NSTX-U: Plans and Status

10th US-PRC Meeting – March 22, 2021

S.M. Kaye
NSTX-U Director of Research
Low aspect ratio “Spherical Torus / Tokamak” (ST) vital for toroidal science and fusion energy development

- ST accesses unique regime of high $\beta_T$
  - Fundamental changes in nature of turbulence, MHD stability
  - Enhanced electromagnetic and super-Alfvénic effects
- STs can more easily measure electron-scale turbulence
  - Important transport channel at all aspect ratio
- Neutral beam fast-ions in present STs mimic DT $\alpha$ populations
  - Study burning plasma science
- Expanded parameter space crucial for model validation
- If physics results favorable, STs could provide more economical fusion development & energy systems
  - Potentially reduced magnet and device size and cost
Outline of Presentation

• What is NSTX-U?
• NSTX-U Mission
• NSTX-U Research Plan
• NSTX-U Recovery status
Outline of Presentation

• What is NSTX-U?
• NSTX-U Mission
• NSTX-U Research Plan
• NSTX-U Recovery status
NSTX → NSTX-U: Two major upgrades

1. New Central Magnet
2. Tangential 2nd Neutral Beam
NSTX ➔ NSTX-U: Two major upgrades

1. New Central Magnet
   ➢ 2× toroidal field (0.5 ➔ 1T)
   ➢ 2× plasma current (1 ➔ 2MA)
   ➢ 5× longer pulse (1 ➔ 5s)

2. Tangential 2nd Neutral Beam

→ Unique regime

Study new transport and stability physics
NSTX → NSTX-U: Two major upgrades

1. New Central Magnet
   ➢ 2× toroidal field (0.5 → 1T)
   ➢ 2× plasma current (1 → 2MA)
   ➢ 5× longer pulse (1 → 5s)

2. Tangential 2\textsuperscript{nd} Neutral Beam
   ➢ 2× heating power (5 → 10MW for 5s)
     • Tangential NBI → 2× $\eta_{cd}$
     • Up to 15MW NBI + 4MW RF for 1-2s
   ➢ Up to 10× higher nT$\tau_E$ (~MJ plasmas)
   ➢ 4× divertor heat flux (→ ITER levels)

→ Sustain plasma without transformer
   Not yet achieved at high-$\beta_T$, low $\nu^*$
   Essential for any future steady-state ST
## Engineering parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NSTX</th>
<th>NSTX-U</th>
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<tbody>
<tr>
<td>R/a</td>
<td>0.85/0.65 m (A=1.3)</td>
<td>0.95/0.55 (A=1.7)</td>
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<td>$B_T (@R_0)$</td>
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<td>$I_p$</td>
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<td>SN, DN – conventional, SF</td>
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<td>Wall conditioning</td>
<td>B &amp; Li evaporation</td>
<td>B &amp; Li evaporation</td>
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Outline of Presentation

- What is NSTX-U?
- NSTX-U Mission
- NSTX-U Research Plan
- NSTX-U Recovery status
NSTX-U will provide unique regimes in the initial years of operations required to **optimize the geometry** \((R/a, \kappa, \delta)\) **of next-step devices**

- NSTX-U will explore ST physics towards reactor relevant regimes (low A Pilot Plant, Fusion Nuclear Science Facility,)
- NSTX-U will provide unique regimes for studying burning plasma-related physics and improve predictive capabilities
- NSTX-U will evaluate integrated operations with liquid metal PFCs that would enable compact systems
Research thrusts of NSTX-U address routes to optimizing design for compact Pilot Plant

High-\(\beta_n\) (>5) and strong shaping (\(\kappa>2.5\)) route to non-inductive operation

Dimensionless confinement time scales inversely with collisionality at low-A

Kinetic stabilization of RWM provides increase of stability for \(\beta_n/l_i \rightarrow 10\) at critical rotation

Provides possible transformative route to next-step, compact device
NSTX-U will access unique regimes critical for prediction and optimization in Burning Plasmas

NSTX-U will produce and study EP modes relevant to alpha driven instabilities expected at both high- and low-aspect ratio

NSTX-U will play important role in understanding how the power exhaust width extrapolates to future devices

![Diagram]

- XGC1 simulations
- 2MA NSTX-U
- $R^2 = 0.86$

\( \lambda_q [\text{mm}] \text{ (exp.)} \)

\[ \beta_{\text{fast}} / \beta_{\text{total}} \]

~ (EP-instability drive)/(EP-instability damping)
The longer-term (5-10 yrs) mission has directed its focus on testing Liquid Metal PFCs.

**NSTX:** Higher lithium deposition $\rightarrow$ higher confinement

**NSTX-U** near-term: Li deposition, effect on confinement (carbon tiles)

**Long-term (2026-2030):** Test liquid metals as transformative wall solution:

**Possible sequence**

- Phase I: prefilled high-Z tiles/LM modules
- Phase II: complete toroidal coverage (LM divertor/Vapor Box)
Outline of Presentation

• What is NSTX-U?
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NSTX-U Research Plan targets three high-level Objectives

1. Extend confinement and stability physics basis at low-A and high beta to lower collisionality relevant to burning plasma regimes

2. Develop operation at large bootstrap fraction and advance the physics basis required for non-inductive, high-performance and low-disruptivity operation of steady-state compact fusion devices

3. Develop and evaluate conventional (shorter-term) and innovative (liquid lithium – longer term) power and particle handling techniques to optimize plasma exhaust in high performance scenarios

• Support additional critical fusion science and technology development (e.g., ITER) needs utilizing the unique regimes accessible in NSTX-U
Obj. 1: Extend confinement and stability physics basis at low-A and high beta to lower collisionality relevant to burning plasma regimes

- NSTX-U will operate at up to a factor of six lower ν* than NSTX to verify collisionality scaling at low A ($\Omega_{ci}\tau_E\sim\nu^{*-0.8}$)
- Transport at low A is fundamentally different from that at conventional A: high β drives electromagnetic instabilities (microtearing, KBM/EPM)
  - ETG & TEM may also be important
  - Research priority to understand transport mechanisms beyond just ITG/TEM/ETG
- Ideal MHD does not accurately describe NSTX ELM stability: resistive MHD, microinstabilities important
  - Research priority to understand transport & stability mechanisms setting pedestal structure (n & T) and ELM stability, especially at reduced ν
Obj. 2: Develop operation at large bootstrap fraction and advance the physics basis required for non-inductive, high-performance and low-disruptivity operation of steady-state compact fusion devices

- NSTX-U will explore the unique high-$\beta_n$ (>5) and strong shaping ($\kappa$$>$2.5) route to high bootstrap current fractions ($f_{bs} \sim \kappa \beta_n/l_i$)
  - Access to high $\kappa$ enabled by operating at low-$l_i$
  - Low $l_i$ facilitated by early L-H transition in ramp-up

- NSTX-U will avoid core MHD that constrained operational space on NSTX
  - Operations in 2016 demonstrated MHD quiescent ramp-up with larger $B_T$, tangential NBI, slower $I_p$ ramp rate and different error fields
NSTX-U will explore means of controlling EP-driven instabilities that can inhibit non-inductive operations

- EP-driven instabilities degrade NBI deposition and both fast-ion & thermal confinement
  - TAE, RSAE reduce neutrons and CD efficiency [Podestà 2019]
  - GAE, CAE hypothesized to limit central $T_e$ [Gorelenkov 2010; Belova 2015]

- Modification of fast-ion distribution using tangential NBI can stabilize EP modes that enhance transport
  - Study and develop techniques to suppress alpha-driven modes through phase-space engineering
  - RF (HHFW) has also shown ability to suppress EP-driven modes

Fredrickson 2018
Obj. 3: Develop and evaluate conventional and innovative power and particle handling techniques to optimize plasma exhaust in high performance scenarios

- NSTX-U heat flux metrics advance towards those of next-step devices (P/R, P/S)
  - Castellated, toroidally fishscaled tiles designed for high heat flux regions (temperature, not stress limited)
- Enhanced divertor and core radiation solutions will be investigated
  - Access radiative and detached divertors, using impurity gases and solid powders
- Compare boron and lithium wall conditioning techniques
  - Longest discharges obtained with lithium wall pumping: stationary with $f_{GW} \rightarrow 1$
  - Highest confinement obtained with lithium wall pumping: $H_{98y,2} \sim 1.8$
Outline of Presentation

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Recovery scope extends beyond PF coils

Machine Core Structures

Tiles

Outer Poloidal Field Coil

Casing – Inner Vacuum Boundary

Tiles

Inner-PF Coils

Machine Core Structures

2 m
Recovery components

• New inner PF coils designed to improve testability and ease of manufacture

• New centerstack casing being fabricated to accommodate full load spectrum

• Passive plates modified to support full EM loads

• Plasma Facing Components are being designed to meet full performance thermal and EM loads with high reliability

• Machine instrumentation system will allow benchmarking and trending
Summary

• NSTX-U high-level research goals directed towards optimizing designs of next-step compact devices, studying aspects of burning plasma physics
  • Vital for developing predictive capability for fusion science through leverage provided by expanded operating regime
• Researchers from 19 institutions comprise the NSTX-U research team
  • Operate as a User Facility
• NSTX-U researchers are presently preparing for NSTX-U operation, and they are involved in domestic and international collaborations that can impact NSTX-U research
• NSTX-U Recovery project delayed significantly due to COVID
  • Presently working towards early finish in Summer 2022
NSTX-U and MAST-U are the most capable devices in a world-wide ST research program

**NSTX-U**

**Similar features:**
- Major radius $R = 0.8\text{-}1\text{m}$
- Plasma current up to 2MA
- Pulse durations $1\text{s} \rightarrow$ up to 5s
- Strong neutral beam heating

**MAST-U (UK)**

**Having both NSTX-U and MAST-U important to confirm unique ST results**

**Complementary Research:**

**Core emphasis**
- Highest magnetic field, pressure
- Highest plasma beta in large ST
- $2\times$ higher max power (NBI+RF) and edge heat fluxes
- $2\times$ higher self-driven current
- Only large ST with RF heating

**Boundary emphasis**
- Highly-flexible “long-leg” divertor for power exhaust research
- Only large ST with off-midplane 3D magnetic field coils for edge instability control
STs will provide leading contributions to development and understanding of advanced divertors

**NSTX-U:** Short-leg flared divertor + radiation to mitigate heat flux

**MAST-U:** World-leading pumped long-leg + flexible flaring, radiation

New PF1 magnets for flaring control, highest shaping, highest ST edge parallel heat flux

Together provide science basis to integrate high performance ST core with advanced power exhaust
Obj. 1: Extend confinement and stability physics basis at low-A and high beta to lower collisionality relevant to burning plasma regimes

- Dimensionless confinement time on NSTX scaled inversely with collisionality at low-A ($\Omega_{ci}\tau_E \sim \nu^* - 0.8$)
  - NSTX-U will operate at up to a factor of six lower $\nu^*$ than NSTX to verify scaling
- Transport at low A is fundamentally different from that at conventional A: high $\beta$ drives electromagnetic instabilities
  - Microtearing modes (MTM) $\sim \beta_e \cdot \nabla T_e$ (large scale & amplitude $\sim \delta B$)
  - Kinetic ballooning modes (KBM) & energetic particle modes (EPM) $\sim \alpha_{\text{MHD}} \sim q^2 \nabla P / B^2$ & $\nabla P_{\text{fast}}$
- Additional mechanisms may also be important
  - Electron temperature gradient (ETG) at $k_{\perp} \rho_e \sim 1$; dissipative TEM [W. Wang, 2015]
- Research priority to understand transport mechanisms beyond just ITG/TEM/ETG
MHD-based pedestal model (EPED) successful at conventional-A, **insufficient** to predict NSTX H-mode pedestals

- “Boundary critical pedestal” (BCP) model for KBM does not recover NSTX ELMy or ELM-free width scaling
  - KBM alone also insufficient to predict kinetic profiles (n, T)

- NSTX pedestals typically close to KBM thresholds, but GK analysis predicts additional instabilities (ETG, TEM, MTM)
  
  [Canik 2013, 2016; Coury, 2016; Battaglia, 2020]

- Ideal MHD does not accurately describe NSTX ELM stability → resistive MHD possibly important in NSTX ($v^*_{,ped} > 0.5$)

- Research priority to understand transport & stability mechanisms setting pedestal structure (n & T) and ELM stability, especially at reduced n
NSTX-U will explore means of controlling EP-driven instabilities that can inhibit non-inductive operations

- EP-driven instabilities degrade NBI deposition and both fast-ion & thermal confinement
  - TAE, RSAE reduce neutrons and CD efficiency [Podestà 2019]
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- Modification of fast-ion distribution using tangential NBI can stabilize EP modes that enhance transport
  - Study and develop techniques to suppress alpha-driven modes through phase-space engineering
  - RF (HHFW) has also shown ability to suppress EP-driven modes

More unstable to EP-driven modes
Obj. 3: Develop and evaluate conventional and innovative power and particle handling techniques to optimize plasma exhaust in high performance scenarios

- Enhanced divertor and core radiation solutions will be investigated
  - Access radiative and detached divertors, using impurity gases and solid powders
  - Measure heat flux mitigation in standard and Snowflake divertor shapes and compare with 2-D numerical model predictions, e.g. UEDGE
- Test diagnostics for feedback control
- NSTX-U heat flux metrics advance towards those of next-step devices (P/R, P/S)
  - Castellated, toroidally fishscaled tiles designed for high heat flux regions (temperature, not stress limited)
Boron and lithium wall conditioning techniques will be compared

- Longest discharges on NSTX enabled by lithium wall pumping
  - Stationary density with $f_{GW} \to 1$
  - ELMs, which mitigate accumulation of impurities, can be controlled through amount of lithium deposited
  - Highest energy confinement on NSTX realized with largest lithium wall pumping ($H_{98y,2} \sim 1.8$)

- Full parameter (5s, 2MA, 10 MW) discharges may challenge PFC limits
Objective 1 deliverables and impacts (three Thrusts)

- Impacts
  - Results inform design of aspect ratio and geometry for FPP
  - Validated understanding of processes leading to optimized performance
  - Integrated whole-device simulations/predictions for next-step devices
Objective 2 deliverables and impacts (three Thrusts)

- **Impacts**
  - Particle control for long-pulse stable long-pulse operation
  - Disruption prediction/avoidance for next-step tokamaks, including ITER
  - Real-time profile control capability development
  - Integrated non-inductive operation techniques from discharge current ramp-up through sustainment phases for next-step devices, including FPP

**5 year plan period**

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<th>FY</th>
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<td><strong>Thrust 3</strong></td>
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</table>

- Particle control enabling long pulse
- High \( f_{bs} \): ELM-free, impurity heat flux mitigation
- Kinetic stabilization of RWM at low collisionality
- Disruptivity at high \( f_{bs} \): R/T disruption predict/avoid
- Fully non-inductive for multiple \( t_{cur} \)
- Faster than R/T forecasting
- V-s reduction during ramp-up

FY 21-25 (5 year plan period)
Objective 3 deliverables and impacts (four Thrusts)

- **Impacts**
  - Ability to engineer solid PFCs for compact high heat flux devices
  - Heat flux control for high power densities; Real-time wall conditioning techniques
  - Expanded liquid Li PFC program on NSTX-U
  - Surface chemistry changes in long pulse wall
First detailed measurements of high-k (electron-scale) turbulence across L-H transition in NSTX reveal broad spectral changes

- Multiple turbulence phases identified across the L-H transition
- Suppression of high-k turbulence at lower wavenumbers, i.e., $k_{\perp\rho_s} \leq 9-10$ (higher wavenumbers unaffected); similar to changes at ion scale (BES)
Mechanisms leading to Enhanced Pedestal (EP) H-mode are being better understood

- EP H-mode is an attractive, potentially steady-state ELM-free regime
  - $H_{98y,2}$ typically $\sim$1.5, reached 1.8
  - Reduced density and impurity accumulation
- Decrease in edge density following an ELM initiates a period of reduced edge collisionality
  - Reduced $\nu^*$ drives reduction in neoclassical transport
- Increased edge $\nabla p$ leads to higher anomalous transport (KBM/TEM)
  - Maintains lower edge density
- Balance between the two transport mechanisms results in maintenance of reduced $\nu^*$, edge $\nabla p$, higher $\tau_E$
Gyrokinetic analyses shed light on source of core and edge transport

- Linear CGYRO analysis identifies unstable MTM & TEM outside \( r/a \geq 0.6 \) (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 \( T_e \)
Electron-scale (ETG) turbulence can account for anomalous electron loss in lower-\(\beta\) 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 simulations in an NSTX H-mode at intermediate \(\beta\) suggest multiscale simulations may be important
  - Similar to multiscale effect found in C-Mod
  - Strong ETG drive + near-marginal ion-scale stability (Howard, NF 2016)

Ruiz Ruiz talk (next)
Obj. 3: Develop and evaluate conventional and innovative power and particle handling techniques to optimize plasma exhaust in high performance scenarios

- Enhanced divertor and core radiation solutions will be investigated
  - Access radiative and detached divertors, using impurity gases and solid powders
  - Measure impurity fraction for power exhaust and compare with analytic models (Goldston PPCF 2017, Reinke NF 2017)

- Measure heat flux mitigation in standard and SFD shapes and compare with 2-D numerical model predictions, e.g. UEDGE
  - Poloidal injection location, divertor compression ratios, impurity species…

- Test diagnostics for feedback control
Pre-filled liquid Li plugs inserted in a high-z tile will be evaluated for heat flux mitigation

- Liquid Li PFCs have potential to increase power exhaust capability relative to solids, and increase confinement

- Two concepts considered for power exhaust: slow flow, evaporative systems (Li vapor box) and fast flow, convective flow systems

- We plan to implement pre-filled Li plugs into high-Z tile within five years
  - Builds on MAGNUM-PSI results that show favorable use of pre-filled Li reservoirs in 3D printed W mesh ($q_{\text{peak}} \geq 11 \text{ MW/m}^2$)
  - System will be tested in a vacuum test stand and possibly on LTX-β

Rindt Ph.D. Thesis, 7/2019
Modification of fast-ion distribution using tangential NBI can stabilize EP-drive modes

- Computational (HYM) and analytic models reproduce AE stabilization with tangential beam
  - Models identify regions of stability with regards to NBI parameters
  - Calculations indicate only a small fraction of tangential beam particles needed to stabilize mode

- Experiments and theoretical understanding allow for development of techniques to suppress EP (and potentially alpha)-driven modes through phase space techniques

J. Lestz APS invited 2019
E.V. Belova et al., PoP submitted
Reduced models for EP transport due to sub-TAE instabilities being developed

- ‘Kick model’ in TRANSP extended from high-f (AE) version to include EP transport by low-f modes
  - Low-f NTMs, kinks, fishbones, and sawteeth coexist with AEs
  - Extended kick model validated with NSTX-U data
    - Improves upon ad-hoc models already implemented in TRANSP
    - Critical for understanding effect of modes on beam-driven current (and development of non-inductive scenarios)

- 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
Global stability increased for \( \beta_N/l_i > 10 \) at critical rotation

- Kinetic stabilization of the RWM for critical rotation
- Prediction that stabilization could improve at lower collisionality will be tested on NSTX-U

- NSTX-U will explore the high-\( \beta_n \) (>5) and strong shaping (\( \kappa > 2.5 \)) route to high bootstrap current fractions (\( f_{B_S} \sim \kappa \beta_N/l_i \))
- Coupled with enhanced transport and stability properties at low-A (Obj. 1), provides possible transformative route to non-inductive operation
- ST/Tokamak HTS Fusion Pilot Plant concepts: \( H_{98y,2} = 1.5 – 2 \) for \( f_{BS} > 60\% \)
Reduced tearing mode models allow for mapping stable regimes in high-performance scenarios

- Full toroidal $\Delta'$ required to predict TM stability in high-$\beta$, ST geometry with ‘extreme toroidicity’

- RDCON is a reduced model that can calculate toroidal $\Delta'$
  - 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

Onset of tearing modes

$\Delta'(q=2)$ in NSTX-U 2MA, 1T, 12MW scenario

$\Delta'(q=2)$

Z. Wang
New tiles installed in high heat flux regimes

- NSTX-U heat flux metrics advance towards those of next-step devices
- Castellated, toroidally fishscaled tiles designed for high heat flux regions (temperature, not stress limited)
- Pre-filled liquid lithium high-Z prototype tile proposed for later in Five-Year period

<table>
<thead>
<tr>
<th>Machine</th>
<th>$R_0$ [m]</th>
<th>$P_{SOL}(P_{Aux})$ [MW]</th>
<th>$P/I_R$ [MW/m]</th>
<th>$P/S$ [MW/m$^2$]</th>
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<td>161</td>
<td>0.9</td>
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Studies of observed global modes in MAST and NSTX allow for understanding the effect of wall proximity on mode structure.

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VALEN code analysis reproduces similar distortions to respective NSTX and MAST observations.
3D calculations indicate sensitivity of divertor footprints to error fields

- 5 mm shift of TF coil produces 10 cm wide footprint on outer divertor plates
- Footprint size linearly proportional to magnitude of TF, PF5 misalignment
- Study predicts that error fields in NSTX-U will not expand footprints outside of divertor PFCs

Munaretto (2019)
Fast camera imaging of divertor turbulence provides new insights into SOL turbulence

- Divertor leg fluctuations observed by fast imaging in NSTX-U
  - Intermittent; localized to bad curvature side
  - Simulations with ArbiTER code find unstable resistive ballooning modes [Baver (2016)]

- Disconnection of midplane turbulence from divertor plate due to X-point
  - Consistent with expectations from two-regime blob model [Myra (2005)]
Wall conditioning studies using low-Z impurity powder injection on EAST, DIII-D, KSTAR and ASDEX-U

- **EAST**: compared ELM suppression with Li powder injection (reduced recycling) with B powder (low frequency edge mode)
- **DIII-D**: B powder injection successfully used for wall conditioning to reduce recycling and density
- **KSTAR**: BN powder injection led to periods of ELM quiescence
  - Dependence on injection rate
- **AUG**: BN powder injection led to enhanced radiated power, reduced heat flux, improved stored energy
  - Similar to N$_2$ gas injection
- **Powder dropper** is being considered for early deployment on NSTX-U
QUEST provides unique opportunity to understand and optimize non-inductive start-up/ramp-up

- Experiment and modeling of 2\textsuperscript{nd} harmonic electron cyclotron heating and current drive solenoid-free start-up in QUEST

- Transient CHI on QUEST has shown reliable discharge initiation, and plasma growth in biased electrode configuration
  - CHI to be tested also on URANIA
Numerical modeling is exploring optimization of HHFW using minority H species

- Performed through RF SciDAC collaboration

- 2D power deposition calculated by AORSA full wave code

- Looking at 0 to 10% H concentrations over range of wave numbers and TF
  - Find significant electron absorption of HHFW power

- Could provide attractive path for 2\textsuperscript{nd} harmonic H minority heating in NSTX-U to assist in non-inductive ramp-up
ST-specific collaborations established

• MAST Upgrade collaboration will afford opportunities for direct connection to NSTX-U research program (PPPL + collaborators)
  • Start-up, ramp-up, control (PPPL)
  • Equilibrium and stability, including EF and TM physics (PPPL, Columbia U)
  • Transport and turbulence, including gyrokinetic analysis (PPPL, UCLA)
  • Divertor physics (PPPL, ORNL, LLNL)
  • Energetic particle physics (PPPL, UC Irvine, Florida Int. U., UCLA)

• ST40 collaboration (public-private partnership with Tokamak Energy, Ltd., UK) funded and officially started
  • Three year collaboration including PPPL, ORNL, UC Irvine, U. Washington, Columbia Univ)
  • Areas of collaboration include:
    • Pedestal physics: PBLS (PPPL), divertor physics (ORNL)
    • Confinement, EP physics, EF/tearing physics (PPPL, UC Irvine)
    • Disruption prediction (Columbia U)
    • RF modeling for start-up/ramp-up (PPPL, ORNL)
    • Scoping of future capabilities: turbulence diagnostic (PPPL), CHI (U. Washington), Li injection (PPPL)
NSTX-U Mission Elements Support the NAS Vision

- Exploit unique Spherical Tokamak (ST) parameter regimes to advance predictive capability - for ITER and beyond

- Develop solutions for plasma-material interface (PMI) challenge

- Explore ST physics towards reactor relevant regimes (Fusion Nuclear Science Facility, low-A Pilot Plant)
NSTX-U targeting major performance increase to explore new physics regimes

1. New Central Magnet

- 2× toroidal field (0.5 → 1T)
- 2× plasma current (1 → 2MA)
- 5× longer pulse (1 → 5s)

2. Tangential 2nd Neutral Beam

- 2× heating power (5 → 10MW for 5s)
  - Tangential NBI → 2× current drive efficiency
  - Up to 15MW NBI + 4MW RF for 1-2s
- Up to 10× higher nTₜₑ (≈MJ plasmas)
- 4× divertor heat flux (→ ITER levels)

Ultimate Performance Goals:
NSTX-U vital for addressing key ST / fusion questions

**Highest normalized pressure at high T**
Unique regime, study new transport and stability physics

**Sustain steady-state plasma**
Not yet achieved at high-$\beta_T$, low $\nu^*$

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**Two new tools:**

1. **New Central Magnet**
2. **Tangential 2nd Neutral Beam**

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**Ultimate Performance Levels:**

- $B_t = 1$T
- $I_p = 2$ MA
- $P_{NB} = 10$ MW
- Flat top duration = 5s
NSTX-U vital for addressing key ST / fusion questions
Will access new physics with 2 new tools:

1. **New Central Magnet**
   - Highest normalized pressure at high T
     - Unique regime, study new transport and stability physics

2. **Tangential 2nd Neutral Beam**
   - Sustain plasma without transformer
     - Not yet achieved at high-$\beta_T$, low $\nu^*$
     - Essential for any future steady-state ST

- 2$\times$ field, current, power
- 4$\times$ heat flux, 5$\times$ pulse length
- Up to 10$\times$ higher $nT_{\tau_E}$
NSTX-U design enables access to 2-3× higher plasma pressure, temperature than MAST-U

- NSTX-U central magnet provides 1.5× higher toroidal field current
  \[ \rightarrow \sim 1.5 - 2\times \text{higher } B_T^2 \]
  (depending on plasma shape)

- Conducting plates can suppress global kink instabilities,
  \[ \sim 1.5\times \text{higher } \beta_T \]

- \[ p \propto \beta_T B_T^2 \]
  2-3× higher

- Expect \sim 2\times higher edge “pedestal” pressure due to higher B, shaping
Transport at low-A is fundamentally different than transport at conventional-A

- Many features of low-A, high-$\beta$ stabilize ES modes (ITG, TEM, ETG) in core
  - Neoclassical ion transport, MTM, KBM and EP modes drive electron transport
- Dimensionless confinement time scales inversely with collisionality at low-A ($\Omega_{ci}\tau_E \sim n_*^{-0.8}$)
  - Scaling extrapolates to an A=2 CPP with $H_{ST} = 0.9$ equivalent to $H_{98y,2} = 1.75$
  - NSTX-U will operate at up to a factor of six lower $n_*$ than NSTX

[Diagram showing electron beta ($\beta_e$) vs. normalized collisionality ($\nu_n (c_s/a)$) for NSTX and NSTX-U, with increasing $\beta$ and high R/a.]
Stability at large $\beta_N/l_i$ is a strong lever for a compact device

- $f_{BS} \sim \beta_N/l_i \rightarrow$ Broad current and pressure profiles
  - NSTX achieved large $\beta_N/l_i$ with $\beta_N / \beta_{\text{no-wall}} > 2$
- Stability increased as $\beta_N/l_i \rightarrow 10$ at critical rotation
  - Kinetic stabilization of the RWM
  - Prediction that stabilization improves at lower collisionality will be tested on NSTX-U

- NSTX-U has expanded suite of real-time control measurements and actuators
  - RT profile control using tangential NBI, density and shape actuators
  - Increased flexibility in the 3D field spectrum for EFC + rotation control

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S. Sabbagh et al., Nucl. Fusion 53, 104007 (2013)

J.W. Berkery, et al., PoP 21 (2014) 156112,
NSTX-U will access unique regimes in fast particle physics critical for prediction and optimization

- NSTX-U will produce and study EP modes relevant to alpha driven instabilities expected at both high- and low-aspect ratio
  - Characterizing fast ion interaction with RF (see Diallo talk)
  - Important for ITER and CPP

- Modification of fast-ion distribution using tangential NBI can stabilize EP modes that enhance transport
  - Study and develop techniques to suppress alpha-driven modes through phase-space engineering
NSTX-U will play important role in understanding how power exhaust width extrapolates to future devices

XGC1 simulations predict turbulence will widen edge heat flux in ITER

C.S. Chang et al 2017 Nucl. Fusion 57 116023

Recovery includes divertor tile improvements to access high current, power, shaping

XGC1 studies of NSTX-U indicate enhanced TEM transport in the low $v^*$, 2 MA NSTX-U pedestal, similar to mode expected for ITER