Overview of Physics Results from the National Spherical Torus Experiment (NSTX)

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Outline:

1) Lithium Research
   - Confinement improvement
   - ELM stability
   - Liquid lithium divertor

2) ITER Support
   - L-H thresholds
   - Error field amplification
   - Resistive Wall Mode
   - Fast ion instabilities & effects
   - ELM pacing & divertor heat loads

3) Advanced Scenarios
   - Snowflake divertor
   - CHI start-up
   - Partial non-inductive sustainment
   - Feedback control

Aspect ratio A: 1.3 – 1.6
Elongation κ: 1.8 – 3.0
Major radius R₀: 0.85m
Plasma Current Iₚ: 1.5MA
Toroidal Field: 0.55 T
Auxiliary heating:
   - NBI (100kV): 7 MW
   - RF (30MHz): 6 MW

NSTX Studies Toroidal Confinement Physics at Low Aspect-Ratio & Supports ITER Research

OV2-4, 23rd IAEA FEC (Raman) 11-16 Oct. 2010 2
Lithium Research

- Confinement improvement
- ELM stability
- Liquid lithium divertor
NSTX Experiments are Exploring the Benefits of Lithium to Magnetic Fusion Research

Dual Liquid Lithium Evaporator
For Li wall coatings
Now routinely used

Typically 50 to 300mg lithium now deposited between shots

H.W. Kugel FTP/3-6Ra
Improved Electron Confinement With Lithium Coating Arises from Broadening of $T_e$ Profile

- TRANSP analysis confirms electron thermal transport in outer region progressively reduced by lithium coating. Measure reductions in high-k turbulence near edge.
- Thermal ion confinement remains close to neoclassical both with and without lithium
- New confinement mode, **Enhanced Pedestal H-mode**, found with $H_{98y2}=1.8$ [R. Maingi, et al., PRL 135004 (2010)]

Pedestal Profiles Broadened and ELMs Suppressed by Lithium Wall Coatings

Edge stability calculations (ELITE)
- Colors represent contours of ratio of linear mode growth rate to diamagnetic drift frequency
- Pre-Li discharges close to kink/peeling stability boundary

- No Lithium
- With Lithium

Normalized Pressure Gradient ($\alpha$) vs. Edge current $<(j_{\text{max}}+j_{\text{sep}})/2>$

$\gamma_{\text{lin}}/(\omega^*/2)$

Kink/Peeling

Stable

Post Li

Pre-Li

R. Maingi EXD/2-2
Now Investigating Pumping Capability and Plasma Effects of a Liquid Lithium Divertor (LLD)

- 4 LLD plates form ~20cm wide annulus in lower outboard divertor
  - Heatable surface of porous molybdenum
  - Loaded with lithium by LITER deposition

- Observed preliminary indications of D pumping when surface heating by plasma liquefies lithium coating on LLD
  - Lower single null divertor plasmas with outer strike point on LLD raise peak surface temperature to ~300°C
Toroidal Confinement Physics and ITER Support

• L-H thresholds
• Error field amplification
• Resistive Wall Mode
• Fast-ion instabilities and effects
• ELM pacing & divertor heat loads
NSTX Strongly Supports ITPA Joint Experiments

**Transport and Confinement**
- TC-1 Beta degradation of energy confinement
- TC-2 Hysteresis and access to H-1
- TC-4 Species dependence of L-H threshold
- TC-9 Scaling of intrinsic rotation
- TC-10 Exptl. identification of turbulence and comparison with codes
- TC-12 Confinement at low aspect ratio
- TC-14 RF rotation drive
- TC-15 Dependence of momentum and particle pinch on collisionality

**Macroscopic Stability**
- MDC-2 RWM physics
- MDC-14 Rotation effect on NTMs
- MDC-15 Disruption database development
- MDC-17 Active disruption avoidance

**Energetic Particles**
- EP-1 Measurement of damping rate of TAEs
- EP-2 Fast ion loss/redistribution from localized Aes
- EP-4 Effect of dynamic friction at resonance on non-linear AE evolution

**Pedestal**
- PEP-6 Pedestal structure and ELM stability in DN
- PEP-19 Edge transport with RMP
- PEP-23 ELM suppressions by magnetic perturbations
- PEP-26 Critical edge parameters for achieving L-H
- PEP-27 Pedestal profile evolution following L-H transition

**Divertor and Scrape-Off Layer**
- DSOL21 Dust transport

**Integrated Operating Scenarios**
- IOS-5.2 Maintaining ICRF coupling in expected ITER regimes
NSTX Equipped with Midplane Non-Axisymmetric Coils for MHD, Confinement and Pedestal Studies

Produce $n = 1$, 3 or 2 (4) radial field perturbations

Used for studies of:
- H-mode threshold
- Error field correction (EFC)
- Resistive Wall Mode (RWM)
- ELM pacing
- Momentum transport
L-H Threshold Experiments in NSTX Have Explored Many ITER and ST-Relevant Issues

- **Species dependence**
  - \( P_{\text{LH}} \) (He) \( \sim \) 1.2-1.4 \( P_{\text{LH}} \) (D): RF-heated
  - \( H_{98y,2} \) \( \sim \) 1 with no ELMs after L-H transition

- **Non-axisymmetric field application**
  - \( P_{\text{LH}} / n_e \) increased \( \sim \) 65% with several Gauss \( n=3 \) fields

- **Plasma configuration**
  - Lower \( P_{\text{LH}} \) at increased major radius of X-point

- **Lithium coatings**
  - \( P_{\text{LH}} / n_e \) decreased by \( \sim \) 35% with lithium coating
  - Additive influence for \( R_X \), USN vs. LSN

- **Strong \( I_p \) dependence (ST effect)**
  - Lower \( P_{\text{LH}} \) with lower \( I_p \)
  - XGC0 calculations show larger \( E_r \) shear at lower \( I_p \)

- **Role of ion-scale turbulence**
  - Beam Emission Spectroscopy now operational

S.M. Kaye EXC/2-3Rb
Inclusion of Plasma Response Important to Understanding Effects of Error Fields

- Measure dependence on the line-average density of resonant 2/1 amplitude at $q = 2$ surface at which mode locks
- Ohmic L-mode plasmas at low density show familiar proportional dependence
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- Linear scaling with density breaks down in high-density, high-\( \beta \) NBI-heated plasmas
  - mode locks at anomalously low error field

![Graph showing weighted \( \delta B_{2,1} \) vs. density at EF penetration]
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- Ohmic L-mode plasmas at low density show familiar proportional dependence
- Linear scaling with density breaks down in high-density, high-\(\beta\) NBI-heated plasmas
  - mode locks at anomalously low error field
- Linear scaling is restored when plasma amplification of applied field included
  - Plasma response is calculated by IPEC

IPEC:
Ideal Perturbed Equilibrium Code

Calculates
- Ideal plasma response
- Shielding currents
- Total resonant field at q=m/n
Resistive Wall Mode (RWM) Stability Depends on Thermal Kinetic Resonances and Fast-ion Content

- Observe that RWM can be unstable despite significant plasma rotation
- **MISK code** predicts stabilization of RWM from:
  - precession drift resonance \( \omega_D \) at low rotation
  - bounce resonance \( \omega_b \) at high rotation
- Plasma marginally unstable at intermediate rotation
- Stability to RWM predicted to improve with fast ion content
  - Lower rotation speed required to stabilize RWM for higher fast-ion density
  - Important for high-beta ST-FNSF and ITER advanced scenarios
TAE-Avalanche Induced Neutron Rate Drop Modeled Successfully Using NOVA and ORBIT Codes

- Toroidal Alfvén Eigenmode (TAE) avalanches in NBI-heated plasmas associated with transient reductions in D-D (beam-target) neutron rate
- Change in beam-ion profile measured with Fast-ion D-alpha (FIDA)
- Modeled using NOVA and ORBIT codes
  - Mode structure obtained by comparing NOVA calculations with reflectometer data
  - Fast ion dynamics in the presence of TAEs calculated by guiding-center code ORBIT

E. Fredrickson EXW/P7-06  M. Podestà EXW/P7-23  G-Y. Fu THW/2-2Rb
ELM Pacing Developed With Pulsed Non-Resonant Fields and Vertical Jogs

Rapid, Reliable Triggering with Pulsed 3-D Fields

- Reduction in radiated power
- Rapid ELMs lead to smaller per-ELM energy loss

ELM Pacing Via Vertical Jogs

- Vertical jogging successful despite thick continuous vacuum vessel.
- ELMs become phase locked to upward motion

Graphs showing:
- Stored Energy
- Electron Density
- Radiated Power
- D-Alpha
- Edge Bol. (A/#m²)
- EL M-Jog Phase
Heat Flux Profile Width Decreases Strongly with $I_p$ in NSTX, Largely Independent of $P_{\text{loss}}$, Flux Expansion, and $B_T$.

- Divertor heat flux width, magnetically mapped to the midplane, shows a strong decrease as $I_p$ is increased.
  - $\lambda_{q\text{mid}}$ further decreases in ELM-free Li conditioned discharges.
  - Research continuing to determine if adverse $I_p$ scaling is offset by favorable size scaling to future devices.

- Divertor heat flux inversely proportional to flux expansion over a factor of five.

T.K. Gray, EXD/P3-13
Advanced Scenarios

- Snowflake divertor
- CHI start-up
- Partial non-inductive sustainment
- Feedback control
“Snowflake” Divertor Configuration Resulted in Significant Divertor Heat Flux Reduction and Impurity Screening

Higher flux expansion (increased div wetted area)
Higher divertor volume (increased div. losses)

• Maintained “snowflake”-like configuration for 100-600 ms
• Maintained H-mode confinement with core carbon reduction by 50%

V. Soukhanovskii EXD/P3-32
Coaxial Helicity Injection (CHI) has Produced Substantial Flux Savings and Scales Favorably with Size and $B_T$

Enabling capabilities
- Elimination of arcs in absorber region
- Conditioning of lower divertor

Generated 1MA using 40% less flux than induction-only case
- Hollow $T_e$ maintained during ramp
- Low internal inductance ($l_i \approx 0.35$)
- High elongation
- Suitable startup for advanced scenarios

B.A. Nelson EXW/P2-8
Developed Sustained High-Elongation Configurations Over a Range of Currents and Fields

**High-$\beta_T$**  
$q^*=2.8$  
$B_T=0.44$ T  
$I_p=1100$ kA

**Long Pulse**  
$q^*=3.9$  
$B_T=0.38$ T  
$I_p=700$ kA

**High-$\beta_P$**  
$q^*=4.7$  
$B_T=0.48$ T  
$I_p=700$ kA

$\kappa \sim 2.6-2.7$  
$\delta \sim 0.8$

Double Null

$q^* = \frac{\epsilon(1 + \kappa^2)\pi a B_{T0}}{\mu_0 I_p}$

$H_{98} \geq 1$

Plasma current

Poloidal beta EFIT

Toroidal beta EFIT

Current in central solenoid

Pressure Driven

Neutral Beam

S. Gerhardt EXS/P2-8
NSTX is Developing Shape and Stability Control Techniques Relevant to ITER and Next-Step STs

- New inner & outer strike-point control
  - In-line system ID for single-shot optimal gain identification
  - Used for LLD experiments and snowflake divertor control
- Feedback-based $n=1$ error field correction and RWM control.
  - Routine with PID controller + first state-space RWM controller in high-$\beta$ tokamak.
- Control $\beta_N$ using NBI power modulation
- Combined controllers result in improved performance.
  - Example: simultaneous RWM + $\beta_N$ control w/ different levels of rotation.

Controlled Strike-Point Motion

Simultaneous Control of $\beta_N$ and $n=1$ RWMs

E. Kolemen EXD/P3-18  S. Gerhardt EXS/P2-8  S.A. Sabbagh EXS/5-5
Summary: Considerable Progress Made in NSTX Towards Sustained Operation in Support of STs and ITER

- Developing understanding of transport and stability changes from Li
- Strongly supporting ITER (LH threshold, ELM triggering, SOL width scaling)
- Using CHI to initiate ST plasmas, advanced control to sustain ST plasmas

FUTURE: Major upgrade of NSTX to occur 2012-2014 with 2 elements:

- New center stack for 1T, 2MA, 5s to access reduced $\nu^*$, 100% non-inductive ST plasmas
- 2$^{nd}$ NBI with larger $R_{\text{tangency}}$ for sustained and controllable 100% NICD + high $\beta$ at low $\nu^*$
## NSTX related papers at this conference

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Electron Gyro-scale Turbulence in Edge Reduced with Lithium

- k spectra of normalized density fluctuations
- Reduction of high-k turbulence power is observed in the pedestal region as Lithium is added.

![Graph showing the effect of Lithium on high-k turbulence power](image)
New high confinement regime with HH$98y2 < 1.8$ observed in NSTX

“Enhanced Pedestal” H-mode
Standard H-mode
separatrix

R. Maingi, PRL 2010