National Spherical Torus eXperiment Upgrade

NSTX-U Research Milestone and Research Activities Update and Plans

NSTX-U PAC-40 – Sept. 11, 2019

D.J. Battaglia
On behalf of the NSTX-U Research Team

PPPL PRINCETON PLASMA PHYSICS LABORATORY
PRINCETON UNIVERSITY

NSTX-U PAC-40 Charge

- The NSTX-U Research Program requests advice from PAC-40 in three areas:
  - Please comment on the quality and importance of recent research results, including collaborative activities, and how they advanced the NSTX-U Mission and Milestones
  - How well the FY20 and 21 Research Milestones **address issues critical to the ST and fusion** as well as the **preparation for operations** of NSTX-U, and the **suitability of expertise and resources** needed to achieve these milestones successfully.
  - The role, uniqueness and importance of NSTX-U in developing a national fusion strategy and to contribute to the design of a next-step tokamak device. In particular, is the proposed R&D program well-positioned to close gaps needed for a compact pilot plant as outlined in the recent NAS and FESAC TEC studies?

NSTX-U Research Milestones address key scientific missions that will be initiated upon restart

- FY19/20 Research Milestones focused on modeling and data analysis
  - At this time, Milestones are led by PPPL scientific staff while ”Research Activities” can be led by NSTX-U collaborators
  - Talk by Ahmed will highlight recent research supporting NSTX-U science program not captured in FY19 Research Milestones and Activities
- FY21/22 Research Milestones target operations on NSTX-U
  - Milestones will benefit from reconstitution of NSTX-U research team
  - Some elements can be performed through collaborations on other devices
- Achievement of Research Milestones will benefit from timely increase in scientific resources
  - Necessary to balance support of Recovery Project with progress on scientific mission

Research Milestones address critical issues in fusion research and prepare for NSTX-U operations

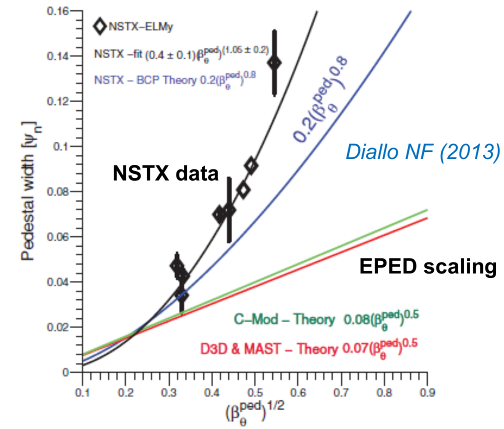
- Understand mechanisms governing the pedestal structure at low-A
- Advance core transport models applicable to high-β and low-$\upsilon*$
- Develop predictive models to understand and optimize fast-ion transport, instabilities and current drive
- Enable low-disruptivity scenarios at high β_{N} and develop tools for disruption avoidance and mitigation
- Develop and optimize the real-time control and scenario capabilities needed to sustain high-non-inductive fraction discharges

Research Milestones address critical issues in fusion research and prepare for NSTX-U operations

- **Understand mechanisms governing the pedestal structure at low-A**
- Advance core transport models applicable to high-β and low-υ^*
- Develop predictive models to understand and optimize fast-ion transport, instabilities and current drive
- Enable low-disruptivity scenarios at high β_N and develop tools for disruption avoidance and mitigation
- Develop and optimize the real-time control and scenario capabilities needed to sustain high-non-inductive fraction discharges

NSTX-U data critical for developing a predictive pedestal model that spans low-A to high-A

- Pedestal width at low-A scales more strongly with β_θ compared to conventional-A
  - Width is enhanced relative to prediction assuming KBM pedestal transport



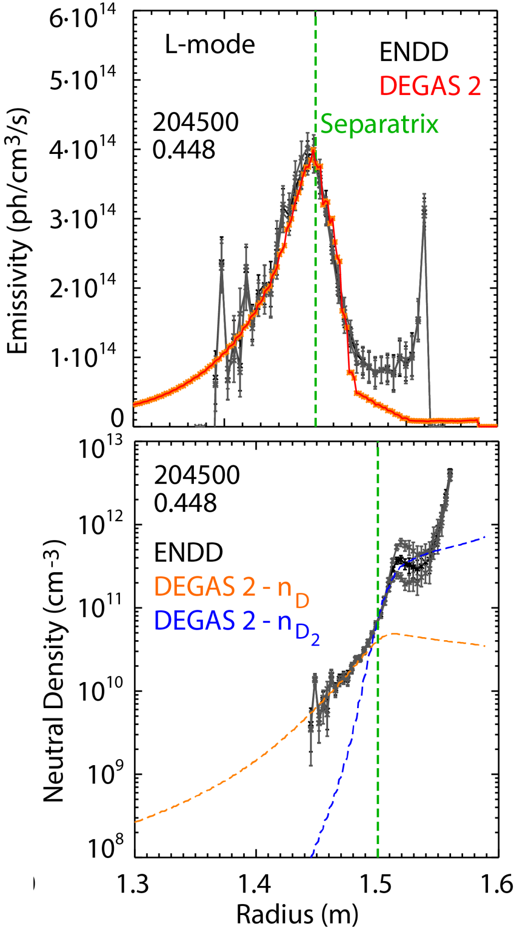
- JRT and milestones advance understanding of pedestal structure at low-A
  - JRT-19: Identify role of fueling in pedestal structure
  - R20-1: Apply gyrokinetic and neoclassical modeling to advance understanding of pedestal transport at low-A
  - R21-1: Characterize pedestal at larger I_p, B_T, A and lower υ^* compared to NSTX
    - Elements of milestone may be deferred to FY22

NSTX-U

JRT19: Understand role of neutral fueling and transport in determining pedestal structure

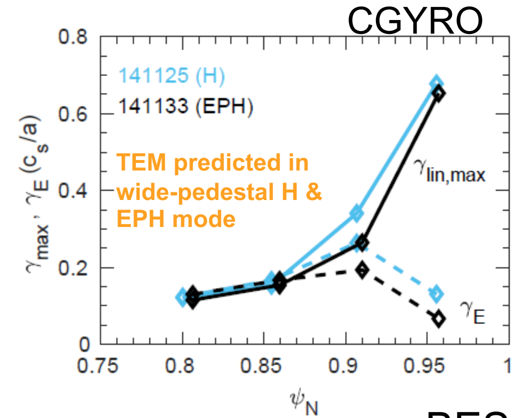
- Neutral density (n_D) measurement developed and validated via neutral transport simulations
  - n_D profile inferred from from ENDD and GPI diagnostics
  - Automated workflow for DEGAS 2 simulations developed to validate inferred n_D profile

- Measurements (ENDD, GPI) and calculations (DEGAS2) support ongoing detailed analysis of particle fueling and transport mechanisms

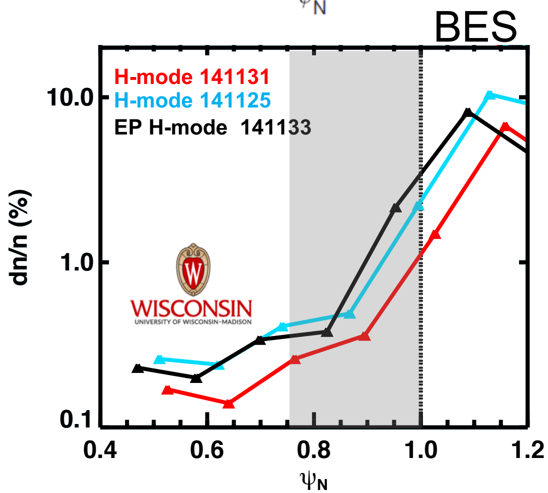


R20-1: Pedestal transport simulation and modeling
R21-1: Characterize pedestal at higher field, lower-ν*

- Extend previous linear gyrokinetic analysis demonstrating TEM and ETG pedestal transport
  - Begin work with non-linear gyrokinetic analysis relevant for the pedestal (CGYRO, XGC1, GS2)
  - Revisit neoclassical analysis of ion dynamics in setting pedestal structure (NEO, XGCa)



- FY21/22-1 milestone: characterize the pedestal structure and instabilities
  - Collaborate with MAST-U in experimental analysis and simulations supporting pedestal structure and transport research
  - Commissioning profile and turbulence diagnostics on NSTX-U

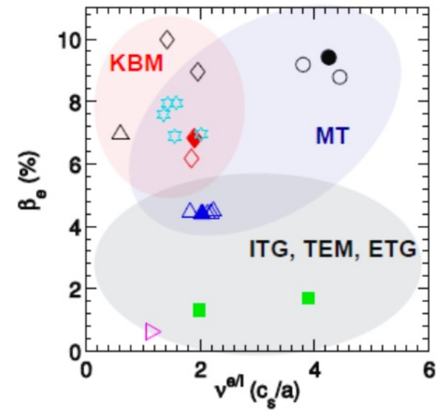


Research Milestones address critical issues in fusion research and prepare for NSTX-U operations

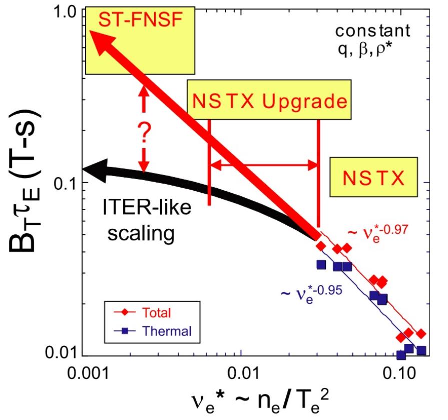
- Understand mechanisms governing the pedestal structure at low-A
- **Advance core transport models applicable to high-β and low-υ***
- Develop predictive models to understand and optimize fast-ion transport, instabilities and current drive
- Enable low-disruptivity scenarios at high β_N and develop tools for disruption avoidance and mitigation
- Develop and optimize the real-time control and scenario capabilities needed to sustain high-non-inductive fraction discharges

NSTX-U critical for characterizing confinement at low-A and high β as ν^* is reduced

- Next-step devices benefit from a predictive transport model valid across range of β, ν
  - NSTX-U accesses E-M turbulence regimes at high-β
- Milestones aim to develop and validate core transport tools for NSTX-U regimes
  - R19-1: Validate transport models for high-β ST H-mode plasmas and assess the importance of multi-scale effects in NSTX-U turbulent transport
  - JRT20: Validation of impurity transport models
  - RA20-1: Global EM simulations at high-β
  - R21-1: Assess H-mode confinement on NSTX-U and/or MAST-U
    - Elements of milestone may be deferred to FY22

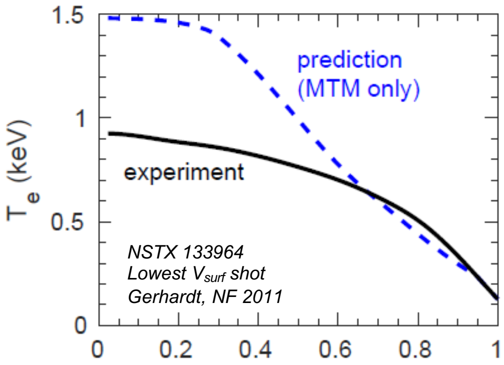


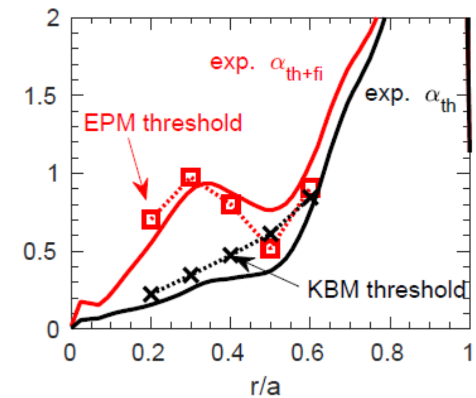
W. Guttenfelder et al., NF 53 (2013)



R19-1: Validate transport models for high-β ST H-mode plasmas; assess importance of multi-scale effects

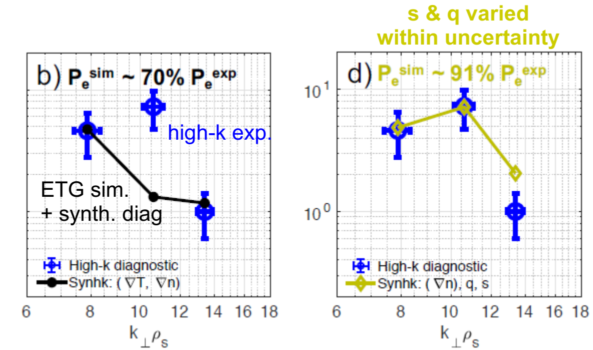
- Linear CGYRO analysis identifies unstable MTM & TEM outside r/a≥0.6 (top of pedestal)
  - Reduced Rafiq MTM model (part of Multi-mode transport model) predicts outer T_e profile
- Central profiles predicted to be very near or above threshold for energetic particle mode (EPM)
  - EPM threshold depends on total pressure (thermal + fast ion) gradient
  - Global, low-n ballooning modes also predicted unstable (M3D-C1)
- Developing hypothesis: central T_e ultimately clamped by pressure limit
  - GAE/CAE modes also postulated to influence core T_e





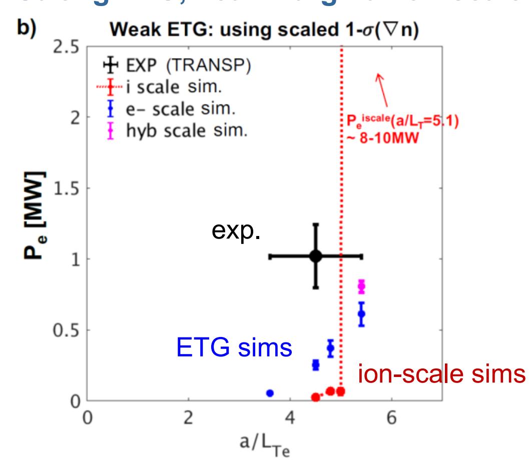
R19-1: Electron-scale (ETG) turbulence can account for anomalous electron loss in lower-β NSTX H-mode

- Comprehensive validation effort suggests e-scale (ETG) accounts for anomalous e-transport
  - Utilized high-k turbulence measurements + novel synthetic diagnostic to constrain simulation results using numerous sensitivity scans
  - Small variation in geometry (s and q) improves match to high-k fluctuation spectra



- Single-scale conditions identified in an NSTX H-mode at intermediate β
  - Similar to multiscale effect found in C-Mod for conditions with strong ETG drive + near-marginal ion-scale stability (Howard, NF 2016)

Strong ETG, near-marginal ion-scale



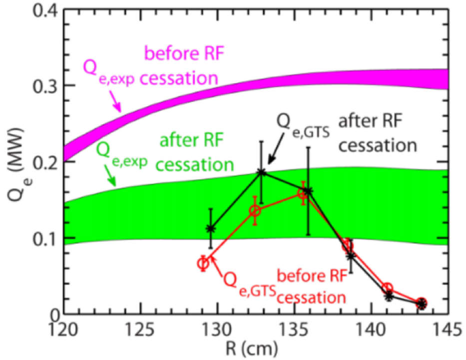
Ruiz-Ruiz, MIT Ph.D. (2019); PPCF (2019, accepted), APS invited (2019)

RA20-2: Global E-M simulations in high-β
R21-1: Assess confinement at higher field, lower-ν*

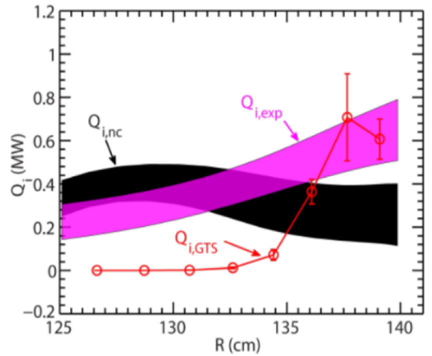
- Benchmark global electromagnetic simulation capability of GTS using high-β NSTX discharges
  - Assess single-n, linear calculations for large range of modes, from low-n (shear Alfven, tearing modes) to drift-wave instabilities (KBM, MTM)
  - Extension to non-linear calculations and/or multiple-n

- FY21/22-1 milestone would characterize core confinement at lower ν*
  - NSTX-U: B_T ~ 0.85 T, I_p ~ 1.4 MA at end of first year of ops: ν^* ~ factor 1.5-3 lower than NSTX

RF-heated NSTX L-mode plasma



NBI-heated NSTX H-mode plasma



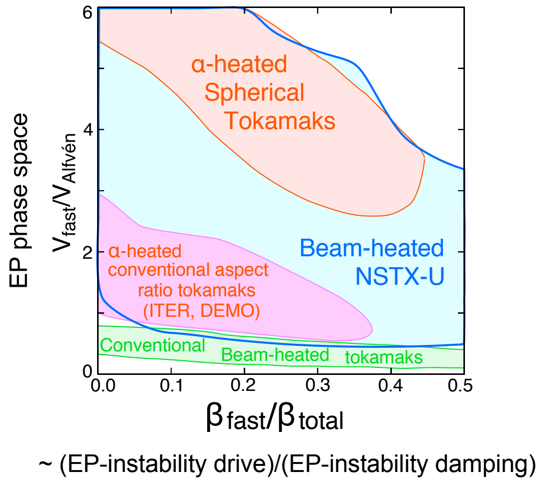
Y. Ren et al., PoP 2015

Research Milestones address critical issues in fusion research and prepare for NSTX-U operations

- Understand mechanisms governing the pedestal structure at low-A
- Advance core transport models applicable to high-β and low-$\upsilon*$
- **Develop predictive models to understand and optimize fast-ion transport, instabilities and current drive**
- Enable low-disruptivity scenarios at high β_N and develop tools for disruption avoidance and mitigation
- Develop and optimize the real-time control and scenario capabilities needed to sustain high-non-inductive fraction discharges

NSTX-U can access unique fast-ion regimes and instabilities that directly inform burning plasma scenarios and optimization

- Explore impact and control of fast-ion heating, current drive and instabilities in burning-plasma regimes
  - NSTX-U has very flexible NBI system for modifying the fast-ion phase space

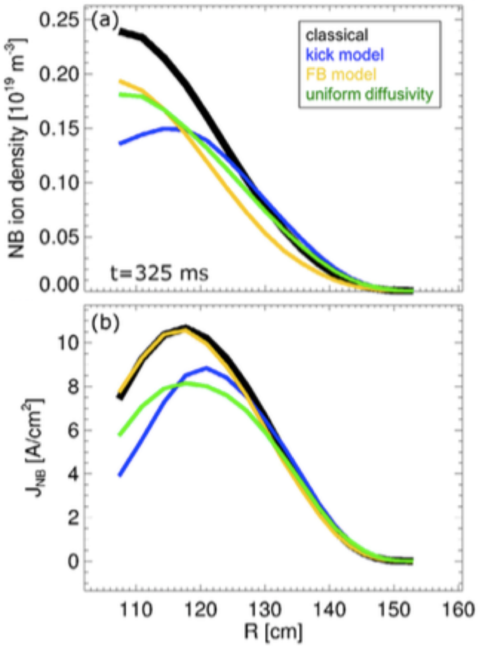


- Milestones aim to develop a validated EP transport models for predictive modeling
  - R19-4: Assess energetic particle transport by sub-TAE instabilities and develop reduced EP transport modeling tools
  - R20-4: Assess the effects of NBI parameters on the fast ion distribution function and NBI driven current profile
  - R21-3: Optimization of NBI mix for AE mitigated scenarios
    - Elements of milestone may be deferred to FY22

R19-4: Assess energetic particle transport by sub-TAE instabilities and develop reduced EP transport modeling tools

- ‘Kick model’ in TRANSP extended from high-f (AE) version to include EP transport by low-f modes
  - NTMs, kinks, fishbones, and sawteeth coexist with AEs
  - Low-f modes: fewer, larger-amplitude resonances with EPs than AEs may lead to non-diffusive transport

    D. Kim et al., NF (2019)
  - Extended kick model validated with NSTX-U data
    - Improves upon ad-hoc models already implemented in TRANSP



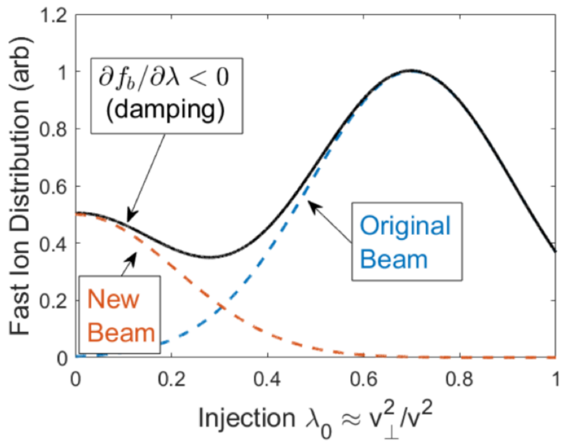
Podestà, NF 2019 (in press)

- Kick model with NTMs applied to DIII-D and NSTX
  - Use Mirnovs and USXR to infer NTM parameters to study impact of NTM on EP transport
  - Presently investigating impact of EPs on NTM trigger and saturation toward comprehensive NTM module in TRANSP

J.-H. Yang, APS-DPP 2019

R20-4: Fast ion distribution and NB current profile vs NBI param.
R21-3: Optimization of NBI mix for AE mitigated scenarios

- Flexible NBI system on NSTX-U offers opportunity to optimize fast-ion distribution
  - Computational (HYM) and analytic models reproduce AE stabilization with tangential beam
  - Models identify regions of stability with regards to NBI parameters



J. Lestz APS invited 2019
E.V. Belova et al., PoP submitted

- Validate models and optimize NBI parameters for stability and current drive
  - Utilize dataset and joint experiments with NSTX(-U), MAST(-U) and DIII-D

- FY21/22 milestone would test optimization from simulations
  - Complete experiments on MAST-U, DIII-D and NSTX-U (if operating)

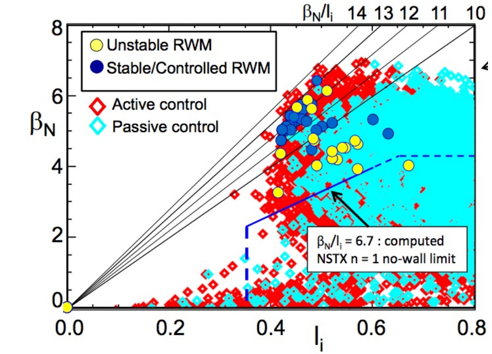
Research Milestones address critical issues in fusion research and prepare for NSTX-U operations

- Understand mechanisms governing the pedestal structure at low-A
- Advance core transport models applicable to high-β and low-υ^*
- Develop predictive models to understand and optimize fast-ion transport, instabilities and current drive
- **Enable low-disruptivity scenarios at high β_N and develop tools for disruption avoidance and mitigation**
- Develop and optimize the real-time control and scenario capabilities needed to sustain high-non-inductive fraction discharges

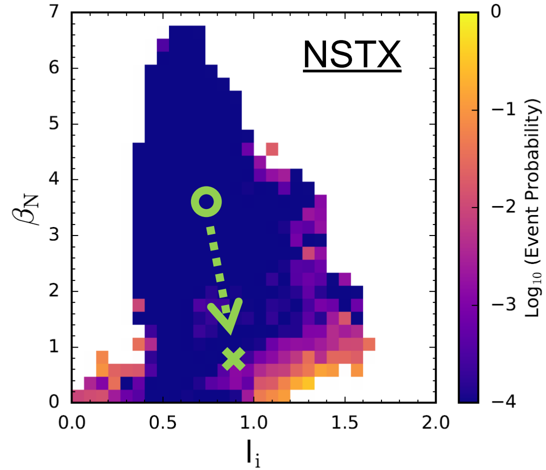
High-performance scenarios on NSTX-U enabled by low-disruptivity at high β_N

- Performance and scientific productivity strongly linked to ability to operate near stability boundaries with minimal disruptions

- Research Milestones and Activities
  - R19-3: Validate tearing mode physics for tearing avoidance in high-performance scenarios
  - RA19-1: Expand disruption prediction and avoidance capability for tokamaks
  - R20-3: Integrated disruption modeling for NSTX-U
  - RA20-1: Application of expanded disruption prediction and avoidance capability for NSTX-U
  - R21-4: Multi-mode correction of error fields in NSTX-U and tokamaks
    - Elements of milestone may be deferred to FY22



Plasma disruptivity in (l_i,β_N) space

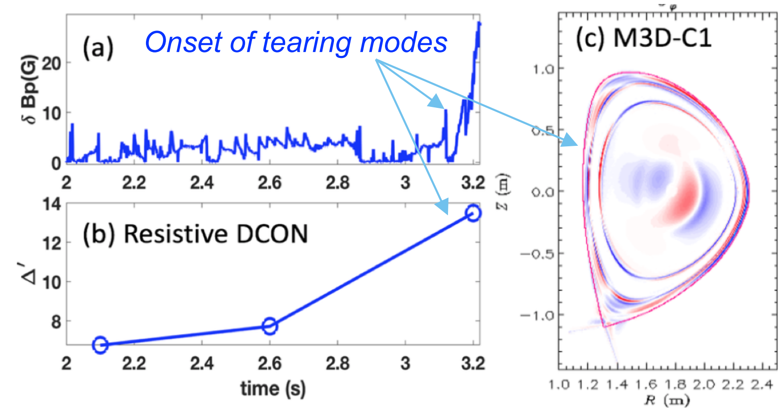


S.A. Sabbagh, APS DPP Invited (2018)

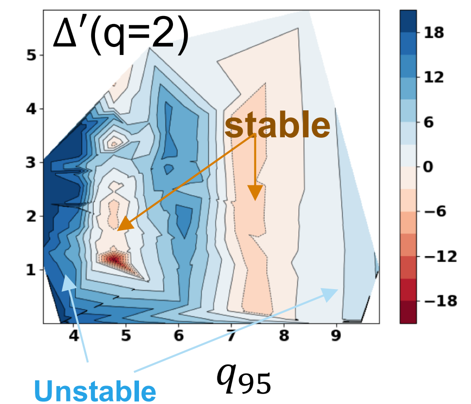
R19-3: Validate tearing mode physics for tearing avoidance in high-performance scenarios

- Full toroidal Δ′ required to predict TM stability in high-β, ST geometry with ‘extreme toroidicity’
- RDCON and STRIDE are reduced models that can calculate toroidal Δ′
  - Verified against full-MHD predictive simulations (M3D-C1) for DIII-D IBS cases
- RDCON used to map out stability space for NSTX-U
  - Being coupled to TRANSP through a reduced NTM model for scenario development
  - Also used for MTF stability calcs. (General Fusion)

Prediction of tearing modes in DIII-D IBS



n=1 Δ′(q=2) *in NSTX-U 2MA, 1T, 12MW scenario*



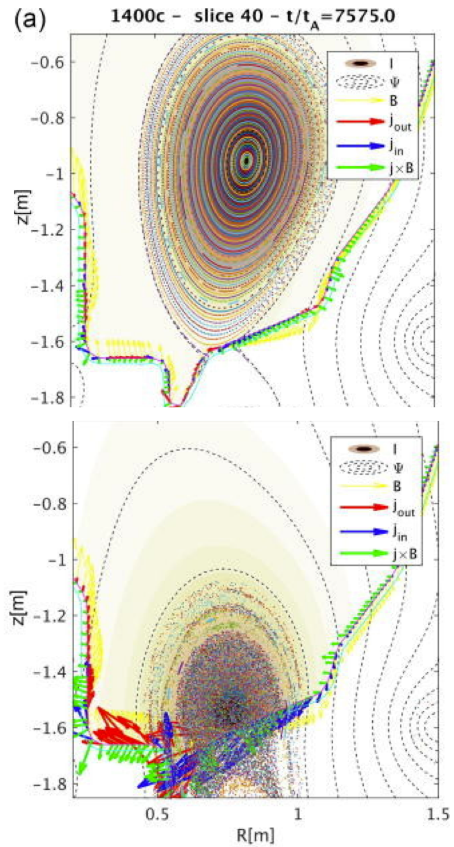
R20-3: Integrated Disruption Modeling for NSTX-U
R21-4: Multi-mode correction of error fields

- Avoidance and mitigation of VDE would benefit from validated high-fidelity integrated modeling
  - Reduce stress and loads of VDE at high-fields
  - Model will integrate realistic resistive walls, impurity ionization, radiation and transport, 3D physics, and runaway electrons

Ferraro, et al. Phys. Plasmas **23**, 056114 (2016),
Ferraro et al Nucl. Fusion **59** 016001 (2019)
Pfefferle et al Phys. Plasmas **25**, 056106 (2018)

- FY21/22: Develop EF mode-locking threshold scalings and correction strategies
  - Plasma response is sensitive function of dynamic nature of error fields
  - Validate island dynamics from simulations by hybrid and extended MHD codes against experiment

Ferraro et al. NF **59** 086021 (2019)



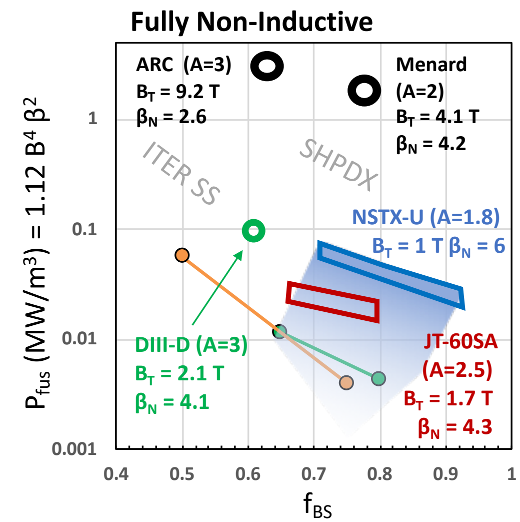
Research Milestones address critical issues in fusion research and prepare for NSTX-U operations

- Understand mechanisms governing the pedestal structure at low-A
- Advance core transport models applicable to high-β and low-$\upsilon*$
- Develop predictive models to understand and optimize fast-ion transport, instabilities and current drive
- Enable low-disruptivity scenarios at high β_{N} and develop tools for disruption avoidance and mitigation
- **Develop and optimize the real-time control and scenario capabilities needed to sustain high-non-inductive fraction discharges**

NSTX-U will demonstrate non-inductive regimes at high β_N and large bootstrap fraction

- Compact Tokamak Fusion Power Plant concepts leverage large f_{BS}
  - NSTX-U has unique capabilities for demonstrating high f_{BS} at high β_N

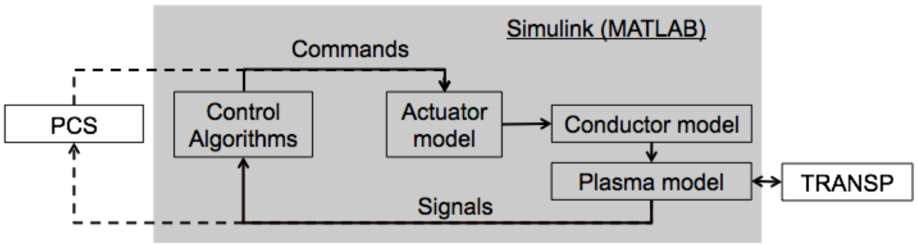
- Milestones will accelerate progress toward non-inductive operation
  - R19-2: Develop optimized ramp-up scenarios in STs
  - R20-2: Scenario optimization algorithm development base on reduced models
  - R21-2: Commission operational tools that enable high-performance discharges on NSTX-U
    - Elements of milestone may be deferred to FY22

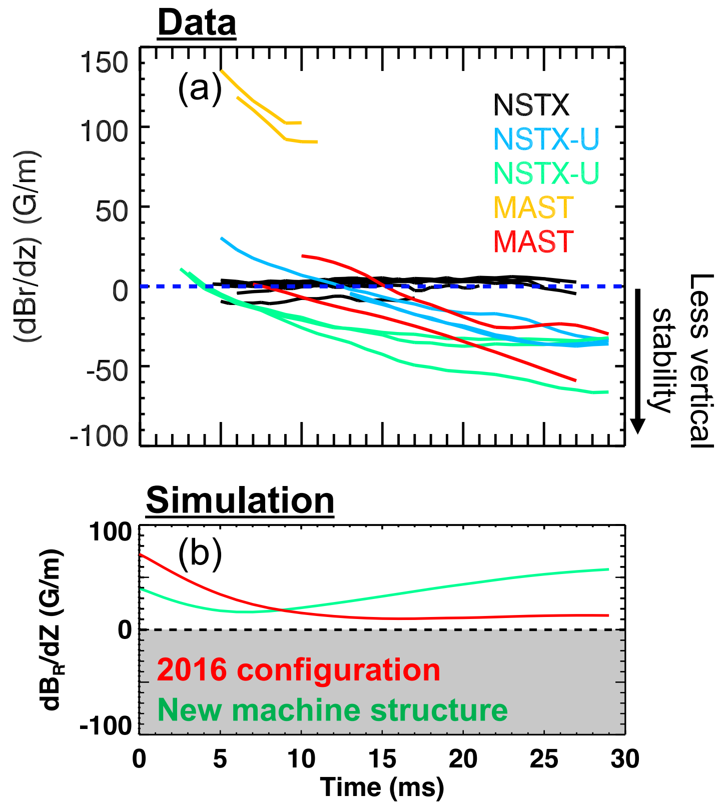


R19-2: Develop optimized ramp-up scenarios in spherical tokamaks

- Simulation framework developed over FY18-19
  - Reduced models include development of neural net models for fast ions, kinetic profile shapes, and q-profile

Vail et al., PPCF 2019
Boyer et al., Nuclear Fusion 2019
Ilhan et al., Fus. Eng. Des. 2019





D. Battaglia et al., NF *accepted*

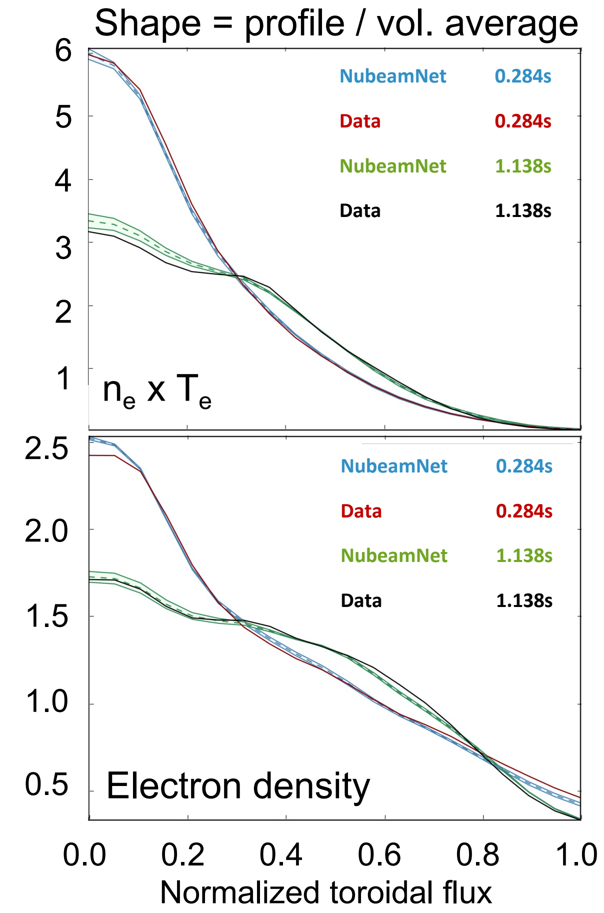
- Milestone work includes development of metrics for a successful startup
  - NSTX-U struggled to achieve passive vertical stability at target I_p ramp rate = 10 MA/s
  - Applied to MAST-U and NSTX-U to optimize startup

R20-2: Scenario optimization using reduced models
R21-2: Commission operational tools

- Reduced models (such as NN models) enable rapid prediction of scenario evolution
  - Apply optimization algorithms to identify actuator trajectories to achieve performance goals
  - TRANSP simulations will be used to test and refine the optimized trajectories
  - Builds off of recent work using optimization algorithms to optimize NSTX-U ramp up

Wehner et al., Fusion Engineering and Design 2019

- FY21/22 Milestone commissions operational tools on NSTX-U and/or supports MAST-U operations
  - Ramp-up optimization, vertical stability at high elongation, RWM feedback, ELM pacing



NSTX-U Research Milestones address key scientific missions that will be initiated upon restart

- The FY19 Research Milestone and Activities address critical issues in fusion research and advances preparations for NSTX-U operations
- The FY20 Research Milestones and Activities build on this progress with efficient use of the resources presently available
- Rebuilding the NSTX-U research team well before operations is essential for preparing for operations and to rapidly advance progress with the FY21/22 milestones during the first physics campaign