Neutral Beam Injection Experiments in the MST Reversed Field Pinch

D. Liu¹, A. F. Almagri¹, J.K. Anderson¹, V. V. Belykh², B.E. Chapman¹,
V.I. Davydenko², P. Deichuli², D.J. Den Hartog¹, S. Eilerman¹, G. Fiksel¹,³,
C.B. Forest¹, A.A. Ivanov², J. Kolinear¹, M.D. Nornberg¹, S. V. Polosatkin²,
J. S. Sarff¹, N. Stupishin², and J. Waksman¹

¹Department of Physics, University of Wisconsin-Madison, WI, USA
²Budker Institute of Nuclear Physics, Novosibirsk, Russia
³Laboratory for Laser Energetics, University of Rochester, NY, USA

12th IAEA Technical Meeting on Energetic Particles in Magnetic Confinement Systems
September 7-10, 2011, Austin, Texas USA
Fast Ions are Barely Studied in RFP Concept

- Fast ion confinement and transport in Reversed Field Pinch (RFP) devices could be quite different from in Tokamaks.
  - $B_t \sim B_p$, $\rho_{fi}/a$: 0.1~0.25 $\to$ large prompt loss
  - Large magnetic fluctuations, stochastic magnetic field $\to$ could lead to rapid diffusion of charge particles
  - $v_{\text{fast-ion}} > v_{\text{Alfvén}}$ $\to$ fast ions could drive Alfvén instabilities

- The newly installed 1 MW neutral beam injector on MST provides a good test-bed for fast ion study in RFPs.
  - Interplay between magnetic fluctuations and fast ion confinement
  - Fast ion driven instabilities
  - Control of MHD dynamo and tearing modes?
  - Plasma beta limit?
Outline

- Hardware: MST, heating neutral beam and major diagnostics
- Experiments of fast ion confinement
  - Comparison with classical theory and TRANSP modeling
- Effects of neutral beam injection on thermal plasmas
  - Reduction of core mode amplitude and increase of mode rotation
  - Fast ion induced bursting modes
  - Electron heating in improved confinement regime
- Conclusions
Madison Symmetric Torus Reversed Field Pinch (MST RFP)

- $R = 1.5$ m; $a = 0.52$ m
- $I_p$: 200-600kA
- Density $n \sim 10^{13}$ cm$^{-3}$
- Temperature $T_e$ up to 1.5 keV
- $B_T$, $B_P$ are comparable (<0.5T)

- **Standard RFP plasmas**
  - Non-reversal plasmas $F = B_\varphi(a)/\langle B_\varphi \rangle = 0$ (q(a)=0)
  - Standard reversal plasmas, $F < 0$ (q(a)<0) characterized by magnetic reconnection bursts

- **Improved confinement (PPCD)**
  - $\tilde{b} / b$ reduced by a factor of ~5
Significant Population of Fast Ions are Generated by Neutral Beam Injection

- 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, $\Delta t$: ~0.1 ms

### NBI Parameter Specification

<table>
<thead>
<tr>
<th>NBI Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>25 keV</td>
</tr>
<tr>
<td>Beam power</td>
<td>1 MW</td>
</tr>
<tr>
<td>Pulse length</td>
<td>20 ms</td>
</tr>
<tr>
<td>Composition</td>
<td>95-97% H, 3-5% D</td>
</tr>
<tr>
<td>Energy fraction</td>
<td>86%:10%:2%:2%</td>
</tr>
</tbody>
</table>
Fast Ion Confinement Time is Inferred from Neutron Flux Decay Process After Short Pulse Neutral Beam Injection

- Neutron:
  \[ \Gamma_n(t) \propto \int n_{fi}(t) \langle \sigma_{dd}(E_{fi}(t)) v_{fi}(t) \rangle dV \]

- Neutron decay process is the combination of fast ion loss and fast ion slowing down. If these two terms are decoupled,
  \[ 1/\tau_{n-exp} \approx 1/\tau_{fi} + 1/\tau_{n-classical} \]

- Assuming no fast ion loss, \( \tau_{n-classical} \) can be calculated from classical slowing down theory
  \[ \tau_{n-classical} = -\int_{E_n}^{E_b} \frac{dE_{fi}}{dt}_{classical} \approx \tau_{se} \ln \frac{E_b^{3/2} + E_c^{3/2}}{E_n^{3/2} + E_c^{3/2}} \]

- Strong magnetic reconnection events are excluded for this analysis

* J. D. Strachan et al. Nucl. Fusion, 21 (1981)
Fast Ion Behavior is Roughly Consistent with Classical Theory in Spite of Stochastic Magnetic Field

- $\tau_{n-exp} \sim \tau_{n-classical}$ → Fast ions behave roughly classically
- $\tau_{fi}$ is much larger than thermal particle and energy confinement time
  - Standard F=0 and F=-0.2 RFP plasmas
    - $\tau_{fi}(10ms) > \tau_{i,thermal}(1 \sim 2ms)$
    - $\tau_{fi}(25ms) > \tau_{i,thermal}(10ms)$
- Improved confinement regime (PPCD)
  - $\tau_{fi} \sim 1/2$ of $\tau_{slowing-down}$ → may affect NB heating efficiency
- Peak value of neutron flux increases with plasma density, as expected
Slowing Down of Hydrogen Fast Ions is Observed on Advanced Neutral Particle Analyzer (ANPA)

- Charge exchange H signals persist a few ms after NB turn-off until a sawtooth occurs. → Good fast ion confinement

- Neutron detector and advanced NPA look at different portions of fast ion distribution
  - Neutron: volume-averaged, mainly from passing fast ions (D⁺) in the core
  - Advanced NPA: passive CX, mainly from trapped fast ions (H⁺) near the edge

E: 1-30 keV
ΔE: 2-3 keV
Δt: ~0.1 ms
Hydrogen: 10 channel
Overlapping of magnetic islands can cause magnetic stochasticity and result in rapid transport of charged particles. E.g. electrons in standard RFP plasmas, \( \tau_e = 1 \sim 2 \text{ms} \).

- Particle orbit of fast ions may not be affected since the guiding center drift (grad B and curvature drifts) make fast ions out of resonance with background magnetic fluctuations. \( \rightarrow \) good confinement of fast ions.

*G. Fiksel et al. PRL 95 (2005)*

B. Hudson PhD Thesis 2006
TRANSP/NUBEAM Modeling Predicts Centrally Peaked Fast Ion Density

\[
F = B_\varphi(a)/<B_\varphi> = 0 \text{ or } q(a) = 0
\]

- \(l_p = 400\text{kA}\)
- \(n_e(0) = 1.0 \times 10^{13}\text{cm}^{-3}\)
- \(T_e(0) = 400\text{eV}\)
- 1MW NBI between [20,40] ms

**TRANSP/NUBEAM Modeling of NBI into a Standard F=0 Plasma shows that:**

- Local \(n_{fi}\) could be as high as 15% of \(n_e\)
- Fast ions are confined in the plasma core (\(r/a < 0.2\))
- Mainly passing particle with pitch \(v_{||}/v = 0.9\)
- 20% shine-through loss, similar to measurements
- 55% power loss due to charge exchange
- Neutron decay time similar to the measurements
- \(\beta_{fi} \sim 3\%\) vs \(\beta_{thermal} \sim 8\%\)
Outline

- **Hardware**: MST, heating neutral beam and major diagnostics
- **Experiments of fast ion confinement**
  - Comparison with classical theory and TRANSP modeling
- **Effects of neutral beam injection on thermal plasmas**
  - Reduction of core mode amplitude and increase of mode rotation
  - Fast ion induced bursting modes
  - Electron heating in improved confinement regime
- **Conclusions**
NBI Reduces Core-most Tearing Mode Amplitude and Increases Plasma Rotation and Shear

- Strong stabilizing effect on the core-most $n=5$ tearing mode with co-injection, not obvious in counter-injection
- All the other tearing modes ($n=6-10$) are unaffected in co- or counter-injection
- Toroidal rotation and shear increase in co-injection
- NBI applies a significant torque to plasmas
- Mechanism of mode stabilization not yet identified
  - Altered $J_\parallel$ profile affects tearing mode stability
  - Altered $J_\parallel$ profile removes core mode resonance condition
  - Stabilization due to fast ions at tearing mode layer by finite Larmor radius effect

$F = B_\psi(a)/<B_\psi> = 0$, $I_p = 300$ kA
NBI Induces Bursting Modes

- NBI induced bursting magnetic fluctuations have been detected on magnetic coils in \( F=0 \) (or \( q(a)=0 \)) plasmas with co-NBI, not in any \( F<0 \) plasmas.
- Frequencies are in the range of 60~150kHZ with \( n=4 \) or \( n=5, \ m=1 \), much less than the predicted TAE frequency (~300kHz)
- The strongest coherence activity scales inversely with density, but does not scale with magnetic field strength.
- The mode is not identified yet, could be EPM…. 

\[ F = B_\varphi(a)/\langle B_\varphi \rangle = 0 \text{ (or } q(a)=0 \text{) } \]
\[ I_p = 300\text{kA} \]
\[ n_e = 0.7 \times 10^{13} \text{cm}^{-3} \]
NBI Induced Electron Heating is Consistent with Classical Theory

- ~100 eV electron heating is observed during NBI into 200kA PPCD plasmas
- Heating continues at a steady pace during the enhanced confinement (PPCD) period, even after the NBI is turned off.
- Agrees with a 1-D classical heating model
- No obvious electron or ion heating observed in standard RFP plasmas

$\Delta T_e(0)$
Fast ions in MST behave roughly classically in spite of stochastic magnetic field. The confinement time is much better larger than thermal particle and energy confinement time.

TRANSP modeling is largely in agreement with observations. TRANSP suggests that charge exchange with background neutrals is the dominant fast ion loss mechanism and fast-ion beta could be as large as 3%.

**Effects of NBI on MST Plasmas**

- NBI reduces core mode amplitude and increases plasma rotation and shear.
- NBI induces bursting modes at frequencies of 60-150kHz that scales with density, not magnetic field.
- Over 100 eV electron heating is observed in PPCD plasmas with NBI. It can be explained by a 1-D classical heating model. No obvious electron or ion heating observed in standard RFP plasmas.