NSTX-U

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# NSTX-U Initial Operations Plan
# 5 Year Plan for Scenarios and Control


**S.P. Gerhardt, PPPL**

*E. Kolemen, PPPL*

*for the NSTX-U Research Team*


**NSTX-U 5 Year Plan Review**
**LSB B318, PPPL**
**May 21-23, 2013**


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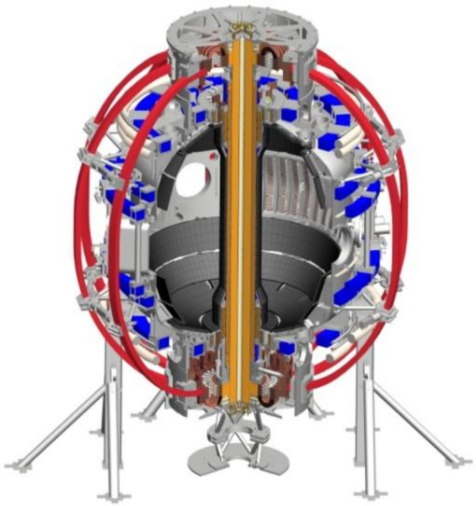


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*IPP, Jülich*
*IPP, Garching*
*ASCR, Czech Rep*

# Outline

- Plans for Entering the First NSTX-U Operations Period
- ASC Research Plans for 5-year Period

# Operations Activities Designed to Fit in the Existing NSTX-U Project Schedule

Projected Near Term Schedule:

| Time | Activity |
|---|---|
| July-Nov., 2013 | Diagnostic Reinstallations/Calibrations In Parallel with Construction Activities |
| Dec. 2013 – March, 2014 | Close Machine (w/o CS), Leak Checking, Prep. for CS installation. |
| April-May, 2014 | CS Installation |
| June, 2014 | Final Calibrations, Particularly Those Diagnostics Requiring CS for Calibration |
| July-Sept., 2014 | Run Prep, Internal and DOE Readiness Reviews, Integrated Systems Testing, First plasma (CD-4) |

# Initial Operations Plans Designed to Rapidly Recover Physics Operations Capabilities

ISTP:
(Integrated Systems Test Procedure)
Establishes facility in state of readiness for operations.

Plasma Operations with:
$I_p \leq 1.0$ MA, $B_T \leq 0.5$
Develop:
- Breakdown and current ramp scenarios
- Shape & position control
- Reliable H-mode
- Diagnostic operations

Continue to add diagnostic & control capabilities while initiating physics experiments.

$I_p \leq 1.5\text{-}1.6$ MA
$B_T \leq 0.75\text{-}0.8$

***July-Sept. 2014***

**ISTP-1 & CD-4 Prep** → **MPTS Calibrations, Bake Out, CD-4** → **Operations Commissioning** → **Phys. Ops** → **ISTP-2** → **Phys. Ops**

***~ 2-3 Months***

Attempt 50 kA CD-4 plasma before bake-out. If water in PFCs prevents success, then repeat after bake-out.

ISTP-2
Required to increase the field and current for later research phase

# NSTX-U Field and Current Capabilities Will Be Increased Over a ~3 Year Period

| | NSTX (Max.) | Year 1 NSTX-U Operations (2015) | Year 2 NSTX-U Operations (2016) | Year 3 NSTX-U Operations (2017) | Ultimate Goal |
|---|---|---|---|---|---|
| $I_P$ [MA] | 1.2 | ~1.6 | 2.0 | 2.0 | 2.0 |
| $B_T$ [T] | 0.55 | ~0.8 | 1.0 | 1.0 | 1.0 |
| Allowed TF $I^2t$ [$MA^2s$] | 7.3 | 80 | 120 | 160 | 160 |
| $I_P$ Flat-Top at max. allowed $I^2t$, $I_P$, and $B_T$ [s] | ~0.4 | ~3.5 | ~3 | 5 | 5 |

- 1st year goal: operating points with forces up to ½ the way between NSTX and NSTX-U, ½ the design-point heating of any coil
  - Will permit up to ~5 second operation at $B_T$~0.65
- 2nd year goal: Full field and current, but still limiting the coil heating
  - Will revisit year 2 parameters once year 1 data has been accumulated
- 3rd year goal: Full capability

NSTX-Upgrade engineers developing a plan for mechanical diagnostics to assess the accuracy of the mechanical models underlying protection levels

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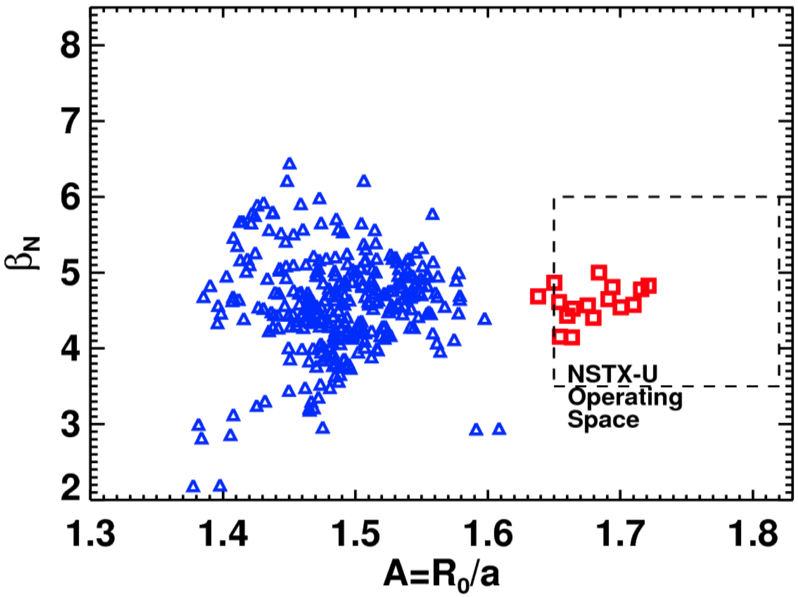
- Plans for Entering the First NSTX-U Operations Period
- ASC Research Plans for 5-year Period

# ASC Research Targets Integrated, Steady-State Scenario Needs for FNSF/CTF and ITER

Steady-state scenarios for ITER or a CTF/FNST must:

- Have 100% non-inductive current drive.
  - NSTX-U ASC: Explore a range of $\beta_N$ with 100% non-inductive CD.
- Control the divertor heat flux to be within acceptable material limits.
  - NSTX-U ASC: divertor geometry and radiation control.
- Simultaneously optimize confinement and passive global stability.
  - NSTX-U ASC: optimization and control of the boundary, rotation and current profiles.
- Detect and respond to disruptions and off-normal events.
  - NSTX-U ASC: disruption detection and soft-shutdowns.

NSTX Operational Space: $\beta_N$ vs A
>$1\tau_E$ average for each point




Conventional NSTX Operating Space
High-A Experiment During FY-11 Run

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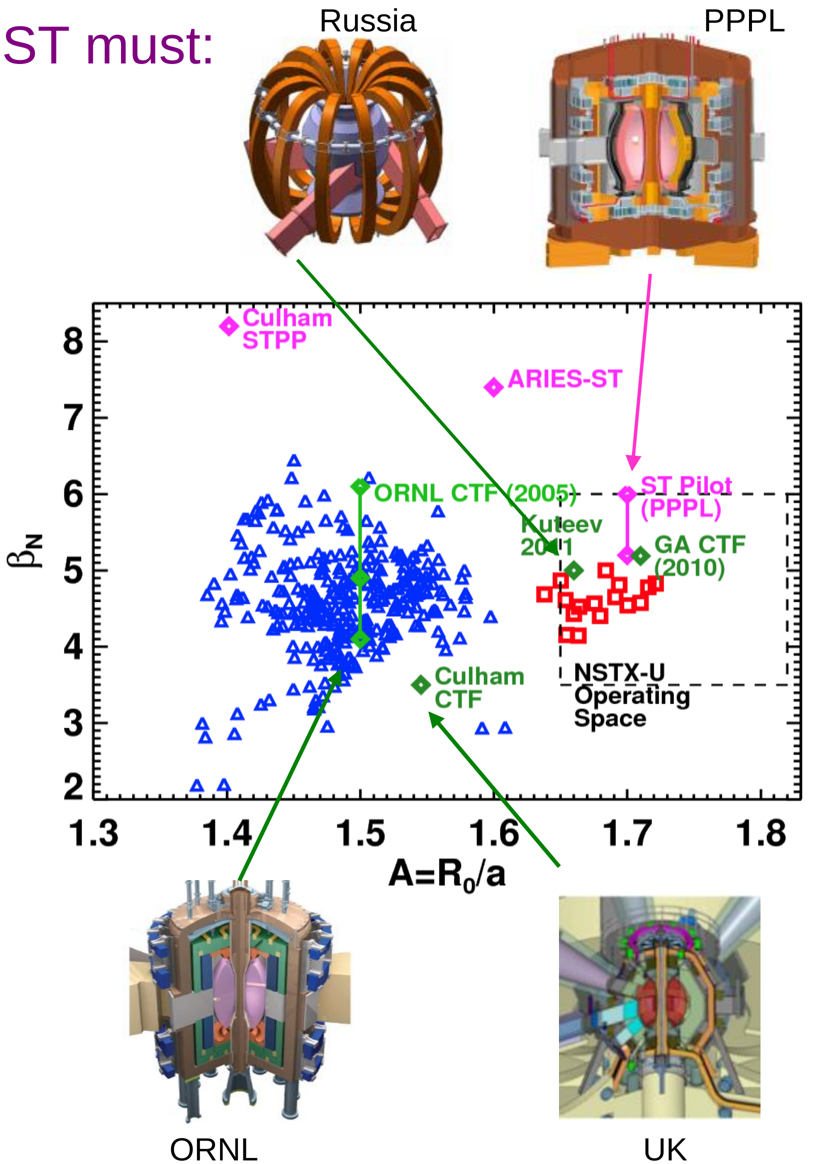
- Detect and respond to disruptions and off-normal events.
  - NSTX-U ASC: disruption detection and soft-shutdowns.



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**ASC Programmatic Goal For 5 Year Plan:**
Develop the basis for integrated, steady-state operation and axisymmetric control for next-step STs, while helping resolve key scenario and control issues for ITER.

**ASC Operational Goal For 5 Year Plan:**
Establish stationary, 100% non-inductive operation, and partial inductive operation up to $I_P$=2 MA, for 5 seconds over a wide range of Greenwald fractions.

Research required to meet these goals divided into four thrusts.

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- ASC Research Plans for 5-year Period
  - Thrust 1: Scenario Physics
  - Thrust 2: Axisymmetric Control Development
  - Thrust 3: Disruption Avoidance By Controlled Discharge Shutdown
  - Thrust 4: Scenario Physics for Next Step Devices

Four thrusts support all 5 high-level programmatic goals for NSTX-U (see J. Menard talk)

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    - Develop techniques for the automated termination of discharges.
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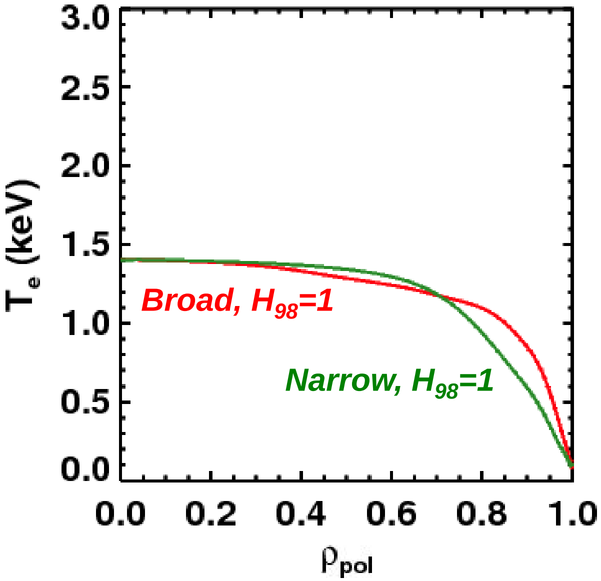
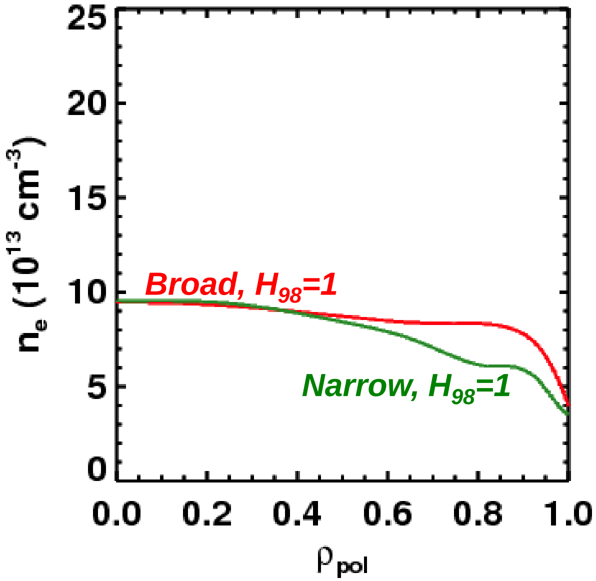
    - Determine the optimal, simultaneous q- and rotation profiles.
    - Study the conditions for classical beam current drive.
    - Explore & validate integrated models for projections to FNSF.

# Anticipate The Non-Inductive Current Level at $B_T$=1.0 T and $P_{inj}$=12.6 MW To Be Between ~900 & ~1300 kA

*Thrust #1*



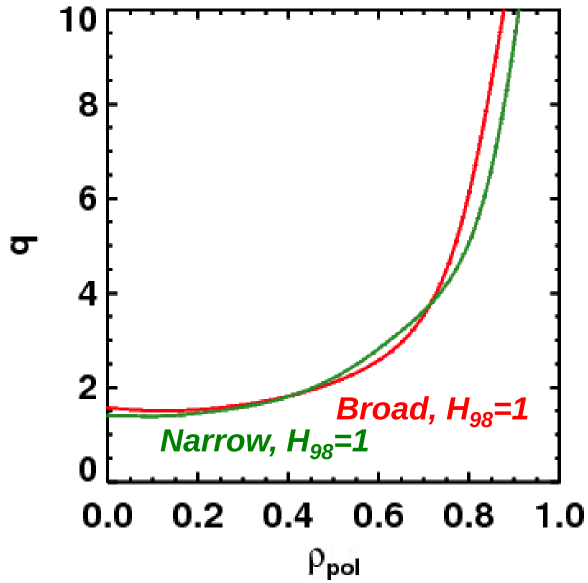




Dashed: ITER-98 confinement scaling

$$\tau_{98y,2} \propto I_P^{0.93} B_T^{0.15} \bar{n}_e^{0.41} P_{Loss}^{-0.69}$$

**Free-Boundary TRANSP Calculations**

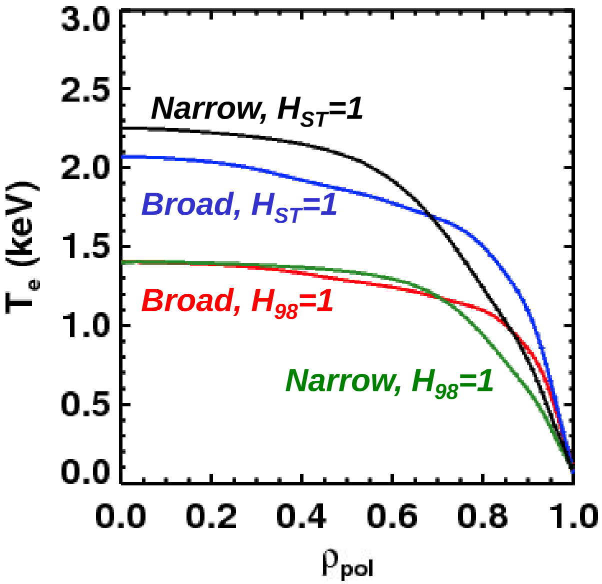
S.P. Gerhardt, et al, Nuclear Fusion **52** 083020 (2012)

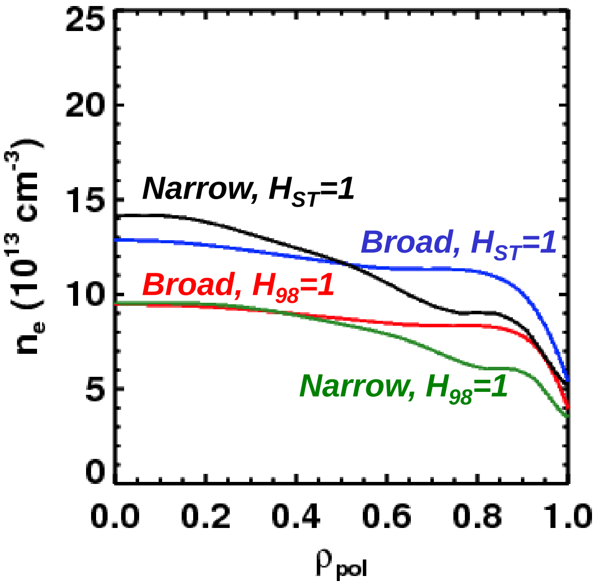



- **Fix: 1.0T, $P_{inj}$=12.6 MW, $f_{GW}$=0.72**
- **Fix: A=1.75, κ=2.8**
- Determine the non-inductive current level for 2 confinement and 2 profile assumptions…*yields 4 different projections.*

| Confinement | Profiles | $I_P$ [kA] | $\beta_N$ | $q_{min}$ |
|---|---|---|---|---|
| $H_{98}$=1 | Broad | 975 | 4.34 | 1.5 |
| | | | | |
| $H_{98}$=1 | Narrow | 875 | 4.87 | 1.4 |
| | | | | |

# Anticipate The Non-Inductive Current Level at $B_T$=1.0 T and $P_{inj}$=12.6 MW To Be Between ~900 & ~1300 kA




Dashed: ITER-98 confinement scaling

$$\tau_{98y,2} \propto I_P^{0.93} B_T^{0.15} \bar{n}_e^{0.41} P_{Loss}^{-0.69}$$

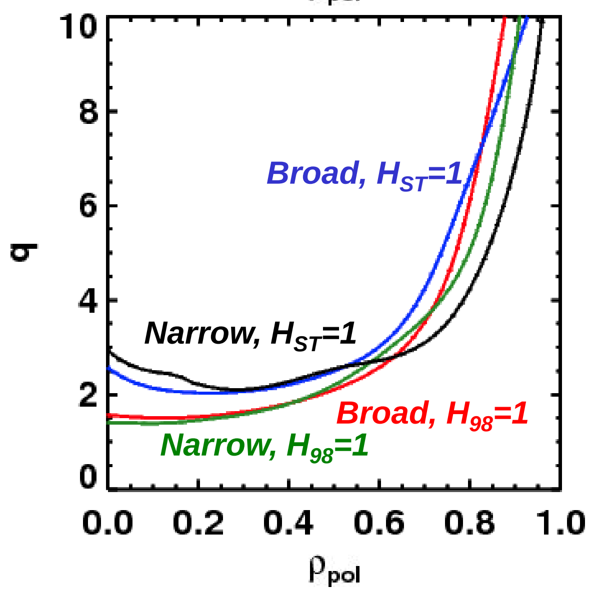
Solid: ST confinement scaling

$$\tau_{ST} \propto I_P^{0.57} B_T^{1.08} \bar{n}_e^{0.44} P_{Loss}^{-0.73}$$

(S. Kaye, NF 2006)

**Free-Boundary TRANSP Calculations**

S.P. Gerhardt, et al, Nuclear Fusion **52** 083020 (2012)

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| $H_{98}$=1 | Broad | 975 | 4.34 | 1.5 |
| $H_{ST}$=1 | Broad | 1325 | 5.32 | 2.0 |
| $H_{98}$=1 | Narrow | 875 | 4.87 | 1.4 |
| $H_{ST}$=1 | Narrow | 1300 | 5.97 | 2.1 |

# Non-Inductive Operating Points Projected Over a Range of Toroidal Fields, Densities, and Confinement Levels

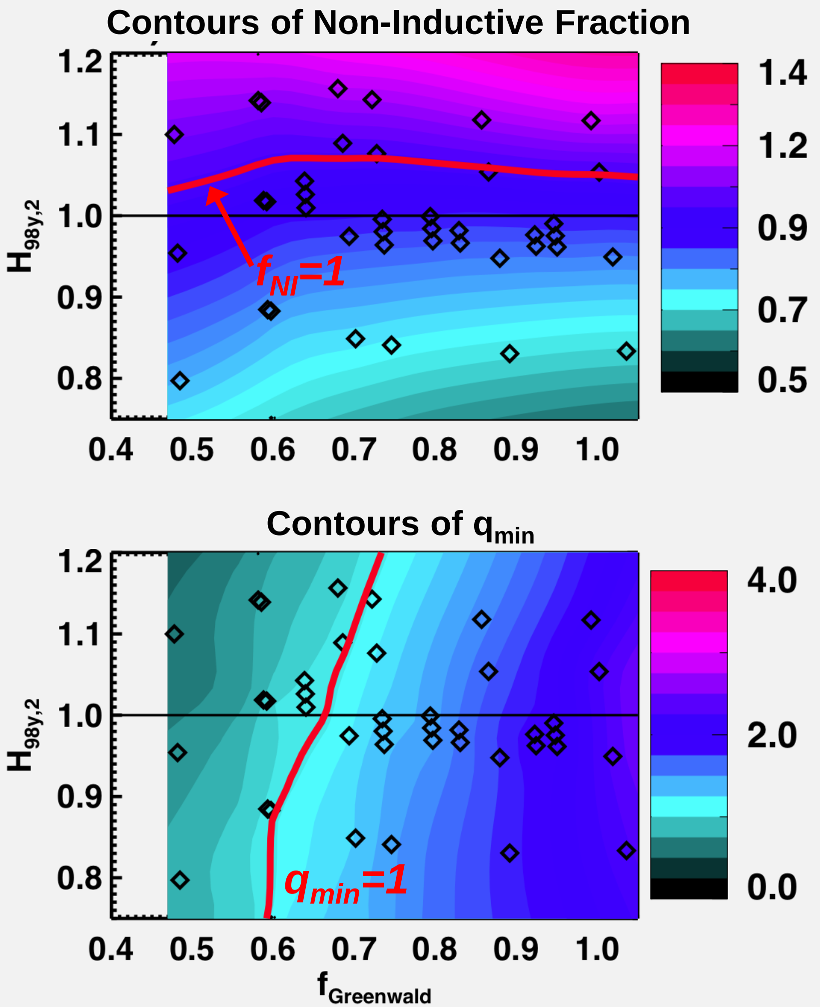
- TRANSP calculations yield research goals for 100% non-inductive sustainment.

| Operation Year | $B_T$ [T] | Current Goal [kA] | Duration Goal |
|---|---|---|---|
| 1 (2014) | 0.75 | ~600-800 | A few $\tau_E$ |
| 2 (2015) | 0.75-1.0 | ~600-1000 | 1-2 $\tau_R$ |
| 3-4 (2016-17) | 1 | 800-1300 | Up to 4.5 s at lower $I_P$ |

- Related research: non-inductive ramp-up:
  - Reduce $I_P$ beneath the 100% non-inductive operating point, assess non-inductive overdrive.
  - See SFSU talk by R. Raman for details.
- Goal for end of 5YP: demonstrate non-inductive formation, ramp-up, and sustainment in a single discharge.

Particle & heat flux control, NBCD tools required to realize these scenarios discussed in upcoming slides.

$B_T$=1.0 T, $I_P$=1 MA, $P_{inj}$=12.6 MW



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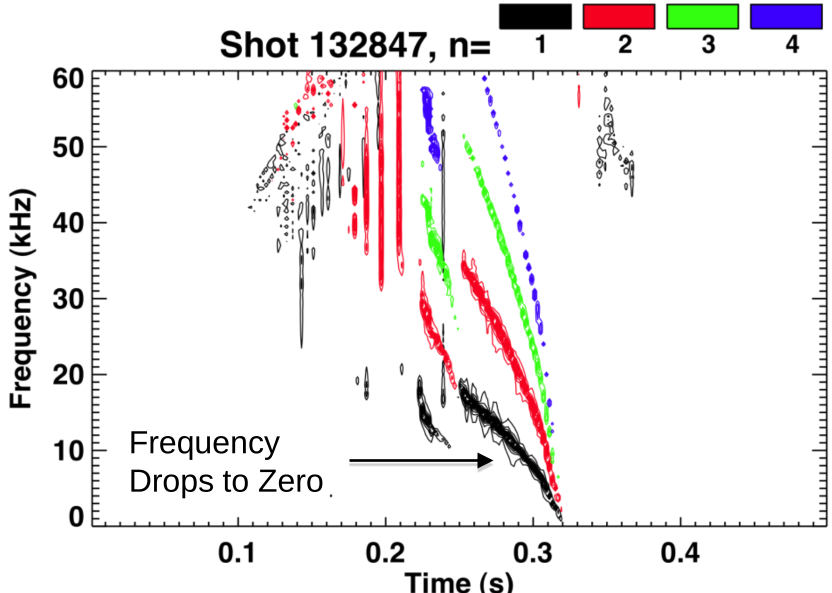
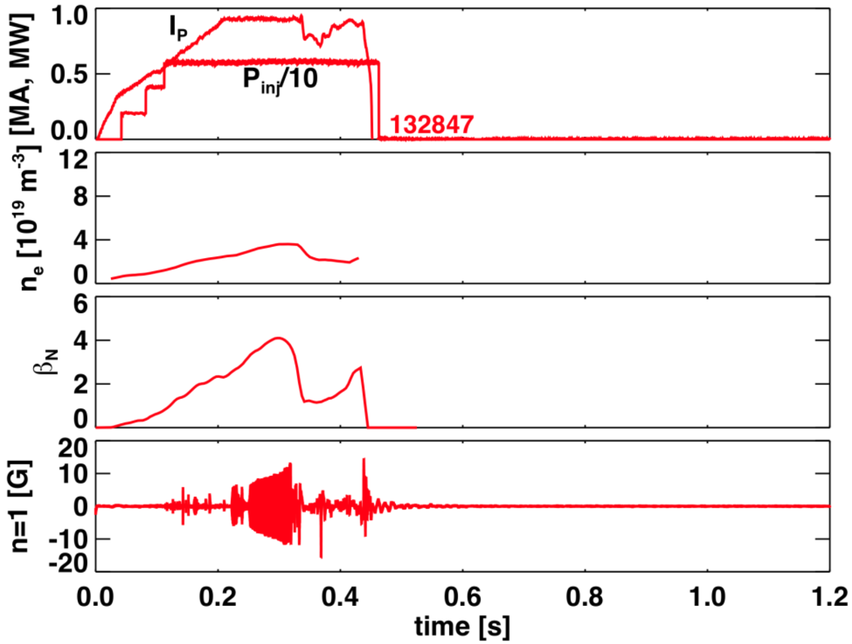
# Optimizing the Early Discharge Evolution Will Play an Important Role in Achieving Low Collisionality at High-Current




132847: Fueled from low-field side



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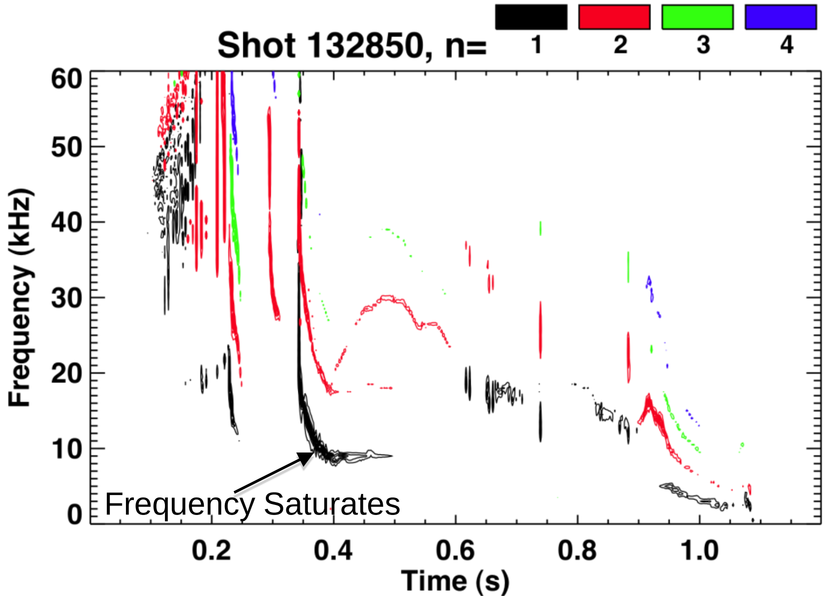
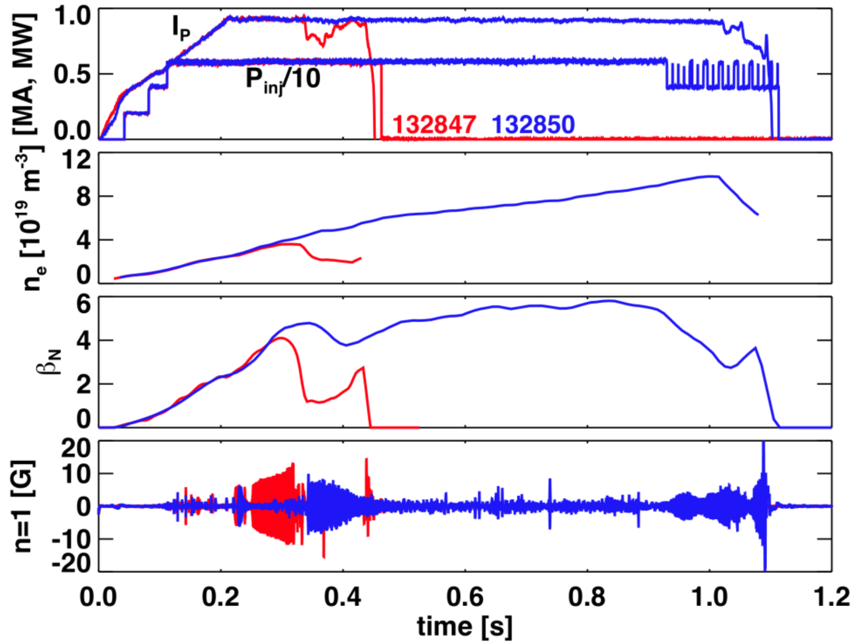



132847: Fueled from low-field side

132850: Fueled from both low- and high- field sides

- Timing and magnitude of fueling has profound impact on discharge evolution, will be optimized in NSTX-U.
  - Will slower $I_P$ ramps w/ larger solenoid facilitate reduced fueling?
  - Will improved solenoid design and reduced error fields improve lower-density startup?
  - Will the extra torque from the new beams reduce prevalence of locking?

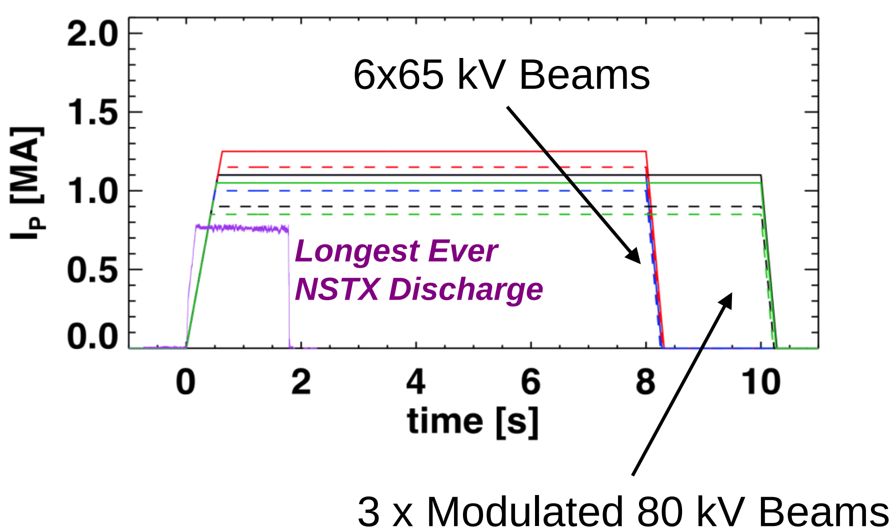
**Milestone R14-1**

# Will Develop Long-Pulse Partial Inductive Operation Up to 2 MA with High Power

*Thrust #1*

- Two motivations for partial inductive operation:
  - High-$I_P$ operation supports collisionality scaling and divertor heat flux studies
  - Long pulse operation for particle retention and disruptivity reduction studies
- Years 1 & 2 of ops. (2015 & 2016): Re-optimize startup for reduced fueling and low collisionality.
  - Optimize fueling, ramp-rate, error field correction, torque input to facilitate reduced density
- Years 3 & 4 of ops. (2017-2018): Performance Extension
  - Discharges up to 2 MA for 5 seconds.
  - Long pulse at ~1 MA for up to 10 seconds
  - Assess HHFW for increased power and profile variations.
- High-$I_P$ & long pulse development will be connected to progress in:
  - Particle Control
  - Heat flux mitigation

$B_T$=0.75 T, ***8-10 Second Discharge***
Scenarios Limited by $q_{min}$>1.1 or OH Coil $I^2t$
2 Confinement and 2 Profile Assumptions




**Addresses milestone R15-3, Supports milestone R15-1**

# Operation Tools for Density & Impurity Control

*Thrust #1*

Years 1 & 2 of ops. (2015-2016): Examine Wall Conditioning, Fueling, and ELM Pacing

**Boronized PFC Studies**

- Utilize regimes with natural ELMs to control impurity accumulation
- Between-shot He glow for wall conditioning
- Deuterium inventory may rise throughout the discharge

**Lithiated PFC Studies**

- High-$\tau_E$, ELM-free regimes w/ Li conditioning
- Pulsed 3D fields or lithium granules for ELM pacing to provide impurity control
- Deuterium inventory likely well controlled, but unclear if target $Z_{eff}$~2 can be achieved

**Techniques to Be Covered in Greater Detail in Talks By Maingi, Soukhanovskii, Jaworski**

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**Both Scenarios:**
Realtime Density Measurements via FIReTIP
PCS control of Supersonic Gas Inj. for Density Control

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# Operation Tools for Density & Impurity Control

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## Years 3 & 4 of ops. (2017-2018): Utilize Cryo-pumping and Partial NCC

### Cryo-pump in lower-divertor to provide deuterium inventory control

- Natural or paced ELMs to control core impurity accumulation
- Make comparisons to regimes with paced ELMs and lithium pumping

### Partial NCC to aid in ELM pacing and RMP studies

- Attempt direct modification of pedestal particle transport via RMP
- Determine optimal spectrum for magnetic ELM pacing, with minimal rotation damping

**Techniques to Be Covered in Greater Detail in Talks By Maingi, Soukhanovskii, Jaworski**

# Full Utilization of the NSTX-U Will Require Heat Flux Mitigation Solutions

- Limit #1: Thermal stresses in target tiles can exceed ATJ graphite limits.
  - Inner horizontal target tiles qualified for 5 sec operation at $Q_{ave}$=5 MW/m$^2$, $Q_{Pk}$=8.0 MW/m$^2$
- Limit #2: Desire to avoid tile surface temperatures exceeding $T_{max}$~1200 C.
  - Due to enhanced sublimation.
- Conservative assumption: $\lambda_q = 0.92 I_P^{-1.6}$ $\quad Q_{Pk} = \dfrac{P_{heat} f_{div} \sin(\theta)}{2\pi R \lambda_q f_{\exp}}$ $\quad Q_{ave} = 0.63 Q_{Pk}$

| | Discharge Parameters | | | Worst-Case Standard DN Divertor $f_{exp}$=15 & $f_{div}$=0.4 | | $f_{exp}$=60 & $f_{div}$=0.4 or $f_{exp}$=15 & $f_{div}$=0.1 | |
|---|---|---|---|---|---|---|---|
| | $I_P$ [MA] | $P_{inj}$ [MW] | Heating Duration [s] | $Q_{Pk}$ [MW/m$^2$] | Time to $T_{max}$ [s] | $Q_{Pk}$ [MW/m$^2$] | Time to $T_{max}$ [s] |
| 100% NI → Long Pulse | 0.75 | 10.2 | 5.0 | 6 | 12.6 | | |
| Long Pulse | 1.5 | 10.2 | 5.0 | 18 | 1.4 | | |
| Long Pulse | 2.0 | 10.2 | 5.0 | 28 | 0.5 | | |
| Highest Power | 1.5 | 15.6 | 1.5 | 27 | 0.6 | | |
| Highest Power | 2.0 | 15.6 | 1.5 | 43 | 0.25 | | |

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- Primary solutions: Broadening the heat channel ($f_{exp}$) via the snowflake divertor
  Increasing the fraction of radiated power (decreasing $f_{div}$)

100% NI → 0.75 MA row

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| Long Pulse | 0.75 | 10.2 | 5.0 | 6 | 12.6 | 1.5 | 200 |
| Long Pulse | 1.5 | 10.2 | 5.0 | 18 | 1.4 | 4.5 | 22 |
| Long Pulse | 2.0 | 10.2 | 5.0 | 28 | 0.5 | 7 | 8.7 |
| Highest Power | 1.5 | 15.6 | 1.5 | 27 | 0.6 | 7 | 9.3 |
| Highest Power | 2.0 | 15.6 | 1.5 | 43 | 0.25 | 11 | 4.0 |

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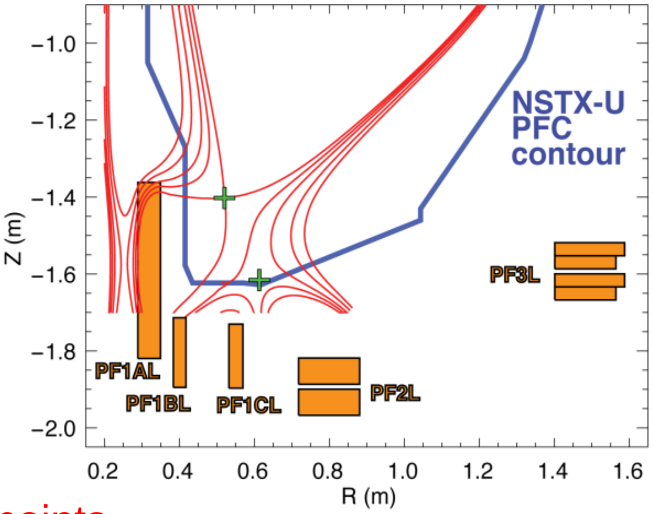
# Snowflake Geometry and/or Divertor Radiation Control Required for High-Current Operation

*Thrust #2*

- Physics of these techniques to be covered in Boundary Physics talk
- Control development plans
  - Pre-operational year (2014):
    - Collaborate on snowflake divertor physics and control experiments at DIII-D
  - Years 1 & 2 of ops (2015-2016):
    - Develop schemes for snowflake divertor control (dual X-point control) using new divertor coils
    - Assess magnetic balance control in the presence of 4 X-points
    - Develop the realtime measurements for divertor radiation control
    - Assess impact on core physics performance
  - Between years 2 & 3 of ops: Install cryo-pump
  - Years 3 & 4 of ops (2017-2018):
    - Utilize cryo-pump + snowflake divertor for increasing the pulse length at higher current
    - Begin implementation of closed loop radiative divertor control
    - Assess impact of divertor/edge impurities on the core scenario

**Snowflake Divertor in NSTX-U**
Increases divertor volume and flux expansion.

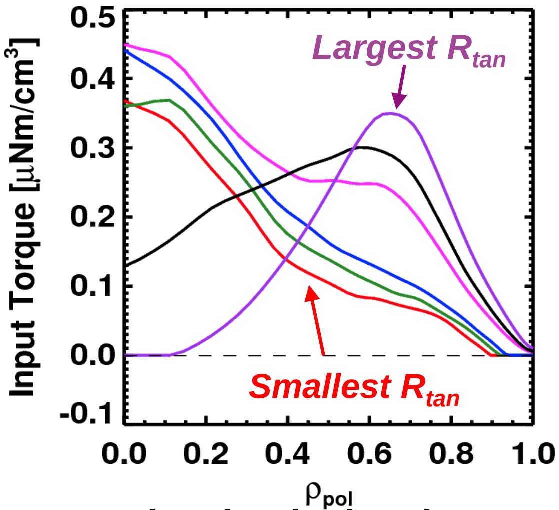



***Milestone R14-3***

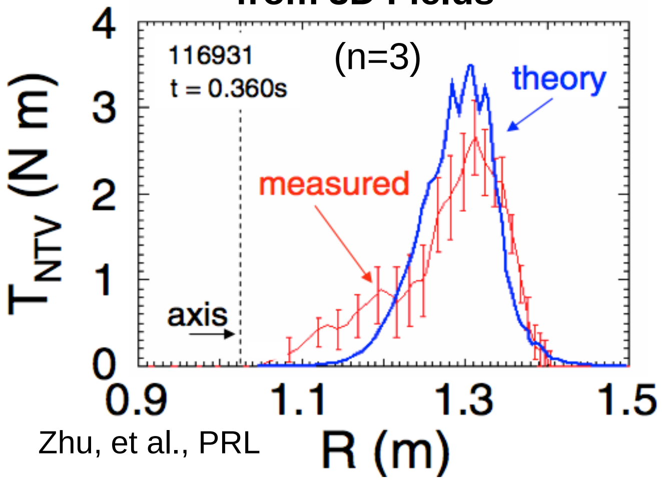
# NSTX-U Will Have Significant Actuators For Profile Control Studies

## Rotation Profile Actuators

**Torque Profiles From 6 Different NB Sources**




**Measured and Calculated Torque Profiles from 3D Fields**




Zhu, et al., PRL

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*Thrust #2*

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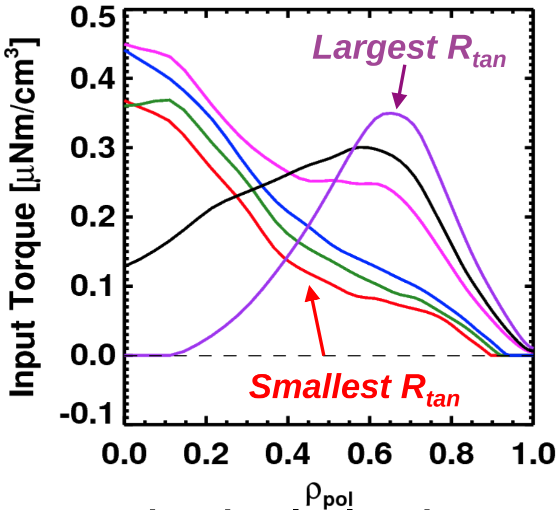


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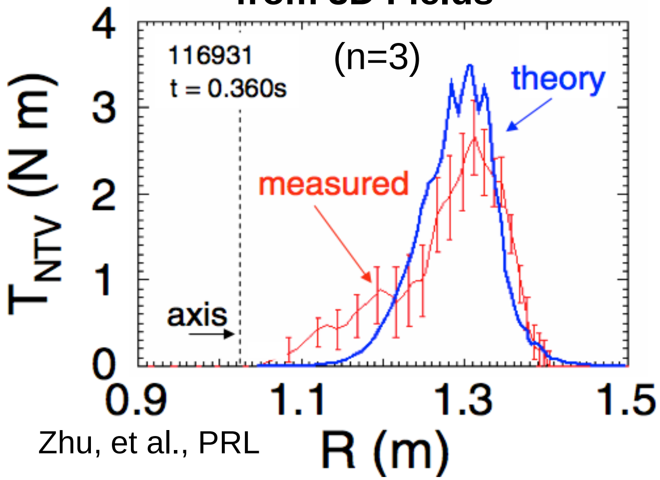
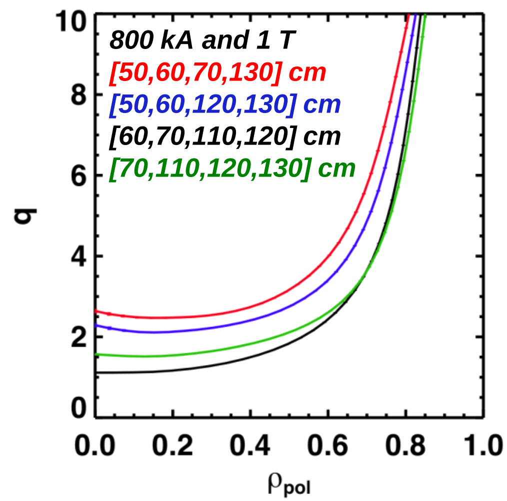


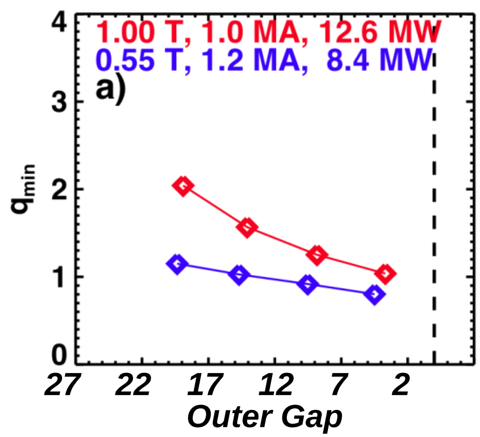

Zhu, et al., PRL

## q-Profile Actuators

**Variations in Beam Sources**
**800 kA Partial Inductive, 87% < $f_{NI}$ < 100%**




**Variations in Outer Gap (1.69<A<1.81)**




**Milestone R14-3**

# Profile Control Techniques Will be Developed To Support NSTX-U Physics Studies and Next-Step ST Designs

*Thrust #2*

- Pre-ops. Year: Continue developing control schemes for NSTX-U actuators.
  - Lehigh: Collaboration on q-profile control algorithms, building on their experience at DIII-D.
  - Princeton University: Collaboration on rotation profile control algorithms.
  - Continue operations collaborations on KSTAR and EAST.
- Years 1 & 2 of ops. (2014-2015):
  - Test ability of different NB source selection to change the q-profile.
    - Study as a function of density, fast-ion $\beta$, source voltage.
    - Assess the NBCD calculations underpinning NSTX-U and most next-step ST studies.
  - Commission real-time MSE (Nova Photonics) and rotation (PPPL) diagnostics.
  - Make first tests of $\beta_N$ + central rotation ($F_{T,0}$) and, if feasible, $\beta_N$+$q_{min}$ control.
- Years 3 & 4 of ops. (2016-2017):
  - Expand rotation control to the full profile.
  - Complete $\beta_N$+$q_{min}$ control and assess combined control, e.g., $\beta_N$+$F_{T,0}$+$q_{min}$.
  - Assess NTV capabilities from NCC for enhanced rotation profile control.
  - Work with MS group to develop physics-based requests for disruption avoidance goals.

***Milestone R14-3***

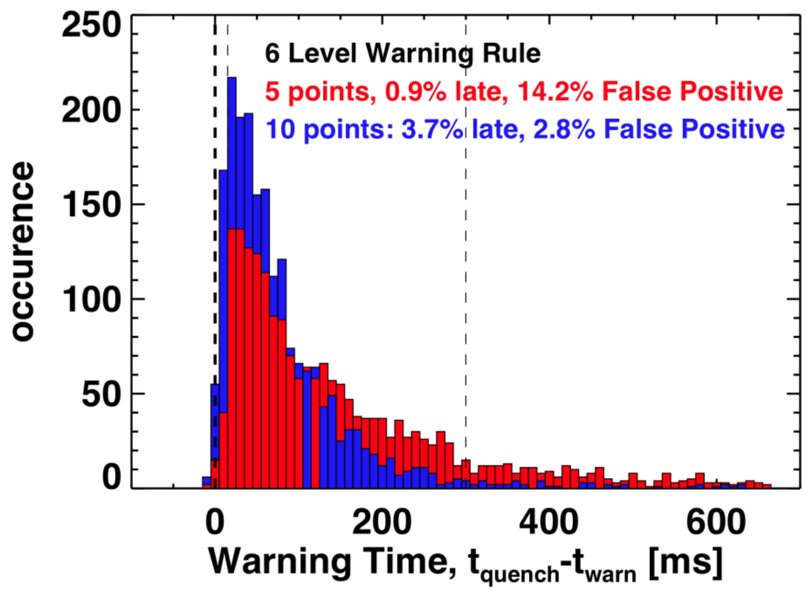
# Outline

- Plans for Entering the First NSTX-U Operations Period
- ASC Research Plans for 5-year Period
  - Thrust 1: Scenario Physics
    - Development of 100% non-inductive operation.
    - Extend the high-current, partial-inductive scenarios to long-pulse.
  - Thrust 2: Axisymmetric Control Development
    - Develop methods to control the heat flux for high-power scenarios.
    - Develop rotation and current profile control.
  - Thrust 3: Disruption Avoidance By Controlled Discharge Shutdown
    - Develop detection of impending disruptions.
    - Develop techniques for the automated termination of discharges.
  - Thrust 4: Scenario Physics for Next Step Devices
    - Determine the optimal, simultaneous q- and rotation profiles.

# Disruption Avoidance Via Discharge Shut-Down Will be Developed

*Thrust #3*

- Disruption detection algorithms have been developed using NSTX data
  - Compare diagnostic data to thresholds & assign “penalty points” when thresholds are exceeded.
  - Sum the “penalty point”, and declare a warning when the point total exceeds a given threshold.
- Provides the foundation of disruption detection in NSTX-U.
- Years 1 & 2 of ops.:
  - Implement basic detector in PCS, and design architecture of control response.
  - Assess accuracy of predictor for NSTX-U disruptions, and refine as necessary.
  - Do initial tests of automated rampdowns.
- Years 3 & 4 of ops.:
  - Add additional realtime diagnostics for improved detection fidelity.
  - Optimize rampdowns for different types of alarms.
  - Incorporate on-line MGI if it appears promising.




Under consideration for an ITPA joint experiment.

(S.P. Gerhardt, et al., accepted for publication in Nuclear Fusion)

**Connections of MS TSG:**

- n>=1 control, including disruption avoidance scenarios, covered by MS TSG.
- MGI physics covered by MS TSG

***Milestone R13-4***

# Outline

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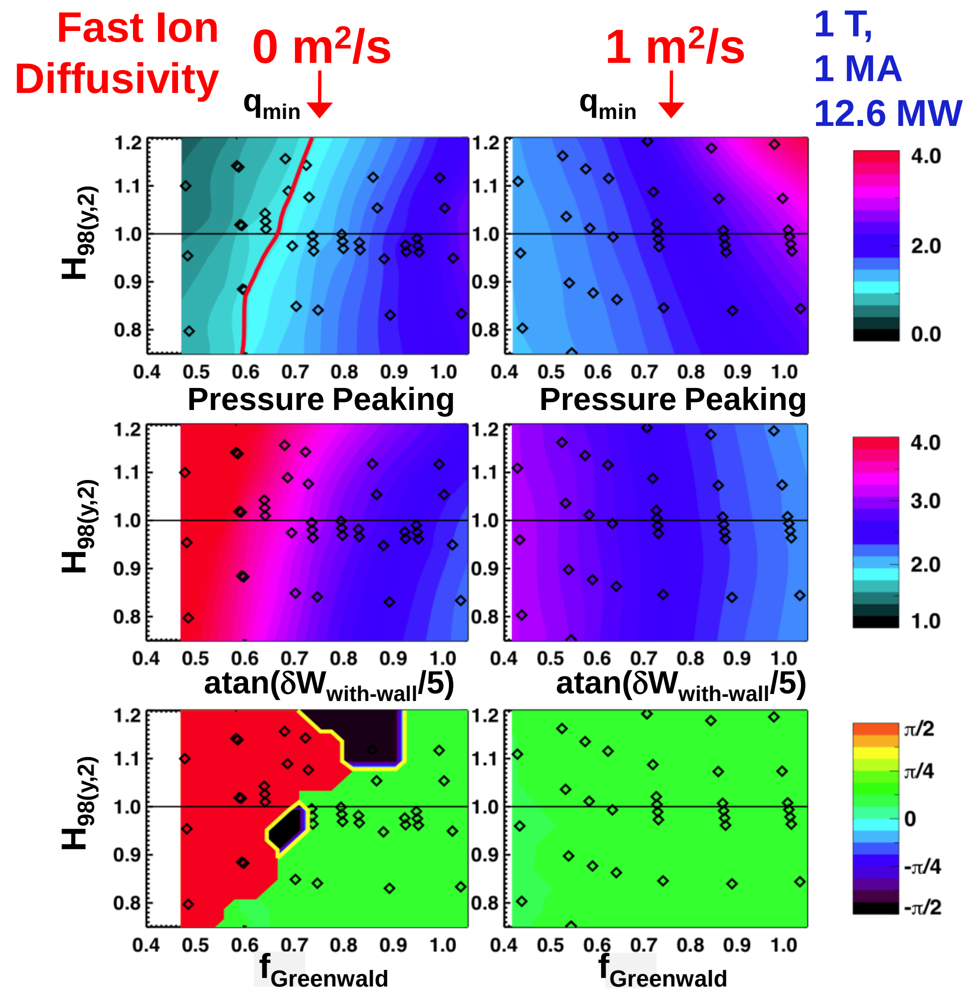
    - Develop rotation and current profile control.
  - Thrust 3: Disruption Avoidance By Controlled Discharge Shutdown
    - Develop detection of impending disruptions.
    - Develop techniques for the automated termination of discharges.
  - Thrust 4: Scenario Physics for Next Step Devices
    - Determine the optimal, simultaneous q- and rotation profiles.
    - Study the conditions for classical beam current drive.
    - Explore & validate integrated models for projections to FNSF.

# Explore Optimal Scenarios for Next Step STs
# All Topics in Collaboration with Other TSGs

- Study optimal current and rotation profiles for confinement and stability.
  - e.g., what value of $q_{min}$ provides the best core confinement and stability?
  - Explore alternative optimal scenarios, such as EPH or w/ ITBs.
- Study the conditions for classical beam current drive
  - Study what parameters determine when *AE modes lead to anomalies in the fast ion diffusion and NBCD.
  - Can anomalous diffusion be used for scenario optimization?
- Assess integrated models for projections to FNSF.
  - Compare NBCD & q-profile predictions from integrated codes to NSTX-U.
  - Project scenarios to ST FNSF devices.




**Red: Internal Modes Unstable**

**Green: stable**

**Blue/Black: External modes unstable**

**Milestone R15-2**

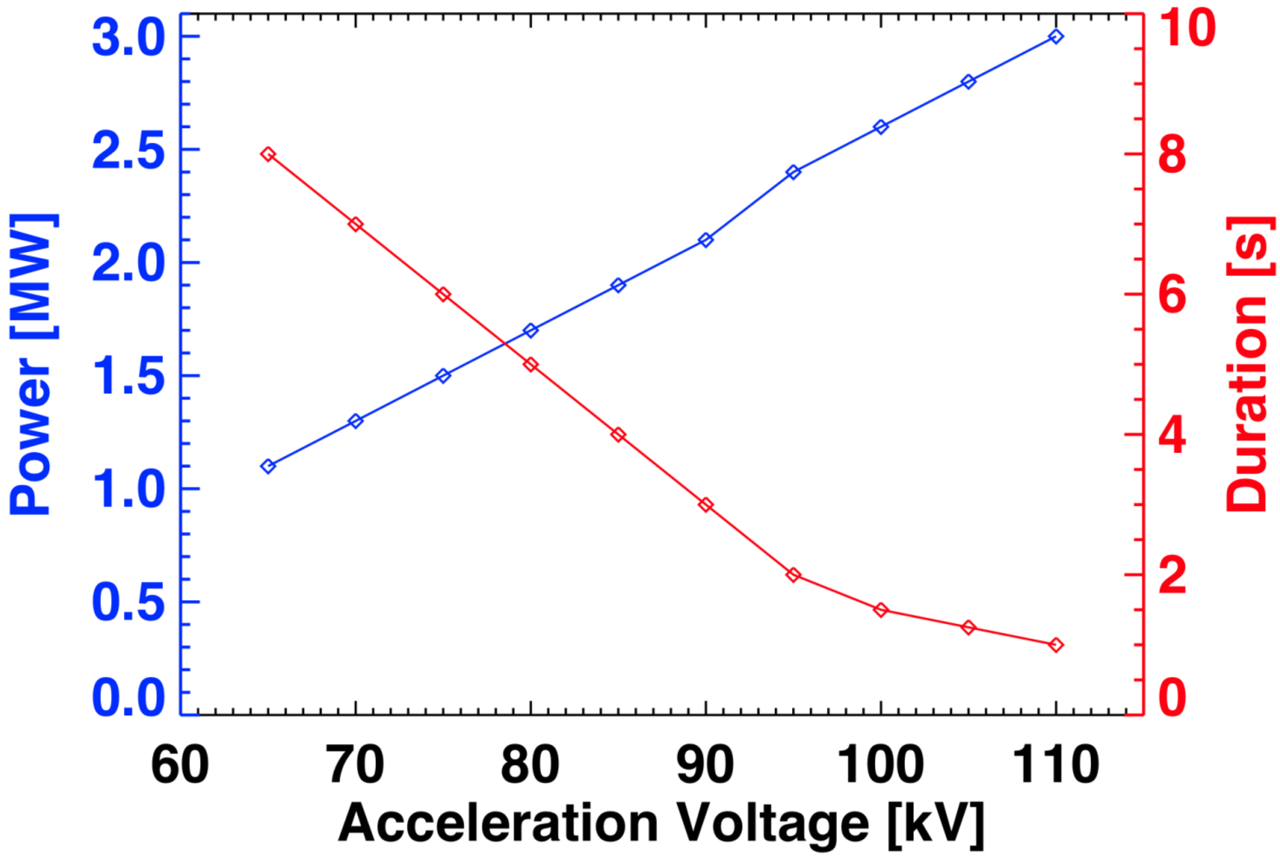
# ASC Research Supports Development of High-Performance Integrated Scenarios for NSTX-U, FNSF & ITER

- Plans for initial NSTX-U operations have been formed, in support of physics program objectives
- ASC 5-year plan designed to provide solutions for
  - the operations needs for the NSTX-U research program, and
  - scenarios for next-step ST scenarios
    - while providing important scenario and control support for ITER.
- Research will address outstanding needs by
  - developing stationary scenarios over a range of non-inductive fractions, plasma currents, and collisionalities
  - developing measurements, algorithms, and actuators for control of
    - the current & rotation profiles,
    - the core density,
    - the divertor geometry and radiation,
  - validating models for NBCD & thermal transport to enable projections for next-step STs

# Backup

# Trade-Off Between Power and Pulse Length For the NSTX (TFTR) Neutral Beams

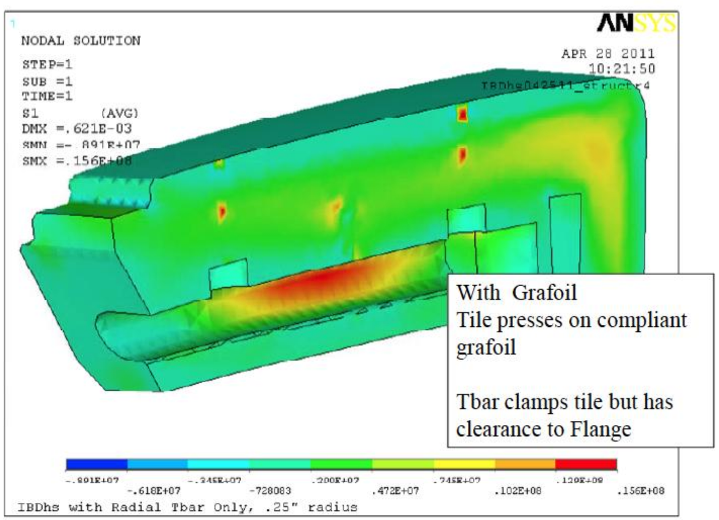
- Pulse duration at a given power limited by heating on the primary energy ion dump.
  - Designs exist to increase the size of the ion dumps, increase the allowed pulse duration.



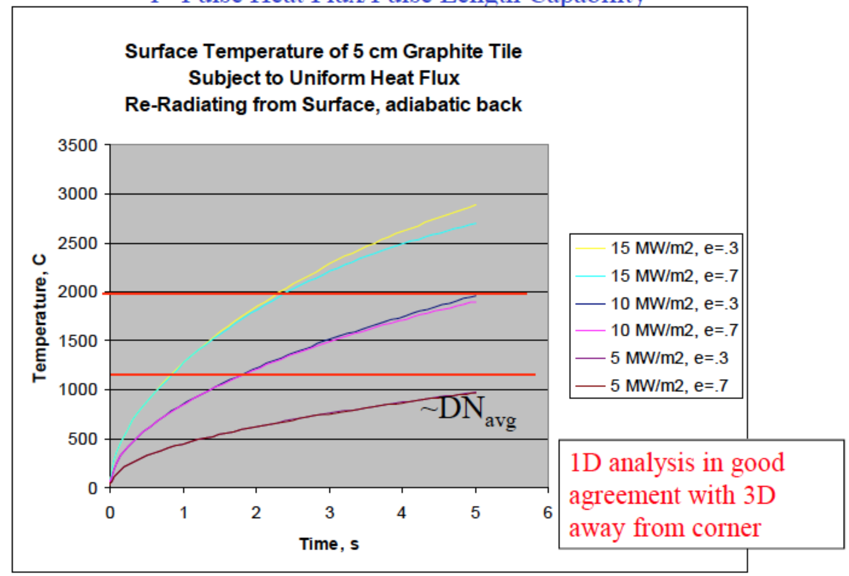
# Criterion For Heat Flux Limits

- Calibrate expression for tile surface temperature against engineering models:
  - $T_{surf}=CQ_{ave}t^{1/2}$
  - Use $T_{surf}$=1000 C, t=5 s, $Q_{avg}$=5 MW/m$^2$.
    - Derive C~90 Cm$^2$/MWs$^{1/2}$
- Derive heat flux Q from simple scalings:

$$Q_{peak}=\frac{P_{heat}f_{div}\sin(\theta)}{2\pi R\lambda_q f_{\exp}} \qquad \lambda_q=0.92I_P^{-1.6}$$




1st Pulse Heat Flux/Pulse Length Capability




11 Single pulse without ratcheting with ATJ Graphite

| | Summary of Tile Thermal Structural Response | | | | |
|---|---|---|---|---|---|
| | Heat Flux for 5s | Ratcheted Temperature | Peak Tensile Principal Stress, S1 | Peak Compress Principal Stress, S3 | Max Deflection |
| | mw/m2 | C | MPa | | mm |
| IBDhs, surface | 5.0 | 1062 | 15.6 | -58.0 | 0.6 |
| Hot Spot at Corner | | 1512 | | | |
| IBDvs, surface | 1.6 | 425 | 7.0 | -16.3 | 0.1 |
| Hot Spot at Hole | | 560 | | | |
| CSAS, surface | 1.6 | 327 | 8.2 | -10.7 | 0.2 |
| Hot Spot at Hole | | 417 | | | |
| CSFW | 0.2 | 260 | 1.6 | -6.5 | 0.01 |

# Physics and Engineering Operations Activities Over the Next ~Year Will Provide the Baseline For NSTX-U Operations

- Upgrading the Plasma Control System (PCS) for NSTX-U.
  - Upgrading to new 32-core computer.
  - Switching to 64 bit real-time Linux with advanced debugging tools.
  - Upgrading shape-control codes for new divertor coils, gas injector controls for new/additional injectors, additional physics algorithms
  - Improving the real-time data-stream.
  - Assisting with development of a new Digital Coil Protection System (DCPS).
- Upgrading HHFW antenna feedthroughs for higher disruption forces.
- Boundary Physics Operations
  - Improving the PFC geometry in the vicinity of the CHI gap to protect the vessel and coils.
  - Developing an upgraded Boronization system.
  - Developing lithium technologies (granule injector, upward LITER).
- Diagnostic Upgrades
  - Fabricating new port covers to support high-priority diagnostics.
  - Installing additional, redundant magnetic sensors.
  - Upgrading diagnostics: Bolometry (PPPL), ssNPAs, spectroscopy (collaborators)
- Physics & Engineering Operations
  - Replacing electronics that control & protect rectifiers.
  - Upgrading the poloidal field coil supplies to support up-down symmetric snowflake divertors.
  - Developing PF null/breakdown scenario w/ new CS.

# Pursue 100% Non-Inductive Current at Progressively Higher $I_P$ and $B_T$

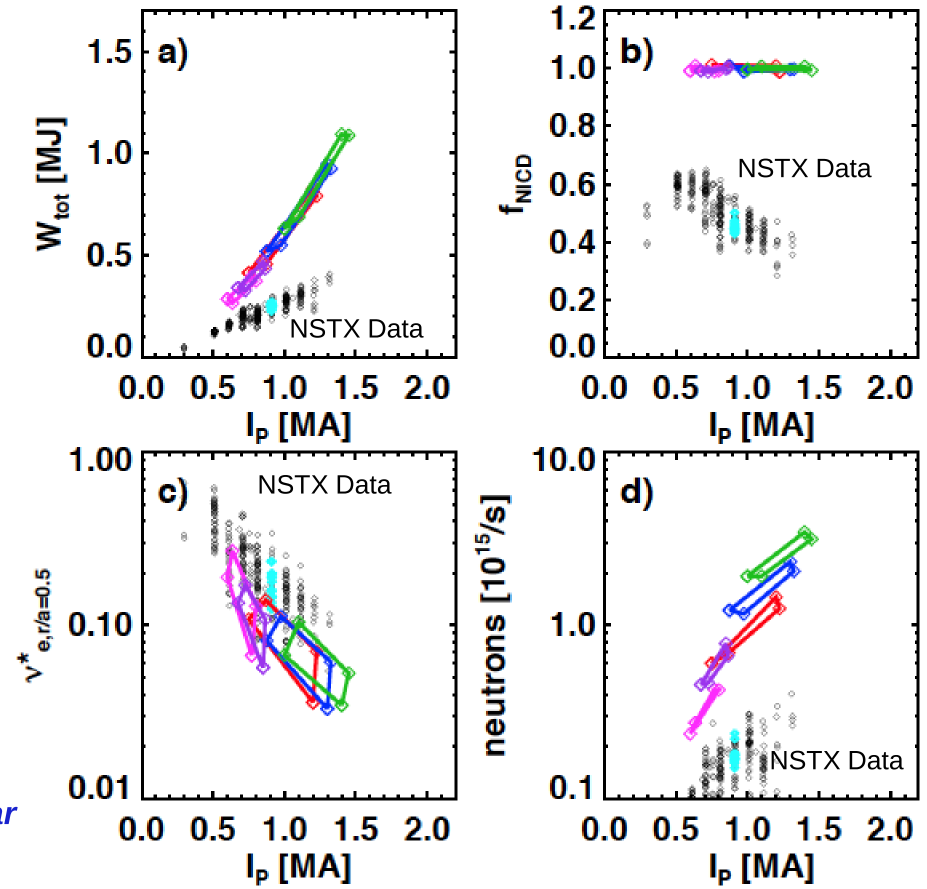
- Free-Boundary TRANSP calculations of NSTX-U operations points.
  - See: S.P. Gerhardt, et al, Nuclear Fusion **52** 083020 (2013)

Projected Non-Inductive Current Levels for $\kappa$~2.85, A~1.75, $f_{GW}$=0.7

| $B_T$ [T] | $P_{inj}$ [MW] | $I_P$ [MA] | Heating Duration [s] |
|---|---|---|---|
| 0.75 | 6.8 | 0.6-0.8 | 5 |
| 0.75 | 8.4 | 0.7-0.85 | 3 |
| 1.0 | 10.2 | 0.8-1.2 | 5 |
| 1.0 | 12.6 | 0.9-1.3 | 3 |
| 1.0 | 15.6 | 1.0-1.5 | 1.5 |

## TRANSP Projections for 100% Non-Inductive Scenarios

Each polygon for a given engineering configuration, multiple profile and confinement assumptions




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 } *End of year 1 target*

# Shape/Position & Fueling Control Will Be Developed to Support NSTX-U Operations



- Shape/Position Control Considerations
  - Vertical control of high-A NSTX plasmas found to be problematic when $l_i$ exceeded ~0.6.
  - Boundary and PMI research programs will require accurate control of the strikepoints.
- Years 1 & 2 of ops.
  - Assess vertical stability of NSTX-U plasmas.
  - Improve control as necessary via better algorithms or measurements.
  - Re-tune strike-point controllers for new divertor coils.
- Years 3 & 4 of ops.
  - Implement realtime n=0 stability and loss of control assessments.
    - Connection to Thrust #3.

- Fueling Control Considerations
  - Realization of lowest-collisionality will require high-efficiency fueling.
  - Full utilization of the cryo-pump will require better control of fueling
- Years 1 & 2 of ops.
  - Utilize super-sonic gas injection for improved fueling during the current ramp.
  - Develop realtime density measurements.
  - Assess closed-loop density control during the current ramp.
- Years 3 & 4 of ops.
  - Utilize cryo-pumping + advanced fueling to achieve closed-loop density control during the discharge flat-top.