White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	19 June 2015

Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	S
• Interactions of plasmas and waves	
• Plasma self-organization	P
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	X
Poster	
Either Oral or Poster	
Will not attend	

Title:	Magnetospheric Reconnection Explored in the Laboratory
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**(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format*.)**

- ***The importance of reconnection to the Earth's magnetosphere*.**

The Earth is embedded in the Sun's extended atmosphere, where the Earth's magnetic field acts as a shield against the incoming solar wind plasma. However, this shielding is not perfect, and, through the process of magnetic reconnection [1], solar particles can penetrate the magnetosphere, greatly influencing the conditions in space that affect the Earth and its technological systems (space weather).

Although reconnection occurs in microscopic diffusion regions, it often governs the macroscopic properties and behavior of the system. It controls the evolution of explosive events such as solar flares, coronal mass ejections and magnetic storms in the Earth's magnetotail. The latter drives the auroral phenomena [2–5]. In magnetic fusion devices magnetic reconnection is responsible for the periodically occurring internal relaxation events (e.g., sawtooth reconnection) which can degrade the plasma confinement [6, 7].

As a new frontier of research, recent theoretical and numerical studies show that in large systems (compared to either the ion skin-depth, d_i, for low guide-field reconnection and the ion sound Larmor-radius, $\rho_s = (m_i(T_e + T_i))^{1/2}/eB$, for strong guide fields) a transition occurs from "laminar reconnection" to "turbulent reconnection" involving multiple reconnection sites. As a valuable tool for displaying the

various regimes of reconnection, Daughton and Roytershteyn [8] developed the reconnection phase diagram spanned by the normalized system size $\lambda = L/\min(d_i, \rho_s)$ and the Lundquist number S (this diagram was also used by Ji and Daughton [9] for articulating the need for larger experiments on reconnection). As shown in Ref. [9], the transition from laminar to turbulent reconnection occurs when $\lambda \geq 50$ and is indicated by the vertical line marked $\lambda = \lambda_c$ in the diagram below.

Another emerging frontier in reconnection research is the study of kinetic effects in reconnection. So far the term "collisionless reconnection" has referred to systems where the electron and ion distributions can remain near Maxwellian but the collisionallity is sufficiently low that their collective fluid behaviors decouple at the ion scale such that Hall currents become important. However, in a truly collisionless plasma, pressure anisotropy develops which strongly impacts the properties of the reconnection process in ways not accounted for in traditional Hall reconnection. In fact, spacecraft observations [10] and 2D kinetic simulations (at the full ion to electron mass ratio m_i/m_e) [11] show that large scale electron jets/current layers are driven by electron pressure anisotropy that builds in the reconnection region due to kinetic electron trapping effects.

Compared to the Hall effects, the pressure anisotropy is much more sensitive to collisions as the time between electron collisions must be long compared to the full transit time of a fluid element through the reconnection layer. As shown by Le et al. [12], with the known inflow speed of reconnection, this constraint can be characterized as $S > 10(m_i/m_e)L/d_i$. The anisotropy is particularly important to the dynamics of reconnection for the low guide-field case (where $d_i < \rho_s$). The corresponding "anisotropic pressure region" of phase space is indicated in the figure below. Further research is needed to evaluate the role of pressure anisotropy in particle heating. In addition, the narrow current layers driven by the anisotropy may in 3D be unstable to reconnection at oblique angles, and thus be important to the self consistent evolution and generation of configurations with multiple X-lines.

Within these collisionless regimes, some of the key unresolved questions include:
1) **How does the reconnection rate scale with the asymmetric inflow condition?**
2) **Is the onset of reconnection suppressed in the limit of a strong guide magnetic field?**
3) **What is the role of electron pressure anisotropy, and how is it influenced by the reconnection guide magnetic field?** The scientific interest for these questions is rooted in reconnection observed in the solar wind. Furthermore, in the dayside magnetopause, the relatively dense plasmas from the solar wind reconnect with magnetospheric plasmas that have densities about two orders of magnitude less. Based on fluid models with isotropic electron and ion distributions, the Cassak-Shay model [13] provides an expression for the reconnection electric field of the asymmetric geometry. Also, as explored theoretically by Swisdak [14] and consistent with observations, diamagnetic flows driven by the asymmetry can suppress reconnection with a guide magnetic field. In addition, recent spacecraft observations document that electron pressure anisotropy develops in the reconnection region and kinetic simulations have confirmed that this anisotropy strongly influences the structure of the reconnection region.

The scientific focus on such kinetic aspects of reconnection is slated to intensify as NASA's MMS mission, launched in the Spring of 2015, completes its Phase I objective to measure the details of the electron dynamics during reconnection events in the Earth's magnetopause. During Phase II of the MMS mission, symmetric reconnection will be explored in the magnetotail, where again the objective is to understand the details of the electron dynamics.

- ***Requirements on new laboratory experiments and simulation tools***

Complementary to spacecraft observations, laboratory experiments have the advantage that the reconnection physics can be isolated and studied under controlled and repeatable plasma conditions. However, so far the high collision frequency between electrons and ions has prevented laboratory experiments to reach a regime where pressure anisotropy and non-Maxwellian distribution functions can develop unimpeded. Therefore, for experiments to remain relevant in this rapidly maturing field of research and help push forward the new frontiers, new devices are needed which access the regime of pressure anisotropy and large system size (large values of S and λ). Carefully designed experiments will be able to reach the regime where pressure anisotropy may develop unimpeded by collisions. This requires relatively hot (T_e ~20 eV) and moderately dense ($n \sim 10^{18}$ m^{-3}) plasma, in combination with the ability to drive reconnection hard with a loop-voltage reaching 5 kV. In addition, a large plasma volume (L ~ 3m) is required for the experiment to accurately capture dynamics relevant to magnetospheric phenomena.

Numerical simulations of reconnection relevant to the magnetosphere are currently pushing the boundaries of scientific computation. Fully kinetic 3D simulations are now feasible using petascale computers, however, the spatial domain size is typically quite limited to fairly small regions containing the reconnection layers. A key challenge is to understand how the ion and electron kinetic effects feed back onto the large-scale dynamics of the magnetopshere. For the present and next generation of supercomputers, the main approach will have to be to incorporate the knowledge garnered from fully kinetic simulation, experiments, and space observations into global simulations based on reduced models, such as MHD, multi-fluid, and kinetic/fluid hybrid codes. This will entail formulating improved fluid closures for the electrons and ions, and using hybrid codes that treat the ions kinetically. These new plasma simulation codes must be adapted to changing computer architectures and data management paradigms in order to make full use of future high-performance computing resources. This is crucial for advancing our ability to simulate reconnection, but also is needed to remain competitive with other disciplines, since the competition for computing time on the largest machines has become quite fierce and performance as well as science metrics are used to award the computing time.

- ***Summary***

Understanding the basic physics of magnetic reconnection is crucial for determining the coupling between the solar wind in the Earth's magnetosphere. Furthermore, the physics of reconnection and its connection with turbulence has widespread application throughout many applications in space and astrophysics. The magnetosphere represents one setting where these questions can be studied in systematic manner. In addition, the spatial regions of primary interest can now be simulated directly with laboratory experiments and 3D kinetic simulations. The ideas and understanding that are emerging from these studies can be directly tested with both current missions such as Cluster and THEMIS, and with even greater fidelity with the new MMS mission.

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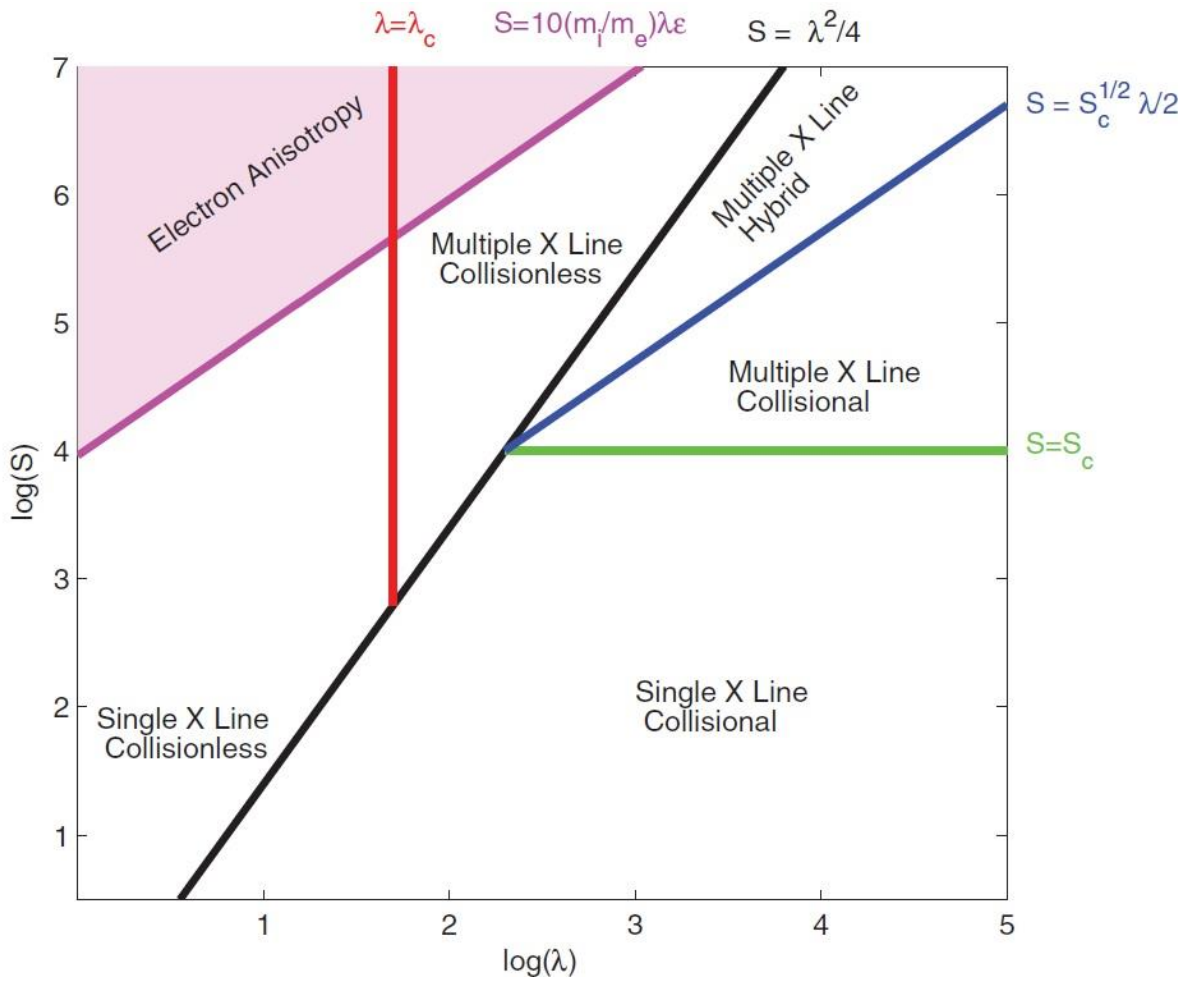
Figures



Phase diagram of reconnection as developed in Refs. [8, 9]. The area of electron pressure anisotropy was established in Ref. [12].