Studies of Fast Ion Confinement in the MST Reversed Field Pinch

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Are fast ions also well confined in RFPs, as in Tokamak devices?
• $B_t \approx B_p (<0.5T)$, $\rho_{fi}/a: 0.1 \sim 0.25$
• Large magnetic fluctuations
• $V_{\text{fast-ion}} > V_{\text{Alfvén}}$

Fast ion diagnostics:
- Scintillator-based neutron detector
- Advanced Neutral Particle Analyzer
  • 10 H and 10 D channels
  • $E: 1-30$ 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>
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<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</td>
<td>86%:10%:2%:2%</td>
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<td>(E:E/2E/3:E/18)</td>
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Madison Symmetric Torus Reversed Field Pinch (MST RFP)

- $R = 1.5 \text{ m}; a = 0.52 \text{ m}$
- $I_p$: 200-600kA
- Density $n \sim 10^{13} \text{ cm}^{-3}$
- Temperature $T_e$ up to 2.0 keV

**Standard RFP plasmas**
- $\tau_p = 1 \sim 2ms$
- Non-reversal plasmas $F = B_\phi(a)/\langle B_\phi \rangle = 0$ ($q(a) = 0$)
- Standard reversal plasmas, $F < 0$ ($q(a) < 0$) characterized by magnetic reconnection bursts

**Improved confinement (PPCD)**
- $\tau_p = 5 \sim 10ms$
- $\tilde{b} / b$ reduced by a factor of $\sim 5$
Fast Ion Confinement is Inferred from Neutron Flux Decay Process After Short Pulse Neutral Beam Injection

Neutron: \( S_n(t) \propto \int_{V} n_{fi}(t) n_{i}(t) <\sigma_{dd}(E_{fi}(t))v_{fi}(t)> dV \)

Neutron decay process is the combination of fast ion loss and fast ion slowing down.

\[ \frac{1}{\tau_{n-exp}} \approx \frac{1}{\tau_{fi}} + \frac{1}{\tau_{n-classical}} \]

Assuming no fast ion loss, \( \tau_{n-classical} \) can be calculated with classical slowing down theory.

\[ \tau_{n-classical} = -\int_{E_n}^{E_b} \frac{dE_{fi}}{\int_{E_n} \{dE_{fi}/dt\}_{classical}} \approx \tau_{xe} \ln \frac{E_b^{3/2} + E_c^{3/2}}{3 E_n^{3/2} + E_c^{3/2}} \]

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

- $\tau_{n-exp} \sim \tau_{n-classical} \Rightarrow$ 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: $\tau_{fi}(10\,\text{ms}) > \tau_{i,\text{thermal}}(1 \sim 2\,\text{ms})$
  - Improved confinement regime (PPCD): $\tau_{fi}(25\,\text{ms}) > \tau_{i,\text{thermal}}(5 \sim 10\,\text{ms})$
- But $\tau_{fi} \sim 1/2$ of $\tau_{slowing-down} \Rightarrow$ may affect NB heating efficiency
- Neutron flux increases with density and temperature
Neutron Measurements can be Simulated with a Simple Zero Dimensional Classical Model

**0-D neutron model:** Similar to 0-D neutron model in Tokamak devices

\[ S_{n-0D} \propto n_{fi}(0)n_i(0) < \sigma_{dd} v_{fi} > \]
\[ n_{fi}(0) \propto \tau_{fi} n_{NB}(0)n_e(0) < \sigma v >_{ionization} \]
\[ n_{NB}(0) \propto \frac{P_{NB}}{E_{NB}} \gamma_{atten} \]
\[ n_i(0) \sim n_e(0) \]
Slowing Down of Hydrogen Fast Ions is Observed with an Advanced Neutral Particle Analyzer

- Neutron and NPA measurements confirm a significant population of fast ions
- 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

Charge exchange H signals
- E: 1-30 keV
- ΔE: 2-3 keV
- Δt: ~0.1 ms
- Hydrogen: 10 channels
TRANSP/NUBEAM modeling of NBI into a standard F=0 plasma shows that:

- $n_{fi}$ could be as high as 15% of $n_e$
- Confined in the plasma core ($r/a<0.2$), $v_{||}/v=0.9$
- 20% shine-through loss, similar to measurements
- 55% power loss due to charge exchange
- $\beta_{fi} \sim 3\%$ vs $\beta_{thermal} \sim 8\%$

**Equations and Parameters:**

- $F = B_\phi(a)/<B_\phi> = 0$ or $q(a)=0$
- $I_p=400kA$
- $n_e(0)=1.0\times10^{13} cm^{-3}$
- $T_e(0)=400eV$
- 1MW NBI between [20,40] ms
Neutron flux and ANPA data suggest that fast ions in MST behave roughly classically. Neutron flux evolution can be simulated with a simple classical 0-D model.

Fast ion confinement is much better than thermal particles.

CX loss is the dominant fast ion loss mechanism.

TRANSP modeling is largely in agreement with observations.

NBI into high current PPCD plasmas is not well understood. (BP9. 00080)

Effects of NBI on MST Plasmas

NBI reduces core mode amplitude and increases plasma rotation and shear. (BP9. 00079, BP.00084)

NBI induces bursting “EPM-like” and “TAE-like” modes at frequencies of 60-150kHz. (PO4. 00003, BP9. 00089)

~100 eV electron heating is observed in PPCD plasmas with NBI. (BP9.00082) No obvious electron or ion heating is observed in standard RFP plasmas.