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Energetic particle physics: progress and plans

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Eric D. Fredrickson

23rd NSTX PAC Meeting
PPPL

Jan. 22-24, 2008

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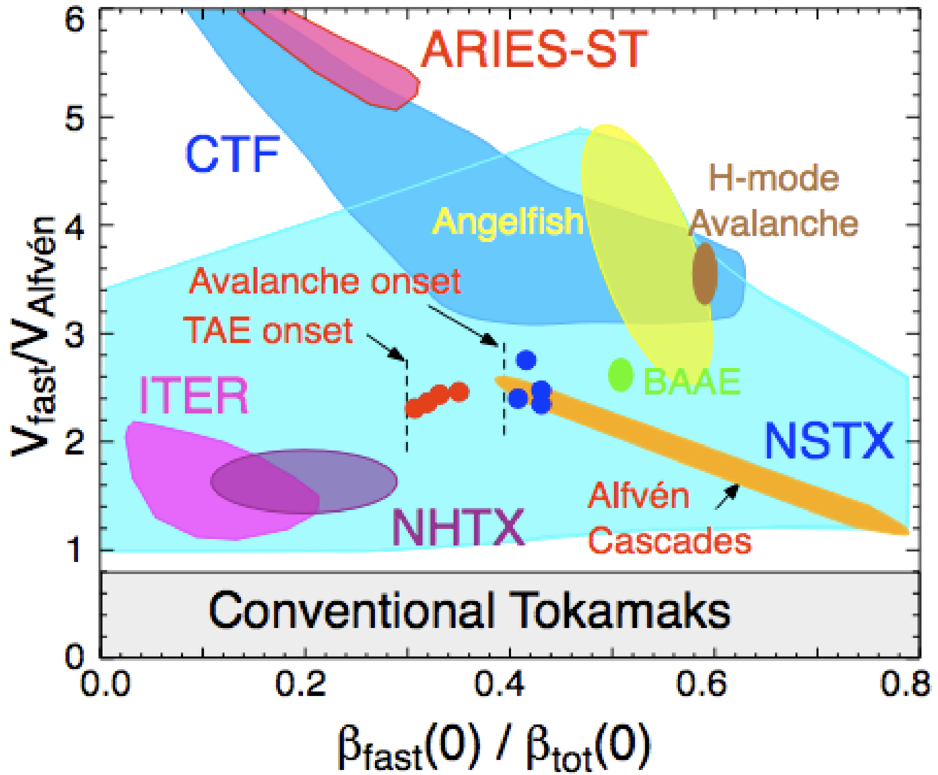
NSTX is uniquely positioned to study energetic particle physics required for next-step devices

- For next step, need to have predictive capability for:
  - Fast ion confinement; impact on ignition conditions
  - Fast ion redistribution; model beam driven currents for next-step ST's and ITER.
  - Fast ion losses; model PFC heat loading.
- NSTX routinely operates with super-Alfvénic fast ions.
  - Neutral beam energy at 60 - 100 kV, $1 < V_{fast}/V_{Alfvén} < 5$
  - Neutral beam power up to 6 MW, $\beta_{fast}(0)/\beta_{th}(0) \leq 0.8$
    - Fast ion parameters relevant to ITER/NHTX/ST-CTF
  - Fast ion losses have been correlated with both TAE and EPMs.
  - Losses typically largest when multiple modes interact; predicted loss mechanism for ITER.

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.

Comprehensive and growing diagnostic set

- 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
  - CIF/LIF MSE; internal mode amplitude/structure in δB, total pressure profile
  - BES; higher spatial resolution, mode structure at higher/lower density
- Fast particle diagnostics:
  - Fast neutron rate monitors
  - Scanning NPA; high energy resolution, vertical and radial scan
  - ssNPA; 5-channel compact NPA 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
  - Neutron collimator; spatial profiles of fastest ion populations
  - Improved internal magnetic fluctuation diagnostic

Pre-2008
2008-2010
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
  - 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.
  - HINST; local, fully kinetic, stability modeling
  - HYM; non-linear shear *and* compressional Alfvén waves
- 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)
  - Direct measurement of adiabatic index (ratio of specific heats)
  - Phase-space engineering; HHFW modification of fast ion profile

PAC21 recommendations guide run planning

- ✓ PAC21-07 The proposed use of non-resonant braking to separate the effect of rotation would be interesting for more detailed study of Alfvén cascade modes.

  Part of proposed experiments, "2nd priority".

- ✓ PAC21-08 NSTX is uniquely positioned to effectively study the detrimental effects of nonlinear Alfvén eigenmode coupling on energetic particle confinement. … This set of experiments should be a high priority

  Multi-mode transport in avalanches/EPM are highest priority experiments.

- ✓ PAC21-09 Simulation code validation (e.g., M3D-k) … is an important activity…

  124781 is basis of M3D-k simulation; validation of linear NOVA/HYM AE structure

- ✓ PAC21-10a Use of variable rotation speed to characterize AC modes and BAAE is a valuable study.

  Some initial studies in 2007; needs more analysis.

- PAC21-10b Fishbone physics in context of shaping/high β which can modify/reverse fast ion precession velocity (important for resonant drive of fishbones)

  Experiment planned to document fast ion transport, q(0), β, "2nd priority".

- PAC21-40 Phase-space engineering for energetic ions … important topic for ST physics, ITER and general tokamak science.

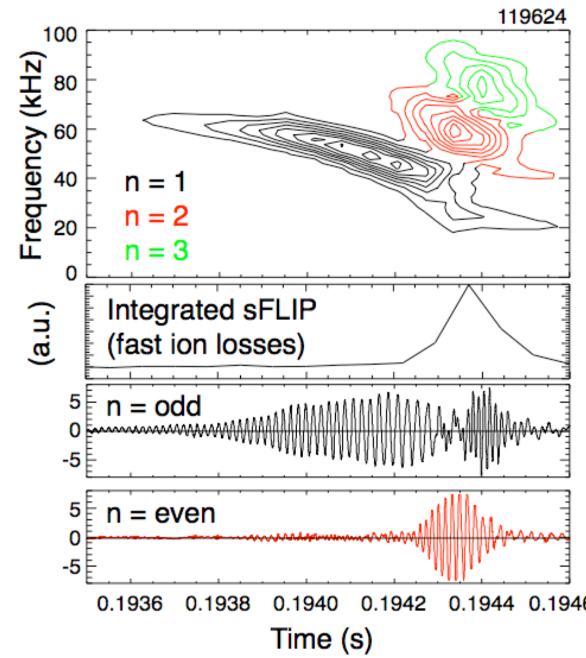
  Experiment to document Angelfish, study suppression with HHFW "2nd priority".

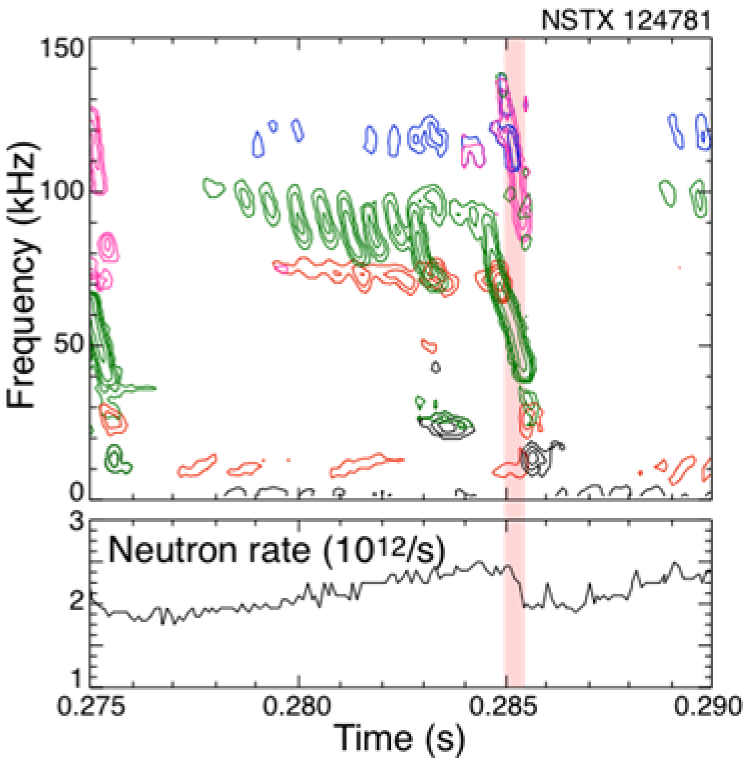
– Each experimental goal pursued over multiple years

Fast ion losses seen with TAE Avalanches, EPMs, of most concern for ITER, ST-CTF

PAC21-08, 10b

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





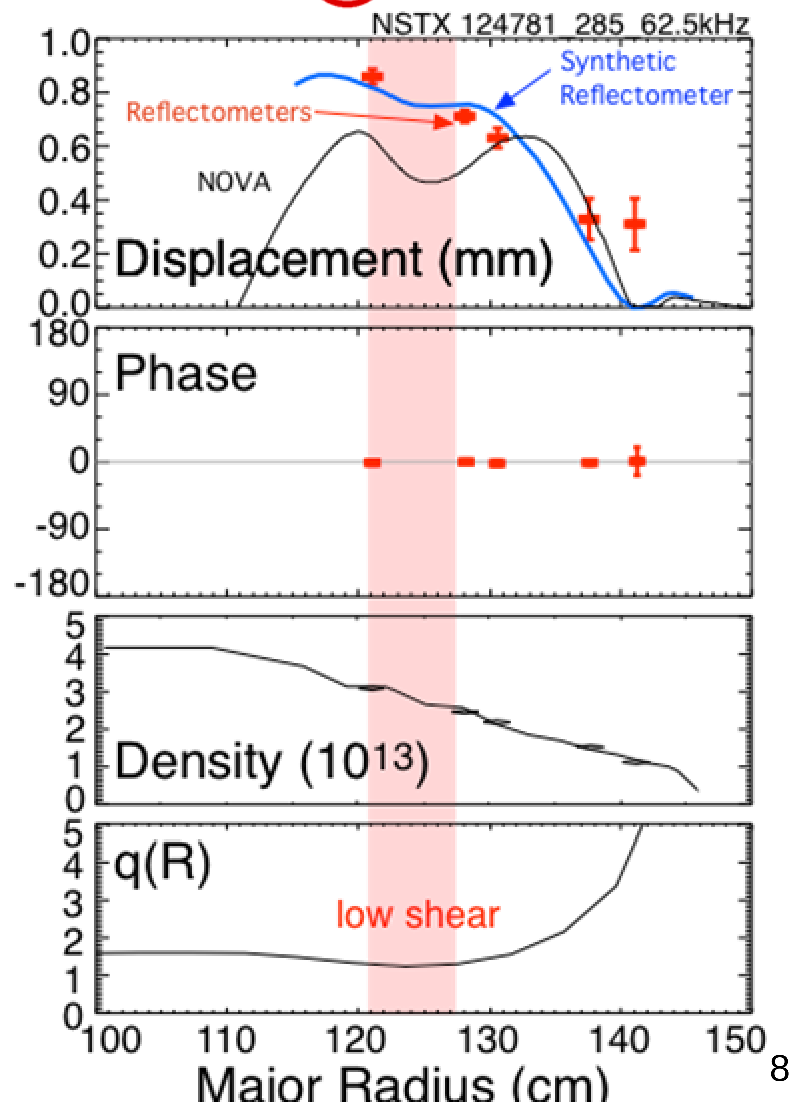
- TAE avalanches identified on NSTX
- Threshold in β_{fast} identified for one operating condition.
  - ST-CTF in avalanche parameter regime

NOVA simulation of mode structure compared with reflectometer array measurements

PAC21-08

NSTX

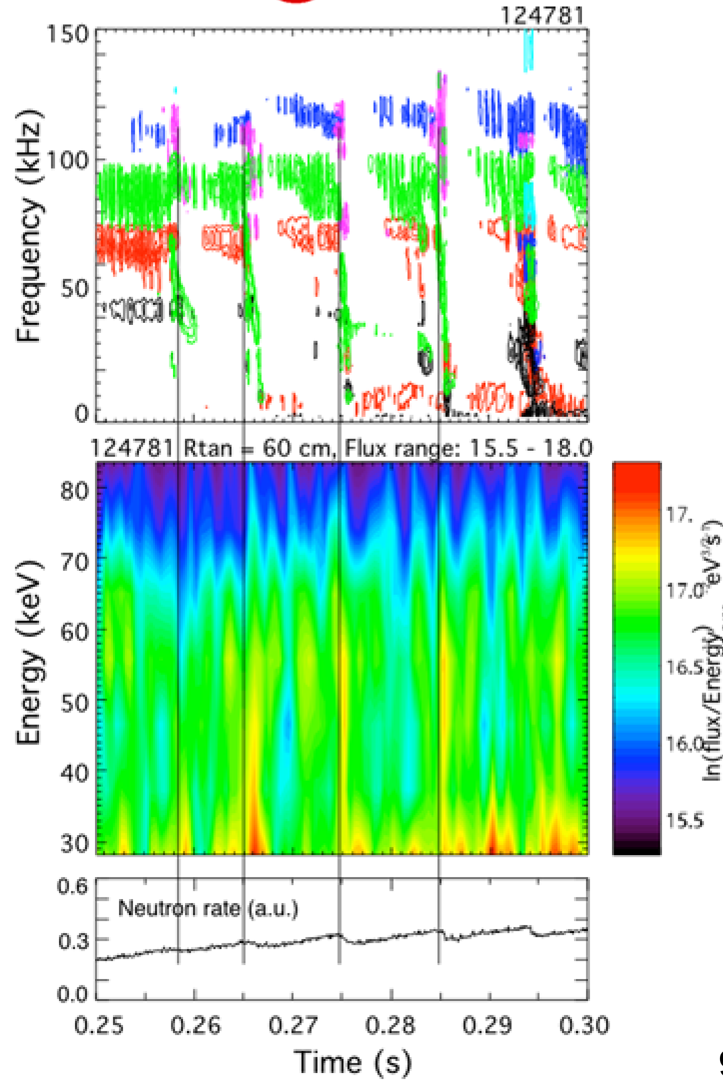
- NOVA is a linear code, mode structure is scaled to measured amplitude for use in ORBIT code.
  - Comparison of modeled eigenmode is through "synthetic reflectometer diagnostic"
- Similar analysis is done for each of the detected modes.
- ORBIT can be used to simulate fast ion redistributions.
- Parallel effort to model full, non-linear TAE avalanche with M3D-k (GKM) code.



Documentation of fast ion transport highest priority goal for EP group

PAC21-08

- Fast ion redistribution indicated by neutron drops and in ssNPA and NPA data.
- Lower energy ions (still resonant) 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 lost to another part of machine



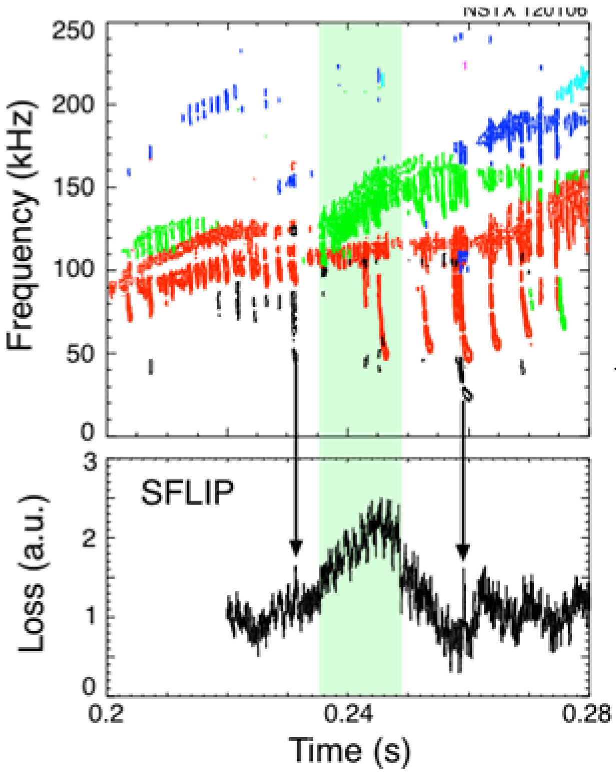
Predictive capability for fast ion transport highest priority goal for 2008-2010

- 2008-2009
  - 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.
  - EPM effect on fast ions, measure internal mode structure
  - EPM scaling studies with q(0) and β scaling, precession drift reversal
  - Milestone to complete study of J(r) modification by super-Alfvénic ion driven modes
  - BAAE high-k scattering radial scan, mode structure (using BES)
  - Alfvén Cascade (AC) fast ion redistribution, scaling of $C_s(\beta_{fast}, \beta_e, \beta_i)$, $\omega_{GAM}(\beta')$
  - Documentation of Angelfish, HHFW suppression study.
- 2010 (this research not possible without NSTX operation in FY10)
  - Avalanche studies in low density H-modes w/BES for internal structure
  - EPM scaling studies with q(0) and β scaling, study precession drift reversal
- 2011 - 2013
  - TAE avalanches, EPM fast ion redistribution in high density H-modes; neutron collimator.
  - BAAE fast ion redistribution, stability boundary studies
  - Alfvén cascade mode structure in low density plasmas, rsAE ⇔ TAE coupling
  - How much or what type of RF needed to suppress fishbones? TAE avalanches?
  - HHFW power scan for Angelfish suppression threshold

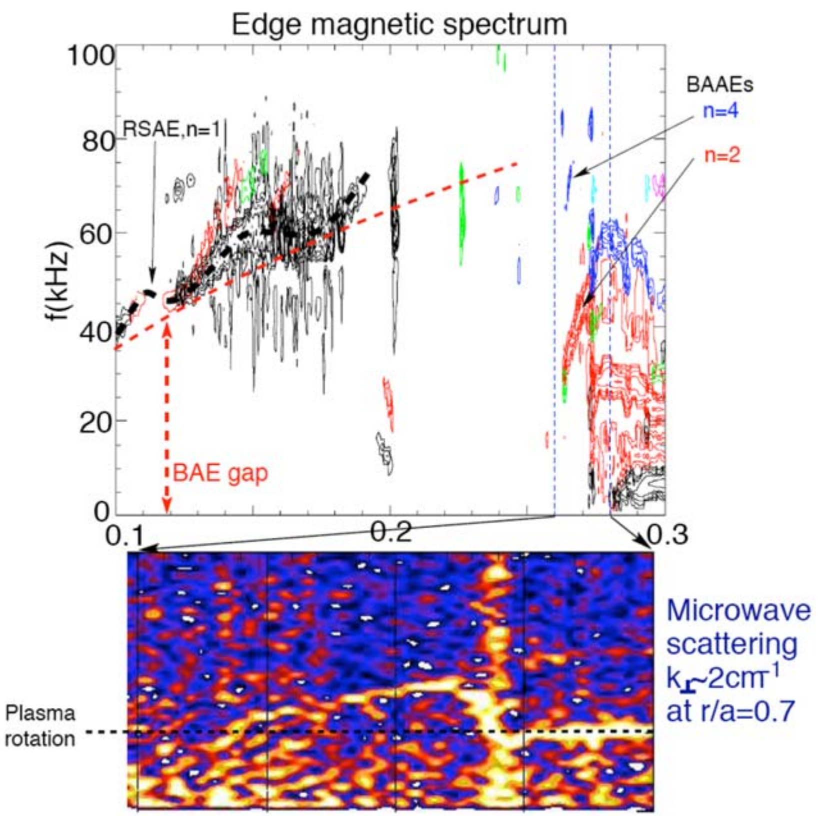
Highest priority
2nd priority
3rd priority

Fast ion losses expected from other instabilities

PAC21-07,10



- Losses during n = 3 frequency sweep seen on sFLIP diagnostic.
- NSTX rsAE studies will address mystery of fast ion redistribution on DIII-D.



- β-induced Alfvén-Acoustic modes could explain some low-frequency fast particle modes on NSTX, e.g., EPMs.
- Coupling to Kinetic Alfvén Waves detected with High-k scattering diagnostic.

Studies of Alfvén Cascades/BAAE are 2nd priority in near-term and extended run-plans

NSTX

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  - Effect on NBI current will be investigated during TAE avalanches with:
    - FIDA, vertically scanned NPA, ssNPA, neutron and sFLIP diagnostics.
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Highest priority

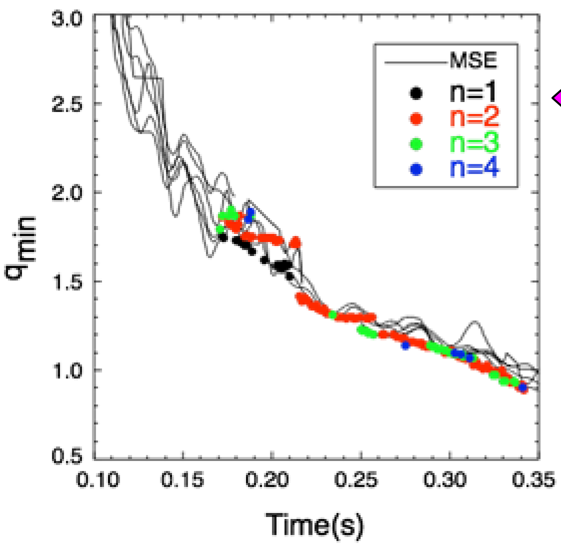
2nd priority

3rd priority

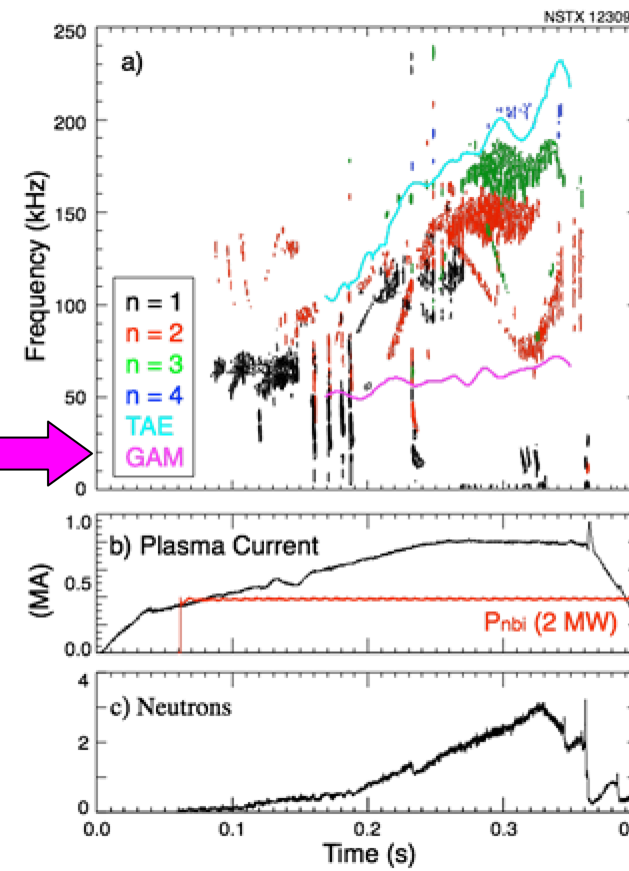
*AE are diagnostics of fast ions and plasma: q_{min}, adiabatic index (γ), fast ion diffusivity

PAC21-07,10

NSTX



- Cascade Modes (rsAE) identified on NSTX
  - Confirmation of MSE measured q_{min}
- Frequency sweeps suppressed at high β
  - Experiments done at very low β, density

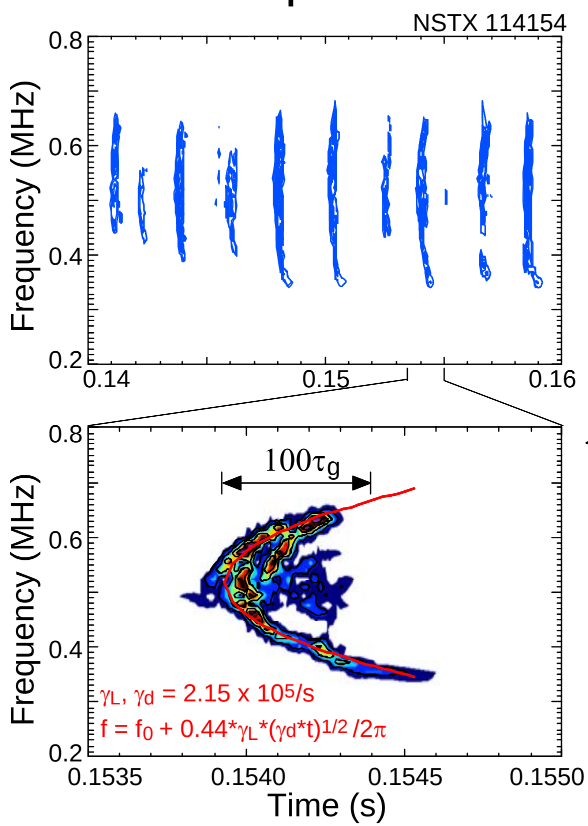


- Frequency minima equal GAM frequency
  - Diagnostic of adiabatic index; particularly important to measure for fast ions.
- Non-resonant braking used to study effect of rotational shear on frequency minima.

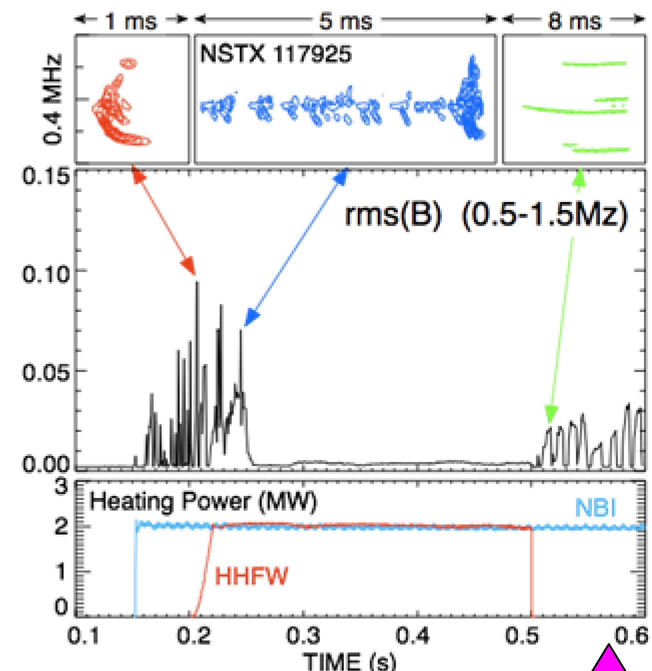
Studies of Angelfish (hole-clumps) illuminate physics of fast ion phase space structures

NSTX

- 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

2011-2013 research focused on avalanches in high density H-modes and fundamental *AE physics

NSTX

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  - Effect on NBI current will be investigated during TAE avalanches with:
    - FIDA, vertically scanned NPA, ssNPA, neutron and sFLIP diagnostics.
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  - Alfvén cascade mode structure in low density plasmas, rsAE $\Leftrightarrow$ TAE coupling
  - How much or what type of RF needed to suppress fishbones? TAE avalanches?
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Highest priority
2nd priority
3rd priority

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

- Understanding fast ion redistribution effects on NB current could guide design of next step experiments, NHTX, ST-CTF or ITER.
  - 3 year program would extend redistribution studies into H-mode regime with addition of BES diagnostic.
- Probability of success in a 3 year program would be greatly improved with extended run time.
  - NSTX has substantial diagnostic capabilities which could be exploited over the next 3 year period.
- A two year program (2008-2009) would limit fully diagnosed plasmas, which form the basis of modeling efforts, to L-mode plasmas
  - Internal measurements of mode structure in H-mode, or higher density, plasmas with BES will not be available until 2010.
  - All benchmarking of codes would thus be done on L-mode plasmas.
- Runtime beyond 2010 would provide time for experiments addressing avalanches in high-n_e H-modes, and fundamental fast ion physics issues.

Energetic Particle Physics research time line

NSTX

	FY08 – FY09 (milestone) – FY10	FY11 – FY12 – FY13
Avalanche (multimode)	Onset scaling, EP transport, onset in H-mode	Onset scaling in H-mode, Chirp suppression with HHFW
Cascades	Onset threshold, GAM frequency scaling, fast ion transport	Mode structure studies in L-mode and H-mode, fast ion transport
Fishbones	Fast ion loss, q(0) scaling, β scaling, soft x-ray mode structure	q(0) scaling, β scaling, Mode structure (BES, MSE-LIF/CIF)
BAAE	High-k scattering, mode structure	Stability scaling, rotational shear, fast ion transport
CAE/GAE	Phase-space structures, chirp suppression	Chirp suppression, phase-space structures

	FY08	FY09	FY10	FY11
Diagnostics	FIDA, high-k, Firetip 2MHz, MSE-CIF	MSE-LIF	BES	Neutron collimator