Electromagnetic Torques Exerted on Single and Multiple Modes in the Reversed-field Pinch

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Motivation

- In MST, the flow and mode rotation are fairly rapid (~20 km/s).
- We therefore have the opportunity to look for nonlinear effects in the kinematics of the modes whenever sudden changes in the rotation occur.

Major Results

- We have seen experimental evidence for a nonlinear electromagnetic torque under three experimental situations.
  - Application of a magnetic perturbation.
    - Similar results have been reported for RFX.
  - The episodic deceleration of the $m=1$ modes during sawteeth.
  - The absence of the effects such a torque when the $q=0$ surface is removed.

Outline:

- Mode dynamics and nonlinear torque.
- Experimental results.
  - Static perturbation.
  - Sawtooth cycle mode dynamics.
  - $q_{edge} > 0$
- Future work.

The rotation of tearing modes is governed by electromagnetic and viscous torques.

- The evolution of the toroidal rotation of a tearing mode is given by the balance between the island inertia and the torques on it:

$$I\frac{d\mathbf{\Omega}}{dt} = \mathbf{T}_{em} + \mathbf{T}_{vis}$$

  where Ω is the (toroidal) angular phase velocity of the mode, I is the moment of inertia (density), $\mathbf{T}_{em}$ is the electromagnetic torque (density), and $\mathbf{T}_{vis}$ is the viscous torque.
- The viscous torque is due to differential rotation between the mode and the surrounding plasma.
- The electromagnetic torque is due to $\mathbf{J}\times\mathbf{B}$ forces on the modes produced by other magnetic structures.
  - A spatial resonance condition between the perturbing agent and the mode must be satisfied for a torque to be exerted.

Nonlinear torques involve a three-wave interaction between modes.

- In Fourier representation:

$$\mathbf{T}^{NL} \sim \mathbf{j}_{\mathbf{k}}^{NL} \times \mathbf{b}_{\mathbf{k}},$$

$$j_{\mathbf{k}}^{NL} \sim \sum_{\mathbf{k}'} C_{\mathbf{k}',\mathbf{k}-\mathbf{k}'} b_{\mathbf{k}'} b_{\mathbf{k}-\mathbf{k}'},$$ (from the dynamical equations).

$$\Rightarrow T^{NL} \sim \sum_{\mathbf{k}'} b_{\mathbf{k}'} b_{\mathbf{k}-\mathbf{k}'} b_{\mathbf{k}} \sin\left(\delta_{\mathbf{k}'} - \delta_{\mathbf{k}} + \delta_{\mathbf{k}-\mathbf{k}'}\right)$$

- Or, in terms of poloidal and toroidal mode numbers (*m* and *n*):

$$T_{(m,n)}^{NL} \sim \sum_{(m',n')} b_{(m,n)} b_{(m',n')} b_{(m-m',n-n')} \sin\left(\delta_{(m',n')} - \delta_{(m,n)} + \delta_{(m-m',n-n')}\right).$$

The presence of m=0 *modes in the RFP permits nonlinear torques that involve two* m=1 *modes.*

- The dominant term in the nonlinear (internal) torque should be produced by the interactions between the (1,*n*), (1,*n*±1), and (0,1) modes:

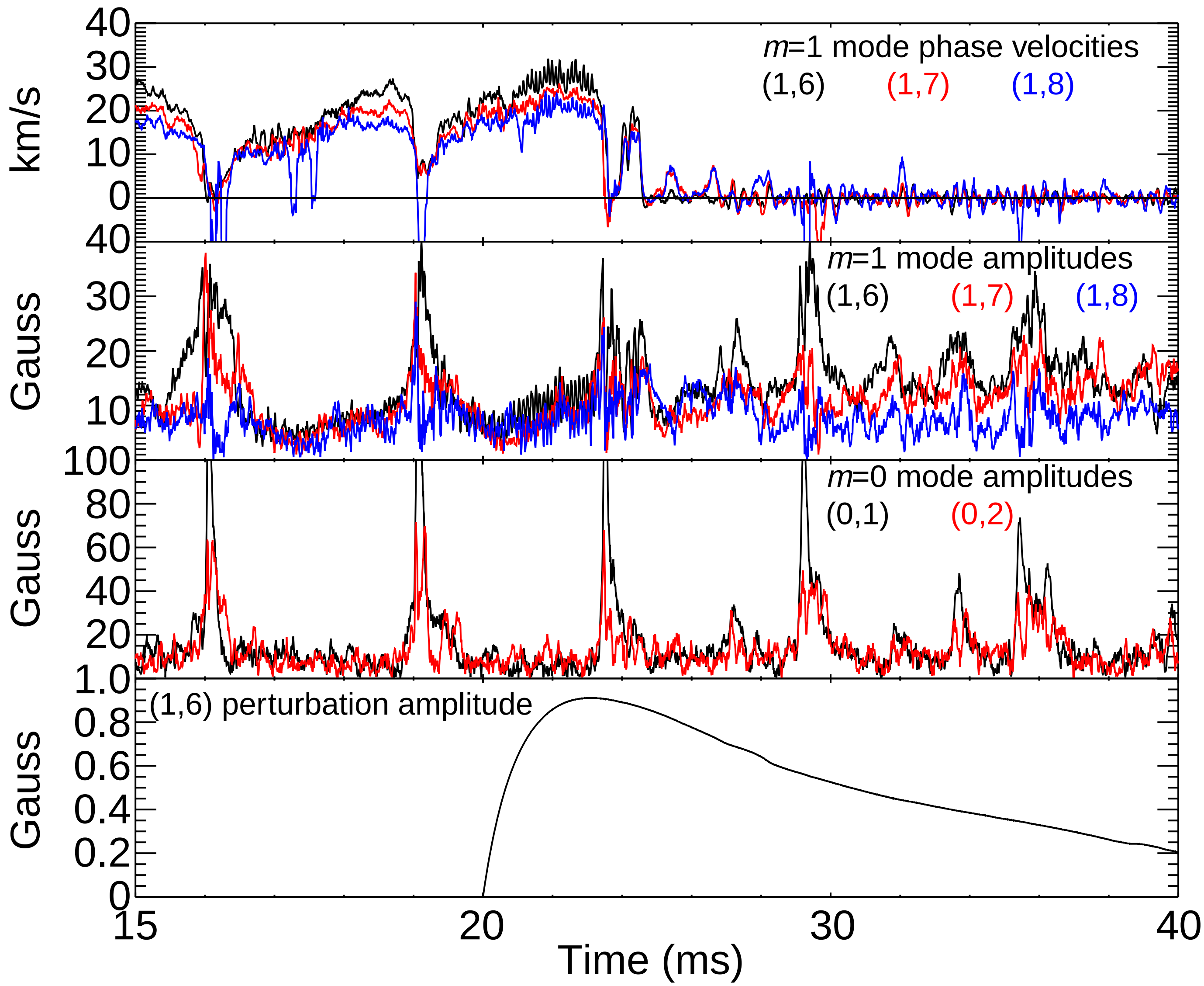
$$T^{NL}_{(m,n)} \sim b_{(0,1)} b_{(1,n)} b_{(1,n+1)} \sin(\delta_{(1,n+1)} - \delta_{(1,n)} - \delta_{(0,1)})$$

$$- b_{(0,1)} b_{(1,n)} b_{(1,n-1)} \sin(\delta_{(1,n)} - \delta_{(1,n-1)} - \delta_{(0,1)})$$

- The amplitudes of the (0,1) and (1,5-9) modes are typically fairly large, resulting in the potential for a large nonlinear torque
  - ~ 0.5%-10% of the equilibrium field for the (0,1) mode
  - ~ 0.5%-3% of the equilibrium field for the *m*=1 modes

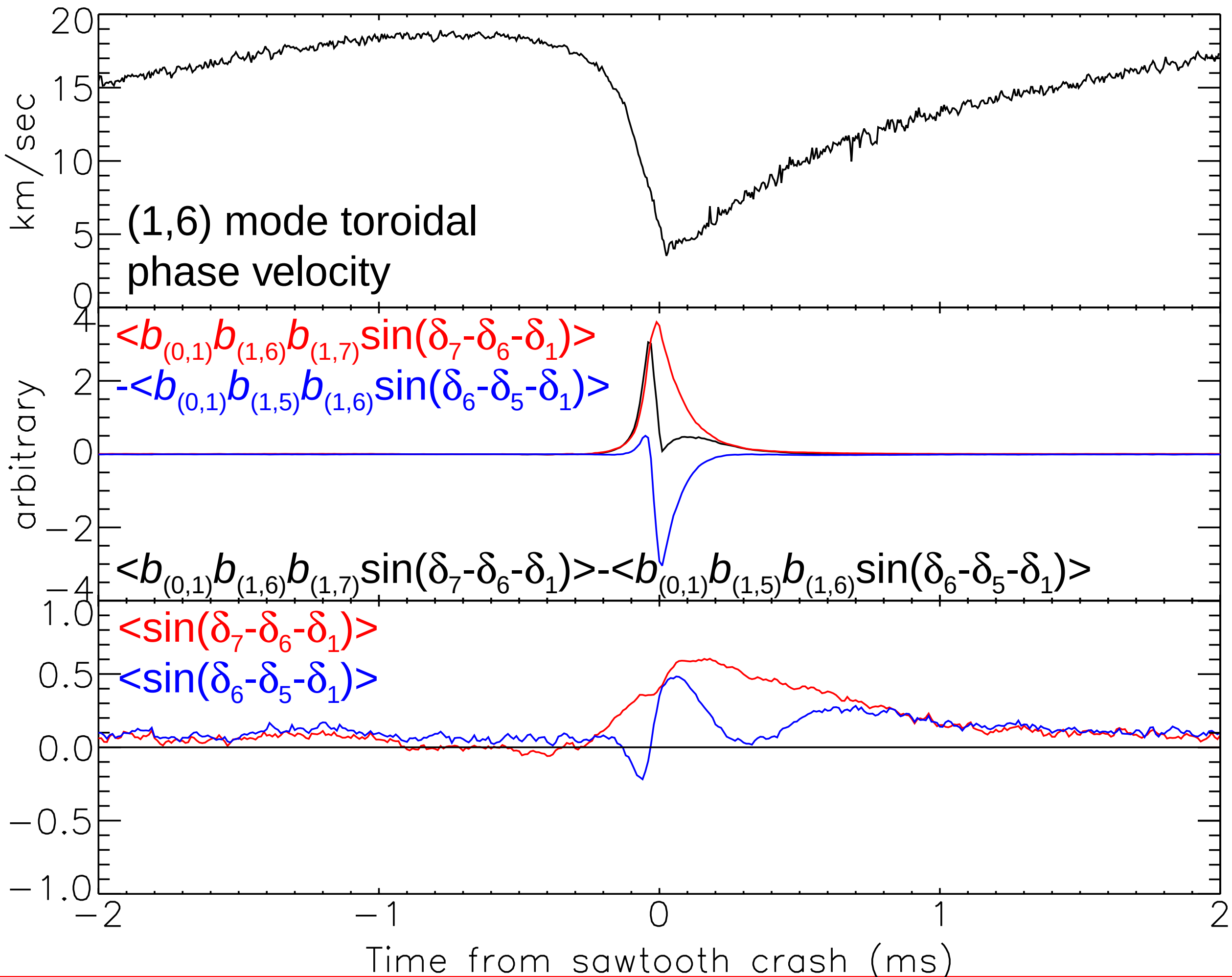
An n=6 perturbation also affects the (1,7) and (1,8) modes.

- The major *m*=1 modes all lock when the (1,6) mode does.
- That the (1,7) and (1,8) modes are affected at all is a signature of a nonlinear interaction with the (1,6) perturbation.
- The inferred field-error produced external torque is several times larger than when we have applied an *m*=1 perturbation.



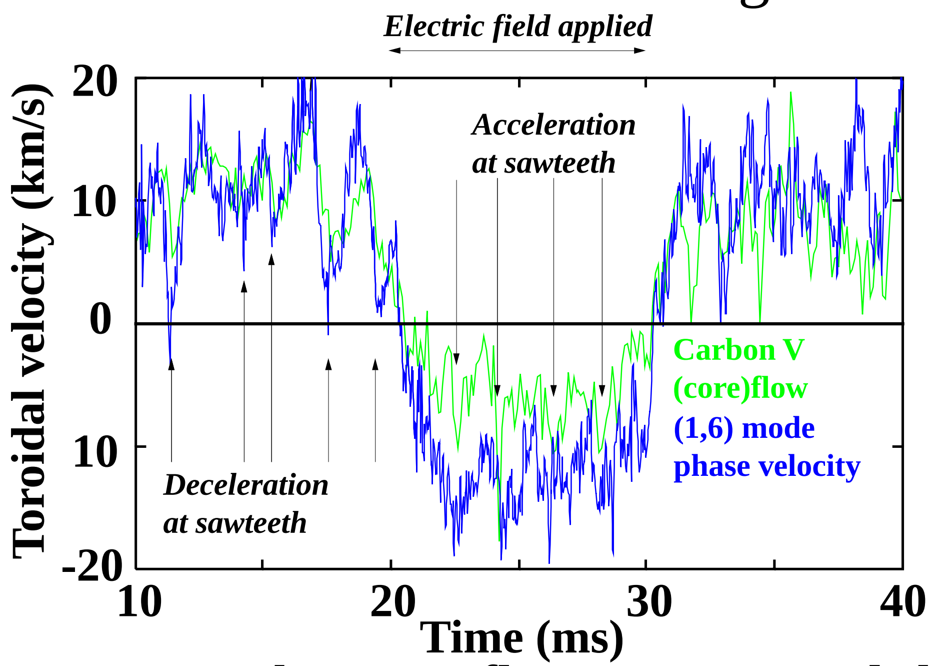
The nonlinear torque becomes large during a sawtooth event.

- Plot is of a ~700 event ensemble.
- The short timescale where the torque is active is consistent with that of the fast deceleration phase of the *m*=1 modes.
- The phase changes to the sense to produce a torque as the sawtooth crash is approached, and produces no torque away from the crash.

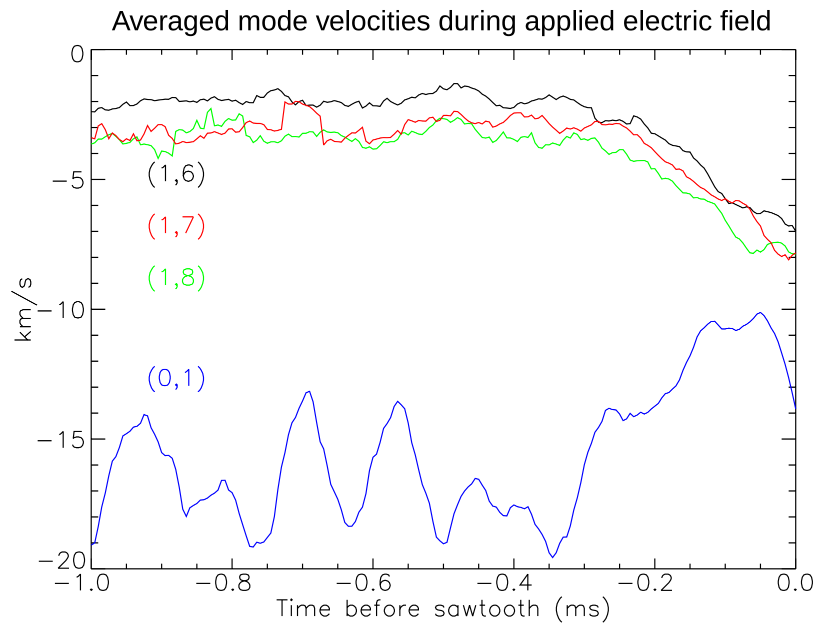


While the m=1 rotation is reversed, the m=1 modes accelerate on sawtooth crashes.

Individual discharge



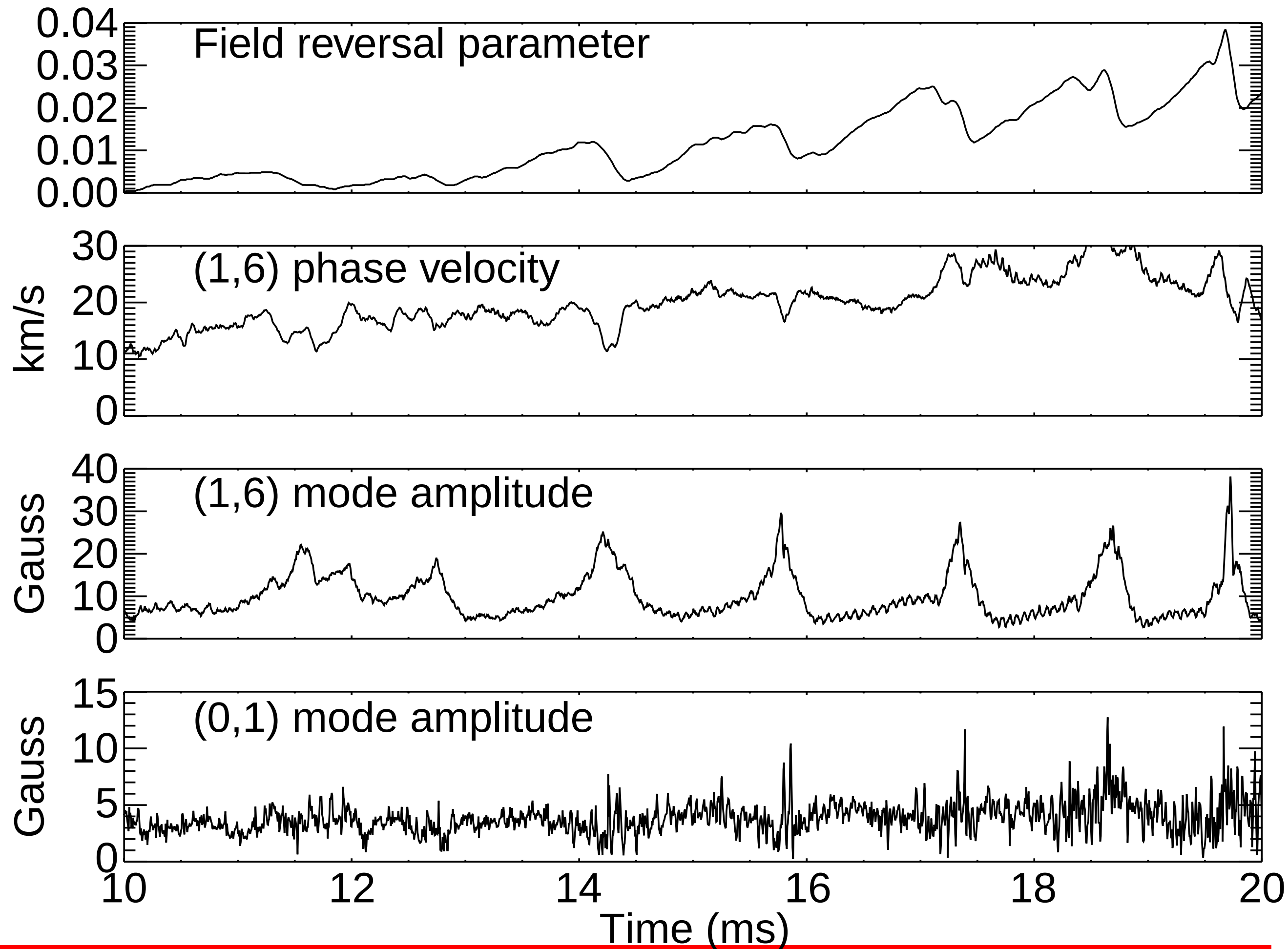
Ensemble



- The core flow is reversed through an applied radial electric field.
- The *m*=1 modes *accelerate* just before the crash.
- The (0,1) mode *decelerates* just before the crash.

Removing the q=0 resonance reduces the m=1 mode deceleration

- The *m*=1 modes still show sawtooth-like behavior
- The *m*=0 modes are small, and don't show bursts.
- There is still deceleration in the *m*=1 modes, but it is much less pronounced than in standard discharges.
- These results indicate that the nonlinear electro-magnetic torque is the largest contributor to the mode deceleration in standard discharges.



Future work

- We are investigating various schemes to control multiple modes via rotating magnetic perturbations.
  - Reduce electromagnetic coupling between islands.
  - Prevent mode locking.

Summary

- We have presented evidence for nonlinear electromagnetic torques in MST.
  - applied static magnetic perturbation experiments.
    - A perturbation with a single *n* can lock modes with different *n*.
  - sawtooth cycle
    - A triple product which is proportional to a term in the nonlinear torque exhibits the proper temporal behavior.
    - The m=1 modes accelerate rather than decelerate on sawtooth crashes when their rotation is reversed.
    - When the q=0 surface is removed from the plasma, the deceleration of the m=1 modes is much reduced.