Overview of Results in the MST Reversed Field Pinch

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\[ a = 0.5 \text{ m}, \; R = 1.5 \text{ m}, \; I \sim 0.5 \text{ MA} \]
Two physics regimes in the RFP

• Standard confinement
  	large magnetic fluctuations
  large transport
  strong magnetic self-organization
  (reconnection, dynamo.....)

• Improved confinement
  reduced magnetic fluctuations
  reduced transport
  reduced magnetic self-organization
Standard regime

*Vehicle for understanding magnetic self-organization*

Improved confinement regime

*new physics regime*

$(q < 1 \text{ everywhere, with tokamak-like confinement and high beta})$
Outline

Standard confinement regime

• Hall effects on dynamo and reconnection
• locking of tearing modes by wall eddy currents
• nonlinear origin of edge-resonant mode

Improved confinement regime

• suppression of the dynamo
• restoration of magnetic surfaces
• suppression of transport from stochastic fields
The dynamo

Dynamo = self-generation of current by fluctuations

\[ E \neq \eta j \Rightarrow \text{strong dynamo} \]
How is the dynamo current generated?

\[
\langle E \rangle + \langle \tilde{v} \times \tilde{B} \rangle - \frac{\langle \tilde{j} \times \tilde{B} \rangle}{ne} = \eta \langle \tilde{j} \rangle
\]

**MHD dynamo**

The standard model

**Hall dynamo**, two-fluid effect

significant in quasilinear theory

\[ \tilde{j} \quad \text{and} \quad \tilde{B} \] measured by Laser Faraday Rotation

*(UCLA)*
Measured radial structure of $m = 1, n = 6$ mode

\[ \tilde{B} \]

\[ \tilde{j} \]

$B_r$, $B_p$

global

local, but wider than MHD resistive layer
Hall dynamo is large near the resonant surface

\[ \langle \tilde{j} \times \tilde{B} \rangle \]

\[ \text{ne} \]

Hall dynamo = \[ \langle \tilde{j} \times \tilde{B} \rangle \]

\[ \text{ne} \]

Mean current density

(at \( r/a \sim 0.3 \))

Hall effect contributes strongly to dynamo and reconnection
The tearing modes lock

• test theory of mode locking by wall eddy currents

• employ time-dependent theory (Fitzpatrick)
**Experimental Test of Theory**

One free parameter: momentum confinement time

$V_T(1,5)$

Experiment consistent with theory
A strong edge-resonant mode is observed

\[ \tilde{B} \]

\[ m = 0, n \sim 1 \]

The mode drives transport and dynamo in the edge
What drives the $m = 0$ modes?

From MHD,

$$\frac{\partial \langle B_{0,1}^2 \rangle}{\partial t} = \left\langle \vec{B}_{0,1} \cdot \nabla \times (\nu_{0,1} \times \langle B \rangle) \right\rangle + \text{nonlinear coupling}$$

linear drive

terms measured directly in MST edge plasma
\[
\frac{\partial \langle B_{0,1}^2 \rangle}{\partial t} = \langle \vec{B}_{0,1} \cdot \nabla \times (v_{0,1} \times \langle B \rangle) \rangle + \text{nonlinear terms}
\]

> 0 from initial measurements, nonlinearly driven

linearly damped
Improved confinement plasmas
The confinement problem in standard plasmas:

\( E_\parallel(r) \) is centrally peaked,

yields unstable \( j_\parallel(r) \) profile

fluctuations broaden \( j_\parallel(r) \), increase transport

Solution:

drive a flatter current profile

Technique:

apply flatter electric field, transiently
## Confinement Summary

<table>
<thead>
<tr>
<th></th>
<th>Standard</th>
<th>Improved</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e$</td>
<td>0.5 keV</td>
<td>1.3 keV</td>
</tr>
<tr>
<td>beta</td>
<td>9%</td>
<td>15%</td>
</tr>
<tr>
<td>$\tau_E$</td>
<td>1 ms</td>
<td>10 ms</td>
</tr>
<tr>
<td>$\chi_e$</td>
<td>50 m²/s</td>
<td>5 m²/s</td>
</tr>
</tbody>
</table>

- Nearly tripled
- Nearly doubled
- Tenfold increase

Comparable to tokamak of similar size and current
Suppression of dynamo

Standard Plasma

strong dynamo \( (E \neq \eta j) \)
Suppression of dynamo

Standard Plasma

strong dynamo \((E \equiv \eta j)\)

Improved Confinement

reduced dynamo \((E \approx \eta j)\)

driven current replaces dynamo current
J$_{\parallel}$/B and E$_{\parallel}$ profiles

J/B profile changes slightly, near marginal stability

E profile changes greatly ("driven" current changes)
Restoration of magnetic surfaces

Earlier work on energetic electron confinement:

Hard xray emission up to 100 keV

Fokker-Planck modeling -->

\[ D_e \sim 5 \, \text{m}^2/\text{s}, \text{ independent of electron speed, inconsistent with stochastic magnetic fields} \]
SXR tomography

RFX group

standard plasmas

improved confinement

consistent with stochasticity

magnetic islands appear

(equilibrium contribution removed)
Magnetic Field Puncture Plots

shows restoration of magnetic surfaces
compare thermal conductivity to expectation from stochastic transport

\[ \chi_{\text{theory}} = v_{th} D_m \]
compare thermal conductivity to expectation from stochastic transport

\[ \chi_{theory} = \nu_{th} D_m \]

magnetic diffusivity

\[ D_m \]

stochastic transport

not stochastic, except in narrow layer
Summary

RFP can operate in two distinct physics regimes

**Strong magnetic self-organization and transport**
- Hall effects, mode locking, nonlinear coupling

**Suppressed self-organization (transiently)**
- Transport is tokamak-like
- Dynamo and stochasticity is suppressed
- Possibly dominated by electrostatic fluctuations
- More confinement gains underway
- A new physics regime, beginning to investigate
What is the ultimate confinement and beta in the RFP?
Can improved confinement be sustained?

To answer these questions we are applying

• Lower hybrid current drive
• Electron Bernstein wave current drive
• Neutral beam injection
• Oscillating field current drive
• Pellet injection

See posters by W. Ding, D. Craig