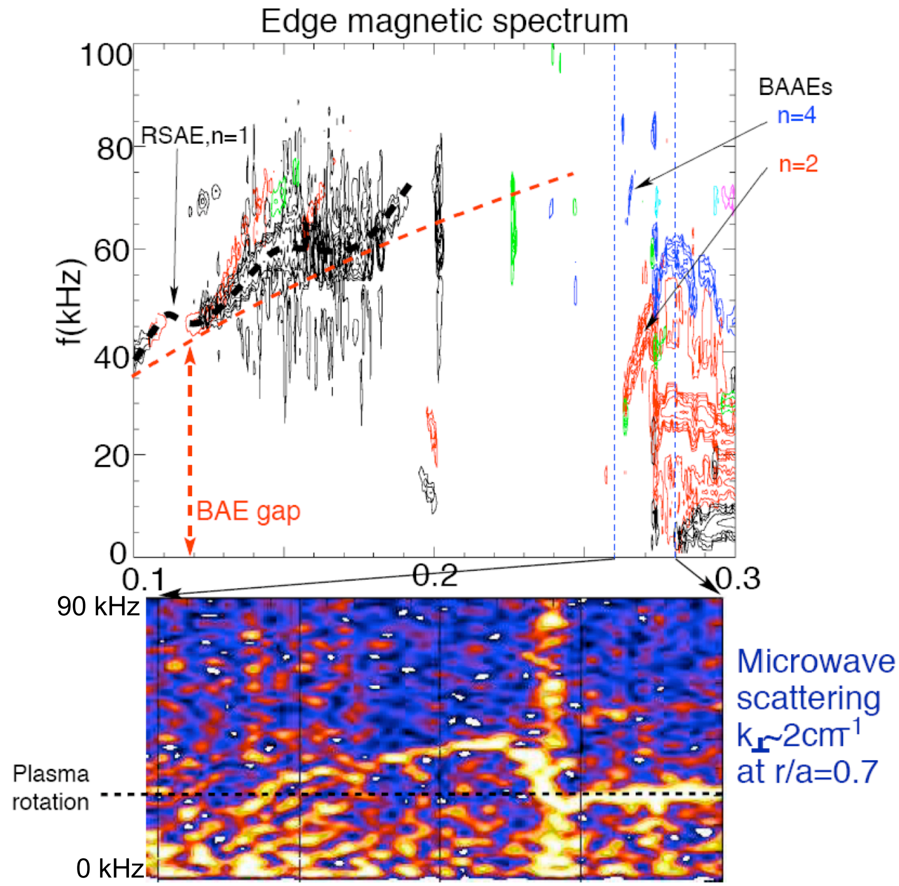


- Frequency minimums are at the GAM frequency
  - Scaling studies of f_{GAM} measure γ of thermal, energetic plasma components.
- Sheared rotation affects stability, frequency; studied with non-resonant braking.
- Mode structure will be measured with BES, and reflectometers and higher field.

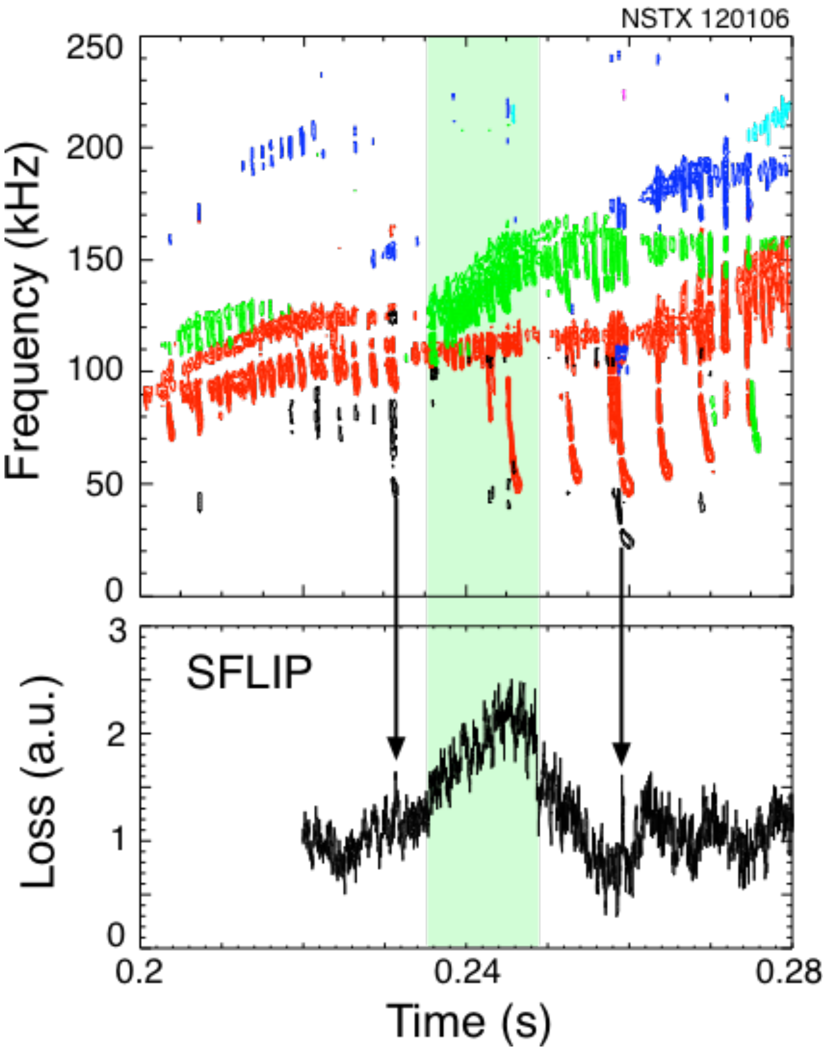
Coupling of Alfvén and Acoustic branches at high β introduce a new 'gap', modes; BAAE

- β-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 β, f_{GAM}/f_{TAE} larger; rsAE eventually become stable
- Modes only seen at low to very low β (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.