Measurement of the Current Sheet during Magnetic Reconnection in a Toroidal Plasma

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The current and magnetic-field fluctuations associated with magnetic-field-line reconnection have been measured in the reversed field pinch plasma configuration. The current sheet resulting from this reconnection has been measured. The current layer is radially broad, comparable to a magnetic-island width, as may be expected from current transport along magnetic-field lines. It is much larger than that predicted by resistive MHD for linear tearing modes and larger than prediction from two-fluid linear theory.

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Magnetic-field-line reconnection—the breaking and reconfiguration of magnetic-field lines in a plasma—occurs in numerous natural settings and in many magnetically confined plasmas in the laboratory. Reconnection permits magnetic fields embedded in plasmas to evolve in ways forbidden by ideal magnetohydrodynamics (MHD). A hallmark of reconnection is that the current density parallel to the magnetic field is expected to become large at the location of the reconnection (singular in the limit of ideal MHD). A current sheet develops a finite amplitude and width through various effects beyond ideal MHD, such as resistivity [1], electron inertia [2–4], the Hall effect [5], electron pressure in combination with ion inertia [6,7], and parallel streaming of charge carriers along magnetic-island-field lines [8–11]. The width of the resulting current sheet is partially determined by the dominant nonideal effect and often corresponds to the width of the region where nonideal MHD effects dominate. The evolution of magnetic fields undergoing reconnection has been experimentally studied in a variety of settings. However, experimental measurement of the current density at the reconnection point has been scarce. Interesting measurements of the current sheet associated with driven reconnection, as well as observations of the evolution of the associated magnetic fields, have been obtained in plasmas in which only the electrons are magnetized [12], in merging compact tori [13–15], and in other kinds of laboratory plasmas [16].

In this Letter, we report measurement of the current sheet and reconnecting magnetic field associated with *spontaneous* reconnection. The measurements were performed in the magnetically confined toroidal plasma configuration known as the reversed field pinch (RFP). The RFP provides an experimental opportunity for basic studies of reconnection. There are multiple radial locations within the plasma at which spontaneous reconnection occurs, a result of the strongly sheared magnetic field. In particular, reconnection occurs in the outer portion of the plasma (at the reversal surface where the toroidal magnetic field passes through zero), which is accessible to direct experimental probing and therefore the focus of this study. This reconnection occurs predominantly in bursts, providing clear experimental signatures. The bursts are cyclic, part of a relaxation process in which many quantities have a sawtooth behavior in time. The bursts of reconnection occur during the crash phase of the sawtooth oscillation. Finally, many of the key scale lengths, which potentially determine the width of the current sheet, may be separable, such as resistive layer width, the ion and electron skin depths, the ion acoustic gyroradius, and the magnetic-island width.

We measure a large current perturbation (parallel to the equilibrium magnetic field) flowing in the vicinity of the surface of reconnection with a spatial structure which is resonant with the equilibrium magnetic field. It is resonant in that its parallel wave number vanishes at the reversal surface. We identify the current perturbation as the current sheet associated with reconnection. This current density perturbation oscillates in time since, along with the plasma, it rotates in the lab frame. Interestingly, the measured magnetic fluctuations in this vicinity have dominant contributions from modes that are resonant in the core of the plasma. This is consistent with the expectation from MHD theory that current density fluctuations associated with reconnection are more spatially localized than the corresponding magnetic fluctuations.

The observed current perturbation, however, is not confined to a resistive tearing layer, as would be expected from resistive MHD theory for linearly evolving resistive tearing modes [1]. Inclusion of additional effects in Ohm's law predicts different spatial scales for the current sheet width. The electron inertial effect in Ohm's law yields a sheet width of the scale of the electron skin depth (c/ω_{pe}) [2–4], while the parallel electron pressure gradient yields a sheet width of the scale of the ion acoustic gyroradius $\rho_s = [(T_e + T_i)m_i]^{1/2}/eB_o$ [6,7]. The radial extent of the measured current sheet is much larger than c/ω_{pe}. It is also somewhat larger than ρ_s, and is of the order of the calculated width of the magnetic island associated with the reconnection. {The island width is given by $4[(\tilde{b}_r/B_{\theta 0})(r/nq')]^{1/2}$, where $\tilde{b}_r$ is the radial field perturbation that produces the island, $B_{\theta 0}$ is the equilibrium poloidal field, r is the radius of the resonant surface, n is the toroidal mode number of $\tilde{b}_r$, q is the safety factor which is a measure of the field winding number, and $q' = dq/dr$ is a measure of the magnetic shear.} Hence, parallel motion of particles along the magnetic field (corresponding to radial transport of parallel current density) may account for the measured layer width [8–11].

These experiments were performed in the MST reversed field pinch (minor radius = 0.52 m, major radius = 1.5 m) [17]. For these experiments, MST was operated at low toroidal plasma current (~ 150 kA) so that probes could be inserted from the vacuum vessel wall to a radius of $r \approx 0.4$ m without significant perturbation to the plasma. This radius is smaller than that of the surface at which the safety factor, q, passes through zero ($r/a \approx 0.88$, where a is the plasma minor radius). The equilibrium magnetic field at the reversal ($q = 0$) surface is resonant with Fourier modes of poloidal mode number $m = 0$. To measure $\tilde{j}_{\|}$, the fluctuating current density (parallel to the equilibrium magnetic field), we employ small, insertable Rogowskii coils (which have cylindrical holes ~2 cm in diameter and 2 cm in axial length through which plasma may pass) in conjunction with an array of toroidal magnetic sensing coils that are evenly distributed around the wall of MST in the toroidal direction. All probe sizes are small compared to the poloidal and toroidal wavelengths, and smaller than the radial scale of the fluctuations. The poloidal mode number spectrum of $\tilde{j}_{\|}$ is obtained from measurements made simultaneously at pairs of locations by using the two-point spectral analysis technique. The toroidal mode number spectrum of $\tilde{j}_{\|}$ is estimated by measuring the correlation between $\tilde{j}_{\|}$ and individual Fourier modes of toroidal magnetic-field fluctuations at the edge of the plasma. The resulting current fluctuation spectrum represents the components of $\tilde{j}_{\|}$ that correlate with the magnetic-field fluctuations at the wall. We perform similar analyses for internal magnetic fluctuations at different radii in the edge region by using magnetic sensing coils built into the probes containing the Rogowskii coils. The Rogowskii and magnetic sensing coils function with a frequency response of ≤ 100 kHz, much above the frequencies of the dominant fluctuations (1 kHz $< f <$ 25 kHz).

Previous, extensive study of magnetic fluctuations, $\tilde{b}$, in RFPs has shown the dominant source to be core-resonant tearing modes [18]. In MST, these modes have poloidal and toroidal mode numbers $m = 1$ and $n =$ 5–10, respectively. The measurements we report here of $\tilde{b}$ spectra inside the plasma confirm this understanding of magnetic fluctuations in RFPs. MST plasmas exhibit a relaxation oscillation (a sawtooth oscillation) through which all mode amplitudes cycle on a time scale of several milliseconds. The magnetic relaxation is evidenced, for example, by the increase in toroidal magnetic flux [Fig. 1(a)], synchronous with increases in $m = 1$ and $m = 0$ magnetic fluctuations [Fig. 1(b)]. In the edge of MST, all components of $\tilde{b}$ are dominated by core-resonant $m = 1$ modes [Figs. 2(a) and 2(b)] both during and between sawtooth crashes. However, modes resonant at the reversal surface, mostly $m = 0$, $|n| = 1$–3 modes, are also observed, particularly near the plasma surface in a burst during the crash phase in the sawtooth oscillation. Indeed, during the crash phase, these $m = 0$ modes actually dominate toroidal magnetic fluctuations at the plasma surface.

For reconnection to occur, the radial component of the resonant magnetic-field fluctuation must be nonzero at the resonant surface. The radial component is necessary to connect field lines that are separated in radius, with the resonant surface residing between them. The radial field must also be resonant. A nonresonant field will only bend the field lines, not reconnect them. We have measured the radial profile of the $m = 0$, $|n| = 1$ radial magnetic-field fluctuation (Fig. 3). Indeed, it is nonzero at the reversal surface. This measurement of the radial field is consistent with its inference from the measured toroidal magnetic-field fluctuations (Fig. 3), invoking the continuity of the field ($\nabla \cdot \tilde{\mathbf{b}} = 0$). The nonvanishing of the radial field proves that reconnection occurs, and that the measured resonant current density fluctuation is associated with reconnection.

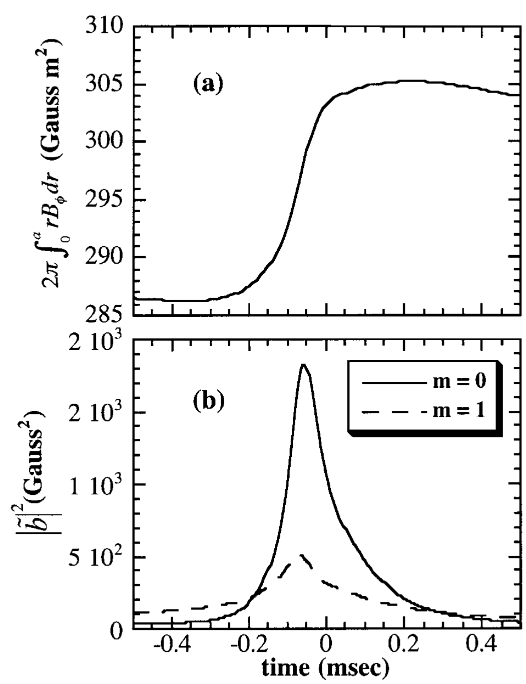

FIG. 1. (a) Toroidal magnetic flux vs time during a sawtooth crash. The time $t = 0$ denotes the end of the sawtooth crash time (time of maximum time rate of change of the flux). (b) Total magnetic-field fluctuation power in $m = 0$ and $m = 1$ poloidal modes at the plasma surface during sawtooth crashes.

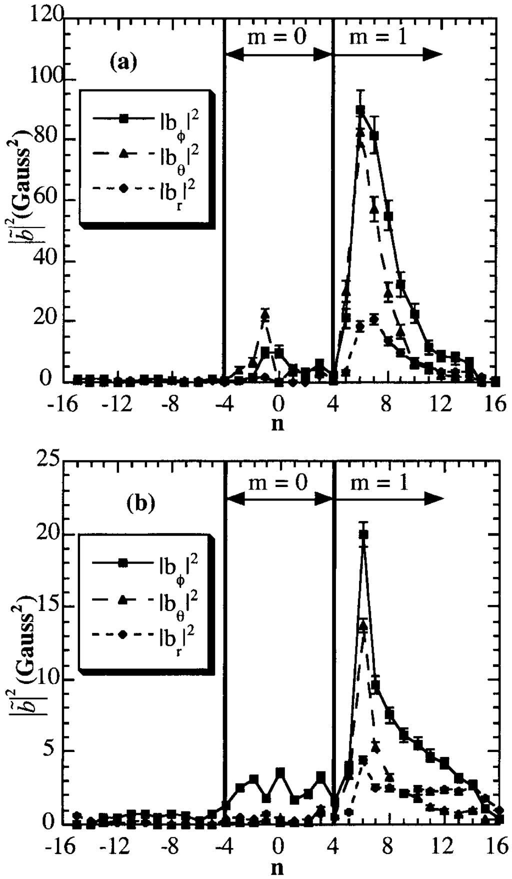

FIG. 2. Toroidal mode spectra of radial, poloidal, and toroidal magnetic fluctuation power at the reversal surface ($r/a = 0.846$): (a) during sawtooth crashes and (b) between sawtooth crashes.

The measured current density fluctuations have a character quite different from that of the magnetic fluctuations. The poloidal two-point spectrum of $\tilde{j}_{\|}$, measured in the vicinity of the reversal surface, is dominated by the $m = 0$ mode during sawtooth crashes, as shown in Fig. 4(a). The current density fluctuation amplitude is about 20% of the equilibrium current density. The toroidal spectrum obtained from correlation of the current density measurement with the toroidal coil array is dominated by low n ($|n| = 1$–3) modes during sawtooth crashes [Fig. 4(b)]. Similarly, between sawtooth crashes, $\tilde{j}_{\|}$ is dominated by $m = 0$, $|n| = 1$–3 modes. Indeed, in the vicinity of reconnection, we expect the associated $\tilde{j}_{\|}$ to become large, but not necessarily the associated $\tilde{b}$ (i.e., it is not singular in the ideal MHD limit). We identify the $m = 0$, low n $\tilde{j}_{\|}$ as the current sheet associated with reconnection at the $q = 0$ surface.

The resonant parallel current density fluctuation is distributed radially over a range of ~7 cm (Fig. 5). At other poloidal locations, the width extends to ~10 cm. This width is comparable to the calculated $m = 0$ island width of ~10 cm. This is consistent with current sheet

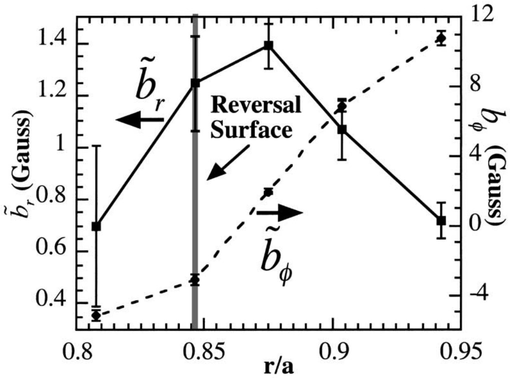

FIG. 3. Radial profile of radial (——■——) and toroidal (- - ◆ - -) magnetic-field fluctuation amplitudes at the reversal surface for the resonant, $n = -1$, toroidal mode during sawtooth crashes.

broadening from current transport across the island (by particle motion along the magnetic field). For this interpretation to apply, the current transport must occur more rapidly than the sawtooth crash time. It is difficult to determine the current transport rate. However, if it is similar to that of particles and energy, which are roughly equal, then the time for the current to transport across the island (about 10 μs) is less than the crash time (about 100 μs). On the other hand, this width is much larger than the resistive layer width ($a/S^{2/5}$, where S is the Lundquist number) of $\gtrsim 0.2$ cm. We note, however, that this resistive layer width is expected for linear resistive

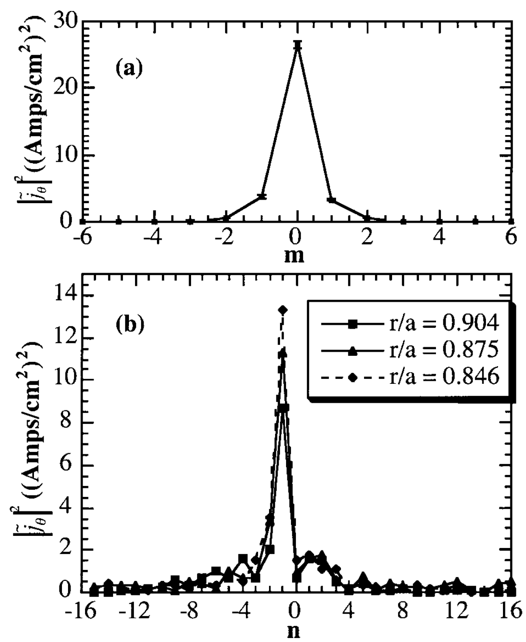

FIG. 4. (a) Two-point poloidal mode number spectrum and (b) toroidal mode number spectrum of poloidal current density fluctuations at the reversal surface during sawtooth crashes.

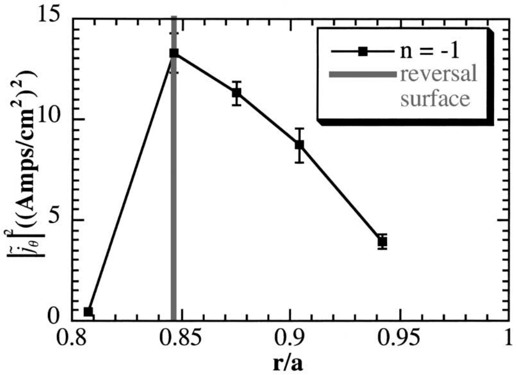

FIG. 5. Radial profile of poloidal current density fluctuation power for the reversal surface resonant, $n = -1$, toroidal mode during sawtooth crashes.

tearing modes rather than saturated tearing modes such as we observe in MST. The observed current sheet width is much greater than the electron skin depth (c/ω_{pe}) of $\lesssim 0.5$ cm and greater than the ion acoustic gyroradius (ρ_s) of $\sim$1.5 cm. The c/ω_{pe} scale arises from electron inertial effects (the $d\mathbf{J}/dt$ term in Ohm's law) and the ρ_s scale arises from a combination of finite pressure effects and ion inertia (the ∇p_e term in Ohm's law). Thus, neither electron inertial nor electron pressure effects can account for the measured width. We note that the layer width is of the order of the ion skin depth ($c/\omega_{pi} \sim 15$ cm); however, the ion skin depth is predicted to determine the current sheet width only in high β, or weakly magnetized, plasmas (for which the magnetic-field pressure associated with the field perpendicular to the plane of plasma flow, or guide field, is small compared to the plasma pressure) [2]. Recent linear two-fluid theory for current-driven tearing modes appropriate for the RFP (low β plasma, strong guide field) indicates that the ion acoustic gyroradius is the radial scale for the current sheet [19]. The larger experimental width implies that either nonlinear or kinetic effects are important.

In conclusion, toroidal and poloidal mode number spectra have been obtained for current and magnetic-field fluctuations measured in the edge of a reversed field pinch plasma, in the vicinity of the $q = 0$ surface about which reconnection occurs. Measurement of radial magnetic-field fluctuations with poloidal mode number $m = 0$ at the $q = 0$ surface provides direct evidence of reconnection. The current fluctuations in the vicinity of the $q = 0$ surface are dominated by modes resonant there, indicating that the current "sheet" of the reversal surface resonant tearing modes is being observed. This current sheet is not radially localized, but shows a broad structure, with an extent comparable to the associated $m = 0$ island width. This might suggest that it results from current transport across the island. It is broader than might be expected from linear two-fluid theory. We also note that the current layer width in MST, measured relative to the ion skin depth, is comparable to that observed in the Magnetic Reconnection Experiment (in which the layer width $\sim 0.4c/\omega_{pi}$) [20]. The current sheet physics of reconnection may depend on the nature of the drive. For example, it is not yet determined whether reconnection at the location of the measurements is driven by a tearing instability (either current or pressure driven) or by nonlinear coupling to core-resonant modes. Quantitative understanding of these results motivates additional theoretical work, such as the development of nonlinear collisionless reconnection theory, and nonlinear pressure-driven MHD reconnection theory, for the reversed field pinch.

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