Fast ion confinement and dynamics in the 3D helical RFP

Scott Eilerman
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J. K. Anderson¹, V. Belykh², B.E. Chapman¹, V.I. Davydenko², D.J. Den Hartog¹, G. Fiksel³, C.B. Forest¹, A.A. Ivanov², J.J. Koliner¹, L. Lin⁴, D. Liu⁵, V.V. Mirnov¹, M.D. Nornberg¹, S.V. Polosatkin², J.A. Reusch¹, H. Sakakita⁷, J.S. Sarff¹, D.A. Spong⁶, N. Stupishin², J. Titus⁸, Y.A. Tsidulko², J. Waksman¹

¹ University of Wisconsin, Madison WI
² Budker Institute of Nuclear Physics, Novosibirsk Russia
³ Laboratory for Laser Energetics, Rochester NY
⁴ University of California, Los Angeles CA
⁵ University of California, Irvine CA
⁶ Oak Ridge National Laboratory, Oak Ridge TN
⁷ National Institute of Advanced Industrial Science and Technology, Tsukuba Japan
⁸ Florida Agricultural and Mechanical University, Tallahassee FL
Fast ion behavior is relatively unexplored in the 3D helical RFP

- In the axisymmetric, stochastic RFP, fast ions are relatively well confined
  - \( \tau_{fi} \sim 10 \text{ ms} \gg \tau_p \sim 1 \text{ ms} \)
- As Lundquist number \( (I_p) \) increases, the RFP spontaneously transitions to a 3D helical equilibrium
- Fast ion confinement and behavior has not yet been explored in this regime, but is crucial to next-step RFP concepts

\[ S \propto I_p \frac{T_e^{3/2}}{n_i^{1/2}} \]

Equilibrium reconstructions courtesy of J.J. Koliner, J.D. Hanson, M. Cianciosa
Outline

• Experimental and diagnostic overview

• Observations of fast ion behavior in the 3D helical RFP:
  – Mode reduction and delayed onset of SHAx
  – Ion energization during the SHAx transition
  – Reduction of fast ion confinement during SHAx
The RFP can transition between several equilibria

Spectral index: Measure of effective number of m=1 modes in spectrum

\[ n_s^{-1} = \sum_n \left( \frac{\tilde{b}_n^2}{\sum_{n=5}^{14} \tilde{b}_n^2} \right)^2 \]

- \( n_s \sim 1 \): “SHAx,” single helical axis
- \( n_s \sim 1-2 \): “QSH,” one dominant mode, several secondary modes
- \( n_s > 2 \): “MH,” multiple helicity, many active modes

For this talk, I will be loose with the QSH and SHAx terminology

We are primarily concerned with the behavior of fast ions in the presence of a large n=5 perturbation
Neutral Beam Injection explores new physics in the RFP

### Madison Symmetric Torus

- \( R = 1.5 \text{ m; } a = 0.52 \text{ m} \)
- \( I_p \sim 200 – 500 \text{ kA} \)
- \( |B| \sim 0.2 – 0.5 \text{ T} \)
- \( T_e(0) \sim 200 – 2000 \text{ eV} \)
- \( n_e \sim n_D \sim 10^{13} \text{ cm}^{-3} \)
- Pulse length \( \sim 60-100 \text{ ms} \)

### Neutral Beam Injection Parameter Specifications

<table>
<thead>
<tr>
<th>NBI Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>25 keV ( \rho_{fi}/a \sim 0.1 )</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>
Key diagnostics measure magnetics and fast ion properties

- E \perp B NPA measures neutral CX products of core fast ions with high pitch
- Global fast ion content inferred from neutron scintillator measurement of beam-target fusion
• Experimental and diagnostic overview

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Fast ions have stabilizing influence on core tearing mode

- Several discharges averaged (fixed $I_p$, $n_e$) to reduce statistical noise
- $n=5$ (core-most) mode amplitude sharply reduced
- Effect is strongest in lower $I_p$ discharges, but observed at higher $I_p$ as well
Recipe for QSH onset in MST: High current, near-zero reversal parameter, low density.

Experiments at $I_p = 450\text{kA}$, $F=0$, $n_e \sim 0.7$ exhibit robust transitions to single helicity.

In this typical, no NBI case, $N_s < 1.1$ at $t = \sim 22\text{ msec}$
Transition to single helicity delayed by NBI

In this typical NBI case, $N_s < 1.1$ at $t = \sim 39$ msec, following NBI turn-off.
Single helicity onset can still occur during NBI at 450 kA.

No NBI. SHAx onset is normally distributed at 22 ms.

With NBI, SHAx onset time is delayed.

SHAx can occur during NBI.

Most common onset follows NBI turn-off.
SHAx transition at lower plasma current (300kA) is less frequent, more strongly affected by NBI.

No NBI. 300kA. SHAx onset is common late in the discharge.

With NBI, SHAx onset time is delayed.

Transition to SHAx during NBI is rare.

Most common onset follows NBI turn-off.
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Inductive electric field likely responsible for fast ion energization during RFP sawtooth events

- MH RFP discharges are characterized by periodic bursts of magnetic reconnection and tearing mode activity leading to rapid profile changes as well as ion heating and acceleration
Inductive electric field likely responsible for fast ion energization during RFP sawtooth events

- MH RFP discharges are characterized by periodic bursts of magnetic reconnection and tearing mode activity leading to rapid profile changes as well as ion heating and acceleration
- Recent data show that the measured fast ion acceleration is consistent with a toroidal inductive electric field generated by changes in the magnetic equilibrium

Electric field measured using FIR polarimetry
W.X. Ding et. al. PRL 2004
Energization observed during SHAx onset

- Ion energization occasionally observed during n=5 mode growth preceding SHAx
- Reason for inconsistent observation not yet understood
- Magnitude of energization consistent with an electric field ~ 1 V/m
- It is posited that the growth of the n=5 magnetic perturbation could produce a toroidal voltage of this magnitude, but further analysis is needed
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Fast ions can be well-confined in standard RFP stochastic magnetic fields

- Fast ion orbit traced through time varying stochastic field
- Particle orbit of fast ions slightly demagnetized, follow different rotational transform
- Fast ions orbits are out of resonance with background magnetic fluctuations \( \rightarrow \) good confinement of co-injected fast ions
- Note \( n=5 \) character of fast ion orbit near \( n=6 \) magnetic island
- Magnetic perturbations can become too large for fast ion confinement

*G. Fiksel \textit{et al.} \textit{PRL} (2005)
Fast D+ are confined much better than thermal particles

- Short pulse of NBI sources test particles without perturbing plasma
- \(^1\)n flux decays due to slowing and fast particle loss
- Fast particles confined much better than thermal particles over wide range of core temperature, stochasticity
- Primary contribution to finite \(\tau_{fi}\) is charge-exchange loss

\[
\frac{1}{\tau_n} \approx \frac{1}{\tau_{cl}} + \frac{1}{\tau_{fi}}
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*D. Liu et al. (2011)*
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*D. Liu et al. (2011)*
NPA signal reduced once SHAx is established

- ANPA flux drops considerably as SHAx state is established
- Neutron flux remains relatively constant, implying fast ions may be shifted out of the ANPA view (spatially or in velocity space) rather than lost
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Beam blip technique used to further examine fast ion confinement in SHAx
Fast ion confinement time decreases with 3D core perturbation.

![Graph showing the relationship between confinement time and n=5 amp (G, % of |B(a)|). The graph includes data points for multiple helicity states such as MH, SHAx, and SHAx.]
Fast ion confinement time decreases with 3D core perturbation

Multiple helicity

Analysis complicated by transitions into/out of SHAx during beam blip
Fast ion confinement time decreases with 3D core perturbation.

Analysis complicated by transitions into/out of SHAx during beam blip.
Phase of n=5 helical equilibrium affects pitch of NBI-born ions

NBI, injection centerline are fixed to MST.

Phase of n=5 perturbation locks at varying positions with respect to vessel, NBI.

Effective scanning of NBI with respect to helical equilibrium.
Global fast ion confinement time unaffected by NBI n=5 phase

Quasi-random locking position has not yet swept out a full phase scan.

No indication of phase effect in existing confinement data.

Experiments in high-current SHAx; will repeat at lower currents.

72 degrees marks full scan of n=5 perturbation
Summary

- While fast ions are relatively well confined in the axisymmetric RFP, confinement times approach bulk particle confinement times as the RFP equilibria becomes dominated by a single helical mode.
  - There is no evident correlation between the fast ion confinement and the phase of the helical mode.

- Ion energization is observed during SHAx onset and may be the result of an inductive electric field, but further study is needed.

- Neutral beam injection can delay or even prevent the occurrence of the SHAx state.

- These observations are providing direction for new computational work:
  - We are currently adapting our particle tracing codes to use V3FIT equilibria.
  - We also plan to explore codes that handle neoclassical effects.
Confinement of classically slowing test particle

- Fast ion guiding center (IGC) rotational transform is different from magnetic field lines (due to grad B and curvature drift)
- Overlapping of islands leads to stochasticity and rapid transport.
Beam power threshold experiment exposes fast ion density saturation!

Full energy, high pitch, core localized ions asymptote to same value.

Signal decrease coincides with bursting mode onset.

Note: TRANSP predicts a steady signal (not ramping up)

Full beam power and 60% power (reduced current, full energy)
Deuterium beam experiments suggest fast ion transport rather than loss

- Injecting a 100% deuterium beam into hydrogen plasmas shows similar behavior, implying fast ions may be shifted out of the ANPA view (spatially or in velocity space) rather than lost.
NPAs heavily influenced by ion pitch

- Tangential viewport designed to measure high pitch ($v_{||}/|v|$) NBI ions
- Some lower pitch ions from the plasma edge can still make it into the ANPA, but data so far shows a strong correlation between ANPA signal and core phenomena (EPM modes, tearing mode reduction, QSH)

$$\Gamma_{meas} = \int_L n_0 n_{fi} \langle \sigma v \rangle_{cx} \delta (\gamma - \gamma_c) (1 - f_r) \, dl$$

Eilerman et. al. RSI 2012
An inductive parallel electric field is generated at each sawtooth crash

- Parallel electric field generated in the core from changing poloidal magnetic flux (measured by FIR)
- Simple $F=qE$ generates term in $\Delta <E>$ that scales with $v_i$ (or $E^{1/2}$)

\[ E_{\phi}(R) = \frac{1}{2\pi R} \left( V_\theta(R-a) - 2\pi \int_R^{R+a} \frac{\partial}{\partial t} B_p(R',t) dR' \right) \]

\[ \Delta U = \frac{(ZeE^*\Delta t)^2}{2m} + ZeE^*\Delta tv_i \]

$E^*$ is the effective electric field felt by ions after considering impurities and trapped electrons

R.M. Magee thesis
W.X. Ding et. al. PRL 2004
Furth and Rutherford 1972
MST is in position to test theories fast ion tearing stabilization

Hegna and Bhattacharjee *PRL* (1989):
- With a fast ion density gradient located at \( r < r_{\text{island}} \) (in RFP B field);
- and fast ions shifted from magnetic surfaces;
- then constant fast ion density, current surfaces differ at X, O points of island.
* Nonlinearly saturated mode amplitude is reduced.
* May be able to test by running MST as a tokamak with \( \nabla n_{fi} \) inside \( m/n = 3/2 \)
  - de-stabilization predicted.

*Cai, Wang, Xu, Cao and Li* *PRL* (2011):
- Co-passing fast ions have stabilizing effect at island; counter- destabilizes.
* Island width \( \ll \rho_{fi} \); not well satisfied in MST.

- FLR effects can alter tearing mode.
- Linear growth rate computed; is reduced for \( \nabla n_{fi} \) at island.
- Mechanism: Perpendicular current across island is governed by ExB flow.
  - quasi neutrality altered by considering fast ion species.

**J**\(_{\perp}\) is zero in two species plasma.

\[
\begin{align*}
J_{\perp} &= -en_e \frac{E \times B}{B^2} + en_i \frac{E \times B}{B^2} = 0 \\
-en_e + en_i &= 0
\end{align*}
\]

Net current possible with fast ions.

\[
\begin{align*}
J_{\perp} &= -en_e \frac{E \times B}{B^2} + en_i \frac{E \times B}{B^2} + en_{fi} \frac{E \times B}{B^2} \\
-e &= 0
\end{align*}
\]