Overview of Initial Operation of NSTX-U

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On behalf of the NSTX-U Team

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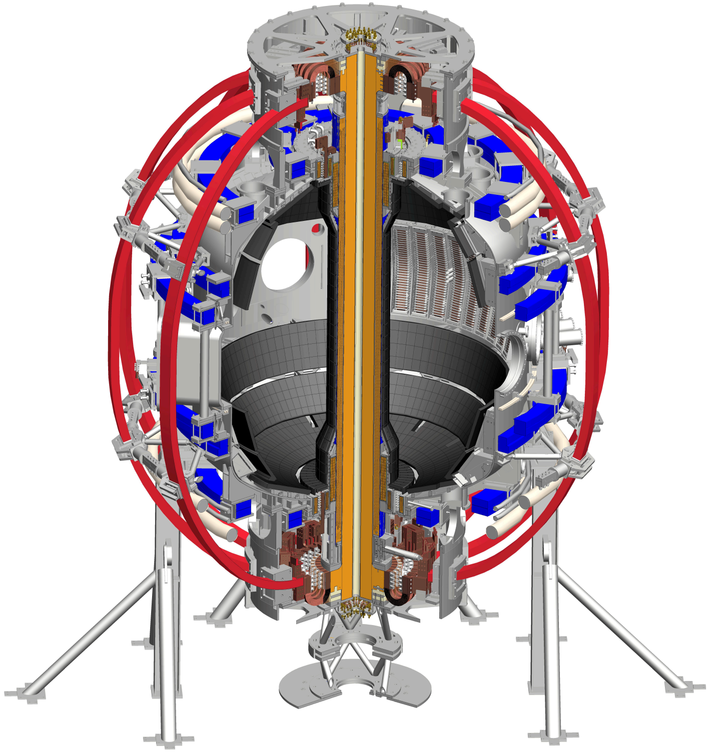


Outline

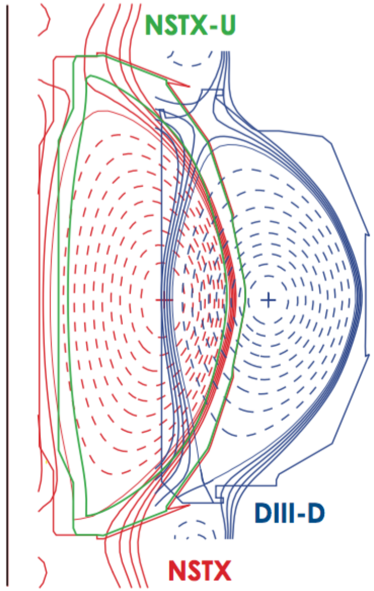
- NSTX-U mission toward advancing magnetic confinement fusion development

- Highlights from the first NSTX-U experimental campaign

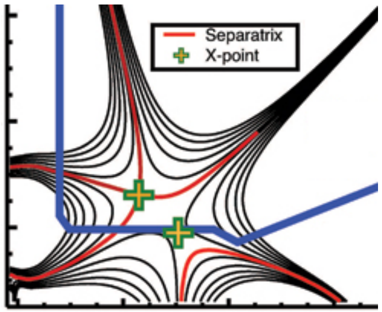
- Initial operations with plasma control and digital coil protection systems on NSTX-U

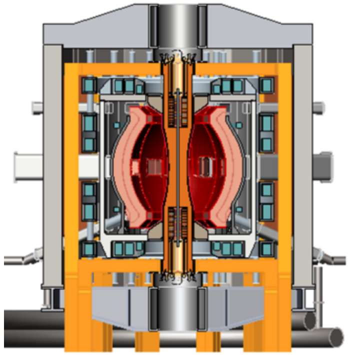
NSTX Upgrade advances the spherical tokamak (ST) concept and complements larger aspect ratio devices

- Explore unique ST parameter regimes to advance predictive capability
- Develop solutions for the plasma-material interface challenge
- Advance ST Fusion Nuclear Science Facility (FNSF) and reactor concepts



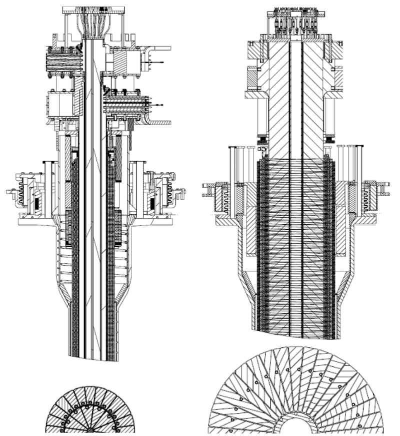
Aspect Ratio R/a = 1.4, 1.7, 2.7



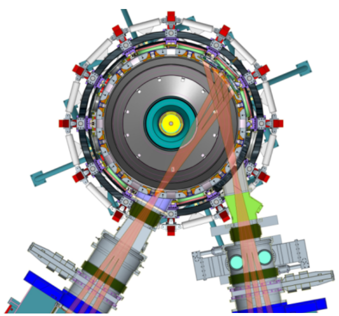


NSTX completed multi-year upgrade to increase field, heating and pulse length

Previous center-stack | **New center-stack**



TF OD = 20cm | **TF OD = 40cm**



Present NBI | **New 2nd NBI**

- National Spherical Tokamak operated 1999 - 2010
- New center column: double toroidal magnetic field, triple solenoid V-s
  - Access to 2 × higher temperatures, lower collisionality
  - Pulse lengths increase 1 → 5 seconds
- Second neutral beam injection system added
  - Doubles NBI heating and increases flexibility in heating profile
  - More tangential injection triples NBI current drive and increases current profile control capability
- Increased flexibility in divertor field to support innovative configurations

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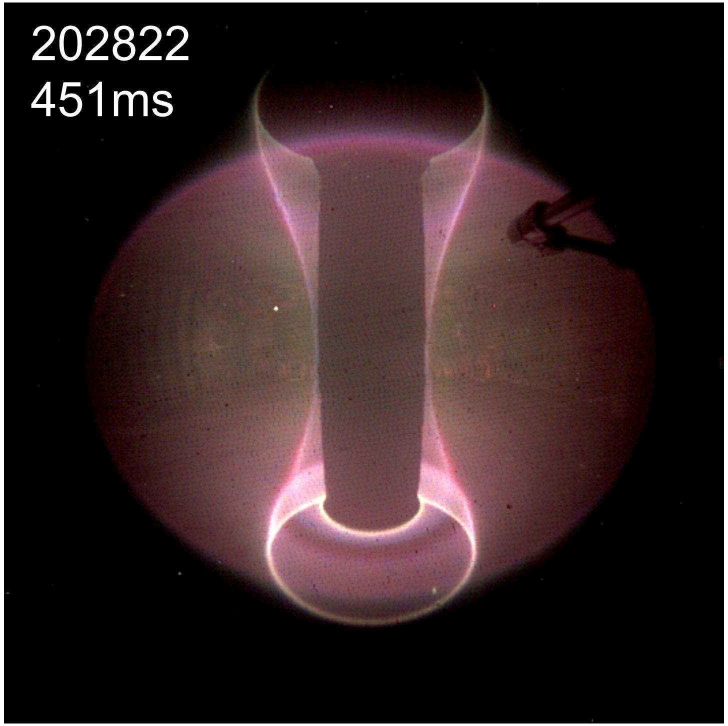
NSTX-U recently completed its first experimental campaign

- First plasma August 10, 2015
  - Signified completion of major construction
- First experimental run from December, 2015 to June, 2016
  - Commissioned control, heating and diagnostic systems
  - Began physics assessment of new capabilities
  - Run ended early due to an internal short within a divertor coil
    - Currently removing coil for inspection and defining corrective actions
- Next campaign slated to begin mid-2017 following coil replacement
  - Restart with new capabilities, including full-field operation at 1 Tesla



One of the first H-mode discharges on NSTX-U
January 13, 2016
(second week of operation)

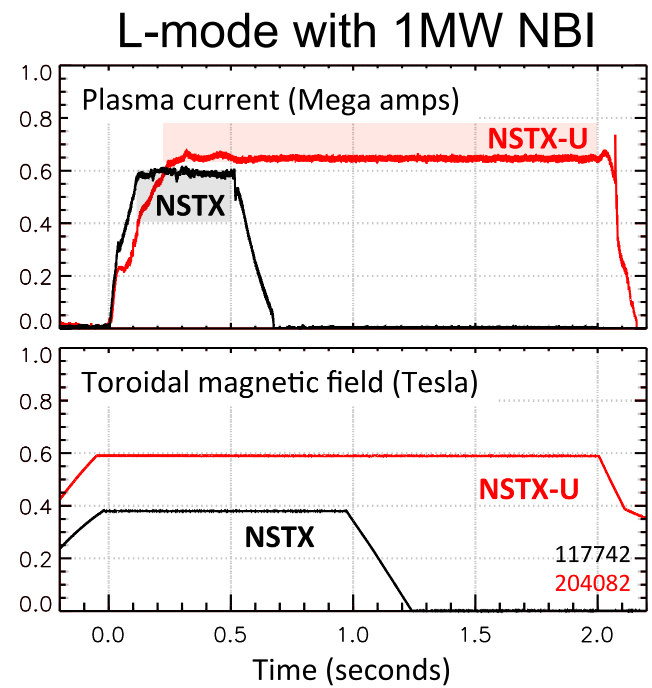
Majority of commissioning activities were completed or nearing completion at the end of the campaign

- XMP-101: Breakdown Optimization
- XMP-102: Gas Flow Rate Calibration
- XMP-106: Magnetics Calibration
- XMP-126: I_P and R Control
- XMP-105: Software Tests for n=0 Control
- XMP-115: ISOFLUX Commissioning
- XMP-116: Initial H-Mode Access
- XMP-127: Neutral Beam Commissioning
- XMP-107: Neutron Calibration Transfer
- XMP-120: Strikepoint & X-Point Control
- XMP-128: Increase L-Mode Elongation
- XMP-132: Fast Rampdown Sequence Commissioning
- XMP-137: Increase κ and I_P in L- and H- Mode
- XMP-138: Improved Vertical Control Checkout
- XMP-121: SPA & RWM Control Checkout
- XMP-140: PF-5 Proportional EFC Test
- XMP-141: Proportional EFC Tests
- XMP-111: MPTS Commissioning
- XMP-142: Reduced MHD H-Mode Development
- XMP-146: Higher-Order Feed Forward EFC in L-Mode
- XMP-147: Integrate control improvements in L-Mode fiducial
- XMP-148: Between-Shot TRANSP Validation
- XMP-110: ssNPA & FIDA checkout
- XMP-150: He Density Scan for Z_{eff} Calibration
- XMP-151: L-Mode Development for Core and Boundary XPs
- XMP-152: Improved dr-sep and rtEFIT Control
- XMP-153: H-mode Access and Rampup Control Development
- XMP-154: Inner Gap Control Development
- XMP-114: CHERS Modulation Study
- XMP-125: MSE-CIF 2nd NB Interference Study
- XMP-130: Granule Injector Commissioning
- XP-1506: Low Beta n=1 EFC

Completed
In progress
Planned

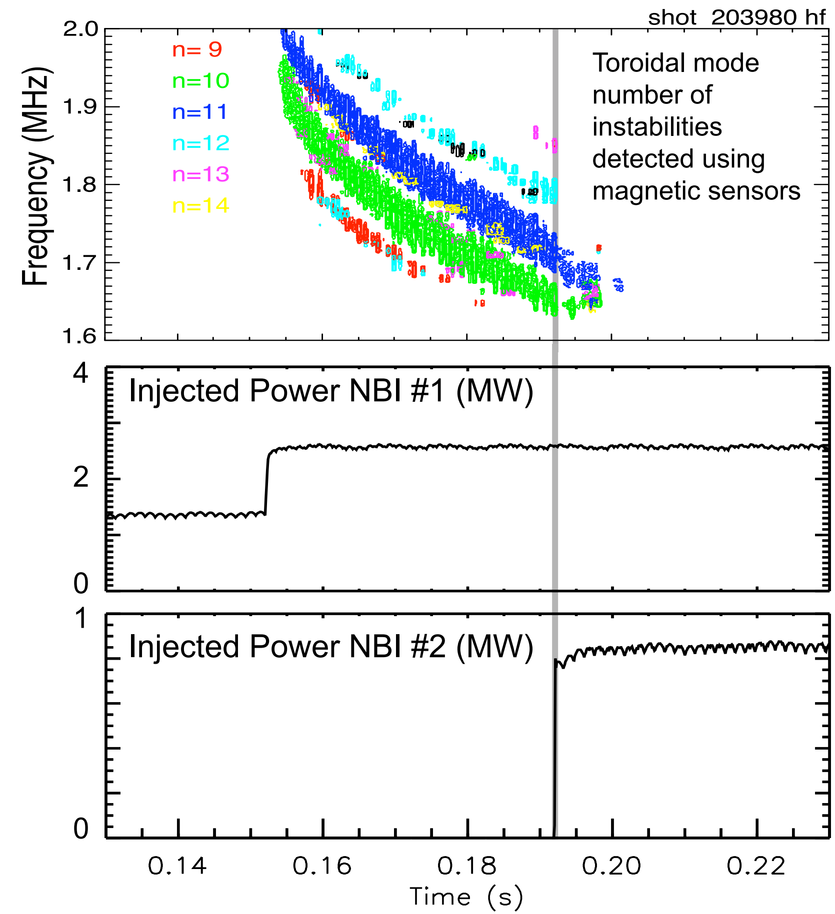
Commissioning activities developed discharges to support planned experiments

- Rapid development of high-performance discharges in first 10 weeks of operation
  - Operated routinely at B_{T0} = 0.65T, greater than maximum NSTX field
  - Wall conditioning: Helium GDC + boronization
  - Many diagnostics available at first plasma
- Stationary L-mode pulse length ~ 4 times longer than NSTX
  - Supported first experiments on error fields, transport, current drive and fast-ion physics
- H-mode discharges comparable to NSTX performance for I_p < 1.0 MA

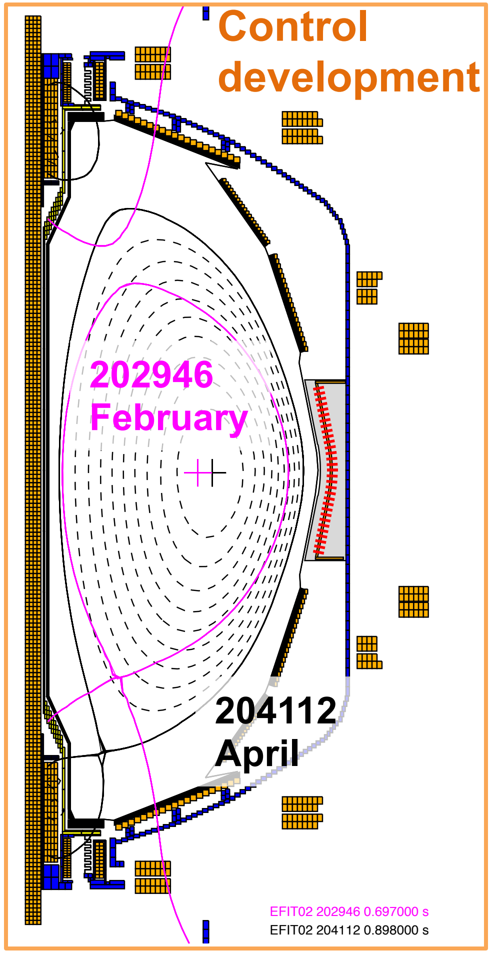


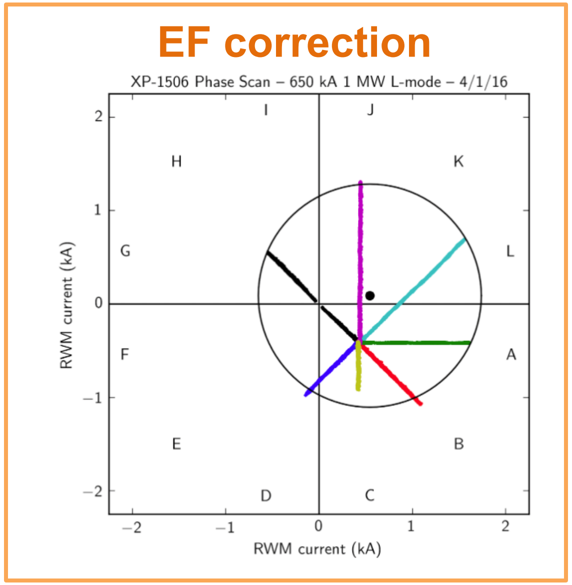
Neutral beam injection using the new beam line immediately demonstrated exciting results

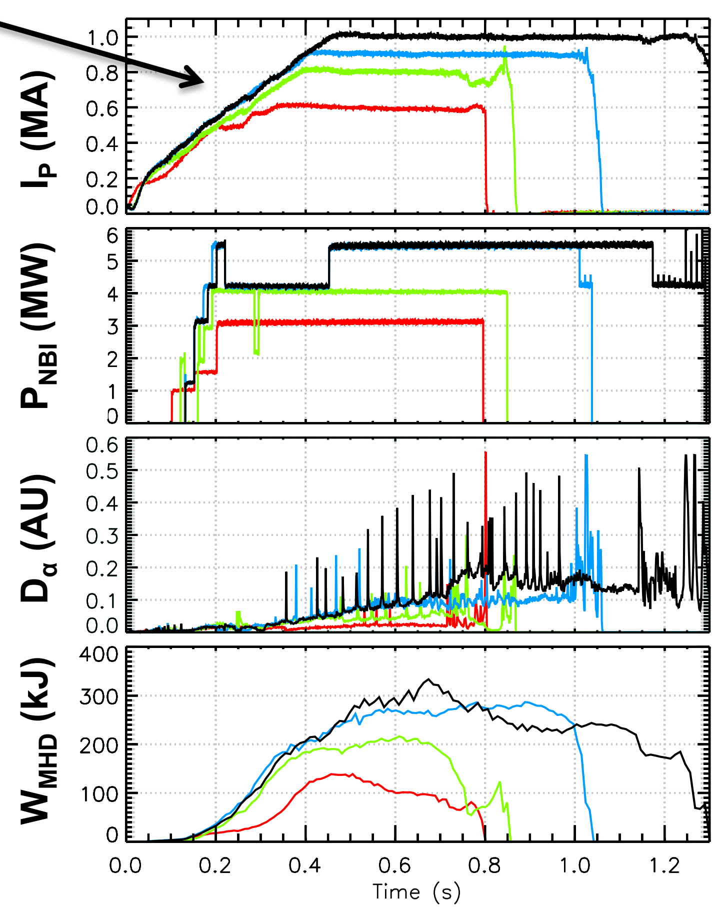
- Plasma instabilities are driven by neutral beam heating
  - Instabilities can increase the transport of thermal energy
  - Example at right, instabilities start with when NBI heating is increased
- Tangential injection suppresses fast ion instabilities
  - Unique result to observe instabilities go away after adding more power
  - Significant tool for improving energy confinement



Steady progress in error field correction, plasma control and NBI heating improved H-mode performance

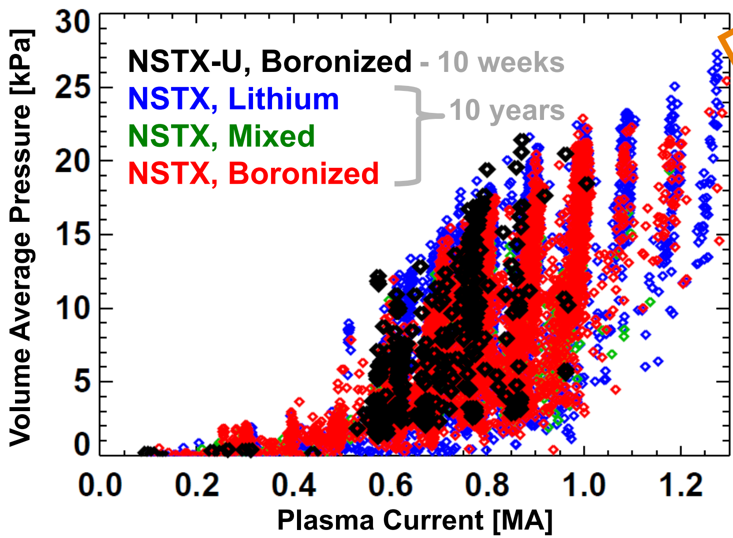


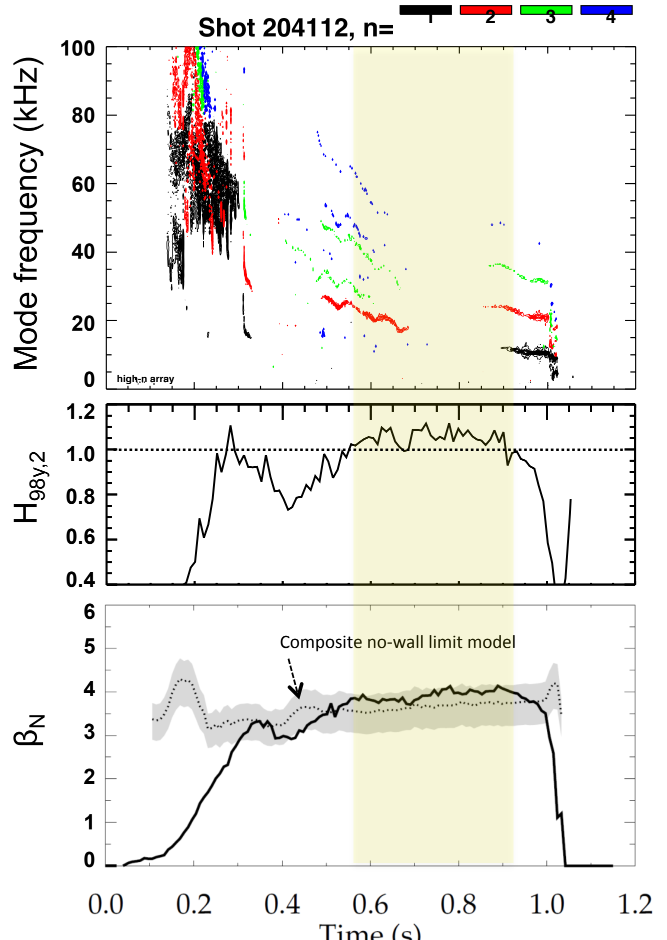




H-mode scenario achieved with $H_{98y,2} > 1$ and $\beta_N \geq$ no-wall stability limit

- Scenario matches best NSTX performance at I_p = 0.9 MA
  - Progress toward larger I_p and longer pulses was interrupted by coil failure





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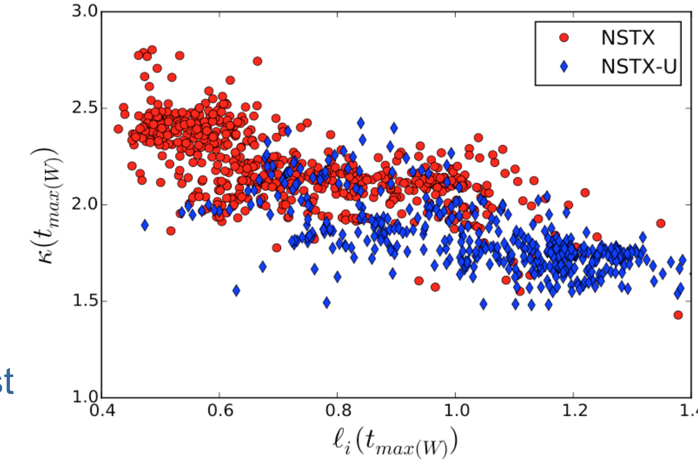
Shape control challenges due to increased aspect ratio (A) of NSTX-U were successfully addressed

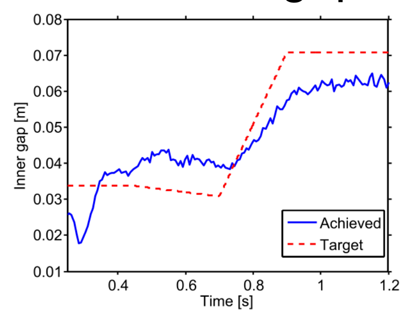
Higher-A operation challenges …

- Vertical stability
  - Improved detection of vertical plasma motion
  - Achieved comparable elongation to NSTX at matched l_i
- Controlling inboard gap without inboard PF coils
  - Coil actuator sharing algorithm (MIMO): find solution that best matches target shape when # control points > # PF coils

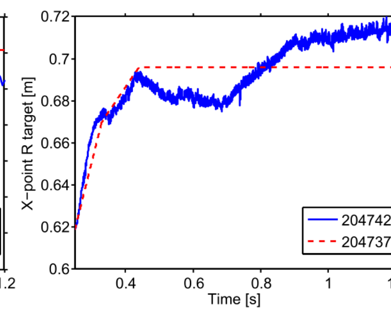


Modify the plasma shape to achieve the best match 8 plasma shape target points (including inboard gap) with only 7 PF coils.

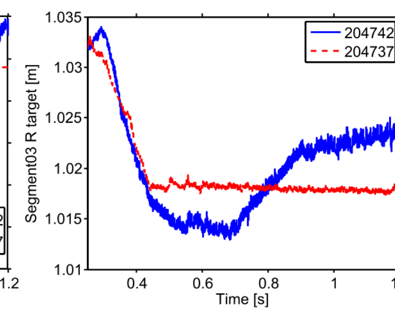
Inboard gap



X-point radius

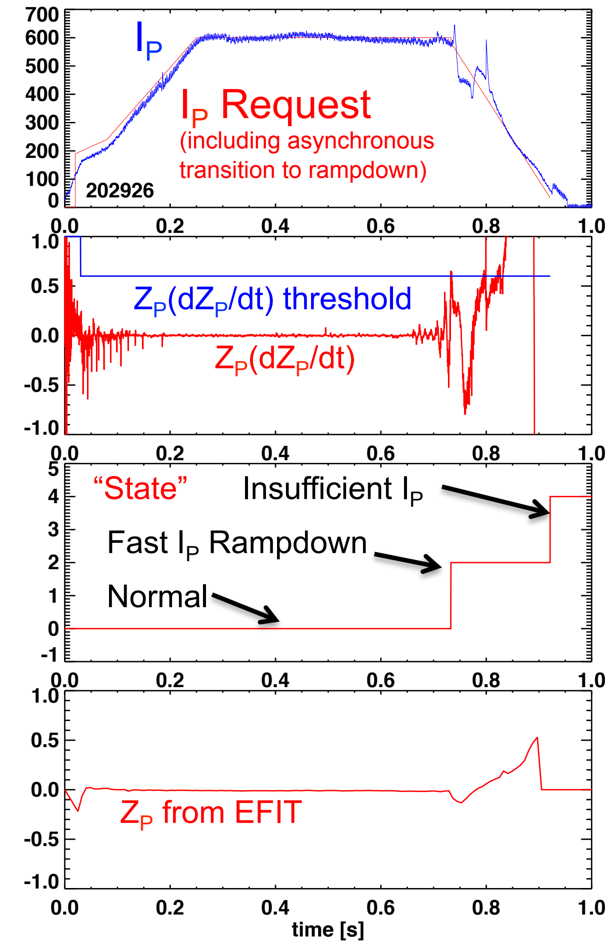


Outer squareness



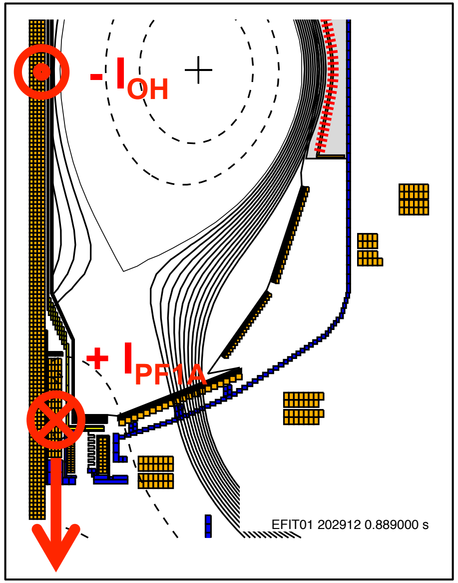
Plasma Shutdown scheme routinely used to initiate controlled rampdown of NSTX-U discharges

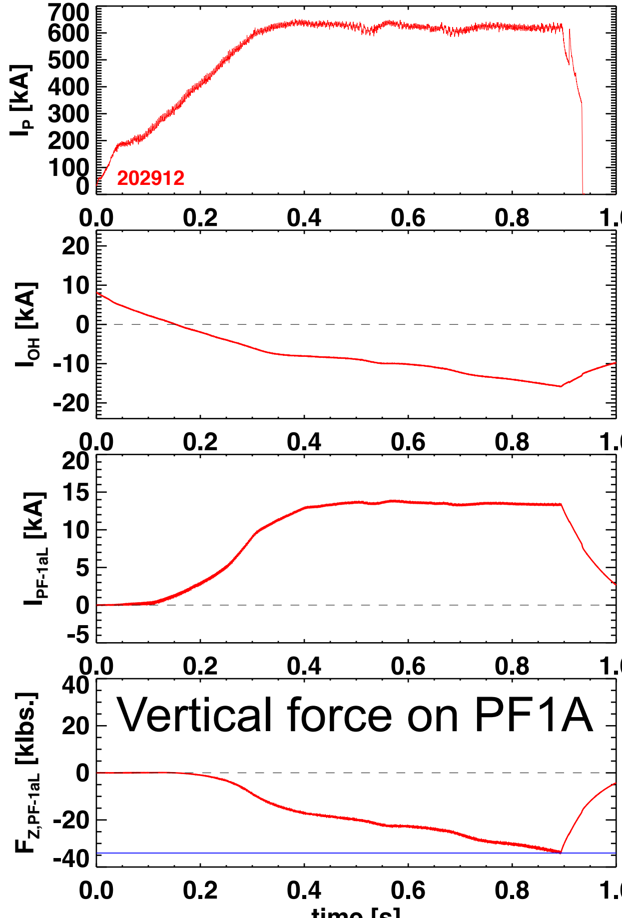
- **NSTX**: No means of detecting a disruption, or ramping down the plasma current based on events.
- **NSTX-U**: State machine orchestrates the shutdown.
  - Examples of events triggering shutdown:
    - Ohmic coil approaching current limit (loss of control)
    - Loss of vertical stability (example at right)
    - Plasma current missing target
    - Insufficient plasma current for control
  - Routinely used in NSTX-U discharges to avoid disruptions
- Supports future research into reactor-relevant disruption avoidance schemes
  - Disruption avoidance may be critical to future divertor material testing on NSTX-U



Digital coil protection system (DPCS) successful in avoiding coil force and heating limits

- DCPS developed to protect coils from exceeding force and thermal limits
  - 400 real-time force and stress calculations using coil and plasma currents
  - Fault detection triggers all power supplies to remove voltage from coils
- System designed for every-shot protection
  - Redundant systems with multiple layers of system status checking and fault tracing
- DCPS successfully avoided exceeding force limits during off-normal events





Summary

- NSTX-U is now the most capable spherical tokamak in the world fusion program
  - NSTX-U will evaluate the ST design for future burning plasma devices and complement conventional tokamak experiments

- Initial operations made rapid progress in discharge scenario development and commissioning heating and diagnostic systems
  - Long (> 1.5 s) L-mode discharges supported first experimental results
  - Progress in H-mode scenario enabled by progress in error field correction, shape control and heating power availability

- New plasma control and coil protection systems were commissioned to support NSTX-U operations
  - Many of the new capabilities applicable to present and future tokamak devices

NSTX-U Talks and Posters at TOFE 2016

- Thermal and structural performance evaluation of the NSTX-U high-z divertor
  - Art Brooks 18403 Monday Poster Session
- NSTX-U 2nd Neutral Beam Relocation
  - Neway Atnafu 18167 Monday Poster Session
- NSTX-U Bake-Out Simulations and Evaluations
  - Peter Titus 18220 Monday Poster Session
- Design and operation of the electrical noise suppression system for CHI on NSTX and NSTX-U
  - Zhi Gao 18163 Tuesday Poster Session
- Studies of Next-Step Spherical Tokamaks Using High-Temperature Superconductors
  - Jon Menard 18205 Tuesday AM Invited Talk

Please come tour NSTX-U on Tuesday evening!