Confinement and heating studies on the National Spherical Torus Experiment (NSTX)

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A program goal is to understand the physics specific to high beta and low aspect ratio

- Overview of operating scenarios, tools
- Neutral beam heating & transport
- Electron heating & transport
- The edge

*Change the aspect ratio, increase beta: what physics changes?*
NSTX operational capabilities increasing, and allow confinement studies to begin

**Baseline** (Achieved)
- Major Radius 0.85 m
- Minor Radius 0.68 m
- Elongation ≤ 2.2 (2.5)
- Triangularity ≤ 0.6 (0.7)
- Plasma Current
  - 1 MA (1.4 MA)
- Toroidal Field
  - 0.6 T (≤0.45 T)
- Heating and CD
  - 5 MW NBI (5 MW)
  - 6 MW HHFW (6 MW)
  - 0.5 MA CHI (0.4 MA)
- Pulse Length
  - ≤ 5 sec (0.5 sec)
Local transport studies focus on understanding global trends.

**NSTX**

- **Core transport physics**
  - NBI: Ion thermal energy *higher than expected* with neoclassical ions
  - NBI & HHFW: Electron channel dominates

- **Thermal transport**
  - Heating: Heating puzzle with NBI

- **Impurity ion particle transport**
  - Close to neoclassical when measured

- **Theory of instabilities**
  - NBI: $k_\theta \rho_i >> 1$ dominant, $k_\theta \rho_i < 1$ stable or suppressed

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*Kaye; Sabbagh (Columbia)*

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**Graph:**
- $\tau_{E}^{99P}$ (ms) on the x-axis
- $\tau_{E}$ (ms) on the y-axis

- Data points marked with circles for maximum stored energy and diamonds for pre-mhd.

- L mode: $x1$ and $x2$.
NSTX Systems, Diagnostics, Analysis Tools Enable Study of Local Transport

- **NBI**: 80 kV, deuterium
- **HHFW**: 30 MHz, 12 strap antenna
- **MPTS**: $T_e(R,t), N_e(R,t)$
  - 10 ch., 60 Hz
- **CHERS**: $T_i(R,t), V_\phi(R,t)$
  - 16 ch., 20 ms
- **EFIT**: Equilibrium
- **TRANSP**: Transport Analysis
- **GS2**: Gyrokinetic Analysis
Neutral beam heating yields high ion temperatures in high current plasmas

- $T_i > T_e$
- $T_i$ broad
- Edge $V_\phi$ pedestal
- Large $V_\phi$: co-directed NBI

$L$ mode
1.2 MA, 0.33 T
4.8 MW NBI
Ion Thermal Confinement Better Than Electrons

- $T_i > T_e$
- Classical $P_{\text{NB}}$ 2:1 electrons:ions
- Peaked NB deposition

\[ \beta_T \sim 23\% \]

$T_e$ (keV), $T_i$ (keV)

$P_{\text{be}}$, $P_{\text{bi}}$
## Power Balance Points To Puzzles

<table>
<thead>
<tr>
<th>Power Source/Sink</th>
<th>ELECTRONS (MW)</th>
<th>IONS (MW)</th>
<th>NET (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OHMIC Heating</td>
<td>1.2</td>
<td>0</td>
<td>1.2</td>
</tr>
<tr>
<td>BEAM Heating</td>
<td>2.77</td>
<td>1.42</td>
<td>4.19</td>
</tr>
<tr>
<td>i-e Coupling</td>
<td>2.73</td>
<td>-2.73</td>
<td>0</td>
</tr>
<tr>
<td>dW/dt</td>
<td>0.11</td>
<td>-0.54</td>
<td>-0.43</td>
</tr>
<tr>
<td>Other*</td>
<td>-0.66</td>
<td>0.26</td>
<td>-0.4</td>
</tr>
<tr>
<td><strong>NET POWER IN</strong></td>
<td><strong>6.15 MW</strong></td>
<td><strong>-1.59 MW</strong></td>
<td><strong>4.56 MW</strong></td>
</tr>
<tr>
<td>“Misplaced Heating”</td>
<td>&lt; -1.59 MW</td>
<td>&gt;1.59 MW</td>
<td>0.0 MW</td>
</tr>
<tr>
<td><strong>NET POWER OUT</strong></td>
<td>&lt; 4.56 MW</td>
<td>&gt; 0.0 MW</td>
<td>4.56 MW</td>
</tr>
</tbody>
</table>

TRANSP 106382A01 @ 0.25 s

*Beam Thermalization, Rotation, Radiation, Convection

**More Power Out of Ions Than In!**  

**Need Extra Ion Heating to Balance Power**
Summary of power balance with NBI

- $T_i$ consistently larger than $T_e$, despite expected large fraction of electron heating by beams
  - $\Rightarrow$ electron conduction is the dominant loss channel

- Power balance makes sense if
  - $\chi_i$ is exceptionally low
  - Ions get more heat from fast ions than expected classically

- Diagnostic validation ongoing

- Non-classical effects in heating and $Q_{ie}$ being explored
Astrophysics and observed MHD may hold one clue to the power balance puzzle

- Being investigated: Compressional Alfven Eigenmodes
- Modes excited by fast ions; waves transfer energy to thermal ions

Fredrickson

However, initial study suggests:
low $E_{\text{beam}} \Rightarrow$ no CAE modes observed, but ion stored energy is still too high

Fredrickson

- Theory of stochastic wave heating of corona developed (White)
- Application of theory to ST has begun
- $V_{\text{beam}} > V_{\text{Alfven}}$ key

Gates, Gorelenkov, White
Low ion particle transport consistent with low ion thermal transport

- After neon puff, almost no neon penetrates the core until MHD event near 260 ms
- Modelling suggests core diffusivity $< 1 \text{ m}^2/\text{s}$, near neoclassical theory

Signals from difference of similar plasmas with and without neon puff

USXR measurements of He-, H-like neon lines
Theory: short wavelength modes may dominate transport, long wavelength modes may be suppressed

- Long $\lambda$, low $k$ (ITG, TEM):
  
  * $growth rate < ExB shear rate$
  
  - Large $\lambda$ associated with ion thermal transport
  - Low aspect ratio: Analysis suggests $\nabla \beta$ strongly stabilizing

- Low $\lambda$, high $k$ (ETG):
  
  * $growth rates large$
  
  - Responsible for electron thermal transport?
  - Non-linear simulations begun to estimate possible fluxes

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C. Bourdelle (PPPL), W. Dorland (U. MD)
• $T_e > T_i$ with auxiliary power to electrons
Electron Loss Channel Also Dominant with HHFW Heating

- Power deposition: HPRT ray tracing code
- $\chi_i \sim 2-2.5 \chi_i^{NC}$, $\chi_e \gg \chi_i$
- ETG unstable
- Low $k_\theta$ modes ITG + TEM
Power balance analysis reveals that reduced electron transport is correlated with high $T_e$.

- Core $\chi_e$ drops as high $T_e$ develops
  - Steep gradients due to transport changes, not source

- Heating source from HPRT ray tracing (Rosenberg)

![Diagram showing electron thermal conductivity vs normalized minor radius]
Bifurcations to enhanced plasma confinement state observed with both NBI and HHFW

Visible light, false color

Before transition  After transition

• NBI: Power required ~ 10x that predicted from empirical scaling laws:
  – Strong magnetic shear?
  – Poloidal damping? Wall neutrals?

• Change in edge transport evident in density profile

• Fluctuations reduced at H mode transition

Edge reflectometry: Peebles, Kubota (UCLA)

Fast camera: Maqueda (LANL)  H mode: Maingi, Bush (ORNL); LeBlanc
Imaging of edge reveals qualitative differences in H- and L-mode turbulence

- BOUT code: turbulence modeling
  - 2-fluid,3D Braginskii equation code

Maqueda, LANL; Zweben

Los Alamos
NATIONAL LABORATORY
Imaging of edge reveals qualitative differences in H- and L-mode turbulence

- Helium puffed; emission viewed along a field line
- $\text{He}^0$ emission observed with a fast-framing, digital, visible camera
  - 1000 frames/sec, 10 $\mu$s exposure each frame

Maqueda, LANL; Zweben
HHFW-driven H modes found

- LSN
- Lower current (350 - 500 kA)
- He and D
- ELMy, ELM-free
- $\beta_p = 1$ observed
  - Large bootstrap?
  - Large dip in surface voltage

Starting scenario for future CD work?
Studies of underlying physics of ST transport has begun

- Kinetic profiles are enabling initial local transport analysis

- **NBI**: $T_i > T_e$, despite prediction that $2/3 P_{NBI}$ goes to electrons
  - Electrons are the dominant loss channel
  - Ion heating not understood
  - Low particle transport correlated with low ion thermal confinement
  - **ExB** shear suppression of low k modes seen in analysis at high beta
  - Exploring role of ETG

- **HHFW**: $T_e > T_i$
  - Electrons are the dominant loss channel
  - Reductions in $\chi_e$ with strong central $T_e$ peaking
  - Possible role of $T_e/T_i$ in determining $\chi_e$ to be investigated
Summary (2)

- L-H transitions observed with NBI and HHFW
  - Turbulent structures observed in L mode state; modelling underway
  - $P_{th} \sim 850 \text{ kW for NBI; } \approx \text{ similar-sized tokamaks, } >> \text{ scaling}$
    - Role of strong poloidal damping at low aspect ratio?

- Near-term transport goals and plans
  - Understand ion heating
  - Turbulence measurements to be extended into core
  - Scans of beta: is beta or $\nabla \beta$ favorable for transport?

- Long-term goals
  - Establish a physics-based understanding of the underlying causes of ST transport trends
    - Comparison with moderate-aspect-ratio trends will reveal new physics relevant to all