NSTX-U

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FY14-18 Five Year Plan
Energetic Particle (EP) Physics

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for the NSTX-U Research Team

NSTX-U PAC-33 Meeting
PPPL – B318
February 19-21, 2013

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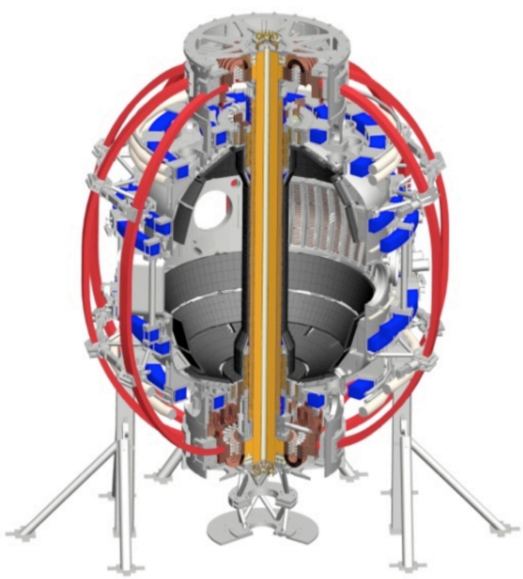

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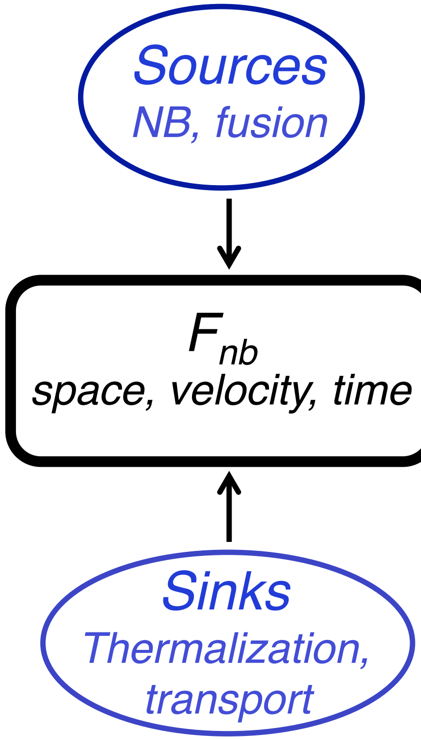
Goal: enable predictions of fast ion behavior and associated instabilities in high-β, super-Alfvénic regimes (ITER/FNSF)

- Need to understand/predict fast ion distribution behavior
  - Fast ions affect power balance, MHD stability
  - Provide current drive, torque



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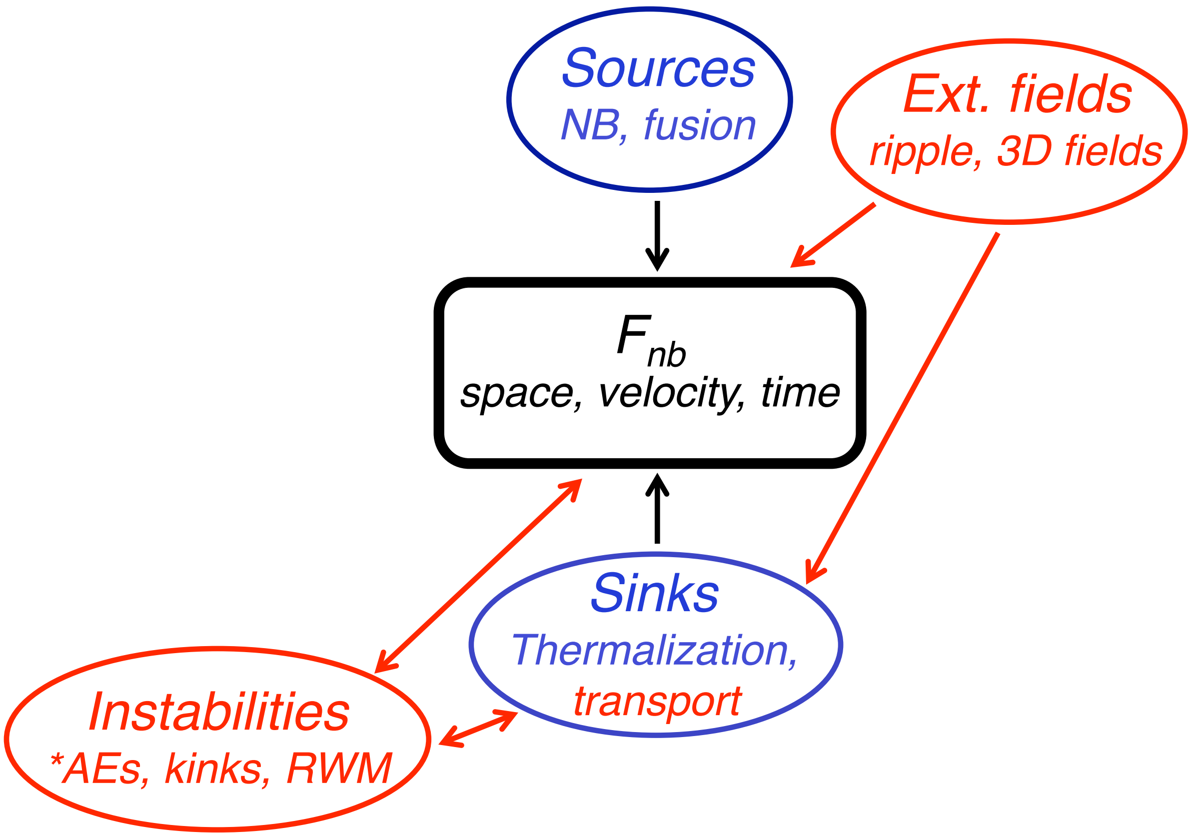
  ...especially when it deviates from "classical"

  > Non-linear physics dominates



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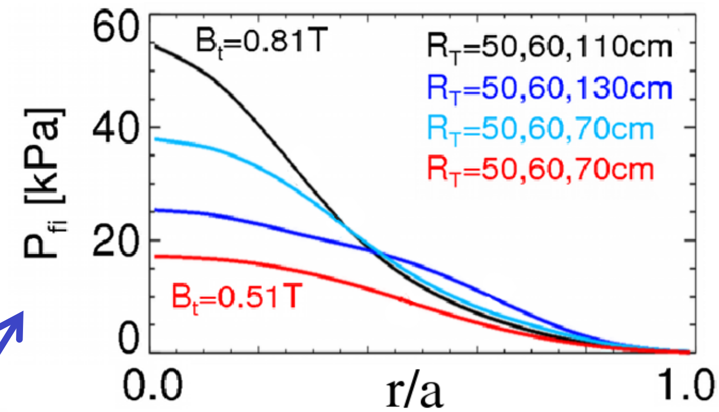
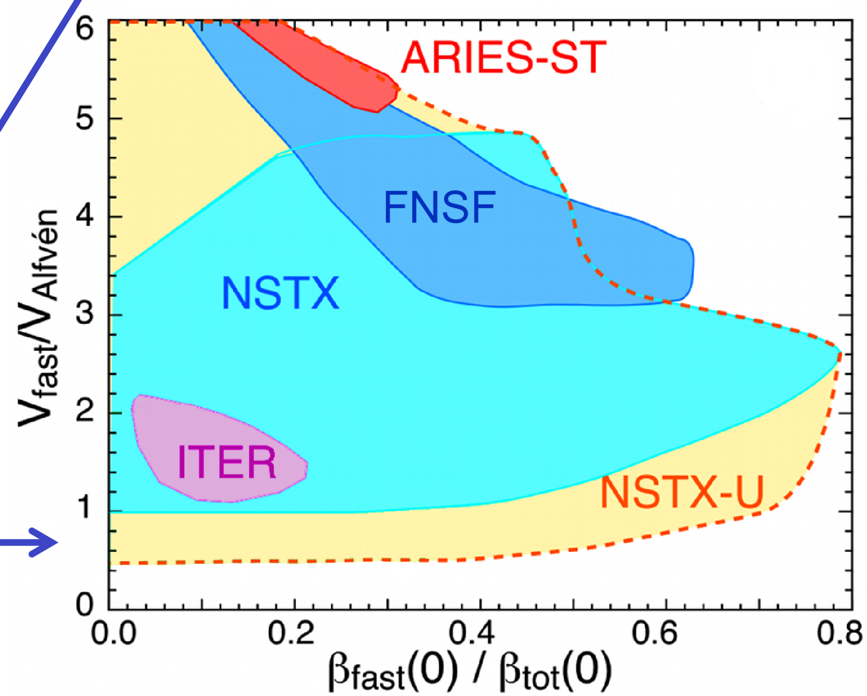
  ...especially when it deviates from "classical"

  > Non-linear physics dominates

NSTX-U features unique capabilities for EP studies towards ITER, FNSF, next-steps

- 3 additional NB sources, 3D fields, q-profile/density control
  - Improved flexibility to **manipulate fast ion distribution** F_{nb}, NB-CD
- Higher B_t, current, longer pulses with super-Alfvénic ions and high β
  - **Expand regimes** for EP physics towards ITER, FNSF





Outline

- EP Thrusts and Milestones for FY14-18
- 5 year Research plans and goals
  - FY14 : preparing for beginning of NSTX-U operations

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  - FY15-18 : EP research in support of 2 main EP Thrusts
- Theory, diagnostics in support of EP research
- Summary

10% incremental budget: **Incr.**

Backup Slides: ***B#Z***

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EP Thrusts & Milestones: assess predictive capability, tools & techniques for F_{nb} and *mode control*

Thrust EP-1: Develop predictive tools for *AE-induced fast ion transport **B#25**

- Reproduce fast ion transport for broad range of modes' properties (frequency, spectrum, structure)
- Verification&Validation vs. NSTX-U data to assess *predictive capability*

Thrust EP-2: Assess requirements for fast ion *phase space engineering* **B#26**

- Assess techniques to affect F_{nb}, modes' properties through NB, rf, 3D fields, external antennae

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FY14 Milestone: Assess reduced models for *AE-induced fast ion transport. **B#27**

FY15 Milestone*: Assess the effects of NB injection parameters on fast ion distribution function, NB driven current profile. **B#28**

*(w/ WH&CD, ASC, MS, SFSU Topical Science Groups)

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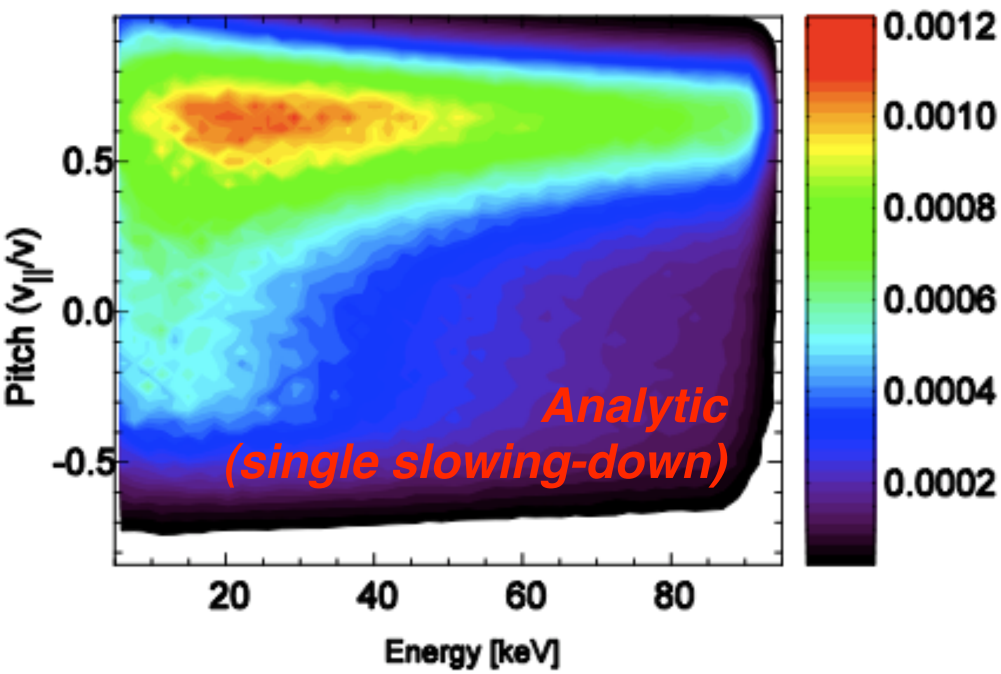
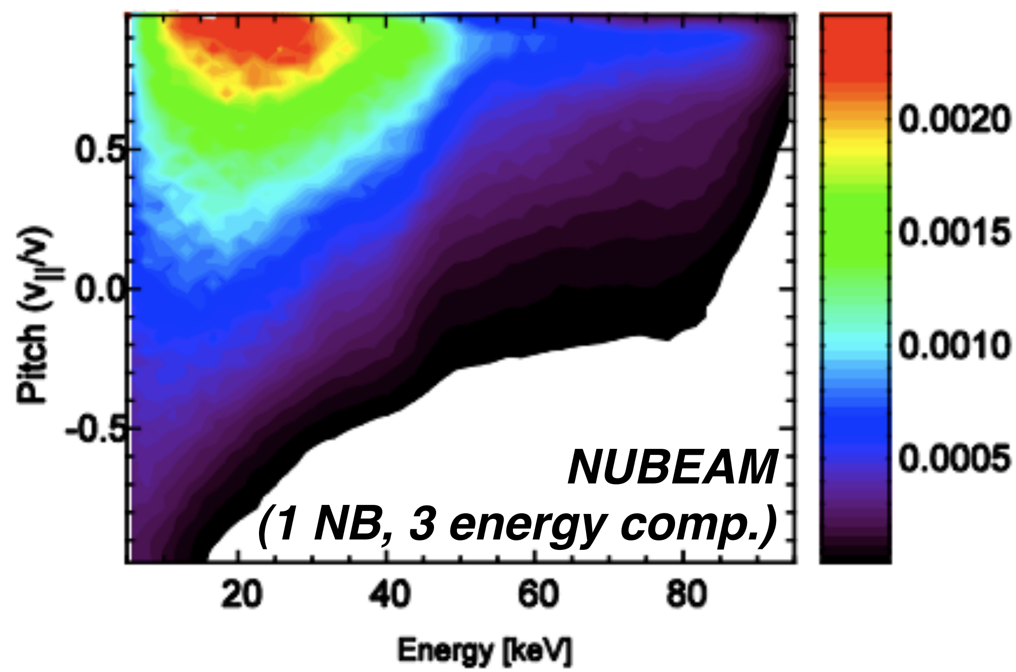
EP research in FY14: develop new analysis tools, prepare for FY15 operations

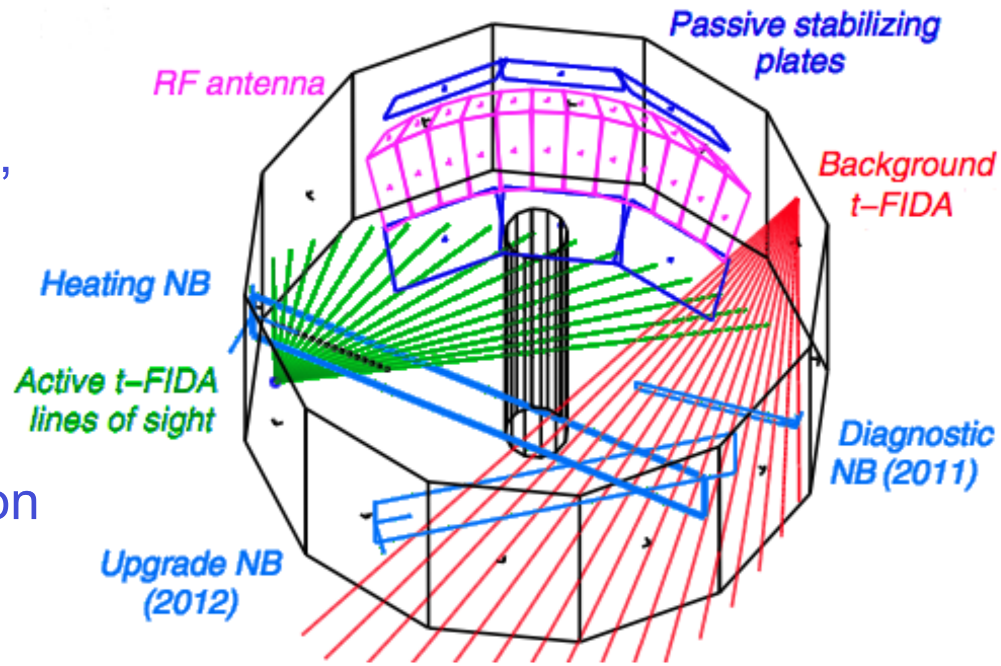
- FY14 Milestone: assess reduced models for *AE-induced fast ion transport **B#27**
  - Model for Quasi-Linear relaxation of fast ion profile for given *AEs
  - Model for *resonant* fast ion transport (NUBEAM/TRANSP) to complement existing “diffusive/convective” models
- Planned improvements of numerical tools **B#29**
  - 3D ‘halo’ model in TRANSP (analysis/simulation of CX data)
  - Improved F_{nb}, rotation description (M3D-K, NOVA-K, HYM)





EP research in FY14: develop new analysis tools, prepare for FY15 operations

- FY14 Milestone: assess reduced models for *AE-induced fast ion transport **B#27**
  - Model for Quasi-Linear relaxation of fast ion profile for given *AEs **B#30**
  - Model for *resonant* fast ion transport (NUBEAM/TRANSP) to complement existing "diffusive/convective" models **B#31**
- Planned improvements of numerical tools **B#29**
  - 3D 'halo' model in TRANSP (analysis/simulation of CX data)
  - Improved F_{nb}, rotation description (M3D-K, NOVA-K, HYM)
- Prepare for NSTX-U operations
  - Diagnostics being upgraded, reinstalled, calibrated (e.g. FIDA, NPAs, sFLIP, reflectometer, BES)
  - *Add Charged Fusion Product array, collimated neutron detectors* **Incr.**
  - Start planning experiments, with focus on FY15 Milestone

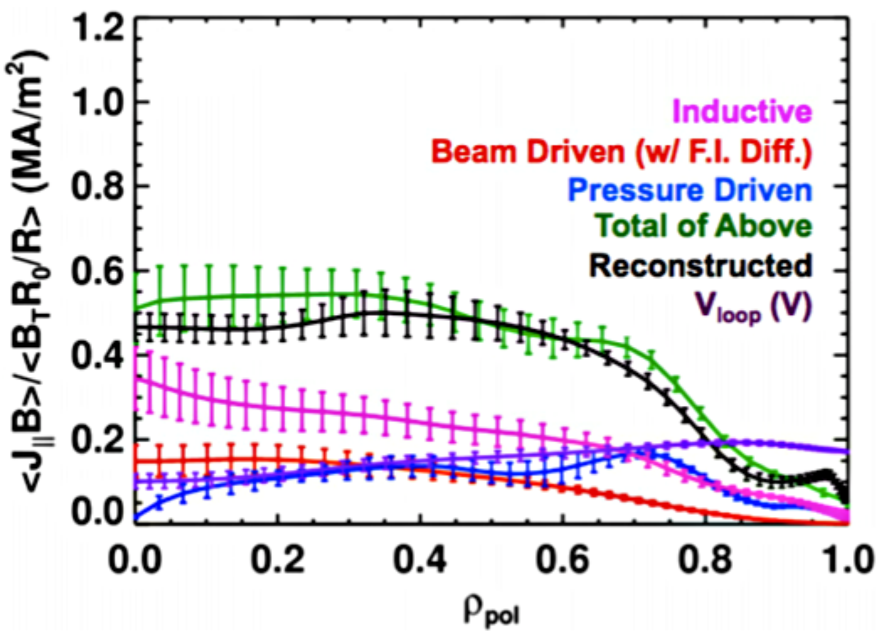


Thrust EP-1 Plans & Goals: focus on *AE dynamics, stability and induced fast ion transport

FY15

FY16

- Compare (classical) NUBEAM predictions for 1st+2nd NBI to experiments **B#28**
  - Use MHD-quiescent discharges, improved diagnostics (FIDAs, ssNPA, sFLIP, neutrons) to address **FY15 Milestone**
  - Compare measured current profile (MSE) w/ NUBEAM/TRANSP
  - > **Map NB parameters space, establish baseline for future fast ion/*AEs studies**
- Characterize beam ion driven *AE activity
  - Compare *AE properties (wavenumber/frequency spectra, structure) measurements to predictions from NOVA-K, M3D-K
  - Extend simulations to full 1T, 2MA NSTX-U scenarios



TRANSP reconstruction of current profile.
Anomalous D_{fi}:
$1 m^2/s$ (baseline)
$50 m^2/s$ (impulses)

Thrust EP-1 Plans & Goals: focus on *AE dynamics, stability and induced fast ion transport

FY15

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  - Compare *AE properties (wavenumber/frequency spectra, structure) measurements to predictions from NOVA-K, M3D-K
  - Extend simulations to full 1T, 2MA NSTX-U scenarios

FY17

- Study effects of high-frequency GAE/CAEs on thermal electron transport (w/ T&T TSG)
- Extend *AE studies to **non-linear, multi-mode physics**
  - Compare fast ion transport measurements to simulations
  - Improved codes for stability, dynamics, induced transport (NOVA-K, ORBIT, SPIRAL, M3D-K, HYM) **B#29**

FY18

> **Extend simulations/predictions of fast ion transport to FNSF/Pilot (stationary phase)**

Incr. (Y4) Extend *AEs projections to FNSF/Pilot ramp-up phase

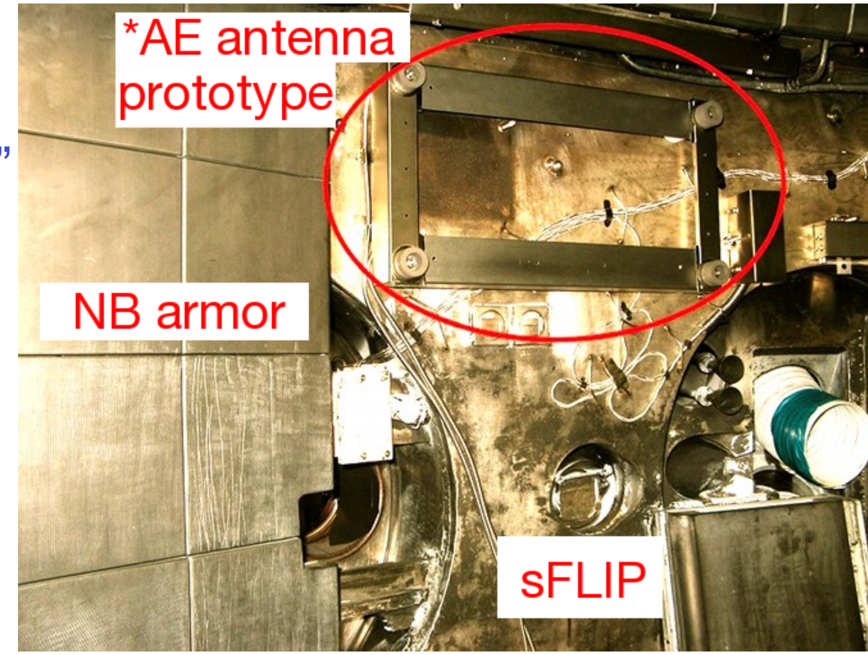
Thrust EP-2 Plans & Goals: assess development of *F_{nb}, mode control* tools/techniques

B#26

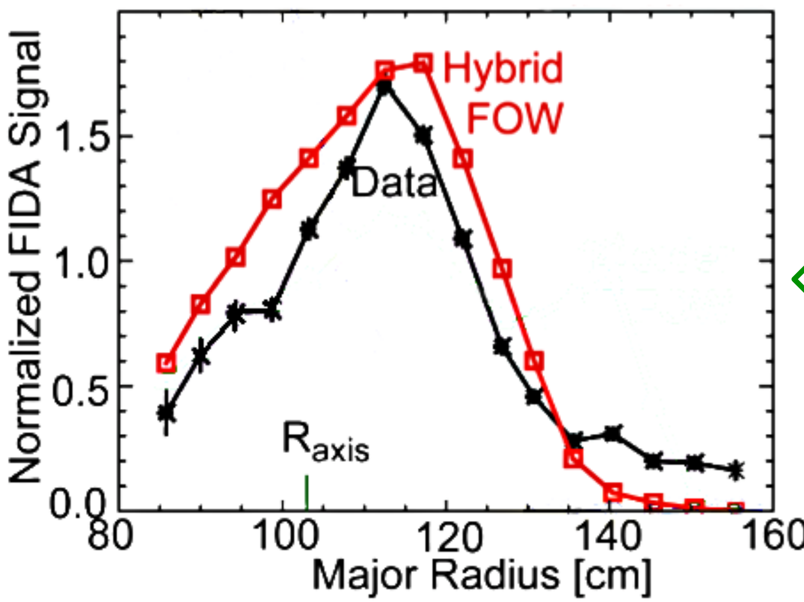
FY15

FY16

- Test *AE antenna system →
  - Up to 4 coils, target "physics operations" @ low power (<5kW) for FY16
- Compare measured *AE damping rates to theory, simulations
  - Challenge *AE damping models
  - Expand previous work (C-Mod, JET, MAST) to unique ST regimes



- Characterize scenarios with combined NBI + rf heating



Ex.: Measured vs simulated (CQL3D) $F_{nb}(r)$ for NBI + HHFW scenarios on NSTX

See WH&CD presentation (next)

Thrust EP-2 Plans & Goals: assess development of F_{nb}, *mode control* tools/techniques B#26

FY15 FY16 FY17 FY18

- Test *AE antenna system →
  - Up to 4 coils, target "physics operations" @ low power (<5kW) for FY16
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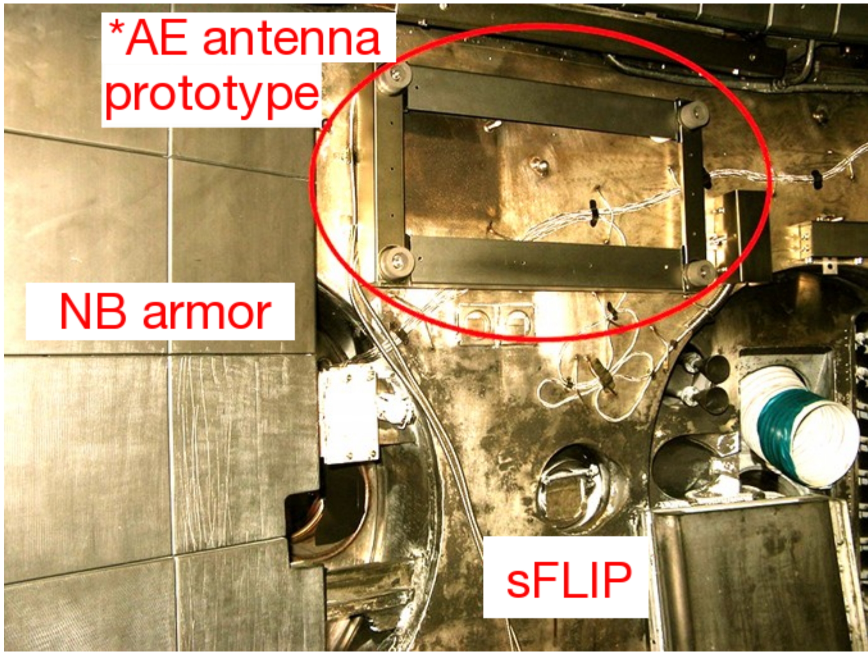
  - Expand previous work (C-Mod, JET, MAST) to unique ST regimes



- Characterize scenarios with combined NBI + rf heating
- Study rotation, 3D fields effects on *AEs (RWM, upgraded SPAs for improved rotation control, NCC after FY16) B#23
- Extend stability measurements to high-frequency *AEs
  - Test/validate theories on high-f *AEs drive, damping

> **Assess capability of & requirements for selective mode excitation using NB, rf, 3D fields, possibly (Incr.) antennae**

Incr. (Y3-4) Implement and test high-power (>10kW) *AE excitation system

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10% incremental budget: ***Incr.***

Backup Slides: ***B#Z***

Theory & code developments complement EP Research, enable detailed theory/experiment comparison for V&V

FY13 | FY14 | FY15 | FY16 | FY17 | FY18

Upgrade Outage

5 year plan period

Theory

Improved rotation, F_{nb} description in NOVA-K, M3D-K and HYM

ORBIT, SPIRAL for fast ion response to *AE modes

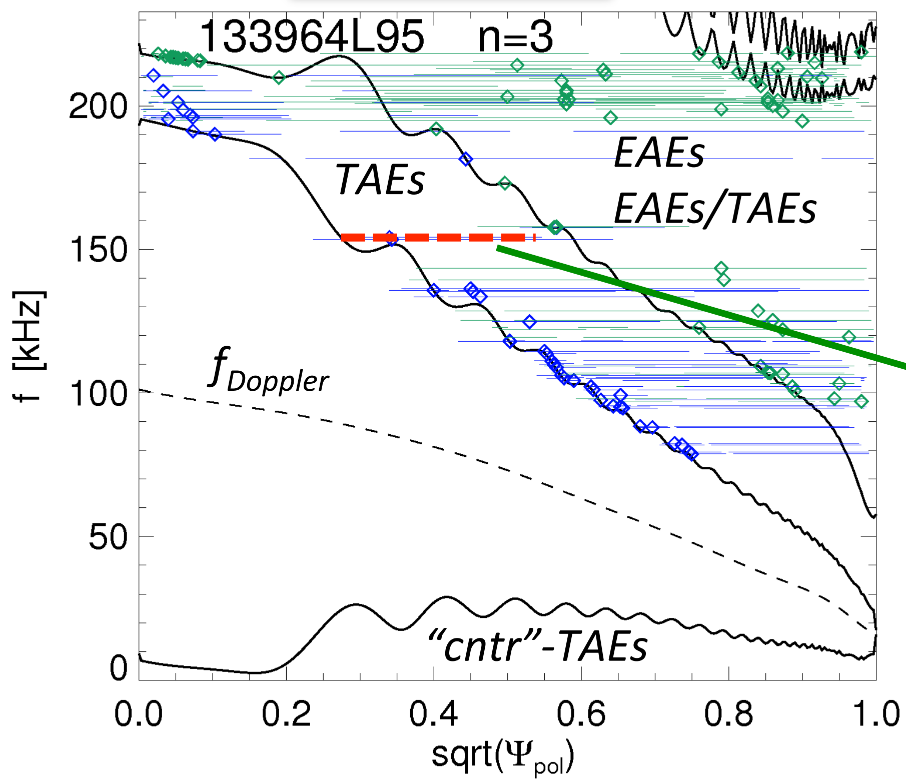
Extend simulations to full 1T, 2MA NSTX-U scenarios

Develop/apply reduced fast ion transport models

Extend to FNSF/Pilot

3D 'Halo' model in TRANSP

Extend to current ramp up in FNSF/Pilot (Incr.)



Ex.: NOVA-K stability of n=3, f~154kHz TAE mode for NSTX-U scenario:

	w/o rot.	w/ rot
$\gamma_{damping}/\omega$ [%]	-60	-5.2
γ_{drive}/ω [%]	4.8	4.6

> Rotation MUST be taken into account!

Diagnostics well suited for *AEs and F_{nb} characterization; incr. budget required for better measurements at high-n_e

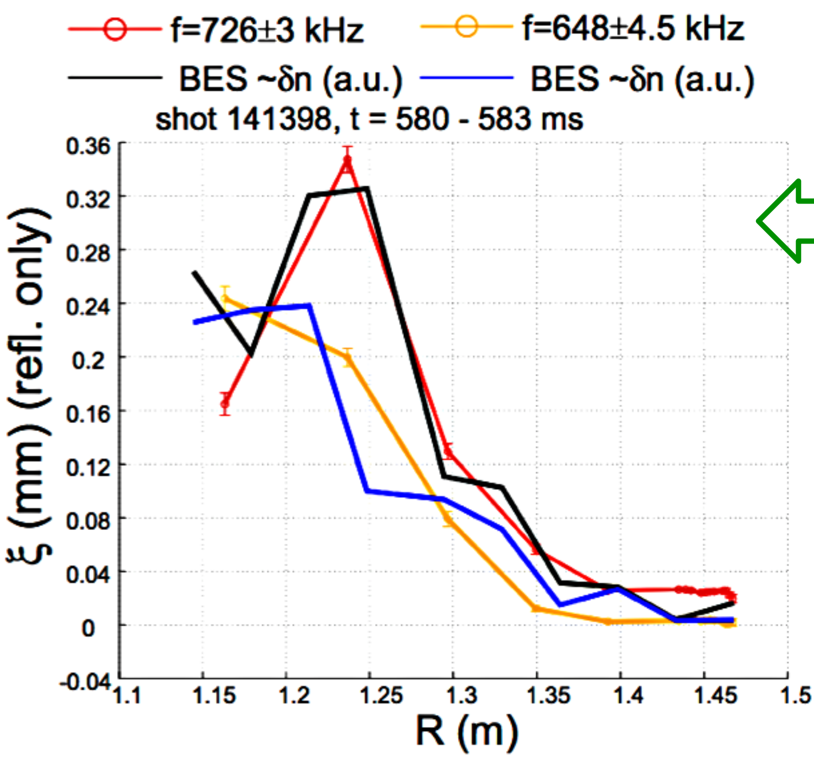
FY13 | FY14 | FY15 | FY16 | FY17 | FY18

Upgrade Outage

5 year plan period

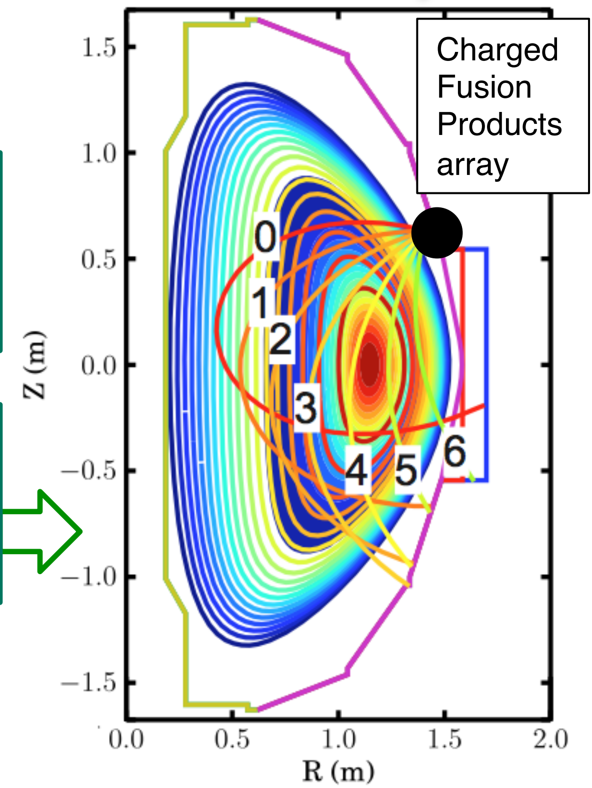
Diagnostics

- Fast ion distribution measurements: Vert.+Tang. FIDA; upgraded ssNPA
- Mode structure measurements: BES, reflectometers
- *AE antenna for damping rate measurements
- *Incr.* *fusion source profile array*
- *Incr.* *neutron collimator for high n_e*
- *Incr.* *Optimize *AE antenna for more efficient coupling to *AEs (broad f range)*



Reflectometers, BES provide detailed mode structure measurements.

High n_e: data quality reduced, need different approach(es) for F_{nb} measurements.



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Backup Slides: **B#Z**

Summary of EP Research goals and plans for FY14-18 Five Year Plan

- FY14-18 EP Research will improve understanding, prediction capabilities for *AE instabilities, fast ion dynamics
  - Leverage unique **NSTX-U flexibility** (NBI, B_t, I_p, 3D fields)
  - Excellent **synergy with Theory group**, code developers
- Focus on *AE stability, dependence on fast ion distribution
  - Benefits from **active MHD spectroscopy**, including high-f *AEs
  - Target **non-linear, multi-mode physics** toward *AE *mode control*
- Expect unique contributions to EP physics for STs and next-step, *burning plasma* devices
  - High-β, high $v_{fast}/v_{Alfvén}$ has significant overlap with expected EP parameter regime in ITER, FNSF, ST-based Pilot

Backup slides

FY14-18 Energetic Particle Research timeline
Baseline & ~10-15% incremental funding ($)

FY13 | FY14 | FY15 | FY16 | FY17 | FY18

Upgrade Outage

5 year plan period

5 year goal

Physics

Characterize F_{nb} w/ 2nd NB line; compare to TRANSP

Extend fast ion studies to full 1T, 2MA scenarios

Investigate *AE dynamics and fast ion transport mechanisms

Compare with linear/nonlinear predictions

Incr. Develop ramp-up scenarios with reduced/optimized *AE activity

Assess reduced models for *AE-induced fast ion transport

Characterize NBI+HHFW scenarios

NB, HHFW as actuators for *AE activity

Tools

Diagnostics

Fast ion distribution measurements: Vert.+Tang. FIDA; upgraded ssNPA

Incr. fusion source profile array

Mode structure measurements: BES, reflectometers

Incr. neutron collimator for high n_e scenarios

*AE antenna for damping rate measurements

Incr. Optimize *AE antenna for more efficient coupling to *AEs (high power)

Theory

Improved rotation, F_{nb} description in NOVA-K, M3D-K and HYM

ORBIT, SPIRAL for fast ion response to *AE modes

Extend simulations to full 1T, 2MA NSTX-U scenarios

Develop/apply reduced fast ion transport models

Extend to FNSF/Pilot

Incr. Extend to current ramp up in FNSF/Pilot

3D 'Halo' model in TRANSP

Facility

2nd (more tangential) NB line

NCC coils (partial)

Incr. *NCC coils (full)*

Incr. *Assess *AE antenna for mode excitation*

Plasma Control

q-profile, rotation control with 2nd NBI

5 year goal

1. Develop predictive tools for projections of *AE-induced transport to FNSF/ITER
2. Assess requirements for fast ion *phase space engineering* through selective excitation/suppression of *AE modes

Facility & Control developments give access to new physics, enable projections to next-step

FY13 | FY14 | FY15 | FY16 | FY17 | FY18

Upgrade Outage — **5 year plan period**

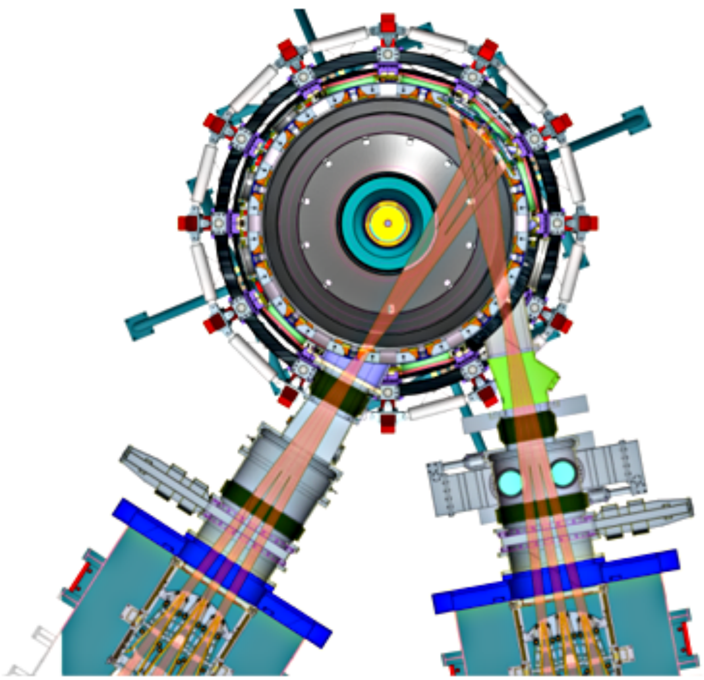
Facility

- 2[nd] (more tangential) NB line
- *NCC coils (partial)*
- *Incr.* *NCC coils (full)*
- *Incr.* *Assess *AE antenna for mode excitation*

Plasma Control

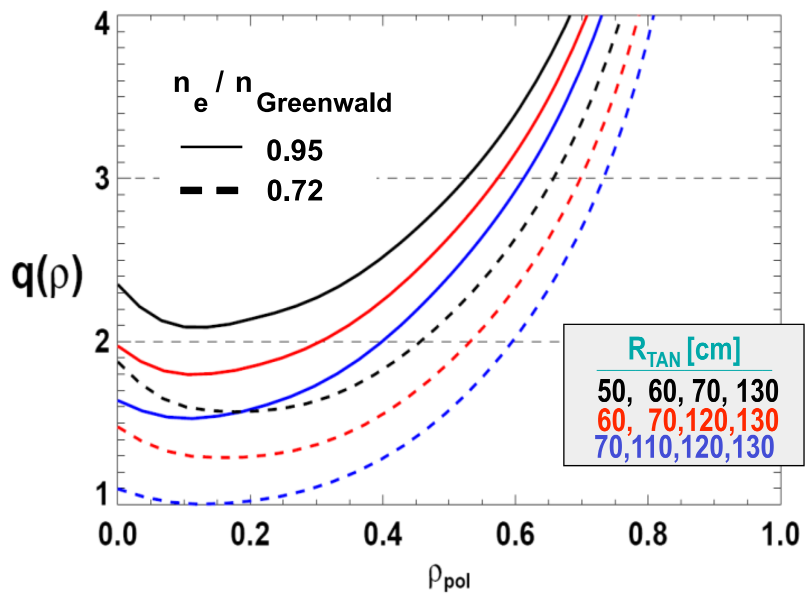
- q-profile, rotation control with 2[nd] NBI; density control

Flexible NBI parameters + NCC coils: control q-profile, rotation; add 3D fields
⇨ **affect mode stability, dynamics**



Present NB line R_{tan}=50,60,70cm

New NB line R_{tan}=110,120,130cm



Collaborations of EP group, FY13-14

- EP group participates to experiments on MAST in FY13:
  - Study of TAE "avalanches" and associated fast ion transport
  - Participate to experiments exploiting active MHD spectroscopy
  - Test Charged Fusion Product array (developed by FIU/PPPL), compare measurements with MAST Neutron Camera

- EP group is involved with experiments on DIII-D in FY13
  - Characterization of regimes with bursting/chirping *AE instabilities, comparison with NSTX results
  - Study of non-linear *AE behavior

- NSTX-U collaborators developing diagnostics, analysis tools supporting EP research (see Chapter 12 of 5-year Plan for details)
  - FIU: developing Charged Fusion Product array
  - UC Davis: fluctuation diagnostics (interferometers)
  - UC Irvine: fast ion diagnostics (FIDA, ssNPA), analysis tools (FIDASIM)
  - UC Los Angeles: mode structure measurements (reflectometers), fluctuation diagnostics (polarimeter, Doppler Back-Scattering), analysis tools
  - UW: fluctuation diagnostics (Beam Emission Spectroscopy)

Thrust EP-1: Develop predictive tools for projections of *AE-induced fast ion transport in FNSF and ITER

- Vary fast-ion instability drive by varying:
  - NBI source to vary $n_{fast}(r)$, fast-ion anisotropy, q, rotation
  - 3D fields to vary rotation, fast-ion transport
  - B_T, I_P, P_{NBI}, and density to vary q, v_{fast} / v_A, $\beta_{fast} / \beta_{tot}$
- Measure *AE mode properties including radial structure, frequency and wavenumber spectrum, and stability
  - Utilize high-f magnetics, BES, reflectometry
- Characterize fast ion transport associated with specific classes of *AEs
  - Utilize fast-ion D-alpha diagnostics, SSNPA, neutron rate
- Utilize linear and non-linear numerical and theoretical tools (ORBIT, NOVA-K, M3D-K, HYM) to understand mode-induced fast-ion transport in NSTX-U, ITER, FNSF

Thrust EP-2: Assess requirements for fast-ion *phase-space engineering* techniques

- Perform active spectroscopy to measure linear *AE damping rates to benchmark stability codes at low aspect ratio
  - Utilize linear stability validation in NSTX-U to improve fundamental understanding of mode drive and stability mechanisms in ITER burning plasmas and for FNSF, ST-based Pilot

- *With incremental funding*, upgrade driving amplifier to higher power, extend bandwidth of *AE antenna system to study high frequency modes
  - Higher-f + possible cyclotron resonances may provide means to controllably modify the non-thermal ion distribution function and possibly lower the overall fast ion pressure

FY14 Milestone R14-2: 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 to include a stochastic transport term or quasi-linear models.

FY15 Milestone R15-2:
Assess the effects of neutral beam injection parameters on the fast ion distribution function and neutral beam driven current profile.

Accurate knowledge of neutral beam (NB) ion properties is of paramount importance for many areas of tokamak physics. NB ions modify the power balance, provide torque to drive plasma rotation and affect the behavior of MHD instabilities. Moreover, they determine the non-inductive NB driven current, which is crucial for future devices such as ITER, FNSF and STs with no central solenoid. On NSTX-U, three more tangentially-aimed NB sources have been added to the existing, more perpendicular ones. With this addition, NSTX-U is uniquely equipped to characterize a broad parameter space of fast ion distribution, F_{nb}, and NB-driven current properties, with significant overlap with conventional aspect ratio tokamaks.

The two main goals of the proposed Research Milestone on NSTX-U are (i) to characterize the NB ion behavior and compare it with classical predictions, and (ii) to document the operating space of NB-driven current profile. F_{nb} will be characterized through the upgraded set of NSTX-U fast ion diagnostics (e.g. FIDA, ssNPA, sFLIP, neutron counters) as a function of NB injection parameters (tangency radius, beam voltage) and magnetic field. Well controlled, single-source scenarios at low NB power will be initially used to compare fast ion behavior with classical models (e.g. the NUBEAM module of TRANSP) in the absence of fast ion driven instabilities. Diagnostics data will be interpreted through the "beam blip" analysis technique and other dedicated codes such as FIDASIM. Then, the NB-driven current profile will be documented for the attainable NB parameter space by comparing NUBEAM/TRANSP predictions to measurements from Motional Stark Effect, complemented by the vertical/tangential FIDA systems and ssNPA to assess modifications of the classically expected F_{nb}.

As operational experience builds up in the first year of NSTX-U experiments, additions to the initial F_{nb} assessment will be considered for scenarios where deviations of F_{nb} from classical predictions can be expected. The latter may include scenarios with MHD instabilities, externally imposed non-axisymmetric 3D fields and additional Fast Wave heating.

(w/ WH&CD, ASC, MS and SFSU TSGs)

Summary of theory and simulation capabilities for EP research

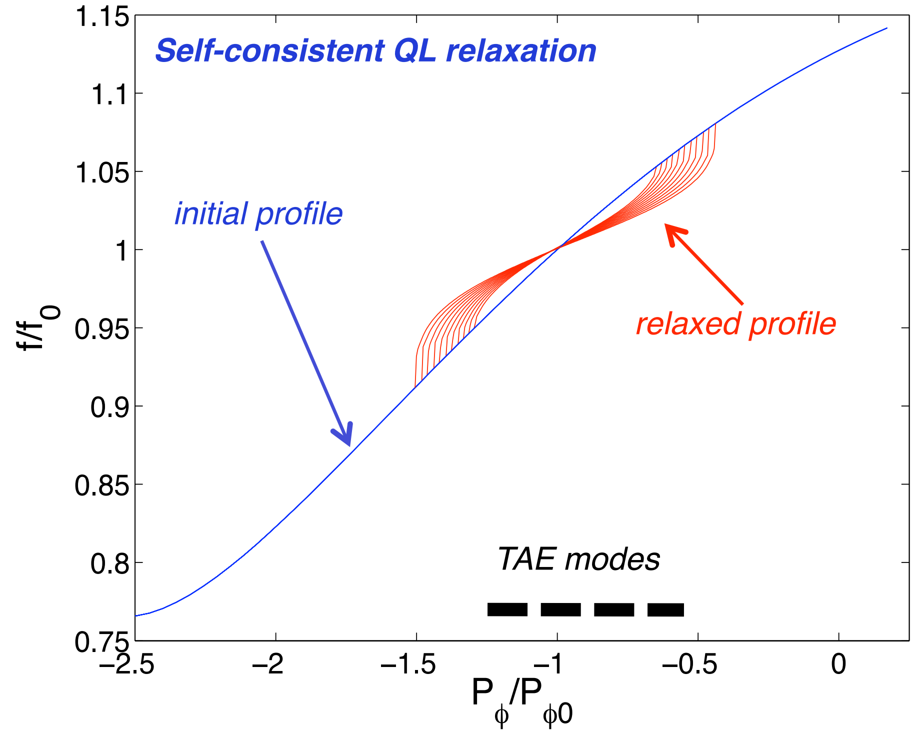
Code	*Description*	*Scope*	*Improvements*
ORBIT	Gyro-center particle following code	Infer fast ion response to given set of modes	Improved methods for resonance identification.
SPIRAL	Full-orbit particle following code	Infer fast ion response to given set of modes	
NOVA-K	Ideal MHD	Compute eigenfunctions, stability for *AEs	Improved F_{nb} model. Improved treatment of finite plasma rotation.
M3D-K	Hybrid model; self-consistent, non-linear	Infer mode dynamics (low-f *AEs, kinks) and fast ion response	Improved F_{nb} model.
HYM	Hybrid model; self-consistent, non-linear	Infer mode dynamics (high-f *AEs) and fast ion response	Improved F_{nb} model. Include sources and sinks.
F_{nb} inversion code	Package for analysis of experimental data	Infer F_{nb} from a set of measurements	Under development. Adapt to NSTX-U.
QL model	Model for quasi-linear relaxation of F_{nb}	Compute relaxed $F_{nb}(r)$ in the presence of *AE modes	Under test. Considering for inclusion in TRANSP/NUBEAM
Resonant fast ion transport model	Reduced model for resonant/stochastic AE-induced fast ion transport	Advance F_{nb} in NUBEAM under the effects of resonant *AE modes	To be included in TRANSP/NUBEAM and validated against NSTX data.

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

Evolution of fast ion distribution, modes:

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

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 :

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

$$\Downarrow$$

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

[K. Ghantous, PoP (2012)]
[H. Berk, IAEA (2012)]
[N. Gorelenkov, APS (2012)]
[K. Ghantous PPPL #4850 (2013)]

- Model being tested for DIII-D, ITER, ARIES; NSTX next

Resonant fast ion transport model is being implemented in NUBEAM to mimic F_{nb} modifications by resonant *AEs

- Resonant/stochastic fast ion transport may not be well described by *diffusive* processes,
  Γ~dn/dr not accurate enough
  - Resonances introduce selectivity in phase space (energy, pitch, magnetic moment)
- Fast ion transport models presently implemented in NUBEAM do *not* include basic physics of wave-particle resonant interaction

> Introduce a *probability distribution function* for particle transport:

$$p(\Delta E, \Delta P_\zeta | P_\zeta, E, \mu, A)$$

- For each *bin* in (E, P_ζ, μ), steps in $\Delta E, \Delta P_\zeta$ can be described by
- Include mode amplitude variations $A_{modes}=A_{modes}(t)$

- Different ways possible (e.g. ORBIT, SPIRAL, theory) to compute $p(\Delta E, \Delta P_\zeta)$

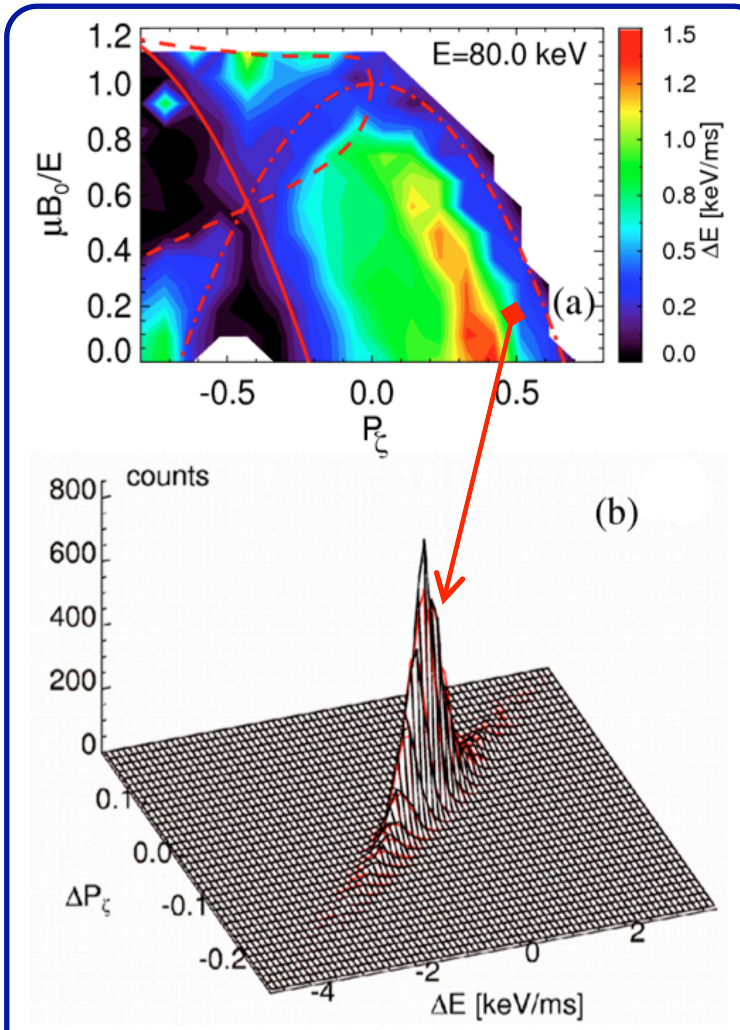


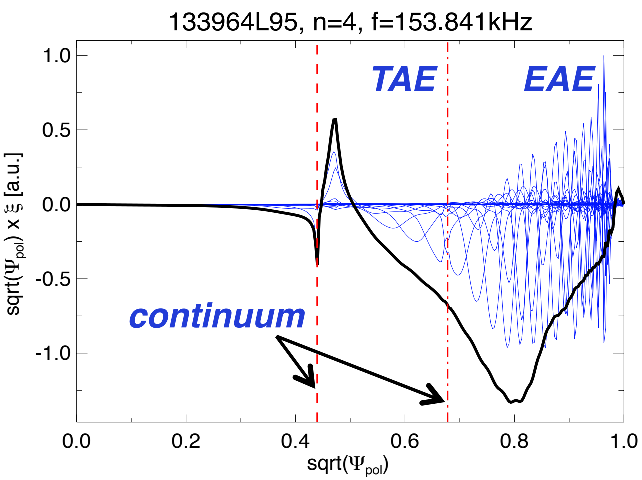
Figure 6.2.1 : (a) ORBIT calculations of the average energy step caused by 4 TAE modes after 1 ms for fast ions with initial energy of 80 keV. Red lines show the different domains in phase space. (b) Example of probability distribution for correlated steps in energy and canonical toroidal momentum for E=80 keV, P_ζ~0.5 and pitch ~0.2.

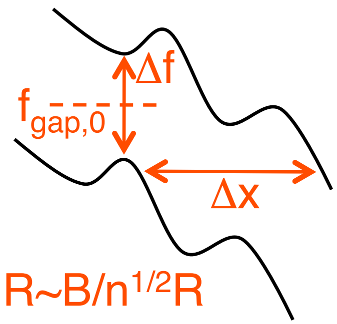
Initial predictions for TAE behavior on NSTX-U

M. Podestà, APS (2012), TTF (2013)

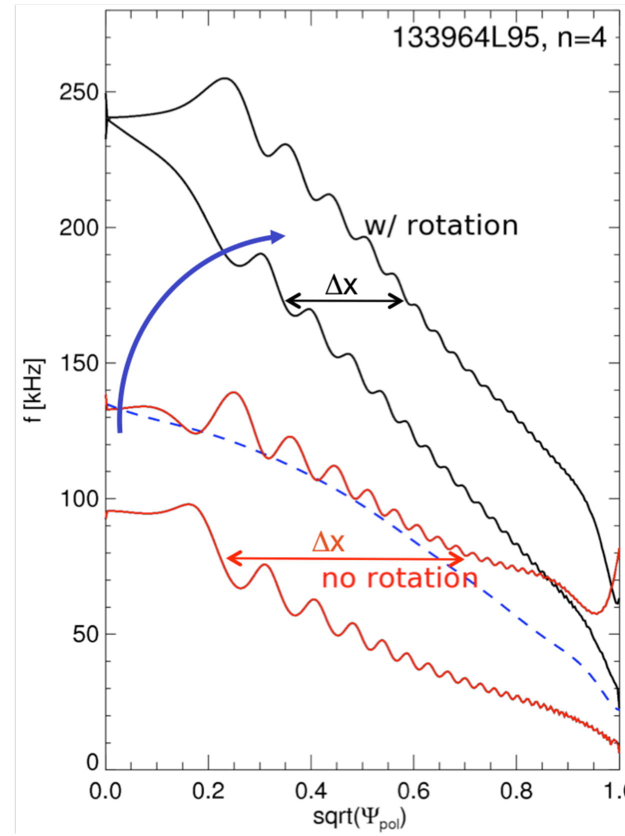
- Expect up-shift of mode number with higher B_t
  - Broad spectrum possible because of large $v_f/v_{Alfvén}$
- TAE gap is broader for NSTX-U scenarios, consistent with 0^{th}-order scaling for gap frequency & width
- On average, Doppler shift alters the radial gap width
  - Radial width of TAEs decreases for higher *n*'s
  - But modes can tunnel through continuum
    - Mixed TAE+EAE modes *[N. Gorelenkov, PRL (2005)]*
    - Antenna could excited edge harmonics

$$\begin{cases} k_\perp \rho_f \sim 1 \Rightarrow \dfrac{nq}{a}\dfrac{v_f}{\omega_{cf}} \sim 1 \\ \Rightarrow n \sim B \Rightarrow n = 2-10 \end{cases}$$





$$\begin{cases} f_{gap,0} \sim v_A/4\pi qR \sim B/n^{1/2}R \\ \Delta f_{gap,0}/f_{gap,0} \sim a/R \\ \Delta x_{gap,0} \text{ : radial "width"} \end{cases}$$



- Consistent treatment of rotation is crucial for correct computation of both damping and drive terms: *improving NOVA-K*

> **TAE modes might be even more unstable in NSTX-U than in NSTX (including H-mode plasmas)**
  - **Higher β_{fast}; more tangential injection favors resonance w/ passing ions**

Reference to Responses to PAC-31 Recommendations /1

Recommendation Number	PAC Recommendations	NSTX-U Response	Ref. slide(s)
PAC31-2	We suggest that milestones that leverage NSTX contributions to ITER physics and operations be moved earlier if possible, e.g., research on fast ion transport and disruption avoidance.	Collaboration with MAST and DIII-D on fast-ion physics will be carried out in FY13, and there are two research milestones for energetic particles - 1 in FY14 and 1 in FY15.	27,28
PAC31-40	Appreciable progress has been made on NSTX in this field despite the short run period. This also prevented the exploitation of the newly installed prototype TAE antenna, which now has to be deferred to NSTX-U. The PAC recommends that this capability be retained and active collaboration be pursued to allow rapid exploitation in NSTX-U.	Agree - the AE antenna will be retained and expanded, and collaboration on MAST pursued in this research area	14,18
PAC31-41	Of particular interest is that the modeled fast ion redistribution in energy and space during TAE avalanches and a low-frequency kink-like mode does not lead to significant fast ion losses. This needs to be reconciled with transport calculations that seem to indicate an appreciable fast particle loss.	Agree	13
PAC31-42	Impressive is the modeling of the electron transport due to GAEs that seems to be consistent with TRANSP calculations. The PAC recommends maintaining a strong crosscutting effort between the Transport & Confinement and the Wave & Energetic Particle topical groups, even strengthening it even further. The PAC strongly endorses plans to develop simplified models to be implemented into predictive transport models. This should be a high priority item reflected in the research milestones for the near term program.	Agree - however progress will likely be slower than desired in this research area due to lack of personnel to work on AE-induced electron thermal transport reduced models in addition to all the standard turbulence modelling and fast-ion transport modelling	13,10 30,31

Reference to Responses to PAC-31 Recommendations /2

Recommendation Number	PAC Recommendations	NSTX-U Response	Ref. slide(s)
PAC31-43	The funding of these "new" diagnostics in the financially challenging budget situation remains a cause for concern. Therefore, the PAC encourages a physics driven priority list to be developed.	Agree	18
PAC31-44	The analysis of NSTX-U scenarios with respect to the expected fast ion physics is important due to the importance of the contribution of the ST in this area with respect to ITER/DEMO physics. The modeling should be used to guide the NSTX-U research plan as well as the diagnostic strategy.	Agree	32
PAC31-45	The PAC is concerned that the proposed time line is not aggressive enough with only one research milestone in FY 2014, not reflecting the importance of the field with respect to NSTX-U and other future tokamaks. The PAC recommends to accelerate the time line in particular with respect to developing simplified models of the *AE induced fast ion transport.	Agree this area could use more emphasis, so an FY15 milestone is also now included in the 5YP to systematically explore the performance of the 2nd NBI (and 1st NBI) w.r.t. AE excitation and fast-ion transport.	27,28 11
PAC31-46	The collaborations indicated with DIII-D and MAST seem to be appropriate and more concrete plans should be developed well in advance, in particular with respect to diagnostics and TAE antenna exploitation	Agree - more concrete plans have been developed	24

Reference to Responses to PAC-31 Recommendations /3

Recommendation Number	PAC Recommendations	NSTX-U Response	Reference Slide(s)
PAC31-47	An important aspect for future devices is the avoidance of detrimental fast particle driven MHD. Here, a further understanding of such operating regimes should be established within the NSTX database. The assumptions for a deeper understanding and the access to these regimes could be tested on other devices with the appropriate actuators and diagnostics (e.g. ASDEX-Upgrade, DIII-D and MAST). This should be done together with the Advanced Scenarios topical group.	Agree	24,28
PAC31-49	The plans presented for the early exploitation of NSTX-U include the most important issues and reflect the capabilities well. In view of developing a strong research plan a clearer understanding of the ITER/DEMO needs compared to the needs for the FNSF with respect to energetic particle physics may help to focus the research activities. The PAC recommends formulating high priority research goals leading to high impact publications to further aid the development of the NSTX-U research plan	Agree - however developing a predictive capability for fast-ion instability onset and associated transport is high priority, and is applicable and supportive of FNSF and ITER	22 [ITER Needs]
PAC31-62	In addition to these activities, the PAC also recommends that a focused activity be included in the plans for this time frame to validate that the off-axis NBI is working as expected in terms of heating, torque, current drive, and energetic particles.	Agree - there is now an FY15 energetic particle research milestone to perform such validation	28