

“Magnetic Reconnection” Studies Conducted at Los Alamos National Laboratory

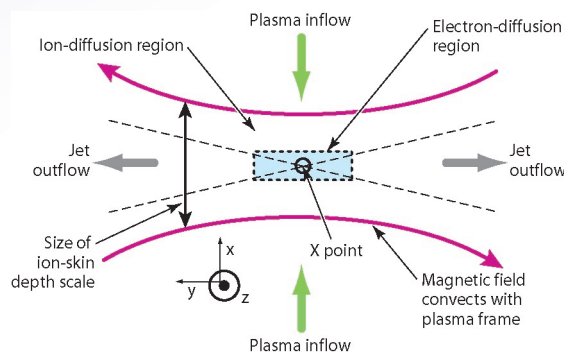
Most of the known universe (about 99%) is composed of plasma, which is an ionized gas. Although ions and electrons are not joined as atoms and molecules, each can flow in fluid patterns. This state not only contains eddies, flow fields, waves, and shocks but also electric and magnetic fields. Some of the most interesting questions regarding the structure and dynamics of our universe involve this coexistence of flows and fields. A structure that generates magnetic fields from conductive-fluid flow is called a *dynamo*, and the annihilation of a magnetic field is called *magnetic reconnection*. When reconnection occurs, the magnetic-field energy is transferred to the plasma. Our research is focused on *magnetic reconnection* and is part of a larger Physics Division effort to establish a plasma-astronomy presence in the world scientific community. Our research connects to Los Alamos National Laboratory (LANL) missions, including the physics of plasma devices for magnetic-fusion research, space “weather,” satellite communications, and ASCI computing.

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During five decades of study, researchers have largely regarded magnetic reconnection as a “black-box” process that begins with the dissipation of magnetic-field energy and ends in plasma-particle acceleration and/or thermal heating. Indeed, the slow build up of magnetic energy followed by an explosion that converts it into particle energy is almost always present in any magnetized plasma.^{1,2,3} These dynamic explosions release energy anisotropically, whereby slow flows occurring in one direction can elicit large accelerations in another. In nature, these fast time scales can be orders of magnitude quicker than expected resistive diffusion times.

A detailed understanding of the magnetic-reconnection process has only recently started to emerge. Understanding this process could help researchers improve the control and confinement of magnetic-fusion plasmas and understand the stability and magnetic structure of magnetic-fusion-confinement devices. Moreover, long-standing solar-physics questions involving the origins of coronal heating, coronal mass ejections, and other coronal-magnetic activity might finally be solved. Accurate predictions of geomagnetic disturbances could be made, and the effect of solar wind interactions with the

Figure 1. Schematic showing the reconnection plane, including slow plasma inflow velocity in the vertical direction. Anti-parallel magnetic fields convect inwards through a region of ion-skin-depth dimension. On the smaller electron-skin-depth scale (dashed box), a diffusion region containing electron microphysics determines the reconnection process. These two spatial scales have never been observed together in the laboratory. Note the similarity between this figure and Figures 3 and 4. The X point would occur if the size of the reconnection region were vanishingly small.



Nuclear Physics and Astrophysics Research Highlights

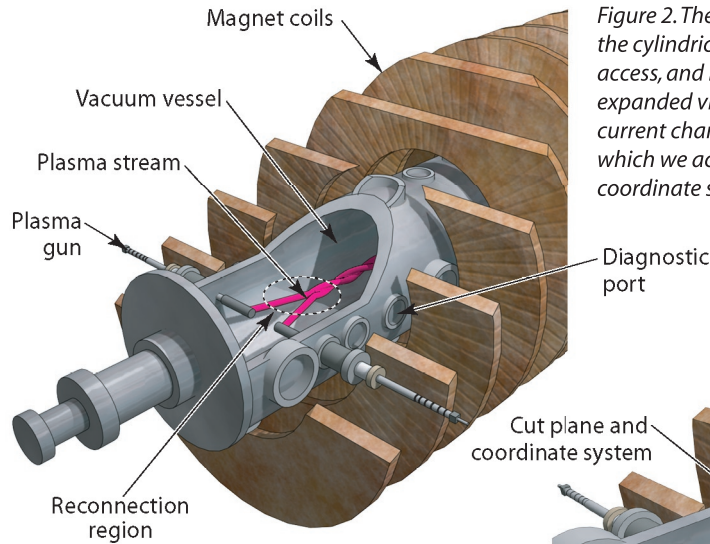
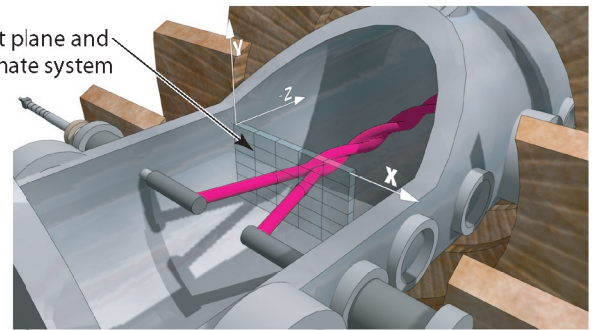


Figure 2. The overall view of the RSX on the left shows the cylindrical vacuum vessel, ports for diagnostic access, and radially inserted plasma guns. The expanded view below shows the twisted plasma current channels that exit the guns, the cut plane from which we acquired the data for Figures 4 and 5, and the coordinate system.



Earth's magnetosphere on spacecraft environments could be determined. Finally, an understanding of the magnetic-reconnection process could connect plasma physics to astrophysical topics such as accretion disks; jet, star, and galaxy formation; and cosmic-ray acceleration—topics that had traditionally been studied only from the perspective of hydrodynamics, general relativity, and atomic physics.

Frozen-Flux Concept and Reconnection

Plasmas can be very good electrical conductors. Electric and magnetic fields cannot penetrate or *diffuse* into perfect conductors because induced eddy currents cancel out these fields. Conversely, fields that are “stuck” inside conductors take a long time to *diffuse* out (i.e., the magnetic flux is *frozen* into the moving plasma). Current flows much more easily along a field than across it, so magnetic field lines can be imagined as conducting wires that move with the plasma. During this process, oppositely directed field lines can be convected toward each other by fluid flow (e.g., the inflow region in Figure 1). Between the oppositely directed fields, there is a magnetically neutral line (*current sheet*) across which there is a reversal of the magnetic field. Diffusion occurs in that region, and the *frozen-in* condition of ideal magnetohydrodynamics (MHD) is broken. The magnetic fields can diffuse through the plasma, allowing the annihilation of oppositely directed magnetic field lines and forcing the lines going in one direction to connect to the ones going in the opposite direction. These “reconnected” field lines act as rubber bands under tension and

pull away horizontally from the diffusion region. Consequently, plasmas are flung as if by a slingshot, which could explain many impulsive phenomena.

Microphysics of Fast Reconnection

At present, a major debate exists regarding the microphysics that influence a fast reconnection rate. This topic has been considered theoretically from two distinct perspectives beyond the scope of resistive MHD. “Anomalous” micro-instability-induced resistivity [which in the collisionless limit can be orders of magnitude larger than the classical (Spitzer) resistivity] can be invoked to explain enhanced dissipation rates inside the reconnection layer. On the other hand, neglected terms of the two-fluid generalized Ohm's law (i.e., the electron momentum equation) can become important on spatial scales smaller than the ion-skin depth c/ω_{pi} , where c is the speed of light, and ω_{pi} (ω_{pe}) is the ion (electron) plasma frequency.⁴ A key experimentally testable feature of the two-fluid reconnection theory is the expected development of a reconnection layer with a two-scale spatial structure. This feature arises because ion and electron motion decouple in between ion and electron c/ω_{pe} skin-depth length scales. With its scalability in collisionality and magnetic fields, the Reconnection Scaling Experiment (RSX), which is currently under way

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at LANL, should allow us to address this question and/or observe signatures of the electron layer. We can independently scale plasma density (and thus the collision frequency), and we can scale the axial magnetic field to change the ion gyro radius.

We are exploring magnetic reconnection in the RSX. Two parallel current plasma channels are produced using plasma guns. Most other experiments are toroidal, but this one has a simpler linear geometry. The RSX cylindrical vacuum chamber has many ports for easy placement of diagnostics and plasma guns (Figure 2). The overall view shows a cutaway schematic of two current channels created by two plasma guns, which are inserted radially into the vacuum chamber. A set of external coils generates the axial guide field B_z . The expanded view shows the helical twisting and merging of these current channels. The coordinate-system axes are indicated for a cut plane through this interaction region. Typically in RSX we generate hydrogen plasmas with a large Lundquist number ($S > 100$), current densities of $J < 1 \text{ MA/m}^2$, and electron densities and temperatures in the range of $n_e \sim 1 \text{ to } 30 \times 10^{13} \text{ cm}^{-3}$ and $T_e \sim 10 \text{ to } 20 \text{ eV}$, respectively. One major advantage of the plasma-gun technology is that no complicated startup scheme or evolution to equilibrium is required. It also allows a high degree of flexibility in scaling the source characteristics independently of the different

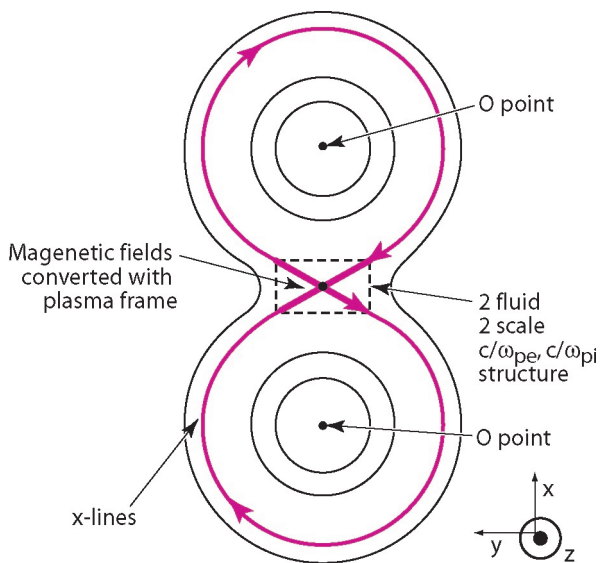


Figure 3. The O points locate the center of each current channel; an X point is located in the diffusion region, which is indicated by dashed lines. The x-y plane corresponds to Figures 1, 3, and 4.

parameters important in the reconnection process.^{4,5} Because the plasma guns create the plasma, both the collisionality (density) and the magnetic-field component, normal to the reconnection layer (current density), can be controlled independently of the plasma-formation process.

Data from RSX

We completed measurements of the magnetic structure in a two-dimensional cut plane (Figures 2 and 3). Figure 3 shows the magnetic topology and diffusion region from the cut plane in Figure 2. Magnetic probes inserted into the plasma gave us a time history at each point, and we explored the full plane over many repetitive shots. An example of vector data (B_x, B_y) in the x-y plane for a time late in the evolution of the reconnection layer is shown in Figure 4. The diffusion region is indicated by the dashed circle, where a jump in B_x is apparent on a vertical cut at $x = 0.280 \text{ m}$. These data were taken using a large-guide magnetic field of $B_{0z} = 400 \text{ Gauss}$. This magnetic field was large enough to magnetize the ions even in the diffusion region where the B_x field vanishes and to maintain a very small beta [$\beta = nT/(B^2/2\mu_0) \ll 1$, which is the ratio of particle pressure to magnetic pressure]. A sketch of the B_x time history for this vertical cut is shown in Figure 5. Four selected times show how the jump in magnetic field increases with time. Interestingly, the scale size of this diffusion layer is approximately 0.5 cm . This scale size is far smaller than the ion-skin depth ($\approx 7 \text{ cm}$) and not too different from the electron-skin depth ($\approx 0.2 \text{ cm}$)

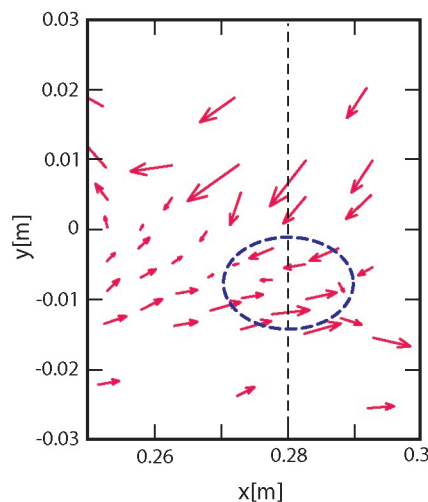


Figure 4. Vector data (B_x, B_y) in the x-y plane. Note the reversal in B_x across the neutral sheet region (dashed circle).

Nuclear Physics and Astrophysics Research Highlights

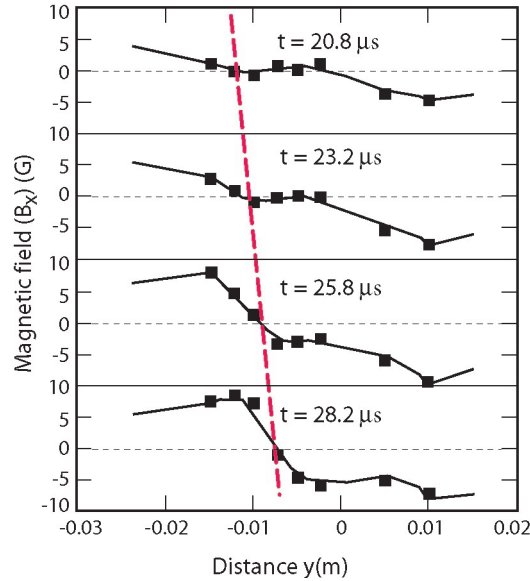


Figure 5. Magnetic field B_x on a vertical cut at $y = 0.28$ m. Note how the jump in B_x becomes steep as time progresses for each time indicated on each panel of the figure.

and the ion gyro radius (0.8 cm). In the near future, we will scan the effects of the externally applied guide field. However, this is at least one example where the size of the diffusion region is quite different from the ion-skin depth predicted by the usual reconnection theories.

Conclusions

Most of the known universe is plasma, and reconnection is ubiquitous in much of it. Magnetic reconnection is thought to convert magnetic-field energy into particle, beam, and thermal energy. The debate concerning the microphysics of reconnection includes predictions that the scale length for the neutral current sheet is the ion-skin depth. Nevertheless, we show here one counter example, using data from RSX at large-guide magnetic field. We intend to investigate the scaling of these results.

References

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