Overview of Physics Results from the National Spherical Torus Experiment

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NSTX research targets predictive physics understanding needed for fusion energy development facilities

- Enable devices: ST-FNSF, ST-Pilot/DEMO, ITER
  - Leveraging unique ST plasmas provides new understanding for tokamaks, challenges theory

**Outline**

- Develop key physics understanding to be tested in unexplored, hotter ST plasmas
  - Study high beta plasma transport and stability at reduced collisionality, for extended pulse
  - Prototype methods to mitigate very high heat/particle flux
  - Move toward fully non-inductive operation

3D effects are pervasive in this research

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_T$</td>
<td>0.5 $\rightarrow$ 1 T</td>
</tr>
<tr>
<td>$P_{NBI}$</td>
<td>6 $\rightarrow$ 12 MW</td>
</tr>
<tr>
<td>$I_p$</td>
<td>1 $\rightarrow$ 2 MA</td>
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<tr>
<td>Pulse</td>
<td>1 $\rightarrow$ 5 s</td>
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</table>
Outline

- Transport and stability at reduced collisionality
- Pedestal transport
- High $\beta$ pulse sustainment, disruptivity, and warning algorithms
- Energetic particles, power handling and first wall
- Non-inductive current and NSTX-Upgrade scenarios
\[ \tau_E \] scalings unified by collisionality; nonlinear microtearing simulations find reduced electron heat transport at lower \( \nu \)

- Increase in \( \tau_E \) as \( \nu_e^* \) decreases
- Trend continues when lithium is used
- NSTX-U computed to extend studies down to < 1/4 of present \( \nu^* \)

- Quantitatively predicted \( \chi_e \), scaling \( \sim \nu_e^{1.1} \)
  consistent with experiment (\( \Omega \tau_E \sim B_t \tau_E \sim \nu_e^{0.8} \))
- Transport dominated by magnetic “flutter”
  - Significant \( \delta B_r / B \sim 0.1\% \)

\[ B_{tE} (\text{T-S}) \]

\[ \nu_e^* (\text{at } r/a = 0.5) \]

\[ q_{a/2} = 2-2.5 \]

\[ \langle \beta_{pl} \rangle = 8-12\% \]

\[ \chi_e (\rho_{cs}^c / a) \]

\[ \chi_e^{\text{sim}} \sim \nu_e^{1.1} \]

\[ NSTX120968A02 \ t=0.560 \text{ s} \]

\[ r/a=0.6 \quad \gamma_E=0 \]

\[ W. \ Guttenfelder, \ et\ al., \ PRL\ 106 \ (2011)\ 155004 \]

\[ \delta B_r \ (\text{Gauss}) \]

Kaye EX/7-1

Guttenfelder TH/6-1

\[ 120968 \]

\[ c_e \sim n_e^{1.1} \]

W. Guttenfelder, et al., PRL 106 (2011) 155004
Plasma characteristics change nearly continuously with increasing lithium evaporation; reach kink/peeling limit

- Global parameters generally improve
  - With no core Li accumulation
  - ELM frequency declines - to zero
  - Edge transport declines
    - As lithium evaporation increases, transport barrier widens, pedestal-top $\chi_e$ reduced

- New bootstrap current calculation (XGC0 code) improves agreement with profile reaching kink/peeling limit before ELM

- Energy Confinement Time ($\tau_E$ in ms) and Pre-discharge lithium evaporation (mg)

- Bootstrap current profile

- $n=1$-$15$, $\left(\gamma/\omega_{ce}/2\right)$ contours

R. Maingi, et al., PRL 107 (2011) 145004

Podesta EX/P3-02

Maingi EX/11-2

Canik EX/P7-16

Chang TH/P4-12

Diallo EX/P4-04
Experiments measuring global stability vs. $\nu$ further support kinetic RWM stability theory, provide guidance for NSTX-U.

- **Theory**: RWM growth rate vs. $\nu$ and $\omega_\phi$
- **Exp**: Resonant Field Amplification (RFA) vs $\nu$

- **Two competing effects at lower $\nu$**
  - Collisional dissipation reduced
  - Stabilizing resonant kinetic effects enhanced (contrasts early theory)

- **Expectations at lower $\nu$**
  - More stabilization near $\omega_\phi$ resonances; almost no effect off-resonance

J. Berkery et al., PRL 106 (2011) 075004

- **Berkery EX/P8-07**

*(trajectories of 20 experimental plasmas)*

- **Mode stability directly measured in experiment using MHD spectroscopy**
  - Decreases with $\nu$ at lower RFA ("on resonance")
  - Independent of $\nu$ at higher RFA ("off resonance")

RFA = $\frac{B_{\text{plasma}}}{B_{\text{applied}}}$
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BES measured low-\(k\) turbulence in ELM-free H-mode pedestal steep gradient region is most consistent with TEMs

- Measurements during MHD quiet periods, in steep gradient region
- Large poloidal correlation lengths
  - \(k_\theta \approx 0.2-0.4 \text{ cm}^{-1}\) and \(k_\theta \rho_i \approx 0.2\)

Smith EX/P7-18
Pedestal width scaling differs from tokamaks; turbulence correlation measurements consistent with theory

- Pedestal width scaling $\beta_\theta^\alpha$ applies to multiple machines
- In NSTX, observed pedestal width is larger
  - Data indicates stronger scaling: $\beta_\theta$ vs. $\beta_\theta^{0.5}$
  - Examining possible aspect ratio effects

- Measured correlation lengths at pedestal top are consistent with theory
  - BES and reflectometry
    - Spatial structure exhibits ion-scale microturbulence ($k_{\perp}\rho_i \sim 0.2 - 0.7$)
    - Compatible with ITG modes and/or KBM

Diallo EX/P4-04

A. Diallo, C.S. Chang, S. Ku (PPPL), D. Smith (UW), S. Kubota (UCLA)
A 30% increase in L-H power threshold is found at high vs. low triangularity, consistent with X-transport theory.

- X-point location is a hidden variable for L-H power threshold scaling ($P_{LH}$).
- $P_{LH}$ increases by 30% for high-$\delta$ vs. low-$\delta$ shape.
- Consistent with predictions of X-transport theory (kinetic neo-classical transport).

- Critical shear rate is satisfied for both shapes when core heating is 30% larger for high triangularity shape.

Battaglia EX/P5-28
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Stability control improvements significantly reduce unstable RWMs at low $l_i$ and high $\beta_N$; improved stability at high $\beta_N/l_i$.

- Disruption probability reduced by a factor of 3 on controlled experiments
  - Reached 2 times computed $n = 1$ no-wall limit of $\beta_N/l_i = 6.7$
- Lower probability of unstable RWMs at high $\beta_N/l_i$

Mode stability directly measured in experiments using MHD spectroscopy
- Stability decreases up to $\beta_N/l_i = 10$
- Stability increases at higher $\beta_N/l_i$
- Presently analysis indicates consistency with kinetic resonance stabilization

S.A. Sabbagh

Berkery EX/P8-07
Disruptivity studies and warning analysis of NSTX database are being conducted for disruption avoidance in NSTX-U

**Disruptivity**

<table>
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<th>$\log_{10}\text{disruptivity [s^{-1}]}$:</th>
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<td>-0.5</td>
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</table>

- $\beta_N$ vs $l_i$
- $\beta_N$ vs $q^*$
- 39258 total samples
- All discharges since 2006

**Physics results**

- Low disruptivity at relatively high $\beta_N \sim 6$; $\beta_N / \beta_N^{\text{no-wall}(n=1)} \sim 1.3-1.5$
  - Consistent with specific disruption control experiments, RFA analysis
- Strong disruptivity increase for $q^* < 2.5$
- Strong disruptivity increase for very low rotation

**Warning Algorithms**

- Disruption warning algorithm shows high probability of success
  - Based on combinations of single threshold based tests

**Results**

- ~ 98% disruptions flagged with at least 10ms warning, ~ 6% false positives
- False positive count dominated by near-disruptive events
Improved stability control includes dual field component feedback and state space feedback, improved by 3D effects.

1. Active \( n = 1 \) \( B_\| + B_R \) feedback (FB) control

- Feedback on \( B_\|, FB \) phase = 225°
- \( \beta_N \)
- \( B_\|, FB \) phase = 0°
- \( B_\|, FB \) phase = 90°

2. RWM State Space Controller

- 3D wall, ports, mode currents
- Inclusion of 3D mode and wall detail improves control

Calculation of \( B_\| + B_\perp \) control (VALEN)

- 0 deg FB phase
- 90 deg FB phase
- 180 deg FB phase

RWM State Space Controller

No NBI port
 With 3D NBI port

Sensor Differences (G)

\( \delta B_p^{90} \)

Controller
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Fast ion redistribution associated with low frequency MHD measured by fast ion $D_\alpha$ (FIDA) diagnostic

- Caused by $n = 1$ global kink instabilities
- Redistribution can affect stability of *AE, RWMs, other MHD
- Full-orbit code (SPIRAL) shows redistribution in real and velocity space
  - Radial redistribution from core plasma
  - Particles shift towards $V_{||}/V = 1$
- Applied 3D fields alter GAE stability
  - By altered fast ion distribution (SPIRAL)
- Fast ion energy redistribution accounts for neutron rate decrease in H-mode TAE avalanches

Core localized CAE/GAEs measured in H-mode plasmas (reflectometer)
Significant fraction of the HHFW power lost in the SOL in front of antenna flows to the divertor region

Visible camera image of edge RF power flow to divertor

SPIRAL modeling of field lines from antenna to divertor

- RF power couples to field lines across entire SOL width, not just to field lines connected to antenna components
- Shows importance of quantitatively understanding RF power coupling to the SOL for prediction to future devices

Snowflake divertor experiments provide basis for required divertor heat flux mitigation in NSTX-U

- Needed, as divertor heat flux width strongly decreases as $I_p$ increases

- Snowflake divertor experiments ($P_{NBI} = 4$ MW, $P_{SOL} = 3$ MW)
  - Good H-mode $\tau_E$, $\beta_N$, sustained during snowflake operation
  - Divertor heat flux significantly reduced both during and between ELMs
    - during ELMs: 19 to $\sim$ 1.5 MW/m$^2$
    - steady-state: 5-7 to $\sim$ 1 MW/m$^2$
  - Achieved by a synergistic combination of detachment + radiative snowflake divertor

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Soukhanovskii EX/P5-21
Toroidal asymmetry of heat deposition measured during standard ELMs, but decreases for 3D field-triggered ELMs

- **2D fast IR camera measurement (6.3kHz), heat flux from TACO code**
- **Toroidal asymmetry**
  - Becomes largest at the peak heat flux for usual Type-I ELMs
  - Reduced by up to 50% in ELMs triggered by \( n = 3 \) applied fields

\[
\text{DoA}(q_{\text{peak}}) = \frac{\sigma_{q_{\text{peak}}}}{\bar{q}_{\text{peak}, 2D}}
\]
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Plasma discharge ramping to 1MA requires 35% less inductive flux when coaxial helicity injection (CHI) is used.

CHI assisted startup in NSTX

- CHI generated plasmas with high elongation, low $l_i$ and $n_e$
- TSC now used for full discharge modeling to 1MA
  - CHI start-up + NBI current ramp-up
- Results imply a doubling of closed flux current > 400kA in NSTX-U

Raman EX/P2-10
Non-inductive current fractions of up to 65% sustained in NSTX, >70% transiently; Upgrade projected to achieve 100%

- Maximum sustained non-inductive fractions of 65% w/NBI at $I_P = 0.7$ MA
- 70-100% non-inductive reached transiently using HHFW CD


S. Gerhardt, et al., Nucl. Fusion 52 (2012) 083020

- 100% non-inductive scenarios found over wide operation range
- Higher A ~ 1.65 of NSTX-U created in NSTX, vertical stability tested

NSTX-U projections

via high harmonic FW

NSTX Results

NSTX-U (100% NI)

(ranges created by profile peakedness, $\tau_E$ scalings, etc.)
Rapid Progress is Being Made on NSTX Upgrade

- 2nd neutral beam moved into place
  (first plasma anticipated June 2014)

- TF conductors being made

Old center stack

NEW Center Stack

TF OD = 20cm

TF OD = 40cm
Continuing analysis of NSTX data targets a predictive physics understanding required for future fusion devices

- **Transport and stability at reduced collisionality**
  - $\tau_E$ scalings **unified** by collisionality; non-linear microtearing simulations match experimental $\chi_e$, predict lower $\chi_e$ at lower $v_e^*$ shown in experiment
  - Nearly continuous increase of favorable confinement with increased lithium
  - Stabilizing kinetic RWM effects **enhanced** at lower $\nu$ when near resonances

- **Pedestal**
  - Width scaling **stronger than usual** $(\beta_{p\text{ped}})^{0.5}$; measured $\delta n_e$ correlation lengths consistent w/TEMs in ped. steep gradient, non-linear gyrokinetics at ped. top

- **Pulse sustainment / disruption avoidance**
  - Global stability **increased** + low disruptivity at high $\beta_N/l_i$, advanced mode control
  - Disruption detection algorithm shows **high (98%) success rate**

- **Power handling and first wall**
  - Large heat flux reduction from **combination** of radiative snowflake divertor + detachment; heat asymmetry from ELMs reduced when triggered by $n = 3$ field

- **Significant upgrade underway (NSTX-U)**
  - **Doubled** $B_T$, $I_p$, NBI power; $5\times$ pulse length, **projected 100% non-inductive sustainment** over broad operating range
### Talks

**Thursday**
- Progress in Simulating Turbulent Electron Thermal Transport in NSTX
  - Guttenfelder **TH/6-1**
- The Dependence of H-mode Energy Confinement and Transport on Collisionality in NSTX
  - Kaye **EX/7-1**

**Friday**
- Disruptions in the High Beta Spherical Torus NSTX
  - Gerhardt **EX/9-3**
- Progress on Developing the Spherical Tokamak for Fusion Applications
  - Menard **FTP/3-4**

**Saturday**
- The Nearly Continuous Improvement of Discharge Characteristics and Edge Stability with Increasing Lithium Coatings in NSTX
  - Maingi **EX/11-2**

### Posters

**Tuesday**
- Lithium program
  - Ono **FTP/P1-14**
- Co-axial helicity injection
  - Raman **EX/P2-10**
- Particle code NTV simulation
  - Kim **TH/P2-27**

**Wednesday**
- Bootstrap current XGC
  - Chang **TH/P4-12**
- Pedestal transport
  - Diallo **EX/P4-04**
- Power scrape-off width
  - Goldston **TH/P4-19**
- Vertical stability at low A
  - Kolemen **EX/P4-28**
- Blob dynamics / edge V shear
  - Myra **TH/P4-23**
- EHOs
  - Park **EX/P4-33**
- Core lithium levels
  - Podesta **EX/P3-02**
- C, Li impurity transport
  - Scotti **EX/P3-34**
- Snowflake divertor theory
  - Ryutov **TH/P4-18**

**Thursday**
- Divertor heat asymmetry
  - Ahn **EX/P5-33**
- L-H power threshold vs. X pt.
  - Battaglia **EX/P5-28**
- NBI-driven GAE simulations
  - Belova **TH/P6-16**
- CAE/GAE structure
  - Crocker **EX/P6-02**
- TAE avalanches in H-mode
  - Fredrickson **EX/P6-05**
- Li deposition / power exhaust
  - Gray **EX/P5-27**
- Liquid lithium divertor results
  - Jaworski **EX/P5-31**
- RF power flow in SOL
  - Perkins **EX/P5-40**
- Snowflake divertor
  - Soukhanovskii **EX/P5-21**

**Friday**
- Global mode control / physics
  - Berkery **EX/P8-07**
- Edge transport with Li PFCs
  - Canik **EX/P7-16**
- Turbulence near OH L-H trans.
  - Kubota **EX/P7-21**
- ELM triggering by Li in EAST
  - Mansfield **PD**
- Electron-scale turbulence
  - Ren **EX/P7-02**
- Low-k turbulence vs. params.
  - Smith **EX/P7-18**
Higher aspect ratio of NSTX-U tested in NSTX, vertical stability growth rate data obtained, compared to simulation.

- NSTX Discharges have matched aspect ratio and elongation of NSTX-U (A = 1.65) without performance degradation.
- Improvements to vertical control capability and understanding:
  - Begun to compare measured growth rates to theoretical predictions (Corsica, GSPERT)
  - Improved plasma position observer
  - Modeled use of RWM coils for n=0 control.
Simulations and lab results show importance of oxygen in the lithium-graphite PMI for pumping deuterium

- Quantum-classical atomistic simulations show surface oxygen plays key role in D retention in graphite
  - P. Krstic, sub. to Nature Comm.

- Accordingly, lab results support that Li on graphite can pump D effectively due to O
  - Measurements show 2 µm of Li increases surface oxygen content of lithiated graphite to ~10%
  - Deuterium ion irradiation of lithiated graphite greatly enhances oxygen content to 20%-40%
    - In stark contrast, D irradiation of graphite without Li decreases amount of surface O
  - Li acts as an O getter, and the O retains D

Jaworski EX/P5-31 J.P. Allain, C. Taylor (Purdue U.)
Kinetic RWM stability theory further tested against NSTX experiments, provides guidance for NSTX-U

- Two competing effects at lower $\nu$
  - Collisional dissipation reduced
  - Stabilizing resonant kinetic effects enhanced (contrasts early theory)

- Expectations at lower $\nu$
  - More stabilization near $\omega_\phi$ resonances; almost no effect off-resonance
    - Active RWM control important

- Improvements to physics model
  - Anisotropy effects
  - Testing terms thought small
    - Already good agreement between theory and experiment of marginal stability point improved

J. Berkery et al., PRL 106, 075004 (2011)