Quantitative Study of Guide-Field Effects on Hall Reconnection in a Laboratory Plasma

T. D. Tharp, M. Yamada, H. Ji, E. Lawrence, S. Dorfman, C. E. Myers, and J. Yoo
Center for Magnetic Self-Organization and Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540, USA
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The effect of guide field on magnetic reconnection is quantitatively studied by systematically varying an applied guide field in the Magnetic Reconnection Experiment (MRX). The quadrupole field, a signature of two-fluid reconnection at zero guide field, is altered by a finite guide field. It is shown that the reconnection rate is significantly reduced with increasing guide field, and this dependence is explained by a combination of local and global physics: locally, the in-plane Hall currents are reduced, while globally guide field compression produces an increased pressure both within and downstream of the reconnection region.

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Magnetic reconnection [1,2] is a fundamental plasma physics process in which magnetic field lines of opposite direction merge, changing the magnetic topology of the plasma. Guide field, the component of magnetic field which is perpendicular to the reconnection plane (see Fig. 1), plays an important role in the dynamics of reconnection. Most instances of reconnection in nature [3–5] and the laboratory [6–10] contain a significant guide field (B_g) in comparison with the reconnecting field strength ($B_{\rm rec}$), prompting the study of this type of reconnection both theoretically and numerically [11–19]. In magnetosphere reconnection [3,4], for example, guide fields often reach the level of the reconnecting field ($B_g \sim B_{\rm rec}$), while reconnection in fusion experiments (such as during tokamak [20] or reversed-field pinch [21] sawteeth) can have guide fields exceeding $20B_{\rm rec}$.

In two-fluid reconnection, Hall effects allow the plasma to achieve fast reconnection and typically produce a characteristic quadrupole field [22], illustrated (without a guide field) in Fig. 1. To date there is no consensus model able to analytically quantify the reconnection rate dependence on guide field strength for a two-fluid plasma. However, simulations (e.g., [15–19]) routinely show that the two-fluid reconnection rate is reduced by the presence of the guide field. This reduction is physically attributed to a nonlinear interaction between the in-plane Hall currents (which produce the quadrupole field) and the applied guide field [12,19]. The electron flow is deflected, and the modified current patterns result in an additional $J \times B$ force which opposes the reconnection flow. In addition to reducing the reconnection rate, this interaction can produce a tilted current sheet [23,24], and reduce or destroy the quadrupole field [17].

In this Letter, we report on a systematic investigation into guide field effects on collisionless reconnection in a laboratory plasma. A toroidal guide field has been applied to reconnection plasmas in the Magnetic Reconnection Experiment (MRX) using a steady-state external toroidal field coil. With the application of guide field, we observe evidence of the expected interaction between Hall currents and guide field, and a reduction of the reconnection rate. The reconnection rate is reduced much more strongly than anticipated, and we attribute this change to magnetic pressure pileup caused by the compression of guide field.

In MRX, plasmas are formed by a combination of poloidal field (PF) coils and toroidal field (TF) coils embedded within two toroidally symmetric flux cores [7]. The PF coils are toroidally wound wires and produce the in-plane reconnecting field, as illustrated in Fig. 2, and by quickly reducing the PF coil current, reconnection is driven with radial inflow and axial outflow.

The TF coil is helically wound within each flux core and produces a time-varying toroidal field inside the flux core; this, in turn, produces a poloidal electric field outside the flux core which is used to break down the plasma. As a result of the MRX plasma formation process, there is always some residual toroidal magnetic field near the

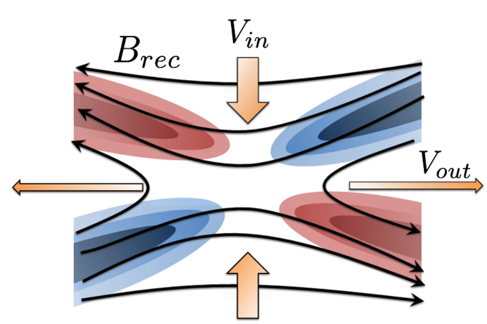

FIG. 1 (color online). A typical reconnection geometry illustrating the reconnecting magnetic field ($B_{\rm rec}$), the flow pattern ($V_{\rm in}$ and $V_{\rm out}$), and the out-of-plane quadrupole field (shaded region). The coloring indicates that for zero guide field plasmas, the quadrupole field is directed into (blue; first and third quadrants) or out of (red; second and fourth quadrants) the reconnection plane. The guide field and reconnection electric field are also directed perpendicular to the plane [2,26,27].

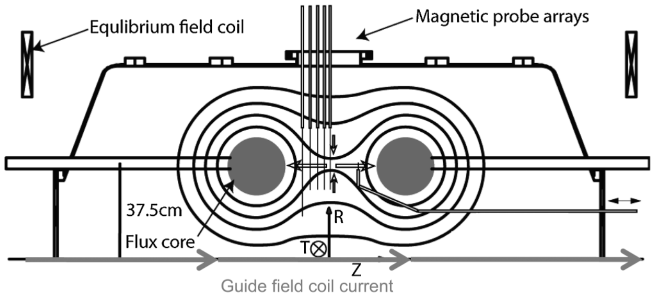

FIG. 2. A schematic of MRX. The picture shown is a cross section of the cylindrically symmetric vacuum vessel with magnetic field lines drawn. The guide field (toroidal) direction is out of the plane.

flux cores. We make use of a mode of operation known as "counterhelicity pull reconnection," in which the residual toroidal field components are oppositely directed, resulting in nearly anti-parallel reconnection. A guide field is independently applied to the plasma by a coil wrapped through the center column of MRX.

The magnetic field is measured using more than 300 magnetic pickup coils inserted into the plasma. By measuring the magnetic field globally, we directly measure the reconnection rate as $E_\phi = -\frac{1}{2\pi r}\frac{\partial \psi}{\partial t}$, where $\psi(r) = 2\pi \int_0^r B_z r' dr'$ is the poloidal flux. This measurement is based on an assumption of toroidal symmetry; although MRX plasmas are not perfectly symmetric, the plasma asymmetry does not result in a substantial error in our measurement. We use a Harris sheet fit [25] to identify the magnitude of the reconnecting field, $B_z \sim B_{\rm rec}\tanh(r/\delta)$. Electron density and temperature are measured at the center of the reconnection layer using a Langmuir probe.

Measurements indicate that the plasmas under consideration are in a two-fluid regime [1,2,26], with the current sheet half width ($\delta \sim 2$ cm) smaller than the ion skin depth ($d_i \sim 5$ cm) and of comparable scale to the ion sound gyroradius ($\rho_s \sim 2.5$ cm) [13]. A strong signature of two-fluid physics is the out-of-plane quadrupole field [27], which is readily identifiable in zero guide field plasmas. As the guide field is increased, the quadrupole field is modified, but still present even for $B_g \sim B_{\rm rec}$. Figure 3 shows contours of the measured out-of-plane field, B_g, for five MRX discharges with different values of applied guide field. In this regime, the ion flow is small ($V_i \ll V_e$), so the contours of the toroidal field in Fig. 3 are a good approximation to streamlines of the in-plane current, and equivalently the electron flow. It is clear from these patterns that the guide field is capable of strongly changing the electron flow dynamics, a result which has been previously studied by simulations [28,29]. The resulting patterns are similar to those of two-fluid simulations [30] and space observations [5], and we interpret this qualitative similarity as physical evidence supporting the conclusion that nonlinear interactions between the Hall currents and an applied guide field result in a modified quadrupole field structure. Simulations have shown [16–19] that this nonlinear interaction is consistent with a modestly reduced reconnection rate. Though there is not yet a consensus on the physical interpretation of this reduction, one interpretation is that a force is produced by $J_p \times B_g$, where J_p is the modified in-plane Hall current and B_g is the applied guide field, and that this force is partially directed against the reconnection flow and hence reduces the reconnection rate.

A further consequence of this nonlinear interaction is that the amplitude of the out-of-plane (modified) quadrupole field is reduced for stronger guide fields [16–19]. In Fig. 4, the measured toroidal field structure is decomposed into a radially varying, z-averaged guide field and a remaining "quadrupole" field component, which varies in the z direction. As the guide field is increased, it is clear that the quadrupole component of the field is reduced in amplitude. This reduction is physically associated with a reduction in the reconnection rate: with a lower reconnection rate, the electron flow is reduced, which is equivalent to a reduction in the Hall current and the associated quadrupole field.

This physical relationship can be expressed quantitatively in terms of the out-of-plane Ohm's law for steady-state two-fluid reconnection [26]. Slightly upstream or downstream of the x point, the Hall term dominates Ohm's law, such that

$$E_{\rm rec} \approx \left(\frac{J_r \times B_z}{ne}\right)_{\rm inflow} \approx \left(\frac{J_z \times B_r}{ne}\right)_{\rm outflow}, \qquad (1)$$

where J_r and B_z are measured 4 cm upstream of the x point (in the inflow region), while J_z and B_r are measured 8 cm

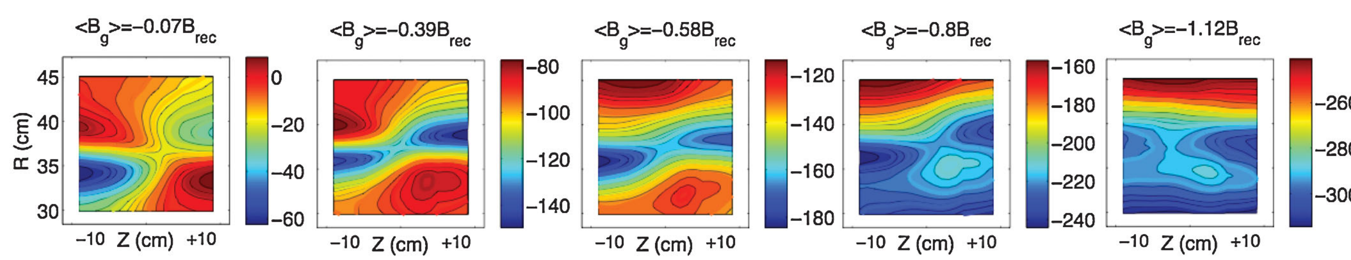

FIG. 3 (color). Contours of the toroidal field for guide fields spanning $B_g \sim 0$ (left) to $B_g \sim B_{\rm rec}$ (right). We have systematically measured the full quadrupole field over a range of applied guide fields in MRX.

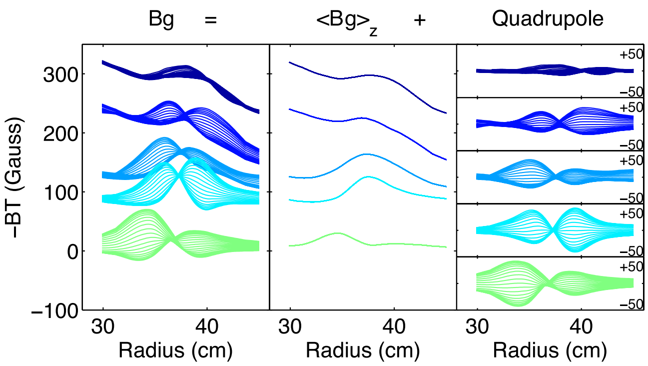

FIG. 4 (color online). Measurements of the Hall field during counterhelicity discharges with five different guide field settings. (These are the same discharges shown in Fig. 3.) In the first panel, each line represents the radial profile of B_g at one z position. The second panel shows the z-averaged guide field. The third panel shows the quadrupole component which is an antisymmetric structure superimposed on the z-averaged guide field; more precisely, the third panel shows $B_g - \langle B_g \rangle_z$, where $\langle\rangle_z$ represents an average over all z positions.

downstream of the x point (in the outflow region). In Fig. 5, we show experimentally that the addition of the guide field substantially reduces the reconnection rate, and we confirm that the relationship of Eq. (1) holds for a range of applied guide field strengths. We normalize the reconnection electric field to $B_{\rm rec}V_A$, where $B_{\rm rec}$ is the magnitude of the reconnecting field (z component), and $V_A = B_{\rm rec}/\sqrt{\mu_0 m_i n_i}$ is the Alfvén speed calculated using $B_{\rm rec}$. (This is a typical normalization because the Sweet-Parker reconnection rate [31,32] is given by $\frac{V_{\rm in}}{V_A} = \frac{E_{\rm rec}}{B_{\rm rec}V_A}$.)

The relationship between Hall currents and reconnection rate confirms that, locally, two-fluid physics is critically important to this reconnection, but this does not fully explain the observed reconnection rate reduction—the measured reduction is significantly stronger than that typically seen by simulations [16–19]. In these simulations, the reconnection rate is typically reduced by a factor of 2 for a guide field of $B_g = 5B_0$, while the experimental result shows the same factor of 2 reduction at a much smaller guide field, less than $B_g = B_0$. Next, we show that the reconnection rate in these MRX plasmas is strongly impacted by global effects associated with the dynamics of a compressible guide field, which explains this discrepancy.

Though we acknowledge that these plasmas are outside the resisitive-MHD regime, the well-known process of Sweet-Parker magnetic reconnection [31–34] can help to contextualize our discussion. In this model, the reconnection rate is determined in two parts,

$$\frac{V_{\rm in}}{V_A} = \frac{V_{\rm in}}{V_{\rm out}}\frac{V_{\rm out}}{V_A}. \tag{2}$$

The geometry of the layer, which controls $\frac{V_{\rm in}}{V_{\rm out}}$, is determined by the local physics of mass conservation and the out-of-plane Ohm's law, while the outflow speed, $\frac{V_{\rm out}}{V_A}$, is determined by the global physics of upstream versus downstream pressure balance. If magnetic tension terms are small [33,34], this condition is

$$\nabla\left(\frac{\rho V^2}{2} + \frac{B^2}{2\mu_0} + p\right) = 0, \tag{3}$$

where V is the ion flow speed, B is the total magnetic field, and p is the thermal pressure of the plasma. In two-fluid reconnection with MRX plasma parameters, we expect that the plasma obeys resistive MHD far from the reconnection layer, and Hall physics nearby. Therefore, it is reasonable to expect that the outflow speed is still controlled by global pressure balance, while two-fluid physics controls the reconnection locally.

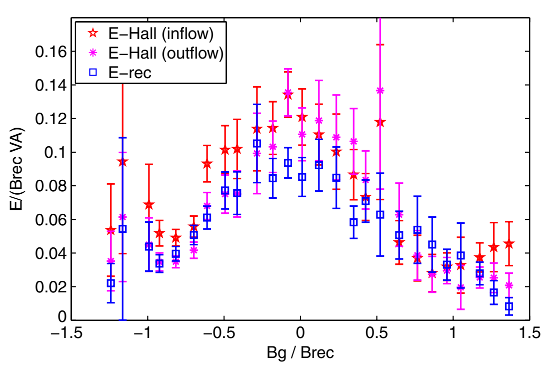

FIG. 5 (color online). Reconnection electric field ($E_{\rm rec}$) and the Hall electric field ($\frac{J\times B}{ne}$) versus normalized guide field, $B_g/B_{\rm rec}$. We plot separately measurements of $J_r \times B_z/ne$ measured 4 cm upstream of the x point (labeled "inflow") and $J_z \times B_r/ne$ measured 8 cm downstream of the x point (labeled "outflow"). Error bars denote the statistical variance over multiple shots. The density is measured in a single location near the center of the reconnection layer.

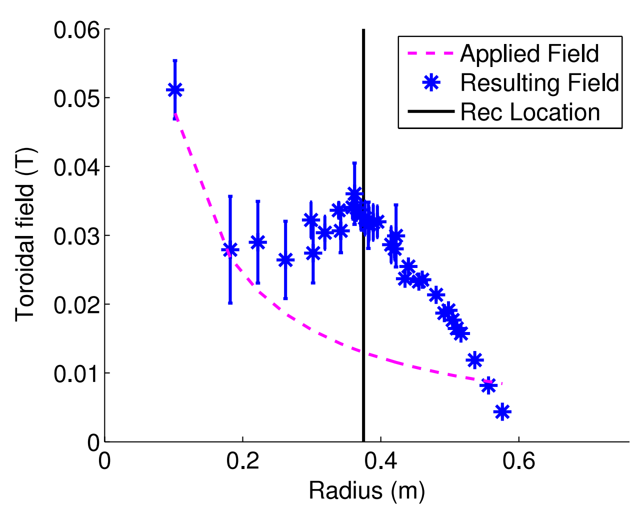

FIG. 6 (color online). Typical toroidal field profile measured at $z = 0$ and spanning over most of the MRX radius.

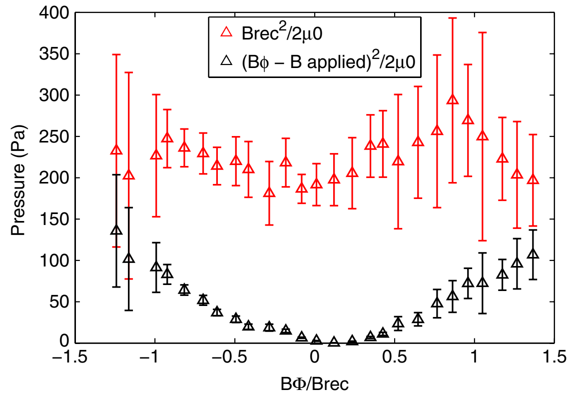

FIG. 7 (color online). Magnetic pressure due to the reconnecting field, $B_{\rm rec}$ (drives outflow) and pressure due to the pileup component of toroidal field at the x point (reduces outflow).

We observe in MRX that guide field dynamics strongly contributes to the reconnection pressure balance. The application of a toroidal guide field to MRX plasmas results in a notable enhancement of the applied field at the reconnection layer. A typical full-scale radial profile is illustrated in Fig. 6. At $z = 0$, the guide field is peaked at the radial location of the current sheet, and has a spatial structure with a characteristic scale that is large compared to the reconnection current sheet width and the quadrupole field. This enhancement can be understood as a large-scale advection and compression of the toroidal field by the reconnection flow. Because the MRX flux cores impede the reconnection outflow, the advected guide field is not ejected from the system and a pileup of toroidal field occurs. This pileup of compressed field produces a significant magnetic pressure which is strongest in the plasma outflow region and extends all the way back to the reconnection inflow region.

The applied toroidal field is constant in time and varies as $B_{\rm applied} \sim 1/r$. This vacuum field does not exert a force on the plasma (magnetic pressure and tension exactly cancel), indicating that the applied field does not play a role in global pressure balance. However, the compressed field, $B_\phi - B_{\rm applied}$, does contribute a net $J \times B$ force which can be approximated as the gradient of magnetic pressure. In Fig. 7, we compare the magnetic field pressure due to the reconnecting field, $B_{\rm rec}^2/2\mu_0$, as determined by the Harris fit, to the pressure due to guide field compression, $(B_\phi - B_{\rm applied})^2/2\mu_0$, measured at the reconnection x point. The relative magnitudes of the reconnection field pressure (which drives outflow) and the compressed toroidal field (which impedes outflow) show that this unexpected effect of guide field pileup is capable of strongly reducing the reconnection rate in high guide field plasmas.

The present data do not separate the reconnection rate reduction into a contribution due to guide field compression (global pressure effects) and a contribution directly attributed to a uniform guide field (local two-fluid effects). Simulations to date have focused on the role of a uniform guide field during reconnection, but our results show that pressure gradients associated with nonuniform guide fields must also be considered for the general case.

In summary, we have systematically applied an external guide field to antiparallel reconnection in MRX, and we observe that the addition of guide field strongly reduces the reconnection rate of these plasmas. We conclude that pressure due to guide field compression plays a critical role in setting global constraints on reconnection in MRX, but the scaling that $E_{\rm rec} \approx \frac{J \times B}{ne}$ and the qualitative similarity between quadrupole field structures in experiment and simulation suggest that two-fluid physics still controls the reconnection locally. These observations indicate that guide field can influence reconnection through both the local physics of two-fluid reconnection and the global physics of pressure balance.

[1] E. G. Zweibel and M. Yamada, Annu. Rev. Astron. Astrophys. **47**, 291, 2009.
[2] M. Yamada, R. Kulsrud, and H. Ji, Rev. Mod. Phys. **82**, 603, 2010.
[3] J. Berchem and C. Russell, J. Geophys. Res. **87**, 8139 (1982).
[4] M. Øieroset, T. D. Phan, M. Fujimoto, R. P. Lin, and R. P. Lepping, Nature (London) **412**, 414 (2001).
[5] J. P. Eastwood, M. A. Shay, T. D. Phan, and M. Øieroset, Phys. Rev. Lett. **104**, 205001 (2010).
[6] J. Egedal, W. Fox, N. Katz, M. Porkolab, K. Reim, and E. Zhang, Phys. Rev. Lett. **98**, 015003 (2007).
[7] M. Yamada, H. Ji, S. Hsu, T. Carter, R. Kulsrud, Y. Ono, and F. Perkins, Phys. Rev. Lett. **78**, 3117 (1997).
[8] Y. Ono, A. Morita, M. Katsurai, and M. Yamada, Phys. Fluids B **5**, 3691 (1993).
[9] M. Yamada, Y. Ono, A. Hayakawa, and M. Katsurai, Phys. Rev. Lett. **65**, 721 (1990).
[10] T. P. Intrator, X. Sun, G. Lapenta, L. Dorf, and I. Furno, Nature Phys. **5**, 521 (2009).
[11] R. G. Kleva, J. F. Drake, and F. L. Waelbroeck, Phys. Plasmas **2**, 23 (1995).
[12] H. Karimabadi, D. Krauss-Varban, N. Omidi, and H. X. Vu, J. Geophys. Res. **104**, 12313(1999).
[13] B. Rogers, R. Denton, J. Drake, and M. Shay, Phys. Rev. Lett. **87**, 195004 (2001).
[14] Cassak and J. F. Drake, Phys. Plasmas **14**, 054502 (2007).
[15] X. Wang, A. Bhattacharjee, and Z. W. Ma, J. Geophys. Res. **105**, 27633 (2000).
[16] P. L. Pritchett and F. V. Coroniti, J. Geophys. Res. **109**, A01220 (2004).
[17] P. Ricci, J. U. Brackbill, W. Daughton, and G. Lapenta, Phys. Plasmas **11**, 4102 (2004).
[18] M. Swisdak, J. F. Drake, M. A. Shay, and J. G. McIlhargey, J. Geophys. Res., **110**, A05210 (2005).
[19] J. D. Huba, Phys. Plasmas **12**, 012322 (2005).
[20] A. Edwards *et al.*, Phys. Rev. Lett. **57**, 210 (1986).
[21] T. D. Tharp, A. F. Almagri, M. C. Miller, V. V. Mirnov, S. C. Prager, J. S. Sarff, and C. C. Kim, Phys. Plasmas **17**, 120701 (2010).

[22] J. Birn, J. F. Drake, M. A. Shay, B. N. Rogers, R. E. Denton, M. Hesse, M. Kuznetsov, Z. W. Ma, A. Bhattacharjee, A. Ottos, and P. L. Pritchett, J. Geophys. Res. **106**, 3715, 2001.
[23] Yagi and Kawashima, Jpn. J. Appl. Phys. **24**, L259 (1985).
[24] A. G. Frank, S. Yu. Bogdanova, G. V. Dreiden, V. S. Markov, and G. V. Ostrovskaya, Phys. Lett. A **348**, 318 (2006).
[25] E. Harris, Nuovo Cimento **23**, 115 (1962).
[26] M. Yamada, Y. Ren, H. Ji, J. Breslau, S. Gerhardt, R. Kulsrud, and Al. Kuritsyn, Phys. Plasmas **13**, 052119 (2006).
[27] Y. Ren, M. Yamada, H. Ji, S. Dorfman, S. P. Gerhardt, and R. Kulsrud, Phys. Plasmas **15**, 082113 (2008).
[28] M. Goldman, G. Lapenta, D. Newman, S. Markidis, and H. Che, Phys. Rev. Lett. **107**, 13 (2011).
[29] C. Huang, Q. Lu, and S. Wang, Phys. Plasmas **17**, 072306 (2010).
[30] A. Bhattacharjee and Y. Huang (Private communication).
[31] P. Sweet, Symp. Int. Astron. Union **6**, 149 (1958).
[32] E. N. Parker, J. Geophys. Res. **62**, 509 (1957).
[33] H. Ji, M. Yamada, S. Hsu, and R. Kulsrud, Phys. Rev. Lett. **80**, 3256 (1998).
[34] H. Ji, M. Yamada, S. Hsu, R. Kulsrud, T. Carter, and S. Zaharia, Phys. Plasmas **6**, 1743 (1999).