Overview of results from the National Spherical Torus Experiment (NSTX)

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For the NSTX Research Team

22nd IAEA Fusion Energy Conference
Geneva, Switzerland
October 13-18, 2008
NSTX has made leading contributions in many areas of toroidal fusion science

• NSTX Mission is to:
  – Establish attractive ST operating scenarios & configurations
  – Complement tokamak physics and support ITER
  – Understand unique physics properties of the ST (in red) ⇒ basis of all the elements of the NSTX mission

Outline

• In support of this mission, NSTX has made significant progress in the areas of:
  – Transport and Turbulence
  – Plasma/wall interactions
  – MHD
  – Waves
  – Non-inductive startup
  – Advanced scenarios and control
  – Direct ITER support
NSTX Designed to Study High-\( \beta \) Toroidal Plasmas at Low Aspect-Ratio

- **Aspect ratio** \( A \) \( 1.27 - 1.6 \)
- **Elongation** \( \kappa \) \( 1.8 - 3.0 \)
- **Triangularity** \( \delta \) \( 0.2 - 0.8 \)
- **Major radius** \( R \) \( 0.85 \text{m} \)
- **Plasma Current** \( I \) \( 1.5 \text{MA} \)
- **Toroidal Field** \( B_T \) \( 0.4 - 0.55 \text{T} \)

**Auxiliary heating:**
- NBI (100kV) \( 5 - 7 \text{ MW} \) (Pulse Length \( 5 - 2 \text{ s} \))
- RF (30MHz) \( 6 \text{ MW} \) (5 s)

**Central temperature** \( 1 - 5 \text{ keV} \)

**Central density** \( 1.2 \times 10^{20} \text{ m}^{-3} \)

- **PF coils for shaping, control**
- **Slim center column with TF, OH coils**
- **Conducting plates for MHD stability**
- **Insulated VV breaks for CHI**
- **Large diagnostic access ports**
- **Graphite/CFC PFCs + Lithium coating**
Observed onset of high-\(k\) electron turbulence consistent with ETG

- **NSTX ideal experiment for electron turbulence measurements** -
  - relatively large \(\rho^*\), large magnetic shear gives strong spatial localization
- Using High Harmonic Fast Wave heating to modify \(T_e\) profiles, observed turbulence
  - scales with \(R/L_{Te}\), rotates in electron direction, has large \(k_{\perp}\rho_i >> 1\) → Inconsistent with ITG turbulence
- GS2 calculations of ETG critical gradient show agreement with the onset of turbulence
- Have begun quantitative assessment of observed fluctuations on transport

See talk by E. Mazzucato EX/10-2

• **Radial location of turbulence measurement**
• **Spectral density for \(k_{\perp}\rho_e \sim 0.2-0.4\)**

Also see poster by H. Yuh EX/P3-1
Non-resonant $n=3$ magnetic braking capability is used to probe effect of $ExB$ shear on confinement

- During beam injection, NSTX typically operates with $\gamma_{ExB} \sim 1\text{MHz} \sim 4-5\gamma_{ITG}$
  - Expect routine flow shear suppression of ion scale turbulence on NSTX

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- **Energy**
  - $n=3$ braking reduces the magnitude of edge velocity shear
  - Leads to an increase of edge ion thermal diffusivity

- **Momentum**
  - TRANSP analysis of rotation data from charge exchange $\chi_\phi \gg \chi_{\phi_{\text{neo}}}$
  - Indicates residual low-k turbulence

See talk by S. Kaye EX/3-2

Lithium coating increases confinement and suppresses ELMs

- Lithium evaporation capability greatly improved
  - Redesigned evaporator with higher temperature, better alignment
  - Second evaporator added in 2008

- Stored energy increases 20% with Lithium

- ~2/3 of the improvement in confinement is in the electron channel

See poster by R. Kaita EX/P4-9
Edge studies investigate scalings and mitigation of large SOL power flows

- Because of low-A effects, NSTX routinely operates with peak divertor heat fluxes ~ 10MW/m
  - Similar in magnitude to ITER heat divertor heat flux
- Important to mitigate heat flux and understand scaling to future low aspect ratio devices
  - **Divertor gas puffing reduces peak heat**
  - **SOL width scaling**
    - **Near SOL:** \( \lambda_T/e/\lambda_q \approx 2.3 \), closer to electron conduction dominant case \((\lambda_T/e/\lambda_q = 3.5)\) than sheath limited case \((\lambda_T/e/\lambda_q = 5)\)
    - **Far SOL:** \( \lambda_T/e/\lambda_q \approx 1.2 \), suggesting other dominant process

See poster by V. Soukhanovskii EX/P4-22
n=1 RFA/RWM control combined with n=3 error correction increases $\beta$ and extends pulse

- **MHD spectrogram w/o n=1 feedback and n=3 correction**

- **MHD spectrogram with n=1 feedback and n=3 correction**

- Non-axisymmetric feedback algorithm has been developed using unique feedback training scheme
  - Prevents onset of MHD modes
  - Plasma rotation is maintained throughout discharge

- Control statistically raises $\beta$ and increase pulse length

Pulse averaged $\beta N$ vs. current flat-top

See talk by S. Sabbagh EX/5-1  See also talk by H. Reimerdes/J. K. Park EX/5-3R
n=3 braking enables investigation of effects of rotation and rotational shear on MHD stability

- Neoclassical island drive is measured at onset of 2/1 NTM
  - Shows clear increase with rotation shear, no clear trend with rotation
  - Also clear increasing trend in required island drive with type of trigger with EPM → ELM → no visible trigger

- Indicates role of flow shear in stabilizing NTMs
- Will impact NTM stability in ITER

\[ \text{Neoclassical island drive vs. rotation frequency at the } q=2 \text{ surface} \]

\[ \text{Neoclassical island drive vs. normalized rotational shear at the } q=2 \text{ surface} \]

See ITER poster by R. Buttery IT/P6-8
Edge density control using lithium coating has improved coupling efficiency of both HHFW heating and EBW emission

- NSTX explores the wave physics of overdense plasmas
  - HHFW heating efficiency improved by operating below the critical density for coupling to surface waves
    \[ n \sim \frac{Bk}{\omega} \]
  - HHFW heats electrons in beam heated deuterium H-mode for first time
  - EBW emission efficiency improved by reducing the collisionality at the mode conversion layer
  - Transmission efficiency increased to \(~70\%\) with lithium from \(~10\%\) without lithium coating

See poster by C. Phillips EX/P6-25

See poster by S. Diem EX/P6-17
Multi-mode TAE avalanches are observed to induce fast particle loss on NSTX

- Because of its low toroidal field and high neutral beam voltage, NSTX routinely operates with $\nu / \nu_{\text{Alfvén}} > 1$

- Avalanches show modes with multiple $n$-numbers
  - TAE mode internal structure and amplitude are measured
  - Avalanche threshold also measured with beam voltage scan

- Particle losses are modeled using data, NOVA, and ORBIT
  - Good agreement found between measured and predicted losses

Important physics for ITER and burning plasmas

Magnetic spectrogram of multi-mode TAE avalanche on NSTX showing ~20% neutron loss

See talk by E. Fredrickson EX/6-3

See talk by N. Gorelenkov TH/5-2

Calculated $n=3$ radial eigenfunctions from the NOVA code

black $n=1$, red $n=2$, green $n=3$, blue $n=4$, magenta $n=6$
Ohmic ramp-up coupled to CHI startup plasma

- Because of low aspect ratio, NSTX has very limited inductive flux ~0.7Vs
- CHI ramps current from 0 to ~100-150kA of closed flux current
  - Current multiplication = \( \frac{I_{\text{inject}}}{I_p} \approx 70 \)
- Fixed loop voltage applied - current ramped to ~0.7MA
- NBI heating applied, plasma often enters H-mode

See poster by R. Raman EX/P6-10
NSTX accesses long pulse at high $\beta$ with extreme plasma shaping scenario

- Because of improved vertical stability at low aspect ratio, NSTX can access very high elongation $\kappa \sim 3$
  - $f_{bs} \sim (1+\kappa^2)/2$

$\forall$ $\beta$ maintained well above the no-wall limit, $\beta_N \sim 5$

- Pulse extended - maintained non-inductive current fraction $f_{NI} \sim 65\%$ for $1-2\tau_{CR}$ - limited by TF coil heating limit
  - Uses $n=3/n=1$ control described earlier
  - Also uses lithium coating to improve confinement

Time history of global parameters and non-inductive current fraction as determined by TRANSP, constrained by MSE

Cross-section of $\kappa \sim 2.7$ equilibrium
NSTX is improving understanding of RMP ELM control and vertical stability for ITER

- Experiments using external n=3 fields with single row of midplane coils did not suppress ELMs
- Pulsed n=3 error fields triggered ELMs in discharges with lithium ELM suppression
  - ELM pacing with RMP coils?
- Typical induced VDE Evolution on NSTX

- Experiments using induced VDEs have measured $\Delta z_{\text{max}}$
- Results consistent with $\Delta z_{\text{max}}/a > 0.1$ for robust control
- Crucial that ITER has robust vertical control - internal control coil added

See rapporteured talk by A. Portone/D. Humphreys IT/2-4

See post-deadline paper by J. Canik

ELMS remove impurities reduce radiation

See post-deadline paper by J. Canik

[Graphs showing typical VDE evolution on NSTX]
NSTX has advanced the science of toroidal confinement and the ST concept across a broad spectrum of topics

- NSTX has progressed towards understanding the unique physics properties of the ST
  - Measured electron-scale turbulence consistent with ETG
  - Improved confinement with lithium
  - Measured and controlled edge and divertor power flows
  - Increased $\beta$ and pulse length with RWM/RFA control
  - Improved wave coupling in over-dense plasmas with lithium
  - Observed and modeled TAE avalanches - important for burning plasmas and ITER
  - Coupled inductive ramp-up to CHI plasma
  - Achieved high $\beta$ simultaneous with extreme plasma shaping
  - Investigated ELM RMP control and vertical stability for ITER

- These results are very promising for proposed future STs, such as NHTX and ST-CTF

See NHTX poster by R. Goldston FT/P3-12
See ST-CTF poster by Y. -K. M. Peng FT/P3-14
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