Analyzing Pulsed Parallel Current Drive and Single Helicity in the Reversed-Field Pinch

Carl Sovinec and Jim Reynolds

University of Wisconsin-Madison

presented at the

University of Colorado at Boulder

August 4, 2003
Outline

• Introduction via experimental results
• RFP magnetohydrodynamics
  • Pinch fields and Ohmic drive
  • Electromagnetic energy transport
• Pulsed Parallel Current Drive
  • On cylindrically symmetric systems
  • On Reversed-field pinches
• Quasi-single helicity
• Summary and Conclusions
Introduction

- Reversed-field pinches do not have the large vacuum toroidal magnetic field that characterizes the tokamak.
- MHD activity in standard operation (Ohmic drive only) leads to stochastic $\mathbf{B}$ transport.
- In the Madison Symmetric Torus (MST—$R=1.5$ m, $a=0.5$ m, $I_p\sim500$ kA), energy confinement time in standard operation is $\sim1$ ms.
Introduction (continued)

• Improvements to RFP performance have resulted from transient electric field pulses and from quasi-single helicity (QSH).

• With Pulsed Parallel Current Drive (PPCD), MST has reached $\tau_E = 10$ ms and $T_e > 1$ KeV [B. E. Chapman, et al., PoP 9, 2061 (2002)]. The emission of 100 KeV x-rays provides evidence of fast electron confinement [R. O’Connell, BAPS 47, no. 9, BI1 6].

• Dynamics are not well understood.

Laboratory PPCD results showing magnetic fluctuation reduction in MST (courtesy of John Sarff)
RFP Magnetohydrodynamics

Q: Why do RFPs have magnetic fluctuations?
A: The current profile is unstable. (gradient of $J/|B|$)

Q: Why is the current profile unstable?
A: This is a more interesting question.
The strong shear of the RFP leaves $E_{\text{ohmic}}$ perpendicular to $B$ over most of the volume.

Magnetic configuration in a straightened RFP.

Equilibrium fields from a Modified Bessel Function Model Equilibrium.
The fields find a force balance on Alfvénic time-scales, but an important consideration also comes from combining Ohm’s law and Faraday’s law.

- Forces balance on rapid time scales,

\[ \mathbf{J} \times \mathbf{B} \cong \nabla p \quad (\rightarrow 0 \text{ for low } \beta, \text{ i.e. } \mathbf{J} \cong \lambda(\psi)\mathbf{B}) \]

- At low \( \beta \) and for macroscopic spatial scales,

\[ \mathbf{E} = -\mathbf{V} \times \mathbf{B} + \eta \mathbf{J} \]

- Faraday’s law tells us that \( \mathbf{E} \) must be curl-free for a steady state (\( \mathbf{E}_{\text{ohmic}} = E_0 z \) in a cylinder), so \( \mathbf{J} \) tends to flow in the interior only. In the exterior, \( \mathbf{E} \) (perp) is largely composed of \(-\mathbf{V} \times \mathbf{B}\), i.e. \( \mathbf{V}_\perp = \mathbf{E} \times \mathbf{B}/B^2 \).
Steady conditions prescribe a unique distribution, but a competition is more realistic for this driven-damped system.

- The Taylor minimum energy state (uniform $J_\parallel/B$) [PRL, ’74] is MHD stable, but it’s not a steady solution.
  - Even with small resistivity, poloidal edge currents (spatial scale $< a$) diffuse significantly over times of interest.

- *The* steady state solution is the paramagnetic pinch with very little edge current (large $J_\parallel/B$ gradient); it is MHD unstable at RFP parameters.

- Competition leads to continuous and/or intermittent MHD activity. [Nonlinear numerical MHD studies have analyzed details—lots of references. Mattor came up with simplified analytical models for the two limits.]
With time- and spatial-averaging, the effects of the MHD fluctuations can be understood as an electromagnetic energy transport process.

- Poynting’s theorem applied to averaged fields:

\[
\frac{1}{2\mu_0} \frac{\partial \langle B \rangle^2}{\partial t} = -\nabla \cdot \left( \langle E \rangle \times \langle B \rangle \right) - \nabla \cdot \langle \tilde{e} \times \tilde{b} \rangle - \eta \langle J \rangle^2 + \langle \tilde{v} \times \tilde{b} \rangle \cdot \langle J \rangle \rightarrow 0
\]

- Contours of \( E_f \cdot \langle J \rangle \) from an MHD computation show the fluctuations removing power from the core and returning it to the edge (sustains reversal).
The fluctuation-induced Poynting flux reflects approximately 10% of the power.

The mean-field contribution is primarily from the pinch flow, and the fluctuation induced part is a property of the tearing modes.
Pulsed Parallel Current Drive

- The dominant tearing modes can be stabilized if additional current can be driven outside the core.

- Originally Pulsed Poloidal Current Drive was conceived as a means to test current profile modification without hardware upgrades in MST (J. Sarff).

- With refinement over the years, PPCD has been effective, but
  - Profiles change during the inductive pulse.

MST data on edge current density, (courtesy of Brett Chapman)
We are using numerical MHD simulations to investigate the propagation of the electric field pulse, its effect on the parallel current profile, and the magnetic fluctuations.

- Solve nonlinear initial value problems with zero- and finite-\(\beta\) resistive MHD models.
- The equations are solved numerically with the NIMROD code (http://nimrodteam.org).
Simple case: PPCD on a paramagnetic pinch

- Poloidal electric is \(\sim 14\%\) of the Ohmic drive.
- 25\% of axial flux is removed over 8\% of \(\tau_R\).

PPCD drives \(B_z < 0\) and pinches \(B_\theta\) at the edge. Edge \(J_\|/B\) is nonmonotonic in time.
Additional Simple case: PPCD on a paramagnetic pinch with decreasing loop volt

- Poloidal electric is \( \sim 14\% \) of the initial Ohmic drive.
- 25\% of axial flux and all Ohmic drive removed over 8\% of \( \tau_R \).

PPCD drives \( B_z < 0 \) and pinches \( B_\theta \).

\( J_\parallel/B \) flattens in time.
Simple case (continued)

- The long time-scale (with respect to $\tau_A$) allows the global force balance to be maintained.

- Pinching leads to global electric and magnetic field changes throughout the pulse.

The Poynting flux to the core increases in magnitude immediately on the pulse time-scale.
Applying PPCD to RFPs

- Using similar parameters as the paramagnetic pinch but solving the system in 3D leads to an RFP configuration.
- The same poloidal electric field changes the reversal parameter from $-0.1$ to $-0.4$, while the pinch parameter increases from $1.6$ to $2.4$.

Initially, the PPCD pulse reduces the magnetic fluctuation energy substantially.
Here, changes to the spectrum influence $\mathbf{E}$ penetration.

Changes in electric fields after 0.024 $\tau_R$ of pulse.

- Top row shows pulse penetration (left) and consequences to axial electric field (right).
- Comparing rows shows the significant impact of $E_f$. 

![Graphs showing electric field changes](image-url)
The parallel current profile changes simultaneously due to the pinch and the loss of dynamo activity.

There is no initial increase in parallel current at \( r \sim 0.75 \), unlike the symmetric case, but the evolution is otherwise similar.

Plotting \( \mathbf{E}_f \cdot \langle \mathbf{J} \rangle \) on the same scale as for the RFP result without PPCD, shows the loss of dynamo by \( t=0.024 \).
Next steps for the PPCD study

• Assess changes in the linear drive of the different modes as the parallel current profile evolves.

• Consider larger S values (only ~2000, here) to examine PPCD interaction with sawtooth oscillations.

• Resume finite-\( \beta \) computation of PPCD and investigate the observed \( m=0 \) activity.
Observation of Magnetic Well in Single Helicity (SH)

- Since $q<1$, curvature in an axisymmetric RFP is bad.
- SH and QSH lead to helical states.
- We have performed flux surface averages of pressure in a computed SH state:

Temperature contours in a plane of constant azimuthal angle.

- Regions of good curvature are possible and may be realized in QSH.
Conclusions

• While the PPCD experiments show dramatic improvement in fluctuation levels and energy confinement, the numerical simulations illustrate the very transient nature of this form of current profile modification.

• Instead of flattening parallel current, an inward-propagating pulse of parallel current appears to stabilize the tearing modes *en route* to a more pinched configuration, which later drives the modes.

• The propagation of the electric field occurs through a coupling of pinching and changes to the fluctuation-induced (dynamo) electric field.