NSTX-U

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Energetic Particle Physics Progress and Plans

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for the NSTX Research Team

NSTX PAC-31
PPPL B318
April 17-19, 2012

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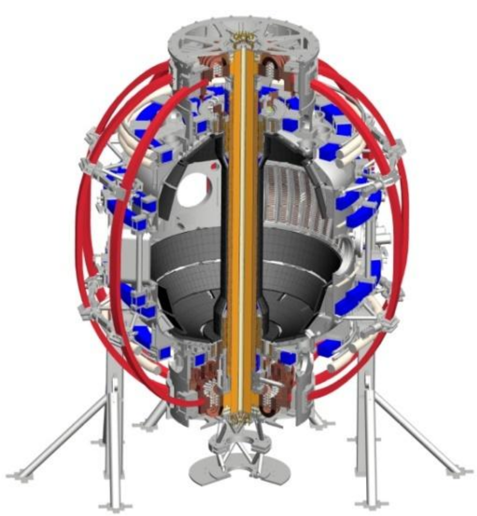

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EP research mission: Advance understanding of Energetic Particle physics, develop predictive capability

- Investigate fast ion transport mechanisms, compare experimental results with theory & numerical codes
- Develop physics-based fast ion transport models, e.g.:
  - Stochastic transport models
  - Quasi-linear models.

Milestone R(14-2):

*Develop models for *AE mode-induced fast-ion transport*

- Assess requirements for *fast-ion phase-space engineering* techniques through selective excitation of *AE modes

Targeting frequencies
from 10's of kHz up to ion cyclotron frequency:
Beta-induced, Toroidal, Global/Compressional AEs, EPMs, ...

Outline

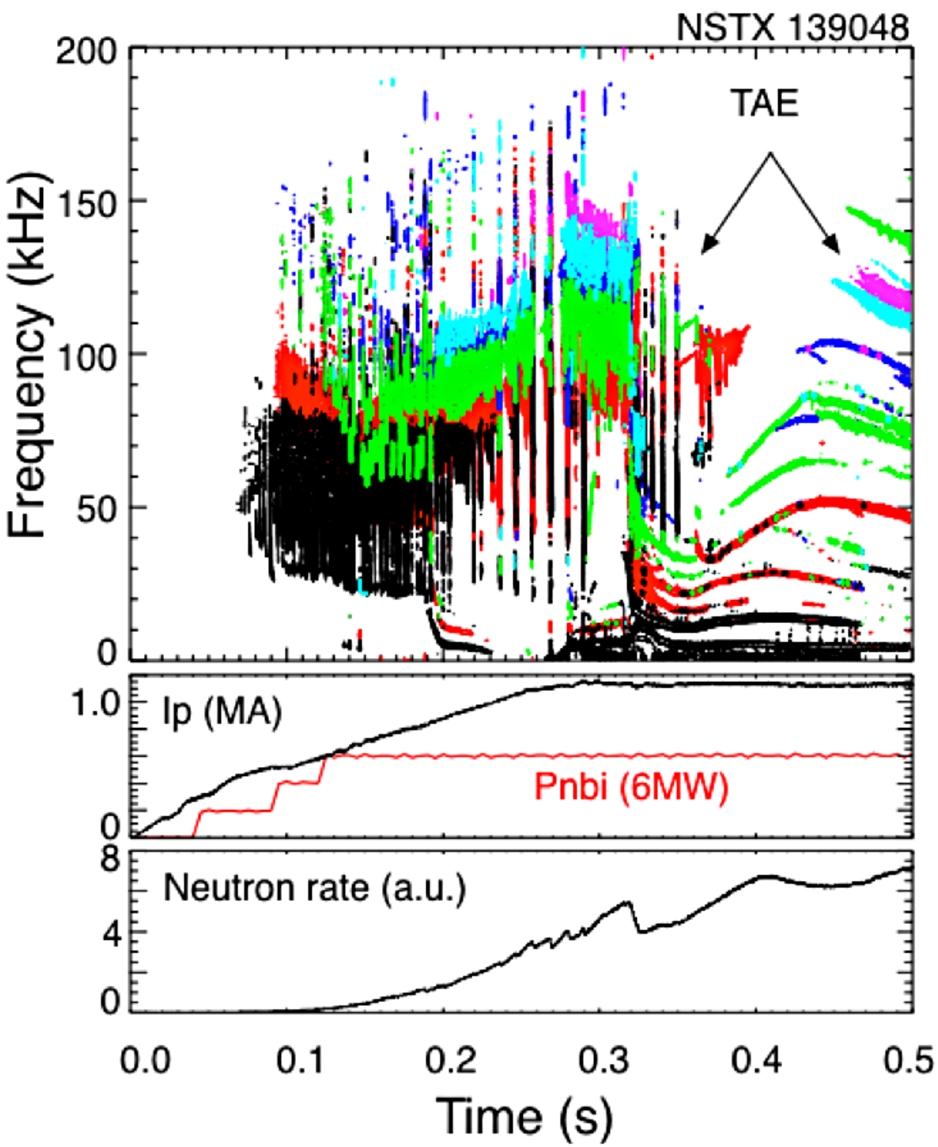
- FY11 Research highlights
  - Alfvénic modes (*AEs) and associated transport
  - Modeling, theory-experiment comparison
- FY12-13 Activities in preparation for NSTX-U
  - Collaborations, EP diagnostic development
- NSTX-U Year 1 and 2, plans for machine start up
- NSTX-U Years 3-5, long term research plans

Response to PAC29 questions: **PAC29-X**

ITPA task: **ITPA EP-Y**

Backup Slides: **B#Z**

Study of TAE avalanches extended to H-mode; impact on fast ion transport confirmed – *now projecting to NSTX-U*



- Bursting/chirping modes, similar to L-mode

ITPA EP-2,4

  - Neutron drops: fast ions affected
  - Evidence for non-linear coupling
- More steady regime at high n_e?
- ***Collaboration with DIII-D (FY12-13), MAST (FY13) to broaden database***
  - Higher B_t, different TAE regimes
- NSTX-U: $k_\perp \rho_f \sim 1 \Rightarrow \frac{nq}{a}\frac{v_f}{\omega_{cf}} \sim 1$

$$\Rightarrow n \sim B \Rightarrow n = 2 - 10$$

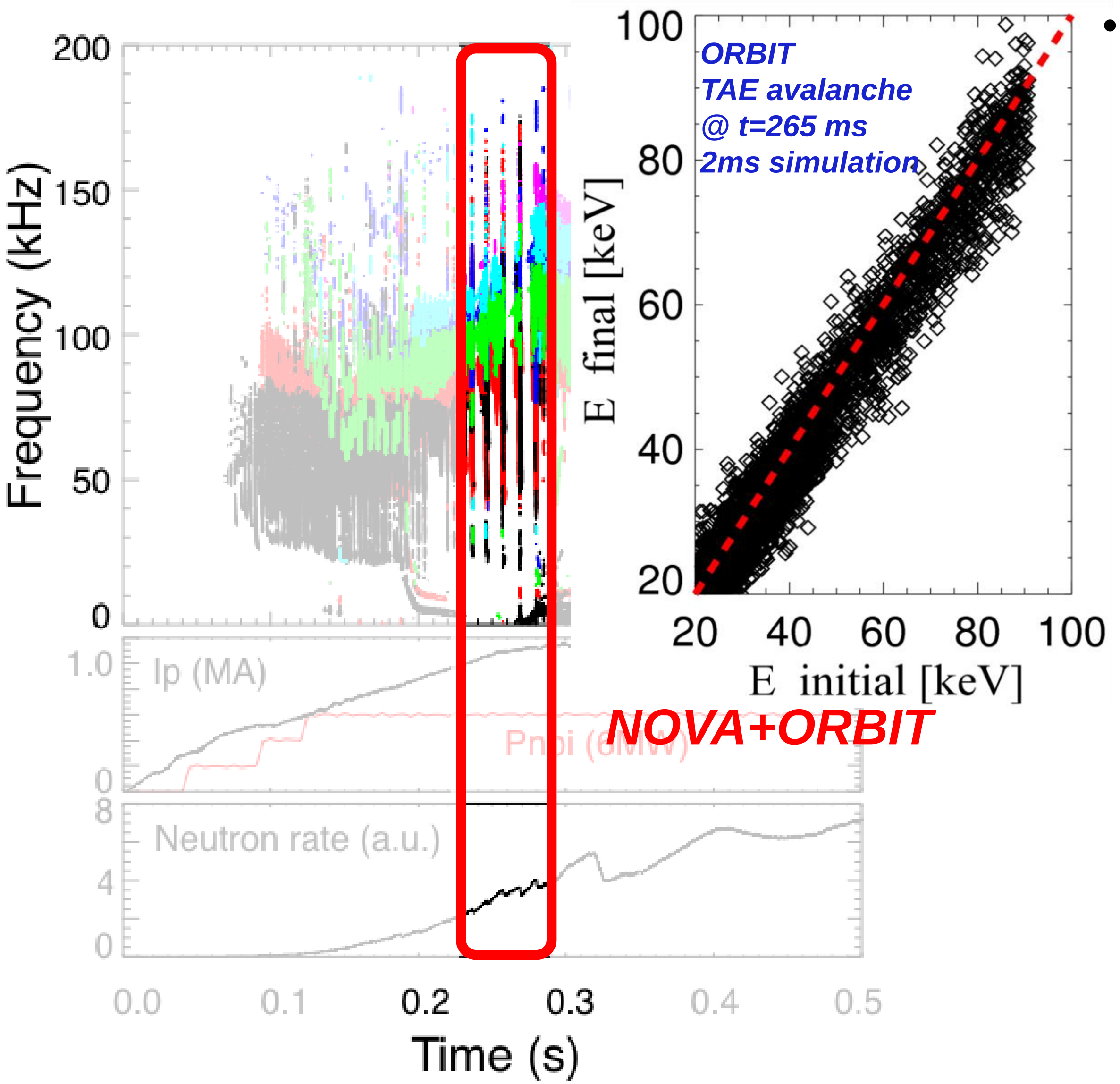
  - Higher *n*' s, similar multi-mode physics?

\> ***NOVA stability analysis being performed (FY12)***

\> ***Extend to M3D-K code (FY13)***

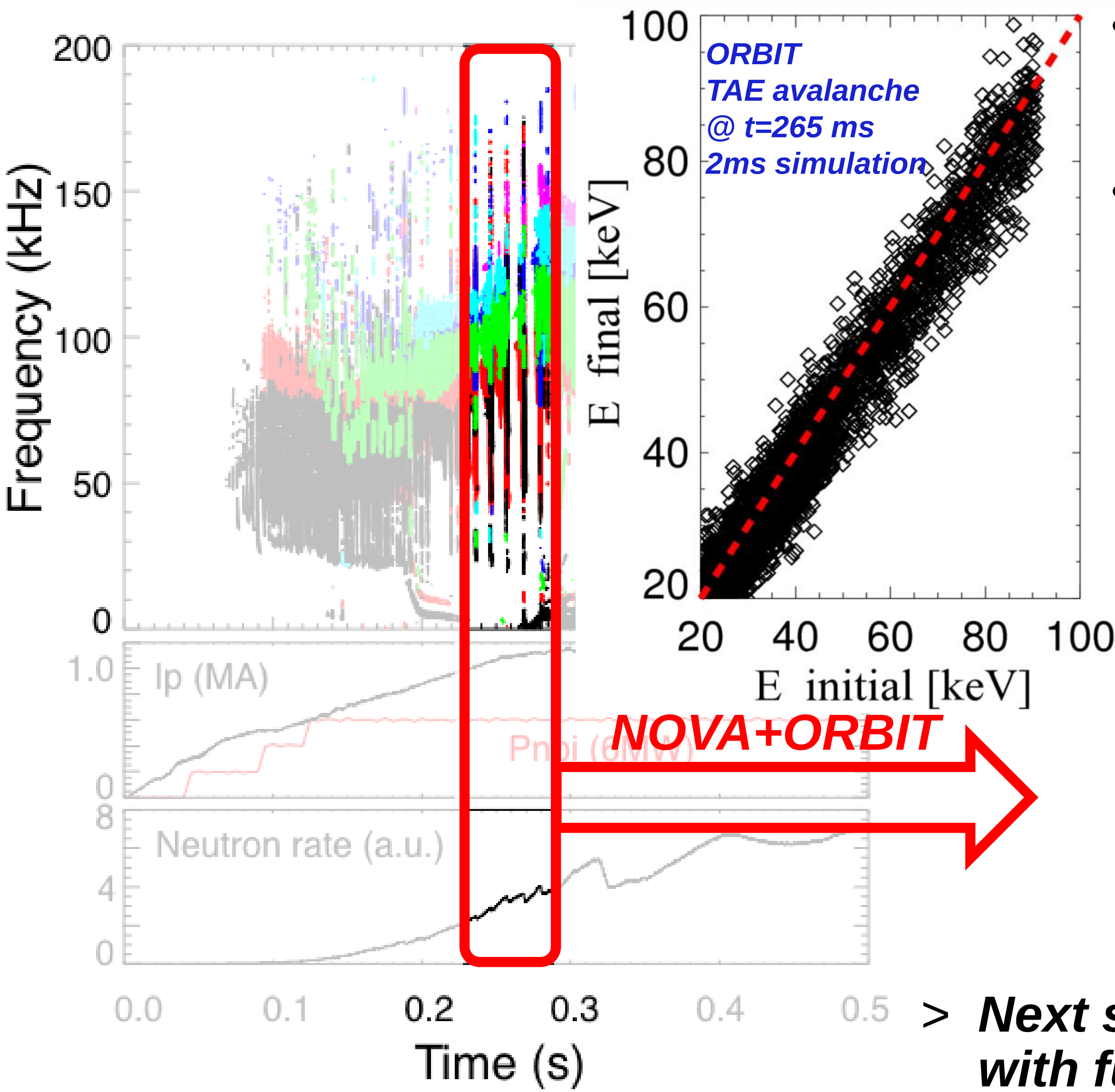
B#33

NOVA+ORBIT modeling of fast ion response reveals role of losses *vs.* redistribution, helps interpretation of experiments

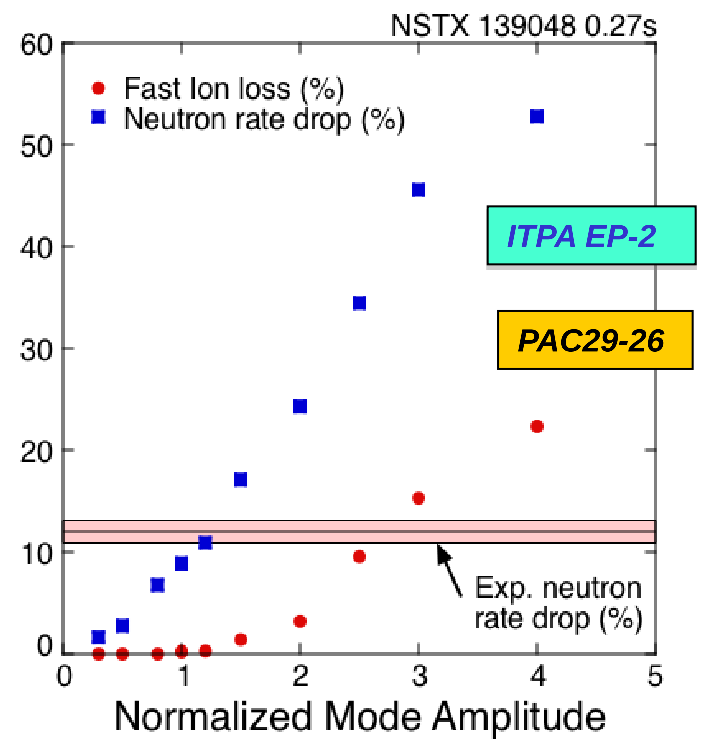


- ORBIT gyro-center analysis: large neutron rate drop can be caused by ΔE, not by loss

NOVA+ORBIT modeling of fast ion response reveals role of losses *vs.* redistribution, helps interpretation of experiments

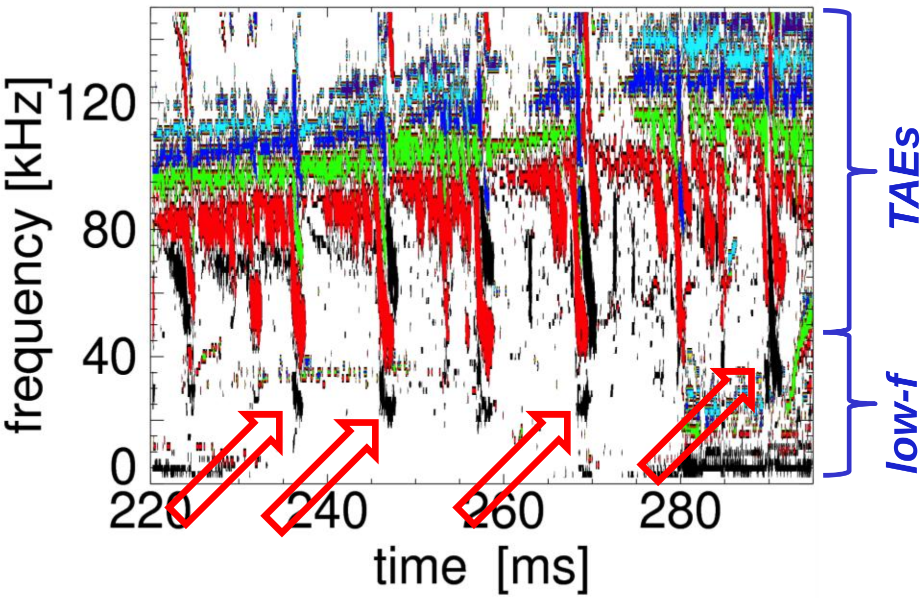


- ORBIT gyro-center analysis: large neutron rate drop can be caused by ΔE, not by loss
- Redistribution enhanced by multi-mode *stochastic* transport



> ***Next step: compare/benchmark with full-orbit code SPIRAL***

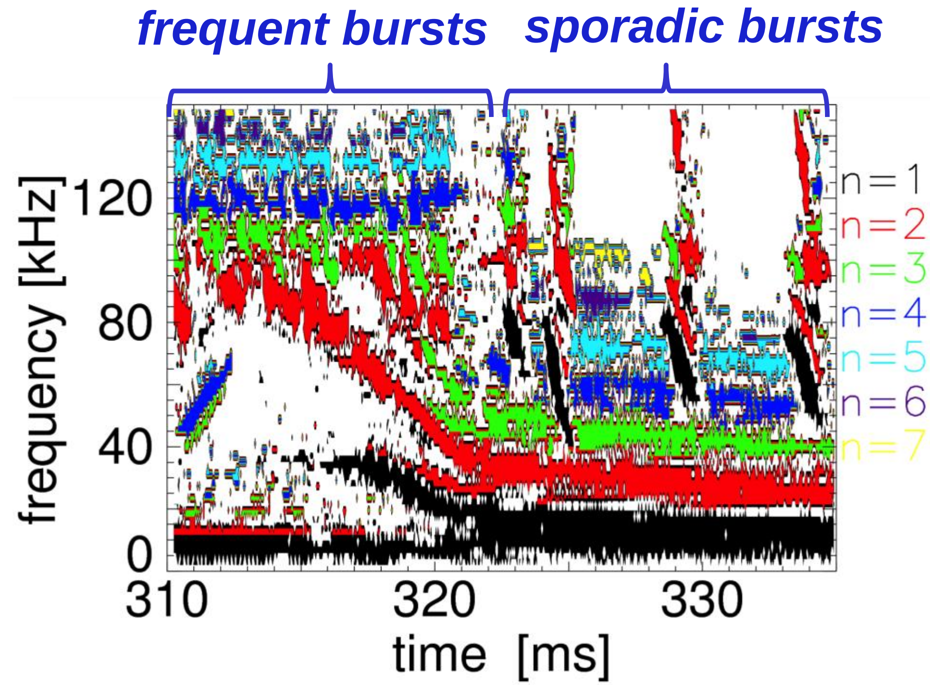
TAE/RSAE dynamics strongly affected by non-linear physics, e.g. interaction and coupling with other MHD modes



- Otherwise stable *n=1* ‘kinks’ excited during strong bursts

> 3-wave coupling with low-f MHD

B#22

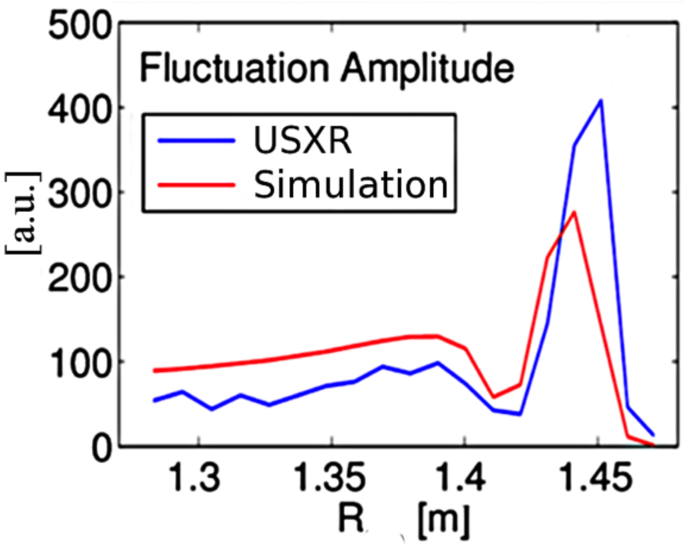


- Change of TAE regime at onset of kink-like mode
- Bursts become more sporadic

> *Indicates modifications of profiles (n_e, T_e, q, v_{tor}), fast ion distribution F_{nb}*

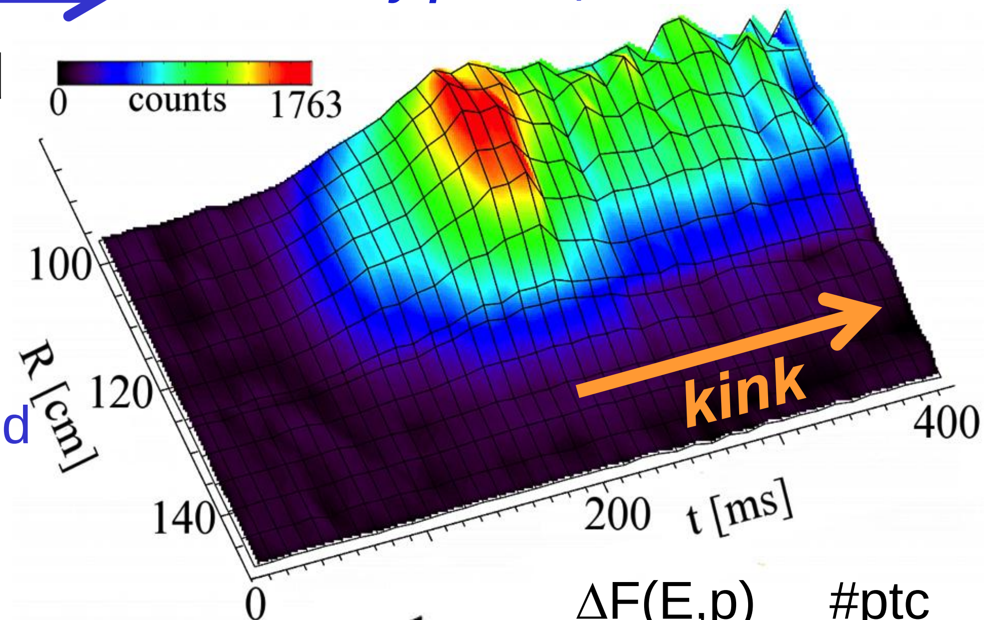
FIDA, sFLIP, neutrons indicate fast ion transport/redistribution by low-frequency (kink-like) modes

- Large drop in FIDA density
- Unstable kink-like mode found from PEST code

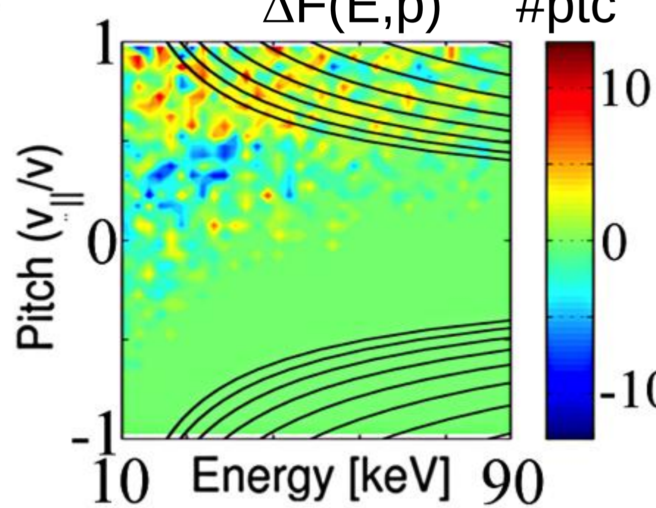


Simulated mode structure matches USXR data

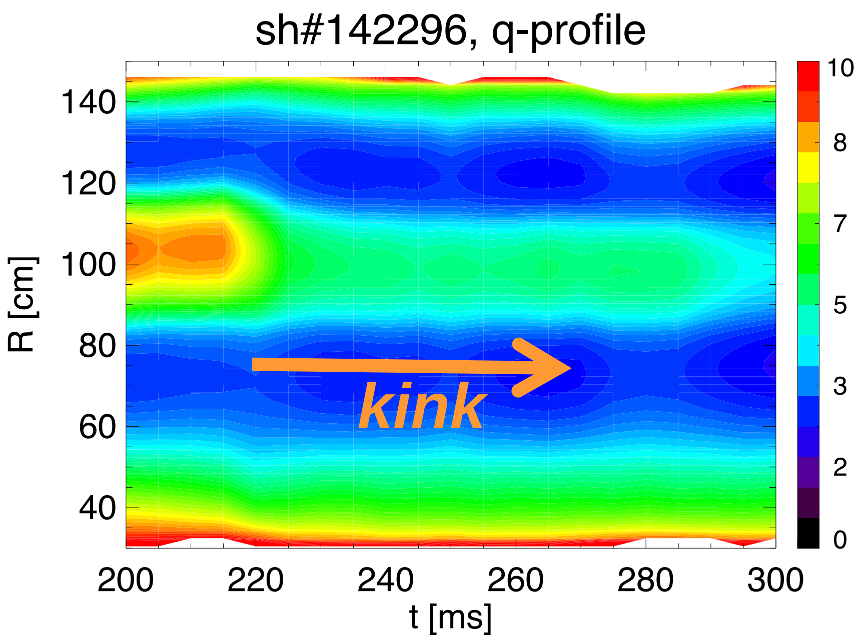
FIDA density profile, sh#142296



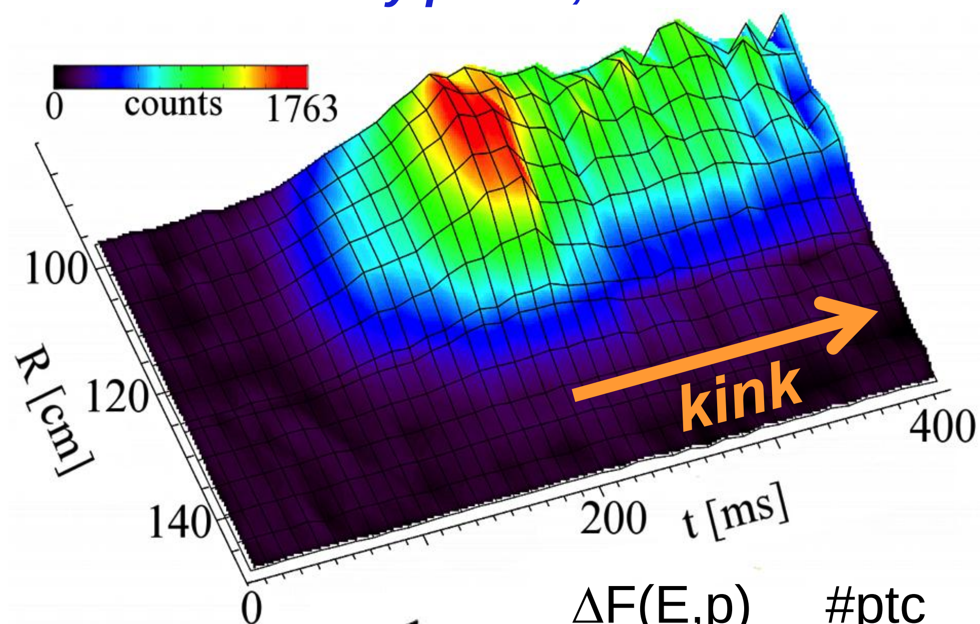
- SPIRAL used to infer fast ion response
- Fast ions redistributed to larger radii and pitch values
  - *Loss* caused by kink remains small
  - Consistent with drop in FIDA signal



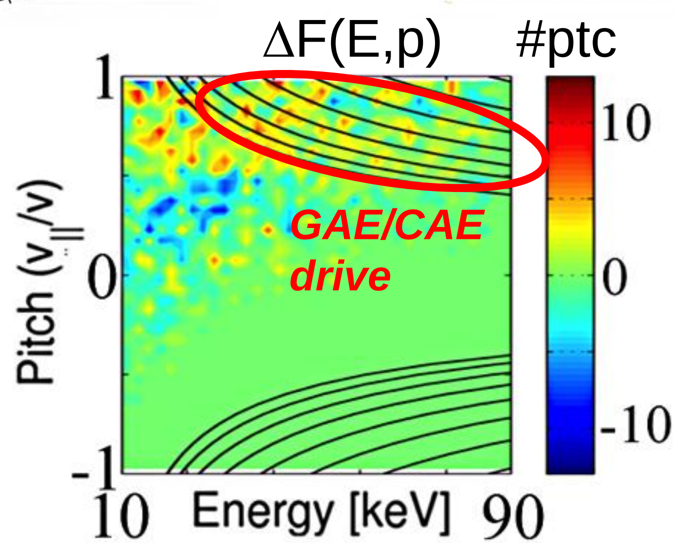
Change in plasma profiles and fast ion response to kink affect NB-CD, stability of other modes



FIDA density profile, sh#142296

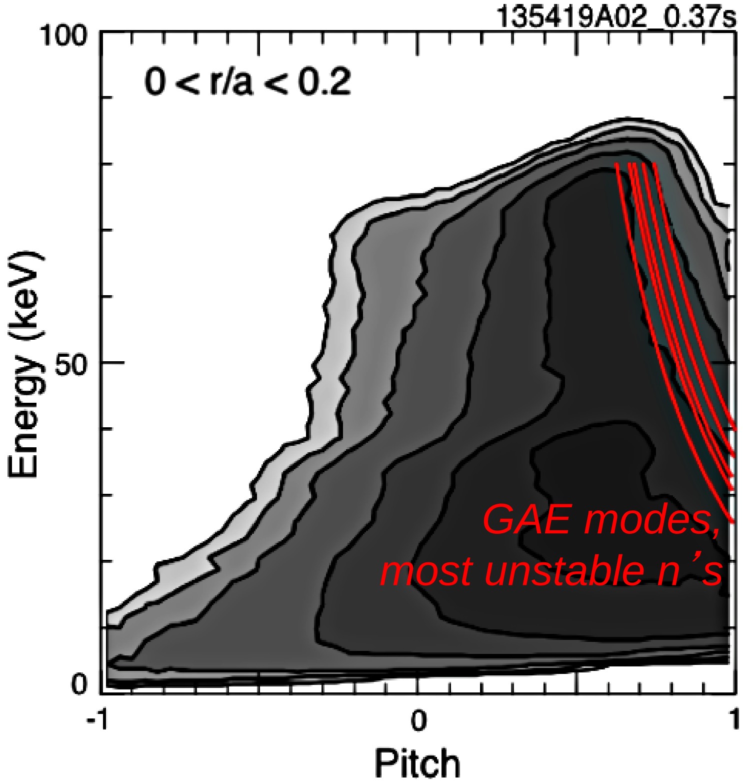


- Kink redistributes NB-driven current
  - *Simulations with M3D-K code under way* **B#24**
- Can affect stability of other modes **B#23**
  - E.g.: GAE/CAEs destabilized soon after kink
  - TAE regime changes when F_{nb}, q-profile modified



Stability, non-linear behavior of high-frequency GAEs/CAEs characterized; good agreement with models, codes

- GAEs destabilized by Doppler-shifted cyclotron resonance: $\omega = \omega_{ci} - k_{||} V_{b||}$ **B#25**
- Resonance extends to low(er) energies
- Avalanching behavior observed
  - Correlates with TAE bursts, suggests fast ion redistribution
- *Prototype antenna installed in FY11* **B#39**
  - Not tested yet; enables studies of *AE stability



- HYM code reproduces frequency, growth rate of unstable modes **B#26**
  - Implementing sources, sinks, δf electrons
- Electron transport by GAEs simulated with ORBIT **PAC29-26**
  - Transport *consistent* with TRANSP estimates **PAC29-22**

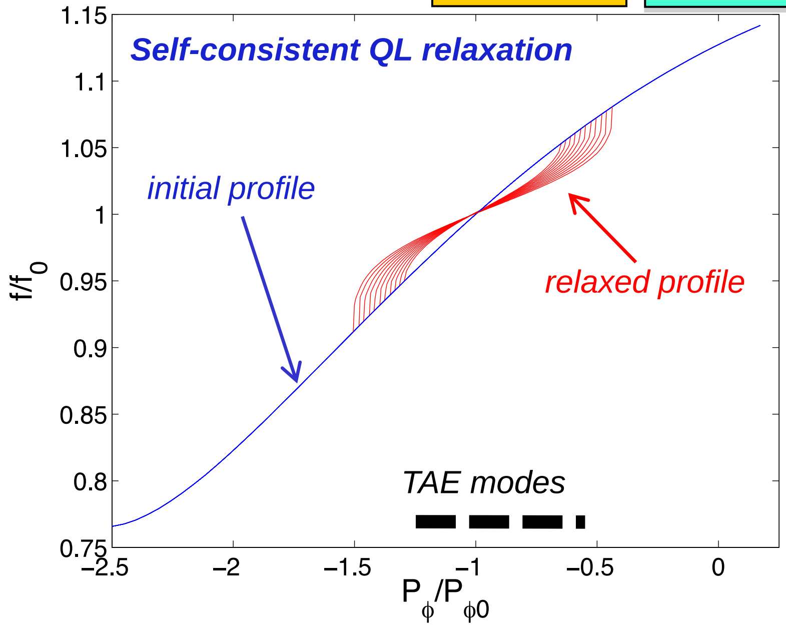
> **Longer term: assess requirements for active excitation of GAE/CAE through antenna**
  - Affect thermal electrons, fast ion transport

Focus in FY12-14 on developing models for improved *interpretive & predictive* capability (R14-2)

B#18

- ORBIT, SPIRAL – particle following
  - F_{nb} response to *AEs, kinks
- NOVA, PEST – ideal MHD
  - Eigenfunctions, linear stability
- HYM, M3D-K – non-linear, hybrid
  - Full mode dynamics, transport

PAC29-26 ITPA EP-2



Under development:

•Parametric models w/ TRANSP B#35

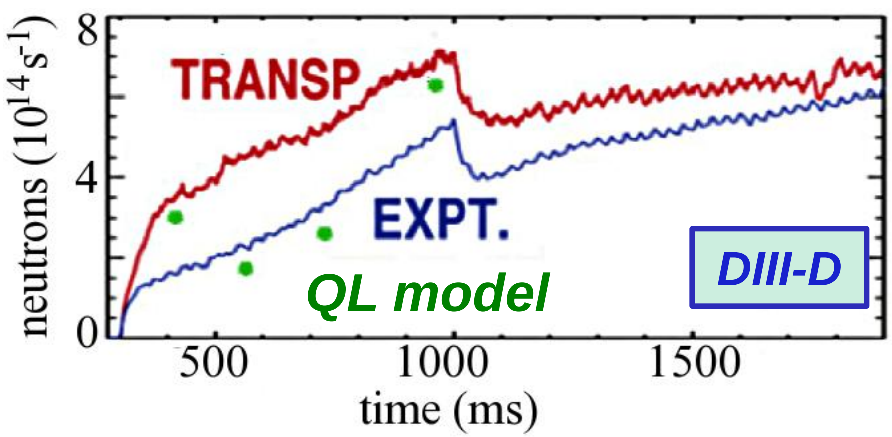
- Transport coefficients from ORBIT, SPIRAL
- *Requires TRANSP development*

•Quasi-linear (QL) models B#37

- F_{nb} response to given set of modes
- *Testing on DIII-D, **NSTX-U (FY14)***

•FIDASIM + F_{nb} evolving codes (longer term: NUBEAM)

- Constrain/invert F_{nb} and its evolution from set of data (FIDA, NPA, neutrons, …)
- *Under development w/ MAST, DIII-D*



Research plans for NSTX-U Outage: prepare for operations, improve analysis/modeling tools through collaborations

- FY12: Develop interface between SPIRAL and HYM codes
  - Model fast ion response to high-frequency GAE/CAE modes
- FY12-13: Linear analysis of TAE scenarios for NSTX-U H-mode plasmas with NOVA code
- FY12-13: Identify optimal fast ion diagnostics for NSTX-U *B#20*
- **FY12-13: Collaborate with MAST and DIII-D on *AE experiments**
  - **Physics of bursting TAEs:** *focus on stability, non-linear physics, control*
  - **Test/evaluate new diagnostics:** *fusion product profile, neutron collimator*
  - **Improve analysis techniques:** *infer F_{nb} from suite of fast ion diagnostics*
- FY13: Extend M3D-K simulations to NSTX-U H-mode scenarios
- FY13-14: Develop parametric and quasi-linear models for *AE-induced fast ion transport, R(14-2)
- FY13-14: Finalize design of upgraded ssNPA diagnostic, prototype *AE antenna

Research Milestone R(14-2):
"Develop models for *AE mode-induced fast ion transport"

Energetic Particle Plans and Goals
NSTX-U Operation Years 1-2

Year 1:

- Compare (classical) TRANSP predictions with FIDA for 2nd NB line
- Measure fast-ion transport with tangential FIDA
- Measure *AE eigenfunctions with BES and reflectometers
  - Compare eigenfunctions to predictions performed in FY12-14
- Test prototype *AE antenna

Year 2:

- Use tangential+perpendicular FIDA, NPA/ssNPA to characterize distribution function modifications induced by *AE modes
- Characterize *AE activity driven by more tangential 2nd NBI
  - Compare to existing (more perpendicular) NBI
  - Extend simulations to operations with full 1T magnetic field
- Compare measured *AE damping rates with models & theory

Energetic Particle Plans and Goals NSTX-U Operation Years 3-5

Year 3:

- Extend study of *AE activity driven by different NBI configurations to full 1T scenarios
  - Compare numerical and theoretical simulations to data on mode dynamics, transport
  - Characterize scenarios with combined NBI+HHFW
- Optimize *AE antenna design for efficient coupling to *AE modes
  - May consider replacing 2 HHFW antenna straps with *AE antenna (w/ HHFW group)
- *Extend simulations of *AE avalanches to FNSF/Pilot*

Year 4:

- Utilize *AE predictive capability to optimize/minimize *AE activity during non-inductive current ramp-up with 2nd NBI
  - Compare simulations to experimental results
- Assess performance of upgraded AE antenna
  - Measure stability of high-*f* *AEs; assess capability of mode excitation

Year 5:

- Assess requirements for "fast-ion phase-space engineering" techniques through selective excitation of *AE modes
  - Actuators: NBs, HHFW, active *AE antenna
- *Extend simulations of *AE avalanches to FNSF/Pilot current ramp-up phase*
- *Assess implications for FNSF/Pilot design (e.g.: optimum NBI geometry), expected NB-CD*

Summary of Energetic Particle Physics research plan for 2012-2018

- Study of **TAE/EPM *avalanches* and associated fast ion transport** extended to H-mode plasmas (+ collaborations)
  - Models, codes under development to improve interpretation and develop predictive capability toward NSTX-U (FNSF, ITER)
  - Verification/Validation against experiments in progress

- Increasing focus on **non-linear, multi-scale physics** involving *AEs, other low-*f* MHD modes
  - Non-linear TAE dynamic; coupling between *AEs, kink-like modes
  - ***High-priority research topic on the path toward FNSF, ITER***:
    - > *All have potentially strong impact on NB-CD in FNSF, ITER*
    - > *Must assess their effects on performance of next step devices*

- Increasing emphasis on **development and validation of** linear and non-linear **theory, codes, transport models**
  - Benefit of strong collaboration with PPPL theory/computation group
  - Contribute to NB-CD research for NSTX Upgrade and next steps
  - Support HHFW group for rf interaction with NB ions

Backup slides

Recommendations from NSTX PAC-29

PAC29-22	Therefore the PAC encourages the NSTX team to pursue its investigations to clarify the relative role of microtearing, GAE and ETG modes. The combination of low and high k fluctuation measurements will certainly be useful in that matter. Regarding this point, the PAC was very pleased to see that the NSTX team is making progress in designing a new high-k diagnostic, which will replace the present one in FY13 or 14.	Agree, see slides 10 + backup
PAC29-26	The PAC agrees with plans of the Wave-Particle Group to continue to validate simulation capability in this area, as this will aid assessment of fast ion losses for NSTX-U. In particular we think it is important to pursue eigenfunction modeling with the HYM code using GAE experiments, comparison of non-linear M3D-K against experiment (mode structure, bursting and chirping behavior), and extend the NOVA-K + ORBIT simulations to include the use of the SPIRAL code. The PAC recommends this validated simulation capability be applied to H-mode plasmas in both NSTX and NSTX-U, especially considering the effect of redistribution of NBI ions due to MHD activity on current profiles in the Upgrade. Because of the increased toroidal field range in NSTX-U, we note that it may be possible to explore the transition regime between $V > V_{Alfven}$ and $V < V_{Alfven}$.	Agree, see slides 6, 8, 9, 10, 11 + backup

R(14-2): Develop models for *AE mode-induced fast ion transport

Good confinement of fast ions from neutral beam injection and fusion reactions is essential for the successful operation of ST-CTF, ITER, and future reactors. Significant progress has been made in characterizing the Alfvénic modes (AEs) driven unstable by fast ions and the associated fast ion transport. However, models that can consistently reproduce fast ion transport for actual experiments, or provide predictions for new scenarios and devices, have not yet been validated against a sufficiently broad range of experiments. In order to develop a physics-based parametric fast ion transport model that can be integrated in general simulation codes such as TRANSP, results obtained from NSTX and during collaborations with other facilities (MAST, DIII-D) will be analyzed. Information on the mode properties (amplitude, frequency, radial structure) and on the fast ion response to AEs will be deduced from Beam Emission Spectroscopy, Reflectometers, Fast-Ion D-alpha (FIDA) systems, Neutral Particle Analyzers, Fast Ion Loss Probes and neutron rate measurements. The fast ion transport mechanisms and their parametric dependence on the mode properties will be assessed through comparison of experimental results with theory using both linear (e.g., NOVA-K) and non-linear (e.g., M3D-K, HYM) codes, complemented by gyro-orbit (ORBIT) and full-orbit (SPIRAL) particle-following codes. Based on the general parametric model, the implementation of reduced models in TRANSP will then be assessed. For instance, the existing Anomalous Fast Ion Diffusion (AFID) and radial fast ion convection models in TRANSP could be improved by implementing methods to calculate those transport coefficients consistently with the measured (or simulated) mode properties. Further improvements will also be considered, for instance to include a stochastic transport term or quasi-linear models.

ITPA tasks 2012, Energetic Particles Physics

Participate in:

- EP-2 Fast ion loss and redistribution from localized AEs
- EP-4 Effect of dynamical friction (drag) at resonance on nonlinear AE evolution

Also considering participation in:

- EP-3 Fast ion transport by small scale turbulence
- EP-6 Fast ion loss and associated heat load from edge perturbations (ELMs and RMPs)

Proposed diagnostics upgrades that support Energetic Particles research in FY14-18

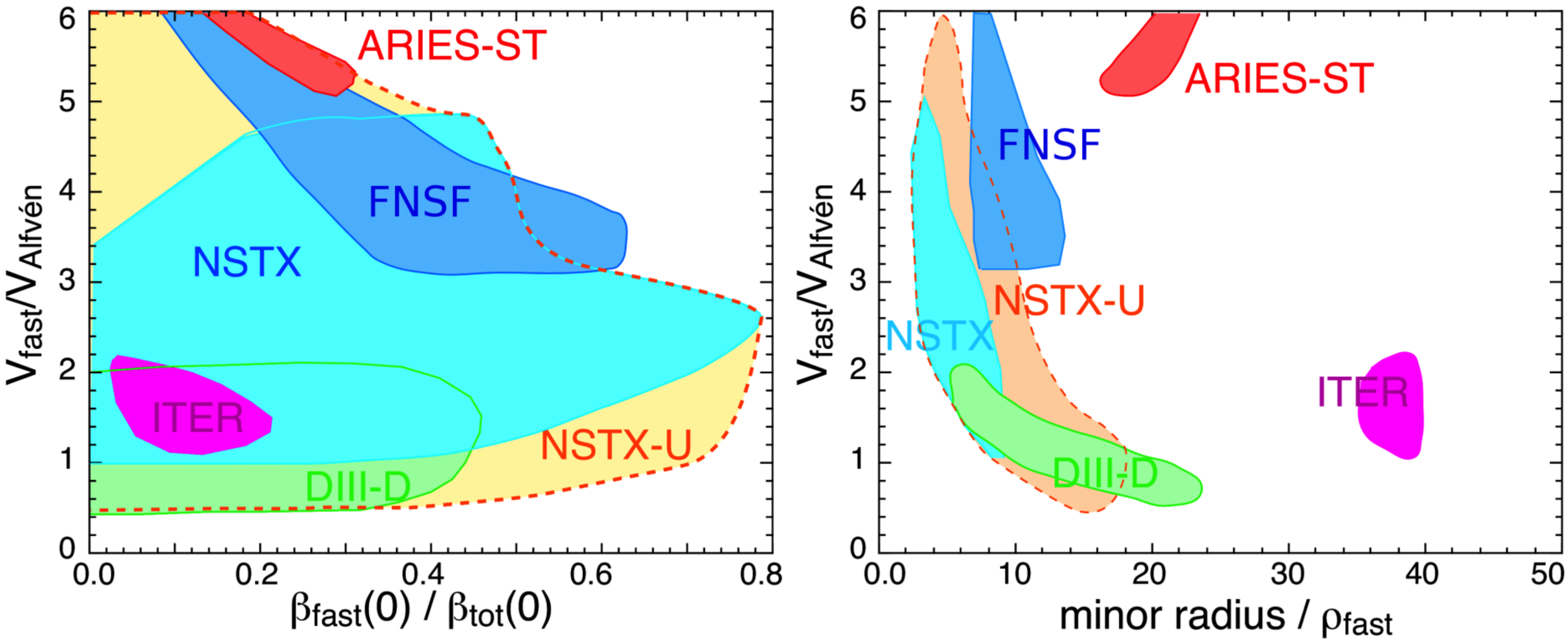
Diagnostics under development during NSTX-U Outage period:

- Tangential FIDA – *complement existing systems*
- Fusion source profile via charged D-D fusion products – *test on MAST*
- Fixed sightline E//B NPA – *must be re-located*
- Upgraded ssNPA
- *AE antenna for stability measurements, excitation of *AE mdoes

New/upgraded diagnostics under consideration - next 5-year plan:

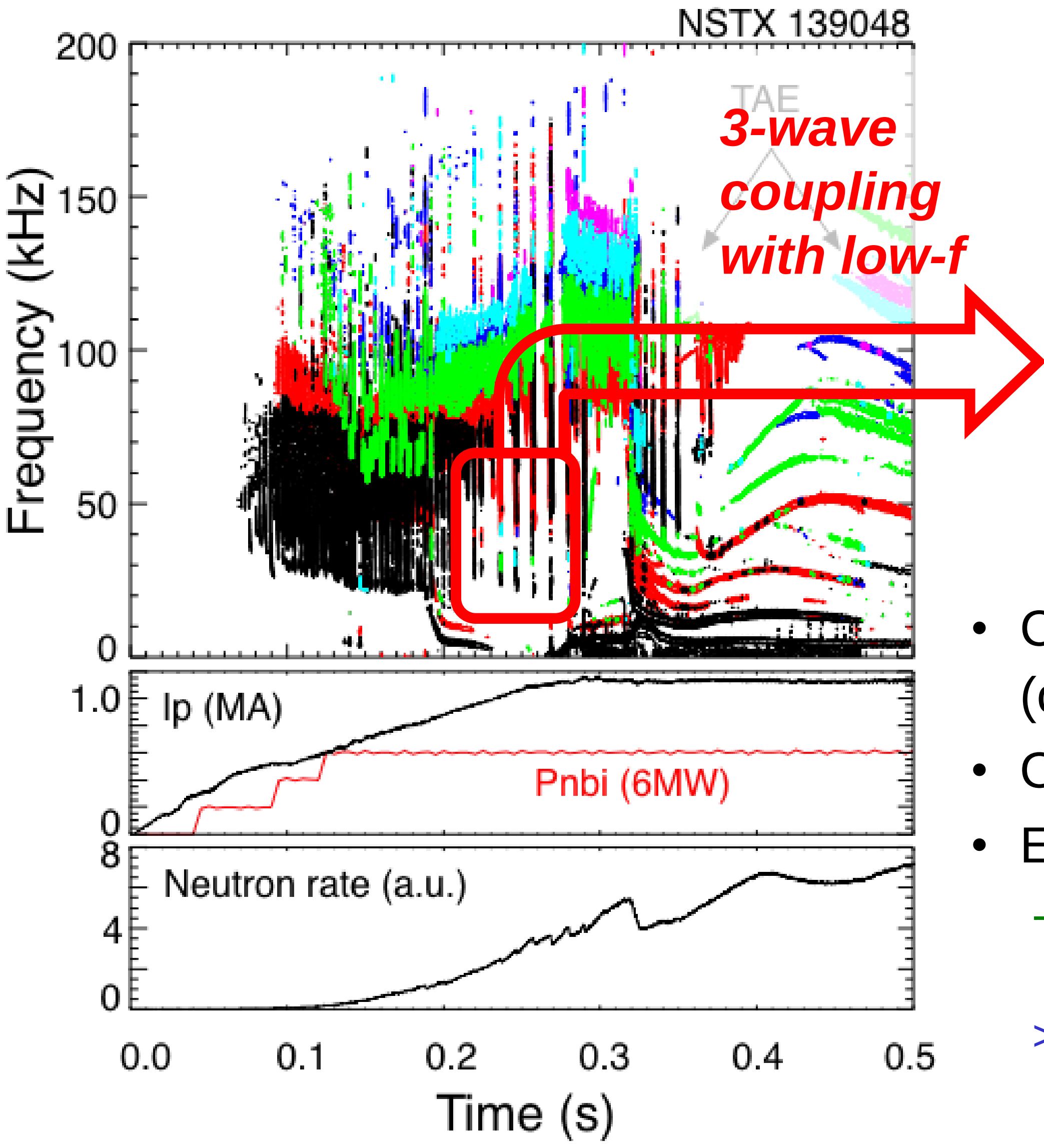
- BES expansion & increased resolution
- Neutron collimator
- Profile reflectometry with increased Δf
- FIDA & BES Imaging
- Radial polarimetry
- Toroidally-displaced in-vessel multi-energy DXR arrays
- Dual-energy, ultra-fast SXR arrays
- VB imaging of AE* modes
- BES passive FIDA view

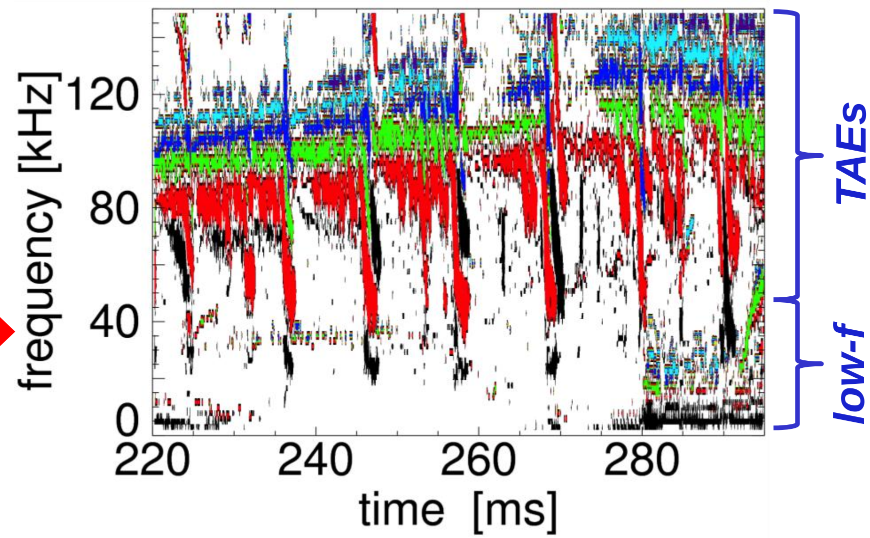
NSTX-U broadens NSTX parameter space for fast ion physics in STs: *need to predict *AE stability, impact on NB current drive*



- Higher B_t, density, NB power; same NB injection energy
  > ***Expect large variety of Alfvénic modes (AEs) destabilized***
- Parameter space complementary to other devices
  - Unique ST features provide excellent test-bed for theory, numerical codes
  > ***Improve predictive capability toward next step devices (ITER, FNSF)***

TAE/RSAE dynamics strongly affected by non-linear physics, interaction with other modes

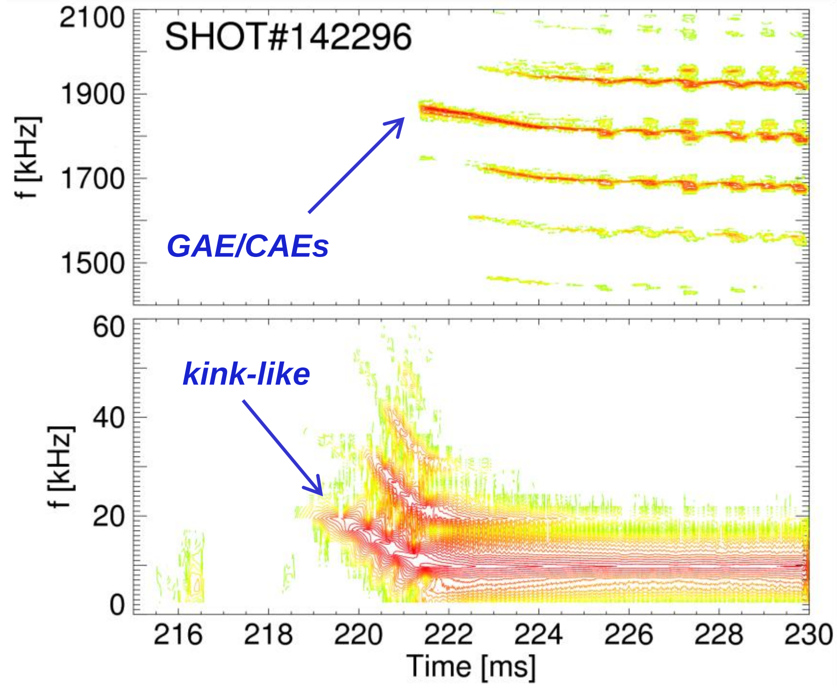




- Coupling between pairs of TAEs and (otherwise stable) low-f mode
- Often seen during large TAE bursts
- Experiment proposed on DIII-D:
  - *Can induce coupling to external perturbations (through I-coils)?*
  - > Trigger bursts, induce **controlled** redistribution

Profile and fast ion response to kink affect NB-CD, stability of other modes

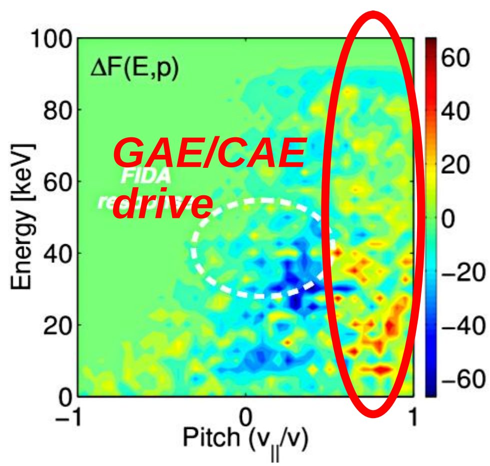
- Unstable kink-like mode found from PEST code
  - Simulated mode structure matches USXR data
- Common in NSTX after current ramp-up
- SPIRAL code used to infer fast ion response
- **Fast ions redistributed to larger radii and pitch values**



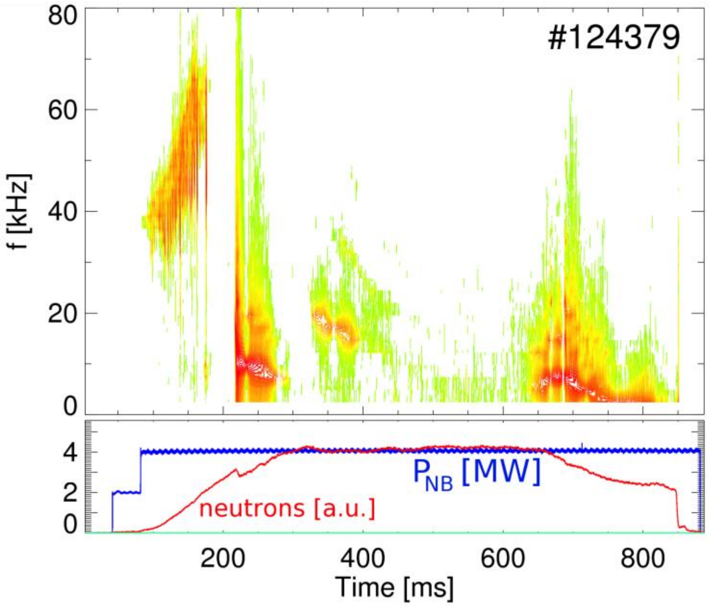
• Can redistribute NB-driven current

> Can affect stability of other modes

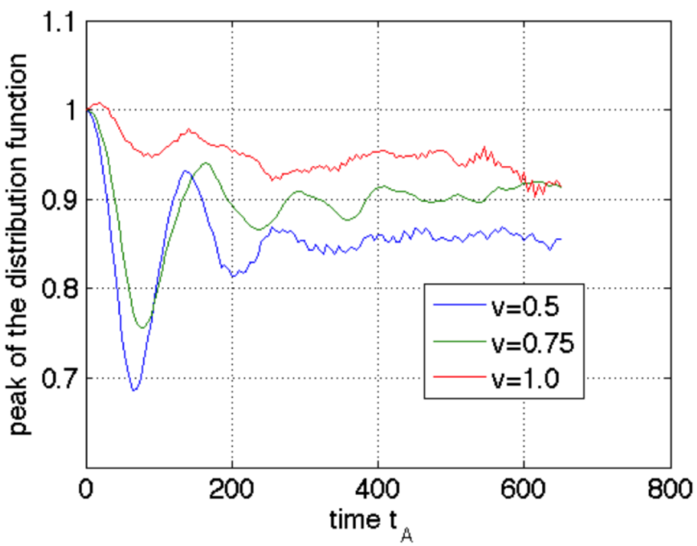
  - E.g.: GAE/CAEs destabilized soon after kink

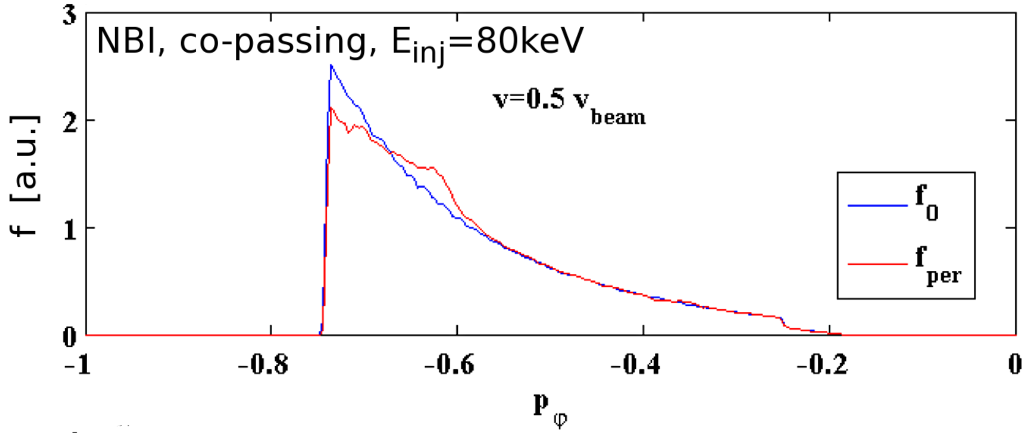


M3D-K results: non-resonant *n=1* kink can develop for q_{min}>1: trigger NTMs, slow down plasma, redistribute fast ions



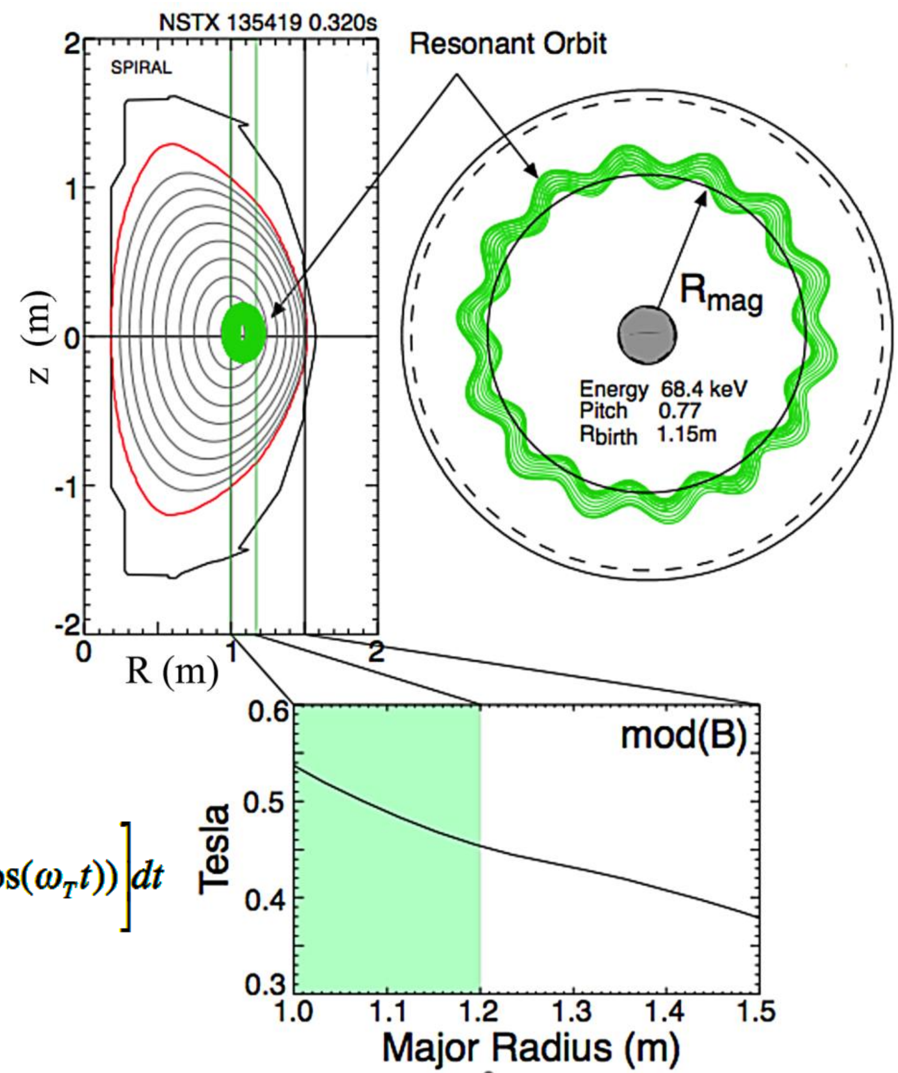
- Ideal MHD mode
- Long-living after non-linear saturation
- **Can induce 2/1 island, trigger NTMs**
- Rotation has weak effect on stability, but large impact on non-linear evolution
  - Reduction of island formation, reconnection
- Mode can flatten central fast ion distribution, cause substantial radial redistribution
  - Lower energies more affected
  - > ***Can impact NB-CD***





Conditions for Doppler-shifted resonance of high-frequency *AEs (GAEs/CAEs) investigated through SPIRAL code

- Full orbit calculation of fast ion orbit with SPIRAL code
- This particular fast ion has resonance between transit and cyclotron frequencies.
- Orbit is also close to stagnation point, very little variation of mod(B) over orbit, thus little variation of cyclotron frequency.
- Approximate range of phase variation between fast-ion resonance and the mode estimated from the dependence of $v_{//}$ on pitch and mod(B) and the variation of the cyclotron frequency with mod (B) over the fast-ion orbit:



$$\delta\phi(t) \approx \int \left[\omega + \langle k_{\parallel} V_{B\parallel} \rangle \left(1 - \frac{\varepsilon}{2}\frac{1-p^2}{p^2}\cos(\omega_T t)\right) - \langle \omega_{ci} \rangle \left(1 + \varepsilon\cos(\omega_T t)\right) \right] dt$$

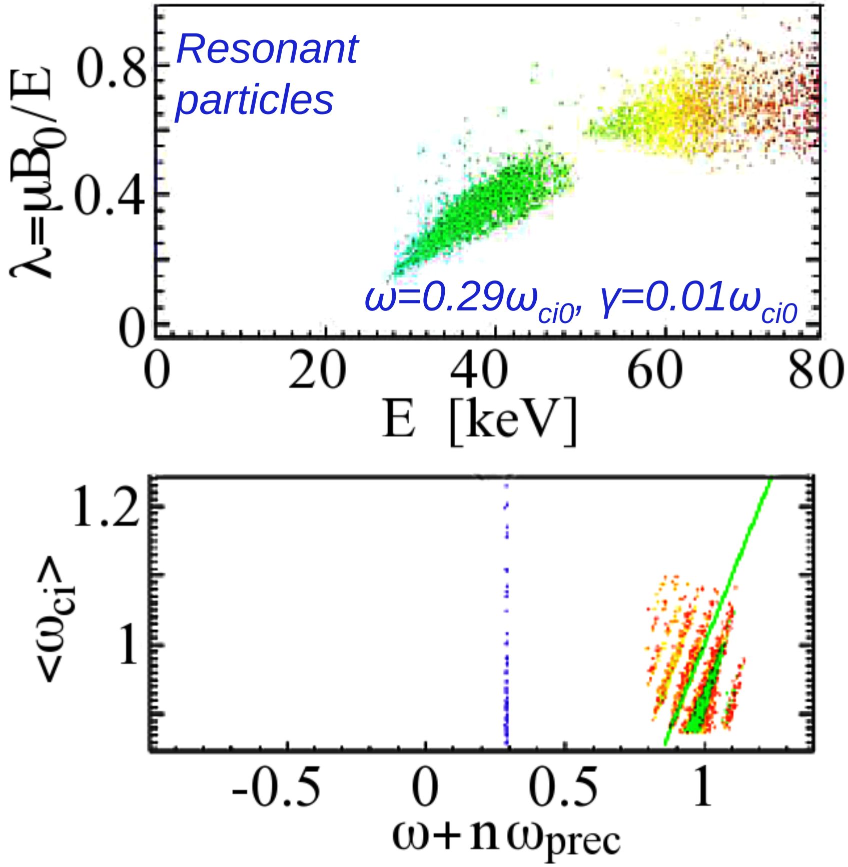
$$\delta\phi(t) \approx \frac{\langle k_{\parallel} V_{B\parallel} \rangle}{\omega_T}\frac{\varepsilon}{2}\frac{1-p^2}{p^2}\sin(\omega_T t) + \frac{\langle \omega_{ci} \rangle}{\omega_T}\varepsilon\sin(\omega_T t)$$

For this fast ion parameters, the phase variation is ≈ ±65º over the fast ion orbit.

HYM code enables accurate numerical modeling of NBI-driven sub-cyclotron frequency *AEs in NSTX

- HYM equilibrium solver has been modified to improve the equilibrium fit to the TRANSP and EFIT profiles.
- Numerical simulations for H-mode, have been performed to study of the effects of GAEs on the fast ion distribution function.
- HYM simulations for L-mode shots, using improved equilibrium fit, show very good agreement in terms of the mode frequency, amplitude, and estimated growth rate.
- Linear/nonlinear simulations performed in order to study in detail resonant wave-particle interaction in order to understand the nonlinear evolution of the instability. It has been shown that most resonant particles have stagnant orbits, and poloidal structure of the unstable mode is relatively coincident with location of the resonant orbits.
- Self-consistent kinetic description for the electrons has been implemented in the HYM code, where the electrons are described as δf drift-kinetic particles. This version of the code will be used to study the effects of GAE and CAE modes on the electron transport.

NSTX #135419, GAE mode n=9, m=1
(f's normalized to ω_{ci0})



Resonant particles shown with orbit-averaged cyclotron and precession frequencies, both normalized to the ion cyclotron frequency at the axis, ω_{ci0}.

Future Plans and development of HYM code

Research goals:

- Study excitation of GAE and CAE modes, and their effects on particle confinement.
- Detailed comparison with experimental results.

Plans:

-Study the effects of the sub-cyclotron modes on fast ion distribution function in NSTX.

-Study the effects of finite frequency (Hall term) on the stability properties of the NBI-driven sub-cyclotron frequency modes.

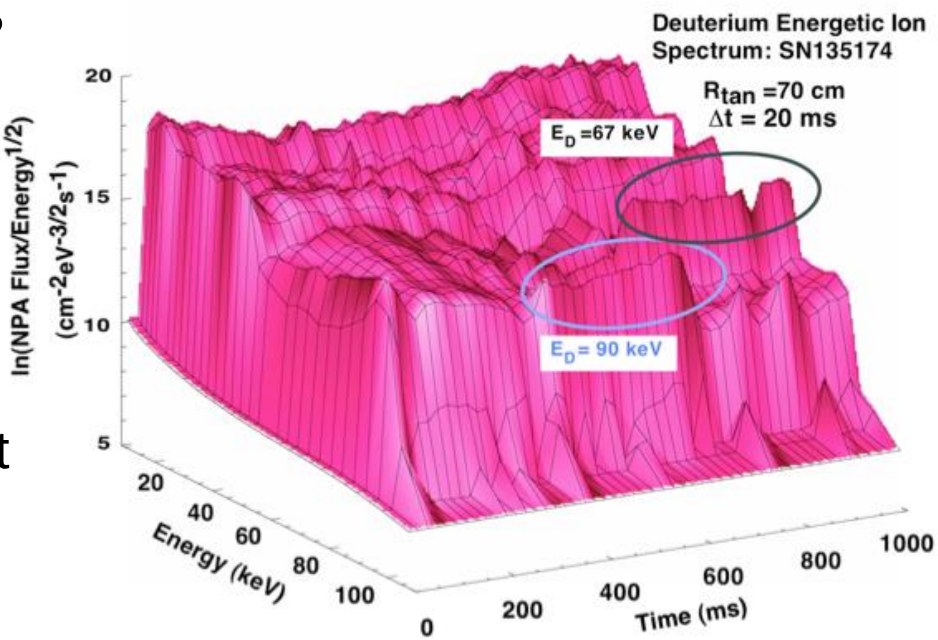
-Effects of GAE modes on the electron transport.

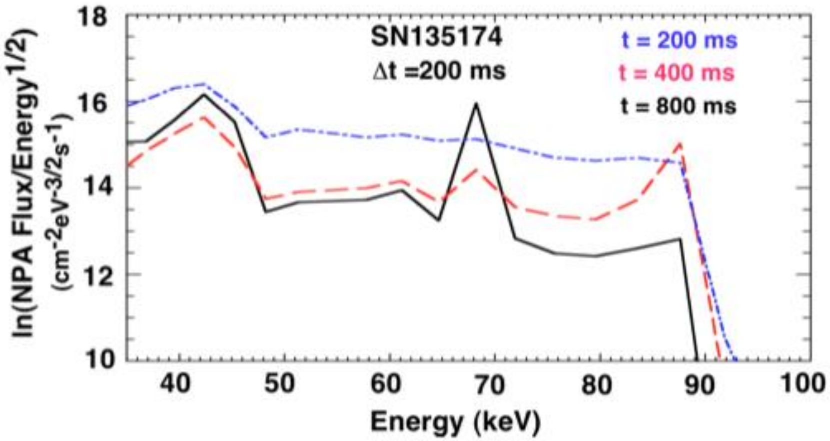
-Add sources and sinks in the HYM numerical model.

-Perform long time scale nonlinear numerical simulations to study the nonlinear evolution of unstable modes.

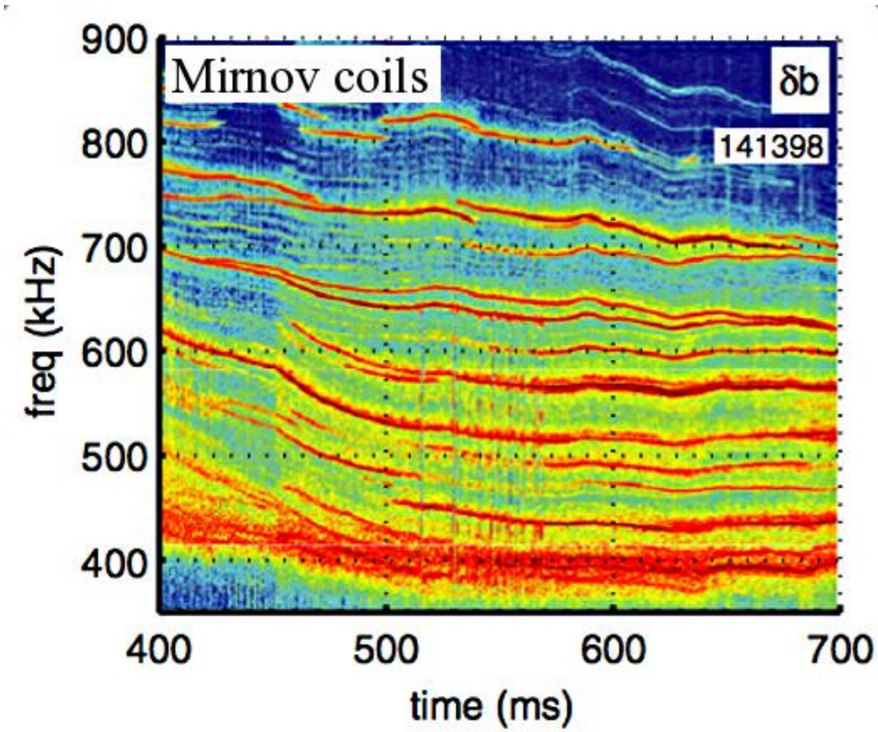
High-Energy Feature (HEF) observed on E//B NPA suggests fast ion redistribution by high-frequency CAEs/GAEs

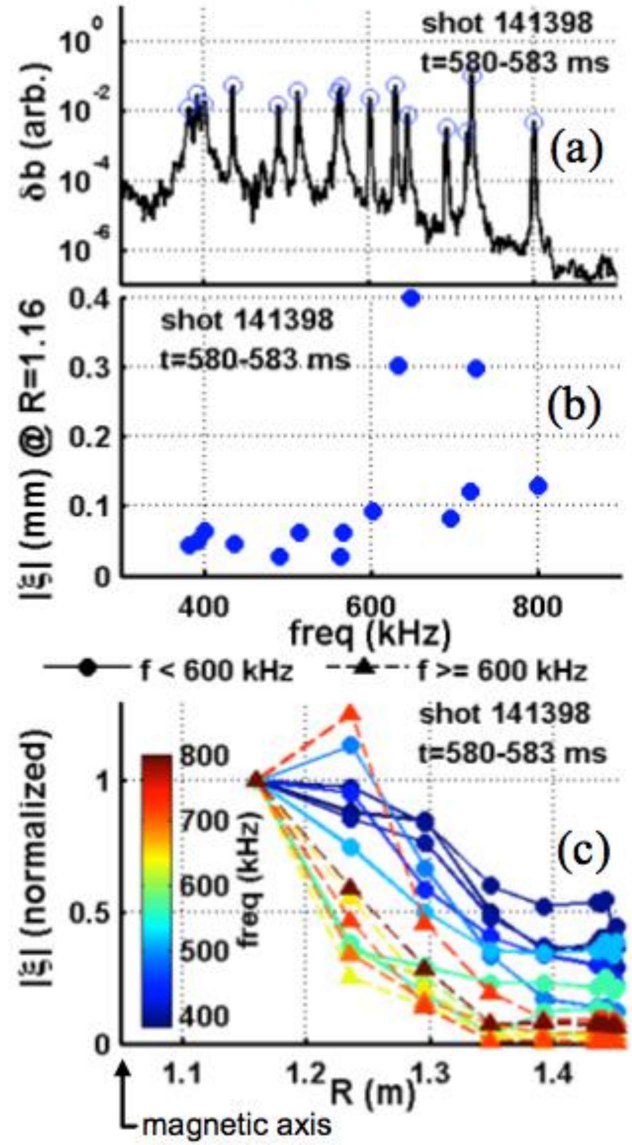
- ***HEF***: An "anomalous" increase in E||B NPA charge exchange neutral flux (~4x) localized at the NB injection full energy.
- Transient phenomenon with durations ~ 100 - 600 ms.
- Spectrum exhibits slowing down of fast ions below HEF energy region.
- HEF existence requires no kink and weak TAE activity
    - Wide range of CAE activity
- May indicate fast ion redistribution in pitch, energy





Improved measurements from UCLA reflectometer provide radial mode structure of *AEs





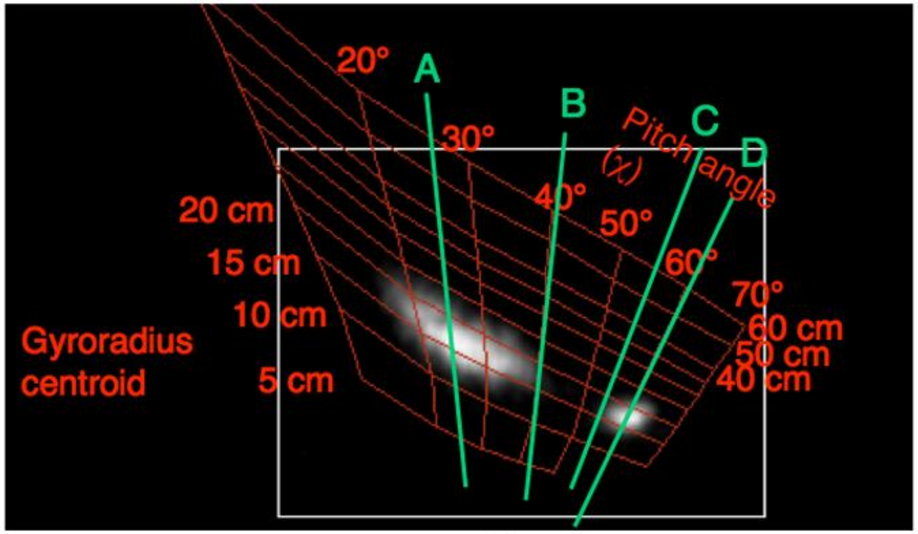
- Up to 16 fixed-frequency radial channels
  - Require monotonic density profile
- O-mode polarization
- Infer δn from phase

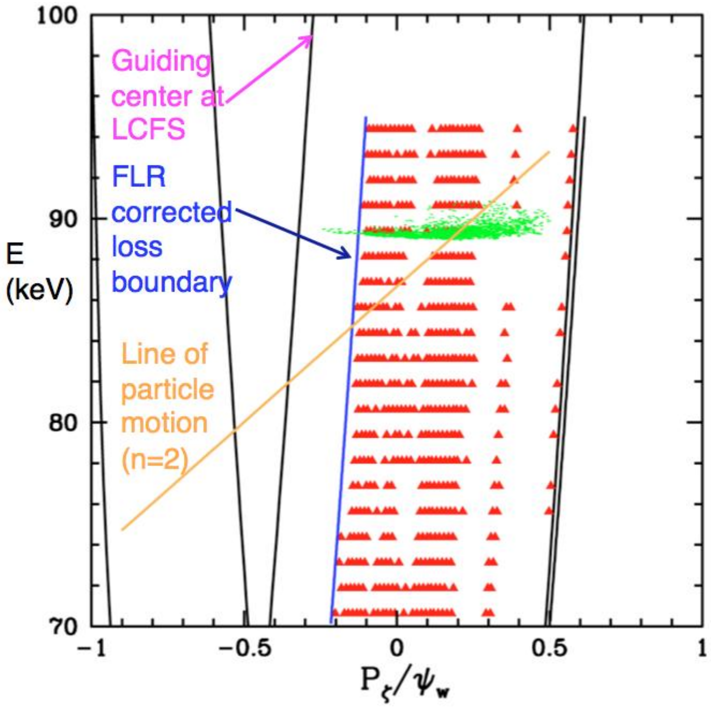
$$\Delta\Phi = \frac{2\omega}{c}\int_{x_{c.o.}}^{x_{inj}} N dx$$

$$N^2 = \frac{k^2c^2}{\omega^2} = \frac{c^2}{\omega^2}k_{inj}^2\left[1 - \frac{n(x)}{n_{c.o.}}\right]$$

Improve understanding of TAE-induced fast ion transport with ORBIT; develop models for improved analysis of diagnostics data, e.g. sFLIP

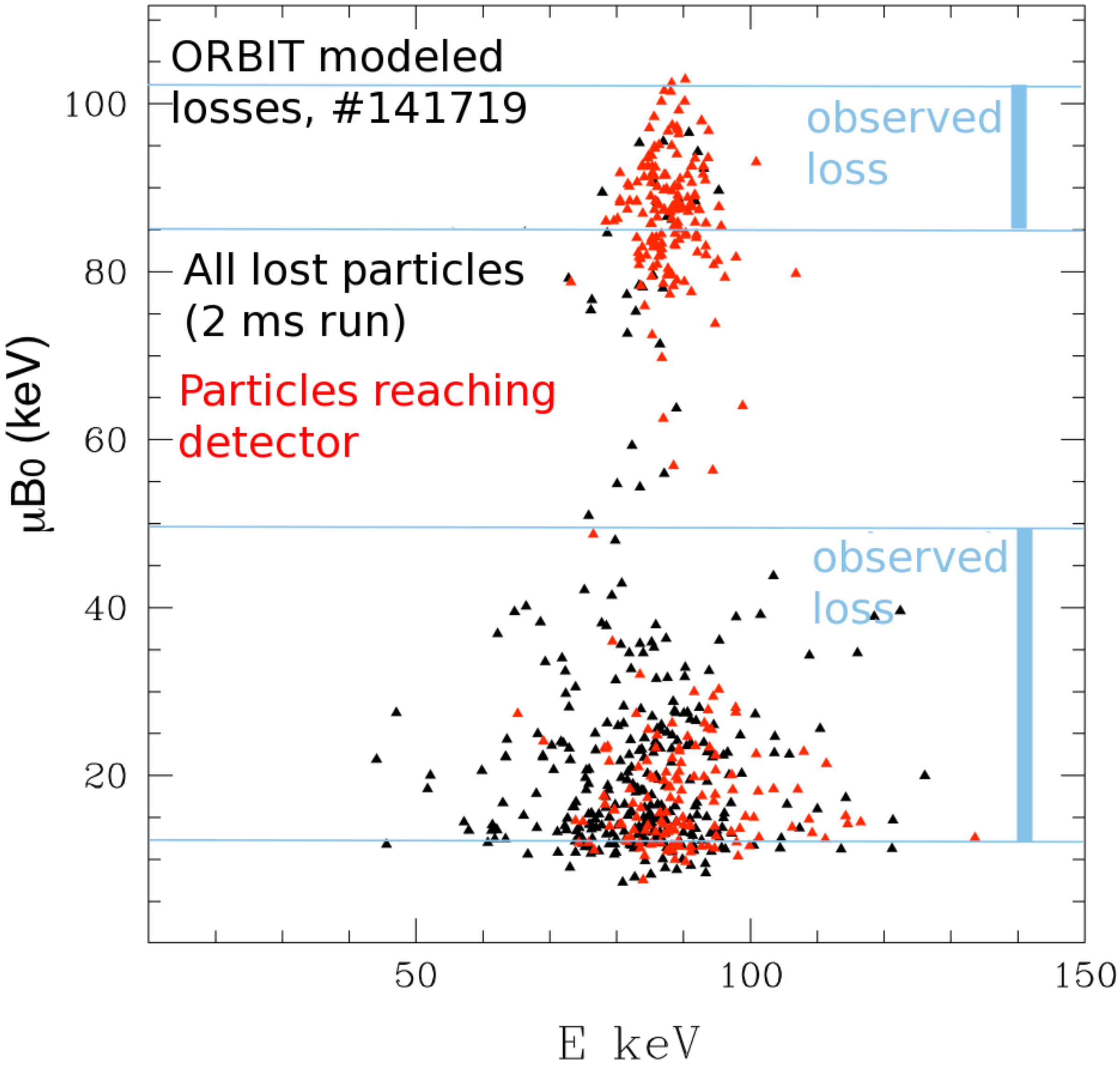
- ORBIT code confirms stochastization of fast ion phase space during TAE avalanches
  - Use modes from reflectometer+NOVA as input
- Compare modeled losses (pitch, energy) with sFLIP data - *next slide*





- Qualitative agreement found
  - Similar features in *reconstructed* sFLIP
- But: pitch, energy regions slightly different
  - Sensitivity to *input profiles*?
  - Sensitivity to *mode radial structures* from NOVA – e.g., non-ideal effects?

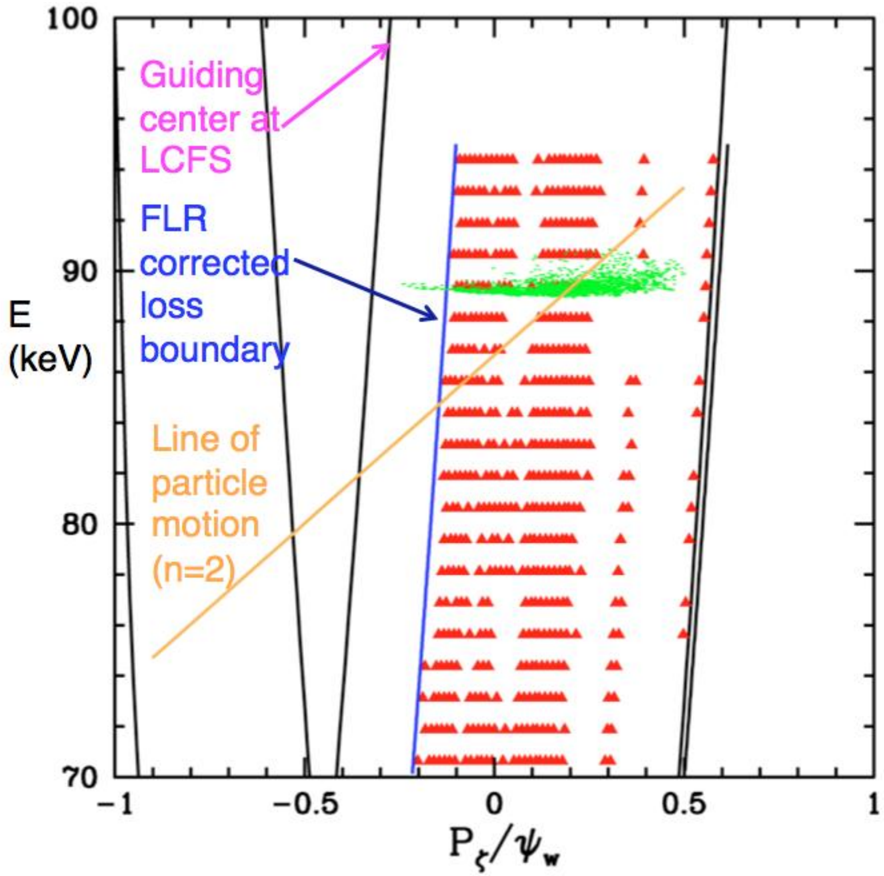
Orbit following including mode structure shows bimodal loss distribution in pitch angle, as observed on sFLIP



- Modeled pitch angle boundaries roughly agree with measurement
- *Same simulation for case with no measurable loss shows no particles reach detector*
- Measured loss on detector (red points) is representative of all losses (black points)

Suite of codes used to investigate *AE-induced fast ion transport; next step: *develop models for improved interpretive & predictive capability*

- ORBIT - gyro-center particle following
  - Stochastic transport by TAEs
- SPIRAL - full-orbit particle following
  - F_{nb} response to kinks, CAE/GAE modes
  - Starting w/ TAEs
- NOVA, PEST – ideal MHD
  - (Ideal) mode eigenfunctions
  - Linear stability/damping rates
- HYM – non-linear, hybrid/MHD
- M3D-K – non-linear, self-consistent
  - Full mode dynamics, transport



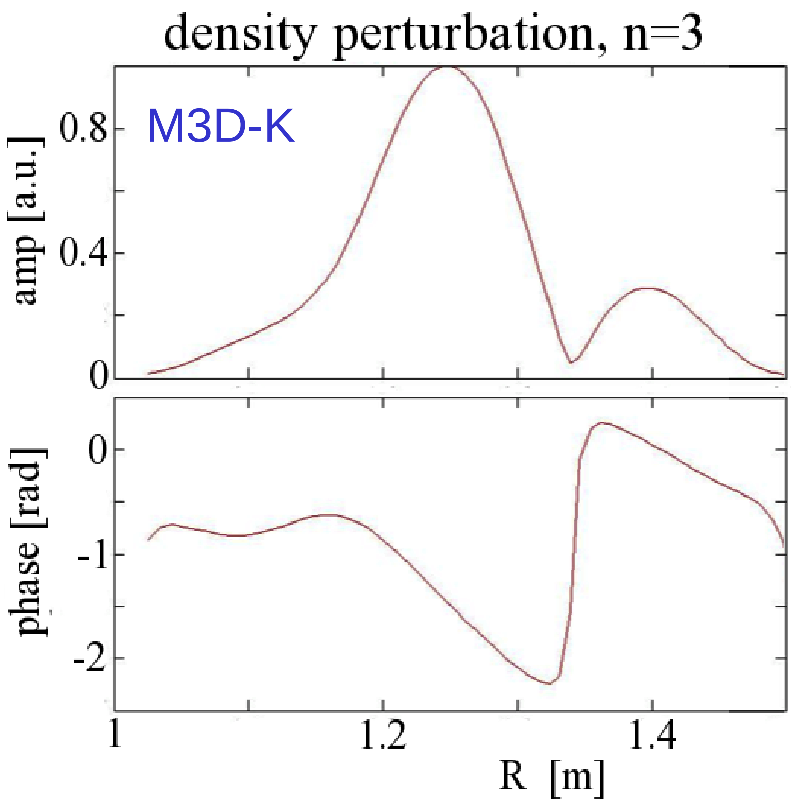
> **Quasi-linear models**
  - F_{nb} response to given set of modes; testing on DIII-D, ***NSTX-U next (FY14)***

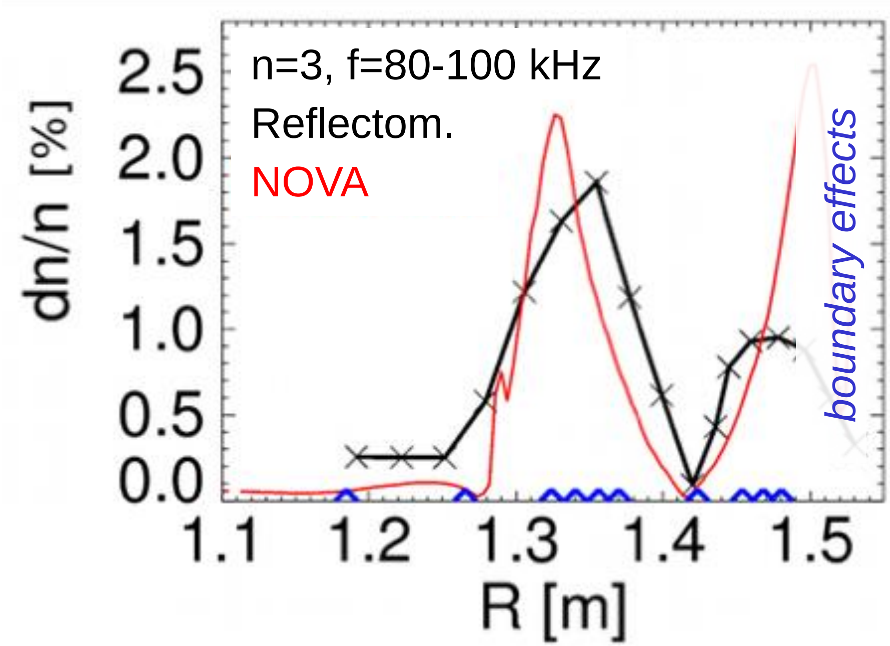
> **FIDASIM + F_{nb} evolving codes (long term: NUBEAM)**
  - Infer F_{nb} from set of data (FIDA, NPA, neutrons, …); under development

Validation of M3D-K code for TAEs in L-mode shows agreement with experiments, NOVA

PAC29-26

- Only L-mode plasmas modeled so far (better diagnostics data)
- Linear analysis shown here
- Radial phase variation – comparable to reflectometer measurements

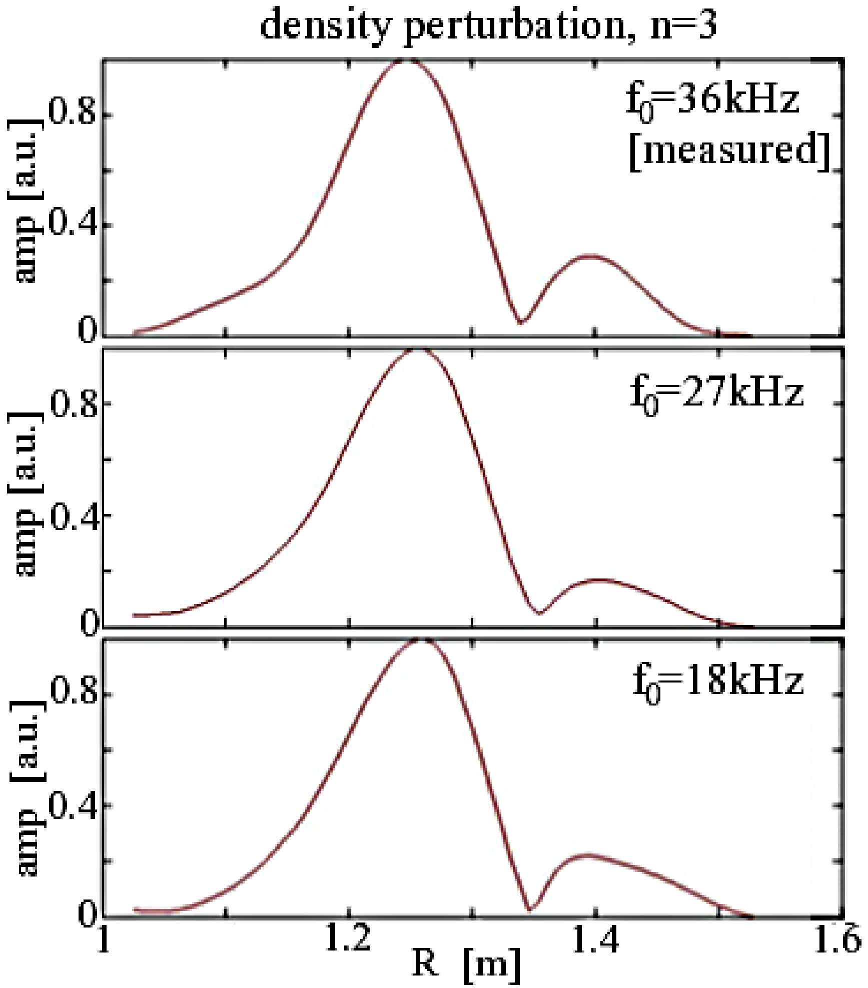




- Mode structure consistent with NOVA, data from reflectometer
- *Modes shifted inward* - under investigation: input profiles? equilibrium?

Moving towards non-linear simulations, extend to NSTX-U in FY13-14

Preliminary results from M3D-K also show little effects of rotation on TAE structure



- Scale rotation profile from measured f_0=36 kHz down to f_0=18 kHz (50% reduction)
- Mode peak location, structure do not change substantially

Reduced models for fast ion transport can be obtained from particle-following codes

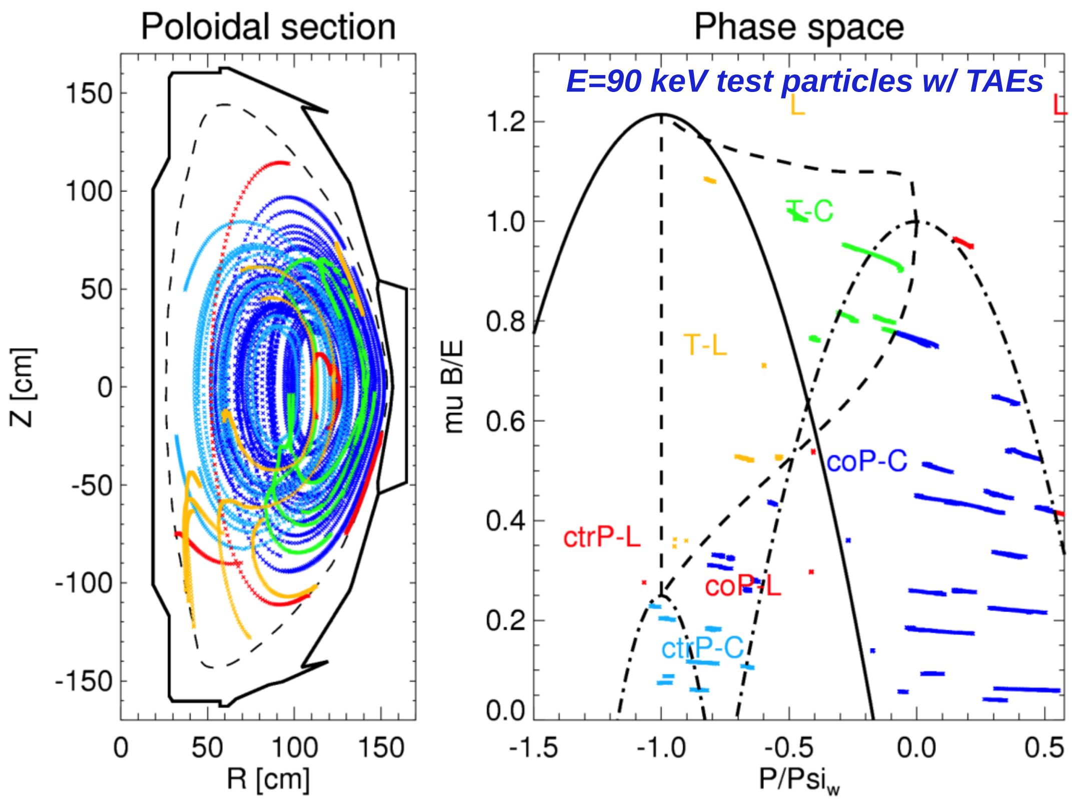
- ORBIT used to model fast ion transport by TAEs:
  - Multiple TAEs
  - Modes from reflectometer+ NOVA modeling
- Particles followed for ~ms
- Characterize typical 'steps' $\langle \Delta P \rangle$, $\langle \Delta E \rangle$ in phase space

⇩

- Infer *equivalent diffusion* coefficients – phase space:

$$\begin{cases} D_E(E,P,\mu|A_{mode},\ldots) \sim \langle \Delta E^2 \rangle / \tau_{sim} \\ D_P(E,P,\mu|A_{mode},\ldots) \sim \langle \Delta P^2 \rangle / \tau_{sim} \end{cases}$$

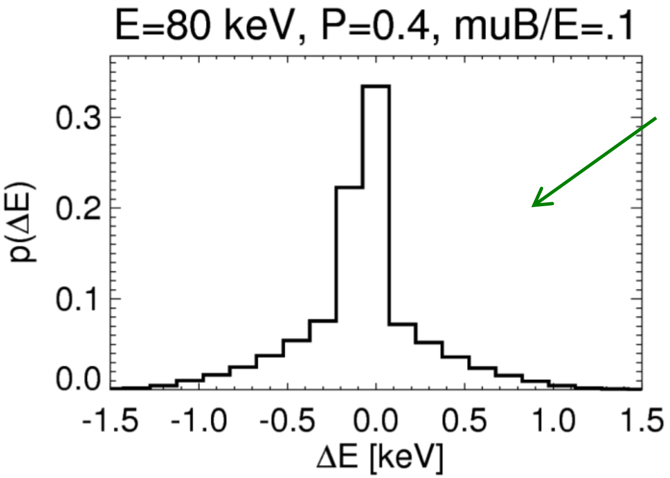
- Or: **use *distribution* of random walks to model non-diffusive transport**



- *Orbit topology used to differentiate specific classes of particles:*
  - co/ctr-Passing, Trapped, Lost, ...

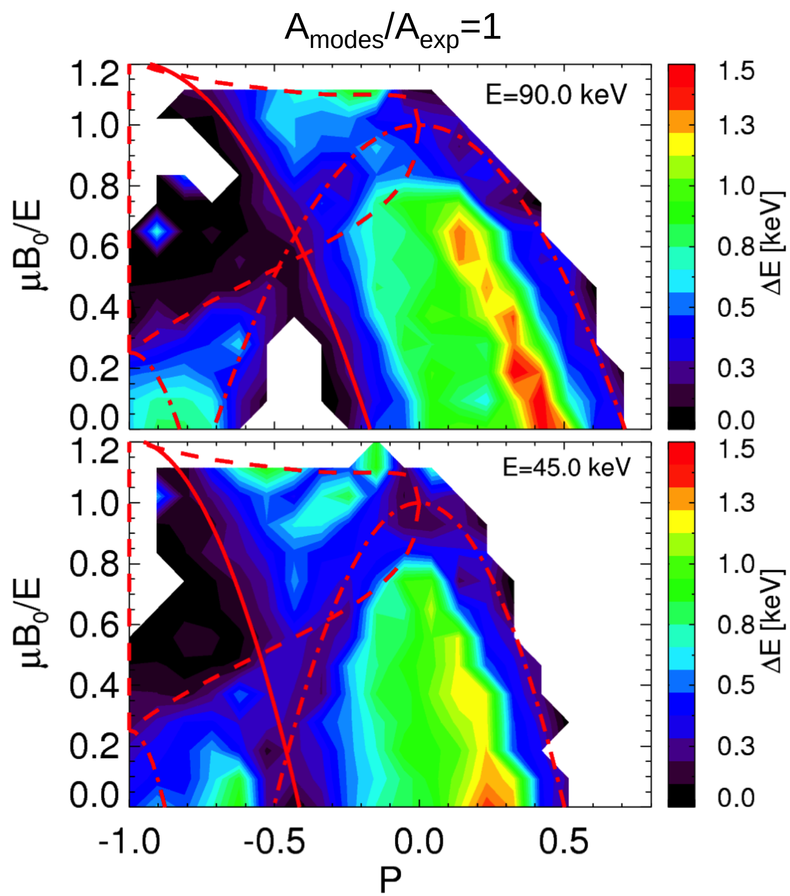
Use of transport coefficients from ORBIT, SPIRAL modeling in TRANSP will be assessed by FY14

- ORBIT (SPIRAL, ...) can provide
  - $\Delta E(E,P,\mu|A_{mode},...)$, energy step
  - $\Delta P(E,P,\mu|A_{mode},...)$, canonical toroidal momentum step
- However: only $D_x(E,r,t)$ implemented in TRANSP
  - ... and TAEs mostly act in phase space through resonances
- Moreover: transport by resonant modes can be non-diffusive (stochastic)
  - Need 'probabilistic' approach – suitable for MonteCarlo implementation in NUBEAM
  - May require non-gaussian distribution of ΔE, ΔP – *not yet available in TRANSP*



Ex: probability distribution function of energy step for fixed E,P, μ, A_{modes}/A_{exp}

$\Delta E(P,\mu|E,A_{modes})$ from ORBIT, sh#139048



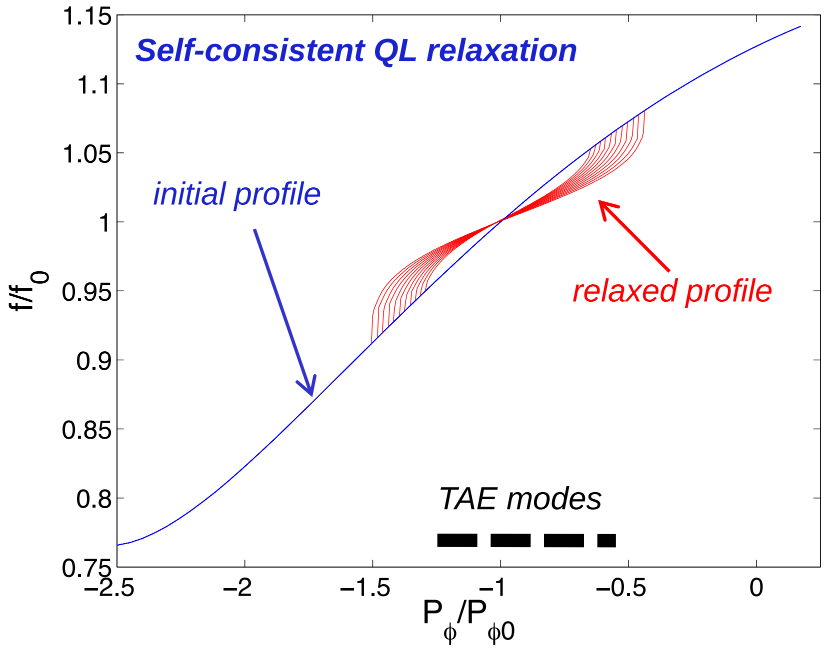
Need more flexible tools in TRANSP/NUBEAM for accurate modeling of*AE-induced fast ion transport

Quasi-Linear model computes critical fast ion profile in the presence of unstable TAEs

Evolution of fast ion distribution, modes:

$$\begin{cases} \dfrac{\partial f}{\partial t} = \sum_k \dfrac{\partial}{\partial P_\phi} D_k(P_\phi) \dfrac{\partial}{\partial P_\phi} f + S \\ \quad \textbf{where} \quad D(P_\phi) \propto W_k \delta(\Omega_k) \\ \dfrac{\partial W_k}{\partial t} = 2\gamma W_k \\ \quad \textbf{where} \quad \gamma = \gamma_{grth} - \gamma_{dmp} \\ \Omega_k = \omega - n\hat{\omega}_\phi + (m+p)\hat{\omega}_\theta \end{cases}$$

At marginal stability: $\gamma_{grth} \rightarrow \gamma_{dmp} \quad \gamma = 0$



- ***QL model*** uses analytic expressions for growth, damping rates *vs.* β_{fast} :

$$\gamma_{grth} = \gamma' \frac{\partial \beta}{\partial r}$$

with γ' {
mode number(s), n
relative mode widths to particle orbit
Plasma parameters
Isotropy

- Compute critical conditions on $d\beta_{fast}/dr$ at each radial position :

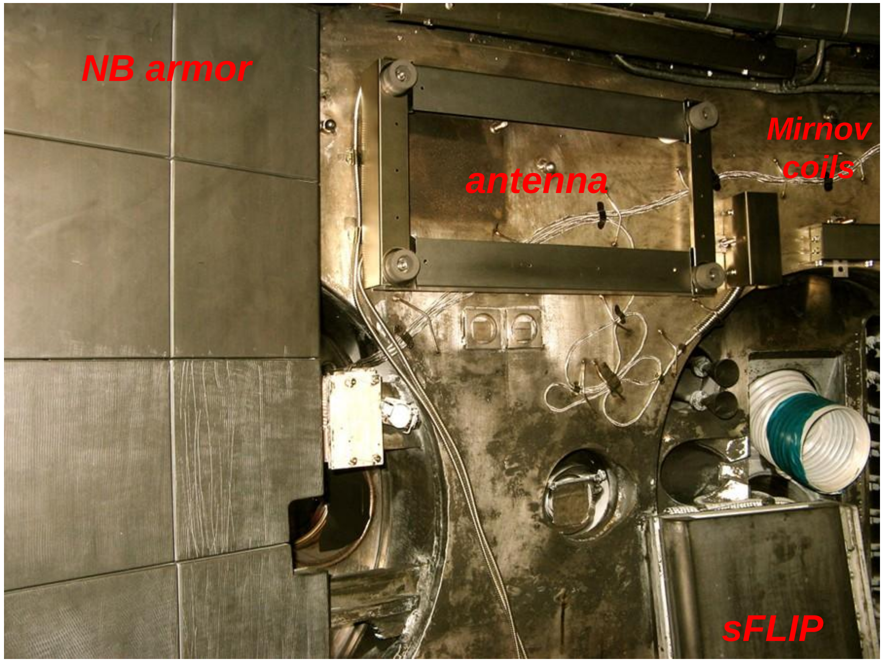
$$\gamma_{grth} = \gamma_{dmp}$$

$$\Downarrow$$

$$\frac{\partial \beta_{crt}}{\partial r} = -\frac{\gamma_{dmp}}{\gamma'}$$

*AE antenna under development to study stability of (and possibly drive) high-*f* CAE/GAEs, TAEs

- Goal: direct measurements of damping rate of stable *AE modes
- Target high-*f* modes
  - NSTX-U will have unique capabilities for CAE/GAE studies
  - Complement JET, MAST data for TAEs
- With upgrades, can assess requirements for "*phase space engineering*" techniques
- *Prototype installed before FY11*



- Tests will be performed at beginning of NSTX-U operations (Year 1)
- Upgrades will be based on initial results & modeling (Year 1-2)
- Under discussion: replace 2 straps of HHFW antenna with upgraded *AE antenna for Year 3 and beyond
  - Pending HHFW antenna assessment in first 2 years of NSTX-U operations

Reference publications

Recent publications:

•*Observation of Global Alfvén Eigenmode Avalanche events on NSTX*, E. D. Fredrickson *et al.*, Nucl. Fusion 52 (2012) 043001.
•*Study of chirping Toroidicity-induced Alfvén Eigenmodes in the National Spherical Torus Experiment*, M. Podestà *et al.*, Nucl. Fusion (in press, 2012).
•*Fast ion losses and redistribution induced by low frequency MHD in NSTX plasmas, based on FIDA observations and full-orbit simulations*, A. Bortolon *et al.*, Nucl. Fusion (in preparation, 2012).
•*Neutral beam ion loss arising from TAE avalanches in NSTX*, D. S. Darrow *et al.*, Nucl. Fusion (in preparation, 2012).
•*Investigation of a transient energetic charge-exchange flux enhancement observed in NSTX*, S. S. Medley *et al.*, Nucl Fusion 52 (2012) 013014.
•*High spatial sampling global mode structure measurements via multichannel reflectometry in NSTX,* N. A. Crocker *et al.*, Plasma Phys. Control. Fusion 53 (2011) 105001.
•*Non-linear dynamics of Toroidicity-induced Alfvén Eigenmodes on NSTX,* M. Podestà *et al.*, Nucl. Fusion 51 (2011) 063035.

Contributions to 12th IAEA-TM on Energetic Particles:

D. Darrow, M. Podestà, A. Bortolon, G.-Y. Fu, J. Lang, E. Fredrickson, K. Ghantous, N. Gorelenkov, S. Medley, G. Kramer, Y. Kolesnichenko

see http://w3fusion.ph.utexas.edu/ifs/iaeaep/program.html

Other references to *AE and EP-related studies on NSTX:

EPMs: "*Bounce precession fishbones in the National Spherical Torus Experiment*", E. D. Fredrickson *et al.*, Nucl. Fusion **43** (2003) 1258.

BAAEs: "*Beta-induced Alfvén-acoustic eigenmodes in National Spherical Torus Experiment and DIII-D driven by beam ions*", N. N. Gorelenkov *et al.*, Phys. of Plasmas **16**, 056107 (2009).

rSAEs: "*Alfvén cascade modes at high β in the National Spherical Torus Experiment*", N. A. Crocker *et al.,* Phys. Plasmas **15**, 102502 (2008)

TAEs: "*Modeling fast-ion transport during toroidal Alfvén eigenmode avalanches in National Spherical Torus Experiment*", E. D. Fredrickson *et al.*, Phys. Plasmas **16**, 122505 (2009)

GAEs/CAEs: "*Theory and Observations of High Frequency Alfvén Eigenmodes in Low Aspect Ratio Plasmas*", N. N. Gorelenkov *et al.*, Nucl. Fusion, **43** (2003) 228.

"Angelfish" modes: *Weak effect of ion cyclotron acceleration on rapidly chirping beam-driven instabilities in the National Spherical Torus Experiment*", W. W. Heidbrink et al., Plasma Phys. Cont. Fusion **48** (2006) 1347

Non-resonant kink: "*Onset and saturation of a non-resonant internal mode in NSTX*", J. Breslau *et al.*, Nucl. Fusion, **51** (2011) 063027.