Plasma heating and core mode reduction during NBI in MST

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New 1 MW Neutral Beam Injector explores new physics

- Tangential injection to maximize beam deposition
- Co-current or counter-current injection by reversing $I_p$
- Fast ion diagnostics:
  - Scintillator-based neutron detector
    - Neutron emission is dominated by beam-target reactions for certain plasma density range
  - Advanced neutral particle analyzer (ANPA)
    - Simultaneously measure charge exchange H and D neutrals
    - 10 channels per mass species
    - E: 1-30 keV, $\Delta E$:2-3 keV, $\Delta t$: $\sim$0.1 ms

<table>
<thead>
<tr>
<th>NBI Parameter</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Beam energy</td>
<td>25 keV</td>
</tr>
<tr>
<td>Beam power</td>
<td>1 MW</td>
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<tr>
<td>Pulse length</td>
<td>20 ms</td>
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<tr>
<td>Composition</td>
<td>95-97% H, 3-5% D</td>
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<tr>
<td>Energy fraction (E:E/2E/3:E/18)</td>
<td>86%:10%:2%:2%</td>
</tr>
</tbody>
</table>
NBI Heating of RFP plasma
- Measureable effect in PPCD plasma
- Requires careful accounting of consistent $\chi_e$, $P_\Omega$ profile evolution

Reduction of core mode amplitude
- Unexpected result; studying possible mechanisms of stabilization
  - Current drive effect?
  - Enhanced flow shear?
  - Fast particle stabilization?

Interesting observations of NBI in PPCD

Summary
Neutral Beam Injection creates large fast ion population in MST.

- NPA, neutron measurements confirm significant population.
- Are they confined?
- Do they thermalize?

Interesting note:

\( \rho_{fi}/a \sim \) same for

- 25 keV H in MST
- D-T \( \alpha \) (3.5MeV) in 8 MA, \( a = 1\text{ m RFP} \)
Net power ~800 kW; shine through significant, low $n_e$

NBI born fast D$^+$ neutron flux

Rapid $T_e$ change without NBI

Magnetic fluctuations suppressed during PPCD

NBI only during early portion of PPCD

200kA PPCD is a good NBI target discharge for NBI heating
PPCD plasma is rapidly evolving; careful power balance is needed to confirm NBI heating

- Core $T_e$ increases $\sim 200$ eV to $\sim 800$ eV
- $T_e(r)$ profiles measured at 1 kHz, Thomson scattering
- Non-NBI discharges used to determine consistent set of $P_\Omega, \chi_e$ profiles

![Graph showing $T_e(0)$ vs Time](image.png)

$T_e(0)$ 200kA PPCD

(No NBI)
Te profile evolution matched by solution to differential equation

- Time dependent temperature profile calculated from initial \( T_e(r) \) (10 msec)
- Matches non-NBI case (by definition)

Modeled \( T_e = T_e(10 \text{ msec}) + \frac{\partial}{\partial t} \left( \frac{3}{2} nT \right) = P_\Omega - P_{e \rightarrow i} - An\chi_e \nabla T \)
NBI into PPCD shows enhanced temperature increase

- Assume NBI does not affect Xe, Zeff
- Adding NBI heat source reproduces data
- Fast ion heating model:
  
  \[
  \frac{\partial}{\partial t} \left( \frac{3}{2} nT \right) = P_\Omega - P_{e\rightarrow i} - An\chi_e \nabla T
  \]

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- TRANSP estimate of beam ionization
- Fast ions:
  * are radially confined.
  * slow down classically.
  * vanish after losing 1/e of energy

![Graph showing temperature profile with NBI and without NBI]
Central temperature change reproduced throughout PPCD

- $\Delta T_e(0) \sim 100$ eV
- Simple, classical model reproduces temporal evolution of core $\Delta T_e$
- NBI heating effect extends beyond beam turn-off
  (Fast ions still confined, are slowing)
- Model matches data after end of PPCD
  Te, $\Delta T_e$ decreasing due to enhanced $\chi_e$
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Summary
NBI suppresses core mode; does not affect outer modes

- Example 1: 200 kA PPCD
  - $q(0) \sim 0.18$
  - $n = 6$ mode reduced
  - $n \geq 7$ unaffected.
NBI suppresses core mode; does not affect outer modes

- Example 1: 200 kA PPCD
  - $q(0) \sim 0.18$
  - $n = 6$ mode reduced
  - $n \geq 7$ unaffected.

- Example 2: Shallow reversed standard plasma.
  - $q(0) \sim 0.21$
  - $n = 5$ mode reduced
  - $n \geq 6$ unaffected.

- Mechanism of mode stabilization not yet identified
  - Altered $J_\parallel$ profile?
  - Enhanced flow shear?
  - Stabilization due to fast ions at island?
Expected NBI current drive is weak but may affect resonance condition.

TRANSP predicts $J_{NBI} < 10\%$ of background

Enhanced toroidal current not observed.
(Not likely stabilizing)

Altered profile which conserves Ip difficult to measure
NBI applies significant torque; alters flow, flow shear.

Enhanced flow shear:
Can lead to window of stability for global modes
M.S. Chu et. al. Phys Plasmas 1995

May have destabilizing effect on m=1 tearing in RFP.
Gatto, Terry, Hegna Nuc. Fusion 2002
Fast particles in vicinity of rational surface could be stabilizing influence.

Flow pattern of island dictated by electric field.

\[ j_\perp = -en_e \frac{E \times B}{B^2} + en_i \frac{E \times B}{B^2} = 0 \]
\[ -en_e + en_i = 0 \]

No net current when e-, bulk ions are quasineutral

Gyro-motion of fast ions (if on same length scale as island) nulls current from those particles.

\[ j_\perp = -en_e \frac{E \times B}{B^2} + en_i \frac{E \times B}{B^2} + en_{fi} \frac{E \times B}{B^2} \neq 0 \]
\[ -en_e + en_i + en_{fi} = 0 \]

Net current possible with fast ions.
Fast ion stabilization can be explored by moving the resonant surface away from fast particles.

- Imposing boundary condition on $B_\phi(a)$ affects $q(0)$, location of $q=1/5$, $q = 1/6$
- Shown here: Six equilibria from NBI experiments.
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- Shown here: Six equilibria from NBI experiments.
- Fast ion deposition presumed to be fixed
Substantial core mode reduction is observed when rational surface overlaps fast ion population.

- Time-averaged mode amplitude reduction computed for duration of NBI pulse.
- Fast ion Larmor radius ~ 5-7 cm.
- Fast ion deposition presumed fixed over varying equilibria.
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Several experimental caveats:
- fast ion density modeling is limited.
- large uncertainty in core q value
- plasma becomes more resistive for F > 0
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Summary
Case (b): “Normal” 500kA PPCD: Neutron flux keeps increasing after NB turn-off → due to bulk ion density profile evolving?

Case (c): High Ti 550kA PPCD. Large thermal neutron flux; no significant neutron flux increase during NBI → Large pitch angle scattering due to hollow impurity profile?
Summary

- NBI heating of enhanced confinement MST plasma is observed.
  - Simple, classical model for fast ion behavior matches data

- Strong stabilizing effect on the core-most tearing mode
  - $n = 5$ reduced for plasmas with $q(0) > 0.2$
  - $n = 6$ reduced in PPCD plasmas with $q(0) \sim 0.18$
  - No reduction observed in standard $F = -0.2$ plasma, $q(0) \sim 0.19$

- Other tearing modes are unaffected

- Mechanism of mode stabilization not yet identified. Considered so far:
  - Altered $J_{||}$ profile affects tearing mode stability
  - Altered $J_{||}$ profile removes core mode resonance condition.
  - Enhanced flow shear can affect stability.
  - Stabilization due to fast ions at tearing mode layer by finite Larmor radius effect