Local Measurements of Nonlinear MHD Phenomena in the MST Reversed Field Pinch: Reconnection, Torques, and Dynamo

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Resistive MHD fluctuations resonant in the reversed field pinch (RFP) have large effect on the macroscopic behavior of the plasma. The fluctuations cause magnetic reconnection which alters the magnetic topology, dynamo effects which alter the current density profile, and electromagnetic torques which alter the flow profile,. In the RFP, the safety factor, q, passes through zero in the outer region of the plasma (at r/a ~ 0.85). Thus, fluctuations with poloidal mode number m = 0 are resonant, and cause reconnection at the q = 0 surface. Since the reversal surface is near the plasma boundary, it is accessible for diagnosis with probes. In addition, by operating the plasma without field reversal (toroidal magnetic field positive at the wall), we can remove the m = 0 resonance, the m = 0 modes, and their associated reconnection. Thus, we can controllably study the effect of m = 0 modes on plasma behavior.

In this paper we report measurements of three nonlinear MHD effects related to reconnection. First, we measure the current density ÒsheetÓ associated with reconnection at the q = 0 surface, and show that it is quite broad in radial extent. Second, we measure the flow velocity associated with the m = 0 mode; we show that it has tearing spatial parity about the q = 0 surface, and that the m = 0 mode constitutes the bulk of the MHD dynamo effect in the edge region. Third, we show through a variety of passive and active measurements that toroidal momentum is rapidly transported in the radial direction through torques associated with the three-wave coupling between magnetic fluctuations. Below we summarize results in each of these three areas.

I Measurement of Current Density Fluctuations Associated with Reconnection

An important question in magnetic reconnection is the spatial structure of the associated current. Resistive MHD predicts that the current will form with a radial width of order $aS^{-2/5}$, where a is the minor radius and S is the Lundquist number. This width can be quite small (of order mm) since S can be large. A variety of effects can broaden the width, such as electron transport along magnetic field lines, finite ion gyroradii, and Hall effects [1]. The width is of substantial interest since it, in part, determines the rate of reconnection. We have measured the current density fluctuations at the q = 0 surface with insertable Rogowskii coils (with a diameter of 2 cm through which the plasma can pass). We employ two, spatially separated Rogowski coils to obtain two-point poloidal and toroidal mode spectra. The current associated with reconnection at the q = 0 surface is that corrsponding to poloidal mode number m = 0. Indeed, we find that in the vicinity of the reversal surface the current density fluctuations are dominantly m = 0, as shown in the poloidal mode number spectrum in Fig. 1. By contrast, the magnetic fluctuations are dominated by core-resonant m = 1 magnetic fluctuations. This is consistent with the expectation that current fluctuations are more localized to the resonant surface than magnetic fluctuations.

The radial width of the m = 0 current density fluctuation (the current sheet) is quite broad, extending at least 10 cm, as shown in Fig. 2. This width is comparable to the calculated m = 0 island width of $\gtrsim$10 cm and the ion skin depth (c/ω_{pi}) of $\gtrsim$ 16 cm (a characteristic scale for the Hall effect). Furthermore, it is much larger than the ion gyroradius of ~1.5 cm, the electron skin depth (c/ω_{pe}) of $\lesssim$ 1 cm (a characteristic scale for the inertial effect in Ohm's law) and the MHD tearing resistive layer of $\gtrsim$ 0.2 cm.

II Velocity Fluctuations and the Dynamo Effect

In addition to measuring the current associated with reconnection, we have measured the velocity field. This is accomplished with an insertable optical probe[2] which detects impurity emission from Helium dopant ions, with a radial localization of about 5 cm and a time resolution of about 200 kHz. By analyzing the Doppler shift we can determine the velocity fluctuations. We find that the radial velocity fluctuation flips sign about the reversal surface (Fig. 3), as expected for a tearing mode. We also have measured the MHD dynamo effect: the correlated cross product between the velocity and magnetic field fluctuations ($\delta\mathbf{v} \times \delta\mathbf{B}$). We find that that the dynamo effect produced by the m = 0 fluctuations is sufficient to account for the driven equilibrium current in the vicinity of the reversal surface. This is consistent with the expectation that the dynamo arises from a superposition of relatively localized reconnection events.

III Momentum Transport by Nonlinear Coupling of Magnetic Fluctuations

During the crash phase of a sawtooth oscillation, we observe that the radial profile of the plasma toroidal rotation changes rapidly, approaching a flatter profile. This corresponds to momentum transport about two orders of magnitude larger than the classical value. We present experimental evidence here that the momentum transport arises from torques in the plasma generated by three wave interactions of tearing modes. At a radius at which a mode with wave number, k, is resonant (i.e., $\mathbf{k}\cdot\mathbf{B} = 0$), the plasma can experience a mean Lorentz force from the resonant fluctuation given by $\langle \mathbf{j_k} \times \mathbf{B_k} \rangle$, where < > denotes an average over the magnetic surface. If there are multiple tearing fluctuations in the plasma, then the current density $\mathbf{j_k}$ can have a component which arises from the nonlinear coupling to two other modes, related to k by the sum rule; i.e., $j_k \propto B_{k1}B_{k2}$, where $\mathbf{k} = \mathbf{k_1} + \mathbf{k_2}$. Then the force on the magnetic surface $\propto \langle B_k B_{k1} B_{k2} \rangle$. This interaction provides no net torque on the plasma, but does provide internal torques on resonant surfaces which redistribute the toroidal momentum.[3,4]

Three pieces of passive and active experimental evidence support the view that this process is responsible for momentum transport in MST. First, we measure a key magnetic field fluctuation triplet and find that it correlates well with the change in toroidal momentum, as shown in Fig. 4. The plasma rotation is indicated in the figure by the toroidal phase velocity of the m = 1, n = 6 mode, which is known to track the core plasma rotation. It is seen (Fig 4a) that the mode (and plasma) rotation in the core decelerates rapidly during a sawtooth crash. The dominant modes in MST are those with mode numbers m = 1, n ~ 6 — 9. These m = 1 modes couple nonlinearly through the m = 0, n = 1 mode. The triplet product of the n = 1, 6, 7 modes, and the phase factor, are shown in Figs. 4b and 4c. Second, we remove one of the interacting modes, and observe that during a sawtooth crash the momentum transport is largely suppressed. The m = 0 mode is eliminated by operating the plasma without a reversal surface (an m = 0 resonant surface) in the plasma. The toroidal field at the wall is kept nonreversed. The m = 0 mode is then absent (Fig. 5c), and the plasma momentum does *not* change significantly during a sawtooth crash (Fig. 5a), despite the continuation of sawtooth oscillations (evident in Fig. 5b). Third, we apply an external n = 6 perturbation, and observe that multiple modes (n = 6 — 9) lock to the external perturbation, consistent with nonlinear interaction between different modes.

IV **Summary**

We have measured several fundamental, local properties associated with reconnection, and the global effect of reconnection on the plasma. The current density and radial flow velocity associated with reconnection have been measured. The m = 0 plasma current perturbation, representing the current sheet, is present as expected. However, its radial width is large; future work is needed to identify the mechanism responsible for the broad extent. The m = 0 velocity fluctuations reverse their sign across the q = 0 resonant surface, as expected for a tearing fluctuation. However, it is not yet known whether the m = 0 fluctuations are linearly excited or are nonlinearly driven by coupling to m = 1 modes. We have also accumulated experimental evidence on the effect of these fluctuations on the plasma equilibrium: they transport momentum through internal torques arising from three wave coupling of tearing modes, and they drive (or transport) current through the dynamo effect.

1. See, for example, D. Biskamp, E. Schwartz, J. Drake, Phys. Rev. Lett. **75**, 3850 (1995).
2. G. Fiksel, D. Den Hartog, P. Fontana, Rev. Sci. Inst. **69**, 2024 (1998)
3. C.C. Hegna, Phys. Plasmas **3**, 4646 (1996).
4. R. Fitzpatrick, Phys. Plasmas 6, 1168 (1999).

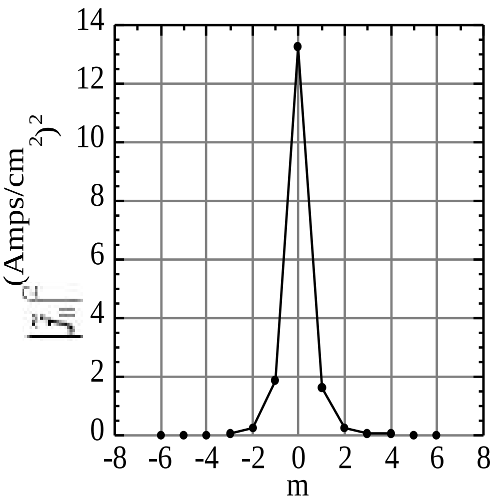

Fig. 1 Two-point poloidal mode number spectrum of parallel current density fluctuations at the reversal surface.

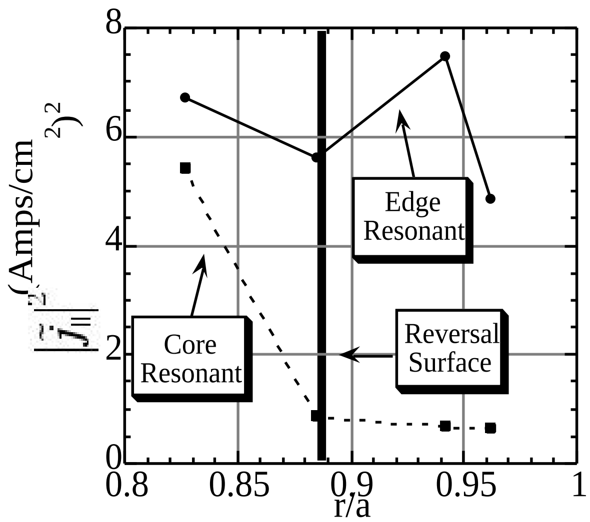

Fig. 2 Radial profile of edge resonant (m = 0) and core resonant (m=1) fluctuations.

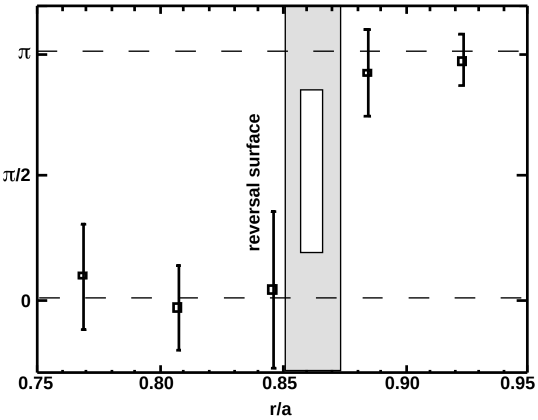

Fig. 3 Relative phase of radial velocity fluctuation vs. radius.

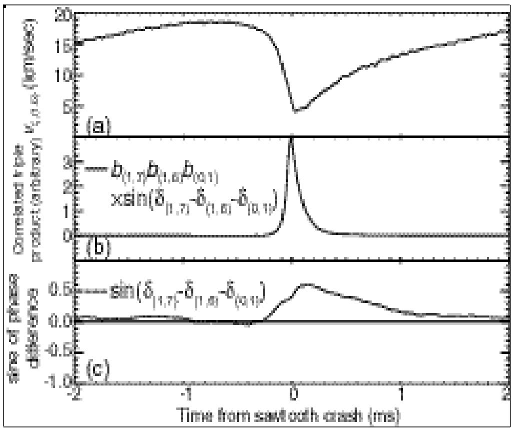

Fig 4 (a) Toroidal phase velocity for m =1, n=6 mode, (b) nonlinear triple product (c) phase factor. All quantities are ensemble averages over many discharges.

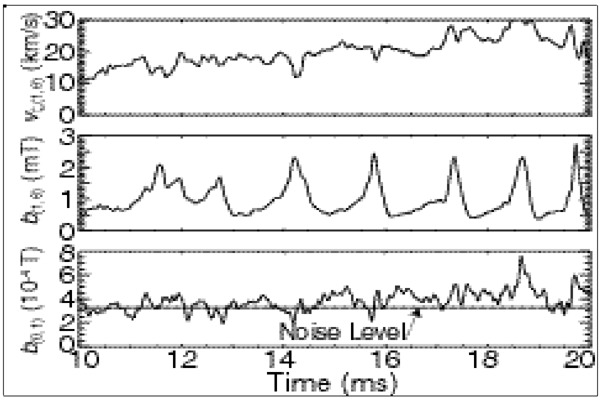

Fig. 5 Discharge with no m=0 resonance. (a) m=1,n=6 toroidal phase velocity, (b) (1,6) mode amplitude, (c) m=0, n=1 mode amplitude.