Plasmoid-like Structures Along the Reversal Surface in Simulations of the MST RFP

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Measurement and simulation show complex island structure along reversal surface at sawtooth crash.

T. Tharp et al, PoP 2009
Plasmoid instability leads to complex evolution of the current sheet and magnetic island like structures.
Does this topological structure lead to an enhanced reconnection rate?

- Structure is topologically similar to “plasmoid” instability
- What is the impact of this structure on the reconnection rate and the evolution of the magnetic equilibrium?

T. Tharp et al, PoP 2009
Outline

- Introduction
  - The MST Device
  - Simulations with the Debs code
- Lowering the number of m=0 modes
  - Equilibrium
  - Sawtooth crash duration
- Magnetic Island Structures
  - Evolution through a sawtooth crash
The Madison Symmetric Torus (MST) is a large reversed field pinch (RFP).

- $R/a = 1.50 \text{ m} / 0.52 \text{ m}$
- $n \sim 10^{19} \text{ m}^{-3}$
- $T_e < 2 \text{ keV}$
- $B < 0.5 \text{ T}$

- $\beta < 25\%$
- $\tau_A \sim 1 \mu\text{s}$
- $S = 5 \times 10^{5-6}$
Tearing instability and nonlinear coupling results in multiple magnetic reconnection sites

Tearing resonance:

\[ 0 = \mathbf{k} \cdot \mathbf{B} = \frac{m}{r} B_\theta + \frac{n}{R} B_\phi \quad \Rightarrow \quad q(r) = \frac{r B_\phi}{R B_\theta} = \frac{m}{n} \]

- \( m \) = poloidal mode number
- \( n \) = toroidal mode number

\( q(r) \approx 0.2 \) minor radius, \( r \)

- \( m=1, n \geq 6 \) resonances
- \( m=0, \) all \( n \)

\( r \) = minor radius, \( a \) = conducting shell

1,6
1,7
1,8
...
Quasi-periodic impulsive reconnection events (sawteeth) are a common feature in MST discharges.

Core-resonant $m=1$ modes are largest, calculated to be linearly unstable from gradient $\nabla_r (J_\parallel / B)$.

Edge-resonant $m=0$ modes are linearly stable, excited by nonlinear coupling to $m=1$ spectrum.
Quasi-periodic impulsive reconnection events (sawteeth) are a common feature in MST discharges. Sawtooth crash duration implies a reconnection time that is much faster than Sweet-Parker. 3-wave cascade: 

- (1,6) couples to (0,1) 
- (1,7) couples to (0,1) 
- (1,8) couples to (0,1) 
- (1,9) couples to many m=1 

etc. Sawtooth crash duration implies a reconnection time that is much faster than Sweet-Parker.
3D, nonlinear, resistive MHD simulations reproduce many of the features of the MST plasma.

- Cylindrical, force-free MHD model was used (DEBS* code run with zero $\beta$)

$$\frac{\partial \vec{A}}{\partial t} = S \vec{V} \times \vec{B} - \eta \vec{J}$$

$$\rho \frac{\partial \vec{V}}{\partial t} = -S \rho \vec{V} \cdot \nabla \vec{V} + S \vec{J} \times \vec{B} + \nu \nabla^2 \vec{V}$$

- Theta, resistivity profile, and Lundquist number from MST ($S \sim 4 \times 10^6$)
- High Prandtl number used to damp sub grid scale fluctuations ($Pr_m \sim 100$)
- Code reproduces equilibrium evolution and sawtooth events well
- At sufficient resolution, reproduces sawtooth duration and period well

Simulations at $S \sim 4 \times 10^6$ produces large, well defined sawteeth.
Probing the role of m=0 harmonics

- Early computational studies of the RFP controlled the mode content to isolate dynamics
  - m=1, single n $\rightarrow$ forced single-helicity
  - Full m=1 spectrum, no m=0 $\rightarrow$ probe nonlinear coupling
  - Above were compared to full m,n case

- Here we probe the role of m=0 structure, by zeroing all n-harmonics except
  - n=1, n$\leq$2, n$\leq$4, n$\leq$10, and n=10
  - For m$\geq$1, full n spectrum maintained in each case
  - Start DEBS in each case, using the high-$S$ setup described earlier

- Note that there is no easy way to do this experimentally!
Behavior keeping only $n \leq 4$ component of $m=0$ spectrum

Short Crash Duration
Behavior keeping only n=1 component of m=0 spectrum

Longer Crash Duration
Behavior keeping only n=10 component of m=0 spectrum
Simulated sawtooth crash duration decreases as the number of allowed m=0 modes is increased.

- Typical sawtooth crash duration in MST is \( \sim 50\mu s \)
- Sawtooth crash duration can be used as a proxy for the reconnection time
- \( \tau_{\text{sweet-parker}} = \tau_{\text{Alfven}} S^{1/2} \sim 0.6\text{ms} \)
- With enough m=0 modes, simulated duration approaches measured value
With multiple modes we do see a more complex structure in the flux plots.

\[ n \leq 1 \]

\[ n \leq 4 \]

\[ n \leq 10 \]
Evolution over the sawtooth crash phase in DEBS

Before Sawtooth

Start of Sawtooth

+30us

+50us

+10us

+100us

\( n=1-10 \)
Summary.

• Simulations with truncated $m=0$ mode spectra allow the study of multiple coincident $m=0$ resonances on the plasma evolution.

• Limiting the number of $m=0$ modes with non-zero amplitude increases the sawtooth crash duration.

• Primary O-point compressed during sawtooth.

• Flux tubes are very dynamic in time, merging and then splitting and spreading out over the course of the sawtooth cycle.