Momentum Transport from Nonlinear Mode Coupling of Magnetic Fluctuations.

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42nd APS-DPP/10th ICPP, 25 Oct 2000, Québec City, Canada

Thanks to: A.F. Almagri, D. Craig, D.J. Den Hartog, C.C. Hegna, S.C. Prager, and J.S. Sarff

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NI2.003 Momentum Transport from Nonlinear Mode Coupling of Magnetic Fluctuations

The cause of anomalous momentum transport in plasmas and the nature of nonlinear mode coupling between tearing modes are two topics of broad significance. We have accumulated experimental evidence that the two effects are linked causally in the reversed field pinch (RFP): toroidal momentum is transported radially through three wave interactions of magnetic fluctuations. The transport is rapid, about two orders of magnitude beyond classical transport. It arises from spatially resonant Lorentz torques which occur at one mode-resonant surface, generated internally by the fluctuations arising at two other resonant surfaces. In such a process, the plasma experiences no net torque, but the momentum is redistributed. This occurs in the MST RFP experiment as a sudden flattening of the momentum profile in about 100 microseconds. We identify this mechanism in MST by multiple passive and active observations: (1) we measure the mode interaction triplet (the time-resolved bispectrum) and correlate it with the momentum redistribution, (2) we remove one of the interacting modes (i.e., the poloidal mode number m= 0 mode by operating with a non-reversed toroidal magnetic field) and observe that the momentum transport is suppressed, and (3) we apply an external magnetic perturbation with a specific toroidal mode number and observe the resulting change in momentum (rotation) at other mode-resonant surfaces. Finally, by observing the momentum changes in plasmas with arbitrary rotational offset (by spinning the plasma with inserted, electrically biased electrodes) we confirm that the rotation changes are a redistribution of momentum, unrelated to locking effects of field errors.Hence, a new phenomenon of momentum transport by magnetic fluctuations has been uncovered.

This work was supported by USDOE

Motivation

- It has been found in the Madison Symmetric Torus (MST) reversed-field pinch (RFP) that the plasma momentum can exhibit large-scale redistribution that occurs in a timescale that is about two orders of magnitude faster than a classical slowing-down time (100 μs vs 10 ms).

Major results

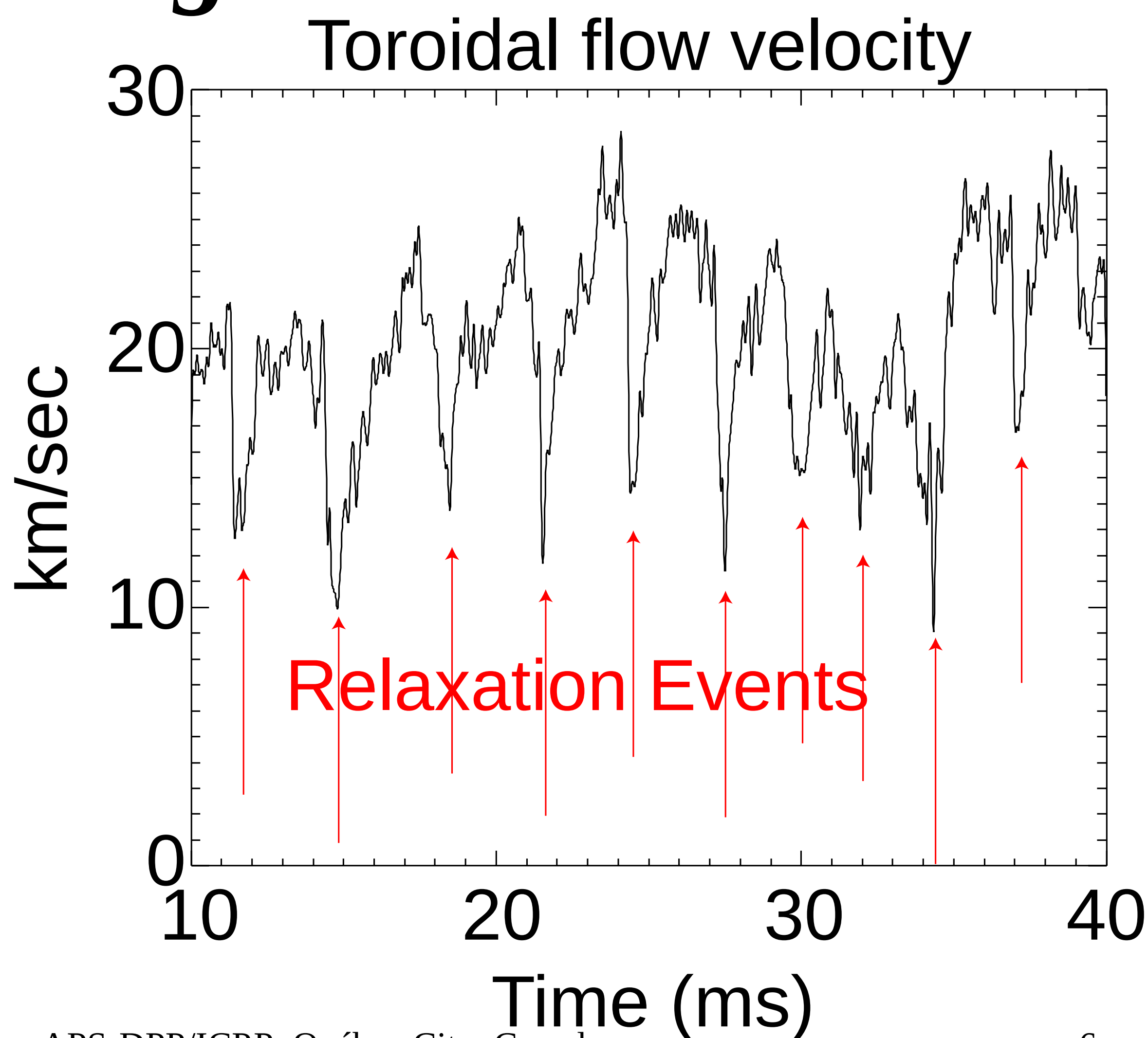
- The change in the plasma momentum is consistent with the action of a nonlinear, nonlocal torque between tearing modes.
  - Triple products of the mode amplitudes characteristic of such a torque correlate with the momentum change.
  - Removal of one of the modes in the interaction triplet essentially removes the change in momentum.
  - Application of an external magnetic perturbation affects multiple nonresonant modes.
- Applying an offset to the flow by means of an applied electric field demonstrates that momentum is being redistributed rather than lost.

Outline

- Background
  - Momentum changes
  - Tearing modes
- Results
- Future Work
- Summary

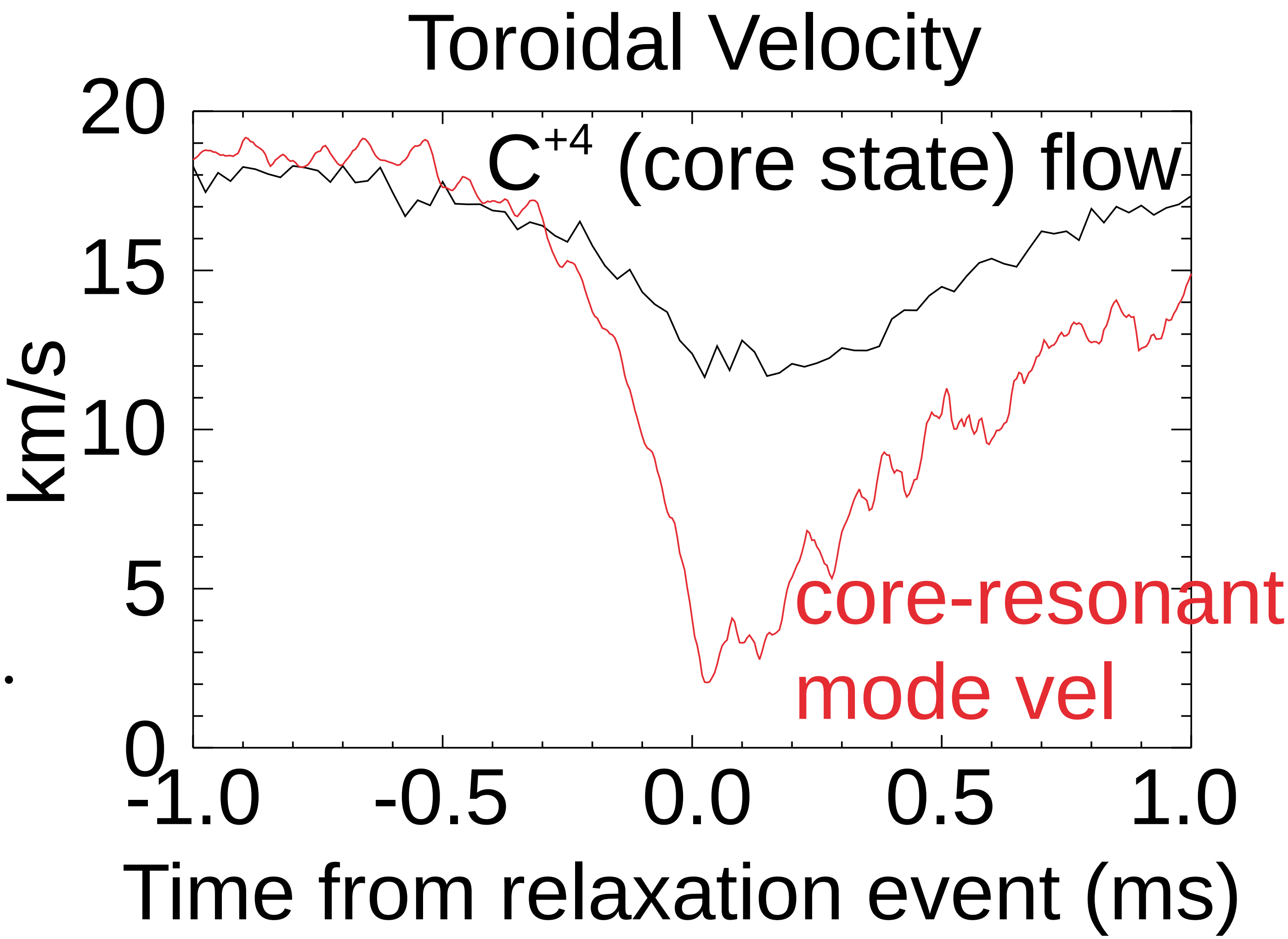
The plasma exhibits episodes of dramatic change in its momentum.

- These events are characterized by large magnetic fluctuations.
- They will be referred to as “relaxation events.”
  - Profiles of *many* equilibrium quantities relax during them.



The kinematics of the modes and the flow are strongly coupled in RFP plasmas.

- Change in mode velocity <-> change in plasma momentum.



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:

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

  where Ω is the (toroidal) angular phase velocity of the mode, I is the moment of inertia, $\mathbf{T}_{em}$ is the electromagnetic torque, $\mathbf{T}_{vis}$ is the viscous torque, and $\mathbf{S}$ is the momentum source term.
- 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.
  - Also can be thought of in terms of magnetic Reynolds stress.

There are several different ways by which the momentum can change.

- Changes in the source term
- Changes in viscous torque
  - Collisional/Anomalous (e.g. due to magnetic stochasticity)
- External electromagnetic torques
  - error fields
  - resistive walls
- Internal electromagnetic torques
  - toroidal coupling
  - **nonlinear coupling**

Nonlinear torques involve a three-wave interaction between modes.

- In (cylindrical) Fourier representation:

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

$$j_{\mathbf{k}}^{NL} \sim \sum_{\mathbf{k'},\mathbf{k''}} C_{\mathbf{k'},\mathbf{k}-\mathbf{k'}} b_{\mathbf{k'}} b_{\mathbf{k}-\mathbf{k'}} \ ,$$

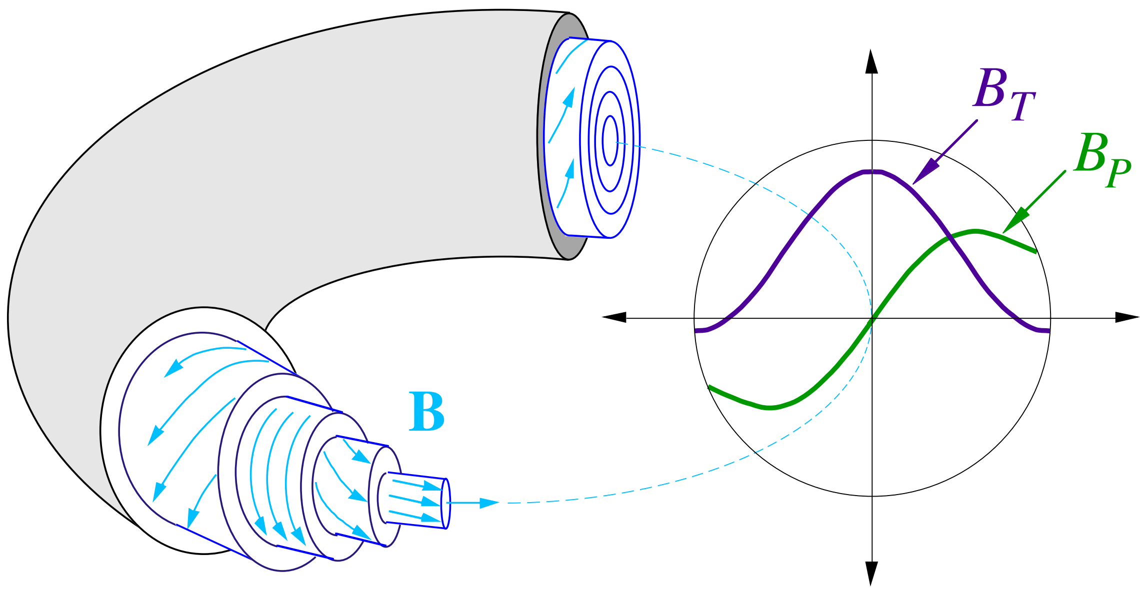
from the dynamical equations, i.e. the current is nonlinearly generated from multiple modes.

$$\Rightarrow T_{NL} \sim \sum_{\mathbf{k'}} C_{\mathbf{k'},\mathbf{k}-\mathbf{k'}} b_{\mathbf{k'}} b_{\mathbf{k}-\mathbf{k'}} b_{\mathbf{k}} \sin\left(\delta_{\mathbf{k'}} - \delta_{\mathbf{k}} + \delta_{\mathbf{k}-\mathbf{k'}}\right).$$

The nonlinear torque has several distinct features.

- Acts on each resonance in a triplet.
  - The torques on the **k**, **k'**, and **k"** surfaces add to zero
    - conserves angular momentum.
- Nonlocal in wavenumber space.
  - Involves triplets of modes at 3 different wavenumbers.
- Nonlocal in radial structure.
  - Modes are resonant at different radial locations within the plasma.

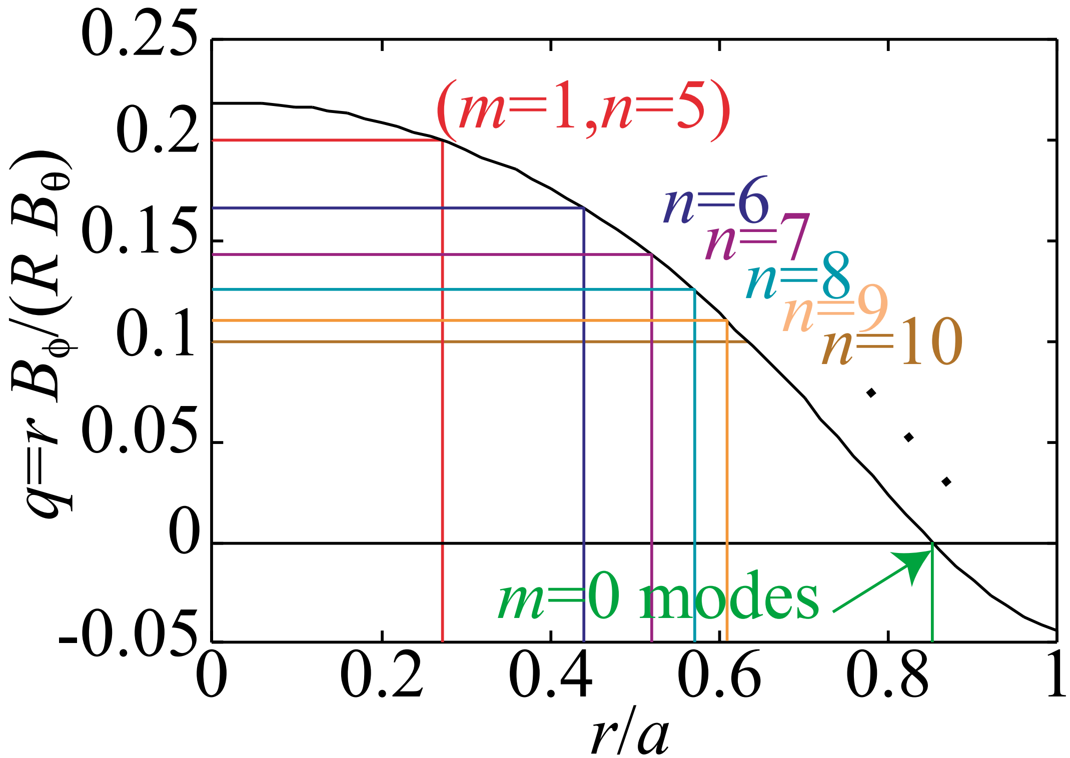
The RFP has an axisymmetric magnetic field structure.



- The magnetic field is generated in part by currents in the plasma.
- The configuration gets its name because the toroidal component of the field reverses direction near the wall.
- The RFP configuration plays host to large fluctuations.
  - Up to a few % of the equilibrium magnetic field.
  - Those of interest in this work have a tearing/resistive kink character.

The RFP q *profile allows for two major classes of global resonant tearing modes.*

Typical safety factor (q) profile, showing locations of relevant mode resonances.



- The (m = 1,n = 5-10) modes are resonant throughout the core of the plasma.
- The (m = 0,n ≥ 1) modes are resonant at the q = 0 surface, i.e. near the edge.

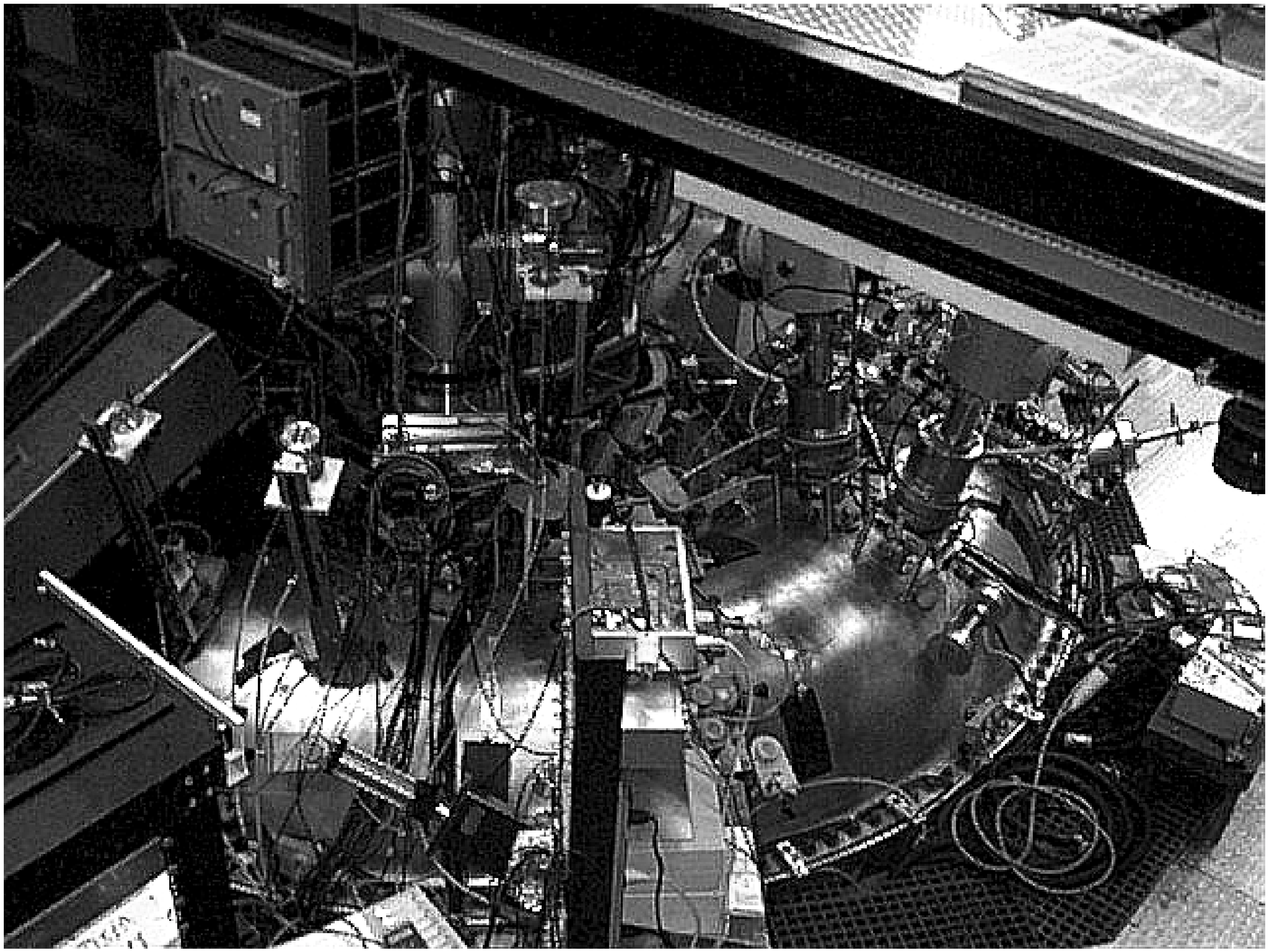
The presence of* m = *0 modes in the RFP permits nonlinear torques that involve two* m = *1 modes.

- The dominant term in the nonlinear (internal) torque should be produced by the interaction between the $(1,n)$, $(1,n\pm1)$, and $(0,\pm1)$ modes:

$$T^{NL}_{(m,n)} \sim b_{(0,\pm1)} b_{(1,n)} b_{(1,n\pm1)}$$

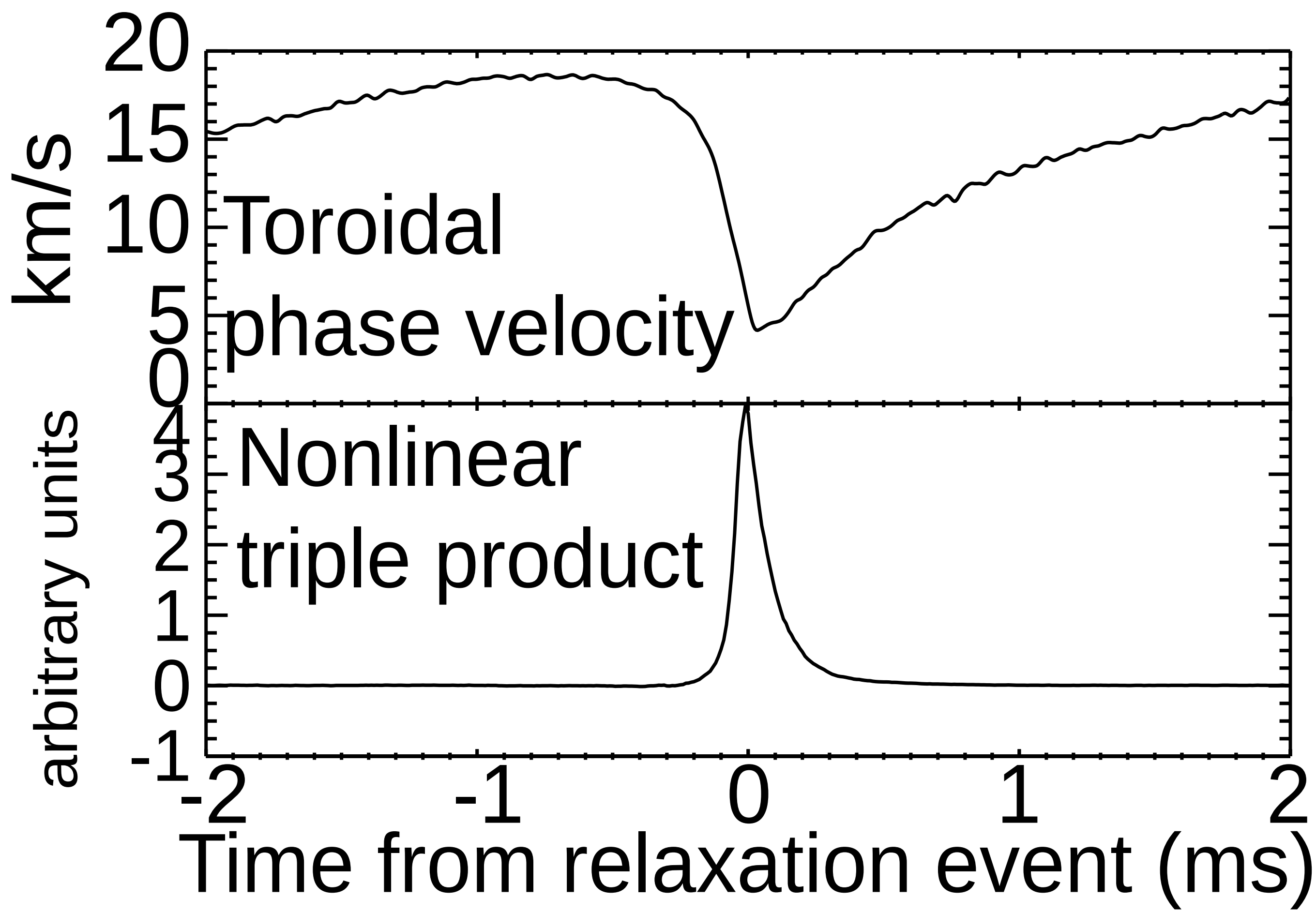
- The $m = 1$ modes are resonant in the core of the plasma, while the (0,1) mode is resonant near the edge --> radial nonlocality

The Madison Symmetric Torus (MST) is one of three large RFP devices in the world.



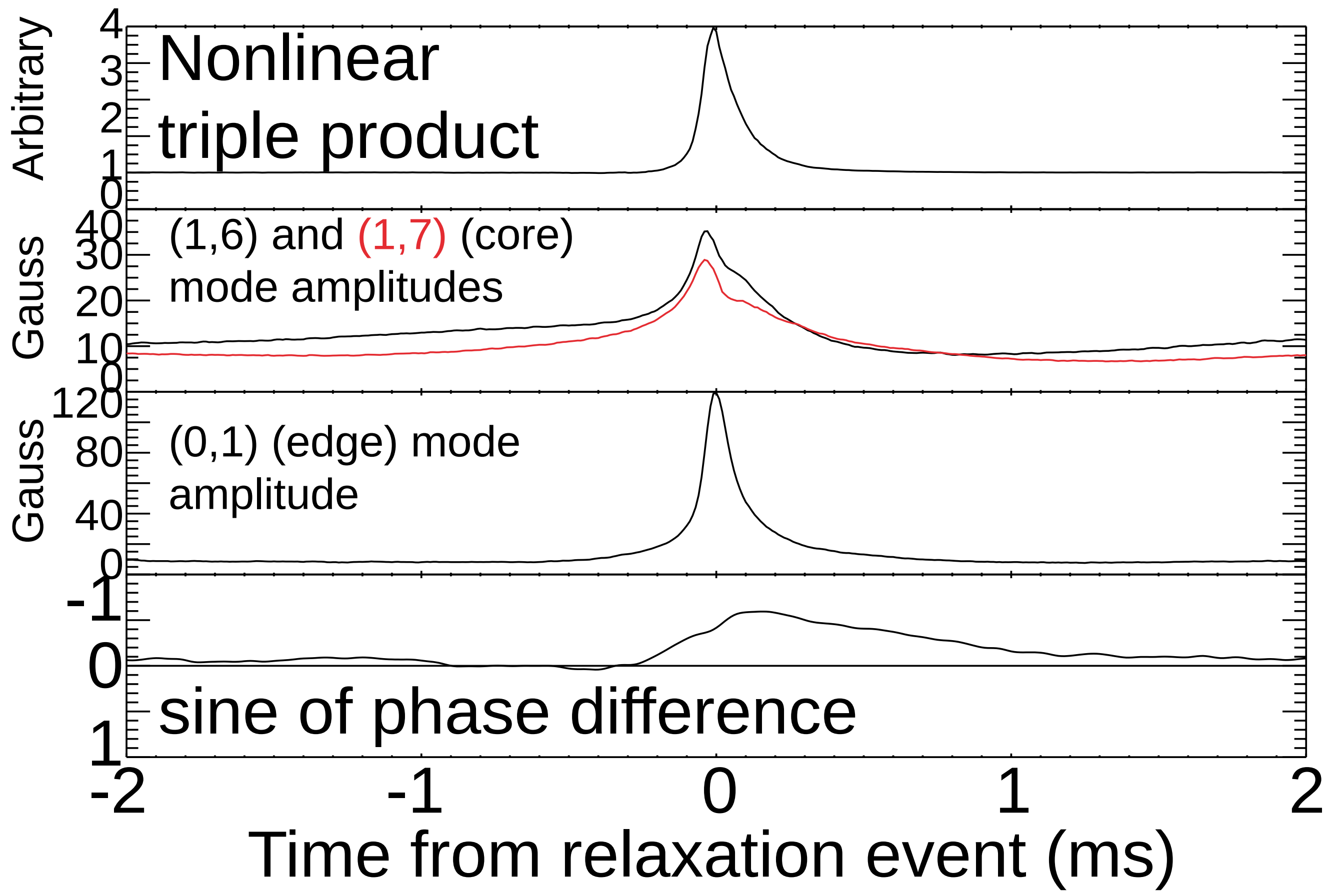
- Relevant diagnostics:
  - Multiple arrays of magnetic pickup coils inside the vacuum vessel.
  - Fast Doppler spectrometer

The nonlinear triple product becomes large during a relaxation event.



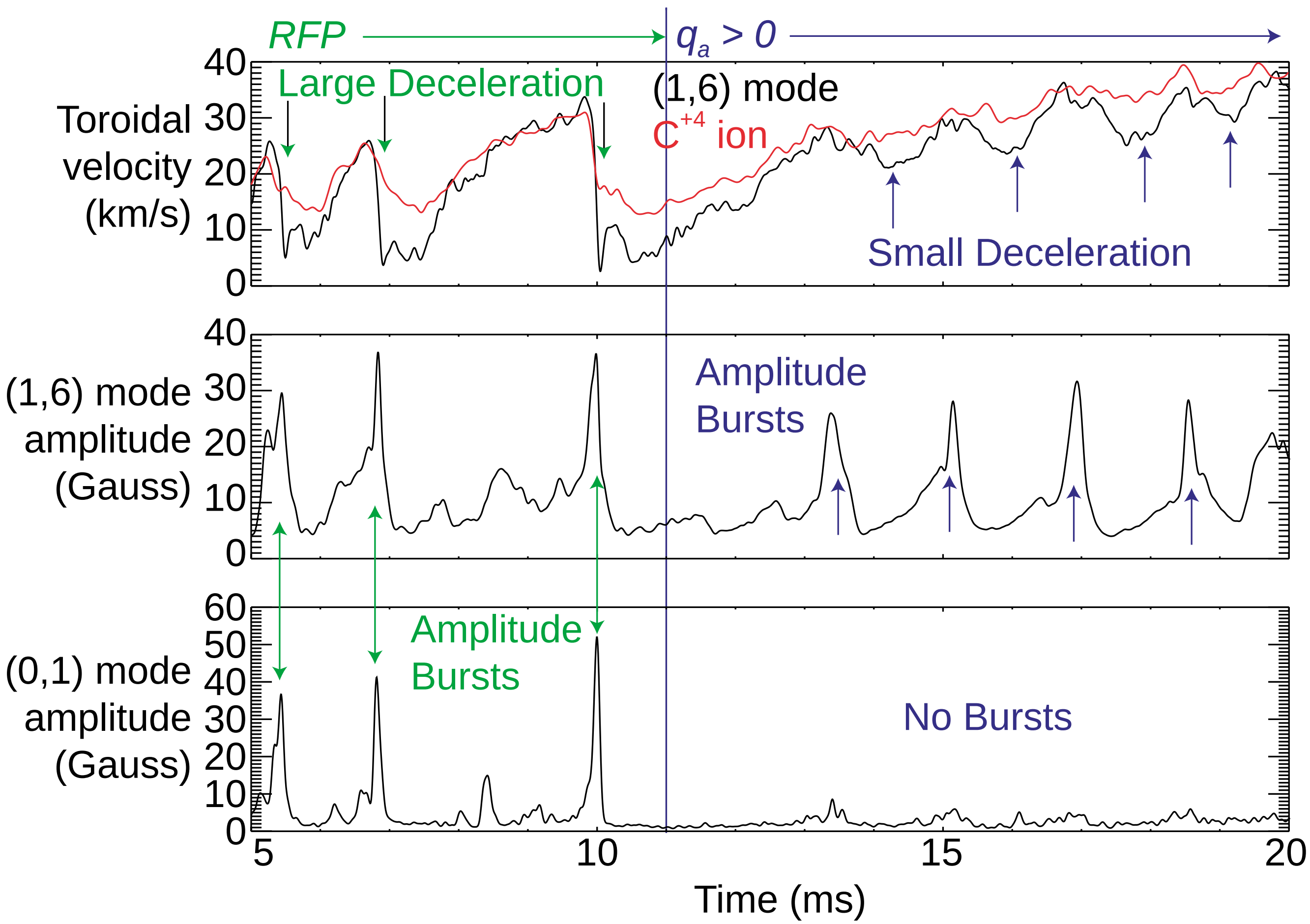
- The large change in the triple product occurs concurrently with the change in the plasma momentum.

The phase between the modes changes during a relaxation event.



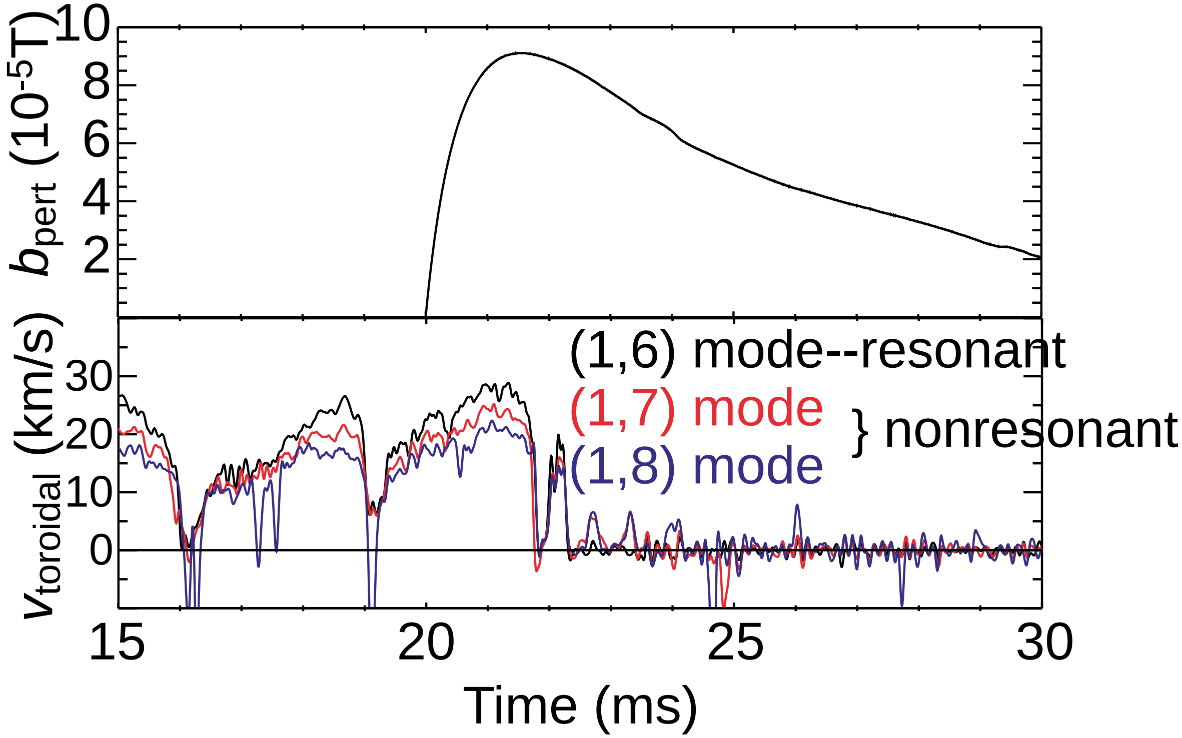
- Although the amplitudes of the individual modes do increase, the change in the phase is also necessary as well to produce the nonlinear torque.
  - The phase is such that no torque is produced away from the relaxation events.

Removal of one of the modes in the interaction triplet removes the momentum change.



- The $m = 0$ resonance is removed by running with a toroidal field that is positive everywhere
- The changes in the rotation of the remaining modes are much reduced.

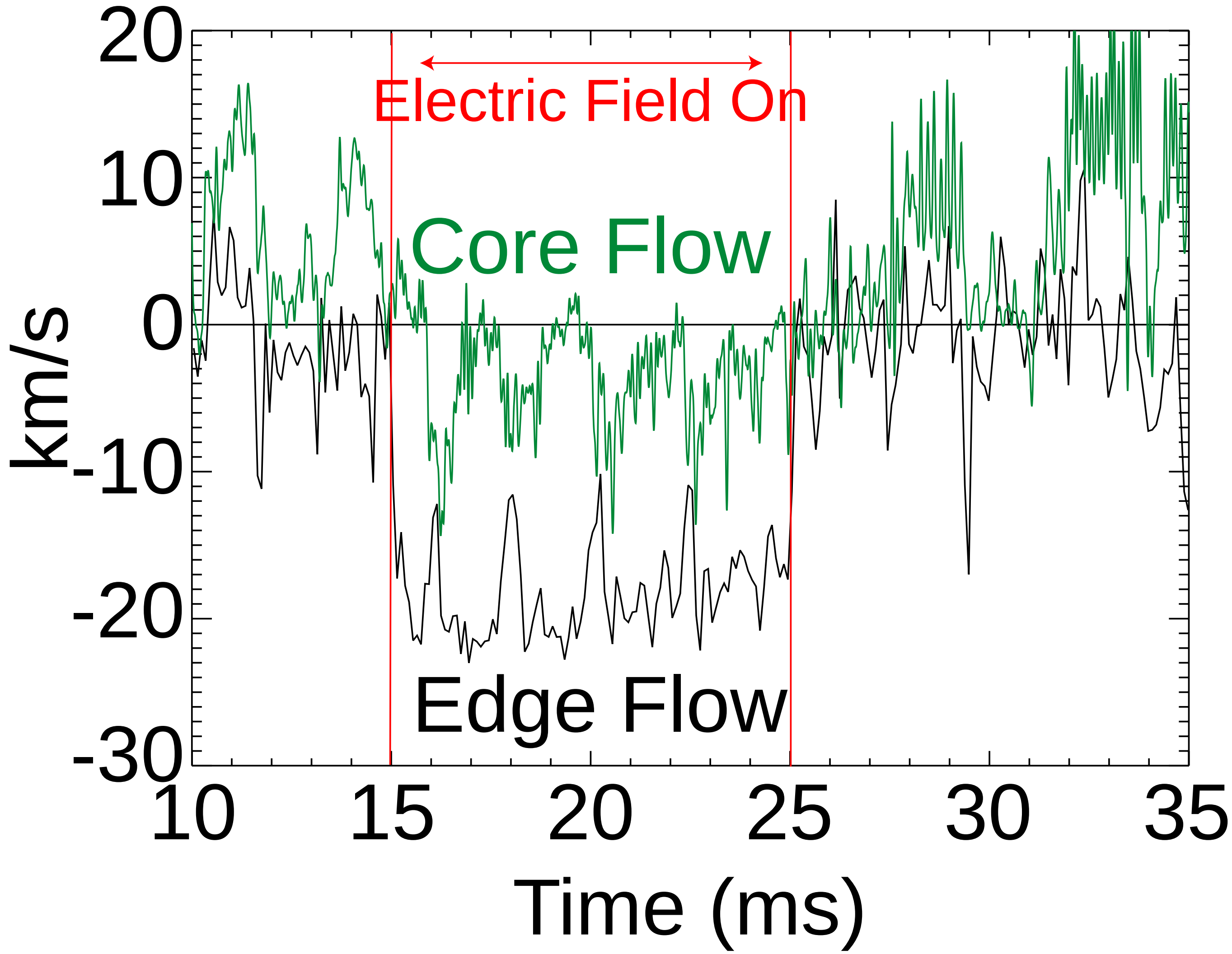
An applied perturbation locks nonresonant modes.



- The perturbation is only resonant with the (1,6) modes.
- This effect is not due to toroidicity.
  - Modes have same *m*.
- Nonlinear coupling of modes to an applied magnetic perturbation seen on RFX.

Momentum is being redistributed during the relaxation events.

- By biasing the plasma, a radial electric field is applied.
  - Produces an offset in the flow profile
- The applied electric field makes it clear that momentum is not just being lost, but is in fact being redistributed.



Future plans

- Simultaneous multiple-helicity rotating magnetic perturbations may provide a means to measure the coupling coefficients between modes.
- Direct measurement of $\langle j \times b \rangle$ will provide a direct measure of the torque.

Summary

- We have seen several experimental pieces of evidence that have identified a nonlinear, nonlocal mechanism for momentum transport in a plasma.

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