Study of Magnetic Reconnection in Collisional (MHD) and Collionless (Kinetic) Plasmas by Upgrading Magnetic Reconnection Experiment (MRX) Device

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Summary of Proposed Activity

As described by the recent NRC report, PlasmaScience2010 [1], a series of Science White Papers [2-10], and a Position Paper [2] to Astro2010, magnetic reconnection is a key plasma physics process important to many astrophysical phenomena including stellar flares, magnetospheric disruptions of magnetars, and dynamics of galactic lobes. However, a number of important questions must be answered in order to provide much needed understanding for these phenomena. Research on magnetic reconnection [11-15], which started with observations in solar coronae and in the earth magnetosphere, was dominated by theory in the early phase. Recent progress in understanding the physics of magnetic reconnection has been made through coordination of results from all three fronts of research: space and astrophysical observations [16,17], laboratory experiments [18], and theory and numerical simulations [19-21]. Laboratory experiments dedicated to the study of the fundamental reconnection physics have tested the physics mechanisms and conditions and provided a much-needed bridge between observations and theory. The MRX group (http://mrx.pppl.gov) has played a major role in this progress by rigorously cross-checking the data though quantitative comparisons of simulations and space astrophysical observations [22]. 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.

Reconnection is influenced and determined both by local plasma dynamics in the reconnection region and global boundary conditions in the 3-D global topology. In the MRX plasmas, magnetic reconnection can be driven in a controlled manner by external forcing. The important characteristics of the local reconnection layer have been studied in a transition region between the collisional and collisionless 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. Proposed research in the next decade will significantly expand the parameter range covering both the collisional MHD regime and collisionless kinetic regime with Lundquist number reaching 10^5. A special focus will be put on magnetic energy dissipation due to reconnection, which has not been resolved in the past decades of research. It will also address the characteristics of magnetic global topology change and important relationships between the local physics of the reconnection layer and the evolution of the global plasma configuration. 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 these research goals, we plan to upgrade our MRX facility substantially to extend our intensive cross-discipline investigation of magnetic reconnection among theory, numerical simulation, laboratory experiments, and space and astrophysical observations.

1. Introduction

Magnetic reconnection, a topological rearrangement of magnetic field, reflects an interplay between magnetic field and plasma leading to conversion of magnetic energy to plasma kinetic and thermal energy. Magnetic reconnection plays a key role in wide range of phenomena in the universe, relaxation events of fusion plasmas, the dynamics of the Earth's magnetosphere, the evolution of solar and stellar flares, and the formation process of stars. In the past several years, there has been significant progress in understanding of the local key physics of magnetic reconnection layer, to which the MRX has made a major contribution by participating in key activities of collaborative efforts with recently advanced numerical simulations as well as with theory and satellite observation groups in astrophysics community. Recently reconnection research in laboratory plasmas has become a representative case for demonstrating the effectiveness of laboratory study for astrophysical processes. In this document we present our plans to expand this fruitful research facility.

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. Thanks to the recent progress in numerical theory [19, 20] and experiments [18, 23-28], two-fluid effects are considered to explain the fast reconnection rate in the magnetosphere, lab plasmas, and even in stellar flares. Recent data from dedicated laboratory experiments show striking similarity to the recent magnetospheric measurements, in which both two-fluid Hall effects and magnetic fluctuations are detected together. Although reconnection often involves change in global topology, analysis of global characteristics of magnetic reconnection has been less developed. This is partly because it is difficult to monitor the plasma parameters of an entire region including boundaries. In the MRX-U research we will address key issues in this area by investigating effects of global boundary conditions including the "line-tied" effects. Another important research goal is to identify the energy flow channel in which magnetic energy is converted to the plasma kinetic energy. A third area for the MRX-U research is to extend our scaling studies to much larger parameter ranges both in terms of Lundquist number and system size, both of which are crucial to apply the physics we learn from a small and low-Lundquist number system to astrophysical systems which are typically large.

2. The past achievements in MRX research

The MRX [Magnetic Reconnection Experiment] device shown in Fig.1, has been continuously generating a series of fundamental data on the physics of magnetic reconnection [27].

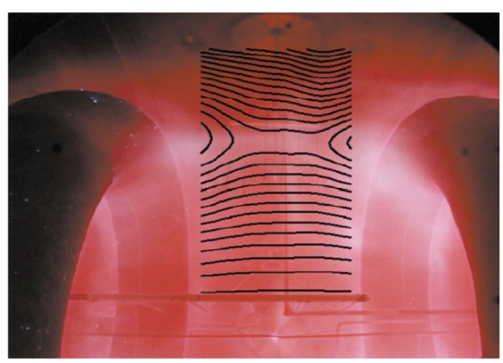

Fig.1 *Reconnection layer in MRX with measured flux contours superimposed on a time averaged photo.*

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 [27]. 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 created, the coil currents are programmed to drive magnetic reconnection generating a neutral sheet or a current layer to study the dynamics of local reconnection layer. 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) which shows time evolutions of the measured flux contours of the reconnecting field. By monitoring this contours, the reconnection rate can be measured as a function of plasma and compared with Sweet-Parker model [18, 26].

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 [18]. 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 [18,23] 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 [11,26] explained the data with an enhancement of the resistivity over the classical value. The effects of plasma turbulence have been investigated. For these earlier work, the 2002 APS Excellence in Plasma Physics Research Award was presented to MRX team. Since then the cause of the enhanced reconnection rates in the collision free regime has been studied intensively and significant breakthroughs have been recently made by the first identification of a correlation of the enhanced resistivity with magnetic fluctuation level [28], as well as by an experimental verification of the Hall MHD effects [18, 23].

During the period of 1997-2008, the MRX team published 9 Phys. Rev. Letts. articles, a dozen Phys. Plasma papers, and several other refereed papers in space astrophysical journals such as JGR and GRL and ApJ. Extending the successful collaboration of the MRX team with the space astrophysical community, Center of Magnetic Self-organization was launched by NSF in partnership with DOE who supports the MRX's Center-related collaborative activities through separate funding.

3. Demonstration of two-fluid effects in the MRX neutral sheet

Important findings and discoveries have been made in the past decade on the fundamental physics of magnetic reconnection. In the study of the local two-fluid physics of the reconnection layer, an out-of-plane quadruple Hall field which was predicted by the recent two-fluid simulations havs been verified in MRX [18,27], MST [29] and SSX [25]. In MRX, 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 MHD 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.

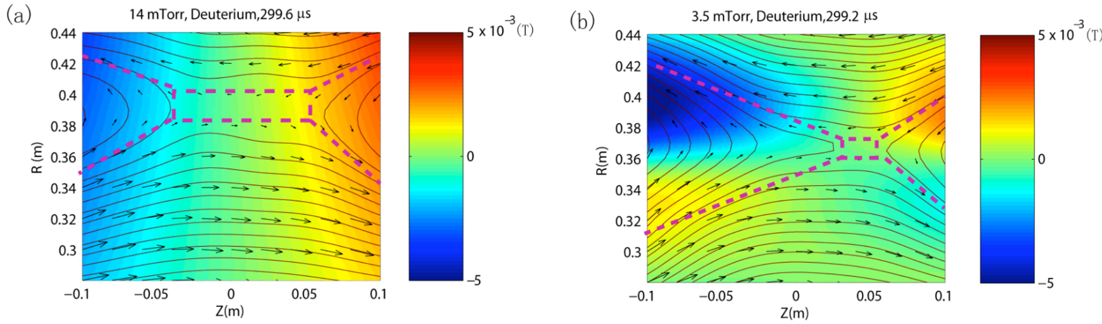

Fig.2*; Comparison of neutral sheet configuration described by measured magnetic field vectors and flux counters for high (collisional) and low density cases; (a) Collisional regime (λ_{mfp} ~1mm << δ)); (b) Nearly collisionless regime (λ_{mfp} ~1cm ~δ). Out-of plane fields are depicted by the color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

It is important to know quantitatively under what conditions the two-fluid dynamics become important. The recent MRX data identified a criteria for the transition from the one-fluid MHD to the two-fluid regime. Fig.3 presents an MRX scaling for effective *resistivity* $\eta^*=\eta_{eff}/\eta_{SP}$, ($\eta_{eff}=E/j$) normalized by the Spitzer value η_{SP} in the center of the reconnection region[28] in comparison with a scaling from a Hall MHD numerical simulation result. The classical rate of reconnection with the Spitzer resistivity is obtained [38] 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 (δ_i) 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 anomalous 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 (18).

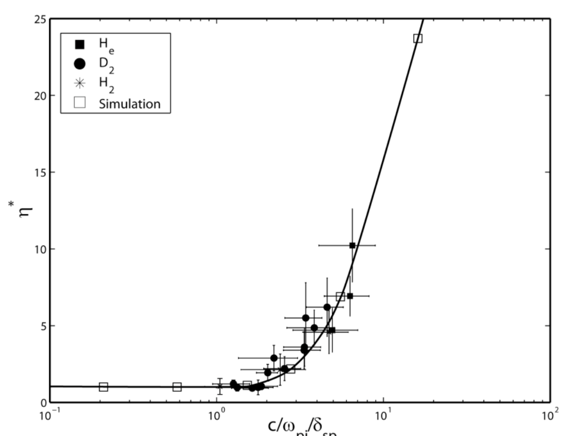

Fig.3*: MRX scaling, Effective resistivity η^* = (E/j) normalized by the Spitzer value η_{SP} versus the ratio of the ion skin depth to the Sweet Parker width is compared with numerical calculation of the contributions of Hall MHD effects to the reconnection electric field. The simulations were based on a 2-D 2-fluid code[28,39].*

We note that this scaling observation does not exclude fluctuations from playing a role in fast reconnection particularly when electromagnetic fluctuations are observed.

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. As is shown in the figure 3, the experimental operation range (a factor of 10) is rather narrow. In the upgraded MRX, we plan to increase the range by factor 10 in both directions of collisionality.

4. Future Research Priorities and Plans in MRX research

Our research plans cover major issues for both local reconnection physics and global reconnection dynamics and also address the interrelationship between the two categories. The former includes issues of two fluid physics which 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 include 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. In the previous research period, fast local reconnection rate observed in the MRX experiments as well as in magnetosphere were attributed to two-fluid effects. However, the mechanisms of energy conversion in the reconnection region has not been resolved. The effects of turbulence, particularly of magnetic fluctuations of wide frequency range will be extensively studied. Multiple reconnection which induces global magnetic self-organization was identified in a toroidal pinch plasma and its application to solar flare dynamics will be investigated. 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.

4.1. Study of local reconnection physics

Our proposed activities for research of local reconnection represents a significant advancement based on our past research. The first phase, which preceded both MRX and the recent satellite observations, was the development of theoretical models that demonstrated the importance of MHD formulations, usually in simple geometry with a focus on local layer dynamics. The second stage, in which MRX played an important role, was the experimental demonstration of non-MHD effects on the reconnection layer, including comparison with local theoretical models and space plasma observations. The third stage, which we propose, includes comparison of experimental data (yet unfolding) with more comprehensive, geometrically accurate computation in two-fluid or full particle 3-D codes (complemented by theory). To find out the true cause of fast reconnection, an important step is to clarify the interrelationships between laminar Hall dynamics and magnetic fluctuations at the neutral sheet.

Inventory of energy flow and the effects of fluctuations

At the moment, there is no consensus with regard to how the observed waves or magnetic turbulence are excited, how they affect the reconnection rate, and how they are dissipated. 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 with the quasi-linear theory developed during the present grant period 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 particlepopulations 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 subtler processes we do not yet understand.

Scaling study for reconnection rate with and without guide field

The scaling of the reconnection rate with the system size- or with a dimensionless parameter such as the ratio of ion skin depth to mean free path or to system size—is critical for understanding basic reconnection mechanisms, as well as for astrophysical applications. We plan to develop a reconnection scaling in collaboration with other reconnection experiments (such as MST [29], SSX [25] and VTF[30])with respect to collisionality, guide field strength and external forcing. Initial results were obtained in MRX for driven reconnection without a guide field (Figure 3). We will extend this scaling study to cover wide span of plasma parameters including cases of guide field reconnection and different boundary conditions.

4.2. Study of global issues for reconnection

Multiple reconnections

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.

Impulsive reconnection

A remarkably general feature of global reconnection phenomena is its impulsive nature. In the RFP, tokamak, magnetospheric substorms [18], 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. For magnetospheric and some laboratory plasmas, two-fluid effects have been considered to be important for impulsive reconnection, with electron inertia breaking field lines and electron pressure gradient playing a key role. For the RFP the key physics could lie within the MHD dynamics of coupled tearing modes, although non-MHD effects are also known to be present. A unified approach to laboratory and astrophysical impulsive reconnection would be productive. Is there similarity between the mechanisms? Are two-fluid effects critical for both? Is the mechanism for impulsive reconnection important, or is there a more general reason that magnetic energy is stored for a long period and then released impulsively, driving the plasma to a preferred state?

These questions will be answered by applying an array of nonlinear MHD and two-fluid computations to both experimental and astrophysical venues.

5. Scope of MRX-Upgrade

To address the key issues mentioned above, we plan to build MRX-U as a leading machine in the world with the following goals in mind.

(1) To extend significantly the parameter range from fully collisional regime of (λ_{mfp} <<L) to collisionless regime (λ_{mfp} >>L). It is very important to obtain high T_e (> 30 eV) and large S (> 10^5) for attaining fully collisionless regime (λ_{mfp}>>L), and for measuring temperature change. We plan to have 1 meter of mean free path with high density (> 10^{13} cm^{-3}), which is clearly larger than the device scale length. 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 30 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.

(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 CO2 laser, better spectroscopy extending into UV regions, and LIF (laser induced fluorescence) diagnostics for Ti measurement.

(4) We plan to further expand our collaborations to broader communities of astrophysics, inclusively to space and solar physics communities, to maximize the productivity and impacts, based on our existing collaborations through Center of Magnetic Self-Organizations in Astrophysical and Laboratory Plasmas (CMSO) (http://www.cmso.info).

6. Estimated budget for MRX hardware upgrade and operation

<u>6.1 Hardware costs: $5.5M (two-year period)</u>

1. A pair of new flux cores (plus one for spare) for high field operation: $1.0M: Fabrication cost includes charges for additional internal coil systems
2. A solenoid coil system for OH and TF with high quality vacuum integrity: $500k
3. Work for MRX-U vessel refurbishment and additional vacuum pumps: $1.0M
4. Addition of capacitor bank capabilities: (to increase coil currents by factor of 2): $1.0M

5. Local fabrication of power supply ($250k) and beam test stand ($250k) for a short pulse 1 MW NBI line (transferred from U. Wisconsin): $1.0M
6. Substantial upgrade of diagnostics with Thomson scattering: $1.0M

6.2. Operation costs: $2.0M per year

The estimate is about $2.0M annual funding to support research on MRX-U including operation of the facility and base diagnostics. We believe that this base funding is crucial for productive research involving multiply tied collaborations, for training post-doctoral fellows, and for graduate school education.

1. Research staff (1 senior + 1 junior research staff + 2 post-doc + students):$1.0M
2. Supporting staff (1 technician + 1 junior engineer): $400k
3. Other operational costs: $600k

References

[1] "Plasma Science: Advancing Knowledge in the National Interest." National Academic Press, Washington, 2007.

[2] H. Ji et al., "Roles, Current Status, Opportunities, Future Trends, and Funding Issues for Laboratory Plasma Astrophysics," submitted to Study Group on Facilities, Funding and Program.

[3] E. Zweibel et al., "Plasma Astrophysics Problems in Star and Planet Formation," submitted to Planetary Systems and Star Formation (PSF) Panel.

[4] D. Uzdensky et al., "Life Cycles of Magnetic Fields in Stellar Evolution," submitted to Stars and Stellar Evolution (SSE) Panel.

[5] D. Uzdensky et al., "Magnetic Fields in Stellar Astrophysics," submitted to Stars and Stellar Evolution (SSE) Panel.

[6] S. Spangler et al., "Plasma Physics Processes of the Interstellar Medium" submitted to Galactic Neighborhood (GAN) Panel.

[7] A. Lazarian et al., "Understanding of the role of magnetic fields: Galactic perspective," submitted to Galactic Neighborhood (GAN) Panel.

[8] H. Li et al., "The Need for Plasma Astrophysics in Understanding Life Cycles of Active Galaxies," submitted to Galaxies across Cosmic Time (GCT) and Cosmology and Fundamental Physics (CFP) Panels.

[9] B. Chandran et al., "Plasma Physics in Clusters of Galaxies," submitted to Galaxies across Cosmic Time (GCT) and Cosmology and Fundamental Physics (CFP) Panels.

[10] J. Arons, "Cosmic Accelerators," submitted to Stars and Stellar Evolution (SSE) and Galaxies across Cosmic Time (GCT) Panels.

[11] E.N. Parker, J. Geophys. Res. **62**, 509 (1957).

[12] P.A. Sweet,in *Electromagnetic Phenomena in Cosmical Physics*, edited by B. Lehnert (Cambridge Press, New York, 1958) p. 123.

[13] H.E. Petschek, NASA Spec. Pub. **SP-50**, 425 (1964).

[14] E. Priest, and T. Forbes "Magnetic Reconnection" Cambridge Univ. Press, UK, (2000)

[15] D. Biskamp, "Magnetic Reconnection in Plasmas," Cambridge Univ. Press, UK, (2000)

[16] S. Tsuneta, Astrophys. J. **456**, 840 (1996); Astrophys. J. **456**, L63-L65 (1996).

[17] G. Kivelson and C.T. Russell *Introduction to Space Physics,* (Cambridge University Press, London, 1995
[18] M. Yamada, Phys. Plasmas **14**, 058102 (2007)
[19] J. Birn, J.F. Drake et al., J. Geophys. Res. 106, 3715 (2001)
[20] D.J. Daughton, S.J. Scudder, and H. Karimabadi, Phys. Plasmas 13, 072101 (2006)
[21] D. Uzdensky and R. Kulsrud, Physics of Plasmas 13, 062305 (2006)
[22] F. Mozer et al., Phys. Rev. Lett 89, 15002-1 (2002)
[23] Y. Ren et al, Phys. Rev. Letts. v.95, 055003 (2005).
[24] M. Yamada et al, Physics of Plasmas v.13, 052119 (2006)
[25] M. Brown et al, Phys. Plasmas, v.13, 056503 (2006)
[26] H. Ji, M. Yamada, S. Hsu, and R. Kulsrud, , Phys. Rev. Lett. **80**, 3256 (1998).
[27] M. Yamada *et al*., Phys. Plasmas **4**, 1936 (1997).
[28] H. Ji, et al., Phys. Rev. Lett. **92**, 115001 (2004)
[29] W.X. Ding et al., Phys. Rev. Lett **99**, 0555004 (2007)
[30] J. Egedal et al, Phys. Plasmas, **8**, 1935 (2001)