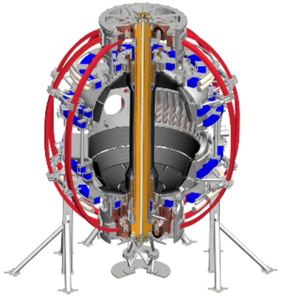
NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
Fusion Energy Sciences

Advanced Scenarios and Control

Devon Battaglia for the NSTX-U team

NSTX-U PAC 39
January 9-10, 2018



Research Thrusts of the Advanced Scenarios and Control Topical Science Group (TSG)

- Demonstrate non-inductive sustainment for multiple τ_R
  - NSTX-U designed to be world-leading in investigating 100% NI scenarios in a low-aspect ratio configuration

- Develop partially inductive scenarios and advanced control to support the broad scientific program

- Advance real-time control and scenario modeling for fusion energy research and next-step devices

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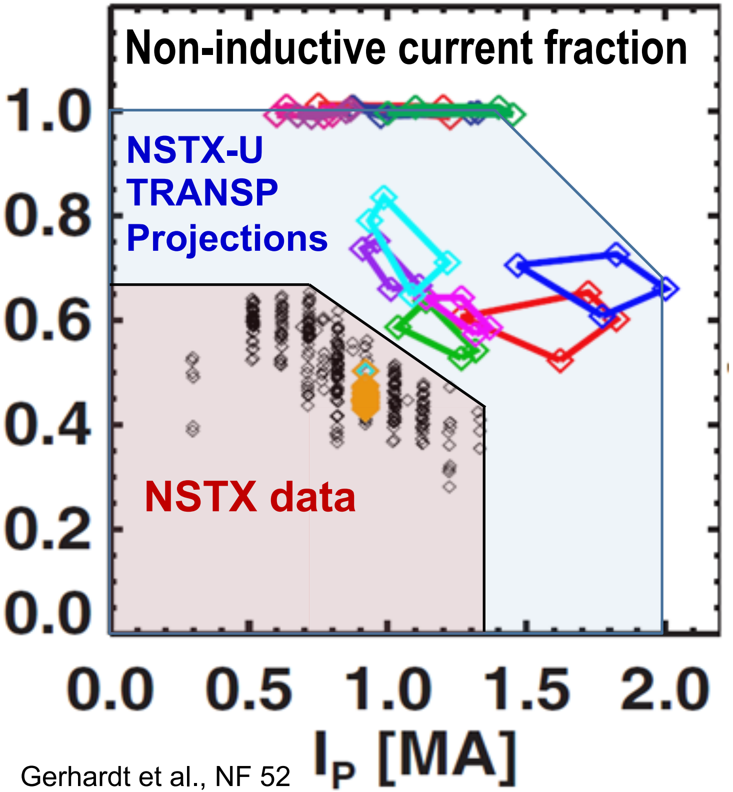
Non-inductive operation on an ST provides crucial information needed to optimize the A of next-step devices

- Non-inductive (NI) current sustainment is required for a continuous tokamak reactor
  - NI operation at low-A will have unique challenges and opportunities
- NSTX-U will have world-leading capabilities for investigating stationary NI scenarios at low-A
  - Largest I_p, B_T NI operation in an ST
  - Real-time control of J, P, v_ϕ profiles



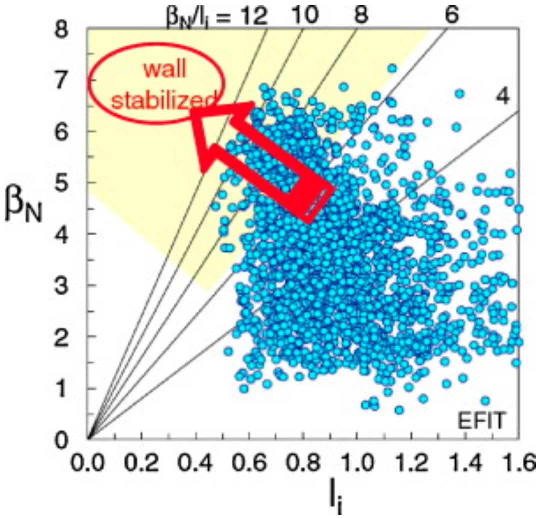
Gerhardt et al., NF 52 (2012) 083020

STs can access a non-inductive (NI) regime with broad pressure and current profiles at high β_N

- Performance of non-inductive scenarios in tokamaks improves with lower q_{cyl}
  - NSTX accesses large β_N/l_i → offset lower q_{cyl} in f_{BS}
  - Broad J (low l_i) aligns with large edge J_{BS} from broad P

$$n\tau T \sim \frac{\beta_N H_{89}}{q_{cyl}^2} B_T^3\, a^3 \kappa^{2.6} f(P,n,\ldots)$$

$$f_{BS} \sim A^{1/2}\left(\frac{\beta_N}{\ell_i}\right)\left(\frac{R_0}{R_M}\right) q_{cyl} \geq 70\%$$



S.A. Sabbagh, NF 46 (2006) 635

- STs achieve naturally large κ, δ

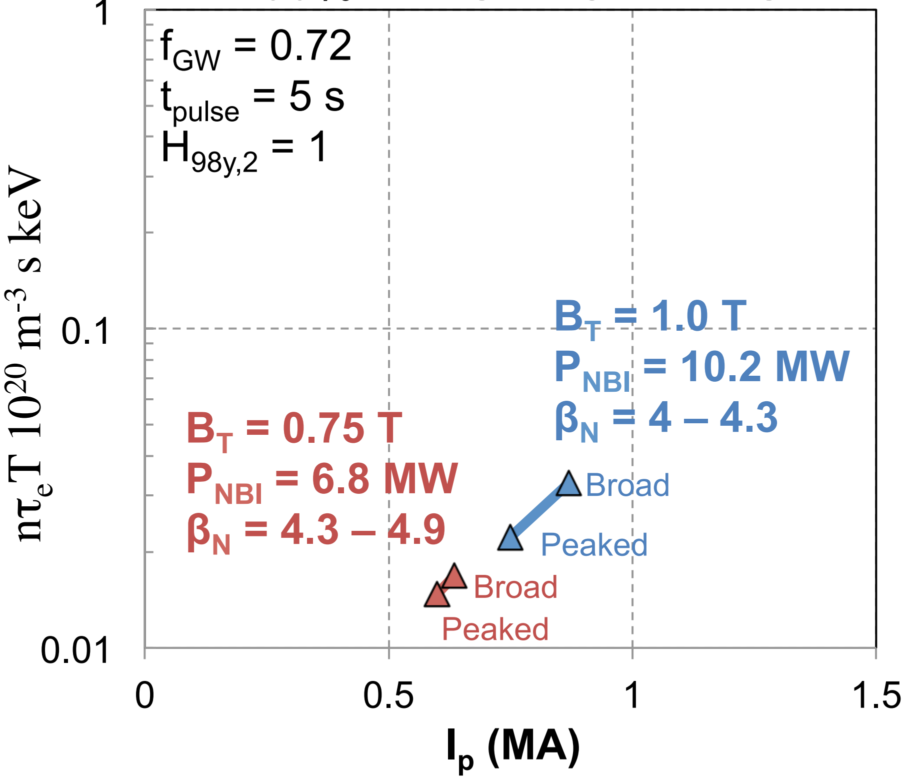
- STs can operate with stability margin at large values of global β_N
  - NSTX-U NI target: β_N ~ 5 - 6, l_i ~ 0.5

Do the potential benefits exceed the challenges of large B_T at low-A?

B_T = 1T operation will enable unique high-performance NI scenarios at high β

- I_p and <nT> of 100% NI increase with B_T
  - β_N limited by q_{min} > 1 at **B_T=0.75T**
  - β_N limited by confinement at **B_T = 1T**

100% NI NSTX-U TRANSP



Adapted from Gerhardt et al., NF 52 (2012) 083020

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- Performance scales with confinement
  - ST scaling projects to larger sustained NI I_p
    - $H_{98y,2} \sim I_p^{1.34} B_T^{0.15} f_{GW}^{.41}$
    - $H_{ST} \sim I_p^{1.01} B_T^{1.08} f_{GW}^{.44}$
  - Differences in performance between scaling relations becomes larger as B_T increases
    - See T&T TSG presentation (Guttenfelder)

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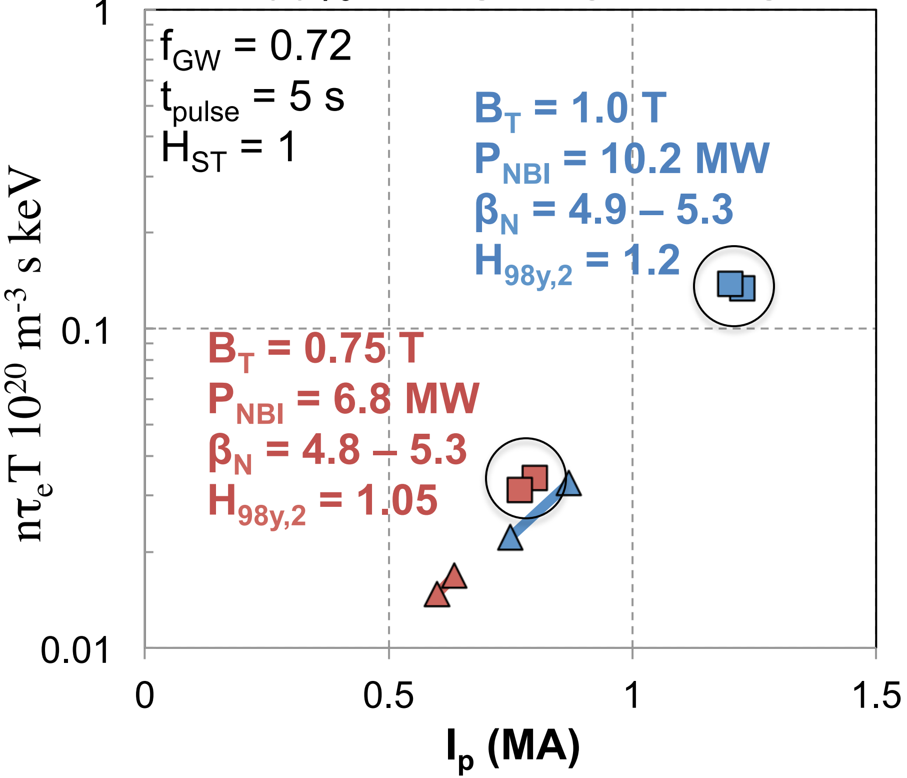

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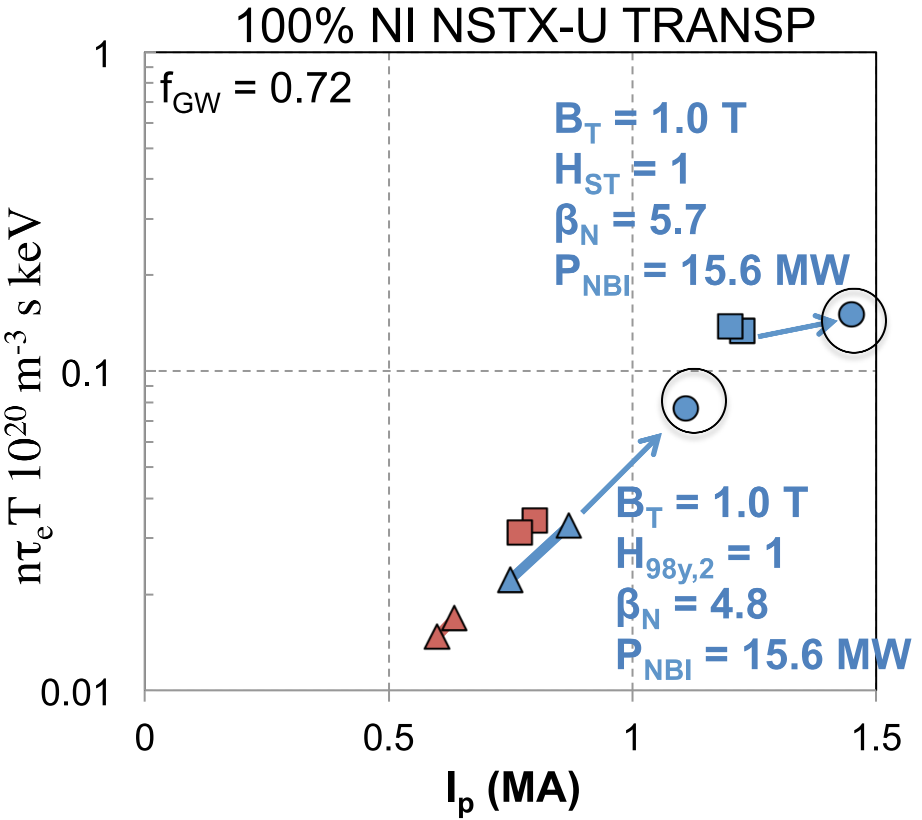
  - Achieve $q_{min} > 1$ with global stability margin at highest P_{NBI} (t_{pulse} = 1.5 s ~ τ_R)



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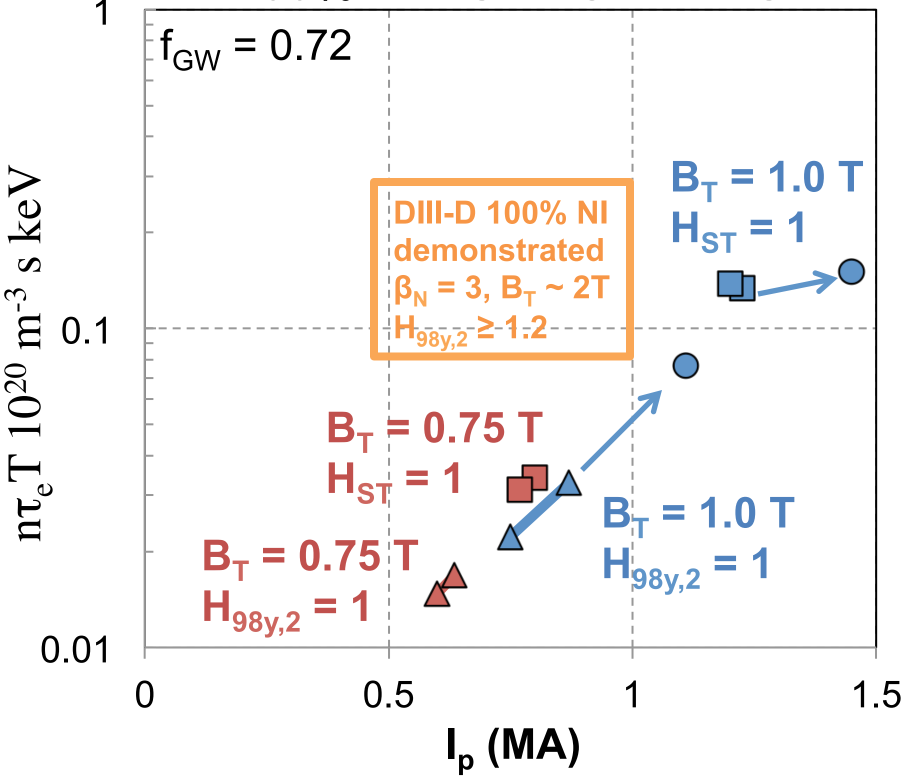
- NSTX-U has potential for demonstrating NI performance similar to A=3 devices

100% NI NSTX-U TRANSP



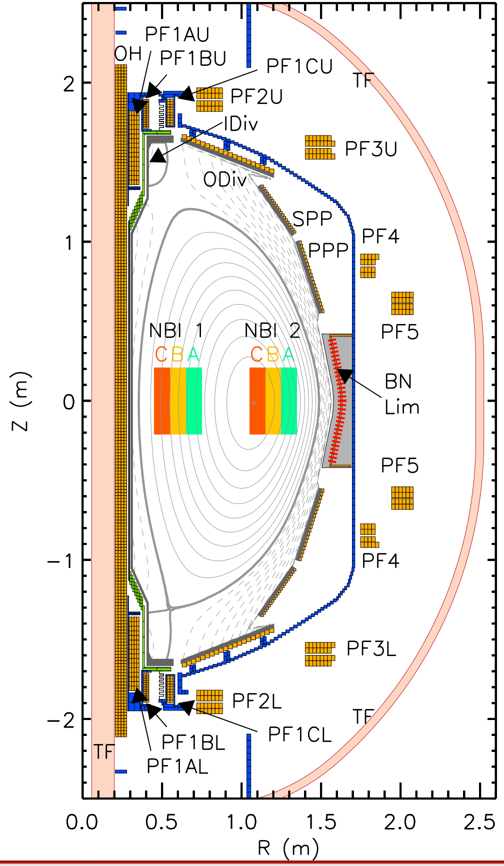
Adapted from Gerhardt et al., NF 52 (2012) 083020

NSTX-U has a suite of real-time control capabilities for optimizing NI scenarios

- Six NBI lines 65 - 100 keV at different R_{tang}

- Real-time profile measurements
  - rtCHERS (RTV): v_ϕ control
  - rtMSE: J and q control (in progress)
  - rtMPTS: P constraint, n_e feedback (in progress)

- Flexible plasma control system (PCS) with parallelized real-time EFIT
  - Profile control algorithms developed and tested via integration with TRANSP
  - Parallelized PCS architecture accelerates rtEFIT solution with profile constraints
    - FY16 run: rtEFIT convergence interval maintained while doubling fitting constraints and resolution



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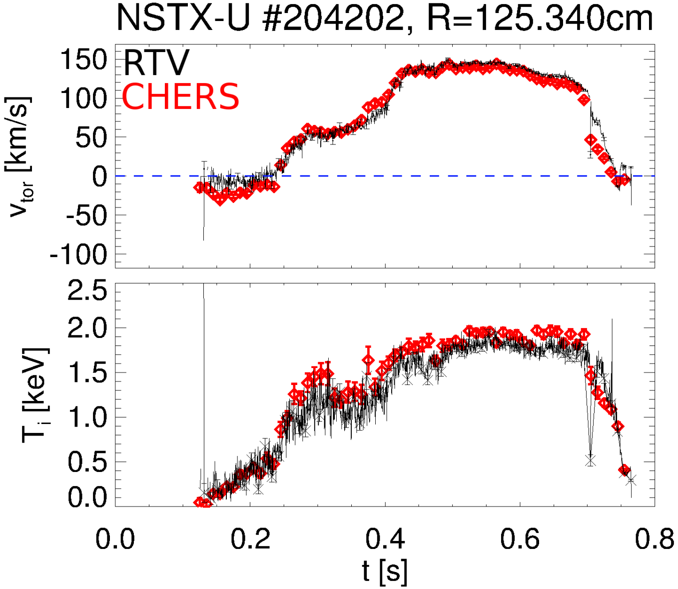
Comparison of real-time CHERS system to standard CHERs



M. Podesta and R.E. Bell, PPCF 58 (2016) 125016

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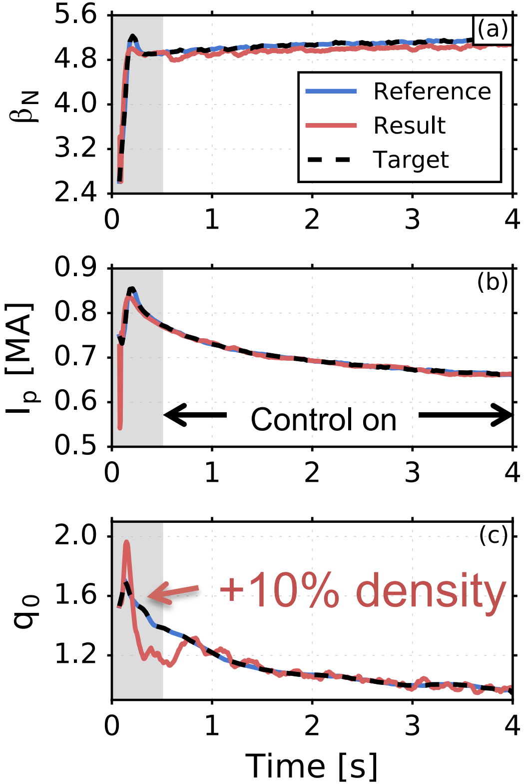
100% NI TRANSP Simulation

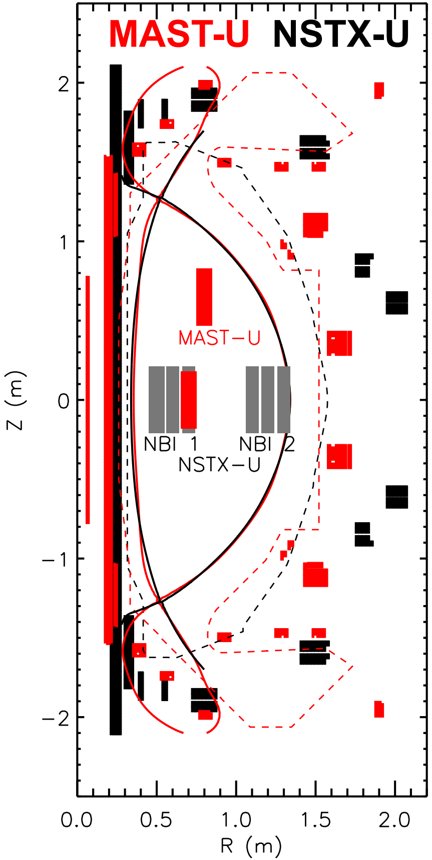


M.D. Boyer et al., NF 57 (2017) 066017

NSTX-U will have unique capabilities for developing NI scenarios compared to MAST-U

- NSTX-U can access higher B_T, P_{heat} in NI scenarios
  - Access high density ($f_{GW} = 0.5 - 1$), large f_{BS} (> 70%) in stationary conditions for multiple τ_R at $I_p \geq 1$ MA
- Real-time NBI deposition control via outer gap and beam selection
- Wall-stabilization for operation at β_N above no-wall limit concurrently with broad J (low l_i)

	MAST-U (2018) Planned	NSTX-U (2016) Achieved	MAST-U (stage 1) Planned	NSTX-U (full field) Planned
Max I_p (MA)	1.0	1.0	2.0	2.0
Max B_T at 0.936 m (T)	0.513	0.635	0.684	1.0
NBI (MW) (Beam voltage)	3.5 (75 keV)	12 (90 keV)	7.5 (75 keV)	12 (90 keV)
t_{pulse} at full field (s)	1	1	5	5



Realization and optimization of fully NI scenarios integrates research and development from multiple TSGs

- Particle and impurity control in long pulse via wall conditioning, ELM control and RF heating
  - Div-SOL TSG + Pedestal TSG + T&T TSG, Wave H&CD (Particle control task force)

- NI scenario intimately linked to confinement and shape of the profiles
  - Transport and Turbulence TSG + Pedestal TSG

- Access to high-β requires stabilization of MHD modes
  - Macroscopic Stability TSG

- Core performance depends on deposition and transport of fast ions
  - T&T TSG + Energetic Particles TSG

- Compatibility of NI scenarios with heat flux control
  - PFC WG + Materials TSG + Div-SOL TSG

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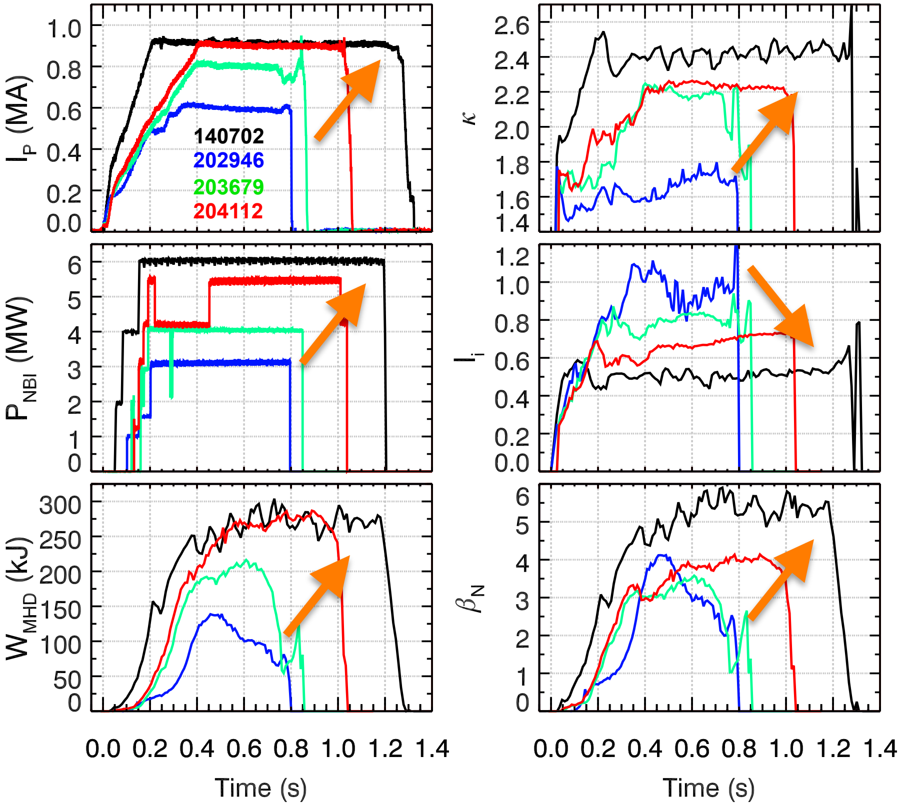
Progress in FY16 toward developing inductive low-l_i, high-κ H-mode scenario

NSTX
0.44 T
H-mode

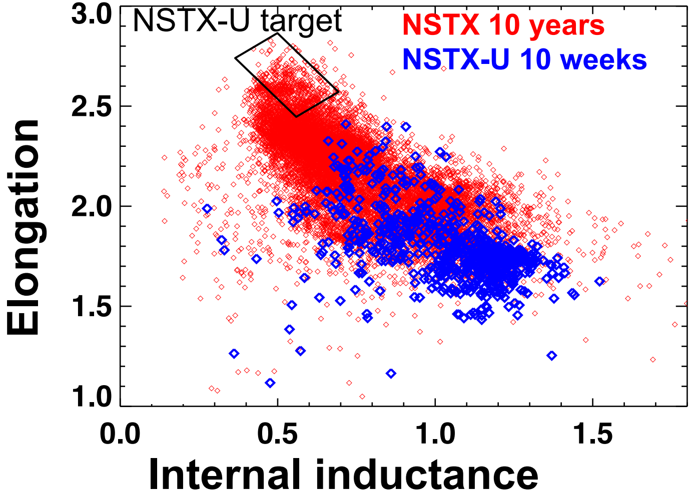
NSTX-U
0.62 T
Week 3
No EFC

Week 5
EFC v1

Week 7
EFC v2

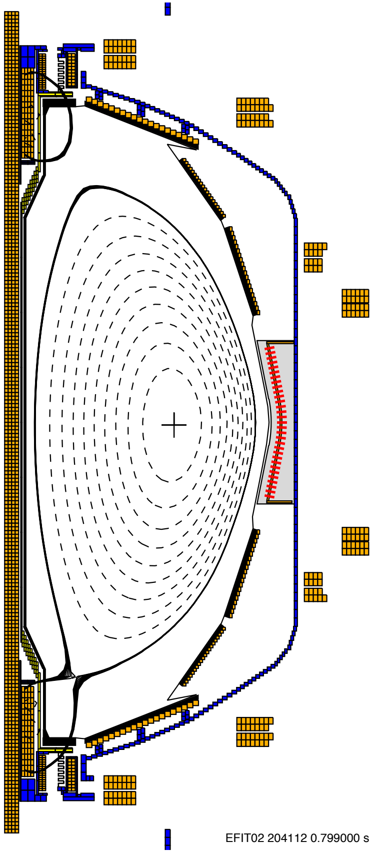


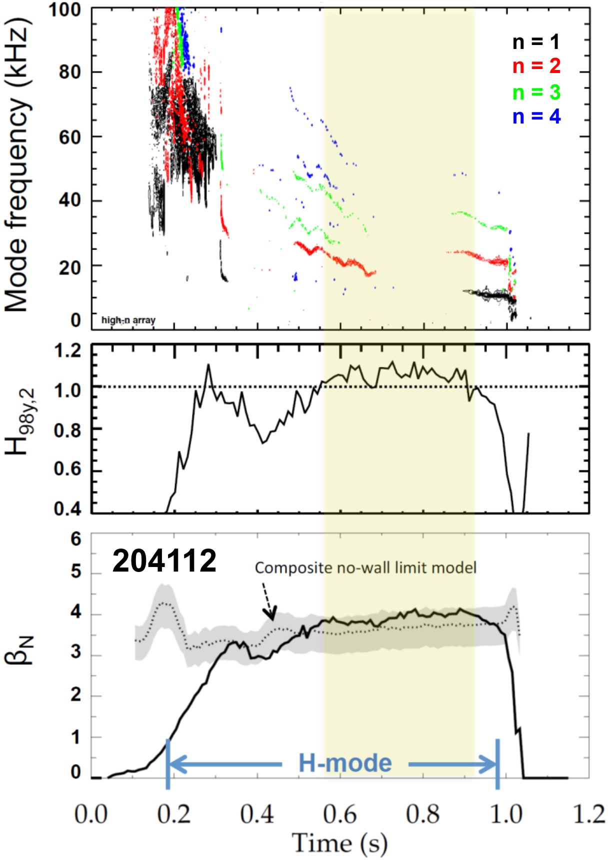
Demonstrated stable operation at κ similar to NSTX despite higher aspect ratio for $l_i > 0.8$



J.E. Menard Nucl. Fusion 2017

MHD-quiescent H-mode discharges sustained with $H_{98y,2} \geq 1$ and $\beta_N/\beta_{no\text{-}wall} \geq 1$





Minimal core MHD

$H_{98y,2} \geq 1$

$\beta_N/\beta_{no\text{-}wall} \geq 1$

204112
I_p = 0.9 MA
B_T = 0.63 T
P_{NBI} = 5.5 MW

H-mode scenario was difficult to reliably repeat during final two weeks of operations

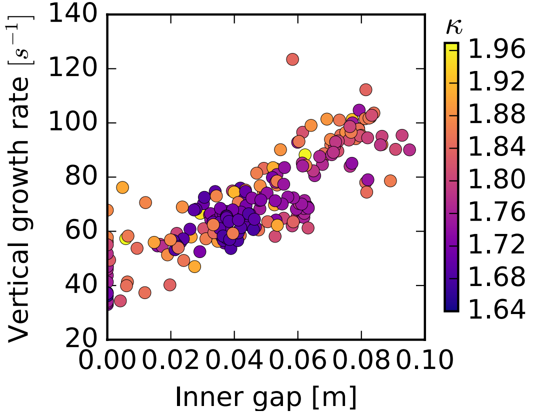
J. Berkery PoP 24 (2017) 056103
J.E. Menard Nucl. Fusion 2017
D.J. Battaglia Nucl. Fusion 2018

Present ASC focus is modeling and analysis to accelerate scenario development at restart

- FY17-19 ASC research milestones: develop reliable ramp-up to low-l_i, high-κ, high-I_p
  - FY17 milestone identified constraints on elongation, stability and the L-H transition
  - FY18-19 develop a framework for predictive modeling for the breakdown and rampup
    - Primary tools: TOKSYS and TRANSP

- Initiated collaboration with MAST-U for developing shared tools and analysis
  - Example: start-up modeling of MAST-U
    - See Stan Kaye's Collaboration talk
  - Focus is development of similar startup and ramp-up modeling tools and experiments

Overshooting the 2cm inner gap target is bad for vertical stability



Solution: active control of the inner gap

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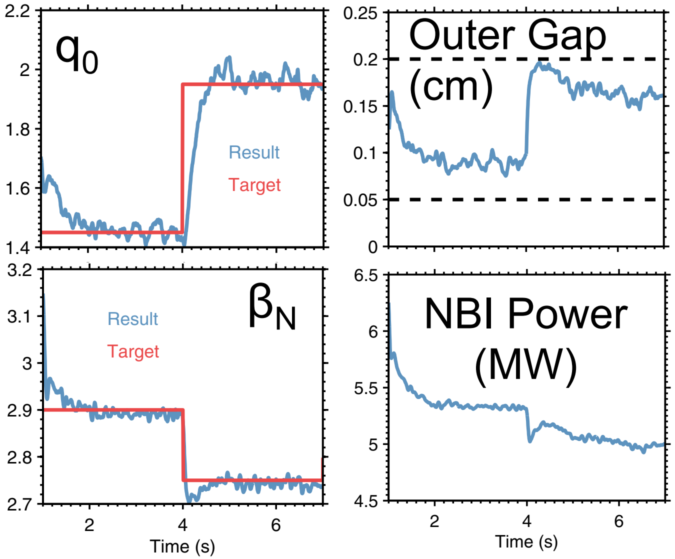
PPPL leads development of TRANSP as a tool for modeling and testing of scenarios and control

- Predictive modeling with assumed transport properties
  - Identify scenarios with relaxed J profile
  - Minimize flux consumption of ramp-up (backup)
- Integrate control algorithm into TRANSP for testing and development (slide 8 and →)
- Use TRANSP database to develop linearized or neural network control model (backup)
  - Planned expansion of PCS computation power to enable "faster than real-time prediction"
  - Disruption avoidance and real-time scenario optimization

Coupled q_0, β_N feedback controller in TRANSP



M.D. Boyer, Nucl. Fusion (2015)

Real-time control development enables science and contributes to broader effort of tokamak control

- State machine logic in PCS enables future expansion of disruption avoidance and protection
  - FY16 demonstrated controlled ramp-down triggered by disruption warnings (backup)

- NSTX-U researchers contribute to the development of advanced shape control algorithms and actuator sharing
  - Involved in collaborations on MIMO shape control including snowflake divertor (Pat Vail, Princeton PhD)

- Heat flux management with fish-scaled surfaces
  - Integrate flaring or sweeping with angle-of-incidence control into target scenarios
  - Possible future investment in heat flux measurements and control

Summary: Recent results and new plans

- Steady progress in FY16 toward developing low-l_i, high-κ H-mode scenario
  - Matched NSTX κ for $l_i > 0.8$ despite larger A
  - H-mode with MHD-free periods, $H_{98y,2} \sim 1$, $\beta_N/\beta_{N\text{-no-wall}} \sim 1$

- Real-time control capabilities commissioned that enable scientific mission
  - Real-time velocity diagnostic, parallelized rtEFIT …

- Applying TRANSP to develop scenarios and real-time control
  - Detailed investigations of access and control of 100% NI scenarios
  - Developing and testing reduced models for control and real-time forecasting

- Increased emphasis on angle-of-incidence control with new PFC design
  - See Matt Reinke's talk
  - Integrate control into target scenarios and other heat flux mitigation methods

Summary: Addressing critical issues

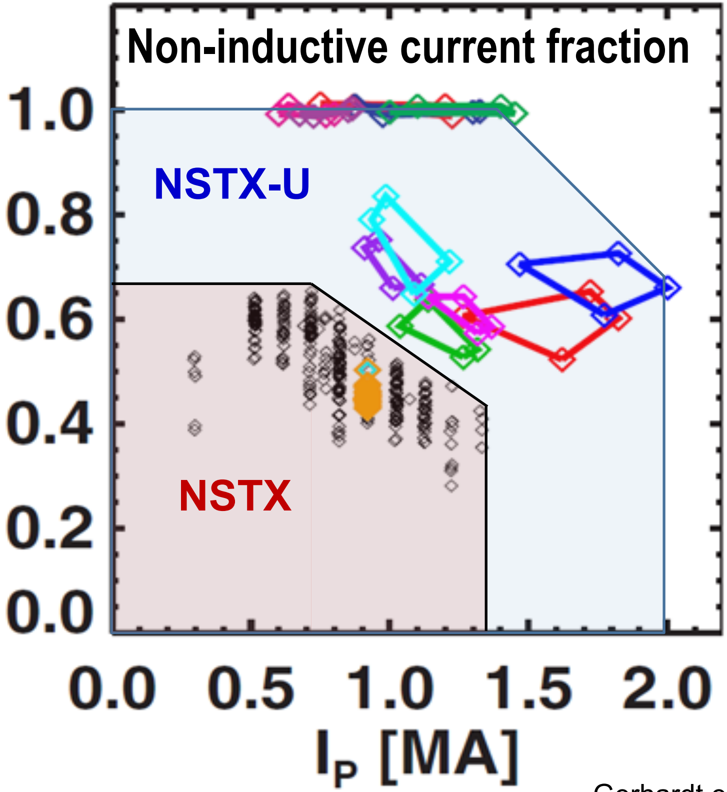
- NSTX-U will be world-leading in the demonstration of fully non-inductive scenarios in an ST
  - High field (B_T = 1T), high power (P_{NBI} = 10 – 15 MW) enables $I_p \geq$ 1 MA at high density (f_{GW} ~ 0.5 - 1) and f_{BS} > 70% for multiple τ_R
  - Real-time measurement and control of J, P, v_ϕ profiles via 6 NBI injectors + outer gap with parallelized rtEFIT

- Development of NI scenarios is a priority of the FY20 campaign
  - Modeling, analysis and collaborations aim to accelerate the progress at restart

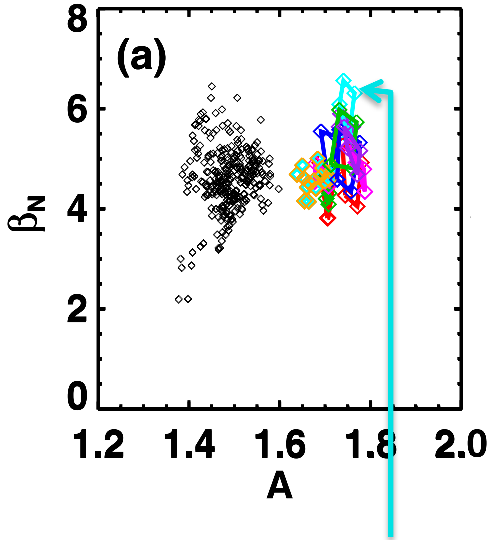
- NSTX-U will continue to contribute to the development of critical control capabilities for tokamaks
  - Profile control, disruption avoidance, actuator sharing, RWM control, real-time forecasting, machine protection …

Back up

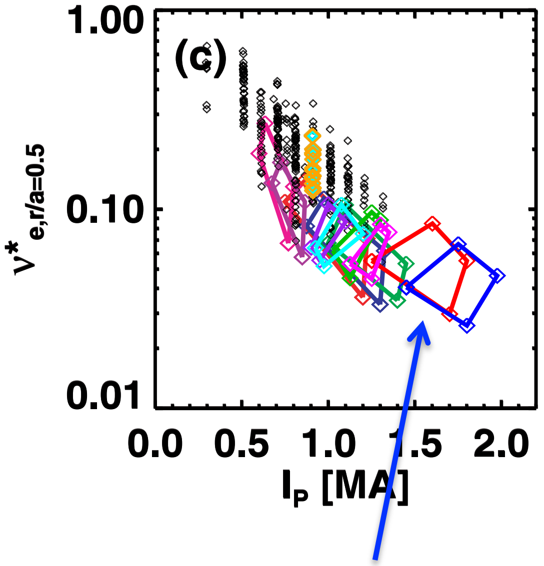
Partially inductive scenarios expand the accessible regimes for scientific discovery



Gerhardt et al., NF 52 (2012) 083020



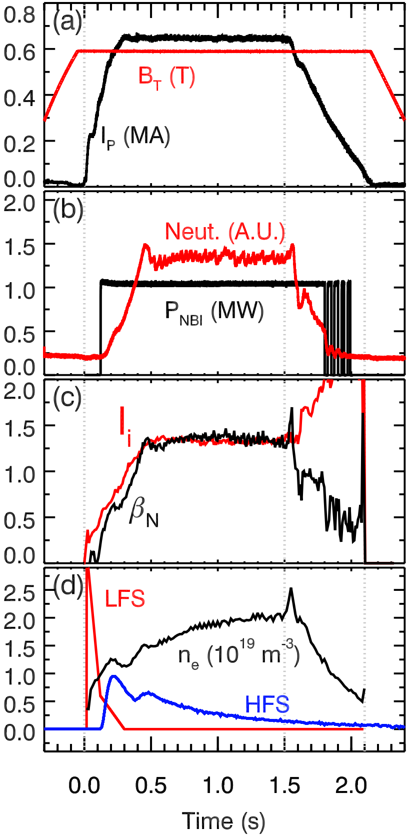
High β_N: $B_T = 0.55$ T, 10 MW most off-axis, $I_p \sim 1$ MA

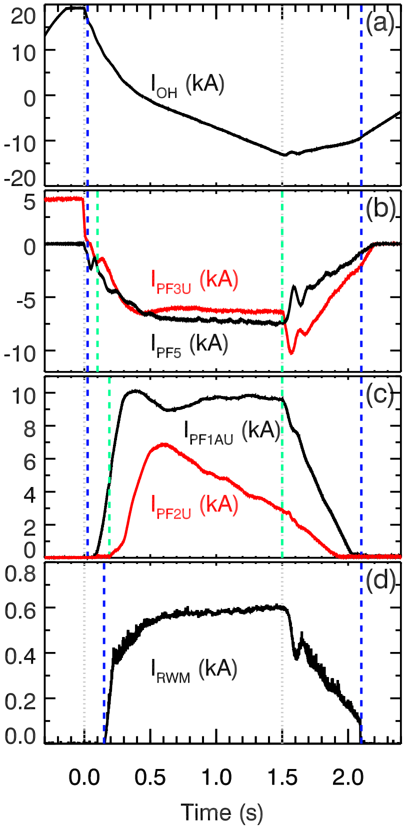


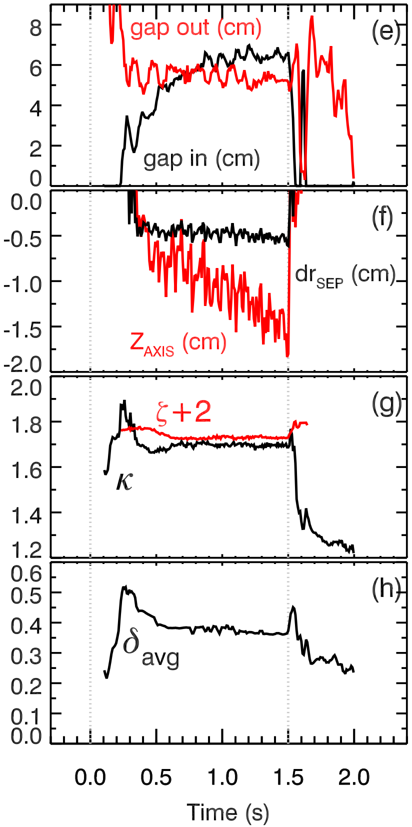
Low ν^*: $B_T = 2.0$T, 15 MW, $I_p \sim 2$MA

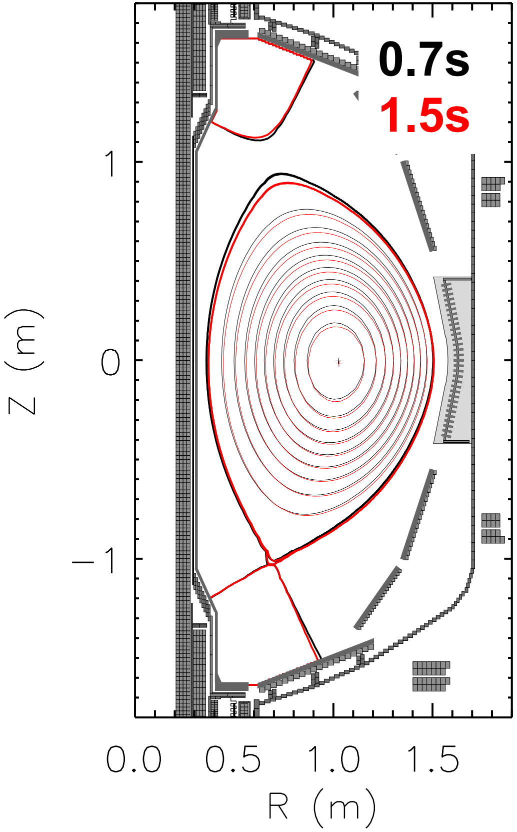
(Trapezoids scan $H_{98y,2}$ → H_{ST} and broad → peaked profiles)

First demonstration of stationary long-pulse sawtoothing L-mode on an ST used for first experiments on NSTX-U



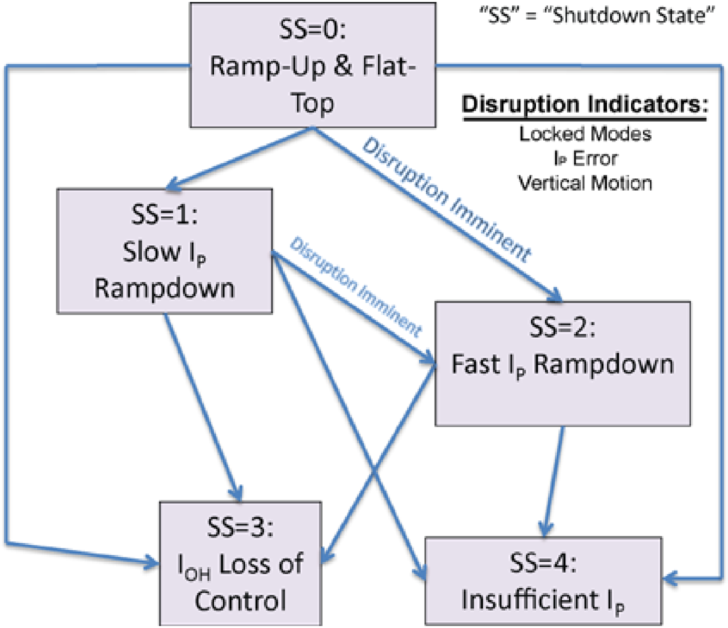






State machine logic in PCS enables future expansion of disruption avoidance and protection

- FY16 run demonstrated controlled ramp-down triggered by disruption warnings



"SS" = "Shutdown State"

SS=0: Ramp-Up & Flat-Top

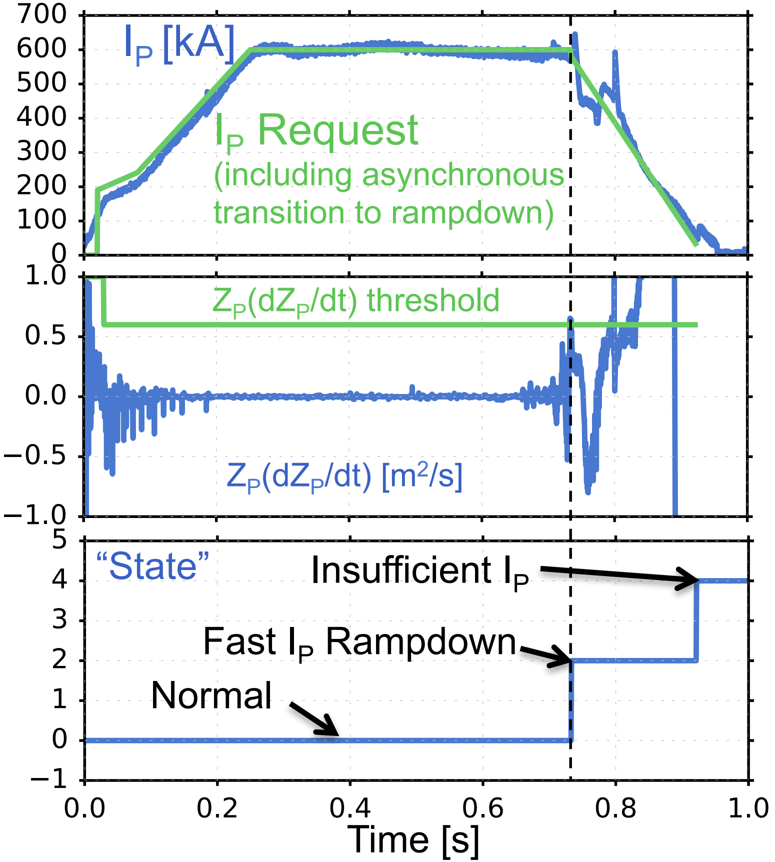
SS=1: Slow I_P Rampdown

SS=2: Fast I_P Rampdown

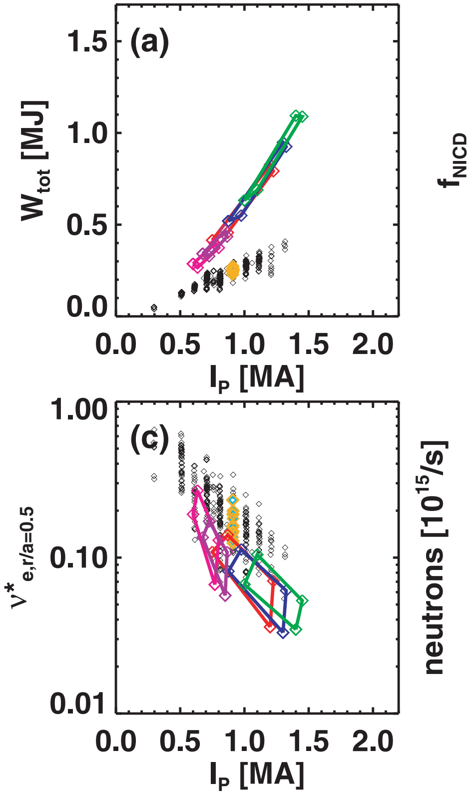
SS=3: I_{OH} Loss of Control

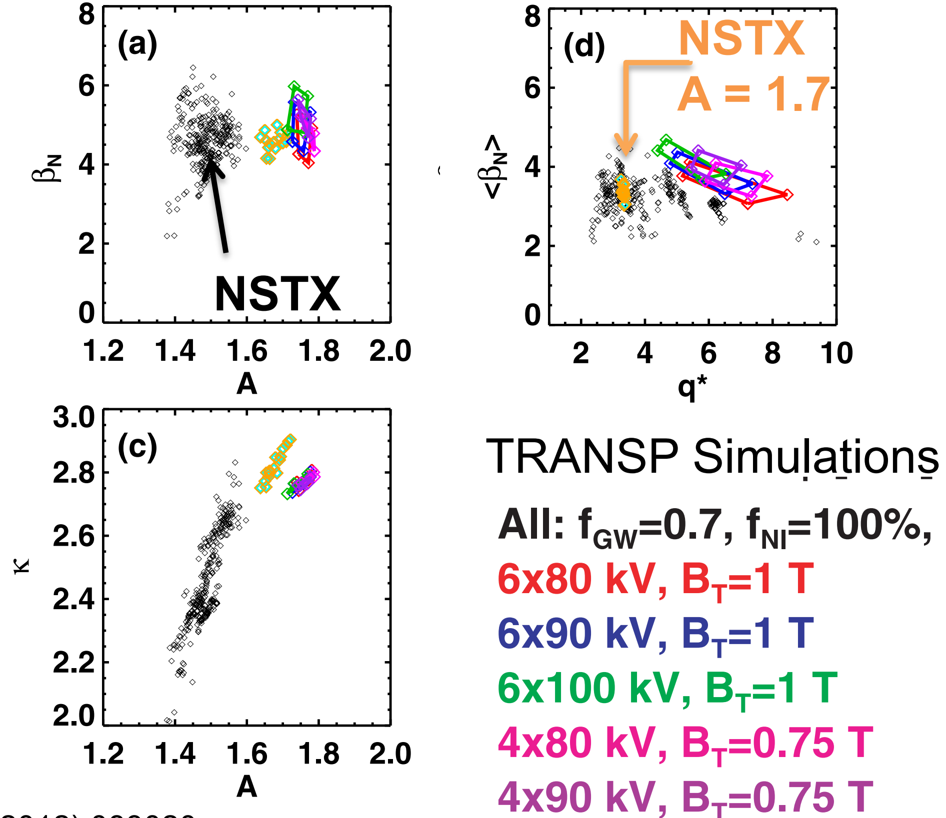
SS=4: Insufficient I_P

Disruption Indicators:
Locked Modes
I_P Error
Vertical Motion



Non-inductive scenarios will access I_p > 1 MA within the stability envelop of NSTX





TRANSP Simulations

All: f_{GW}=0.7, f_{NI}=100%,

6x80 kV, B_T=1 T

6x90 kV, B_T=1 T

6x100 kV, B_T=1 T

4x80 kV, B_T=0.75 T

4x90 kV, B_T=0.75 T

S.P. Gerhardt et al., NF 52 (2012) 083020

Modeling and future experiments focus on reducing inductive current in ramp-up scenarios

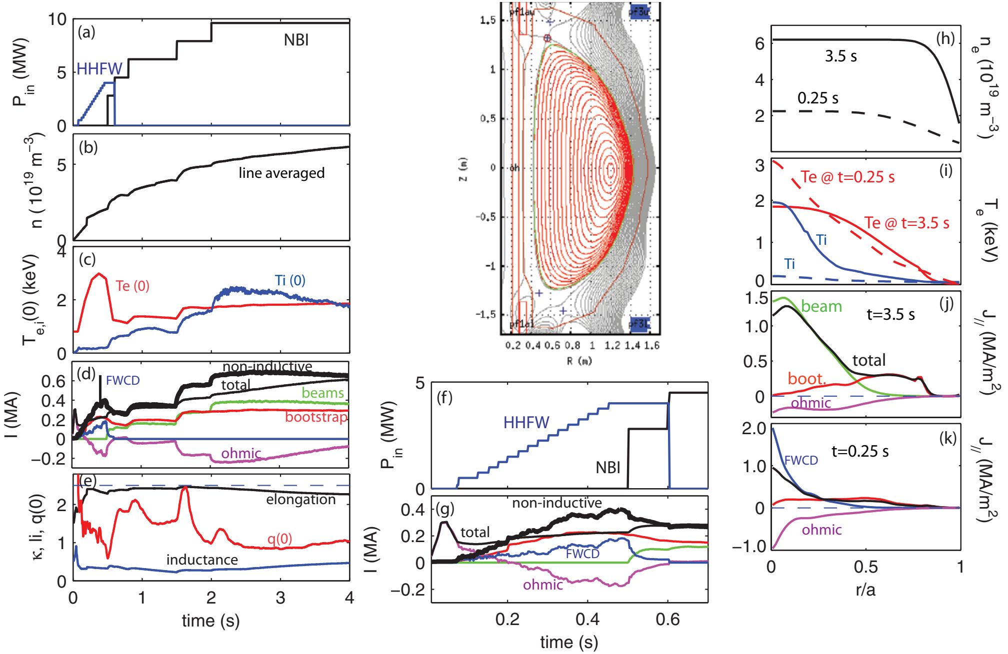


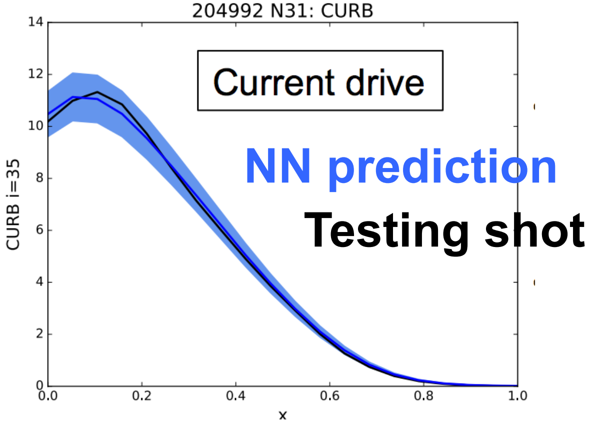
Figure 3. Simulation of a discharge with line-averaged density of $0.75n_G$ that uses up to 4 MW of HHFW and up to 10 MW of NBI to ramp-up and sustain a non-inductive current of 0.7 MA. Left panel: (*a*) injected HHFW and NBI power, (*b*) line averaged electron density, (*c*) central electron and ion temperature, (*d*) total plasma current and individual contributions, (*e*) safety factor on-axis, elongation at the separatrix and internal inductance. Central panel: equilibrium calculated at 3.5 s, (*f*)–(*g*) expanded view of the RF phase. Right panel: profiles of (*h*) density, (*i*) electron and ion temperature at 0.25 s (RF phase) and at 3.5 s (NBI phase), (*j*) current density profiles at 3.5 s, (*k*) current density profiles at 0.25 s.

- Investigate potential of HHFW + NBI for reducing OH flux consumption
  - Couple reduced OH ramp-up to NI scenarios
  - Work aims to determine current drive needs for next-step devices
  - See Roger Raman's talk

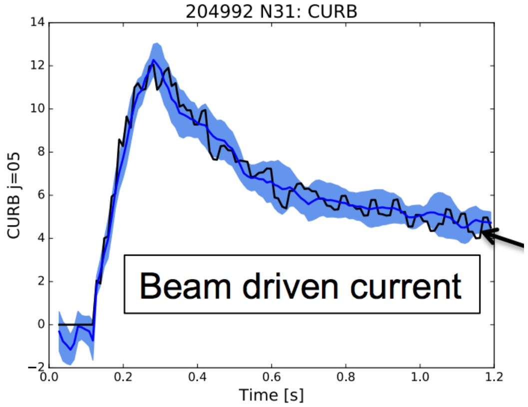
F.M. Poli et al., NF 55 (2015) 123011

Recent work: Developing neural net models from TRANSP database of NSTX-U

- “Faster than real-time” forecasting requires reduced models
  - NUBEAM calculations can not be completed in real-time
  - Solution is to develop a neural net model for the beam heating and current drive



- Neural net model derived from NSTX-U BEAST database will be integrated into rtEFIT and forecasting algorithms
  - BEAST: Between and Among Shots TRANSP



Dan Boyer, NSTX-U Monday Science Meeting 12/5/17