Progress and Plans for Energetic Particle (EP) Physics

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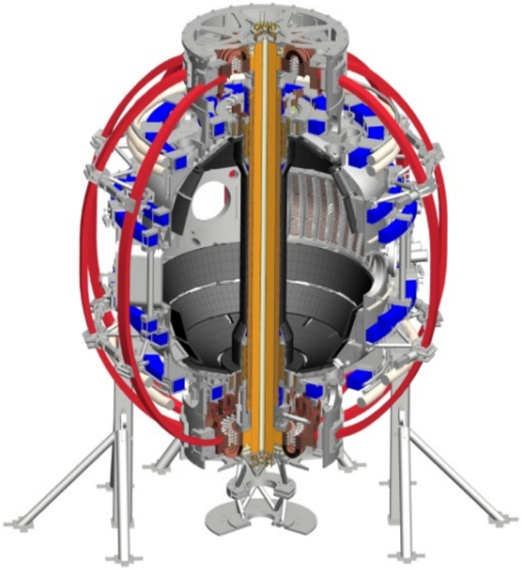
X Science LLC

Mario Podestà
Gary Taylor, Nikolai Gorelenkov

and the NSTX-U Research Team

NSTX-U PAC-35 Meeting
PPPL – B318
June 11-13, 2014



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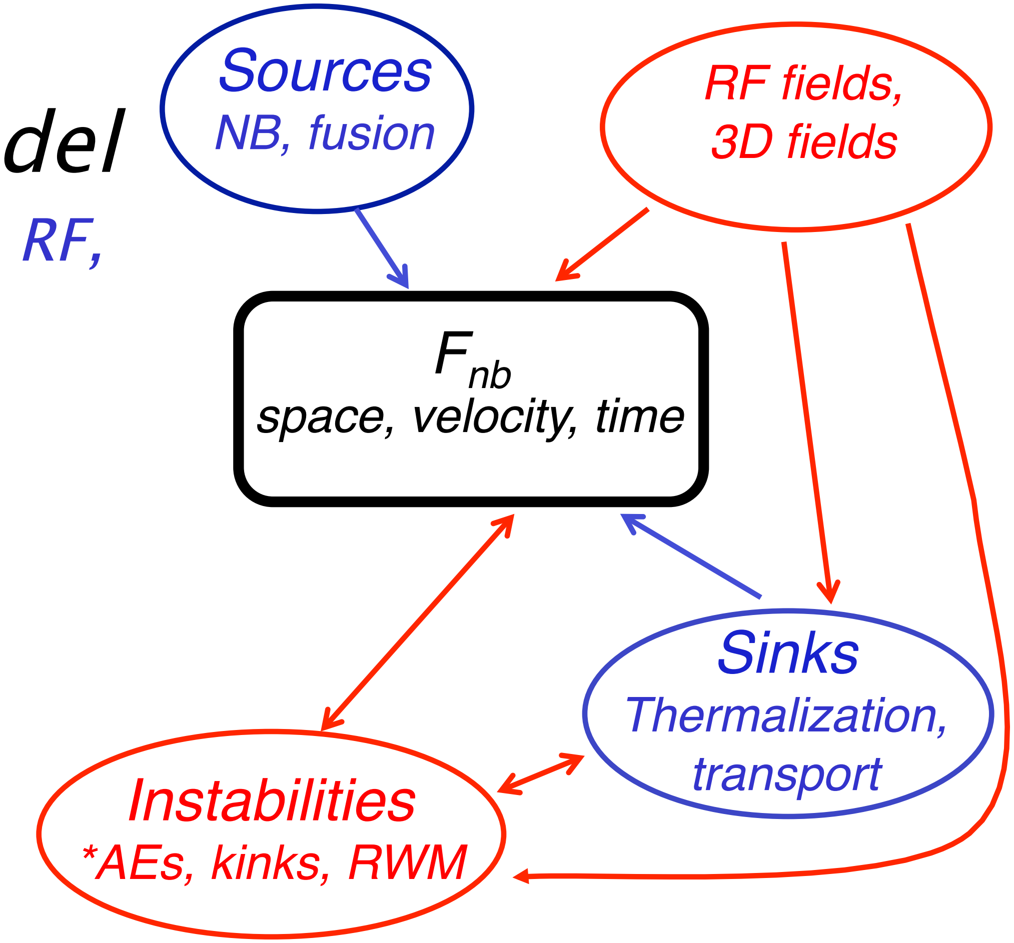
EP research on NSTX-U targets improved understanding & predictions for fast ion physics in ITER, FNSF

- Fast ions affect power and momentum balance, current drive in future devices
- NB ions and fusion alphas interact with RF, 3D fields, instabilities

> *Complex scenario to model*
>
> > *Includes instabilities, 3D fields, RF, feedback on thermal plasma*

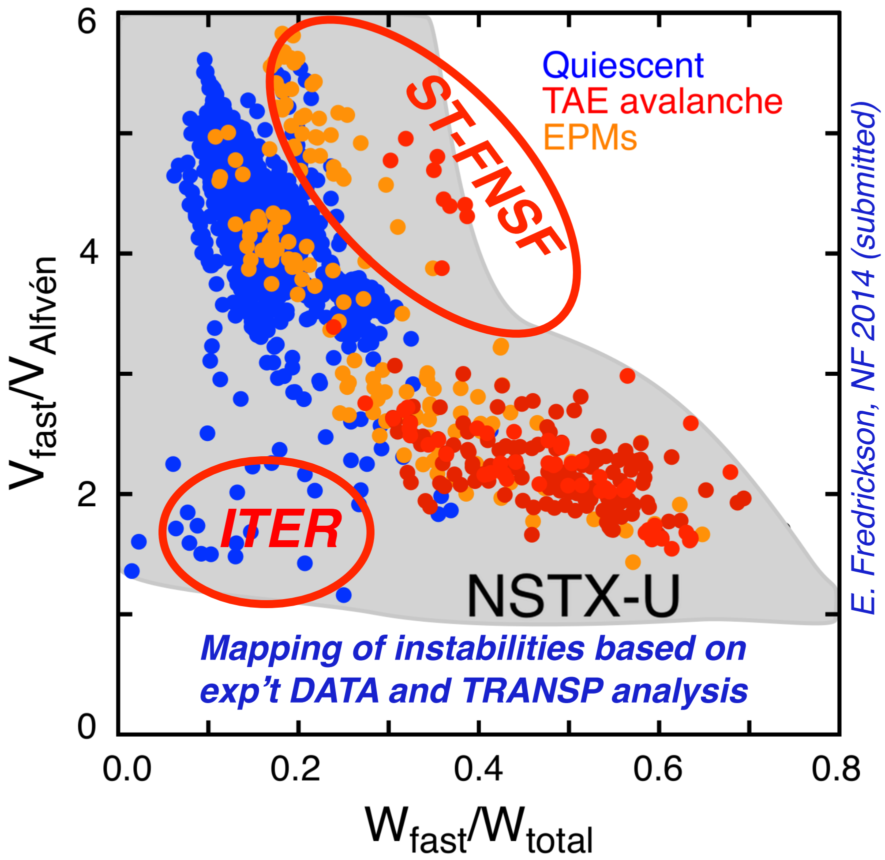


EP research on NSTX-U targets improved understanding & predictions for fast ion physics in ITER, FNSF

- Fast ions affect power and momentum balance, current drive in future devices
- NB ions and fusion alphas interact with RF, 3D fields, instabilities

> *Complex scenario to model*
  > *Includes instabilities, 3D fields, RF, feedback on thermal plasma*

NSTX-U is well equipped to explore broad range of EP scenarios, as required for projections to ITER, FNSF



Mapping of instabilities based on exp't DATA and TRANSP analysis

E. Fredrickson, NF 2014 (submitted)

Outline

- Near-term milestones
- Research highlights
- Research goals for FY-15 and FY-16
- Summary of key activities in FY15-16

Backup Slides: B#

Outline

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- Summary of key activities in FY15-16

Near term goals: develop predictive/interpretive tools for *AEs and fast ion dynamics, validate against experiments

FY14 Milestone R14-2:

Develop/assess reduced models for *AE-induced fast ion transport.

FY15 Milestone R15-2:

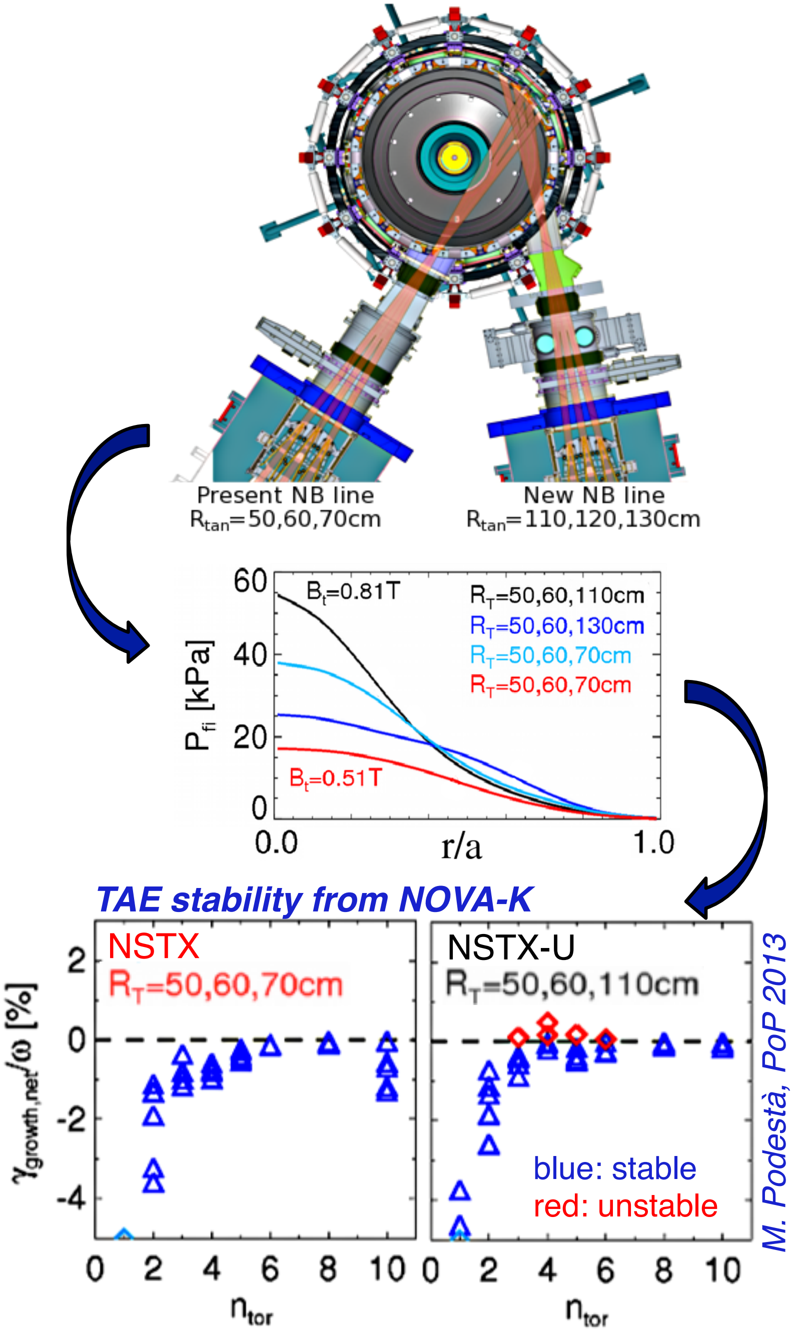
Assess effects of NBI parameters on fast ion distribution function, NB driven current profile.

FY15 OFES Joint Research Milestone:

Quantify impact of broadened current and pressure profiles on confinement and stability.

FY16 Milestone R16-3:

Assess fast-wave SOL losses and core thermal/fast ion interactions at increased B_t and current.



M. Podestà, PoP 2013

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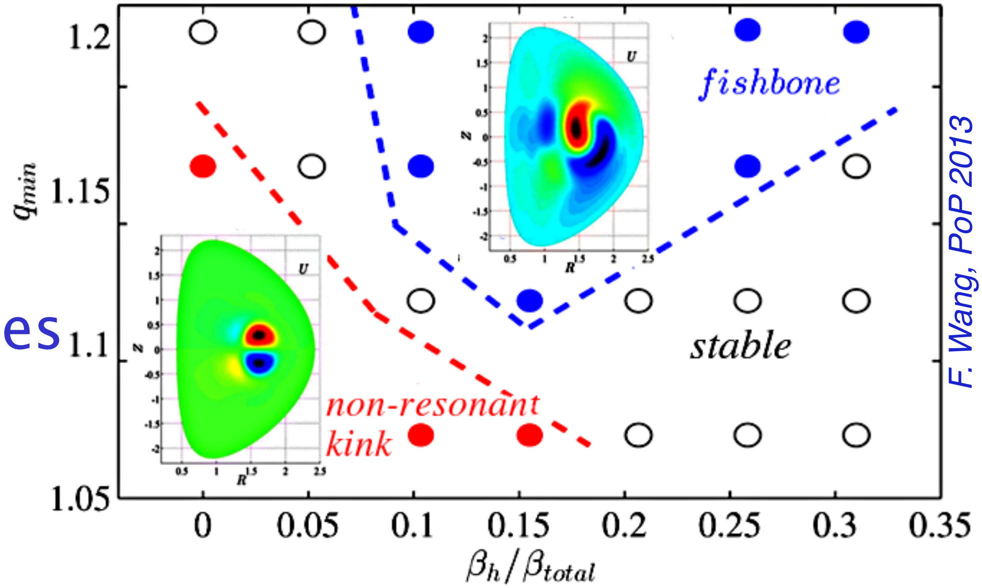
Mapping unstable regimes guides development of discharges with reduced or suppressed MHD

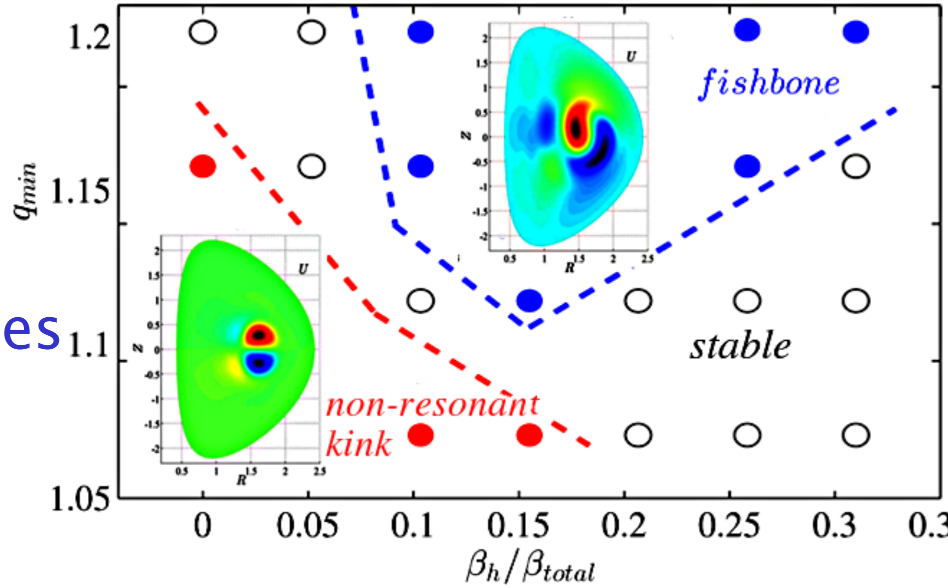
- Stability range for low-f MHD mapped through M3D-K code
  - –Now comparing with NSTX data
  - –Will be used to identify stable regimes in NSTX-U (including ramp-up)
  - >Complements results for *AEs from experiments and simulations



F. Wang, PoP 2013

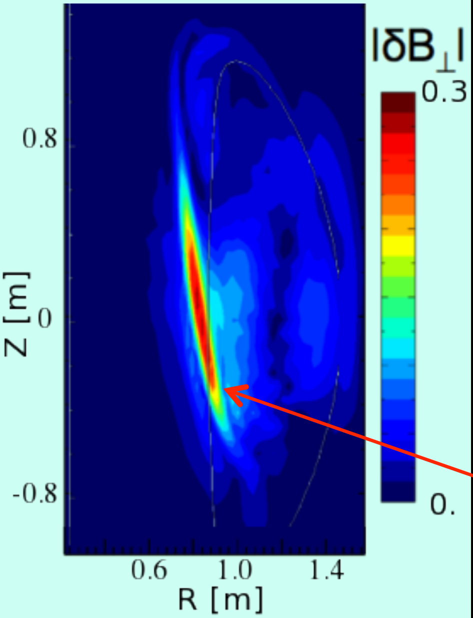
Mode characterization through advanced codes enables interpretation of experiments, development of new tools

- Stability range for low-f MHD mapped through M3D-K code
  - Now comparing with NSTX data
  - Will be used to identify stable regimes in NSTX-U (including ramp-up)
  - >Complements results for *AEs from experiments and simulations
- HYM code shows coupling of Compressional AEs (CAEs) to Kinetic Alfvén Waves (KAWs)
  - >Mechanism for wave energy dissipation to thermal plasma
  - >HYM: essential tool for thermal transport studies on NSTX-U
- Developing tools to simulate $\omega \sim \omega_{ci}$ antenna-driven modes
  - >Preliminary runs with AORSA, TORIC (full wave) also show FW coupling to KAWs



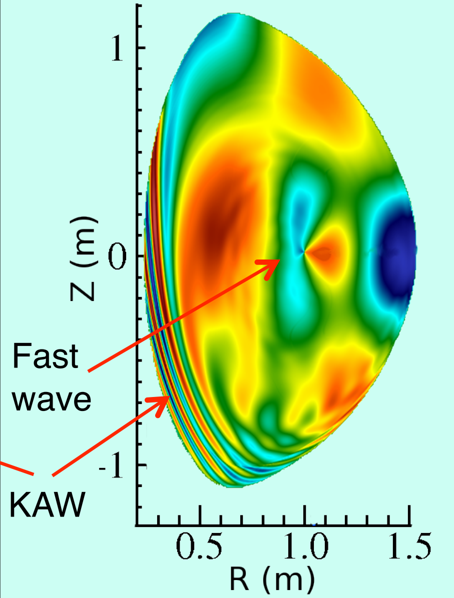
F. Wang, PoP 2013

HYM: n=8 CAE + KAWs



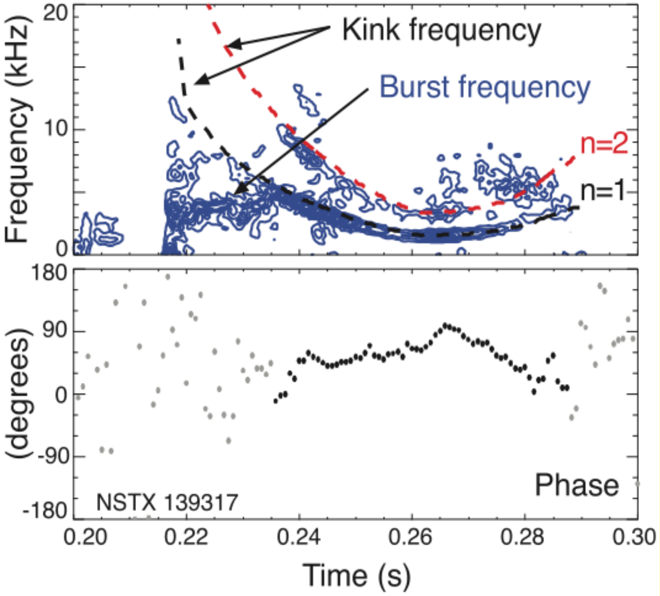
E. Belova, APS 2013

TORIC: 2MHz, n=1
Fast Wave + KAW



C. K. Phillips, APS 2013

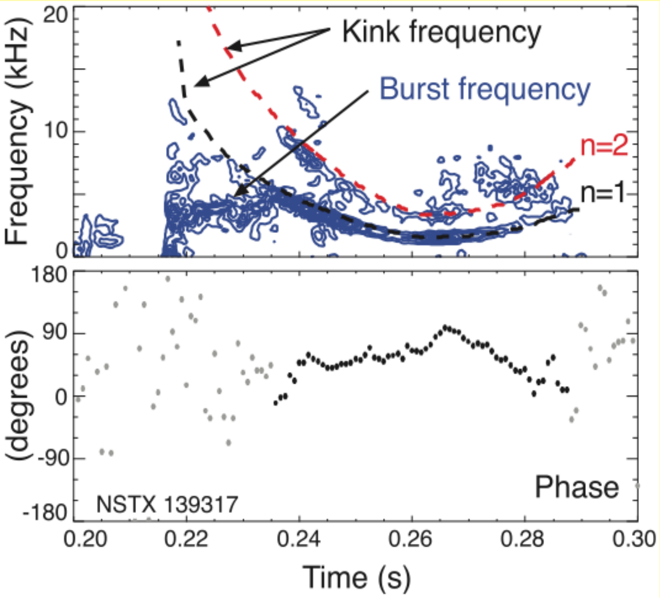
Improved analysis and simulations reveal synergy between different perturbations – *tools for *AE control*



- Dynamics of bursting CAE modes modified by coupling to kinks
  - Predator-prey dynamics
- AE burst frequency locks on kink
- Suggests modulation of AE stability by *low-f* perturbation

E. D. Fredrickson, PoP 2013

Improved analysis and simulations reveal synergy between different perturbations – *tools for *AE control*



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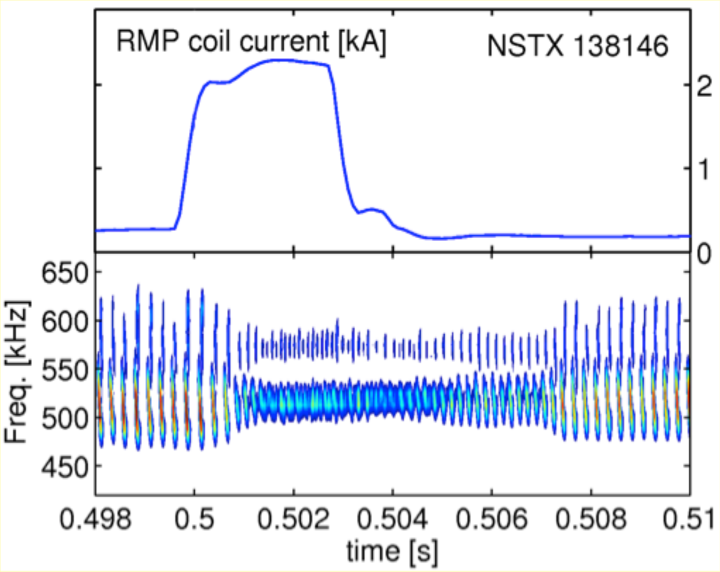
E. D. Fredrickson, PoP 2013



- Global AE dynamic affected through *external* fields
- Burst amplitude, chirp range are reduced
- Effect mediated by F_{nb} modification from 3D fields

A. Bortolon, PRL 2013

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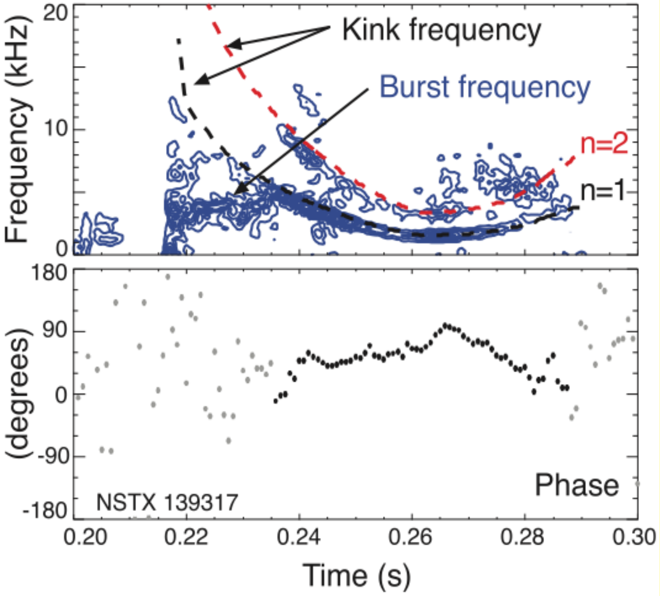

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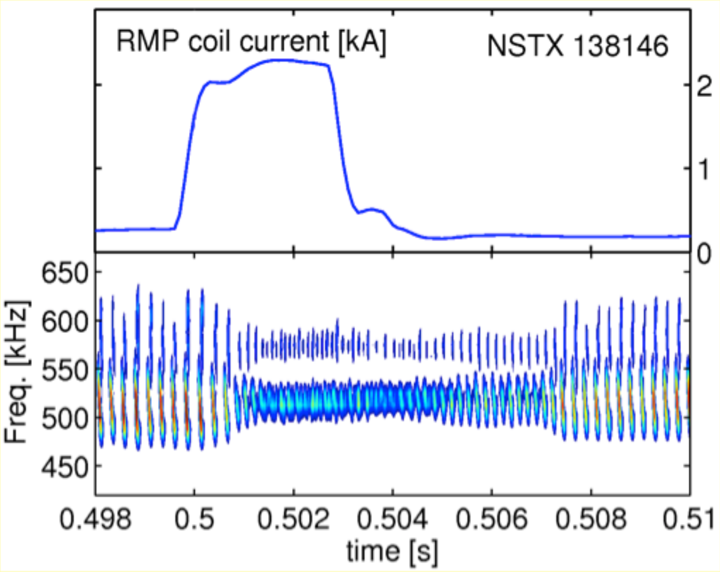
E. D. Fredrickson, PoP 2013



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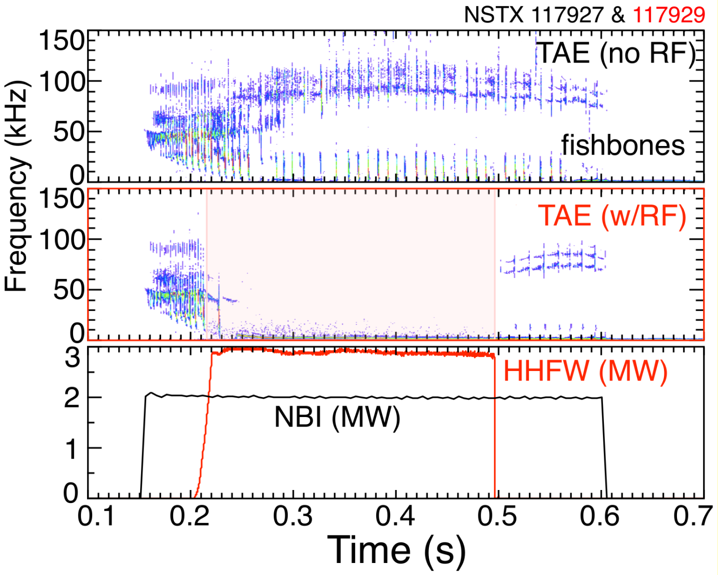
A. Bortolon, PRL 2013



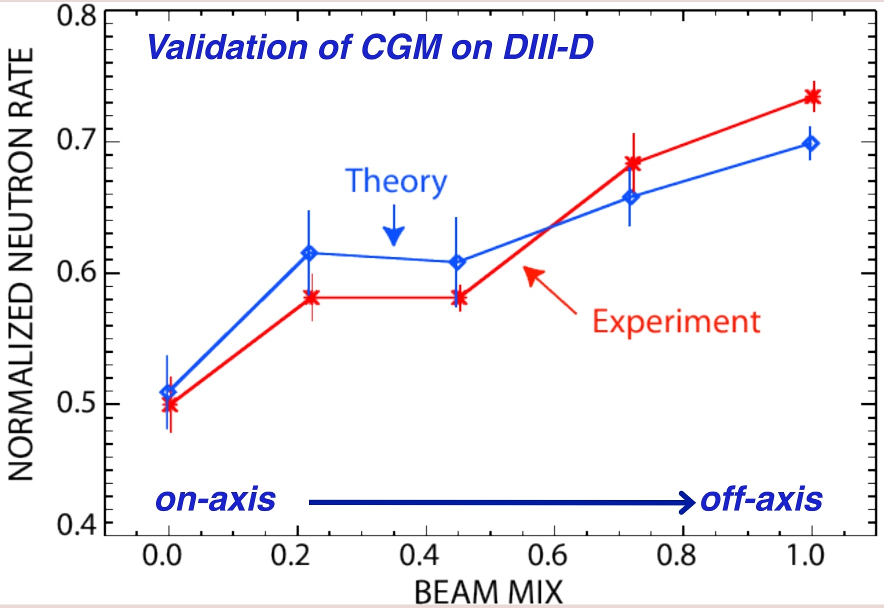
- AEs suppressed by >2MW of RF power
  - Examples of stable AEs *destabilized* by RF are observed, too
- Dependence on RF spectrum, NBI parameters under investigation

E. D. Fredrickson

Validated reduced models for EP transport; extend validation beyond present DIII-D collaboration

- "Critical Gradient" 1.5D model predicts relaxed fast ion profiles for given instabilities
- Model being validated on DIII-D, NSTX
  - >Then will use it for NSTX-U predictions
- Motivates 2D, more accurate Quasi-Linear model
  - Improve treatment of resonances in velocity space
  - Working towards inclusion in TRANSP
- Promising tool for ITER predictions

N. Gorelenkov, APS 2012



W. Heidbrink, N. Gorelenkov, NF 2013

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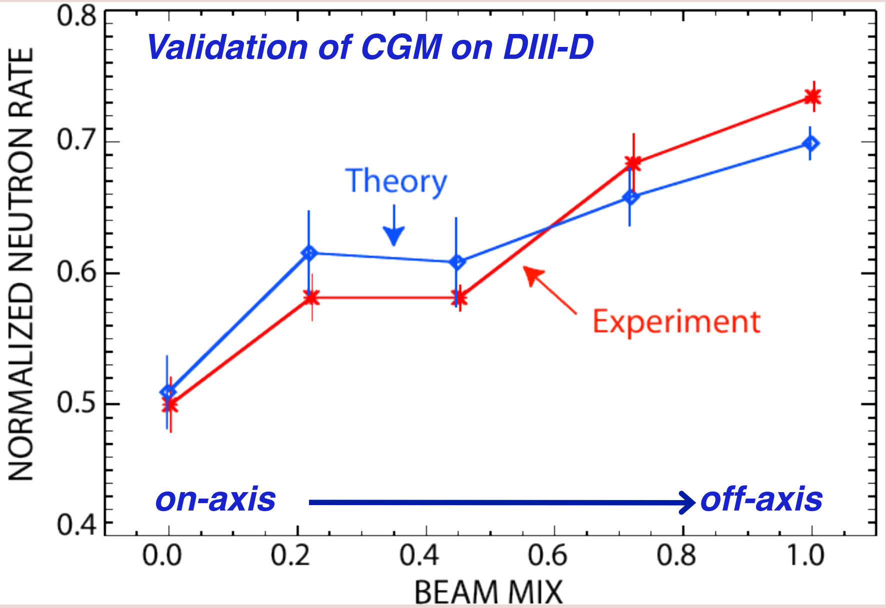
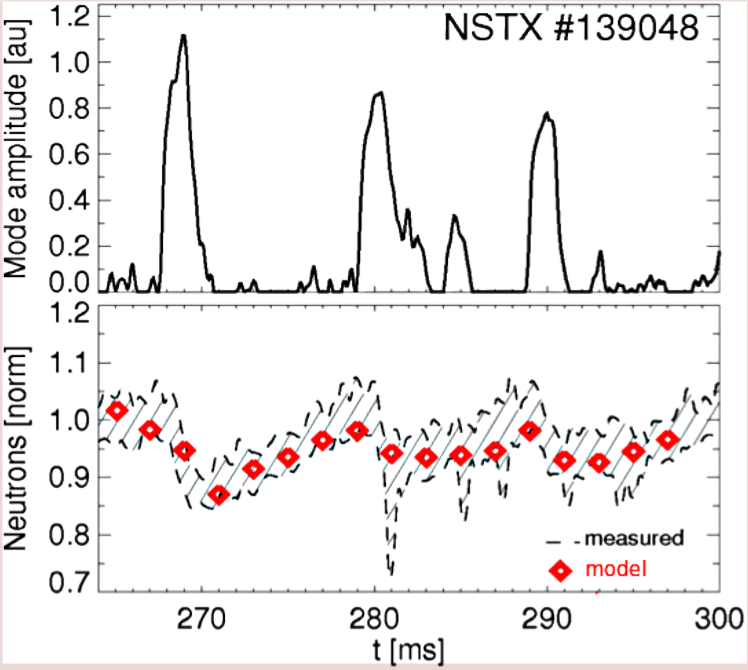
N. Gorelenkov, APS 2012



W. Heidbrink, N. Gorelenkov, NF 2013

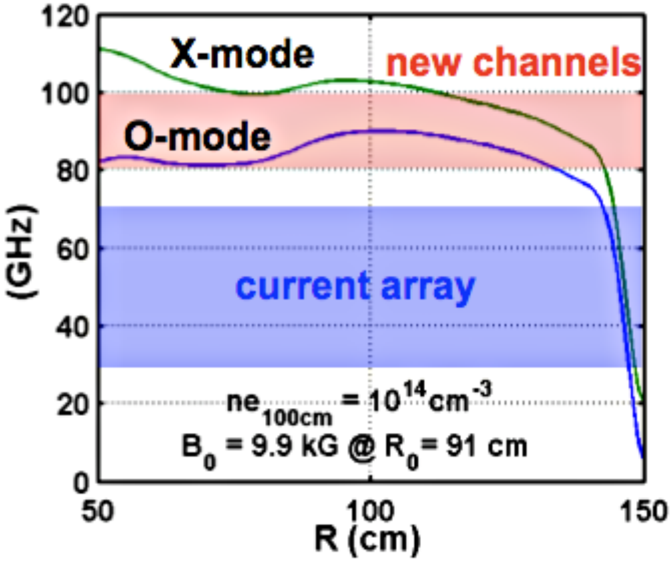


M. Podestà, PPCF 2014

- New "kick" model being implemented in NUBEAM/TRANSP for low-f AEs (μ conserved)
- Uses a probability distribution $p(\Delta E,\Delta P_\zeta|P_\zeta,E,\mu)$ to model phase-space *kicks* by instabilities
  - >Provides detailed evolution of $F_{nb}(P_\zeta,E,\mu)$, hence accurate estimates for NB-driven current
- Can handle multiple instabilities with arbitrary, time-varying mode amplitude
- Initial validation with stand-alone NUBEAM successful for TAEs, kink-like modes on NSTX

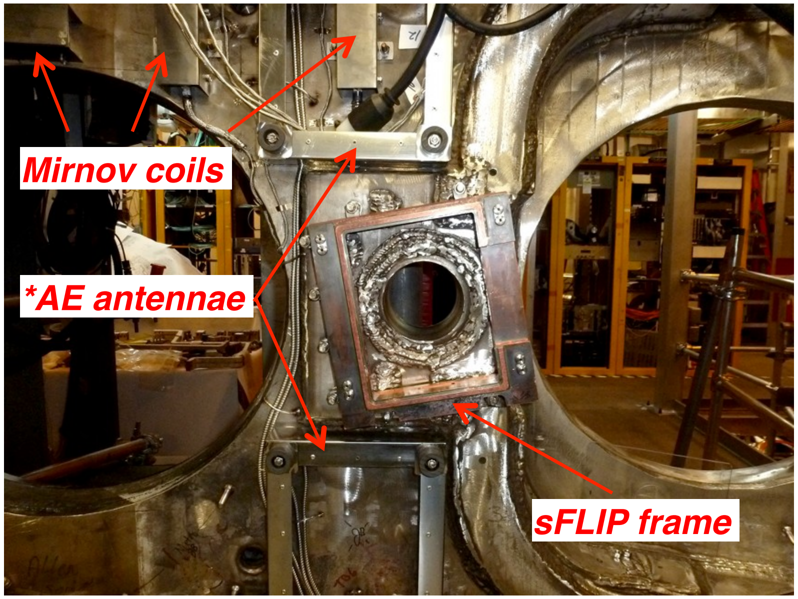
Upgrade and reinstallation of critical EP diagnostics targets operations in early FY-15

Reflectometer (UCLA) – mode structure

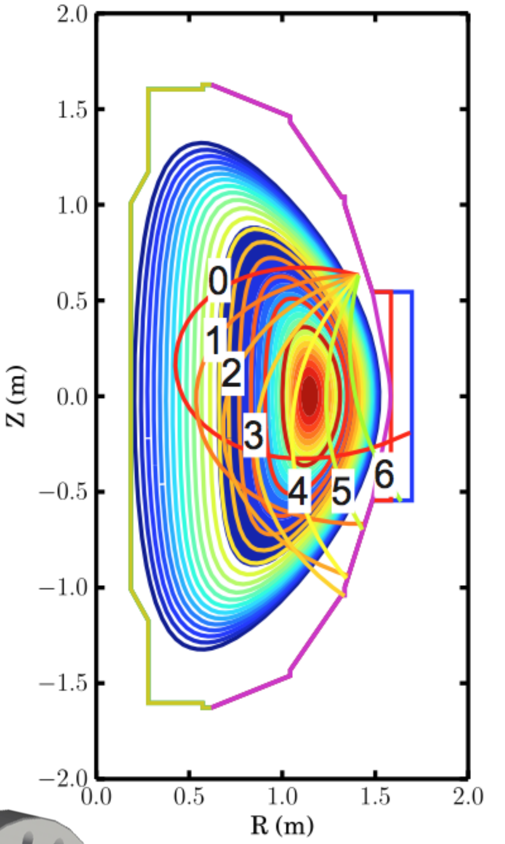


****AE antenna – mode stability***

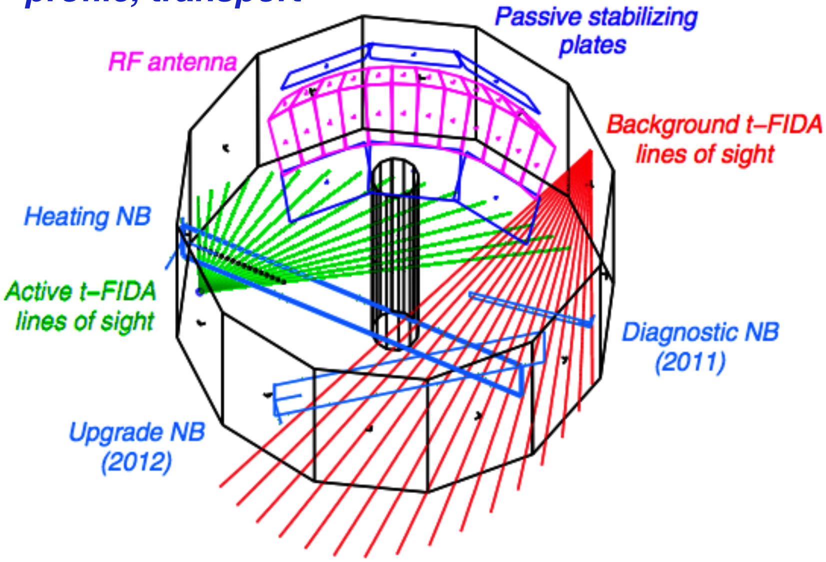
sFLIP – fast ion losses



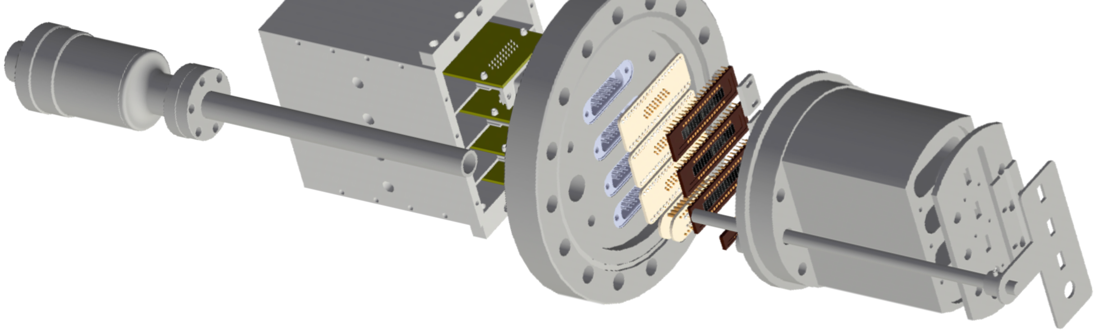
Fusion product array (FIU) – fast ion profile, transport (pending funding)



FIDA systems (UCI) – fast ion profile, transport



ssNPA arrays (UCI) – fast ion profile, transport



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Goals & Plans for FY-15 (1)

- Characterize fast ion distribution with 2nd NB line **R15-2**
  - Use FIDA, ssNPA, sFLIP to measure fast ion profile and losses
  - Compare with classical predictions from TRANSP
    - Benefits from upgraded modules in TRANSP (e.g. 3D “halo” model) **B#42**
  - Assess NB-driven current dependence on NB injection parameters
- Assess effects of broadened pressure, NB-driven current on plasma stability, performance **JRT-15**
  - Investigate effects on *AE stability
  - Compare with linear/nonlinear simulations
    - Characterize mode structure with reflectometers, BES
- Assess *AE antenna performance for damping rate measurements of lower frequency *AEs (TAEs, RSAEs)
- Characterize scenarios with combined NBI+HHFW **R16-3**
  - Assess RF power deposition on fast ions as a function of RF injected spectrum, power

Goals & Plans for FY-15 (2)

Exploit close collaboration with theory (PPPL and collaborators) to meet EP Research goals:

- Validate first-principle codes for extended parameter range of NSTX-U
  - Enabled by improved description of F_{nb}, rotation
  - Target both NB-only and NB+HHFW scenarios
    - Improve estimates of RF power transfer to thermal plasma and fast ions
  - Improve simulations of *AE effects on thermal transport
- Extend validation of reduced models for EP transport by MHD (*AEs, low-f kink-like modes) **R14-2**
  - Validate Critical Gradient & “kick” models for broad range of *AE activity, NB injection parameters

>*Extend predictions of MHD/*AE stability to 1T, 2MA NSTX-U scenarios*

Goals & Plans for FY-16

- Assess *AE stability at full B_t, current
  - Characterize damping rate through *AE antenna
  - Compare with linear/nonlinear codes
- Extend *AE studies to nonlinear, multi-mode regimes
- Characterize F_{nb} modifications by *AEs
  - Obtain detailed measurements of F_{nb} from FIDA, ssNPA, CFPA
  - Compare experiments with first-principle & reduced models
- Contribute to non-inductive ramp-up research
  - Study *AE stability in low-I_p flat-top plasmas prototypical of ramp-up conditions
- Validate codes for GAE/CAE modes
  - Study GAE/CAE effects on electron thermal transport at higher B_t, current (w/ T&T TSG)

> *Assess requirements to affect F_{nb}, NB-driven current through available actuators (NBI, HHFW, external coils)*

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Summary of key activities in FY15-16

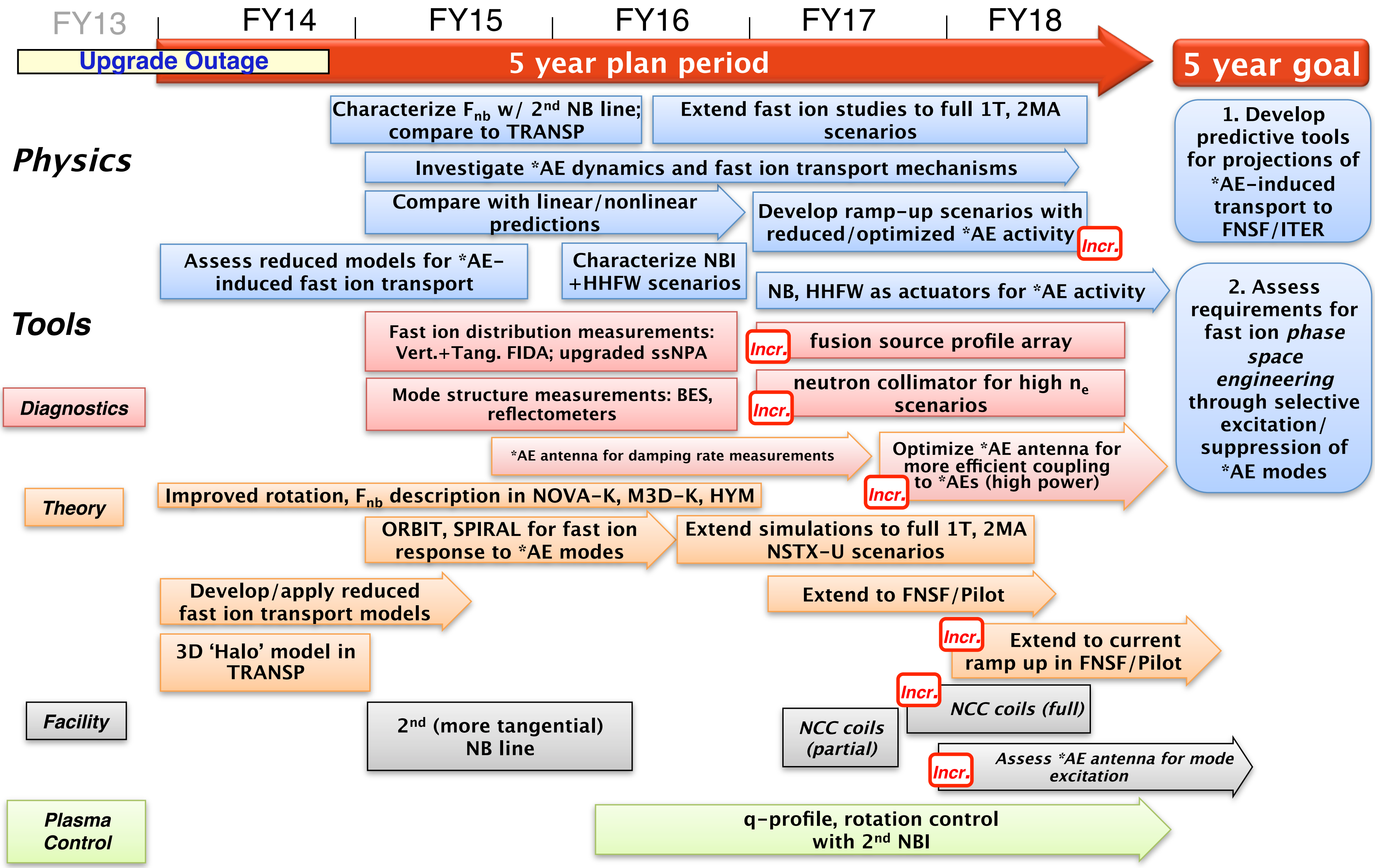
- Develop leading capabilities in non-linear and reduced models for *AE-induced transport
  - Characterize effects of 2nd NB line on F_{nb}, NB-driven current, stability
  - Investigate synergy between NBI and HHFW
  - Develop predictive tools for *AE-induced thermal electron transport

- Support non-inductive ramp-up experiments with reduced/optimized *AE activity

> *Assess* <u>*control capability*</u> *of* F_{nb}*, current through NBI, HHFW, coils*

Backup

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

Physics

Characterize F_{nb} w/ 2^{nd} 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

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

Assess reduced models for *AE-induced fast ion transport

Characterize NBI +HHFW scenarios

NB, HHFW as actuators for *AE activity

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

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

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

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

2^{nd} (more tangential) NB line

NCC coils (partial)

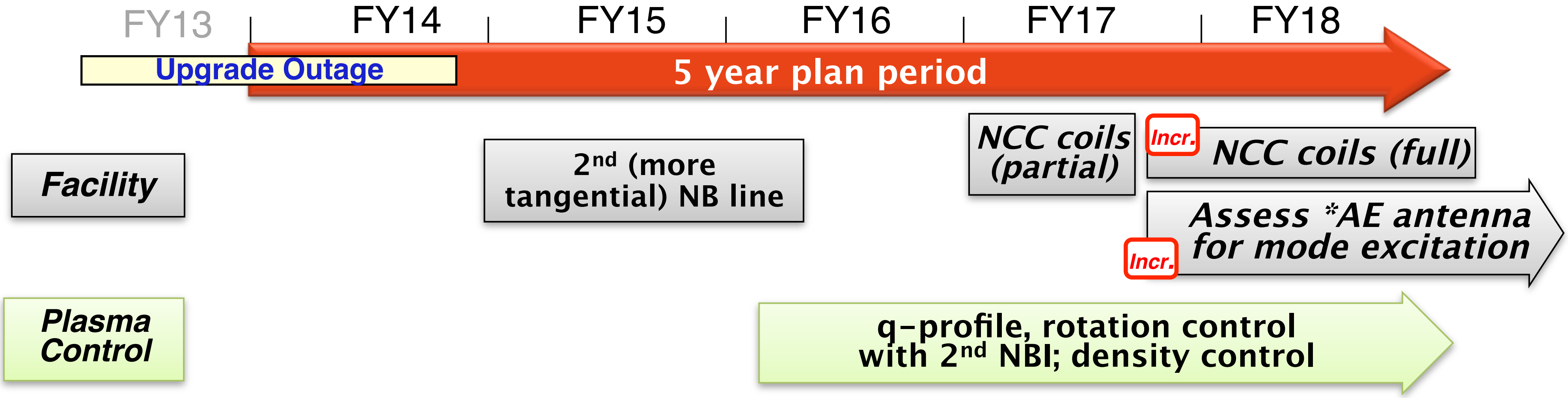
Incr. *NCC coils (full)*

Incr. *Assess *AE antenna for mode excitation*

Plasma Control

q-profile, rotation control with 2^{nd} NBI

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)

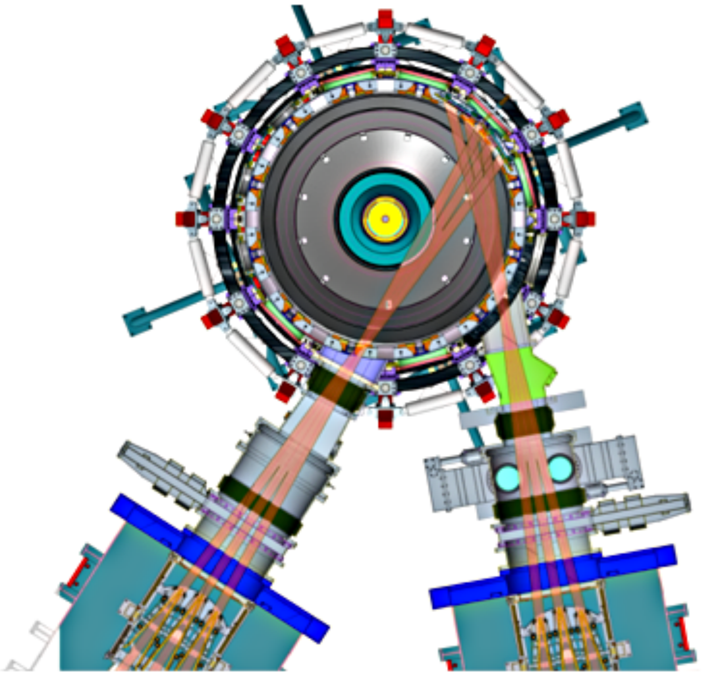
*Assess *AE antenna for mode excitation*

Incr.

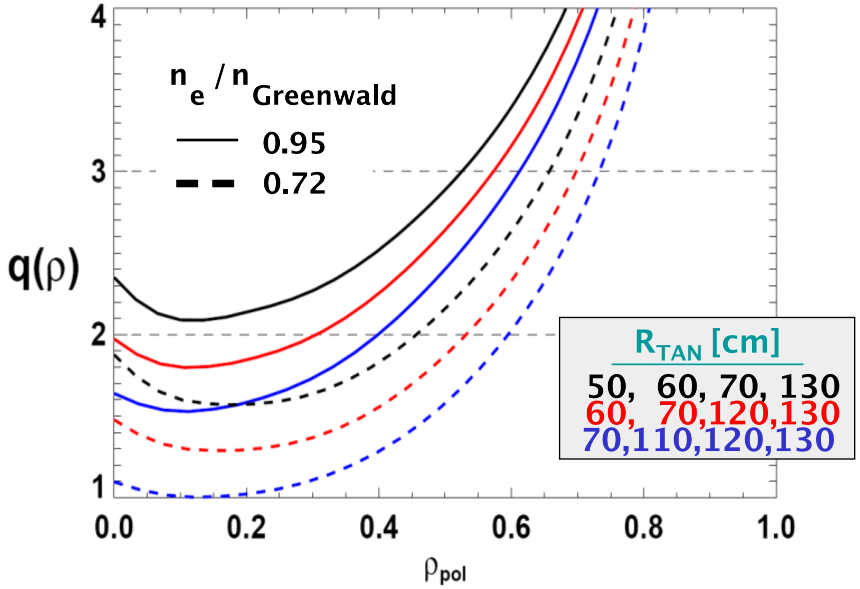
Plasma Control

q-profile, rotation 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



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_{NB}, and density to vary q, $v_{fast}/v_{Alfvén}$, 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 ω_{ci} 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.

(w/ ASC, MS and SFSU TSGs)

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.

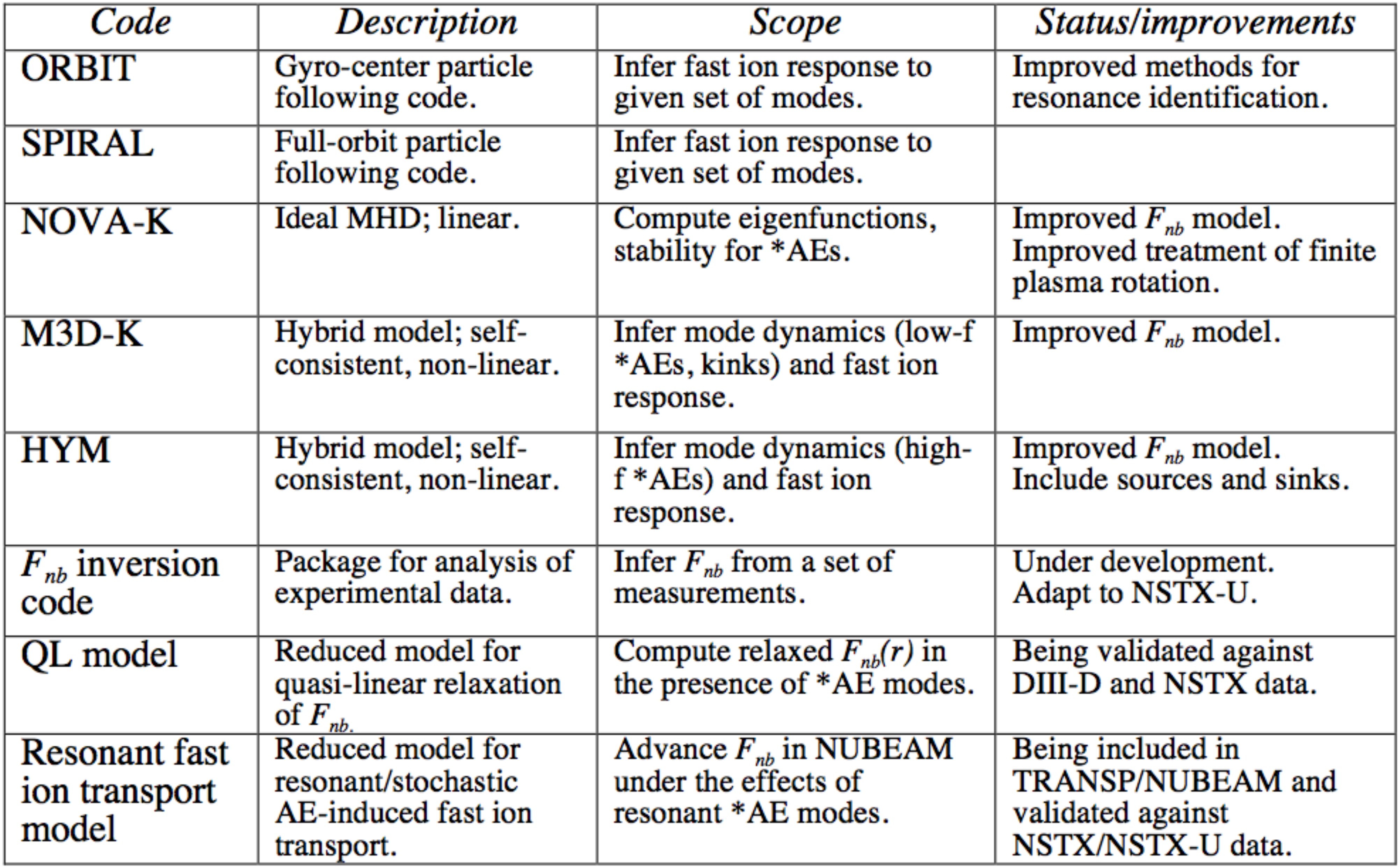
FY16 Milestone R16-3:
Assess fast-wave SOL losses and core thermal and fast ion interactions at increased field and current

Use of high-harmonic fast wave (HHFW) injection for heating and current drive in NSTX-U is important to develop non-inductive start-up/ramp-up schemes, to achieve higher plasma performance, and to validate RF codes in support of the ITER FW program. The successful exploitation of HHFW depends on how much power can be coupled to the core plasma through the scrape-off layer (SOL) and how the coupled power is partitioned between different species in the core. For NSTX-U H-mode plasmas, the latter typically include thermal electrons/ions and fast ions from Neutral Beam (NB) injection. Mechanisms responsible for RF power losses in the SOL will first be addressed to optimize FW coupling to the core as a function of excited wave spectrum, toroidal field and plasma current (B_T and I_P). For instance, full-wave simulations with the AORSA code suggest a local enhancement of RF fields for propagating (rather than evanescent) fast waves in the SOL, which results in increased losses through damping. Losses are predicted to decrease at lower SOL density and/or at higher B_T. AORSA predictions will be tested against improved measurements of RF fields through dedicated probe arrays. The amount of lost power will be quantified through infrared cameras. The improved understanding of SOL loss mechanisms will provide more accurate estimations of the fraction of injected HHFW power reaching the core. The synergy between NB and FW injection in H-mode plasmas will be evaluated for the higher B_T and I_P of NSTX-U. In particular, the efficiency of thermal ions heating at higher B_T, predicted to increase by full-wave simulations, will be investigated. Similarly, modifications of the fast ion distribution, previously observed on NSTX, will be assessed with the enhanced fast ion diagnostics set of NSTX-U as a function of plasma parameters, FW spectrum and NB injection geometry, including the new (more tangential) NB lines. The characterization of scenarios with combined NB and FW injection will provide a valuable dataset to benchmark RF codes (e.g. AORSA, TORIC and CQL3D-FOW), which have been considerably improved in the past years. NSTX-U will provide the required data for extensive validation before their use for scenario predictions in future devices such as ITER and FNSF.

FY15 OFES 3 Facility Joint Research Milestone:
Quantify impact of broadened current and pressure profiles on confinement and stability.

Conduct experiments and analysis to quantify the impact of broadened current and pressure profiles on tokamak plasma confinement and stability. Broadened pressure profiles generally improve global stability but can also affect transport and confinement, while broadened current profiles can have both beneficial and adverse impacts on confinement and stability. This research will examine a variety of heating and current drive techniques in order to validate theoretical models of both the actuator performance and the transport and global stability response to varied heating and current drive deposition.

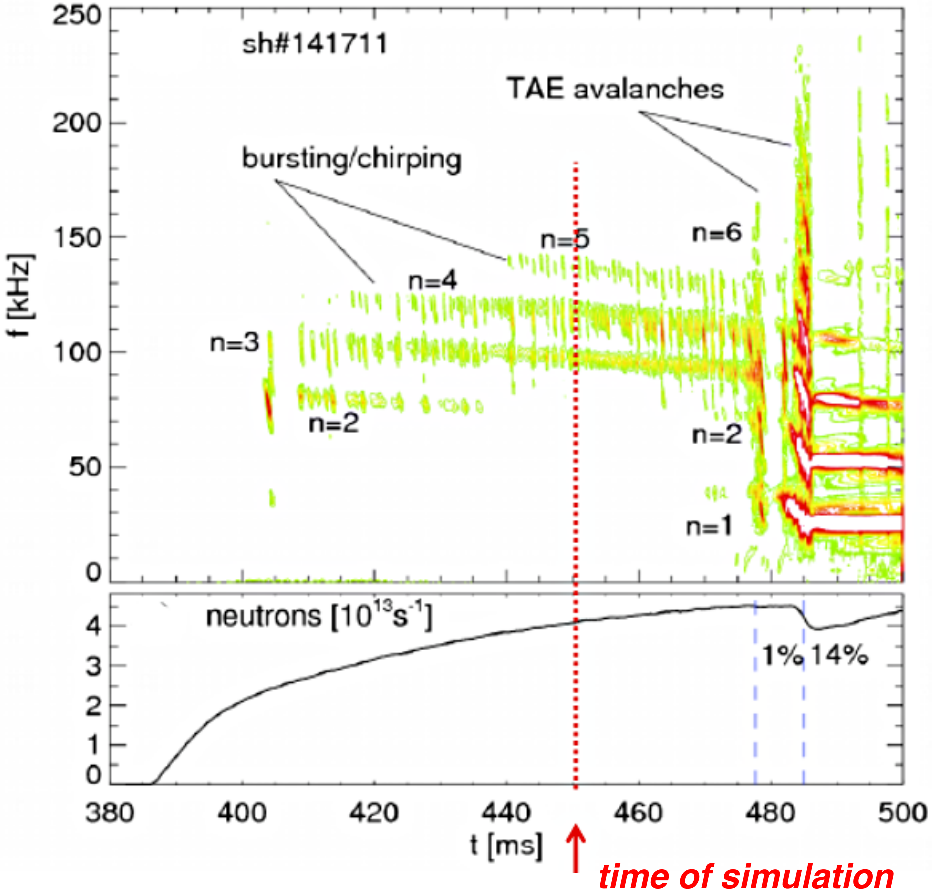
Summary of theory and simulation capabilities for EP research



Code	*Description*	*Scope*	*Status/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; linear.	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	Reduced model for quasi-linear relaxation of F_{nb}.	Compute relaxed $F_{nb}(r)$ in the presence of *AE modes.	Being validated against DIII-D and NSTX data.
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.	Being included in TRANSP/NUBEAM and validated against NSTX/NSTX-U data.

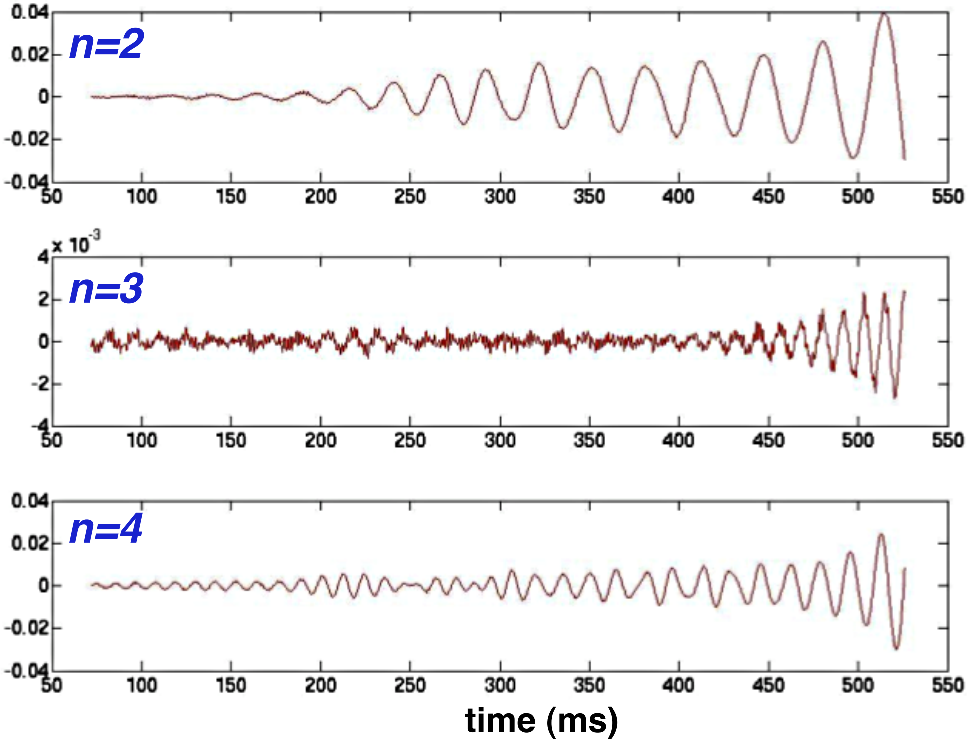
Non-linear M3D-K simulations of multiple TAEs show mode saturation, frequency chirping

D. Liu, G.-Y. Fu



time of simulation

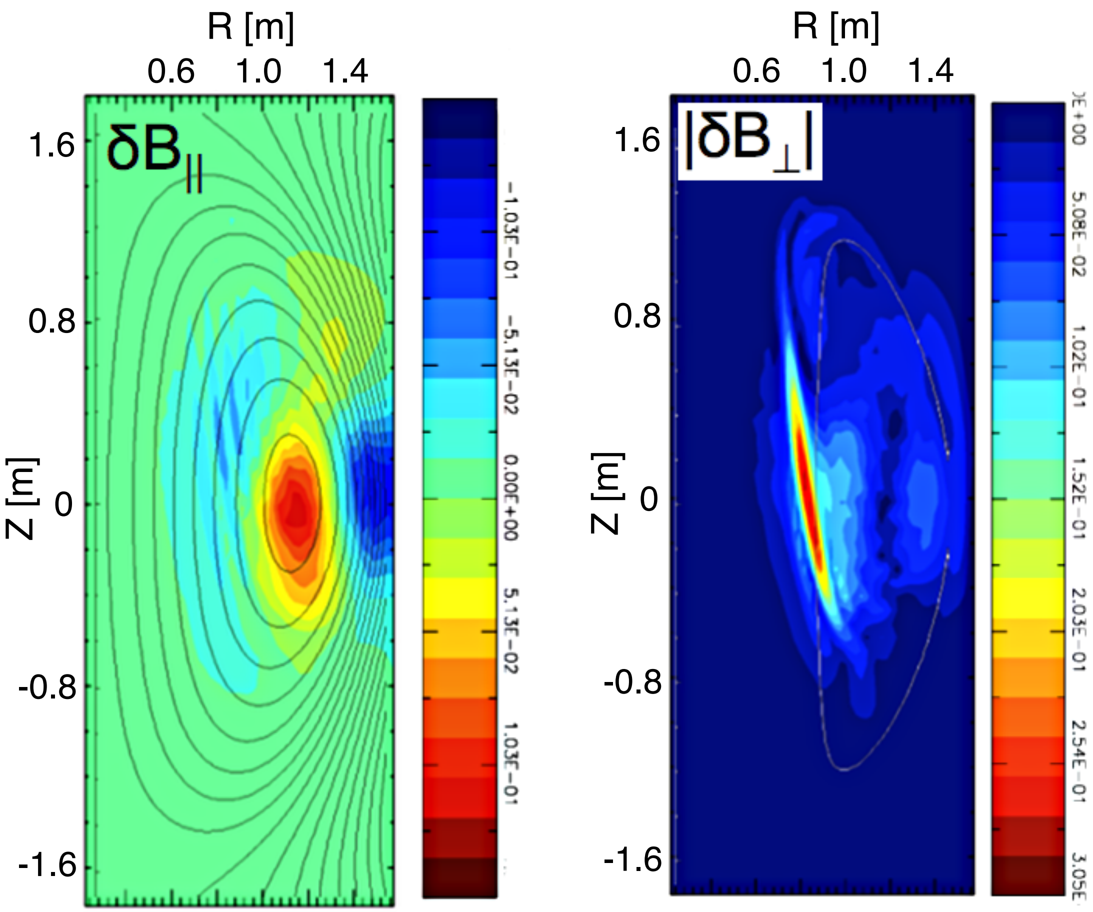
- NSTX scenario with multiple unstable TAEs, n=2-6
- Simulate phase with weakly chirping/bursting TAEs
- Multi-mode simulations retain mode-mode coupling, non-linear effects



Validation during weakly bursting/chirping phase required before moving to *avalanching* phase

HYM code analysis shows high-n, co-rotating CAEs coupling to KAWs at high-field side

E. Belova

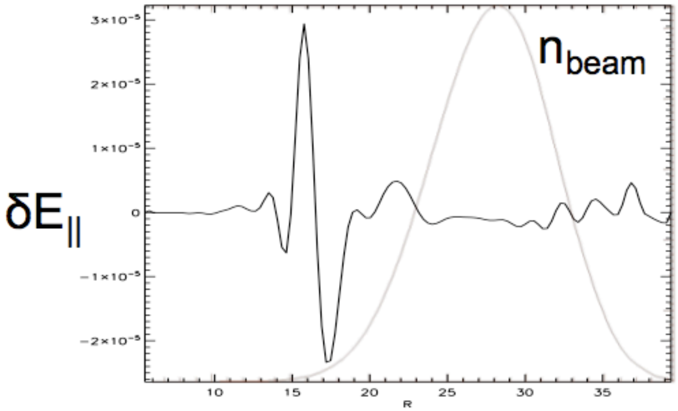


- CAEs peak near magnetic axis
  - Strong compressional character with $\delta B_{//} >> \delta B_{perp}$
- KAWs are located near the $\omega_A(R,Z)=\omega_{CAE}$ surface
- KAWs structure tilted relative to equilibrium B
  - $k_{//}$ along beam velocity
  - k_{perp} towards high-n_b

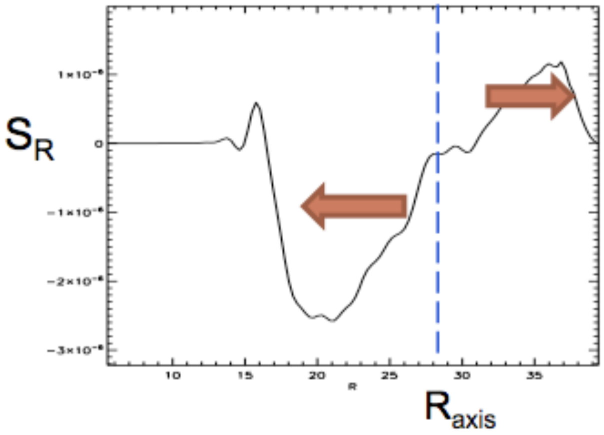
KAW in HYM model:
$$\omega^2 = k_{\|}^2 V_A^2\left(1+\frac{3}{4}\frac{n_b}{n_e}\lambda_b - \frac{n_b}{n_e}\frac{\omega^2}{\omega_{ci}^2}\right), \quad \lambda_b = \frac{k_\perp^2 T_b}{m_i\omega_{ci}^2}$$

- consistent with full kinetic in the limit $\lambda_e \to 0$, $\lambda_i \to 0$, and $\omega << \omega_{ci}$.

CAE/KAW coupling may provide an efficient channel for NB power flow to thermal electrons



Radial profiles of $\delta E_{||}$ and beam ion density for n=4 CAE/KAW.



Radial component of quasilinear Poynting vector **S=<ExB>**. Energy flux is directed away from magnetic axis, ie from CAE to KAW.

Fraction of NBI power transferred to CAE can be estimated as:

$$P = 2\gamma \int (\delta B)^2/4\pi \, d^3x,$$

where $\delta B/B_0 = (0.9\text{-}3.4)\times10^{-3}$ corresponds to measured displacement $|\xi| = 0.1\text{-}0.4$ mm [N.Crocker'13] (based on HYM-calculated linear mode structure for the n=4 CAE).

For $\gamma/\omega_{ci}=0.005\text{-}0.01$, P= (0.013-0.4)MW,

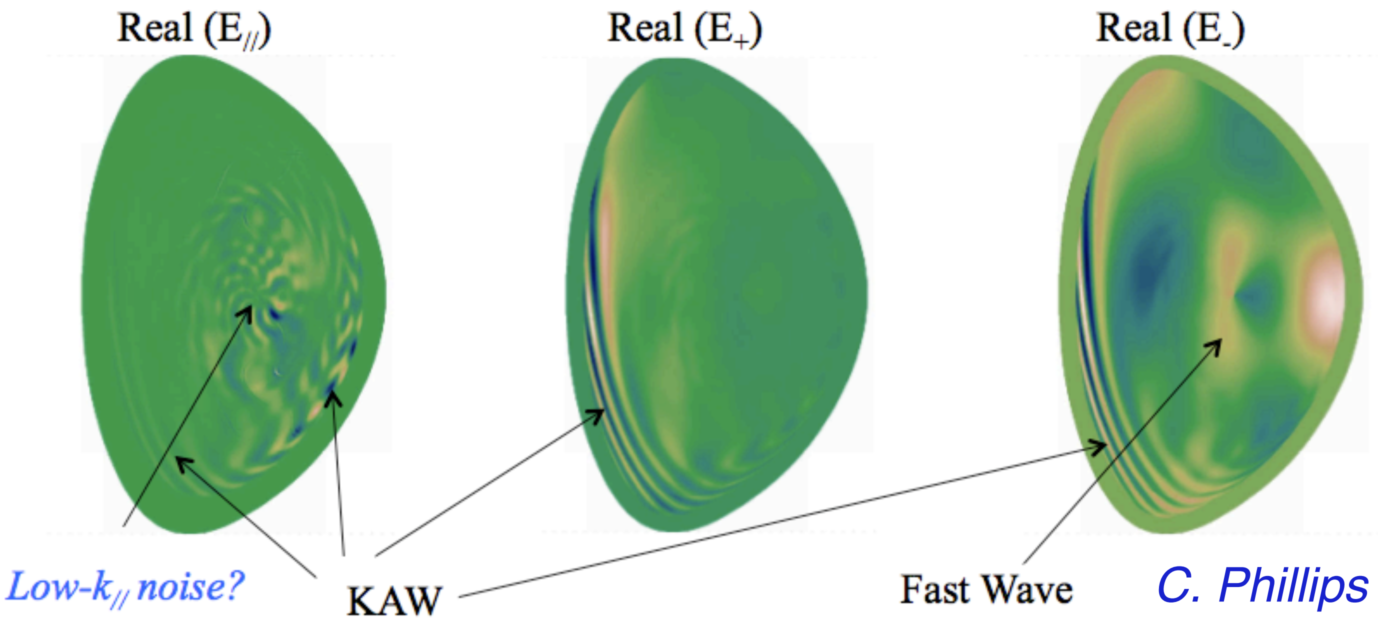
- significant fraction of NBI energy can be transferred to several unstable CAEs of relatively large amplitudes.

Energy flux from the CAE to the KAW and dissipation at the resonance location can have a strong effect on the temperature profile.

E. Belova, N. Crocker

TORIC and AORSA full-wave codes can be used to simulate antenna-driven modes

- Full wave RF codes retain some effects that can be missing in other EP simulation codes
  - Full linear power absorption by species
  - Full FLR, including $\omega\sim\omega_{ci}$ range
  - Full toroidal geometry
  - Can use a measured or predicted (TRANSP) fast ion distribution (AORSA)
- In addition, TORIC/AORSA provide solutions at very high spatial resolution
  - As required for studying KAWs



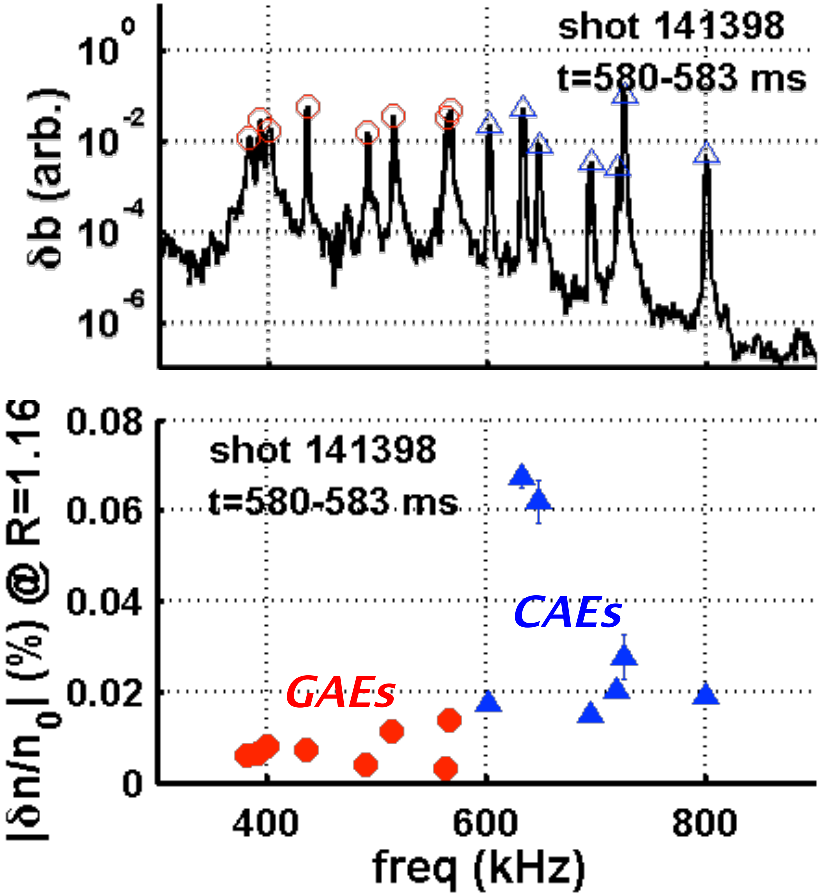
C. Phillips

TORIC results for 2MHz, n=1 excitation

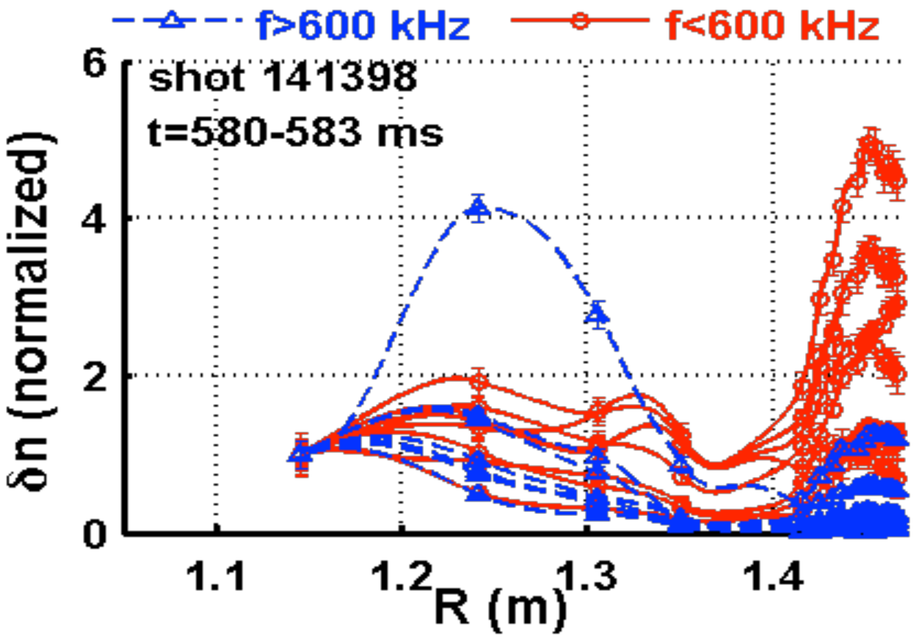
NSTX target plasma at B_t=0.46T

Detailed mode structure measurements through reflectometry enables quantitative comparison with HYM

N. Crocker (UCLA)



- Reflectometer array + Mirnov coils provide δB spectrum, mode structure
  - Density perturbation inferred from phase shift
- Analysis of frequency evolution vs. time used to distinguish between CAEs and GAEs [Crocker, NF 2013]



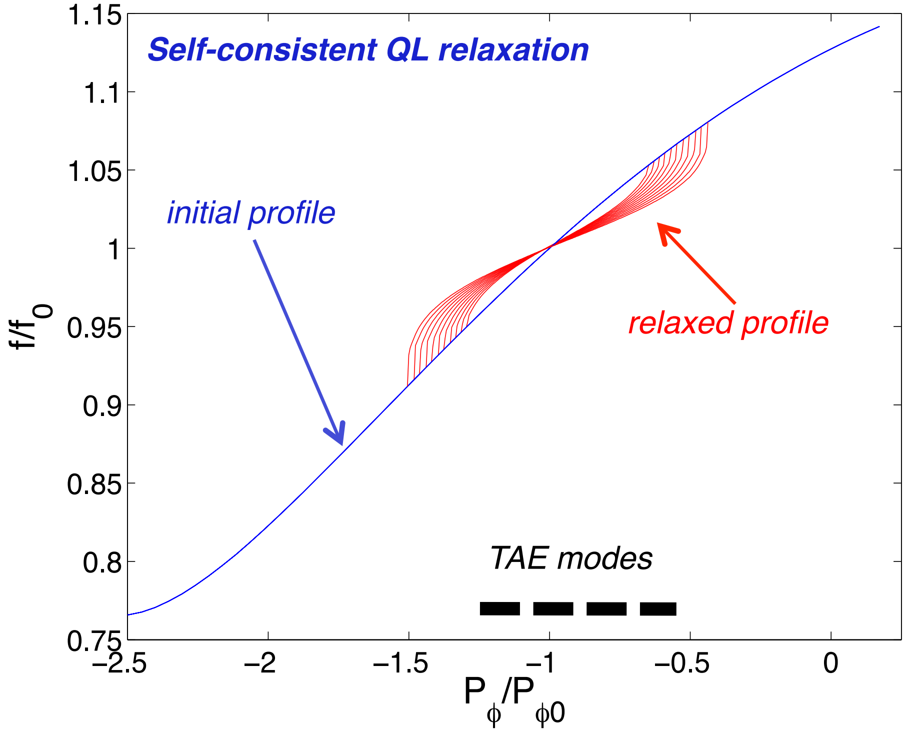
Mode structures, density perturbation level used to infer effects on thermal electron transport

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

Evolution of fast ion distribution, modes:

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

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

New “kick model” is based on a *probability distribution function* for particle transport

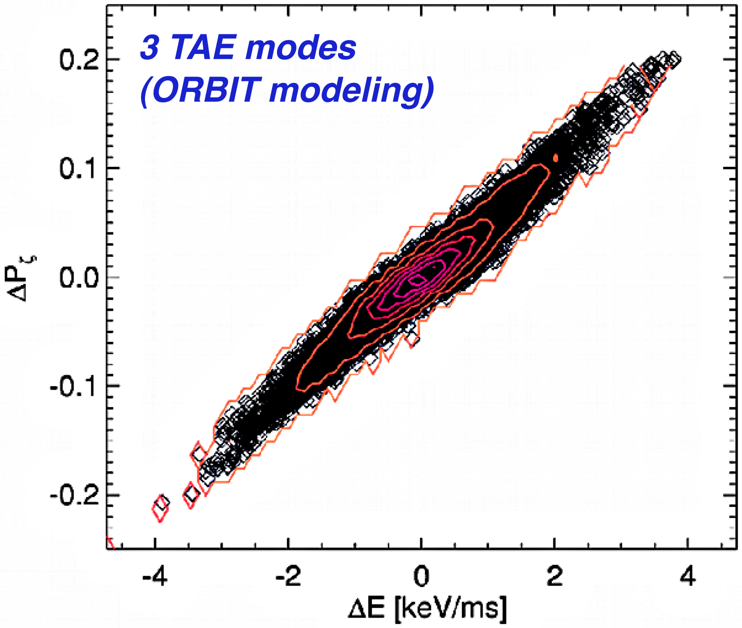
*M. Podestà et al., PPCF **56** (2014) 055003*

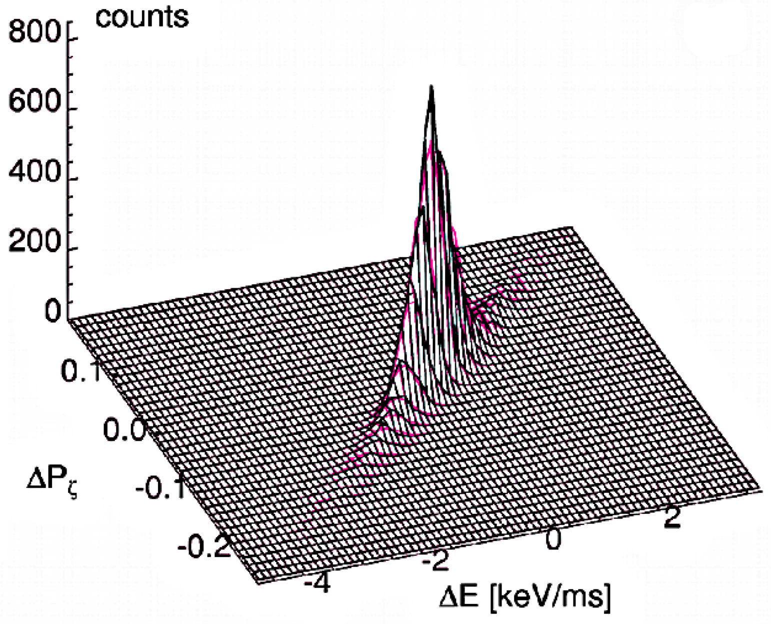
For each “orbit” in (E,P_ζ,μ), describe steps in ΔE, ΔP_ζ by

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

which can include the effects of <u>multiple</u> modes, resonances. ***Correlated random walk in E, P_ζ:***

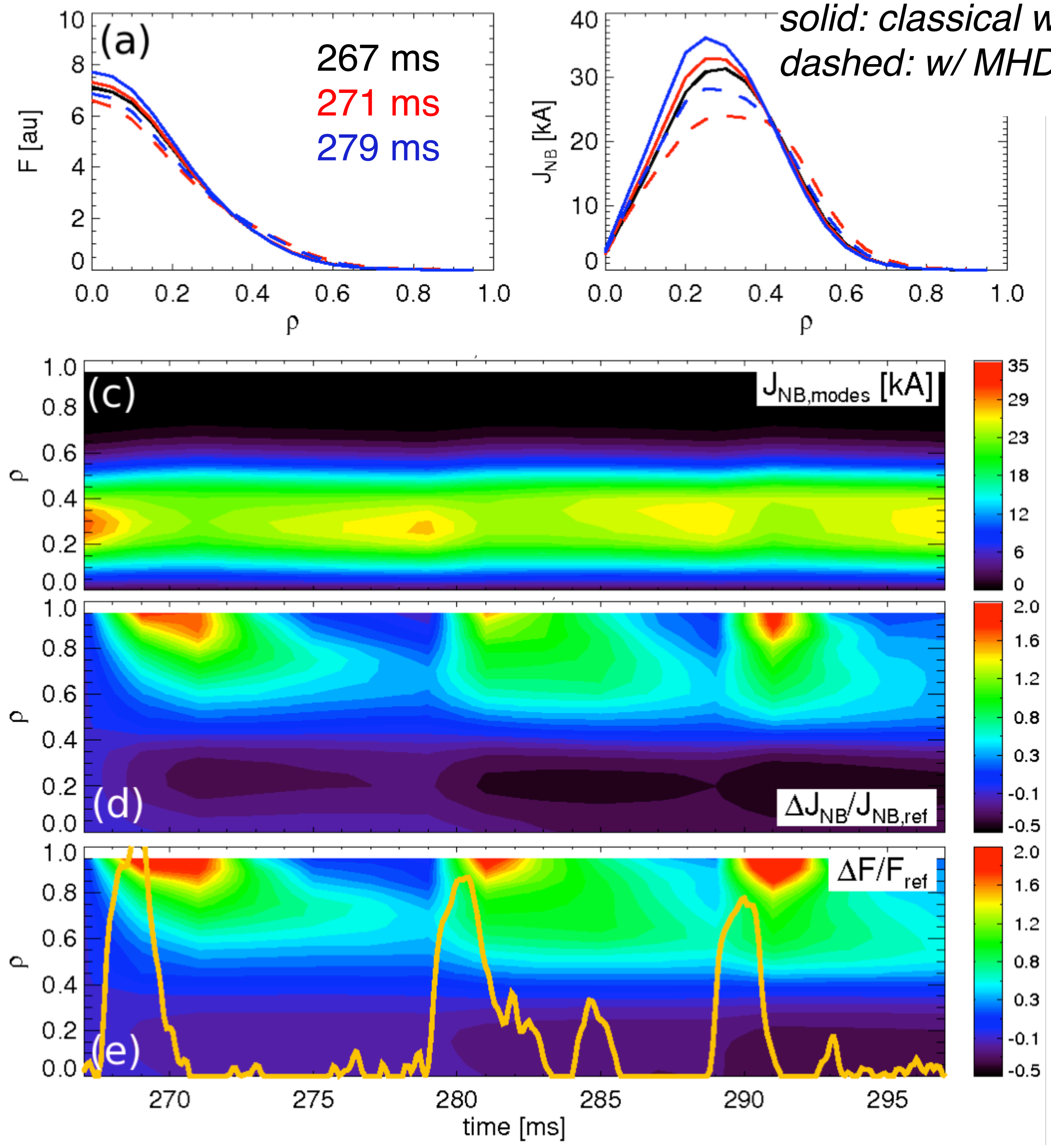
$$\omega P_\zeta - nE = const. \Longrightarrow \Delta P_\zeta / \Delta E = n/\omega$$





In practice, will use the full 5D matrix for $p(\Delta E,\Delta P_\zeta | P_\zeta,E,\mu)$ plus a time-dependent “mode amplitude scaling factor”

Kick model + NUBEAM reproduces fast ion redistribution; NB-driven current strongly affected, too



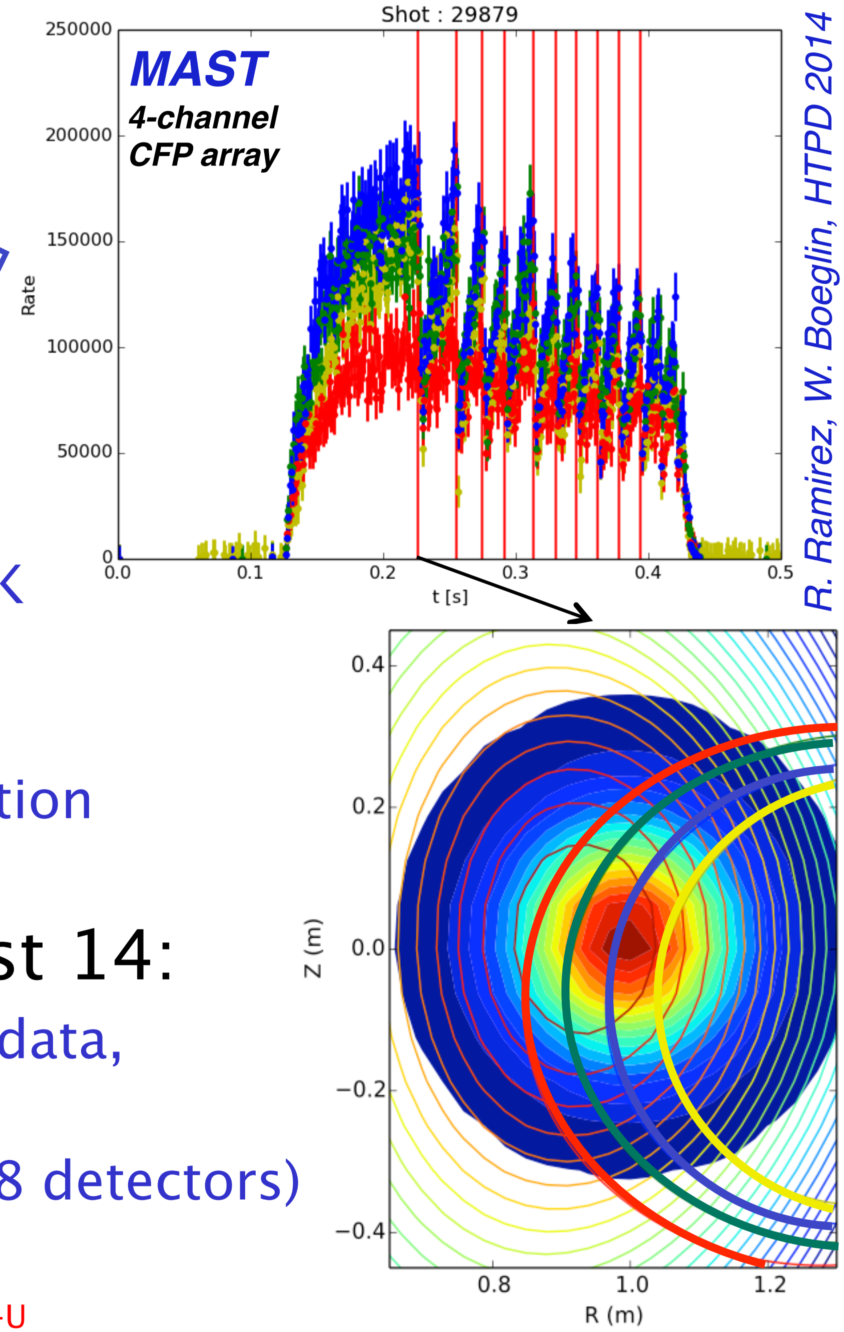
solid: classical w/ AFID
dashed: w/ MHD

- NSTX #139048
- Initial tests show fast ion redistribution induced by each TAE avalanche
- Clear effects on NB-driven current, J_{nb}
  - Stronger effect than on F_{nb}
- AE effects persist on slowing down time scales
  - Constant NB injection counteracts F_{nb}, J_{nb} depletion
- *Resonance patterns* form in $F_{nb}(E,P_\zeta,\mu)$

First results from 3 MeV proton measurements in MAST confirm validity of Charged Fusion Product as fast ion diagnostic

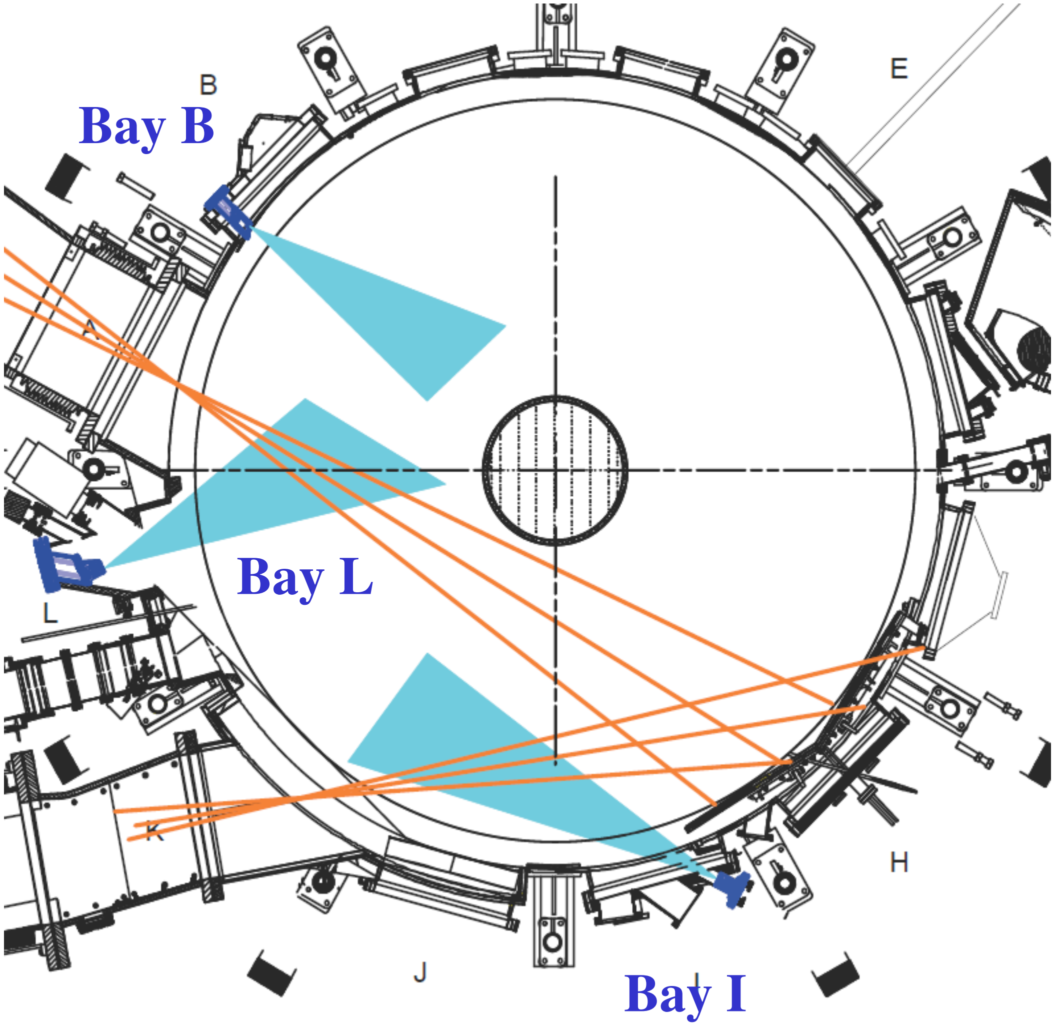
Collaboration Florida International University - PPPL

- Example from MAST scenario with sawteeth (FY13 campaign)
  - Good signal-to-noise @ ~1ms time resolution
  - Clear changes in fusion source profile observed after sawteeth
  - Qualitative comparison w/ neutrons is OK



- Funding status:
  - Current grant ends Aug. 14; new application pending
- Diagnostic work planned by August 14:
  - Analysis of MAST proton/triton/neutron data, including TRANSP comparison
  - Enhance proton detection system (up to 8 detectors)
  - Preparation for installation in NSTX-U
    - Complete conceptual design of new detector mount for NSTX-U

Upgraded ssNPA Views a Large Range of Plasma, and Distinguishes Response from Passing & Trapped Beam Ions



- Passing beam ions: **Bay I**
- Trapped beam ions:
  - **Bay L** for **active** radial views,
  - **Bay B** for **passive** radial views

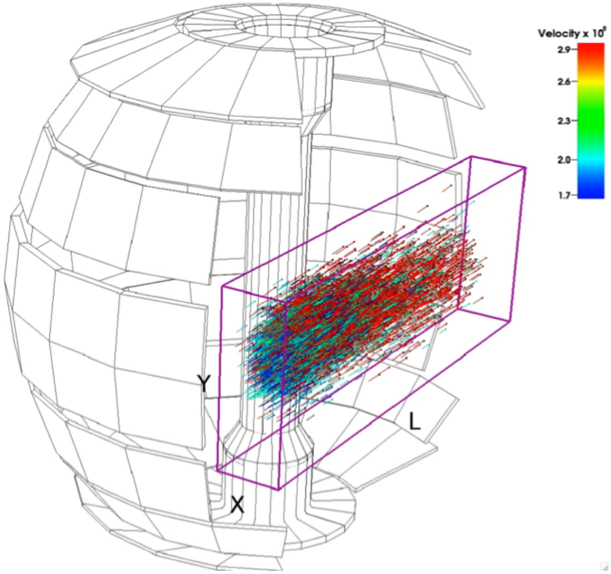
- **Active cooling** is needed at Bay L and Bay B to protect detectors during bake-out
- **Shutter** is needed to protect detectors during glow discharges and lithium dropping

W. Heidbrink, D. Liu (UCI)

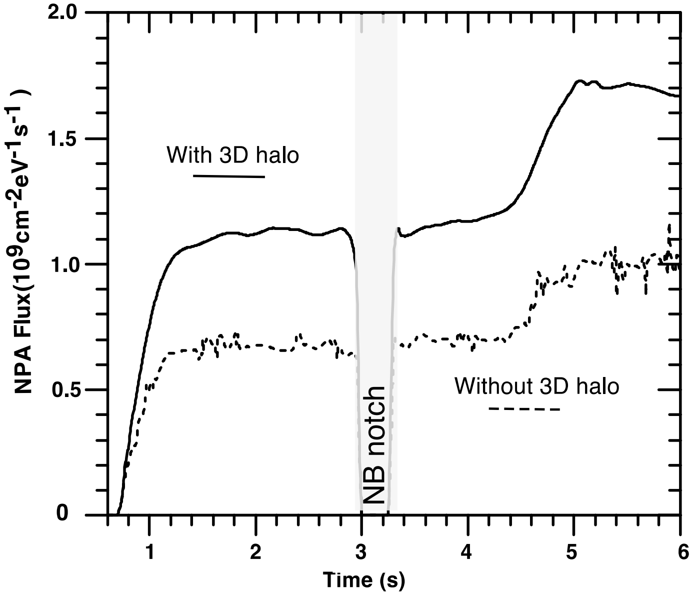
New 3D "halo" model in TRANSP enables more accurate interpretation and simulations of charge-exchange-based diagnostics

- "Halo" neutral density can be of same order as NB neutral density
  - Affect quantitative analysis of NPA, FIDA
- "Beam-in-a-box" model encompasses both NB and halo neutrals
  - 3D geometry around NB paths
  - Provides localized halos, contrary to previous model used by TRANSP
- Simulations of E//B NPA signal show importance of 3D halos
  - Total neutrals increase by ~80%
  - Emissivity increases by similar amount
- Model validated against FIDAsim code

> *Broader validation effort is ongoing*
  - *e.g., effects of different cross-section libraries on NB deposition, charge-exchange reactions*



"Beam-in-box" model for the TRANSP 3D halo neutral code.



S. Medley, 2014

Comparison of the charge exchange neutral flux time evolution for the EIIB NPA sightline with and without 3D halo neutrals.