NSTX-U

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FY14-18 NSTX-U Five Year Plan for Energetic Particle (EP) Research

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for the NSTX Research Team

NSTX-U 5 Year Plan Review
LSB B318, PPPL
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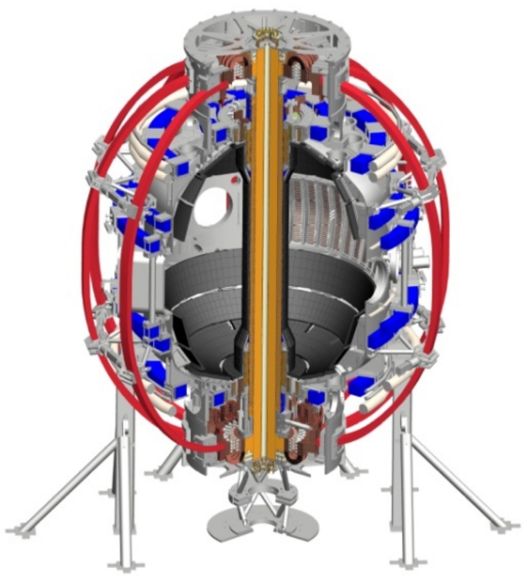

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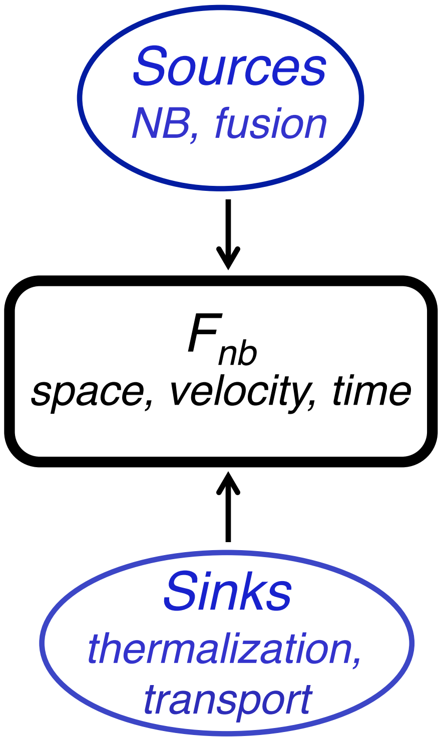
Goal: enable predictions of fast ion behavior and associated instabilities in high-β, super-Alfvénic regimes (ITER/FNSF)

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



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

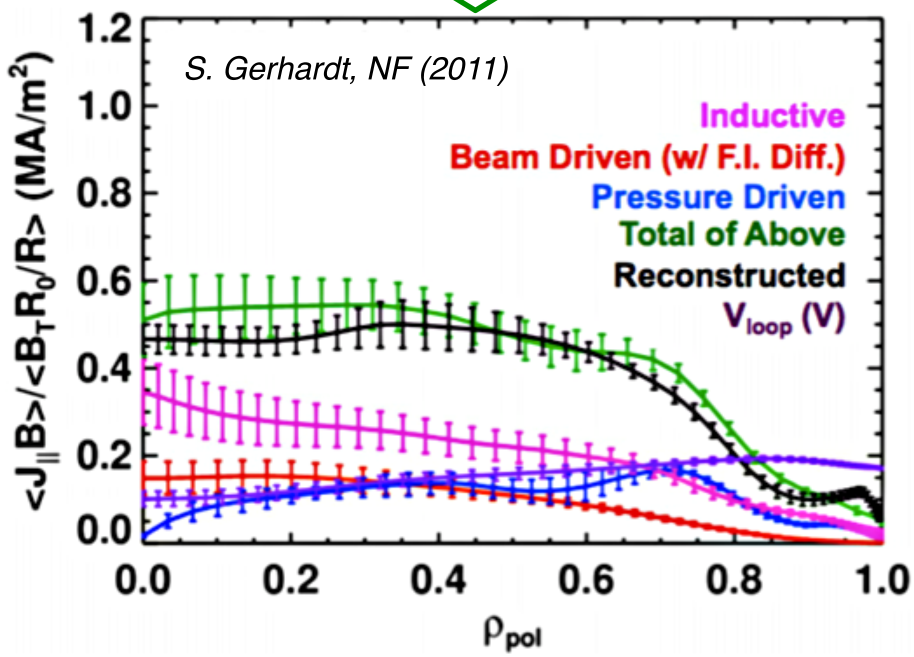
- Need to understand/predict behavior of fast ion distribution

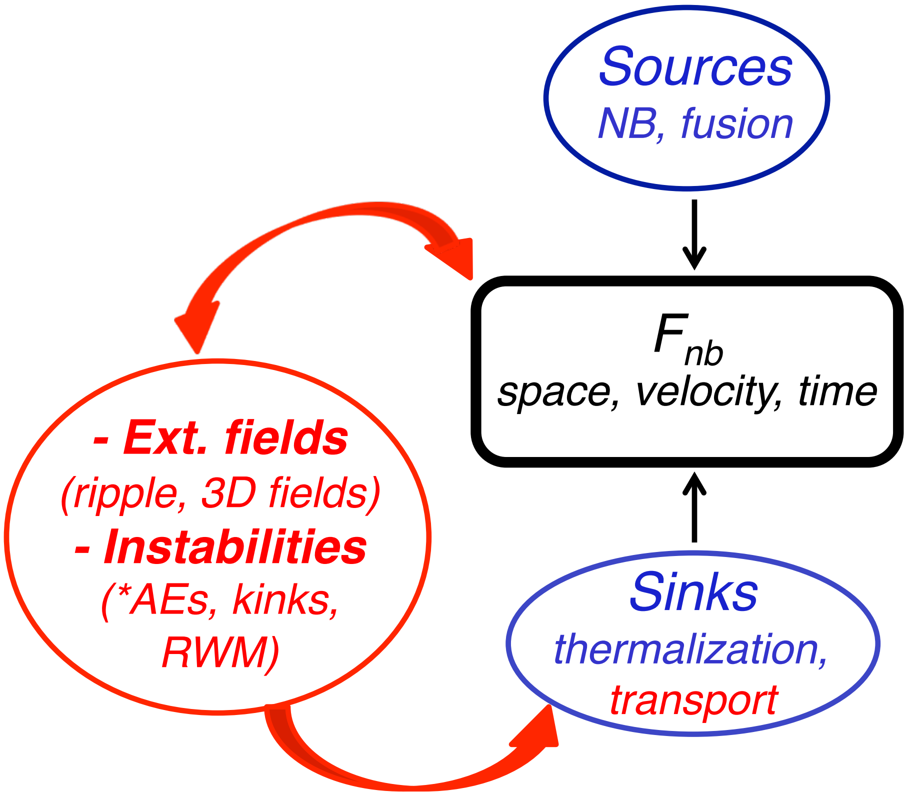
  ...especially when it deviates from "classical"

  > F_{nb} dynamics couple to instabilities, ext. fields

  > Non-linear physics dominates

TRANSP reconstruction of current profile
with anomalous fast ion diffusion:
$1m^2/s$ (baseline) + $50m^2/s$ (pulses)





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

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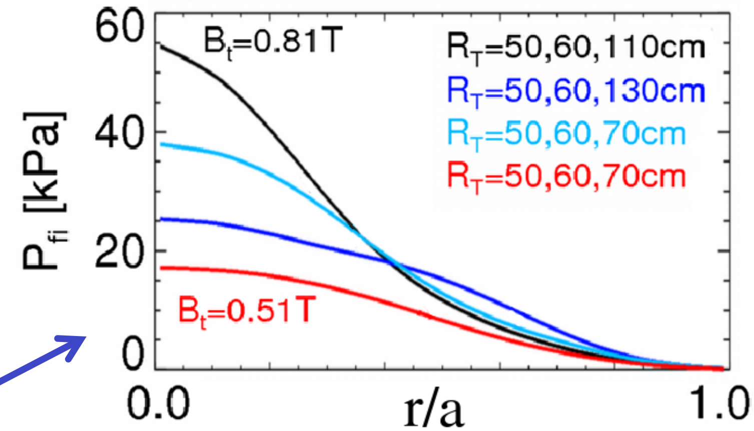
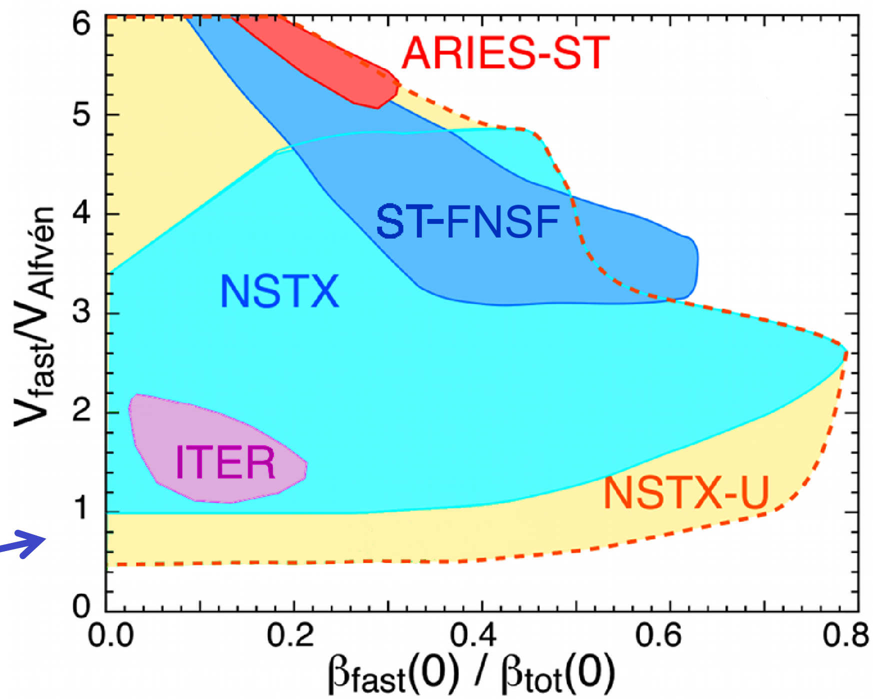
  > Non-linear physics dominates



- Additional NB line, 3 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
  > **Regimes** for EP studies relevant for ITER, ST-FNSF

Outline

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

    ⇩

  - 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, develop 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, regime)
- Verification & Validation vs. NSTX-U data to assess *predictive capability*

Thrust EP-2: Assess requirements for fast ion *phase space engineering* (towards F_{nb} and mode control) B#26

- Assess techniques to affect F_{nb}, modes' properties through application of NB, rf, 3D fields, and/or 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.

*(w/ WH&CD, ASC, MS, SFSU Topical Science Groups) B#28

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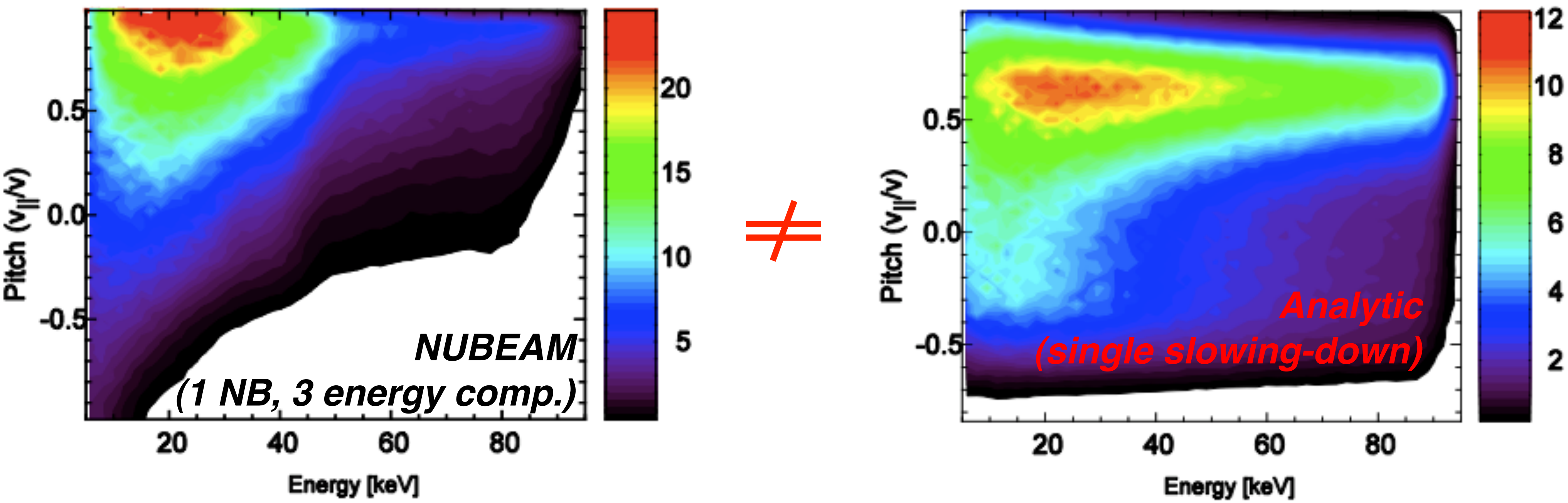
EP research in FY14: develop new analysis tools, prepare for FY15 operations

- 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 **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)



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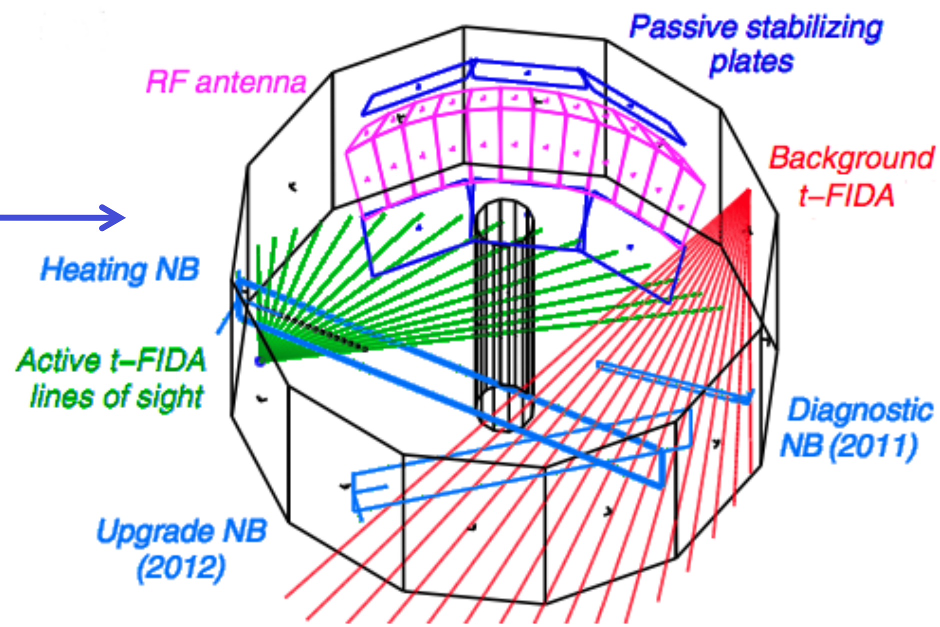
  - 3D 'halo' model in TRANSP (analysis/simulation of CX data)
  - Improved F_{nb}, rotation description (M3D-K, NOVA-K, HYM)
- Prepare for NSTX-U operations
  - Diagnostics being upgraded, reinstalled, calibrated (e.g. FIDA, NPAs, sFLIP, reflectometer, BES)
  - *Develop Charged Fusion Product array, (**Incr.**) collimated neutron detectors for high-n_e scenarios, FY16-18*
  - **Start planning experiments**
    - **Focus on FY15 Milestone**



A. Bortolon, RSI (2010)

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) with NUBEAM/TRANSP
  - > **Map NB parameters space, including non-inductive & low-current (300-500kA) scenarios for ramp-up studies (Thrusts ASC-1/4, SFSU-2)**
- 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

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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.

(FY18) Projections to FNSF/Pilot ramp-up phase, need improved diagnostics (e.g. ECE, reflectometry)

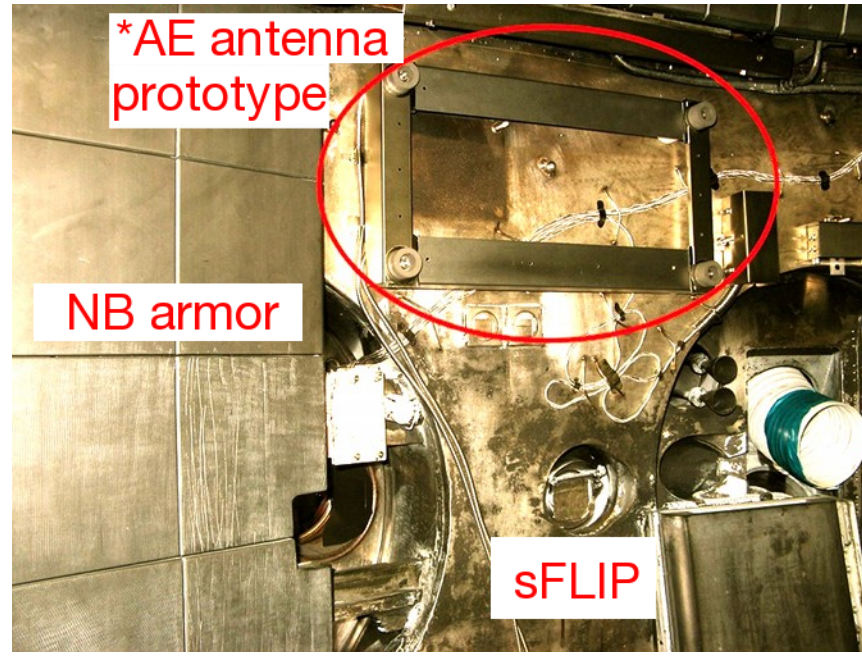
Thrust EP-2 Plans & Goals: assess development of F_{nb}, *mode control* tools/techniques

B#26

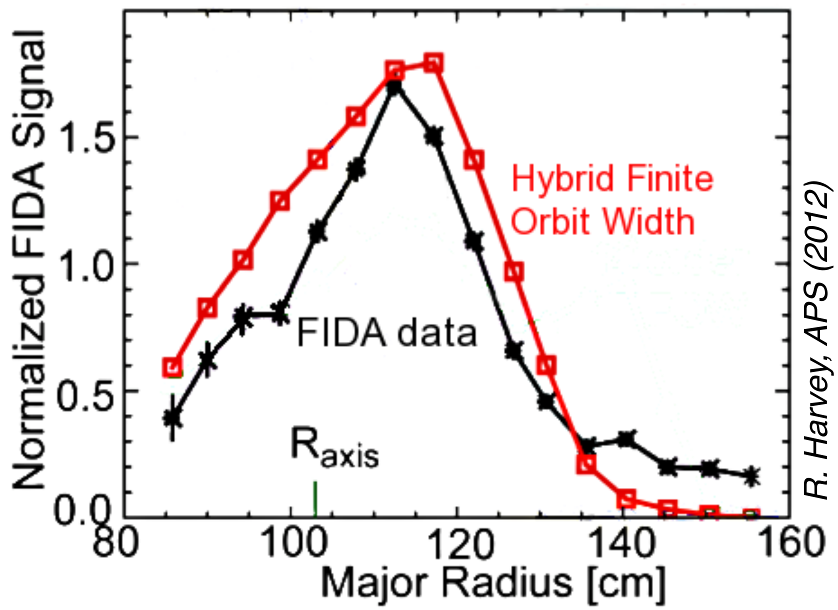
FY15

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 →
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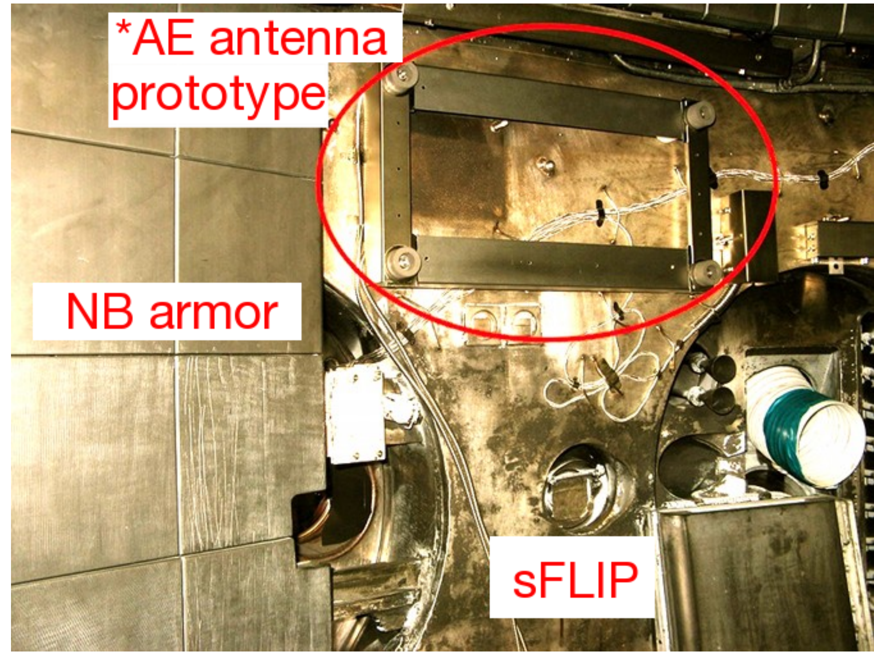

- Characterize scenarios with combined NBI + rf heating
- Study rotation, 3D fields effects on *AEs (RWM, upgraded SPAs for improved rotation control, NCC after FY16) B#23
- Extend stability measurements to high-frequency *AEs
  - Test/validate theories on high-f *AEs drive, damping

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

Incr. (FY17-18) Implement and test high-power (>10kW) *AE excitation system

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

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

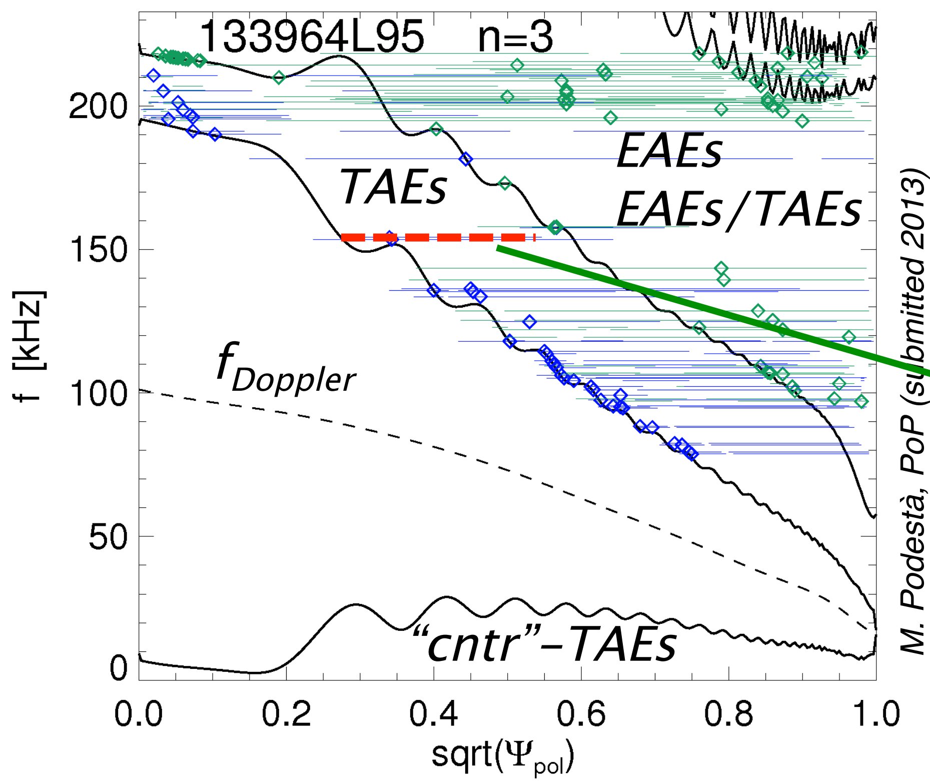
FY13 | FY14 | FY15 | FY16 | FY17 | FY18

Upgrade Outage

5 year plan period

Theory

- Improved rotation, F_{nb} description in NOVA-K, M3D-K, 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, F_{nb} characterization; incr. budget enables improved data at high-n_e

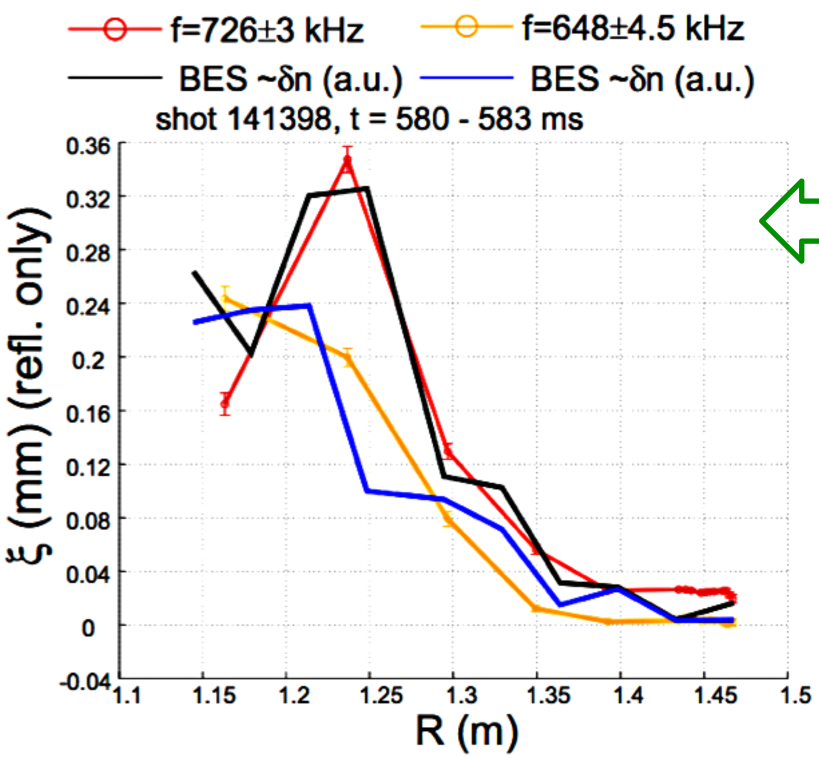
FY13 | FY14 | FY15 | FY16 | FY17 | FY18

Upgrade Outage

5 year plan period

Diagnostics

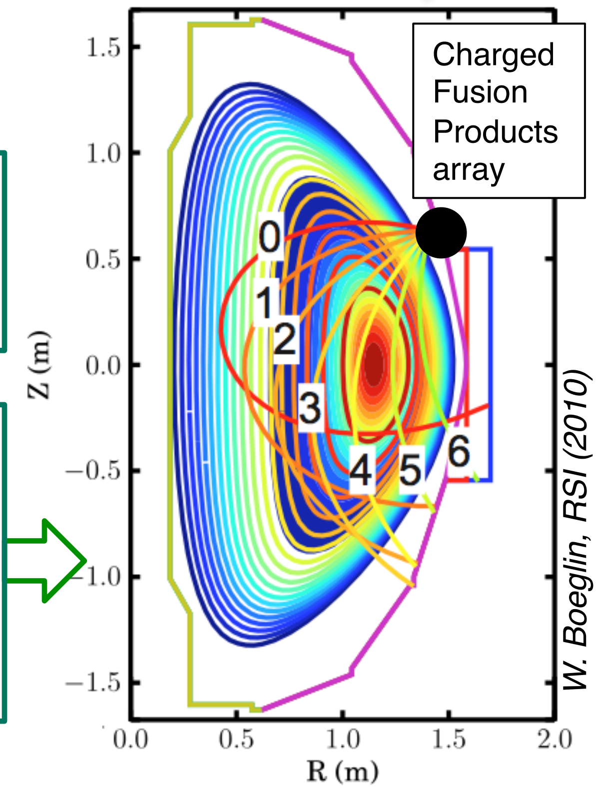
- Fast ion distribution measurements: Vert.+Tang. FIDA; upgraded ssNPA
- Mode structure measurements: BES, reflectometers
- *AE antenna for damping rate measurements
- *fusion source profile array*
- *Incr.* *neutron collimator for high n_e*
- Upgrade **AE antenna for more efficient coupling to *AEs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



Reflectometers, BES provide detailed mode structure measurements.

High n_e: data quality reduced, need different diagnostics for F_{nb} measurements:

- Neutron rate
- Fusion products



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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*
  - Contributes to NI scenarios, NB current ramp-up (w/ ASC, SFSU, WH&CD)

- Expect unique contributions to EP physics for STs and next-step, *burning plasma* devices
  - High-β, high $v_{fast}/v_{Alfvén}$, non-linear physics approach expected EP parameter regimes in ITER, FNSF, ST-based Pilot

Backup slides

FY14-18 Energetic Particle Research timeline

Baseline & ~10-15% incremental funding (Incr.)

FY13 | FY14 | FY15 | FY16 | FY17 | FY18

Upgrade Outage

5 year plan period

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

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
- fusion source profile array
- Mode structure measurements: BES, reflectometers
- Incr. neutron collimator for high n_e scenarios
- *AE antenna for damping rate measurements
- Incr. Upgrade *AE antenna for more efficient coupling to *AEs (high power)

Theory

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

- rotation control
- q_{min} control with 2nd NBI

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

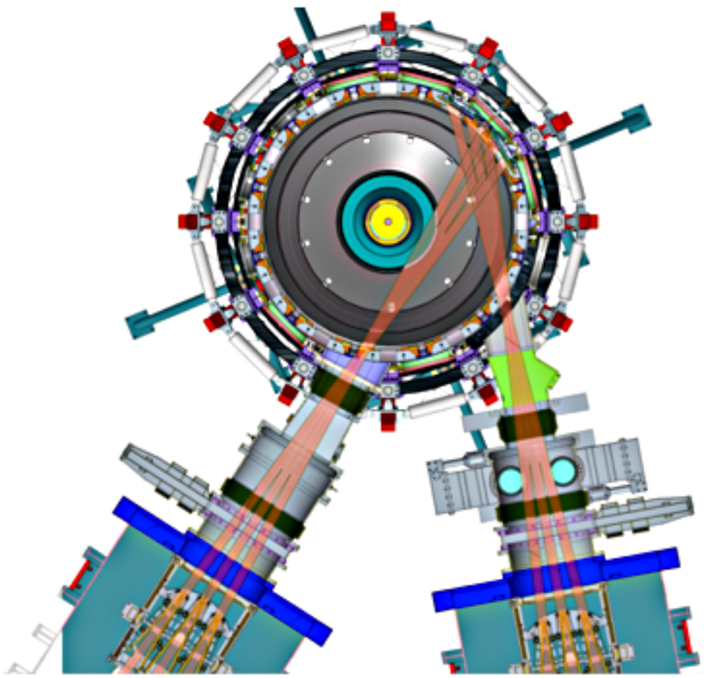
Facility

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

Plasma Control

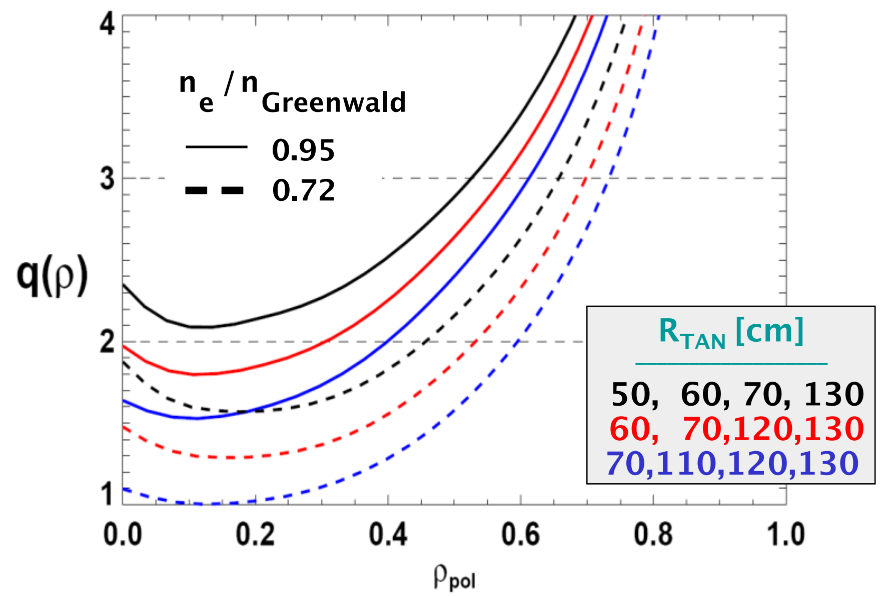
- rotation, q_{min} control with 2nd NBI; density control

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, effects of 3D fields (I-coils)

- 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, β_{fast} / β_{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 ST-based FNSF, 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

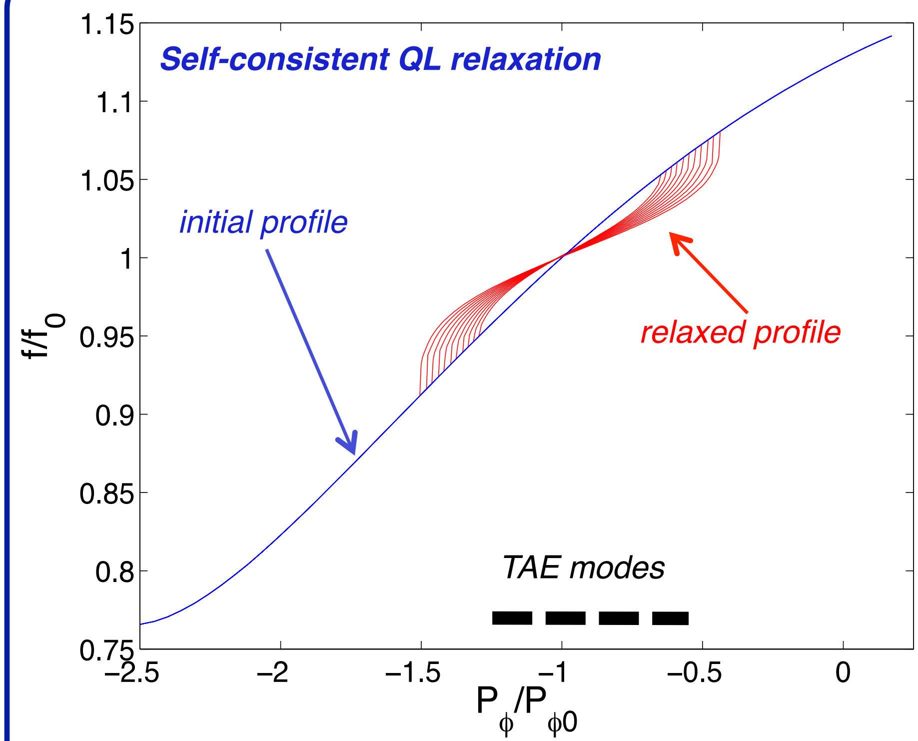
Code	*Description*	*Scope*	*Improvements*
ORBIT	Gyro-center particle following code	Infer fast ion response to given set of modes	Improved methods for resonance identification.
SPIRAL	Full-orbit particle following code	Infer fast ion response to given set of modes	
NOVA-K	Ideal MHD	Compute eigenfunctions, 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:

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

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



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

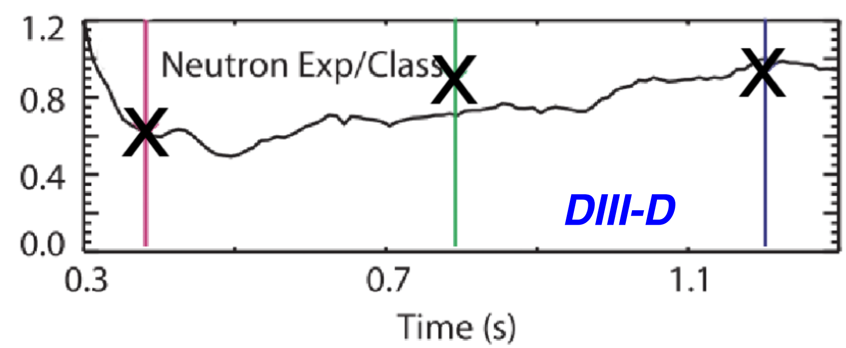
$$\gamma_{grth} = \gamma' \frac{\partial \beta}{\partial r} \quad \textit{with} \quad \gamma' \begin{cases} \textit{mode number(s), n} \\ \textit{relative mode widths to particle orbit} \\ \textit{Plasma parameters, Isotropy} \end{cases}$$

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

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

[K. Ghantous, PoP (2012)] [H. Berk, IAEA (2012)] [N. Gorelenkov, APS (2012)]
[K. Ghantous PPPL #4850 (2013)] [N. Gorelenkov, TTF (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 *$p(\Delta E,\Delta P_\zeta)$*

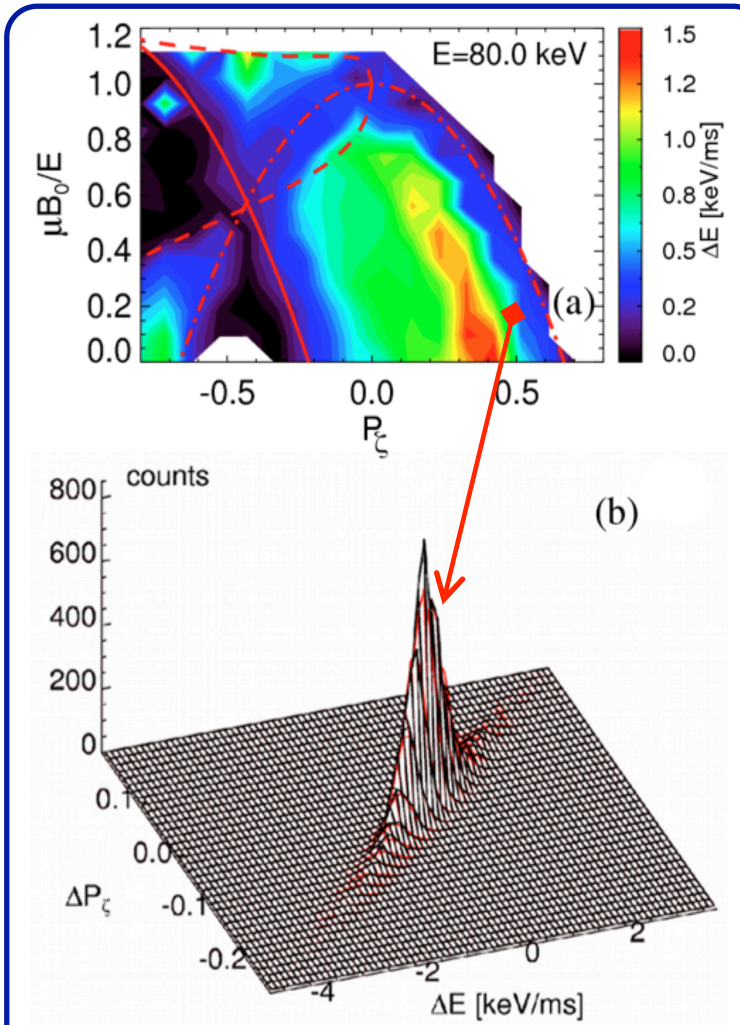


Figure 6.2.1 : (a) ORBIT calculations of the average energy step caused by 4 TAE modes after 1 ms for fast ions with initial energy of 80 keV. Red lines show the different domains in phase space. (b) Example of probability distribution for correlated steps in energy and canonical toroidal momentum for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

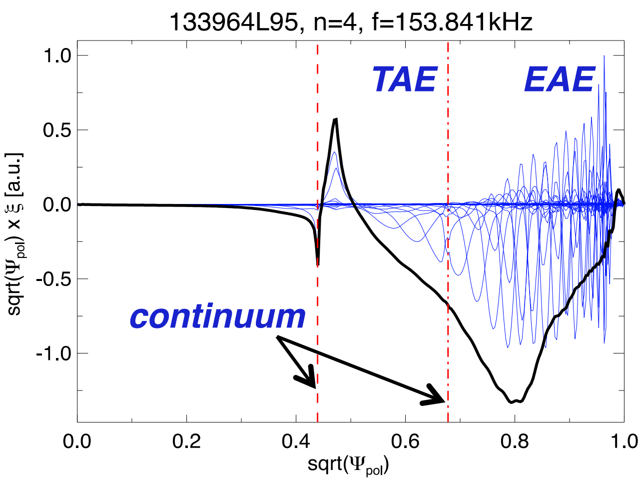
Initial predictions for TAE behavior on NSTX-U

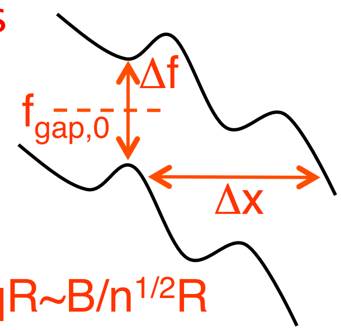
M. Podestà, PoP (submitted, 2013)

- Expect up-shift of mode number with higher B_t
  - Broad spectrum possible because of large $v_f/v_{Alfvén}$

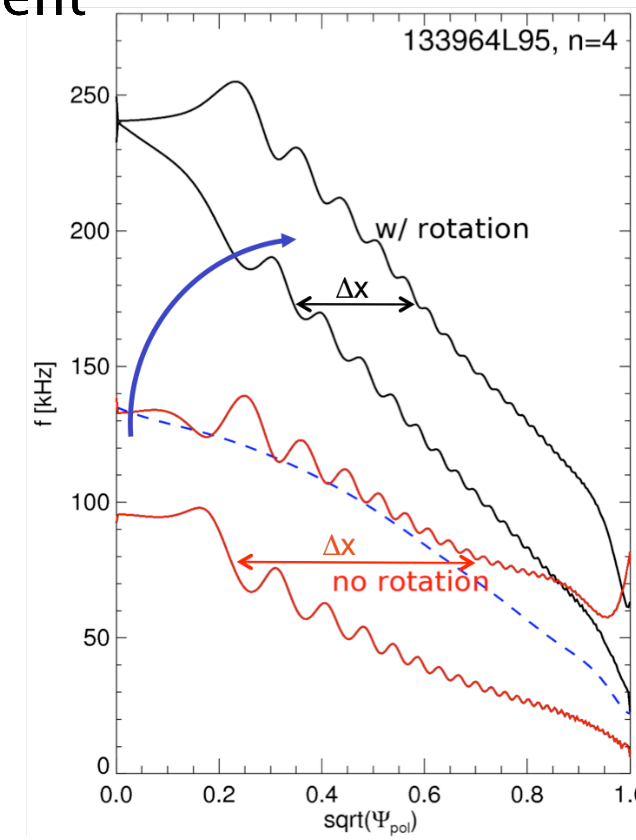
$$\left\{ \begin{array}{l} k_\perp \rho_f \sim 1 \Rightarrow \frac{nq}{a} \frac{v_f}{\omega_{cf}} \sim 1 \\ \Rightarrow n \sim B \Rightarrow n = 2 - 10 \end{array} \right.$$

- TAE gap is broader for NSTX-U scenarios, consistent with 0^{th}-order scaling for gap frequency & width
- Large 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





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



- Consistent treatment of rotation is crucial for quantitative stability calculation: *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**