NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
Fusion Energy Sciences

NSTX-U Energetic Particle Research

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for the NSTX-U Team

NSTX-U PAC-39
PPPL, Princeton University
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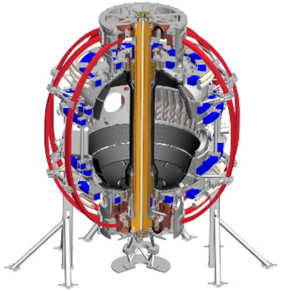
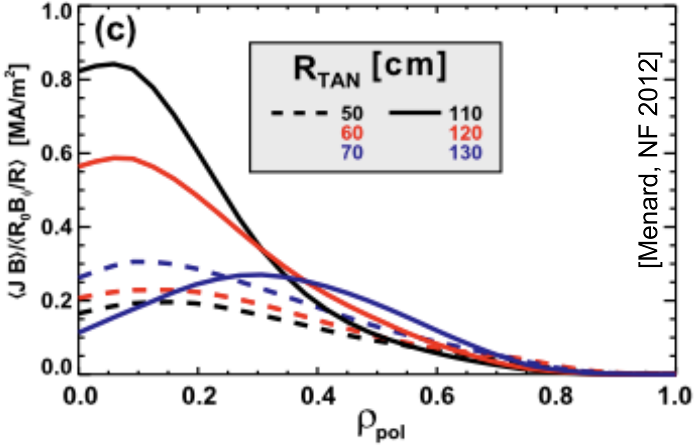
PPPL

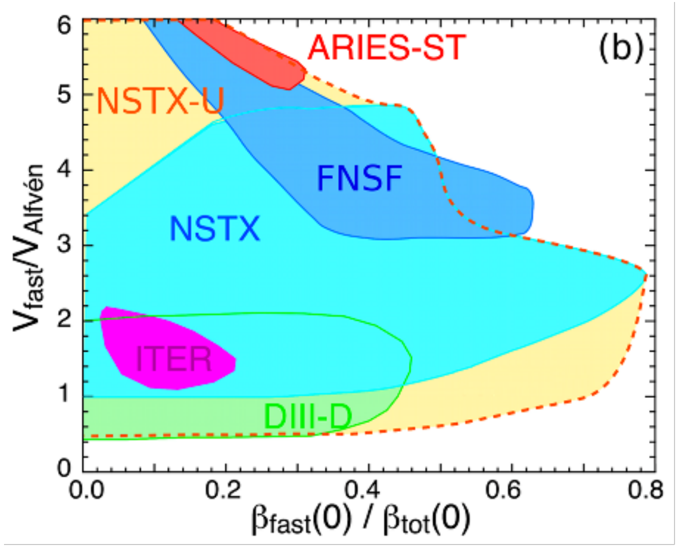


NSTX-U capabilities & operating regimes provide excellent environment to advance Energetic Particle research

- Long pulses >> τ_r, flexible NB injection & shaping (& RF), good diagnostic
  - Enable detailed EP studies towards high/fully NI scenarios *Battaglia's talk*



[Menard, NF 2012]



- Broad range of achievable β_{fast}/β_{tot} and $v_{fast}/v_{Alfvén}$
  - Overlap with conv. R/a regimes, ITER/FNSF
  - Unique capability of parameter scans for new physics, model validation
    - *Already demonstrated from NSTX-U run in FY-16*

Outline

- EP-TSG research highlights
- Near-term goals & NSTX-U operations
- Summary

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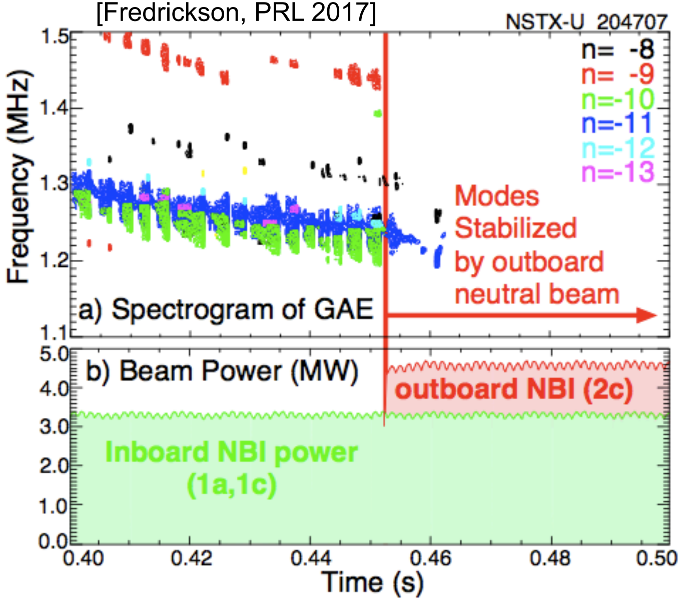
FY-16 results and near term goals (FY18-19) provide improved tools for re-start of NSTX-U operations

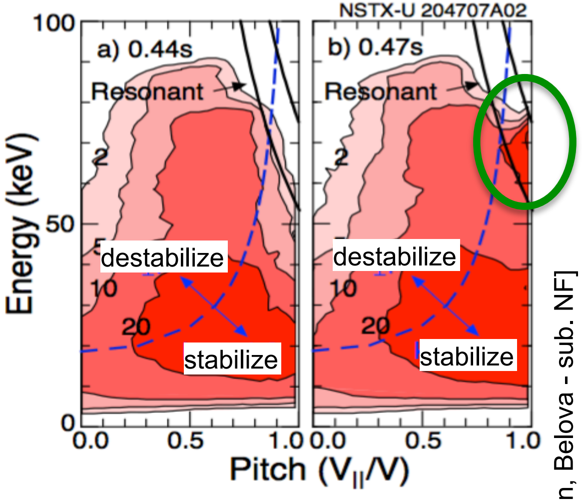
[Fredrickson, PRL 2017]

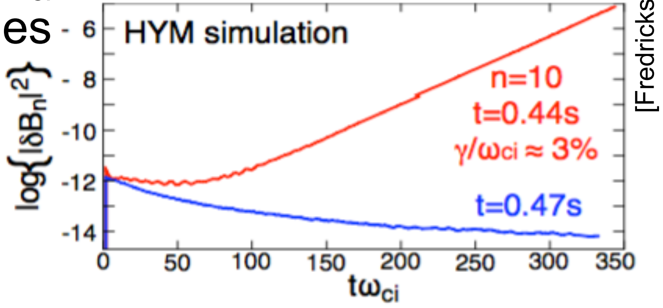


~1MW from 2nd NBI efficiently stabilizes GAEs

NUBEAM + analytic theory [Gorelenkov, NF 2003] reveal role of stabilizing particles from 2nd NBI

Results confirmed by HYM code, unique tool for $\omega_{AE} \sim \omega_{ci}$ instabilities





[Fredrickson, Belova - sub. NF]

- *Leverage partnership with theory (PPPL, SciDAC-EP)*
- *Indicates path for AE control through tailored NBI + other actuators (RF, 3D fields)*

backup: stabilization of cntr-TAEs

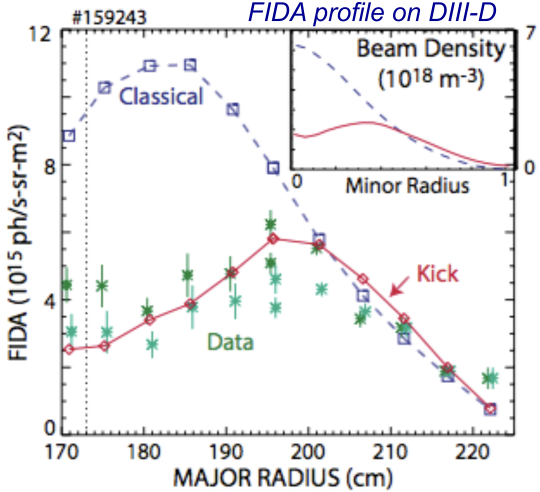
see Perkin's talk

charge 1

Challenging NSTX-U regimes indicate path for integration between experiments, analysis & modeling

- NSTX-U, DIII-D, UCI: *Phase space resolved models required for improved understanding of EP transport*
  - "Kick", Resonance-broadened Quasi-linear (RBQ1D) reduced models (NSTX-U/PPPL) implemented in TRANSP
  - Use of TRANSP puts EP physics in broader context for comprehensive "whole discharge optimization"
    - Critical for cross-TSG research (T&T, Macro, Scenarios), projections

Measured vs predicted FIDA profile on DIII-D



[Heidbrink, PoP 2017]

- New insight applied to NSTX-U to achieve control of AE instabilities, performance optimization
  - Set of tools available to close the loop experiment/modeling/predictions
    - Magnetics + AE antenna, flexible NBI, 3D-fields, RF
    - Modeling: TRANSP + reduced models, NOVA-K, HYM, FIDASim
  - Collaborations strengthen experimental research & modeling efforts

see Kaye's talk

Outline

- EP-TSG research highlights
- Near-term goals & NSTX-U operations
- Summary

FY18-19 research targets urgent issues for EP physics in preparation for NSTX-U ops in FY-20

- Notable Outcome FY-17 (with I&T): “Modeling **EP losses** due to AEs using Resonance-broadened Quasi-Linear (RBQ1D) model”
- JRT-18: “Test **predictive models of fast ion transport** by multiple Alfvén eigenmodes”
  - Coordinated by NSTX-U
  - Main candidate models (*kick*, RBQ-1D from PPPL) being validated on NSTX/NSTX-U and DIII-D
  - Initial results indicate importance of phase-space resolution for quantitative predictions
- Milestone R18-4: “Optimize **EP distribution** function **for improved plasma performance**”
  - Demonstrated AE suppression, mitigation by tailored NBI on NSTX-U
  - Also exploring EP distribution optimization for improved ramp-up scenarios
- Milestone R19-4: “Effects of **NBI parameters** on EP distribution & **NB-CD**”
  - Leverage FY-16 NSTX-U results, extend FY-18 modeling work in TRANSP
  - Will combine AE suppression/mitigation with scenario optimization across NSTX-U program

> *Work being extended through collaborations with DIII-D, MAST-U, AUG, JET et al.*

see Kaye’s talk

NSTX-U operations will provide critical data, challenge validity of codes/theory towards burning plasmas

- Experiments will target AE/EP physics vs properties of fast ion distribution function
  - Supported/enabled by new capabilities, e.g. AE antenna
  - Required to develop AE control strategies based on available actuators
- Extended range of achievable B_t & I_p enables investigation of expected AE regimes
  - E.g. bursting/chirping vs stationary TAEs -> critical for predicting EP transport levels
  - Critical to advance predictions for alphas in burning plasmas (including large ρ_L and orbit width)
- Small R/a, high β_{fast} lead to multi-mode scenarios relevant for burning plasmas
  - Coupling among different types of modes -> highly non-linear regimes

- *Unique NSTX-U regimes lead to identify missing physics for more reliable predictive capabilities & projections*

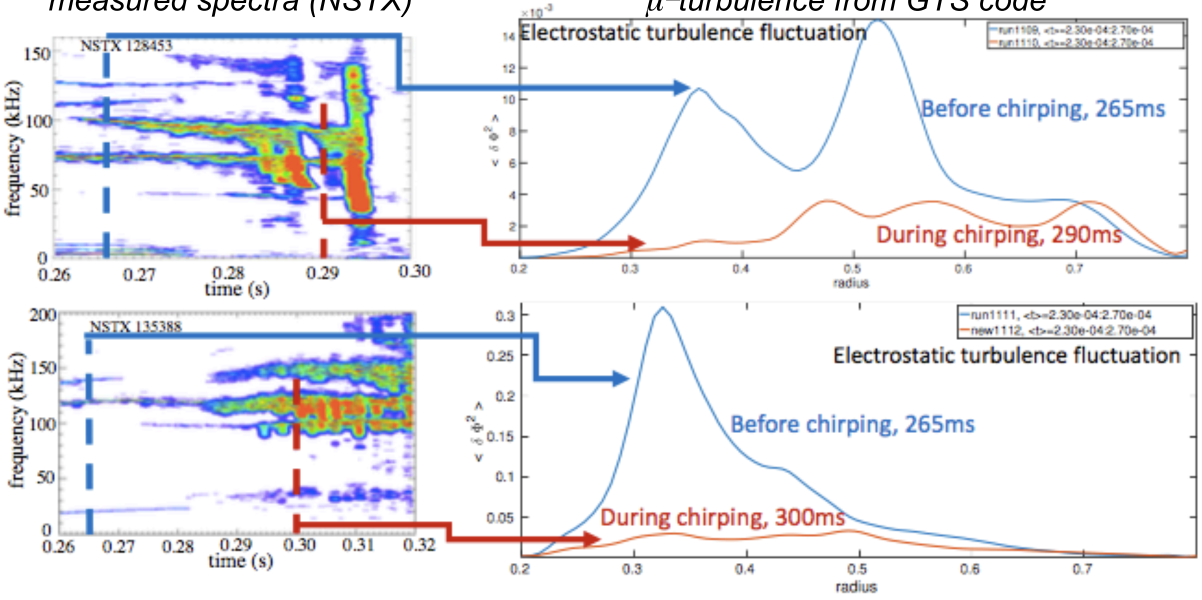
charge 3

Partnership with theory has led to unravel key physics to predict AE regimes in future devices (ITER, FNSF)

- Understand physics of “bursting/chirping” vs quasi-stationary TAEs
  – Common on STs, uncommon on conventional R/a devices
  > Developed predictive theory; tested/validated on NSTX, TFTR, DIII-D

measured spectra (NSTX)

μ–turbulence from GTS code



– Theory indicates key role of microturbulence

– Competition between:

  - Drag: maintain coherence of phase space structures, favors formation of hole/clump pairs
  - Microturbulence: destroys coherence, prevent chirping

> *Chirping onset observed at decreased μ-turbulence levels*

[Duarte, sub. NF 2017]

EP research is integral part of *Core Science* mission for NSTX-U & beyond

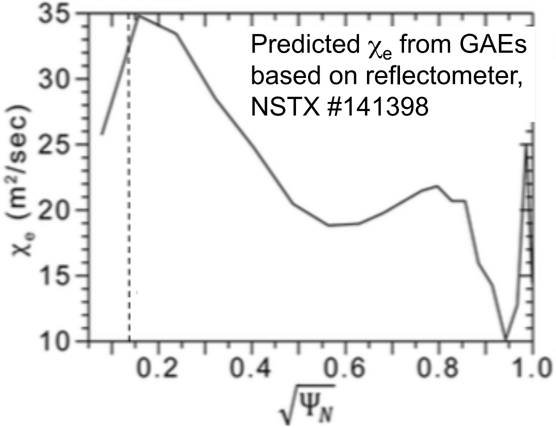
Goal: Demonstrate high performance, high/fully non-inductive scenarios at high β

Challenges: address role of EP & thermal transport by AEs and other instabilities to optimize tokamak plasma scenarios

- AEs
  - Develop & integrate EP transport module(s) in TRANSP
  - Understand thermal electron transport by GAE/CAEs

see Guttenfelder's talk

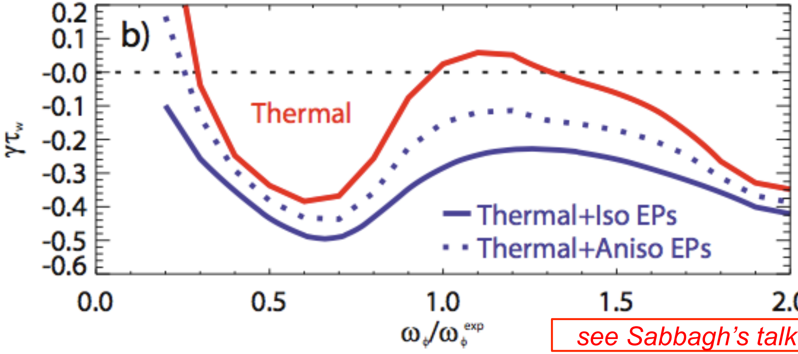
- Other MHD:
  - Assess role of EPs, NB torque in RWM stability (cf .JRT-15)
  - Contribute to comprehensive NTM model in TRANSP
  - Develop improved Sawtooth models in TRANSP



Predicted χ_e from GAEs based on reflectometer, NSTX #141398

[Crocker– UCLA]

RWM stability including EP kinetic effects



[Berkery, PoP 2010]

see Sabbagh's talk

Summary

- EP research on NSTX/NSTX-U is addressing critical issues for burning plasmas
  - Understand stability of EP-driven modes & associated EP transport
  - Inform on modeling, development of control tools for their suppression/mitigation
  - Develop knowledge for *integrated tokamak simulations* across multiple topics

- Near term plans focus on characterizing the effects of complex fast ion distributions
  - Develop predictive capabilities across devices/scenarios for reliable projections

- Restart of NSTX-U operations will enable access to unique operating space
  - Move towards high/fully NI operations
  - Supports model development & validation
  - Leverage strong partnership with theory/codes developers at PPPL and abroad

> *NSTX-U offers unique capabilities & complementarity with other devices*

  - *Unique operating regimes at high β_{fast}, super-Alfvénic ions mimicking alphas in burning regimes*
  - *Excellent platform to inform on, develop & validate models/theory for ITER & beyond*

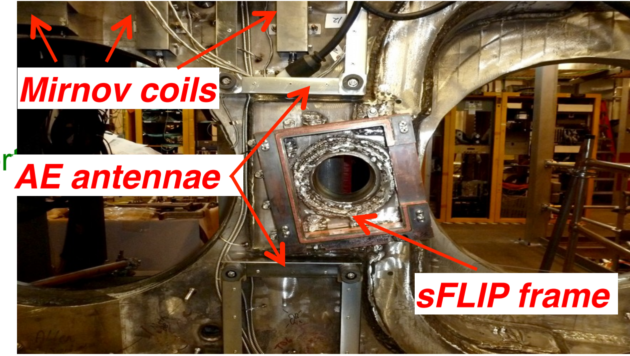
Backup

EP research in high-β plasmas with super-Alfvénic ions addresses critical issues for *burning* plasmas

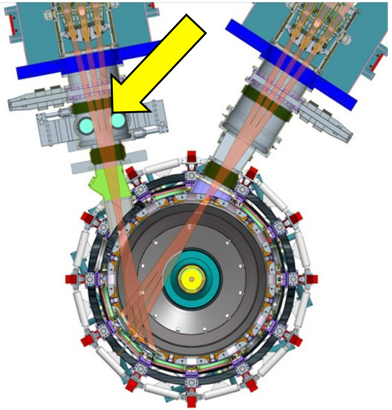
- Investigate drive & damping mechanisms for EP-driven modes
- Study EP transport, inform model development for integrated tokamak modeling
  - Strong partnership with theory at PPPL and abroad (cf. SciDAC-EP)
  - Complement Core Science research (macro-stability, kink/fishbones, thermal transport by AEs)
- Assess NB-CD efficiency, degradation by instabilities
  - Coordinating ITPA EP-8 Joint Experiment on NB-CD

see Guttenfelder & Sabbagh's talks

Mirnovs, AE antenna – mode stability
FIDA, NPAs, sFLIP – fast ions



- Provide alternative scenarios wrt conventional R/a devices
  - Challenge model validation & projections to future devices (ITER, FNSF, DEMO)



> *Integrate EP physics with plasma scenarios*

> *Develop tools for mitigation/suppression (<u>control</u>) of EP-driven instabilities*

Unique NSTX-U capabilities complement other devices for rapid progress in EP physics through collaborative work

- Understand physics of "bursting/chirping" vs quasi-stationary TAEs
  - *See next slide*

- Observed GAE suppression, counter-TAEs w/ OA-NBCD
  - > Analysis reveals key ingredients for AE destabilization
    - Super- vs sub-Alfvenic ions (NSTX-U vs DIII-D), competition in phase space gradients
  - Additional tool to investigate thermal transport by AEs *see Guttenfelder's talk*

- Development/validation of reduced EP transport models
  - Being extended to several classes of instabilities (marco-stability, kink/fishbone, sawtooth)
    - Connects to Macro, Scenarios TSG work *see Battaglia, Sabbagh's talks*
  - Collaboration with several devices (DIII-D, MAST-U, TCV + other ITPA-EP participating facilities)

- Characterize NBI+RF synergy (restart of plasma ops)
  - Important to understand RF-driven TAEs (JET, AUG, …, ITER and RF-heated ST-FNSF)
  - Validate models (under development for TRANSP) -> export to JET DT, ITER

Goals & Plans for year 1-5 (1)

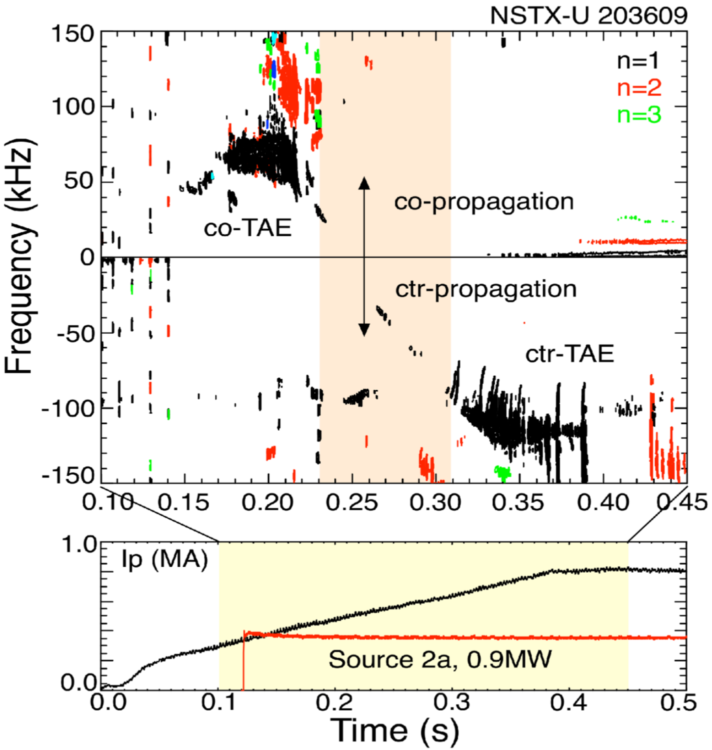
- Extend characterization of fast ion distribution with 2nd NB line beyond FY-16
  - Use FIDA, ssNPA, sFLIP to measure fast ion profile and losses
  - Compare with classical predictions from TRANSP
- Assess effects of broadened pressure, NB-CD profile on plasma stability/ performance
  - Compare with time-dependent simulations
  - Investigate effects on *AE stability
    - Characterize mode structure with reflectometers, BES
    - Characterize damping rate through *AE antenna (TAEs, RSAEs)
    - Compare with linear/nonlinear codes
- Characterize scenarios with combined NBI+HHFW
  - Assess RF power deposition on fast ions as a function of RF injected spectrum, power

Goals & Plans for year 1-5 (2)

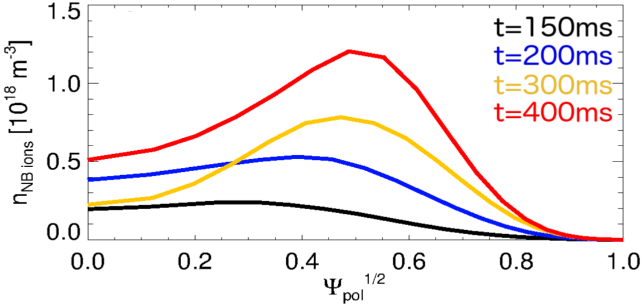
- Extend *AE studies to nonlinear, multi-mode regimes
- Study GAE/CAE effects on electron thermal transport at higher B_t and current
  - Joint task with T&T-TSG
  - Validate codes for GAE/CAE modes
- Contribute to non-inductive ramp-up research
  - Study *AE stability in low-I_p flat-top plasmas prototypical of ramp-up conditions
- Extend validation of reduced models for EP transport by MHD (*AEs, low-f kink-like modes)
  - Validate Critical Gradient & “kick” models for broad range of *AE activity, NB injection parameters

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

Counter-TAEs can be destabilized by off-axis co-NB injection from 2nd NB line

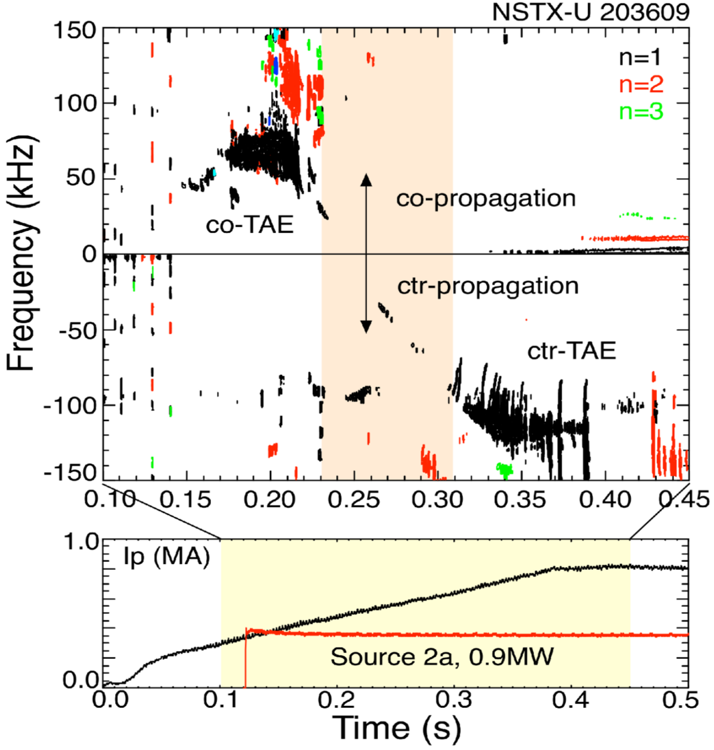


- Single NB source from 2nd NBI
- Low power, P_{NB}~1MW



- Off-axis NBI results in broad/hollow NB ion density profile
- A transition is observed from co-TAEs only to cntr-TAEs

Details of fast ion distribution explain destabilization of *counter*-TAEs by co-NBI



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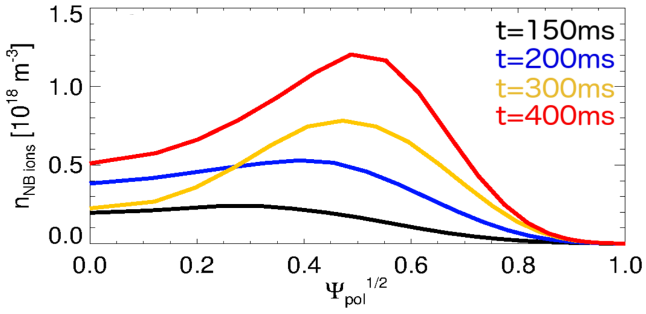
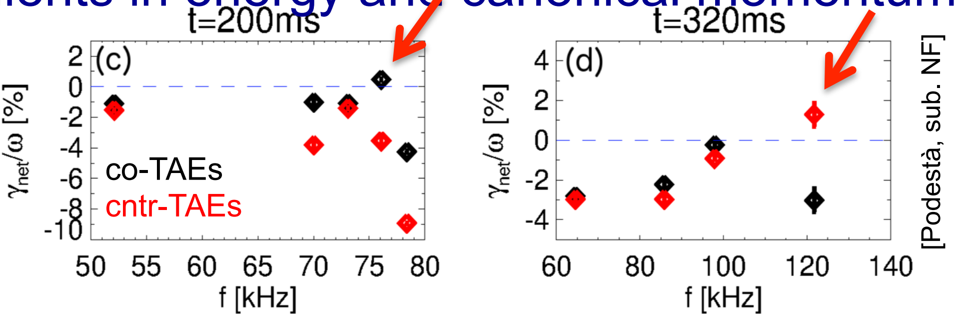
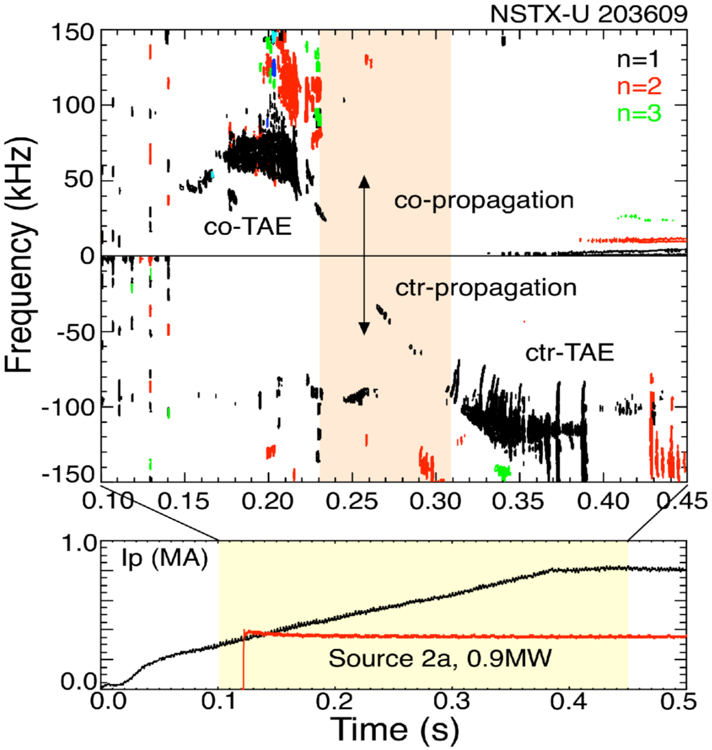


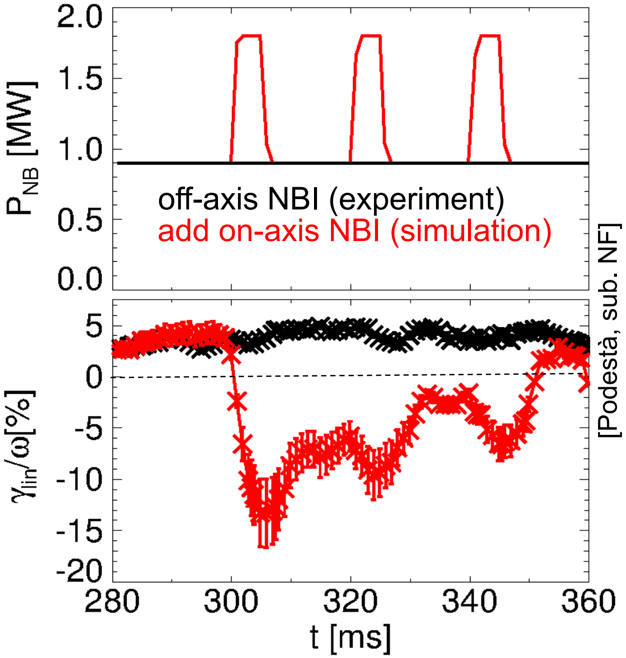
- Stability analysis with TRANSP + kick model recovers observations
- Drive results from competition between gradients in energy and canonical momentum



Understanding drive mechanisms leads to develop control strategies via NBI

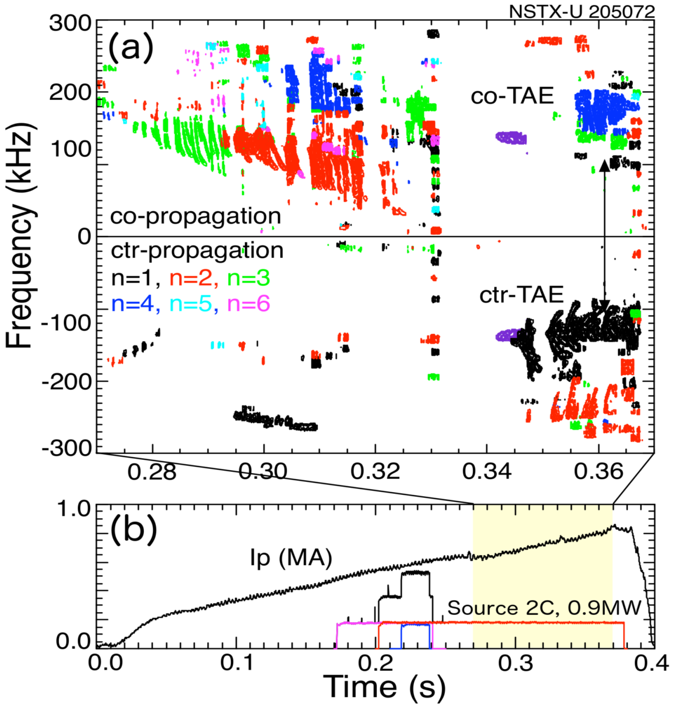


- TRANSP: add 5ms *blips* from more perpendicular, on-axis NBI
- On-axis NBI populates *stabilizing* phase space region
- Enough to suppress cntr-TAEs
  - Minimum perturbation to original scenario
  - > ***To be tested on NSTX-U***

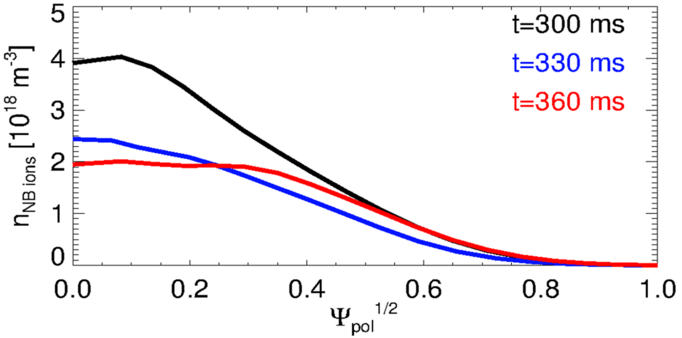


Counter-TAEs are *not* simply destabilized by inversion in radial EP density gradient

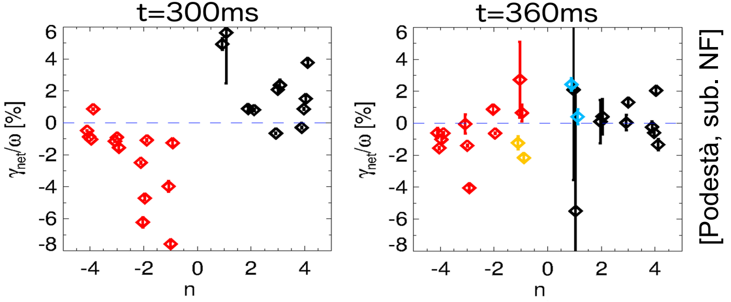
- NSTX-U with 2nd NBI only
- P_{NB}~1MW, tangential injection



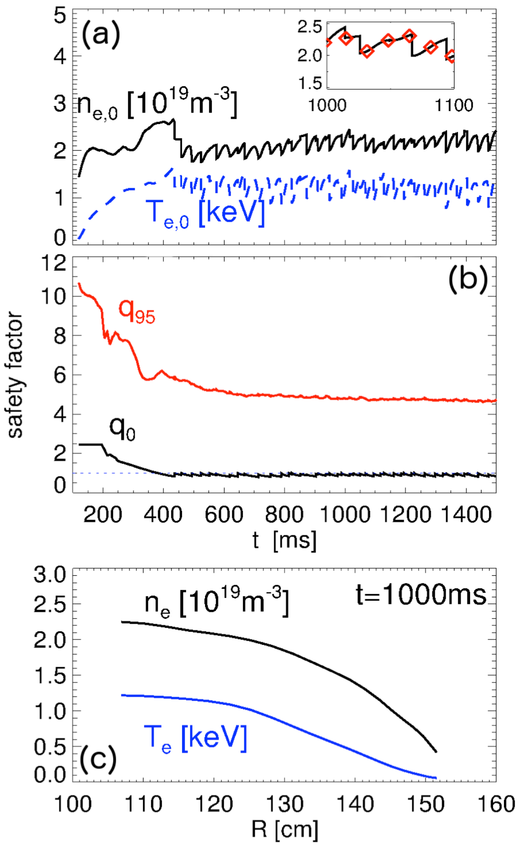
- EP density (TRANSP) remains flat/ monotonic in this case



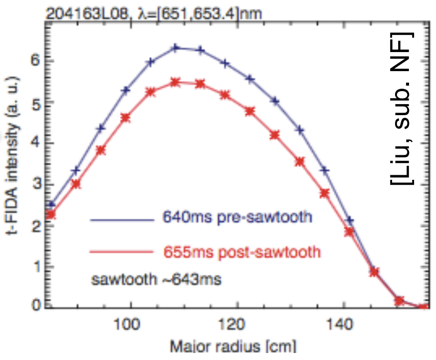
- Stability analysis (TRANSP + kick model) recovers transition in unstable mode spectrum



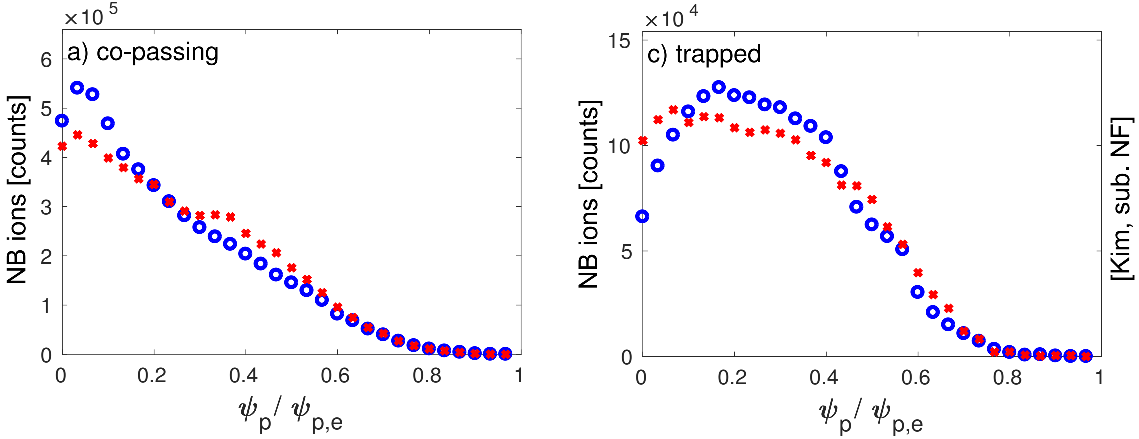
Sawtoothing L-mode scenarios used to test EP transport models in TRANSP



- 2sec long sawtoothing L-mode scenarios enabled by new centerstack
- Fast ion redistribution observed on FIDA
  - Not recovered through TRANSP modeling
- ORBIT analysis shows redistribution

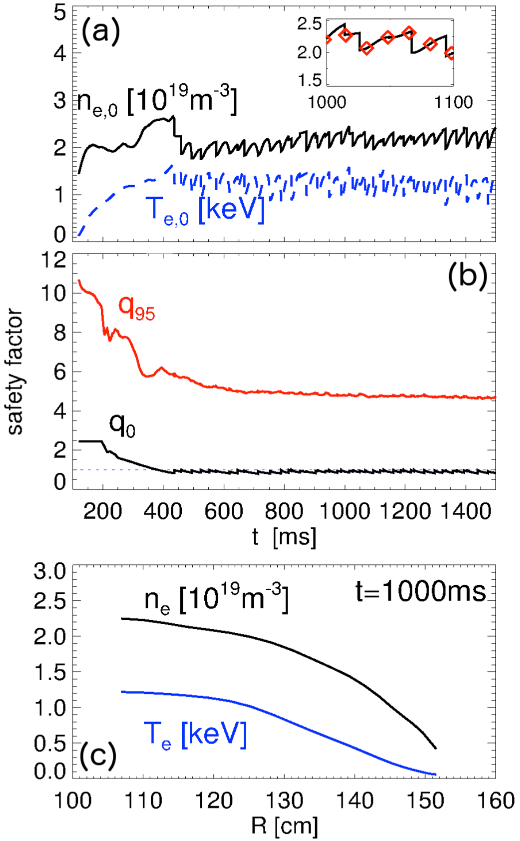


[Liu, sub. NF]



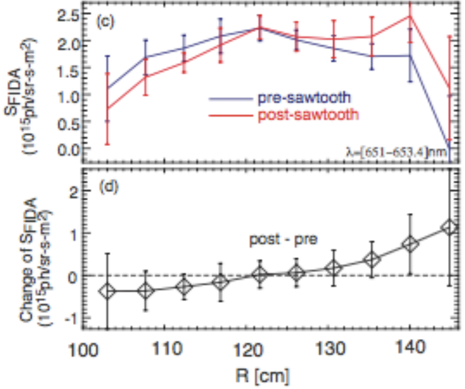
[Kim, sub. NF]

ORBIT modeling provides insight for development of improved models



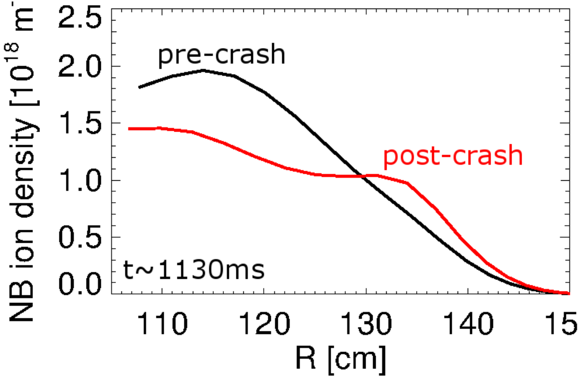
- 2sec long sawtoothing L-mode scenarios enabled by new centerstack
- Fast ion redistribution observed on FIDA
  - Not recovered through TRANSP modeling
- ORBIT analysis shows redistribution
  - Using *kick model* to export ORBIT methodology to TRANSP
  - Initial tests look promising: consistent with FIDA data
  - *But: many uncertainties on input thermal plasma evolution*

tangential FIDA



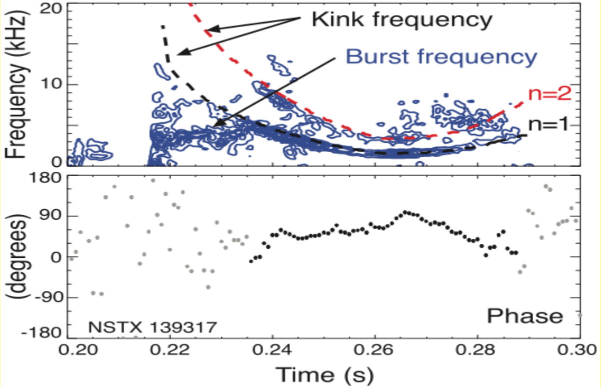
[Liu, sub. NF]

TRANSP + kick model



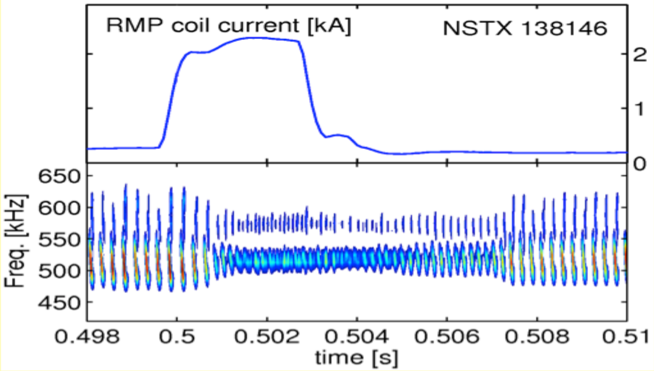
[Kim, sub. NF]

Synergy between different perturbations



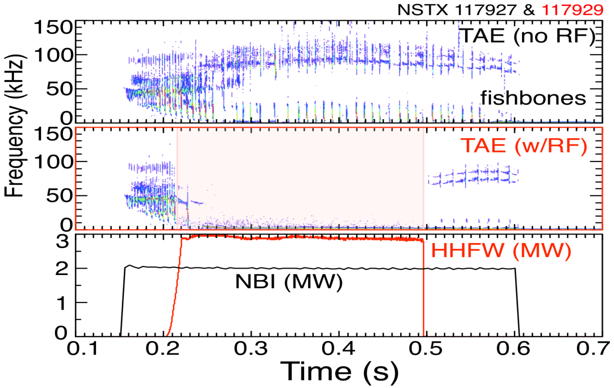
- Dynamics of bursting CAE modes modified by coupling to kinks
  - Predator-prey dynamics
- AE burst frequency locks on kink
- Suggests modulation of AE stability by *low-f* perturbation

E. D. Fredrickson, PoP 2013



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

Bortolon, PRL 2013; Kramer, PPCF2016

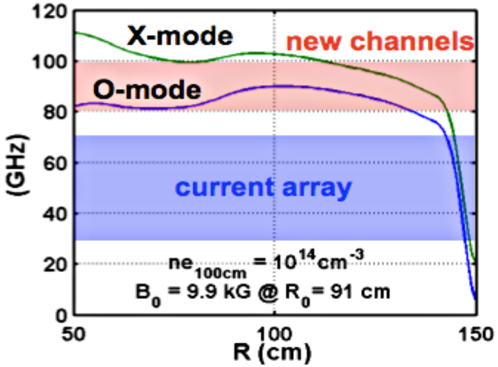


- AEs suppressed by >2MW of RF power
  - Examples of stable AEs destabilized by RF are observed, too
- Dependence on RF spectrum, NBI parameters under investigation

E. D. Fredrickson

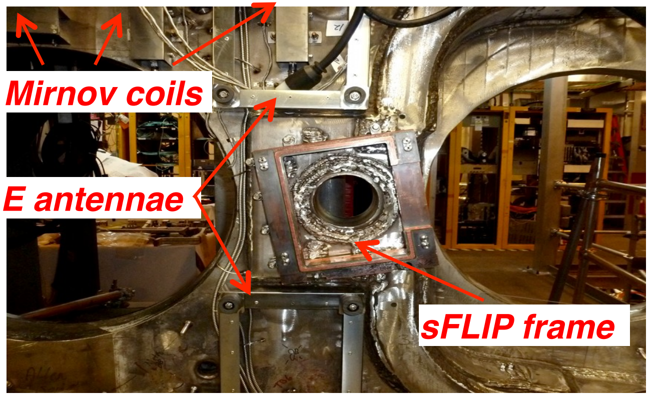
Main EP diagnostics

Reflectometer (UCLA) – mode structure

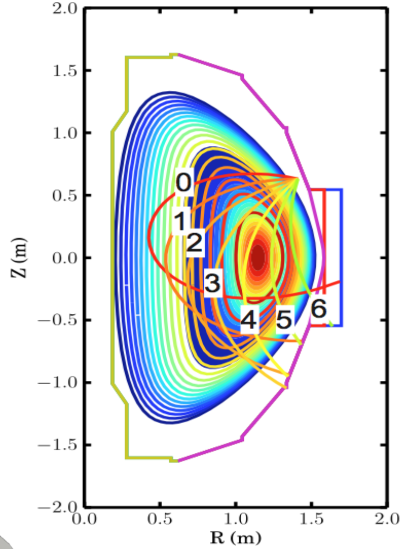


***AE antenna – mode stability**

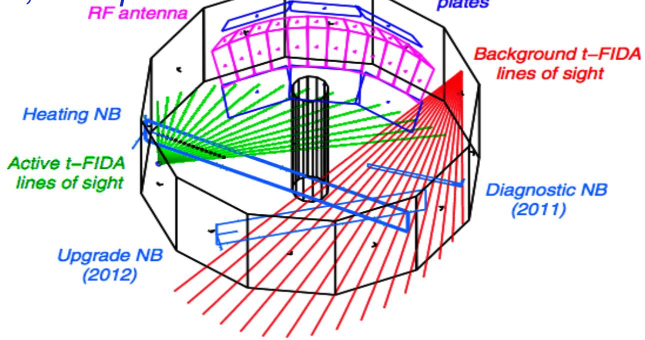
sFLIP – fast ion losses



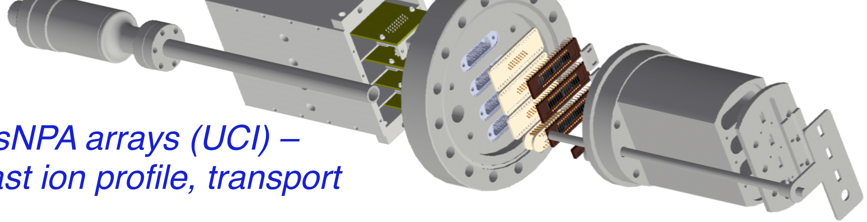
Fusion product array (FIU) – fast ion profile, transport



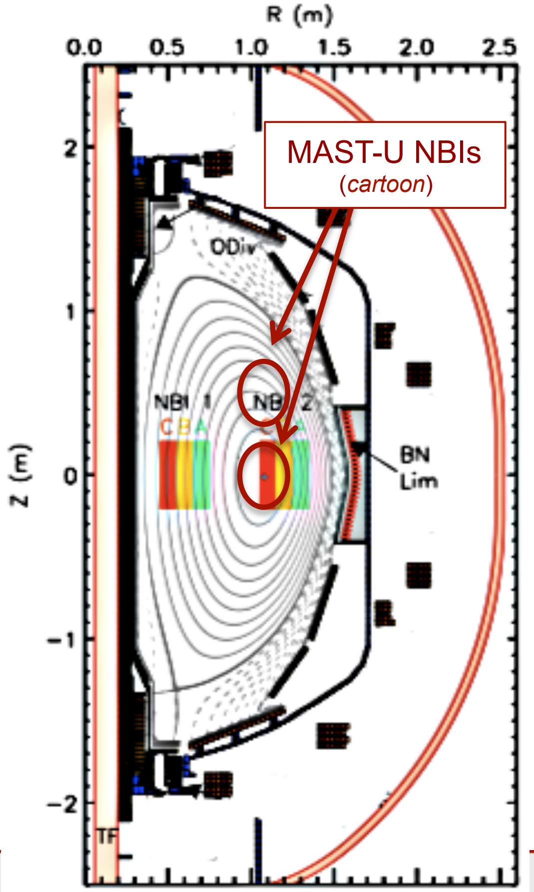
FIDA systems (UCI) – fast ion profile, transport



ssNPA arrays (UCI) – fast ion profile, transport



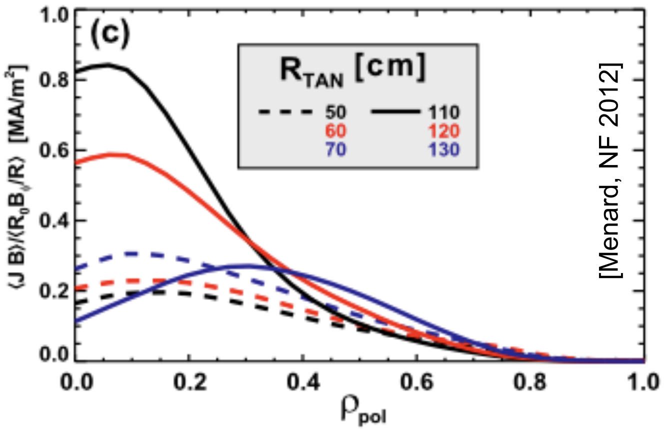
NSTX-U capabilities extend parameter range & flexibility achievable by other devices



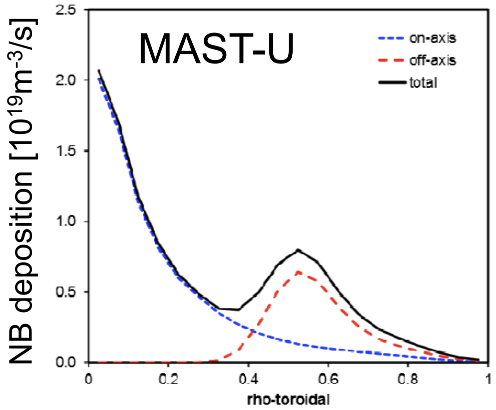
MAST-U NBIs
(cartoon)

- Flexible, independent NBI & shaping
  - Enable fine adjustment of deposition & NB-CD profile
- Broad E_{inj} range, 40-95 keV
  - Control range of achievable v_{fast}/v_{Alfven} and β_{fast}/β_{tot}
- All 6 NB sources available from Day
  - Coditioning achieved at end of FY16
- Main tool for q-profile, rotation control
  - Complement NTV from 3D coils
- Envisioned as tool for AE control
  - Enhanced by sensors such as Mirnov coils and AE antenna

see Battaglia, Sabbagh's talks



[Menard, NF 2012]



Recent publications

- MEDLEY S. et al, Implementation of a 3D halo neutral model in the TRANSP code and application to projected NSTX-U plasmas, PLASMA PHYS. AND CONT FUSION **58** 025007 (2016)
- PODESTA M. et al, Phase space effects on fast ion distribution function modeling in tokamaks, PHYS. PLASMAS **23** 056106 (2016)
- HEIDBRINK W. et al, Analysis of fast-ion Dα data from the National Spherical Torus Experiment, NUCL. FUSION **56** 056005 (2016)
- KRAMER GJ et al, Mitigation of Alfvenic activity by 3D magnetic perturbations on NSTX, PLASMA PHYS. CONT FUSION **58** 085003 (2016)
- LIU D et al, Compact and multi-view ssNPA arrays on National Spherical Torus Experiment-Upgrade, REV. SCI. INST. **87** 11D803 (2016)
- WHITE R et al, Saturation of Alfven modes in tokamaks, PLASMA PHYS. AND CONT FUSION **58** 115007 (2016)
- PODESTA M. et al, Effects of energetic particle phase space modifications by instabilities on integrated modeling, NUCLEAR FUSION **56** 112005 (2016)
- WANG F. et al, Nonlinear Fishbone Dynamics in Spherical Tokamaks, NUCLEAR FUSION **57** 016034 (2017)
- SMITH HM and Fredrickson E., CAEs in rotating spherical tokamak plasmas, PLASMA PHYS. CONTROLLED FUSION **59** 035007 (2017)
- DUARTE V. et al., Prediction of nonlinear evolution character of EP-driven instabilities, NUCLEAR FUSION **57** 054001 (2017)
- FREDRICKSON E. et al., Suppression of Alfvén modes through additional beam heating, PHYS. REV. LETT. **118** 265001 (2017)
- PODESTA M. et al, Computation of Alfvén Eigenmode stability and saturation through a reduced fast ion transport model in the TRANSP tokamak transport code, PLASMA PHYS. CONTROLLED FUSION **59** 095006 (2017)
- DUARTE V. et al., Theory and observation of the onset of nonlinear structures due to eigenmode destabilization by fast ions in tokamaks, PHYS. PLASMAS **24** 122508 (2017)
- LESTZ JB et al, Energetic-particle-modified global Alfven eigenmodes, Submitted to PHYS. PLASMAS (2017)
- HAO G, et al, On the scattering correction of fast-ion D-alpha signal on NSTX-U, Submitted to REV. SCI. INST. (2017)
- HAO G. et al, Measurement of the passive fast-ion D-alpha emission on the NSTX-U tokamak,Submitted to PLASMA PHYS. CONTROLLED FUSION (2017)
- PODESTA M. et al, Destabilization of counter-propagating Alfvenic instabilities by off-axis, co-current NBI, Submitted to NUCL. FUSION (2017)
- CROCKER N. et al, Density perturbation mode structure of high frequency compressional and global Alfven eigenmodes in the National Spherical Torus Experiment using a novel reflectometer analysis technique, Submitted to PLASMA PHYS. CONTROLLED FUSION (2017)