NSTX

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Energetic particle physics: progress and plans

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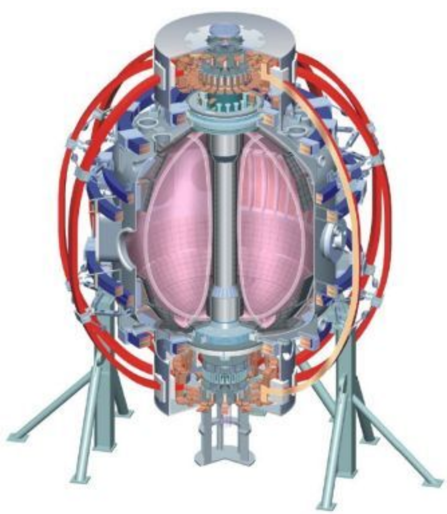
E. D. Fredrickson, PPPL

For the NSTX Research Team

NSTX 5 Year Plan Review for 2009-13
Conference Room LSB-B318, PPPL
July 28-30, 2008



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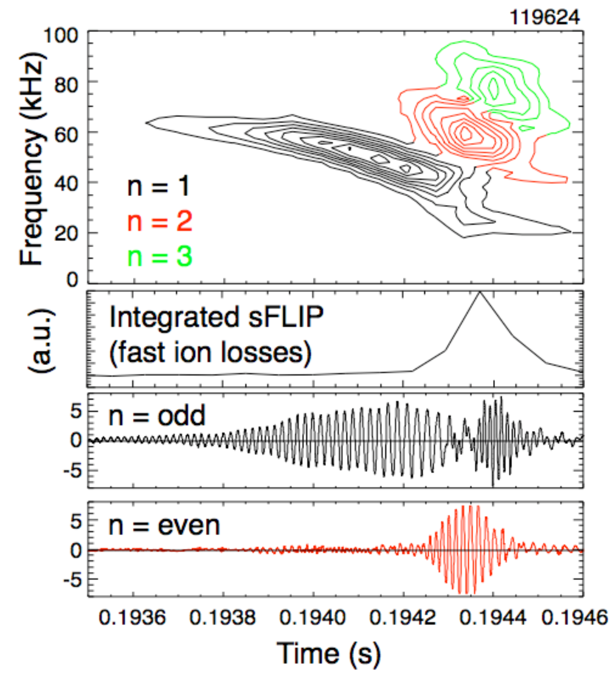
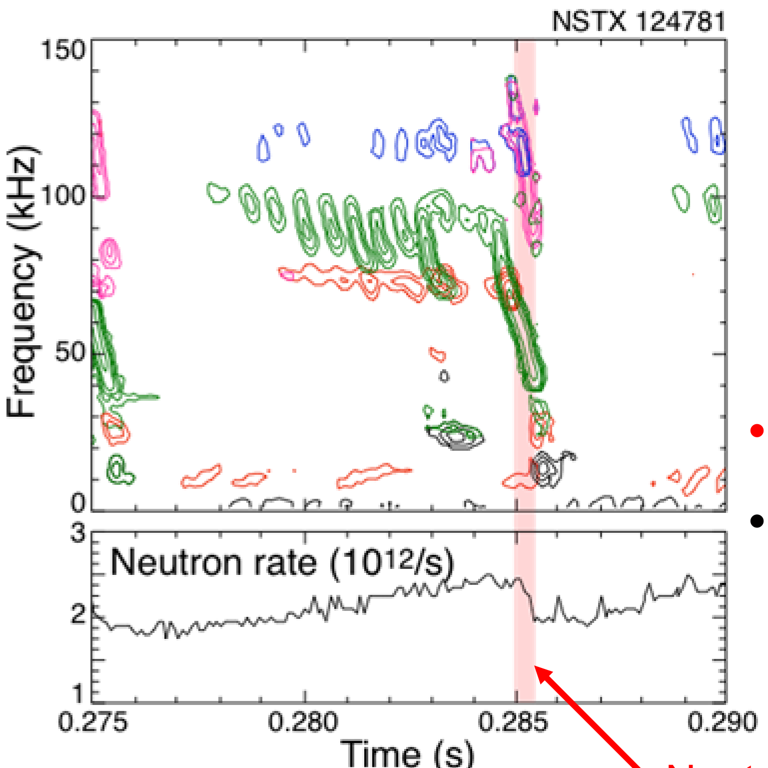
NSTX is uniquely positioned to study energetic particle physics required for next-step devices

- 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.
- NSTX routinely operates with super-Alfvénic fast ions.
  - Neutral beam energy at 60 - 100 kV, $1 < V_{fast}/V_{Alfvén} < 5$
    - 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 relevant to ITER/future STs
  - Fast ion losses have been correlated with both TAE and EPMs.
  - Losses typically largest when multiple modes interact; the predicted loss mechanism for ITER.

Fast ion losses seen with TAE Avalanches, EPMs, of concern for future devices

- Fast ion losses correlated with multi-mode period of Energetic Particle Mode (EPM).
- Not classic fishbones; multiple, independent modes, potentially an issue for future STs.



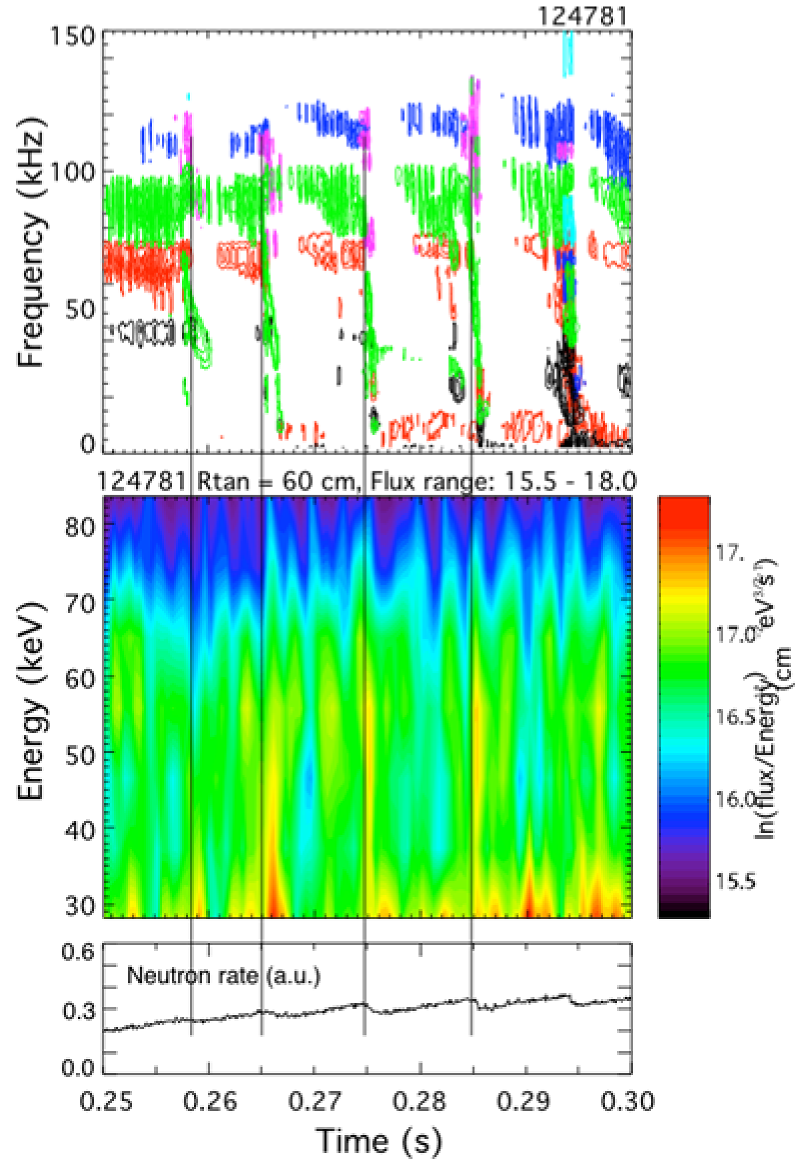


- TAE avalanches identified on NSTX
- Threshold in β_{fast} identified; scaling to follow in future experiments.
  - ST-CTF in avalanche parameter regime

Neutron drop at avalanche

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

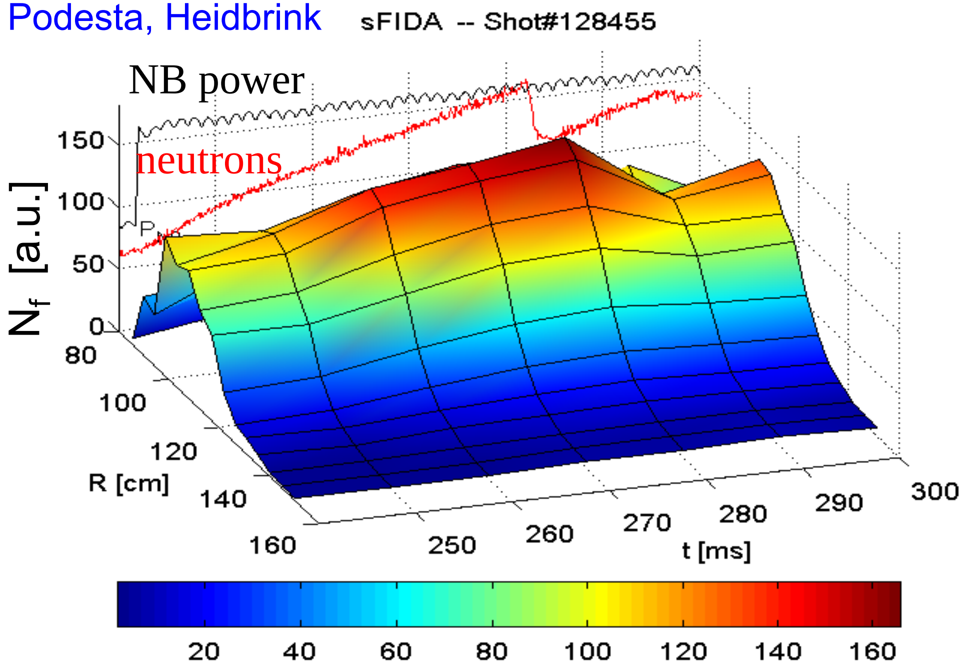
- Fast ion redistribution indicated by neutron drops and in ssNPA and NPA data.
- Lower energy ions ($V_{fast}/V_{Alfven} > 1$) seem most strongly affected.
  - Additional experiments needed for quantitative measurements, identification of fast ions involved.
- No lost fast ions seen on sFLIP detector;
  - However, bursts of H_α light are correlated with avalanches,
  - fast ions may be lost to another part of limiter/wall

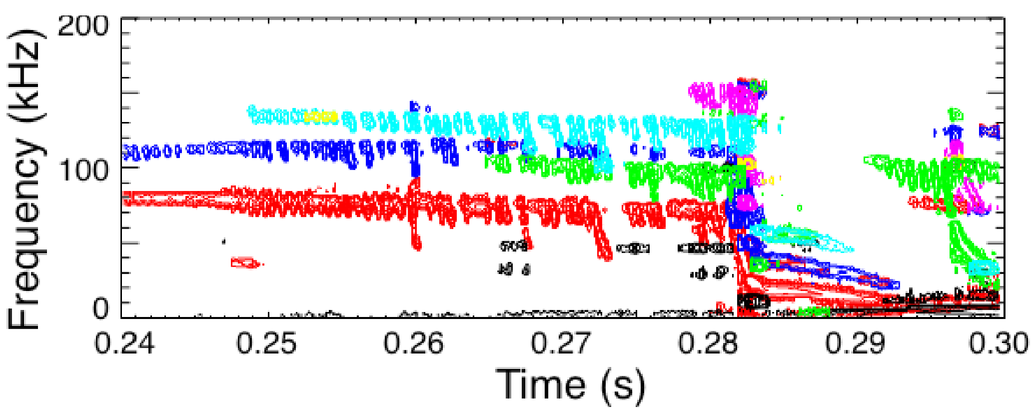


Fast-Ion D-alpha (FIDA) measures confined ions

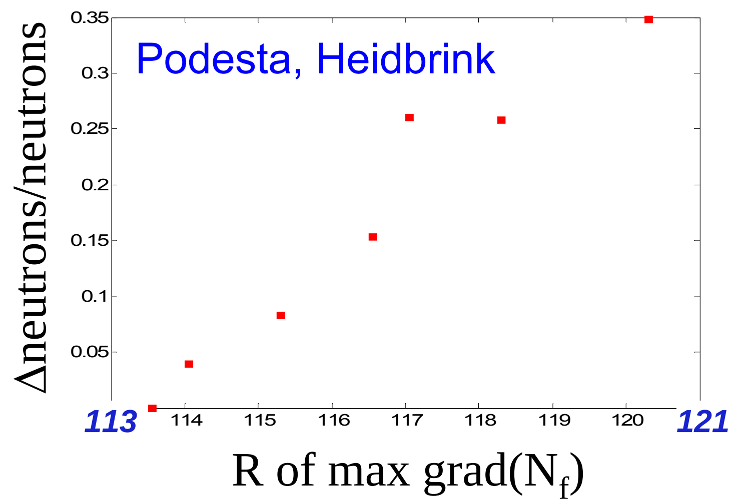
- FIDA measures change in N_f profile for TAE avalanche @ 282ms :

Podesta, Heidbrink



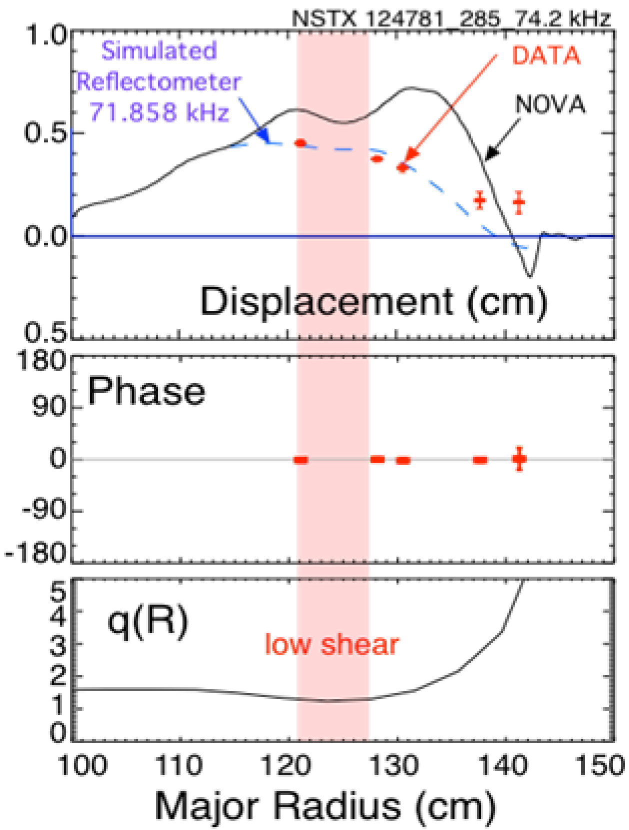


- Fast-ion profiles still centrally peaked after avalanche
- Good correlation between:
  - Drop of neutron rate and of fast-ion density from FIDA.
  - Losses and position of maximum spatial gradient of FIDA density profiles
    - 2nd NB allows control of instability drive

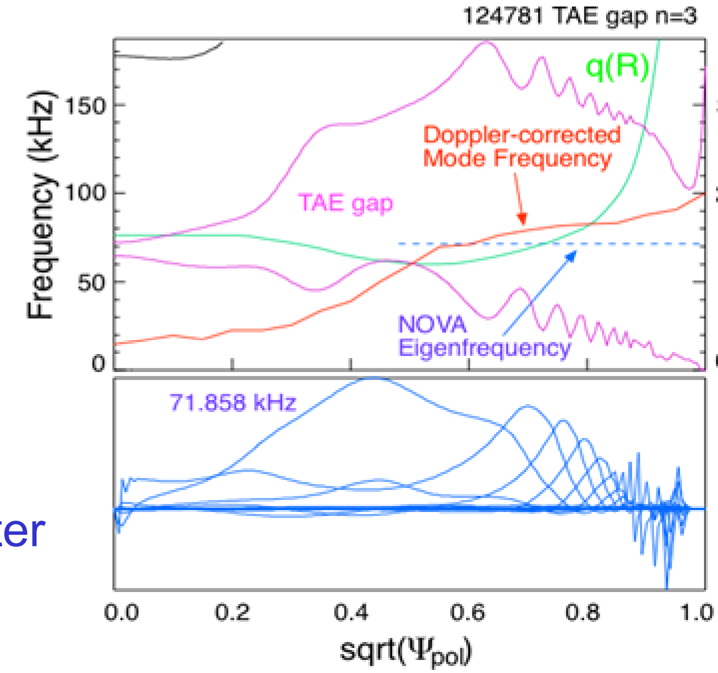


NOVA simulates mode structure, compared to reflectometer measurements

- NOVA is a linear code, mode structure is scaled to measured amplitude for use in ORBIT code.



  - Modeled eigenmode compared with "synthetic reflectometer diagnostic"

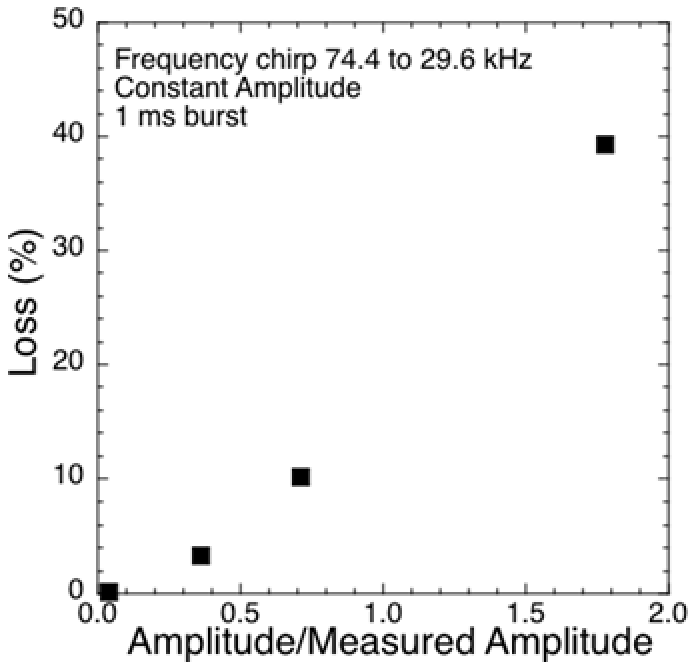


- Similar analysis is done for each of the detected modes.
- ORBIT is used to simulate fast ion redistribution with modeled and measured mode structure/amplitude.

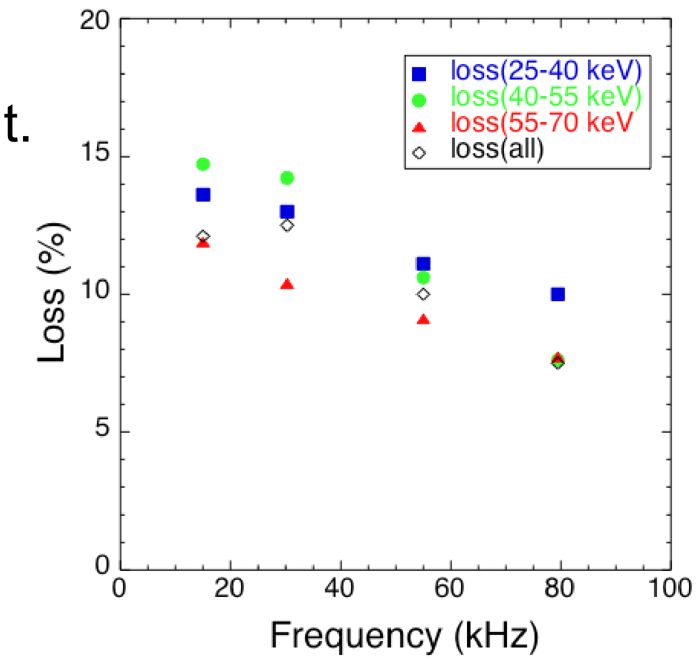
ORBIT simulations of losses consistent with measurements

- Fast ion losses approximately consistent with neutron rate drop.
- Scaling of losses with mode amplitude are slightly non-linear.
- Multiple modes further enhance losses.

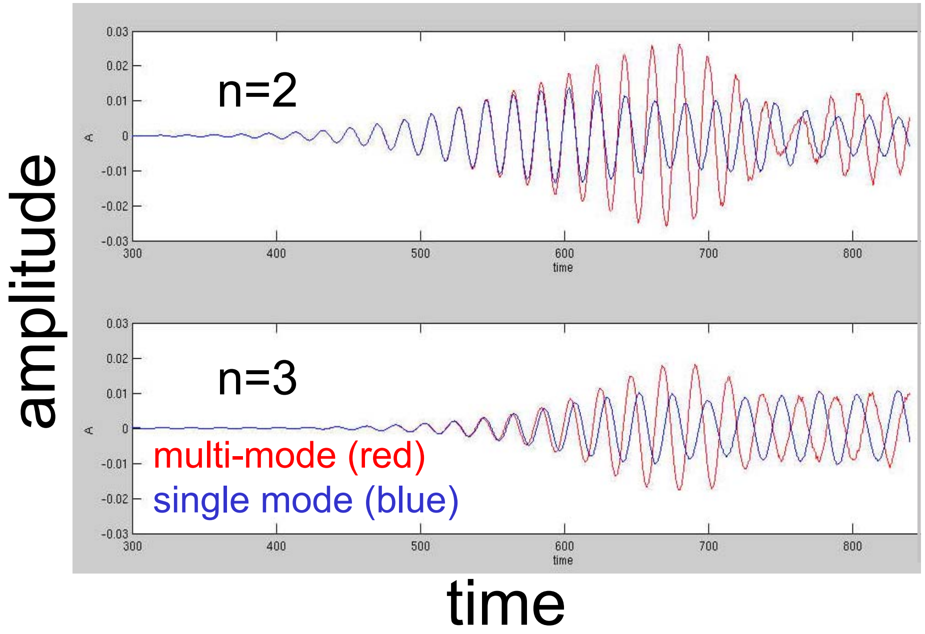
- ORBIT predicts fast ion losses over wide range of energies.
- Losses are larger for lower mode frequencies.
- Drive is stronger for lower energy ions?



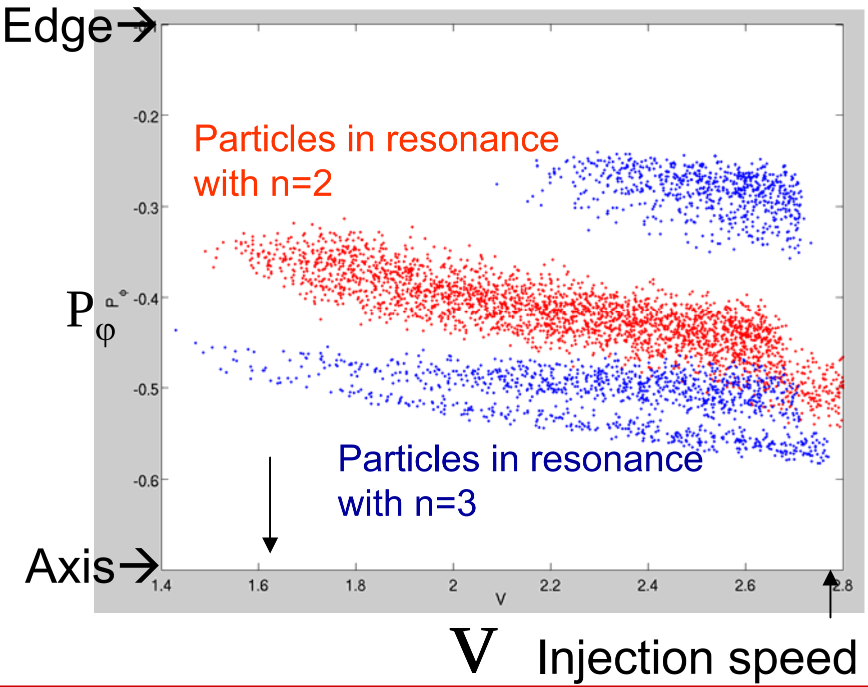
- Simulation is not fully self-consistent.
- Frequency chirps, interaction of modes only approximates resonance interactions; still need M3D (GKM).



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.



- Fast-ion resonances in single mode simulation show that resonances are overlapping.
- Multi-mode simulation shows larger perturbation of fast-ion distribution.

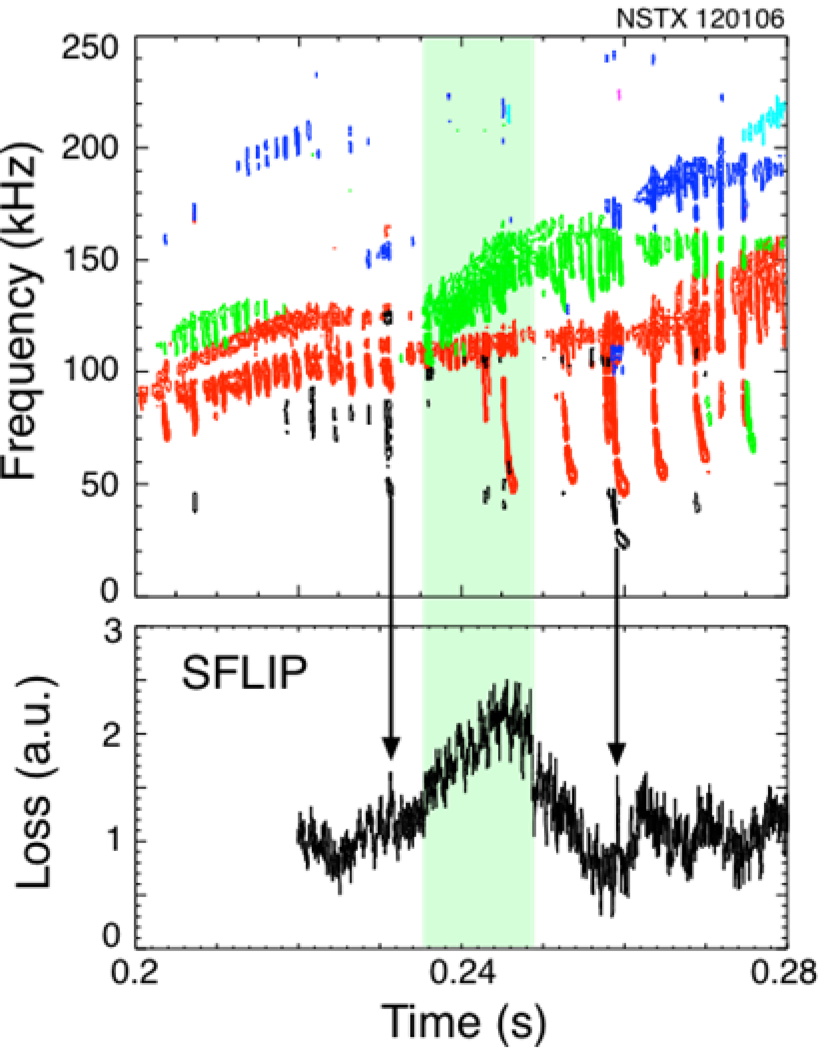
Validating predictive capability for fast ion transport from TAE highest priority goal for 2009-2013

- 2009-2011
  - Effect on NBI current will be investigated during TAE avalanches with:
    - FIDA, vertically scanned NPA, ssNPA, neutron and sFLIP diagnostics.
  - Scaling of Avalanche onset threshold with $V_{fast}/V_{Alfvén}$, and q-profile variations.
  - Complete study of J(r) modification by super-Alfvénic ion driven modes
  - Avalanche studies in H-modes w/BES for internal structure
  - EPM effect on fast ions, measure internal mode structure
  - EPM scaling studies with q(0) and β scaling, precession drift reversal
  - EPM scaling studies with q(0) and β scaling, study precession drift reversal
  - Neutron collimator data as complementary fast-ion redistribution diagnostic for high density H-modes.
- 2012 - 2013
  - New center-stack; avalanche scaling for wider range of ρ^*_{fast} and $V_{fast}/V_{Alfvén}$.
  - First measurements of internal magnetic fluctuations for *AE modes?
  - Pitch-angle, radial fast ion profile studies with 2nd NB (incremental)

Spherical tokamak parameters in new regime; NSTX diagnostics can validate unique EP physics

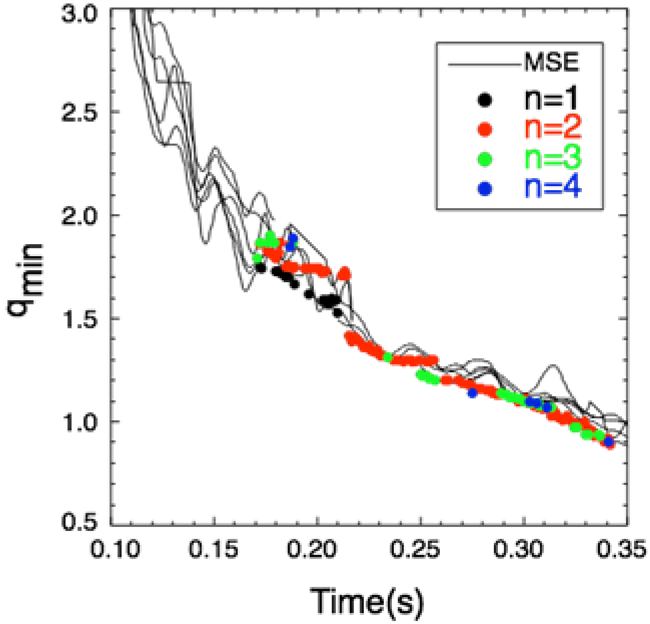
- Low field, high β make Alfvén and Acoustic wave coupling stronger in STs
  - Coupling modifies EP modes seen in conventional aspect ratio tokamaks
  - Understanding new modes important to future STs
  - New physics, modes can be diagnostic of plasma parameters
- Unique diagnostic capabilities on NSTX facilitate code validation of new physics and regimes
  - TF field range on NSTX ranges from 3 kG to 1 T
    - NSTX MSE diagnostic provides q-profile measurements over this range.
  - Extensive diagnostics can directly measure coupling of modes offering unique opportunities for code validation.
    - Coupling to Kinetic Alfvén Wave (high-k scattering)
    - Coupling of rsAE and Geodesic Acoustic modes (GAM)
    - Coupling of TAE and rsAE
    - β-induced Alfvén Acoustic Eigenmode (BAAE)

rsAE in ST plasmas offer multiple opportunities for unique physics studies

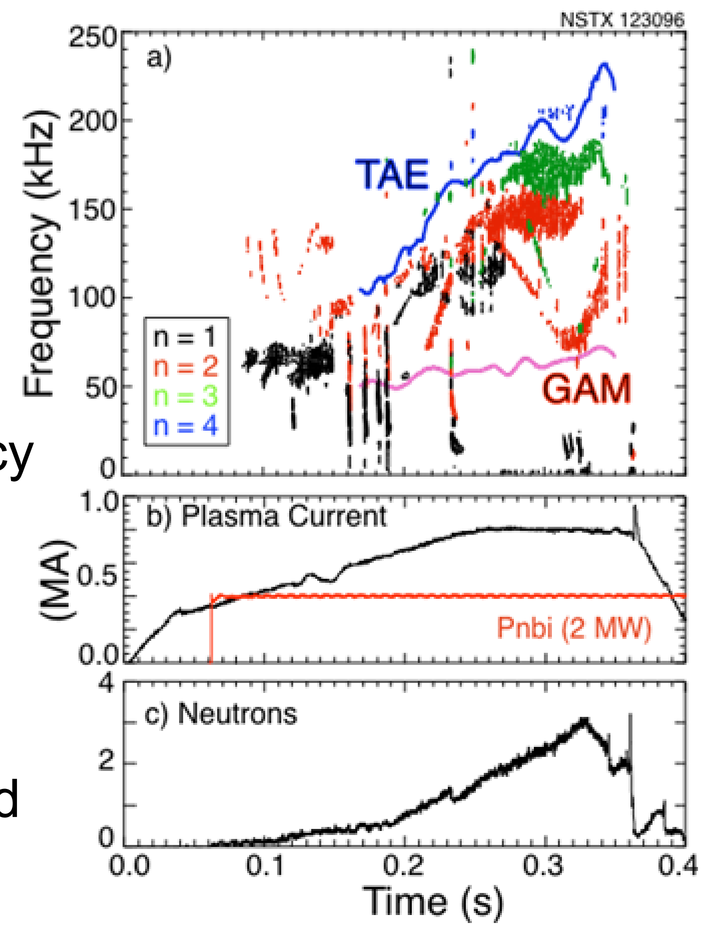


- For higher β, f_{GAM}/f_{TAE} larger; rsAE eventually become stable
- Modes only seen at low to very low β (density) for low field NSTX operation; 1 T will expand range of density.
- BES, reflectometer and low field MSE measurements will be used to validate NOVA and M3D for:
  - Coupling of rsAE to 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.

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.

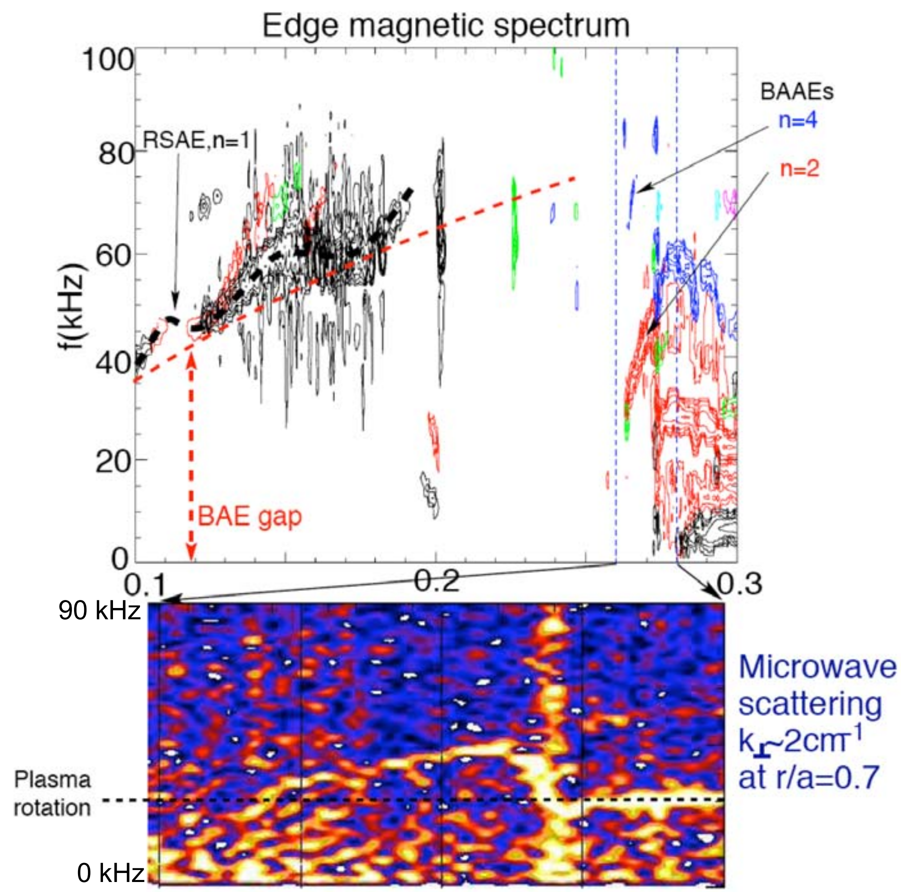


- Frequency minimums are at the GAM frequency
  - Scaling studies of f_{GAM} measure γ of thermal, energetic plasma components.
- Sheared rotation affects stability, frequency; studied with non-resonant braking.
- Mode structure will be measured with BES, and reflectometers and higher field.

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

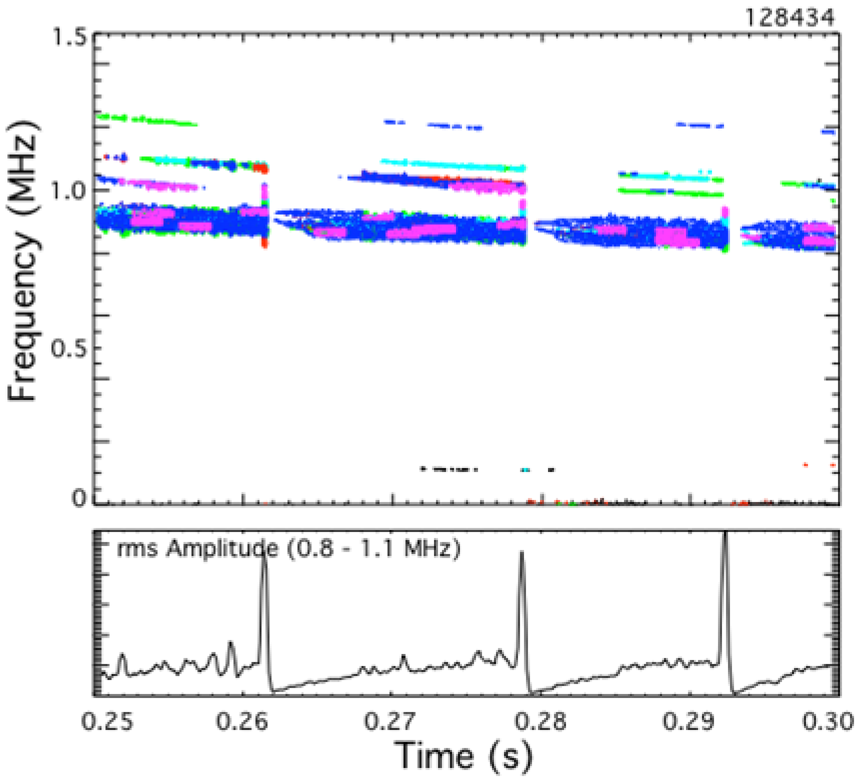
- β-induced Alfvén-Acoustic modes (BAAE) exist in gap opened by coupling of the Alfvén and acoustic branches.
- Frequency sweep can be used for MHD spectroscopy, as with rsAE.

- 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).



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

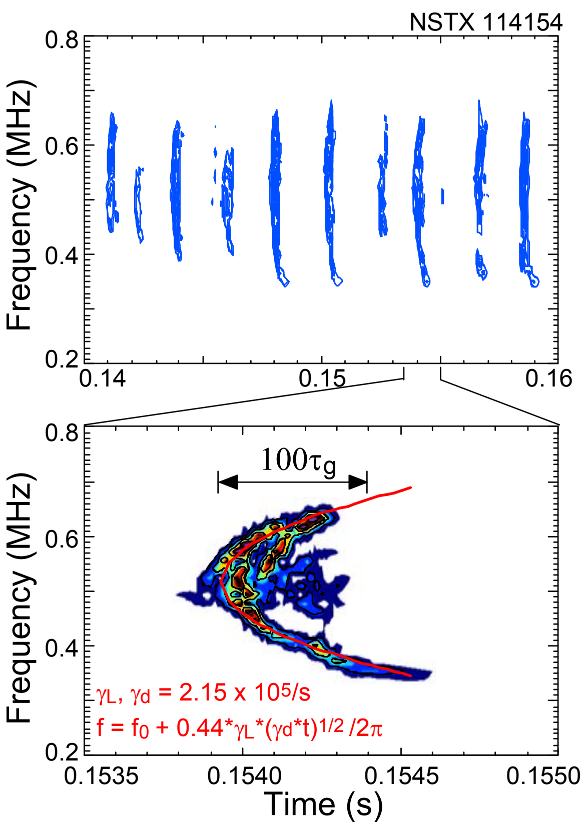
- GAE exhibit avalanche-like behavior.
  - Slow growth of multiple modes, ending in large, multi-mode burst and quiescent period.
  - Evidence that they have significant impact on fast ion distribution.
  - Doppler-shifted cyclotron resonance would take mostly perpendicular energy; fast ions would end up better confined.
- Can be correlated with low frequency EPMs



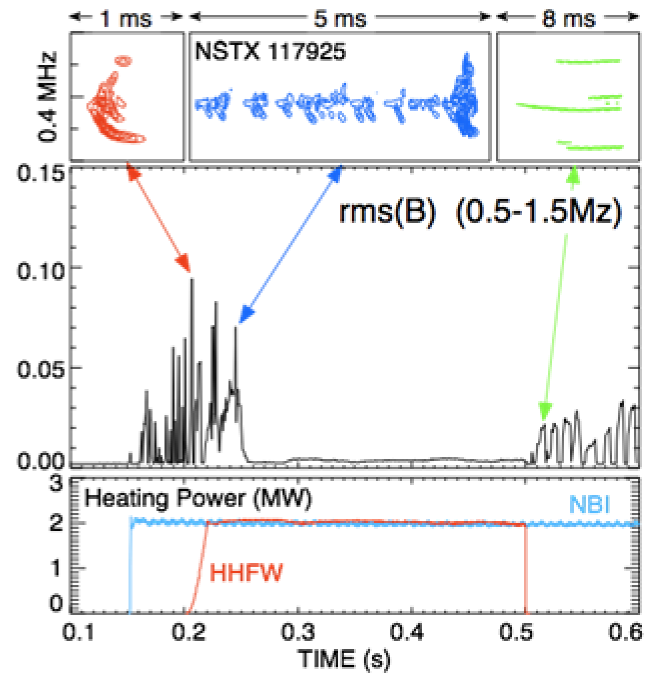
- Trapped electron precession frequency resonant with CAE/GAE
  - Multi-mode interaction can cause electron transport (ORBIT simulations)
- External excitation of multiple modes could heat thermal ions
  - Stochastic heating predicted and experimentally observed.
- Diagnostic of fast-ion diffusivity in fast-ion distribution function

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

Validation of acoustic mode, kinetic Alfvén wave, GAM coupling in NOVA and M3D (GKM)

- 2009-2011
  - BAAE high-k scattering radial scan, mode structure (using BES)
  - rsAE induced fast ion redistribution
    - High-k scattering radial scan
  - scaling of $C_s(\beta_{fast}, \beta_e, \beta_i)$, $\omega_{GAM}(\beta')$ with GAM (rsAE)
  - Documentation of Angelfish, HHFW suppression study, HYM validation.
- 2012 - 2013
  - BAAE stability boundary studies vs. toroidal field
  - Scaling of ρ^* affect on TAE avalanches with larger field range.
  - Alfvén cascade mode structure in moderate density plasmas at 1 T, rsAE - TAE coupling
    - Extension of mode studies to very low β
- 2013 (incremental)
  - Fast ion pitch-angle, radial distribution studies of EP instabilities.

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
  - Improved internal magnetic fluctuation diagnostic (μwave, MSE)
- 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, high time resolution(PMT)
  - iFLIP; Faraday cup lost ion probes
  - FIDA; spatial profile, energy resolved

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 is uniquely positioned to develop a predictive capability for fast-ion transport for next-step STs

- Good progress has been made in benchmarking fast-ion redistribution simulations with NOVA and ORBIT for TAE avalanches.
- Understanding fast ion redistribution effects on NB current will guide design of future experiments, NHTX, ST-CTF or ITER.
- Upgrade of center-stack for 1T, 2MA operation would broaden NSTX fast ion parameters, towards lower ρ^* and ITER.
- Second Neutral Beam Line would allow pitch angle and fast ion density profile control experiments
  - Important parameters for TAE and TAE avalanche and EPM stability.
  - Profile potentially important for GAE and CAE stability as well.
- NSTX has substantial diagnostic capabilities which will be exploited over the next 5 year period.
  - New diagnostics (BES, neutron collimator, high-k scattering, magnetic fluctuations) will substantially expand physics which can be directly addressed with experiments.
- Uniquely positioned to study broader role of CAE/GAE
  - Electron transport, thermal ion heating (α-channeling)

2009-13 Energetic Particle Research Timeline