Progress and Plans on NSTX-U

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On behalf of the NSTX-U Research Team

Fusion Power Associates
37th Annual Meeting and Symposium
FUSION POWER DEVELOPMENT: AN INTERNATIONAL VENTURE
Outline

- NSTX-U mission
- Research highlights
- Goals for next run
- Summary
NSTX-U Mission Elements:

• Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond

• Develop solutions for plasma-material interface (PMI)

• Advance ST as Fusion Nuclear Science Facility and Pilot Plant
NSTX-U will access new physics with 2 major new tools:

1. New Central Magnet
   - Higher T, low $\nu^*$ from low to high $\beta$
   - Unique regime, study new transport and stability physics

2. Tangential 2$^{nd}$ Neutral Beam
   - Full non-inductive current drive
   - Not demonstrated in ST at high-$\beta_T$
   - Essential for any future steady-state ST
NSTX-U will have major boost in performance

1. New Central Magnet
- $2 \times$ toroidal field ($0.5 \rightarrow 1T$)
- $2 \times$ plasma current ($1 \rightarrow 2MA$)
- $5 \times$ longer pulse ($1 \rightarrow 5s$)

2. Tangential 2$^{nd}$ Neutral Beam
- $2 \times$ heating power ($5 \rightarrow 10MW$)
  - Tangential NBI $\rightarrow 2 \times$ current drive efficiency
- $4 \times$ divertor heat flux ($\rightarrow$ ITER levels)
- Up to $10 \times$ higher $nT \tau_E$ (~MJ plasmas)

Performance goals:
NSTX-U had scientifically productive 1st year

- Achieved H-mode on 8th day of 10 weeks of operation
- Surpassed magnetic field and pulse-duration of NSTX
- Matched best NSTX H-mode performance at ~1MA
- Identified and corrected dominant error fields
- Commissioned all magnetic and kinetic profile diagnostics
- New 2nd NBI suppresses Global Alfven Eigenmodes (GAE)
- Implemented techniques for controlled plasma shut down, disruption detection, commissioned new tools for mitigation

- 2016 run ended prematurely due to fault in divertor PF coil
  - Coil + other issues → major reviews of design, fab, procedures
  - Coil forensics complete, prep for new coil fab underway
  - Aim to resume plasma operation during CY2018
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Topical science areas:

– Scenario Development
– Macroscopic Stability
– Transport and Turbulence
– Energetic Particles
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NSTX-U has surpassed maximum pulse duration and magnetic field of NSTX

Compare similar NSTX / NSTX-U Boronized L-modes, $P_{\text{NBI}}=1$ MW

**Plasma current [MA]**

NSTX-U L-mode duration exceeds longest NSTX H-mode

**Toroidal magnetic field [T]**

NSTX-U $B_T >$ highest NSTX $B_T$
Recovered ~1MA H-modes with weak/no core MHD

\[ H_{98} \geq 1, \beta_N \geq n=1 \text{ no-wall limit} \]
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Leading studies of rotating halo currents through ITPA multi-machine analysis and M3D-C1 numerical simulations

**ITPA multi-machine analysis (MDC WG-6):**
- Halo current data from C-Mod, DIII-D, AUG, NSTX
- All measurements in lower divertor (> 400 shots)
- Halo current rotation is predominantly counter-$I_p$
- Consistent rotation velocity, $v_h \sim 5$ km/sec

**M3D-C1 simulations:**
- NSTX(-U) geometry
- Simulate in 2D while $q > 2$
- Switch to 3D to resolve halo rotation (in progress)
- D. Pfefferlé et al. (PPPL)
Disruption characterization and forecasting capability started for NSTX-U as part of disruption avoidance plan

New DECAF (Disruption Event Characterization And Forecasting) code written

- Identify disruption event chains and elements
  - ex: vertical displacement, pressure peaking, tearing modes…
- Predict events in disruption chains
- Cues disruption avoidance system

Example: Reduced kinetic resistive wall mode (RWM) model developed for calculating growth rate vs. time

- Initial tests on NSTX RWM database
  - 86% of RWM shots are predicted unstable
- Possible to predict growth rate in real time
“State-machine”-based automated ramp-down now used routinely during NSTX-U operations

- Plasma control system detects loss of control
  - OH solenoid near maximum current
  - Vertical oscillations exceed threshold
  - ABS ($I_p - I_p\text{ request}$) too large

- Feedback control switches to new “states” that attempt to gently end the discharge
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NSTX-U: Bimodal turbulence seen in some L-modes using upgraded 48 channel Beam Emission Spectroscopy (BES) system

- Modes propagate in opposite directions
  - Similar spectra seen with DIII-D and TFTR BES
  - Gyro-kinetic modelling:
    - Ion-temperature-gradient (ITG) mode unstable – propagates in ion direction
    - Micro-tearing mode (MTM) also unstable - propagates in electron direction

\[ \Delta Z = 3 \text{ cm} \]
\[ R = 142 \text{ cm} \]
\[ \Delta t = 24 \text{ ms} \]

11 km/s in ion diamagnetic direction
13 km/s in electron diamagnetic direction

\[ \Delta Z = 3 \text{ cm} \]
\[ R = 142 \text{ cm} \]
\[ \Delta t = 24 \text{ ms} \]
Same NSTX-U L-modes: Nonlinear ETG simulations give significant transport ($R=129-140$ cm, $r/a=0.47-0.67$)

- $Q_{e,etg}$ large enough to account for $Q_{e,exp}$ if $Z_{eff}=Z_{eff,c}\approx 1.2$
  - Larger $Z_{eff}$ (VB $Z_{eff}\leq 2$) $\rightarrow$ lower $Q_{e,etg}$

- New high-k microwave scattering diagnostic (2018 run) will be ideal for probing region of ETG turbulence

- May require multiscale simulations for validation
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NSTX-U: Most tangential NBI generates counter-propagating Toroidal Alfvén Eigenmodes (TAEs)

- Counter-propagating TAE predicted for hollow fast-ion profiles
  

- TRANSP: As current builds up beam fast-ion beta profile predicted to become hollow

- 1st evidence of off-axis NBI in NSTX-U
NSTX-U tangential 2\textsuperscript{nd} neutral beam suppresses Global Alfven Eigenmode (GAE) – consistent with simulation

HYM code simulation of #204707, n=10

- HYM code: growth of n=10 counter-GAE from 1\textsuperscript{st} NBI
- HYM: suppression of n=10 counter-GAE by 2\textsuperscript{nd} NBI
- Most unstable $n$-number, mode $\omega$ consistent with HYM

New 2\textsuperscript{nd} NBI already powerful tool for fast ion, AE physics
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Improving understanding of SOL heat flux width trends in NSTX using XGC1 simulations

- Experiment shows contraction of SOL heat flux width at midplane with $I_p$ as well as influence of Li conditioning

**XGC-1:**
- Full-f, global PIC, kinetic ions and electrons

- NSTX data and XGC-1: $\lambda_q \sim 1/I_p^{1.5}$

- Simulations for ITER presented at IAEA-FEC 2016 (C.-S. Chang) indicate turbulence can play significant role in setting heat-flux width
  - Will SOL turbulence become important in NSTX-U at high current?

### XGC1 w/ collisions $\Rightarrow$ similar trends

Heat flux width set primarily by neoclassical processes
NSTX-U: First systematic simulations of advanced divertors combined with 3D fields using EMC3-EIRENE

- **Divertor heat-flux trends:**
  - Peaked heat loads in Near Exact Snowflake
  - Lowest heat loads found for X-divertor-like configurations
  - RMP fields do not significantly impact toroidal average heat-flux
Material Analysis & Particle Probe (MAPP) providing new measurements of surface evolution in NSTX-U

- Tracked C/B/O evolution, correlated with plasma performance
- Implemented remote-control + between-shot MAPP analysis
- Future: Use with Li, understand complex Li chemistry/evolution
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Goals for next NSTX-U run campaign
Only a subset, and will decide as a team via next Research Forum

- Increase field to 0.8-1T, current to 1.6-2MA
- Further develop early H-mode / low-$I_i$ / high-$\kappa$ scenarios
- Assess H-mode energy confinement, pedestal, and SOL characteristics with higher $B_T$, $I_P$, $P_{NBI}$
  - Informs collisionality scaling of low-A confinement and stability
- Complete assessment of effects of NBI parameters on fast ion distribution, neutral beam driven current profile
  - Informs goal of full non-inductive operation
- Key physics and operational tools for sustained high-$\beta_N$
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Recent design studies show ST potentially attractive as Fusion Nuclear Science Facility (FNSF) and Pilot Plant

**FNSF**: Provide neutron fluence for material/component R&D (+ T self-sufficiency?)

**Pilot Plant**: Electrical self-sufficiency: \( Q_{\text{eng}} = \frac{P_{\text{elec}}}{P_{\text{consumed}}} \geq 1 \) (+ FNSF mission?)

**FNSF with copper TF coils**
- \( A=1.7, R_0 = 1.7\text{m}, \kappa_x = 2.7, B_T=3\text{T} \)
- Fluence = 6MWy/m\(^2\), TBR ~ 1

**FNSF / Pilot Plant with HTS TF coils**
- \( A=2, R_0 = 3\text{m}, \kappa_x = 2.5, B_T = 4\text{T} \)
- Fluence = 6MWy/m\(^2\), TBR ~ 1, \( Q_{\text{eng}} \sim 1 \)

Designs integrate ST higher \( \kappa \), \( \beta_N \) and advanced divertors (+ HTS TF for Pilot Plant)

*J.E. Menard, et al., Nucl. Fusion 56 (2016) 106023*
Summary: NSTX-U strongly supporting advancing predictive capability, ITER, PMI solutions, next-steps

- Productive first year of operations on NSTX-U
- Developing advanced predictive capability
- Developed attractive ST FNSF, Pilot Plant concepts
- 2017: Recovery, collaborations, write 5 year plan
- Aim to resume NSTX-U physics operation in CY2018