NSTX/NSTX-U Theory, Modeling and Analysis Results & Overview of New MAST Physics in Anticipation of First Results from MAST Upgrade

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J.E. Menard for S.M. Kaye (PPPL), J. Harrison (CCFE) and the NSTX-U and MAST-U Teams
Missions of NSTX(-U) and MAST(-U)

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

• Develop solutions for plasma-material interface (PMI)

• Explore ST physics towards reactor relevant regimes (e.g., Fusion Nuclear Science Facility and Pilot Plant)
NSTX(-U) and MAST address urgent issues for fusion science, ITER and next-step devices

• Spherical Tokamaks (STs) can investigate turbulence over an extended range in $\beta$ (tens %)
  • Electrostatic and electromagnetic effects

• STs Energetic Particle (EP) physics spans phase space expected in Burning Plasmas
  • $v_{\text{fast}}/v_{\text{Alfvén}}$ vs $\beta_{\text{fast}}/\beta_{\text{tot}}$
  • Develop predictive and control methods

• Reduced aspect ratio expands range of field line connection length to study and mitigate divertor heat flux
MAST-U will emphasize boundary physics

Maximum Parameters

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<tr>
<th>Parameter</th>
<th>MAST</th>
<th>MAST-U</th>
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<tr>
<td>$I_p$</td>
<td>$\leq 1.3$</td>
<td>2 MA</td>
</tr>
<tr>
<td>$RB_T$</td>
<td>$\leq 0.44$</td>
<td>0.64 m-T</td>
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<tr>
<td>$P_{NBI}$</td>
<td>$\leq 3.5$</td>
<td>10 MW</td>
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<tr>
<td>$\tau_{pulse}$</td>
<td>$\leq 0.7$</td>
<td>5 s</td>
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On and off-midplane NBI

- Flexible divertor with Super-X capability for exhaust research
- Off-midplane 3D magnetic coils for edge instability control
### NSTX-U will emphasize core physics

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<th>NSTX</th>
<th>NSTX-U</th>
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<tr>
<td>(I_p)</td>
<td>(\leq 1.4)</td>
<td>2 MA</td>
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<tr>
<td>(R\beta_T)</td>
<td>(\leq 0.47)</td>
<td>0.94 m-T</td>
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<tr>
<td>(P_{NBI})</td>
<td>(\leq 6)</td>
<td>15 MW</td>
</tr>
<tr>
<td>(P_{RF})</td>
<td>(\leq 6)</td>
<td>6 MW</td>
</tr>
<tr>
<td>(\tau_{pulse})</td>
<td>(\leq 1)</td>
<td>5 s</td>
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Conducting plates can suppress global kink instabilities

- High \(B_T\) (1 T at \(R_0\)) \(\Rightarrow\) projected largest range in \(\beta\) and (lower) \(v_*\) in an ST
- Greater stability \((\beta_n/l_i \leq 14)\) + flexible NBI \(\Rightarrow\) high non-inductive current

New tangential NBI for \(j(r)\) control
This talk will cover recent complementary results from NSTX(-U) and MAST

- Core transport and stability physics
- Energetic particle physics/mode stability
- Boundary and divertor physics
- Future plans
This talk will cover recent complementary results from NSTX(-U) and MAST

- Core transport and stability physics
  - ST confinement trends differ from those at higher aspect ratio
    - NSTX/MAST: $\tau_E \sim I_p^{0.5} B_T^{1} \sim \nu_*^{-0.8}$
    (ITER-Basis: $\tau_E \sim I_p^{1} B_T^{0} \sim \nu_*^{0}$)
  - Stability control methods necessary for high-β operation
**Core: Measurements and theory help in understanding the turbulence that underlies confinement trends in STs**

- ITG turbulence often suppressed by flow shear
  - **MAST** BES measurements of ITG ñ show flow shear breaks symmetry of turbulence in space (tilt) and amplitude (skewed PDF)
- Collisionality dependence controlled by electron transport due to
  - electrostatic dissipative TEM/electromagnetic microtearing modes on **NSTX**
  - electrostatic ETG on **MAST**

**MAST**

- ETG sims initially produce streamer-like structures before forming ‘vortex streets’
  - Collisionality dependence due to damping of zonal flows

[G. Colyer et al., PPCF 59 055002 (2017)]
[M. F. J. Fox et al., PPCF 59 034002 (2017)]
[F. van Wyk et al., PPCF 59 114003 (2017)]
Core: Multi-scale and non-local effects potentially important for understanding underlying turbulence

- Ion-scale (ITG/TEM) non-linear simulations (GTS) for NSTX L-mode illustrate importance of global effects
  - Transport from global (GTS) lower than from local (GYRO) simulations → profile shearing effects at large $\rho_*$ important
    - $1/\rho_* \sim 75$ (NSTX), 200 (DIII-D), 350 (JET)

- Electron-scale (ETG) non-linear simulations predict significant $Q_e$; close to exp’tl
  - Similarity in $Q_e$, high-$k$ and $Q_i$, low-$k$ indicates cross-scale coupling may be important
Core: Disruption Event Characterization and Forecasting (DECAF) code used to provide a cross-machine comparison of disruptivity

- DECAF analysis of disruption event
  - Shots analyzed at 10 ms intervals during Ip flat-top
  - MAST: 8,902 plasmas analyzed; NSTX: 10,432 plasmas
- Supports published result that disruptivity doesn’t increase with $\beta_N$
- Disruptivity plots provide important information, but can be misleading when used incorrectly
  - Plasma conditions can change significantly between first problem detected and when disruption happens
  - Circles mark the key region to study with DECAF: where events that lead to disruptions (X’s) start
This talk will cover recent complementary results from NSTX(-U) and MAST

- **Energetic particle physics/mode stability**
  - Energetic particle-driven instabilities may reflect those in ITER, next-step devices
  - Will show examples of fast ion distribution effects by sawteeth, high-frequency AE to develop understanding, predictive capabilities, and control methods
  - Instabilities in both frequency ranges may be important for ITER
Energetic Particles: Sawteeth on MAST and NSTX-U have a significant effect on the fast particle population

- **MAST** neutron camera measurements show a drop in neutron rate (fast ion distribution) across profile
  - Modeling indicates that sawteeth have **comparable** effect on both trapped and passing particles
    - [M Cecconello et al., PPCF 60 055008 2018](#)

- FIDA & solid-state NPA measurements on NSTX-U indicate that passing particles strongly expelled from core by sawteeth
  - Little effect on trapped particles

[Image of neutron camera count rates and sawtooth crash](#)
**Energetic Particles:** Different sawtooth models on **MAST** and **NSTX-U** show agreement with experiment

- Full reconnection model (Kadomtsev) consistent with measurements in **MAST**
  - Inversion of real and synthetic FIDA data show expulsion of trapped and passing particles from core
- Simple sawtooth models cannot reproduce spatial redistribution of fast particles in **NSTX-U** [Kim, EX/P6-33]
  - “Kick” model [Podesta, PPCF (2014)], based on orbit-following calculations of fast ions, lead to better agreement

[B. Madsen et al., RSI 89 10D125 (2018)]
Energetic Particles: Different sawtooth models on **MAST** and **NSTX-U** show agreement with experiment

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Are differences due to differences in injection energy, phase space distribution of EP?
Energetic Particles: Progress in developing tool for phase-space engineering of EP-driven instabilities in NSTX-U

- High frequency global Alfvén Eigenmodes (GAEs) suppressed by off-axis beam injection [Fredrickson PRL (2017), Nuc. Fus. (2018)]
- Non-linear HYM simulations show unstable counter-rotating GAEs
  - Maximum growth rates for toroidal mode numbers -7 to -11
  - Predicted frequencies match measurements
  - Peak saturation amplitudes $\delta B/B \sim 5e-3$
  - Effect on electron transport under investigation
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- EP phase space engineering will be explored in MAST-U using on/off-midplane NB and off-midplane RMP coils
This talk will cover recent complementary results from NSTX(-U) and MAST

- **Boundary and divertor physics**
  - Turbulence studies at midplane and in divertor SOL for aid in understanding processes controlling heat flux amplitude and profile
**Boundary: Gas puff imaging & theory being used to study edge turbulence near the midplane in NSTX**

- GPI measurements of edge turbulence show dipole-like 2-D spatial correlations with large negative regions (blue)

- Semi-analytic model assuming blob-hole pairs shows similar 2D correlation patterns, dipole flip across separatrix
  
  [Myra, PPCF (2018)]

- Edge turbulence is being better understood through a combination of semi-analytic models and numerical simulation (e.g. XGC1)
**Divertor: Fast camera imaging of the divertor provides new insights into SOL turbulence**

- Non-linear 3D drift-fluid simulations (STORM/BOUT++) of SOL turbulence performed in realistic MAST geometry [Militello TH/7-1]
  - Reproduces filaments seen in fast camera videos of main chamber and divertor
    - SOL $D_\alpha$ profiles well described by superposition of independently moving filaments
  - Quiescent region in SOL near X-point has been identified [Walkden et al., Nuc. Fus. 57 126028 (2017)]
  - Synthetic diagnostics developed to enable direct comparison with experiments

Background subtracted fast camera data

BOUT++ simulation
**Divertor: Fast camera imaging of the divertor provides new insights into SOL turbulence**

- Divertor leg fluctuations observed by fast imaging in **NSTX-U**
  - Intermittent; localized to bad curvature side
- Evidence for X-point disconnection
  - Inner and outer filament legs not correlated
  - Divertor filaments/midplane blobs not correlated
- Simulations with ArbiTER code find unstable resistive ballooning modes
  - [Baver, CCP (2016)]
  - [Scotti, Nuc. Fusion (2018)]
This talk will cover recent complementary results from NSTX(-U) and MAST

• Future plans
Expected benefits of Super-X divertor will be tested during first experimental campaign of MAST-U

- Super-X expected to improve exhaust mitigation and control of detachment front position
- Detachment in Super-X expected at lower density than in conventional

- Parallel heat flux gradients along Super-X leg should improve detachment control
  - Scales with $B_{x-pt}/B_{\text{target}}$; can be higher is STs ($\sim 3$) than at conventional aspect ratio ($\sim 1-2$)

[D. Moulton et al., Proc 44th EPS Conf. 2017]
[B. Lipschultz, et al., NF 56 056007 2016]
MAST-U preparing for operation

- MAST-U presently baking out; modifying TF linkages
- Expected physics operation Autumn 2019
- Detailed characterization of intrinsic error field carried out to optimize correction and broaden operating space
- New diagnostics
  - Divertor: 850 Langmuir probes, divertor TS, IR & visible cameras, bolometers
  - Energetic particles: ssNPA, FILD
NSTX-U Recovery underway

- NSTX-U operated for 10 weeks in 2016, achieving good H-mode performance, surpassing magnetic field and pulse duration of NSTX
- Run ended prematurely due to divertor PF fault
- Full repair will consist of installing improved PF coils, graphite PFCs to handle heat fluxes of high-power, long-pulse scenarios, minimized error fields to increase reliability [Gerhardt, FIP/P3-63]
- Projected to commence operations in early 2021
  - Study transport and stability physics at high-β/low \( \nu_* \) \( (B\tau \sim \nu_*^{-0.8}) \)
  - Demonstrate full non-inductive operation (\( j(r) \) control with NBI)
Close collaboration between NSTX-U and MAST-U on developing startup scenarios

- Vacuum field calculations support magnetic calibrations and inductive startup scenario development
- Procedure for producing MAST-U first plasma being developed using the PPPL-LRDFIT code
  - Results from NSTX(-U) provide basis for first-plasma scenarios on MAST-U
  - Extended on-site (CCFE) visits facilitate collaboration
Summary: NSTX(-U) and MAST address urgent issues for fusion science, ITER and next-step devices

- Core transport & turbulence studied over an extended range of $\beta$ and $v_*$
  - Electrostatic and electromagnetic effects drive strong favorable $v_*$ scaling
  - Multi-scale effects (low- & high-k) must be considered
- Energetic particle effects and instabilities studied in portions of parameter space expected for $\alpha$-burning plasmas
  - Low and high frequency modes can have profound effect on EP distribution
  - Predictive models and phase-space engineering techniques being developed
- Boundary and divertor studies address processes controlling heat flux width
  - Filamentary structures/turbulence
  - Heat flux mitigation through innovative divertor designs
- When operation commences, NSTX-U and MAST-U will be the most capable devices in the world-wide ST program

Relevant IAEA contributions follow
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<th>Presentation</th>
<th>Date/Time</th>
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<td>J. Menard: Fusion energy development utilizing the Spherical Tokamak</td>
<td>(Mon AM)</td>
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<td>3</td>
<td>M. Podesta: Reduced EP transport models</td>
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<td>E. Belova: Numerical simulations of GAE suppression</td>
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<td>G.Z. Hao: Centrifugal force driven low-f modes in STs</td>
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<td>T. Rafiq: Effects of microtearing modes on Te evolution in NSTX</td>
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<td>11</td>
<td>S. Sabbagh: Disruption characterization and forecasting</td>
<td>(Thurs PM)</td>
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<td>12</td>
<td>N. Ferraro: EF impact on mode locking and divertor heat flux in NSTX-U</td>
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<td>13</td>
<td>E. Fredrickson/M. Podesta: GAE stability dependences on fast ion distribution</td>
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<td>14</td>
<td>D. Kim: Fast ion redistribution by sawteeth on NSTX-U</td>
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<td>L. D-Aparacio: Rotation-induced electrostatic potentials and density asymmetries in NSTX</td>
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<td>16</td>
<td>R. Goldston: Development of Li vapor box divertor for controlled plasma detachment</td>
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<td>17</td>
<td>T. Brown: A toroidal confinement facility to study liquid lithium divertor</td>
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<td>18</td>
<td>A. Hakim: Continuum g-k simulations of NSTX SOL turbulence with sheath-limited geometries</td>
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Backup
NSTX(-U) and MAST research address urgent issues for fusion science, ITER and next-step devices

- STs can investigate turbulence over an extended range in $\beta$ (tens %)
  - Electrostatic and electromagnetic effects at large $\rho^*$

- STs EP physics spans phase space expected in Burning Plasmas
  - Develop predictive and control methods

- Reduced connection length and surface area can lead to increased $q_{\text{target}}$ in conventional divertors in STs
  - Developing strategies to mitigate heat fluxes in STs critical

(move to backup?)
NSTX(-U) and MAST research address urgent issues for fusion
science, ITER and next-step devices

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MOVE TO BACKUP?
Core: Disruption Event Characterization and Forecasting (DECAF) algorithm being developed for stable operation

- DECAF utilizes physics-based models as much as possible to identify event chain leading to disruptions in a time-evolving fashion [Sabbagh et al., EX/P6-26]
  - Couple to real-time control system for stable operation, disruption mitigation

DECAF event chain

- Multi-institutional effort [NSTX, MAST, KSTAR, DIII-D, TCV (so far)]
Energetic Particles: Microturbulence is a mediator of EP instabilities on NSTX-U

- High $\beta_{\text{fast}}$, $v_{\text{fast}}/v_{\text{Alfvén}}>1$ provide significant drive for enhanced wave-particle and nonlinear mode-mode interactions (chirping, avalanches)
  - Seen predominantly at lower than at higher aspect ratio
- Microturbulence can increase scattering of resonant fast ions to reduce chirping and avalanching [Duarte Nuc. Fusion (2018)]
  - Global GTS non-linear simulations support theoretical prediction
Counter-TAEs can be destabilized by off-axis co-NB injection from 2\textsuperscript{nd} NB line

- Single NB source from 2\textsuperscript{nd} NBI
- Low power, $P_{\text{NB}} \sim 1$MW
- Off-axis NBI results in broad/hollow NB ion density profile
- A transition is observed from co-TAEs only to cntr-TAEs
Details of fast ion distribution explain destabilization of counter-TAEs by co-NBI

- Single NB source from 2nd NBI
- Low power, $P_{NB} \sim 1$ MW
- Stability analysis with TRANSP + kick model recovers observations
- Drive results from competition between gradients in energy and canonical momentum

$\gamma_{NB}$ loss [$10^{12}$ m$^{-3}$]

$\psi_{pol}^{1/2}$

$t=150$ ms
t=200 ms
t=300 ms
t=400 ms

$\gamma_{net}(\omega)$ [%]

$\gamma_{net}(\omega)$ [%]
Boundary: Particle confinement control and turbulence being studied in MAST

- Application of Resonant Magnetic Perturbations (RMPs) reduces particle confinement
  - $\tau_{\text{ion}}$ reduced by $\sim 20\%$ in L-mode (with $n=3$ RMP) and $30\%$ in H-mode (with $n=4$ RMP)

- First estimates of radial wave number of Geodesic Acoustic Mode in an ST in an ohmic L-Mode in good agreement with global 2-fluid simulations [Hnat, PPCF (2018)]
  - Oscillation localized to boundary that can influence L-H transition dynamics
  - $10 \text{ kHz, } k_r \rho_p \sim -0.15, \nu_r \sim 1 \text{ km/s, located 2 cm inside the separatrix}
Divertor Physics: SOL turbulence can contribute of cross-field transport: being studied in both MAST and NSTX-U

- **MAST** SOL density profiles are well described by the superposition of independently moving filaments
  - Quiescent region in the SOL near X-point

- Divertor leg fluctuations observed by fast imaging in **NSTX-U**
  - Intermittent; localized to bad curvature side
  - Connected to divertor target plate

- Evidence for X-point disconnection
  - Inner and outer filament legs not correlated
  - Divertor filaments/midplane blobs not correlated

[References]

[F. Militello et al., PoP 25 056112 2018]
[N. Walkden et al., NF 57 126028 2017]
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[N. Walkden et al., NF 57 126028 2017]
Divertor: Linear and non-linear simulations of SOL turbulence being performed in NSTX-U and MAST

- Linear simulations with ArbiTER code for NSTX-U find unstable resistive ballooning modes [Baver, CCP (2016)]
  - Higher mode numbers on outer than on inner legs
- Non-linear 3D drift-fluid simulations (STORM/BOUT++) of SOL turbulence performed in realistic MAST geometry
  - Reproduces filamentary structures seen in fast camera videos in main chamber and divertor
**Divertor Physics:** Intermittent field-aligned filaments localized to bad curvature side of divertor legs in **NSTX-U**

- Divertor leg fluctuations observed by fast imaging [Scotti, Nuc. Fusion (2018)]
  - 10-30 kHz, $k_{\text{pol}}\rho_i \sim 0.01-0.1$, $v_{\text{pol}} \sim 1-2$ km/s
- Connected to divertor target plate
- Evidence for X-point disconnection
  - Inner and outer filament legs not correlated
  - Divertor filaments/midplane blobs not correlated
- Simulations with ArbiTER code find unstable resistive ballooning modes [Baver, CCP (2016)]
  - Higher mode numbers on outer than on inner legs

Images in CIII emission

Rendering

(a)

Separatrix

Inner leg filaments

Outer leg filaments

(b)
**Edge: NSTX is exploring L-H transition physics**

**Turbulence fluctuation energies**

\[
\text{Thermal free energy} \quad \frac{n_{e0}T_{e0}}{2} \left( \frac{\tilde{n}_e}{n_{e0}} \right)^2 + \text{Non-zonal ExB energy} \quad \frac{n_0 m_i \langle \tilde{v}_\theta^2 \rangle}{2}
\]

- Production term, P, related to Reynold’s stress
- Find P<0 just prior to L-H in NSTX
  - Energy transfer from ZF to turbulence
- Inconsistent with Predator-Prey model [Diallo, Nuc. Fusion (2017)]

**Zonal ExB energy**

\[
\frac{n_0 m_i \langle \tilde{v}_\theta^2 \rangle^2}{2}
\]