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Study of magnetic reconnection in collisional and collionless plasmas in Magnetic Reconnection Experiment (MRX)

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1. Introduction

Magnetic reconnection (Parker, 1957; Sweet, 1958; Petschek, 1964; Yamada *et al.*, 2010; Biskamp, 2000; Tsuneta, 1996; Kivelson and Russell, 1995; Yamada, 2007; Birn *et al.*, 2001; Drake *et al.*, 2003) is considered important to many astrophysical phenomena including stellar flares, magnetospheric disruptions of magnetars, and dynamics of galactic lobes. Research on magnetic reconnection started with observations in solar coronae and in the Earths magnetosphere, and a classical theory was developed based on MHD. Recent progress has been made by understanding the two-fluid physics of reconnection, through space and astrophysical observations (Tsuneta, 1996; Kivelson and Russell, 1995), laboratory experiments (Yamada, 2007), and theory and numerical simulations (Birn *et al.*, 2001; Daughton *et al.*, 2006; Uzdensky and Kulsrud, 2006). Laboratory experiments dedicated to the study of the fundamental reconnection physics have tested the physics mechanisms and their required conditions, and have provided a much-needed bridge between observations and theory. For example, the Magnetic Reconnection Experiment (MRX) experiment (http://mrx.pppl.gov) has rigorously cross-checked the leading theories though quantitative comparisons of the numerical simulations and space astrophysical observations (Mozer *et al.*, 2002). Extensive data have been accumulated in a wide plasma parameter regime with Lundquist numbers of $S = 100 - 3000$, where S is a ratio of the magnetic diffusion time to the Alfven transit time.

In this article, we briefly review the recent major results on reconnection in MRX. The characteristics of the local reconnection layer have been studied both in the collisional (MHD) and collisionless (kinetic) regimes. An important scaling law has been obtained with respect to the ratio of the collisional mean free path to the size of reconnection layer. In the current MRX research, a special focus is put on magnetic energy dissipation due to reconnection, which has not been resolved in the past decades of research. Also we aim to address the important relationships between the local physics of the reconnection layer and the evolution of the global topology changes. One of our key questions is how large-scale systems generate local reconnection structures in realistic 3-D geometries, through formation of multiple current sheets or magnetic islands. For this purposes, we plan to upgrade our MRX facility substantially by extending our cross-discipline investigation of magnetic reconnection among theory, numerical simulation, laboratory experiments, and space and astrophysical observations.

2. Profiles of reconnection layer and reconnection rate

One of the most important questions has been why reconnection occurs so rapidly or impulsively with much faster speed than predicted by classical MHD theory. In recent numerical theory (Birn *et al.*, 2001; Daughton *et al.*, 2006) and experiments (Yamada, 2007; Mozer *et al.*, 2002; Ren *et al.*, 2005; Yamada *et al.*, 2006; Brown *et al.*, 2006; Ji *et al.*, 1998; Ji *et al.*, 2004) two-fluid effects have been utilized to explain the fast reconnection rate in the magnetosphere, laboratory plasmas, and even in stellar flares. The data from MRX show striking similarity to the magnetospheric measurements, in which both two-fluid Hall effects and magnetic fluctuations are detected together (Yamada *et al.*, 2010; Mozer *et al.*, 2002).

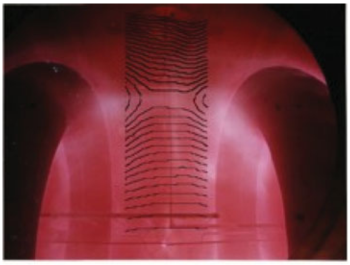

Figure 1. Reconnection layer in MRX with measured flux plots and time integrated photo.

The MRX device shown in Fig. 1, has been continuously generating fundamental data on the physics of magnetic reconnection (Yamada *et al.*, 1997). The MRX plasma can be described globally by MHD, but the reconnection region has to be treated by two-fluid MHD model, since the width of reconnection layer becomes comparable to the ion skin depth.

In MRX, reconnection is driven in a controlled manner with toroidal shaped flux cores which contain two types of coil windings both in the toroidal and poloidal directions. By pulsing programmed currents in those coils, two annular plasmas are created by inductive formation around each flux core utilizing induced poloidal electric fields. After the plasmas are generated, the coil currents are programmed to drive magnetic reconnection producing a current layer or a reconnection region in the central region of Fig. 1 to study the dynamics of local reconnection. The evolution of the magnetic field lines can be seen by way of movies presented at the MRX Web site (http://mrx.pppl.gov/mrxmovies): this shows time evolutions of the measured flux contours of the reconnecting field. By monitoring the flux contours, the reconnection rate was measured as function of plasma parameters (Yamada, 2007; Ji *et al.*, 1998).

The detailed profile of the current sheet was measured, demonstrating important two-fluid MHD features of magnetic reconnection. It was found that the thickness of the current sheet without a guide field was equal to a fraction of the ion skin depth (Ji *et al.*, 2004; Ji *et al.*, 2008) in the collissionless regime. In the collisional regime, a classical Sweet-Parker theory was verified based on the Spitzer resistivity. In the less collisional regime, a generalized Sweet-Parker model (Parker, 1957; Ji *et al.*, 1998) explained the data with an enhancement of the resistivity over the classical value. The effects of plasma turbulence have been investigated. The cause of the enhanced reconnection rates in the collisionless regime has been studied intensively and significant breakthroughs have been recently made by an identification of a correlation of the enhanced resistivity with magnetic fluctuation level (Ji *et al.*, 2004), as well as by an experimental verification of the Hall MHD effects (Yamada, 2007; Ren *et al.*, 2005). The effect of the third component (guide field) of the magnetic field vector on reconnection was assessed, and it was found that the presence of the guide field would often slow down the reconnection rate (Yamada, 2007).

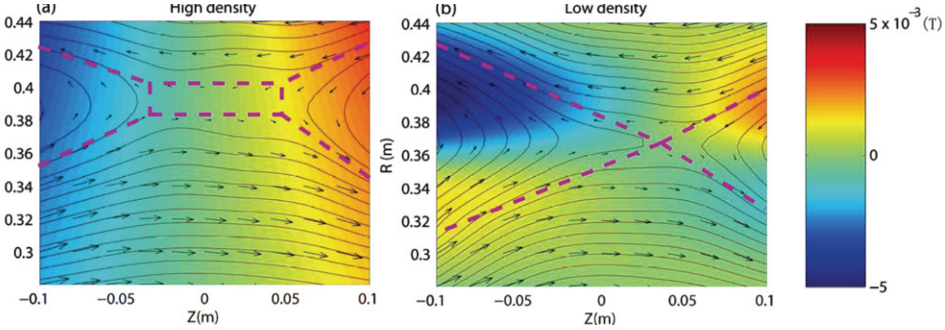

Figure 2. (left) Comparison of neutral sheet configuration described by measured magnetic field vectors and flux counters for high (collisional) and low density cases; (a) Collisional regime (λ_{mfp} ~1mm $\ll \delta$); (b) Nearly collisionless regime (λ_{mfp} ~1cm $\sim \delta$). Out-of plane fields are depicted by the color codes ranged -50 G $< B_t <$50 G.

3. Changes of the reconnection rate and neutral sheet profiles with respect to collisionality

In the study of the local two-fluid physics of the reconnection layer, an out-of-plane quadrupolar Hall field which was predicted by the recent two-fluid simulations has been verified in MRX (Yamada, 2007; Yamada *et al.*, 2006). The measured profile of the neutral sheet changes drastically from high (collisional) to low density (nearly collsionless) cases. In the high plasma density case, shown in Fig. 2(a), where the mean free path is much shorter than the sheet thickness, a rectangular shape neutral sheet profile of the Sweet-Parker model is seen together with the observed classical reconnection rate. There is no recognizable out-of-plane Hall field in this case. In the case of low plasma density, shown in Fig. 2(b), where the electron mean free path is larger than the sheet thickness, the Hall effects become dominant as indicated by the out-of-plane field depicted by the color code. A double-wedge shape sheet profile of Petschek type, which is shown in the flux contours of reconnecting field in Fig. 2(b), is significantly different from that of the Sweet-Parker model [Fig. 2(a)], and a fast reconnection rate is measured. However, a slow shock, a signature of Petschek model, has not been identified even in this collisionless regime to date. This important observation supports the theoretical idea that the Hall effects originating from two-fluid dynamics contribute to the enhanced reconnection rate observed in collisionless reconnection.

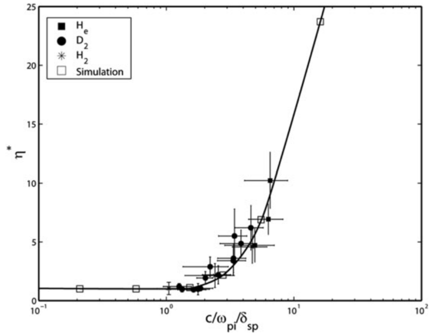

Figure 3. MRX scaling, Effective resistivity $\eta_{eff} = E/j$ normalized by the Spitzer value $\eta_{Spitzer}$ versus the ratio of the ion skin depth to the Sweet-Parker width is compared with numerical calculation of the contributions of Hall MHD effects to the reconnection electric field. The simulations were based on a 2-D 2-fluid code.

It is important to know quantitatively under what conditions the two-fluid dynamics become important. The recent MRX data identified a criterion for the transition from the one-fluid MHD regime to the two-fluid Hall regime. Figure 3 presents an MRX scaling for effective resistivity $\eta^* = \eta_{eff}/\eta_{Spizer}$, ($\eta_{eff} = E/j$) normalized by the Spitzer value $\eta_{Spitzer}$ in the center of the reconnection region in comparison with a scaling from a Hall

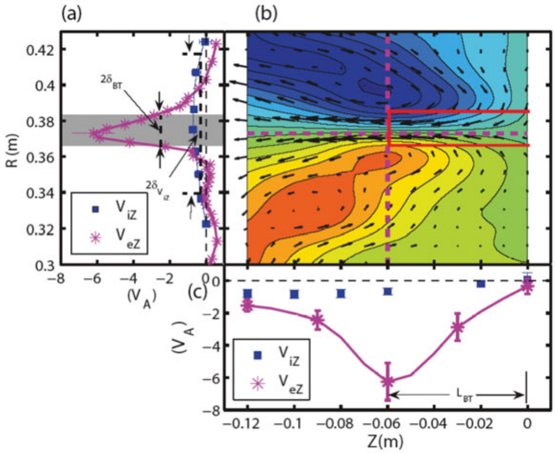

Figure 4. (a)The radial profiles of the electron outflow velocity, V_{eZ} (magenta asterisks), measured in ma Helium plasma. (b) The 2D profile of the out-of-plane field, B_T (color-coded contours), and the in-plane electron flow velocity, V_e (black arrows). (c) V_{eZ} as functions of Z. (a) and (b) represent the cuts at $Z = -6$cm and at $R = 37.5$cm, respectively, in (c). Taken from Ren *et al.* 2008.

MHD numerical simulation result. The classical rate of reconnection with the Spitzer resistivity is obtained (Yamada, 2007) in the collisional regime where $c/\omega_{pi} < \delta SP$. The horizontal axis represents the ratio of the ion skin depth to the classical Sweet-Parker width. This figure shows that the reconnection resistivity (or reconnection speed) increases rapidly from the Spitzer value as the ion skin depth (c/ω_{pi}) becomes large with respect to the Sweet-Parker width (δ_{SP}). The apparent agreement of the MRX scaling with two-fluid Hall MHD code indicates that the measured enhanced resistivity is primarily due to the laminar Hall effect, when the Spitzer resistivity is not large enough to balance the large reconnecting electric field in fast magnetic reconnection. We believe that this scaling observation should not exclude the effects of fluctuations particularly electromagnetic ones. Electrostatic and electromagnetic fluctuations have been observed in the neutral sheets of both laboratory and space plasmas, with notable similarities in their characteristics and theoretical interpretation. In MRX, a correlation was found between the reconnection rate and the amplitude of EM waves (Ji *et al.*, 2004), although the experimental operation range (a factor of 10) is rather narrow as shown in Fig. 3.

4. Identification of the electron diffusion layer

Utilizing high resolution magnetic probes, profiles of electron flow with finer scales were measured. In the neutral sheet of MRX, an electron diffusion region was identified in the reconnection layer for the first time in a laboratory plasma (Ren *et al.* 2008). The rate of reconnection can be controlled in part by dynamics in this small region, in which magnetic field lines tear and reconnect and energy dissipation occurs. The recent 2D numerical simulations by Daughton *et al.* (2006) and by Shay *et al.* (2007) predict a two-scale diffusion layer in which an electron diffusion layer resides in side of the larger ion diffusion layer of width the ion skin depth.

In MRX, the presence of an electron diffusion region was verified and it was found that de-magnetized electrons are accelerated in the outflow direction (Fig. 4). The width of the electron diffusion region was measured to scale with the electron skin depth (c/ω_{pe})

and the electron out-flow scales with the electron Alfvén velocity (0.11VA). The general features of both the electron and ion flow structures agree with simulations. But the thickness of the electron diffusion layer is much larger (5 times) than the values obtained by 2D simulations (Ji *et al.*, 2008). Careful checks of collisional effects have been made to determine how much of the enhanced diffusion layer thickness in MRX should be attributed to 3D effects and how much to collisions (Roytershteyn *et al.*, 2010).

Although the electron outflow seems to slow down by dissipation in the electron diffusion region, the total electron out flow flux remains independent of the width of the electron diffusion region. We note that even with the presence of the thin electron diffusion region, the reconnection rate is still primarily determined by the Hall electric field, as was concluded by the multi-code GEM project (Birn *et al.*, 2001). The ion outflow channel is shown to be much broader than the electron channel, which is also consistent with numerical simulations. Also this electron outflow often occurs impulsively as the collisionality of the plasma is reduced.

5. Outstanding issues on reconnection and future research plans in MRX

Our research plans cover major issues for both local reconnection physics and global reconnection dynamics and also address the interrelationship between the two regions as well. Regarding the local reconnection dynamics, the two fluid and kinetic physics are under intensive investigation in the reconnection research community: the effects of waves and turbulence, mechanisms of energy dissipation, and the dependence on the Lundquist number and system size. The latter covers multiple reconnections, impulsive reconnection and the effects of boundaries which includes line tying effects. These issues are often interrelated. For example, global reconnection often occurs impulsively which can be directly translated to a fast local reconnection. While line-tying effects have been studied based on MHD theory, new experiments are initiated to address this issue and to bridge between the space astrophysical observations and theoretical studies. At the moment, there is no consensus on one of the most important question, how magnetic energy is converted to particle energy during reconnection. We will explore the relationships between anomalous particle acceleration and heating and reconnection events in both laboratory and astrophysical plasmas. By comparing simulations and experimental data we hope to develop a theoretical model for particle acceleration and heating and apply it to explain solar/stellar flare energetic particle populations.

To extend the scope of our study, an upgrade of MRX has been considered. The main features are as follows; (1) To extend significantly the parameter range from fully collisional regime of ($\lambda_{mfp} \ll L$) to collisionless regime ($\lambda_{mfp} \gg L$). It is very important to obtain high T_e (> 30 eV) and large S ($S \sim 10^5$) for attaining fully collisionless regime ($\delta_{mfp} \gg L$), and for measuring temperature change. We plan to achieve effectively larger plasmas where the system size $\sim 10^3$ ion sound radii at high density ($> 10^{13}$ cm^{-3}). With new high-power flux cores, we plan to increase magnetic field by factor of 3 (to 1 kG) and increase T_e by at least 3 to 50 eV.

(2) We have been primarily using the steady pull mode of the local MRX reconnection operation. This mode has been very successful in simulating magnetosphere reconnection. In MRX-U we plan to move further by employing broader operation modes to address the above key issues including modes relevant to solar flare geometries, such as interaction of large plasma arcs or flares. For this we will use a merging plasma mode as well as line-tying solar flare plasma experiments. We will also address spontaneous reconnection in a large medium with new modes of operation.

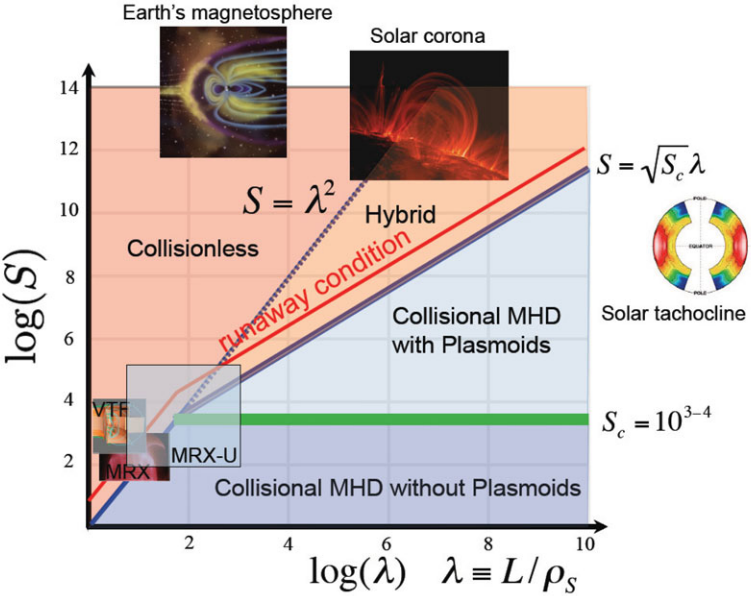

Figure 5. A phase diagram for magnetic reconnection in 2D. If either S or the normalized size, λ, is small, reconnection takes place in collisional MHD (without plasmoids) regime or in collisionless regime. When both S and λ are sufficiently large, two new regimes appear: a regime for collisional MHD with plasmoids and a regime for collisional MHD plasmoids with kinetic current sheets in between. The regimes for reconnection in Earths magnetosphere, solar corona, and solar tachocline are also shown. The existing experiments, such as MRX and VTF, do not have accesses to these new regimes. A new generation experiment, MRX-U based on MRX, is proposed to study reconnection in these new important regimes for direct relevance to reconnection in heliophysical plasmas.

(3) We plan to improve our diagnostics significantly so that we can address the above goals. Main additions are a Thomson scattering system, routine line density measurements by CO_2 laser, better spectroscopy extending into UV regions, and LIF (laser induced fluorescence) diagnostics for T_i measurement.

A new phase diagram) (Daughton and Roytershteyn, 2010; Ji and Daughton, 2011), was considered from recent large-scale numerical simulations as shown in Fig. 5 where four reconnection phases are illustrated: collisional MHD without plasmoids, collisional MHD with plasmoids (corresponding to reconnection in solar tachocline), collisional MHD plasmoids with kinetic current sheets in between (or hybrid, corresponding to solar corona) and collisionless (corresponding to Earths magnetosphere). In order to be directly relevant to reconnection phenomena observed in heliophysical plasmas, it is crucial for laboratory experiments to access all of these reconnection regimes. We note that reconnection in these new regimes is associated with multiple X-points, and thus can possibly provide solutions to the onset problem and the energy problem mentioned above.

In order to understand how magnetic energy is converted to particle energy we will explore the relationships between anomalous particle acceleration and heating and reconnection events in both laboratory and astrophysical plasmas. On the theoretical side, we will gain a new tool for probing how fluctuations are excited, and how they dissipate, through Particle-In-Cell (PIC) and hybrid (fluid electrons and kinetic ions) simulations of the reconnection layer. By comparing simulations and experimental data, we hope to develop a predictive theory of these fluctuations which can be applied to space and astrophysical plasmas and ultimately tested against models of solar/stellar flare energetic particle populations based on their x-ray, radio, and gamma ray emissions. In MHD reconnection theory, fluctuations are generally thought to enhance the resistivity in a position dependent manner; the same may happen in collisionless reconnection, but there may be other processes we have not yet identified.

It is very important to understand how large-scale systems generate local reconnection structures, through the formation of current sheets, either arising spontaneously or forced by boundary conditions. The experimental observation that multiple reconnections qualitatively alter self-organization has opened a new area of study. In upgraded MRX, we will study spontaneous triggering mechanisms for global reconnection phenomena, and magnetic self-organization. Reconnection can occur as a helical tearing instability. Multiple instabilities can also occur, which then interact by nonlinear coupling. With multiple reconnections, global momentum transport, ion heating, and magnetic self-organization should occur. Monitoring evolution of the plasma parameters, we will examine the effect of multiple reconnections on momentum transport in disks, flux conversion in jets and lobes (discussed below) and solar flares. A remarkably general feature of global reconnection phenomena is its impulsive nature. In the RFP, tokamak, magnetospheric substorms (Yamada *et al.*, 2010), and solar flares reconnection occurs suddenly in time. In most of these systems, theoretical ideas are evolving to explain the impulsive behavior, but none of the situations yet enjoys an established explanation. These questions will be addressed as a common issue of global reconnection phenomena.

References

Birn, J., Drake, J. F., Shay, M. A., Rogers, B. N., Denton, R. E., Hesse, M., Kuznetsova, M., Ma, Z. W., Bhattachargee, A., Otto, A., & Pritchett, P. L., *J. Geophys. Res.*, 106(A3): 3715, 2001.

Biskamp, D., Cambridge University Press, Cambridge, 2000.

Brown, M. R., Cothran, C. D., & Fung, J., *Phys. Plasmas*, 13(5):056503, 2006.

Daughton, W. & Roytershteyn, V., 2010, submitted to Proceedings of ISSI meeting (2010).

Daughton, W., Scudder, J., & Karimabadi, H., *Phys. Plasmas*, 13:072101, 2006.

Drake, J. F., Swisdak, M., Cattell, C., Shay, M. A., Rogers, B. N., & Zeiler, A., *Science*, 299: 873, 2003.

Ji, H. & Daughton, W., 2011, to be submitted to Phys. Plasmas.

Ji, H., Yamada, M., Hsu, S., & Kulsrud, R., *Phys. Rev. Lett.*, 80:3256, 1998.

Ji, H., Terry, S., Yamada, M., Kulsrud, R., Kuritsyn, A., & Ren, Y., *Phys. Rev. Lett.*, 92:115001, 2004.

Ji, H., Ren, Y., Yamada, M., Dorfman, S., Daughton, W., & Gerhardt, S. P., *Geophys. Res. Lett.*, 35:L13106, 2008.

Kivelson, M. & Russell, C. T., Cambridge University Press, London, UK, 1995.

Mozer, F. S., Bale, S. D., & Phan, T. D., *Phys. Rev. Lett.*, 89:015002, 2002.

Parker, E. N., *J. Geophys. Res.*, 62:509, 1957.

Petschek, H. E., *NASA Spec. Pub.*, 50:425, 1964.

Ren, Y., Yamada, M., Gerhardt, S., Ji, H., Kulsrud, R., & Kuritsyn, A., *Phys. Rev. Lett.*, 95 (5):055003, 2005.

Ren, Y., Yamada, M., Ji, H., Gerhardt, S., & Kulsrud, R., *Phys. Rev. Lett.*, 101:085003, 2008.

Roytershteyn, V., Daughton, W., Dorfman, S., Ren, Y., Ji, H., Yamada, M., Karimabadi, H., Yin, L., Albright, B. J., & Bowers, K. J., *Phys. Plasmas*, 17:055706, 2010.

Shay, M. A., Drake, J. F., & Swisdak, M., *Phys. Rev. Lett.*, 99(15):155002, 2007.

Sweet, P. A., In B. Lehnert, editor, *Electromagnetic Phenomena in Cosmical Physics*, page 123. Cambridge Univ. Press, New York, 1958.

Tsuneta, S., *Astrophys. J.*, 456:840, 1996.

Uzdensky, D. & Kulsrud, R., *Phys. Plasmas*, 13:062305, 2006.

Yamada, M., *Phys. Plasmas*, 14:058102, 2007.

Yamada, M., Ji, H., Hsu, S., Carter, T., Kulsrud, R., Bretz, N., Jobes, F., Ono, Y., & Perkins, F., *Phys. Plasmas*, 4:1936, 1997.

Yamada, M., Ren, Y., Ji, H., Breslau J., Gerhardt, S., Kulsrud R., & Kuritsyn, A., *Phys. Plasmas*, 13:052119, 2006.

Yamada, M., Kulsrud, R., & Ji, H., *Rev. Mod. Phys.*, 82:603, 2010.