PARTICLE ACCELERATION DURING RECONNECTION IN LABORATORY PLASMAS

R. L. Stenzel and W. Gekelman

Department of Physics, University of California, Los Angeles, CA 90024, U.S.A.

ABSTRACT

The basic physics of magnetic field line reconnection near magnetic null points is investigated in a large collisionless laboratory plasma. The observations focus on the close vicinity of the neutral sheet (±z ± p_c), a region which is difficult to resolve in space. Thus, the high resolution laboratory data are complimentary to the more global space observations. The neutral sheet is generated by applying a pulsed magnetic field with X-type null point to the plasma. The reconnection of field lines and the acceleration of particles are established from time resolved three-dimensional field and flow measurements. Both steady and impulsive reconnection events are observed. The latter are characterized by spontaneous current disruptions and tearing of the current sheet, formation of a double layer at the region of current disruption, and particle acceleration to large inductive voltages due to the impulsive release of stored magnetic field energy. Detailed observations of the particle distribution functions f(v,r,t) have been performed. Suprathermal electron tails are observed in the neutral sheet caused by particle runaway in the electric field along the separator. Beam-like distributions exist adjacent to double layers. While the reconnection electric fields are the source for the particle acceleration the plasma turbulence associated with velocity space instabilities causes enhanced resistivity, heating and dissipation of magnetic energy. This is evident when the current sheet is switched off; it breaks up into intense internally closed current filaments which, via instabilities, enhance the dissipation and explain the anomalously fast loss of internally stored magnetic energy and the rapid electron heating.

INTRODUCTION

In the classical picture of magnetic field line reconnection /1,2/ plasma and magnetic field lines move together toward an X-type magnetic null point such as shown in Figure 1. Near the null point finite resistivity permits magnetic field diffusion such that anti-parallel field lines can be thought to reconnect and to form new pairs of oppositely directed field lines moving away from the null point in the ±x directions. The outgoing fluid is accelerated up to the Alfvén speed. Associated with the flux transfer across the separatrix is an inductive electric field E_z along the neutral line which drives currents and causes particle acceleration in the ±y direction. Thus plasma is accelerated by electric and magnetic forces at expense of stored magnetic field energy or dynamo action.

In spite of the numerous theoretical papers and computer simulations of reconnection processes it is extremely difficult to find a conclusive test of these models by direct experimental observations in space /3/. In situ measurements from spacecraft are point measurements, or at best one-dimensional scans along the satellite orbit, but unfortunately, the plasma conditions vary in time such that spatial and temporal features are difficult to distinguish. For example, the X-point of the magnetotail (β ≈ 0) has not even been found in spite of many satellite crossings of the tail.

Thus, in order to observe and to understand the reconnection physics at the magnetic null point we have built a controlled laboratory plasma with optimum diagnostic capabilities /4-10/. These include time-resolved three-dimensional magnetic and electric field measurements, electron and ion distribution function measurements, ion mass spectrometry, instability analysis in frequency and wave vector domain by means of cross-correlation techniques, and a clear knowledge of boundaries and global circuits. In comparison, the earlier laboratory simulation experiments of a decade ago lacked comparable diagnostics since they were performed in small, collisional high density pinch-type plasmas /11,12,13/.

After a brief description of the experimental setup we show particle acceleration processes during quasi steady-state reconnection, then during impulsive reconnection events which occur either spontaneously or are triggered so as to disrupt the entire current sheet.
**EXPERIMENTAL SETUP**

The UCLA reconnection experiments are performed in a device shown schematically in Figure 2. A linear discharge plasma column is generated in low pressure gases (Ar, He, H, $10^4$-10$^5$ Torr) with a 1 m diameter cathode (see Figure 2b). The plasma of typical density $n_e = 10^{12}$ cm$^{-3}$ and temperature $kT_e$ = 10 eV is uniform, quiescent, essentially collisionless, and highly reproducible in pulses of duration $t_p = 5$ msec, repeated every $t_r = 2$ sec. The plasma column may be immersed in a uniform axial magnetic field of variable strength $B_0 = 0$ to 20 G. For the reconnection experiments a time-varying ($t_{rise} = 100$usec) magnetic field is applied transverse to the plasma column ($\langle B_z \rangle = 20$ G). In vacuum its topology contains an X-type neutral point on the axis of the device as shown in the cross-sectional view of Figure 2a. The field is produced by pulsing currents through two parallel-plate electrodes adjacent to the plasma column and returning the currents coaxially on the cylindrical metallic chamber wall. When the space between the plates is filled with plasma a secondary current is induced anti-parallel to the plate currents. This induced plasma current $I_p$ flows preferentially at the X-point but is so large ($I_p = 1000$A) that it modifies the magnetic field topology self-consistently. Detailed plasma diagnostic tools are employed in conjunction with a state-of-the-art digital data processing system. Time and space resolved probe measurements of fields ($E$, $B$), plasma properties ($n_e$, $T_e$, $\rho$, $\gamma$) and distributions [$f(v_x, v_y, v_z)$] are performed. The analog data are digitized with 100 MHz, 32K A-D converters, evaluated on-line with an array processor, a VAX 11/750 computer linked to a Cray computer. As an example we show in Figure 3 the diagnostic tool to measure the particle distribution functions /14/. It consists of a retarding potential analyser with high directional sensitivity ($\delta \Phi/\delta v = 10^{-4}$) obtained by geometrically filtering particles through a passive microchannel plate. The small detector (-3 mm radius) can be moved in real space $x$, rotated at each position through the two orthogonal spherical angles $\delta, \phi$ so as to measure the particle flux in three dimensional velocity space $v$, and all traces are time resolved to within a few microseconds. A three-dimensional distribution function $f(v_x, v_y, v_z)$ is assembled from individual measurements at typically 300 different angular values $\delta, \phi$. Each flux measurement is repeated at least 10 times so as to form ensemble averages $\langle f(v) \rangle$ and standard deviations $\sigma_{rms}(v)$, indicating fluctuations in velocity space. Variations in position and time produce a very large data flow ($N > 10^8$ numbers) which can only be handled by high-speed on-line digital data processing.

**QUASI-STATIONARY RECONNECTION**

During the external current rise ($0 \leq t \leq 100$usec) the observed magnetic field topology shown in Figure 4a is that of a neutral sheet /1/. The corresponding sheet ($J = \nabla \times B/\mu_0$) has a thickness ($\Delta z = 5$ cm) in the range between the collisionless electron skin depth ($c/\nu_{pe} = 0.6$ cm) and the ion Larmor radius ($r_{ci} = 30$ cm). Thus, we are investigating the
Particle Acceleration during Reconnection

Fig. 2. Schematic picture of the experimental set up. At the left is a cross-sectional view showing parallel plate electrodes with pulsed currents $I_0$ and magnetic field lines $B$ in vacuum. At the right is a schematic sideview of the linear discharge device. A typical axial potential profile shows the build-up of a space charge electric field $E_x = -\gamma E_0$ opposite to the inductive electric field $E_0 = -\gamma E_0$. The coordinate system common in magnetospheric physics has been adopted where $y$ is along the neutral line (device axis), $x$ is along the horizontal neutral sheet, and $z$ is normal to the sheet.

Fig. 3. Schematic view of the directional velocity analyzer for measuring particle distribution functions $f(v_x, v_y, v_z)$. (a) Cross-sectional view with main electrodes. (b) Mounting of the analyzer which permits scanning over two orthogonal spherical angles $\theta, \phi$ as well as variation in the position $r$.

Fine structures in the intermediate and diffusion regions which are difficult to resolve in space plasmas. Reconnection occurs in our experiment at a rate indicated by the axial electric field along the separator ($E_y \lesssim 0.5$ V/cm) /15/ or the normalized inflow velocity of the fluid into the field-reversal region ($\nu/v_A = 0.3$) /16/.

Figure 4b shows the observed ion flow which evolves during reconnection and exhibits the characteristic compression in $\pm z$ direction and jetting in $\pm x$ direction. For initially uniform plasmas and modest current densities (normalized electron drift velocity $v_d/v_e = 0.1$) the current sheet is macroscopically stable on a time scale long compared with the Alfvén transit time across the plasma; hence the reconnection may be considered quasi-stationary.

During reconnection the particles are observed to be energized, i.e. both accelerated and heated. We first consider the electrons and show their distributions in one, two and three dimensional velocity space.

Figure 5 shows the electron flux in the neutral sheet in the $\pm y$ direction for different reconnection rates ($E_y = 0, 0.5, 0.8$ V/cm). In the $y$ direction, i.e. opposite to the electric field along the separator we observe a large flux of energetic electrons in addition to the background electrons. With increasing electric field both flux and energy of the tail electrons increases. Thus, the collisionless tail electrons of the discharge plasma
freely run away in the reconnection electric field acquiring an energy proportional to the voltage \( E_y dy \).

Figure 6 displays electron distribution functions in two dimensions \( f(v_x, v_y) \). On a logarithmic scale \( f(v) \) is displayed over three orders of magnitude so as to clearly resolve the structure of the tail. Below the function we show contour plots, representing cuts \( f(v) = \text{const} \), projected into the velocity plane. The two cases displayed correspond to different spatial locations. In the center of the neutral sheet \((x = z = 0, \text{ Figure 6a})\) the tail of runaway electrons is clearly visible, while at the edge \((x = 20 \, \text{cm}, z = 0, \text{ Figure 6b})\) the normal component \( B_z \equiv 3 \, \text{G} \) prevents electron runaway along \( y \).

Since the distributions in the current sheet are, in general, not axially symmetric we have measured them in the full three-dimensional velocity space, \( f(v_x, v_y, v_z) \). Since it is not possible to display the function and the three independent variables we take cuts through \( f(v) \) and project them into velocity space forming surfaces of constant \( f(v) \). Anisotropies appear as deviations from spherical surfaces. Figure 7 displays a few characteristic surfaces of the three-dimensional distribution function in the current sheet. For a wide range \((1 \leq a \leq 10^{-2})\) of values of the normalized distribution parameter \( a = f(v)/f(0) \) \([f(0) = 10^{-14} \, \text{cm}^{-6} \, \text{sec}^{-3}]\) the surfaces are essentially spherical indicating a relatively small tail at the point of observation \((x = 0, z = 3 \, \text{cm})\). When the value \( a \) is decreased \((a = 2.3 \times 10^{-3})\) several detached surfaces reminiscent of runaway beamlets appear. For still smaller values of \((a = 1.9 \times 10^{-3})\) filaments extend outward from both the main body and beam and join. Side arms which curl across the \( y \) direction along which there is an axial magnetic field component \( B_y = 10 \, \text{G} \) appear as well. For small values of \( a (a = 1.6 \times 10^{-3}) \) but still above experimental noise levels the distribution function is highly distorted.
Fig. 5. Current-voltage characteristics of the directional retarding potential analyzer for electrons at three different reconnection rates $E_{y0}$. The analyzer is located in the neutral sheet and faces in $\pm y$ direction (180°, 0°, resp.). An energetic electron tail is produced by electron runaway in the reconnection electric field $E_{y0}$.

Fig. 6. Electron distribution function in two velocity dimensions, $f(v_{1}, v_{2}) = f(v_{y}, v_{z})$. Top figure shows $\log f(v)$ at the edge of the current sheet, bottom figure at the center where a tail of runaway electrons is present. $E_{z}$ is a magnetic field component along the separator parallel to the reconnection electric field $E_{y}$. In addition, cuts through $\log f(v)$ show one-dimensional distributions $F_{\parallel} = \log f(v_{1}, 0)$ and $F_{\perp} = \log f(0, v_{2})$, and a two-dimensional contour plot $\log f(v_{1}, v_{2}) = \text{const}$. 
The continuous variation from surface to surface is best shown in a computer generated movie of the experimental data which has been shown. The three-dimensional aspect of the function is clearly visible in a stereoscopic view presented with two different angular views of the surface $\alpha = 1.6 \times 10^{-3}$ in Figure 8.

$$f(v)/f(o) = 10^{-2}$$

$$2.3 \times 10^{-3}$$

$$1.9 \times 10^{-3}$$

$$1.6 \times 10^{-3}$$

Fig. 7. Surfaces of constant value of the electron distribution function in the three-dimensional velocity space, $f(v) = \text{const}$. With decreasing value $f(v)/f(o)$ the distribution exhibits beams (detached surfaces) and tails (protrusions) due to runaway electrons in the current sheet.

Fig. 8. Stereoscopic view of the surface of constant $f(v)/f(o) = 1.6 \times 10^{-3}$ of the electron distribution function. The highly structured tail of energetic electrons is due to the electron runaway in the electric field $E_y$ along the separator.*

The rich structure of the velocity space anisotropies do not only reflect the result of complicated single particle orbits in a neutral sheet /17,18/ but also diffusion in velocity space due to wave-particle interactions. The detached surfaces of $f(v)$ imply the existence of positive gradients which can give rise to electrostatic instabilities involving Langmuir waves, Bernstein waves, oblique whistlers and lower hybrid waves. A detailed analysis of the wave turbulence has been performed in the whistler wave regime /9/ and is in progress for other modes. However, since the microinstabilities are not the primary cause for the particle acceleration but rather a mechanism for diffusion in velocity space we will not discuss these results here.

The distribution function can be used to correctly calculate the moments of the non-Maxwellian distribution function. The first moment or density $n = \int f(v) dv = \iiint f(v, \theta, \phi) v^2 \sin \theta d\theta d\phi dv$ has been obtained after calibrating the velocity analyzer in a Maxwellian plasma of known density and temperature. The ratio of tail to background particles has been evaluated by taking the difference of the first moments in two hemispheres, one pointed at the cathode, the second at the anode, and comparing it with the total density. In the center of the neutral sheet $n_{\text{tail}}/n_{\text{total}} = 1.5 \times 10^{-2}$. The current is given by $j = ne v_o = \epsilon / \sqrt{f(v)} dv$ and in the center of the sheet is $j = (0.172, -1.58, -0.175) \ A/cm^2$. We interpret

*Stereoscopic viewing aides described in Ref. /9/.
The significant current component \( j_\perp \left( \tan^{-1} \frac{j_\perp}{j_\parallel} = 24.5^\circ \right) \) as an indication that the net magnetic field at the probe position has components other than the constant axial \( B_0 \); the most probable cause is a slight positional misalignment with respect to the center of the neutral sheet. We point out that this cannot explain the complex structure in Figures 7 and 8; the current density is an integral over all surfaces from \( 0 < \alpha < 1 \). Finally the mean energy tensor \( \mathbf{E} = \frac{1}{2} \mathbf{m} \mathbf{v} \mathbf{v} f(v) dv \) and heat flux \( \mathbf{q} = \frac{1}{2} \mathbf{v} \mathbf{v} f(v) dv \) have been evaluated.

The off-diagonal energy terms are 60-100 times smaller than the diagonal ones. In the center of the neutral sheet the trace of energy tensor yields 10.4 eV. This is the average kinetic energy of the electrons. The tail particles account for 22% of the total mean electron energy and have a parallel heat flow \( (9.1 \times 10^{-11} \text{ watt-cm}) \) 2.1 times larger than that at the sheet edge.

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\text{ION TEMPERATURE}
\]

\[
I \quad \text{NO RECONNECTION} \quad kT_i = 0.7 \text{ eV}
\]

\[
V \quad \text{WITH RECONNECTION} \quad kT_i = 3.1 \text{ eV}
\]

\[
V \quad \text{VOLTAGE} \quad V \quad (3 \text{V/div}) \quad t \quad \text{TIME} \quad t \quad (2 \mu s/\text{div})
\]

Fig. 9. Ion energy analyzer traces showing significant ion heating during reconnection in the current sheet.

The ion distribution function has also been measured. Figure 9 shows retarding potential energy analyzer traces taken in the current sheet, facing into the +y direction. During reconnection the distribution remains essentially Maxwellian but significant ion heating \( (\Delta T_i/T_i \approx 4.4) \) is observed. Runaway ion tails are not observed presumably due to the effective scattering of slow particles by low frequency turbulence /6/. Two-dimensional ion flux measurements reveal drifts in the distribution function consistent with the flow field of Figure 4b. Some ejected ions assume drift velocities up to half the Alfvén speed \( (C_A = C_S = 5 \times 10^8 \text{ cm/sec}) \) but, in general, the maximum energization of ions \( (\Delta m v_i^2 \approx 3 \text{ eV}) \) remains small compared to that of the electrons \( (\Delta m v_e^2 \approx 100 \text{ eV}) \).

**IMPULSIVE RECONNECTION EVENTS**

It is generally believed that a continuous build-up of the magnetospheric cross tail current eventually leads to an impulsive reconnection event, i.e., a substorm. Thus, it is natural to investigate in the laboratory the stability of a current sheet with respect to increasing current densities at the separator /8/. This is accomplished by isolating the central portion of the grounded end anode and by biasing it positively as shown schematically in Figure 10a. When monitoring the collected current \( I_4 \) to this center electrode, we find that at increasing current densities \( (v_d/v_e \approx 0.3) \) spontaneous and repeated current disruptions develop (see Figure 10b). The cause for this current switch-off has been inferred from detailed diagnostics of the local plasma properties as well as the entire circuit properties. During a disruption the plasma potential rises in the perturbed current channel to a value much larger than the dc potential \( (V_{dc} = 10 \text{ V}) \) applied to the end plate. Simultaneously, the plasma density decreases. These processes have a finite spatial extent as sketched in Figure 11. In particular, the plasma potential exhibits an abrupt axial drop \( (\Delta \phi = 30 \text{ V in } \Delta y = 5 \text{ mm} = 100 \lambda_p) \), i.e., a double layer is formed in the region where the current is disrupted and the neutral sheet tears. The large positive plasma potential pulse can only be explained in terms of inductive effects. The distributed circuit inductance \( L \) creates an inductive voltage rise \( L dI/dt \) when the current drops. The inductive voltage drops off where the current opens. It drives the plasma potential positive and causes an expulsion of ions,
SPONTANEOUS CURRENT DISRUPTIONS

Fig. 10. Instabilities of a current sheet at large current densities \( \frac{v_d}{v_e} > 0.3 \). At the left is the schematic set up for increasing the central current density by means of a biased center anode. At right is the typical current and voltage waveforms at the center anode showing spontaneous impulsive current disruptions and voltage spikes.

hence a density and current drop. The magnetic forces during the tearing of the neutral sheet also expel plasma from the perturbed current channel. The current decrease in turn reinforces the inductive voltage so that an explosive disruption develops. The current lost in the center of the original sheet is redirected to the sides, i.e. the disruption is localized. At the double layer particles are accelerated at the expense of magnetic field energy. The kinetic energy first resides in particle beams. Subsequent beam-plasma instabilities transfer the directed energy into waves and heat. Bursts of Langmuir waves and magneto sonic waves are generated. Many of the observed phenomena of current sheet disruptions may apply to space plasmas as well. The dynamic current modifications during substorms and solar flares accelerate particles to high energies which is commonly associated with inductive

Fig. 11. Schematic view of processes involved in a spontaneous current sheet disruption.
The formation of parallel electric fields is well known in auroral physics and it is possible that nonstationary double layers arise from inductive voltages where the energy storage is remote from the region of dissipation. The transport of energy through an ideal MHD plasma does, however, occur at a slower rate than in an electrical circuit in air /20,21/. Thus, it is desirable to study how in-situ stored magnetic field

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**Fig. 12. Principle of generating controlled disruptions of the total current sheet by means of a magnetic switch. At bottom is a typical waveform of the end anode current I_a with and without triggered disruptions.**

**Fig. 13. Magnetic field lines \( \overrightarrow{B} \) (top picture) and current density \( \overrightarrow{J} = \nabla \times \overrightarrow{B}/\mu_0 \) (bottom picture) during reconnection showing a current sheet prior to the disruption.**
energy is transported and dissipated by reconnection processes. Such experiments are described in the next section.

CURRENT FILAMENTATION

While in the localized current disruptions a relatively small portion of the total magnetic field topology was perturbed we now disrupt the entire current sheet and release all the magnetic energy associated with it. This is accomplished as shown schematically in Figure 12. First, a well formed current sheet is formed which, together with the magnetic field topology is displayed in Figure 13. There is no axial magnetic field component present ($B_0 = 0$). The plasma current $I_0$ is mainly carried by electrons drifting through the null region from the cathode toward the anode. We can completely switch off the total plasma current, as observed at the end anode (Figure 12, bottom) with a magnetic switch which produces a thin slab of normal magnetic field $B_\parallel$. The switching is performed rapidly ($\Delta t < 5 \mu s$) compared to an Alfvén time across the plasma ($t_A \approx 30 \mu s$) so as to study the internal relaxation of the magnetic field topology. We also investigate particles, currents and electric fields.

The switch-off of the end anode current is accompanied by a plasma potential rise from $V_p < 0$ to $V_p = V_{\text{floating}} \geq 30 \text{ V}$ which is restricted to the left half of the plasma between the switch and the end anode. In the right half between the switch and the cathode the potential remains near ground. The cathode current continues to flow but now toward the grounded grid just in front of the cathode.

Using magnetic probes we have started to investigate the topology $B(x,z,t)$ in the left half of the device. Figure 14 shows field lines and the current density $J_y = (\vec{\nabla} \times \vec{B})/\mu_0$ during the decay of the current sheet. The Chi-type neutral point has torn into an O-point and two adjacent X-points. However, the distortion of the field lines points to a complex current structure. Indeed, Figure 14b shows that the current sheet has broken up into many current filaments with both positive (dashed) and negative (dotted) currents. The current continues to circulate inside the plasma while the net current to the anode has vanished, indicating the difference in magnetic energy transport in plasmas and in non-conducting media.

In an ideally conducting fluid the magnetic energy might be expected to propagate away in the form of Alfvén waves. However, we find that anomalous dissipation of magnetic field energy dominates over convection. Figure 15 shows magnetic vector fields before (heavy vectors) and after (thin vectors) the current disruption ($\Delta t = 6 \mu s$). Within less than an Alfvén travel time we find a rapid decrease in the vector lengths $|\vec{B}|$ in the plasma center without a temporary increase elsewhere. Thus, the magnetic energy $B^2/\mu_0$ is dissipated which explains the observed strong electron heating ($\Delta T_e/T_e = 100\%$). One may suspect that the intense current filaments are instrumental in enhancing the plasma resistivity and
energy dissipation. Further investigations into these processes are underway.

**Fig. 15.** Superposition of vector magnetic fields before (heavy arrows) and after (light, smaller arrows) a total current sheet disruption. The magnetic field energy density decreases due to anomalously rapid dissipation rather than convection by Alfvén waves.

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