MEASUREMENT OF MAGNETIC HELICITY DURING THE DISRUPTION OF A NEUTRAL CURRENT SHEET

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A basic physics experiment on magnetic field line reconnection in a laboratory plasma is described. A neutral sheet is formed by applying time-varying opposing magnetic fields to a highly conducting plasma. Complete diagnostics for the three-dimensional magnetic field topology \( B(r,t) \), particle distribution \( f(v,r,t) \), fluid properties \( (n,T,v_j,p) \), and waves \( (\delta n, \delta B, \delta E) \) have been developed. Quasistationary reconnection is observed and understood, to first order, by fluid models but, upon closer inspection, modified by kinetic effects (anisotropic in \( f(v) \), microinstabilities, and space charge fields). A controlled disruption of the neutral sheet current results in rapid conversion of stored magnetic energy into particle kinetic energy. The disruption is accompanied by a sharp jump in the helicity, consistent with measured linking of magnetic flux tubes.

INTRODUCTION

Magnetic field line reconnection is recognized as an important process in fusion devices,\(^1\) magnetospheric physics,\(^2\) and the description of solar flares.\(^3\) Reconnection involves a breakdown of the frozen-in condition between field and fluid that takes place at magnetic null regions (X points, neutral sheets) where the finite conductivity has to be considered in order to avoid a current singularity. Diffusion permits a flux transfer across the separatrix. According to Faraday's law the flux change implies an electric field along the separator (neutral line) that can be taken as a measure for the reconnection rate. Reconnection may be driven by an externally imposed plasma flow into a magnetic null region (e.g., magnetotail) or by temporally increasing external magnetic fields (e.g., pinch plasmas). Irrespective of its motional or inductive origin, the reconnection electric field drives a plasma current along the neutral line or sheet. The current density is consistent with the magnetic topology \( j = \nabla \times H \) and, according to fluid theory, with Ohm's law \( E + \nu \times B = \eta j \). The magnetic field associated with the plasma current provides a potential energy source that can be released during a disruption of the current sheet. Such disruptions may arise from tearing modes, resistivity changes due to current driven instabilities, or space charge instabilities (double layers) at large current densities \( (v_u - v_e) \).

Whatever the causes of the disruption, the result will consist of a change in the magnetic field topology (if the field associated with the initial current is comparable to any ambient field) and an energy release. Fundamental questions deal with the conversion of magnetic field energy into particle energy\(^4\) in space physics. A complex chain of events may ensue; for example, the disruption of the crosstail current may give rise to auroras. In fusion plasmas, the importance of reconnection by tearing modes lies in the associated transport processes.

The topological properties of the magnetic field lines are also of fundamental importance. To first order, a magnetized charged particle will spiral about a field line.

If the MHD approximation is valid, the magnetic field is frozen into the fluid plasma. Finally, the magnetic field configuration greatly aids in the visualization of most situations. The magnetic helicity measures the linkage of flux tubes\(^5,6\) and may be associated with changes in the topology.

Detailed measurements of field topologies and current systems are not possible for solar physicists since observations are remote (resolution ~ 500 km, theoretical sheet width 10 m). Magnetotail measurements, although performed in situ, yield data only at a few points and suffer from space-time ambiguities. In hot, dense fusion plasmas, magnetic field measurements are done remotely or inferred from other data (X-rays, cyclotron emissions). Thus, there is a need to establish a case where reconnection can be studied in detail. This is possible in a well diagnosed laboratory experiment.

In the UCLA experiments,\(^7\) the simplest possible configuration has been chosen, i.e., a linear device with an X-type neutral point on axis. A nearly collisionless discharge plasma is generated. By temporally increasing the strength of the antiparallel magnetic fields, a plasma current is induced, which assumes self-consistently the shape of a current sheet. Once established, the current sheet is disrupted with the use of a magnetic switch and is carefully diagnosed using modern digital data processing techniques.

The following section describes the experimental setup. Then the properties of the current sheet prior to disruption are reviewed. The disruption is then discussed in detail with emphasis on the plasma currents and helicity measurements. The summary will include a discussion of this experiment with regard to magnetotail physics.

EXPERIMENTAL ARRANGEMENT

Figure 1 shows schematically the main components of the experiment. A 2 m long discharge plasma is generated between a large cathode (1 m diameter) and anode. The plasma of parameters listed in Fig. 1b is uniform, quiescent, essentially collisionless, and highly reproducible in pulses of duration \( t_p = 5 \) ms repeated every \( t_r = 1.5 \) s. The plasma may be immersed in a uniform
ing the activated (and easily poisoned by oxygen) cathode. The plasma is cool enough to allow probes to be placed in it. The typical density \((1 \times 10^{12}/\text{cm}^3)\) is enough to provide for high \( \beta \) effects but not so large as to make structures of the order of the collisionless skin depth unreasonable or the coulomb collision frequency too high.

Magnetic field measurements are obtained with three orthogonal loops mounted on a coaxial telescoping axial shaft that allows them to be placed anywhere within the plasma volume. In this way, vector magnetic fields \( \mathbf{B}(r,t) \) are obtained in situ at up to 4000 spatial locations \((\Delta r \approx 2 \text{ cm})\) and 1000 temporal points \((\Delta t \approx 100 \text{ ns})\).

From repeated measurements, statistical averages are formed (mean, standard deviation, correlations). Distribution functions are measured with a modified retarding potential analyzer that filters particles through a passive microchannel plate and thereby obtains high directional sensitivity \(\Delta f / f \approx 10^{-3}\). The small detector \((\sim 3 \text{ mm radius})\) can be moved in real space, rotated at each position through the two orthogonal spherical angles \(\theta, \phi\) so as to obtain from the differential particle flux the three-dimensional distribution function \(f(v,\theta,\phi)\) or \(f(v_x,v_y,v_z)\). Electron and ion phase space measurements \(f(v,\tau,t)\) are time resolved to within a few microseconds. Ensemble averages yield fluctuations in velocity space. Measurements of such multidimensional functions produce large data flows \((n > 10^9\) numbers\), which can only be handled by digital techniques.

The analog traces are therefore digitized with 10 MHz, 32 kbyte, 8-bit A/D converters housed in a CAMAC system that is serviced by an LSI 11/23 computer. The LSI serves as a slave to a VAX 11/750 computer and is linked to it by a specialized high-speed (250 kbyte/s transfer rate) network. The data are placed in large arrays that are accessed in real time (the experimental repetition rate is \(-1\text{ Hz}\)) by an array processor that digitally filters and performs correlations and signal averaging. The VAX is in turn linked to a Cray computer for further data analysis and graphics.

**SUMMARY OF RESULTS OF RECONNECTION AT A NEUTRAL POINT**

The magnetic field topology during the time of external plate current rise is shown in Fig. 2a. Whereas in a vacuum the field vanishes at one single point, the \(X\)-point, in the plasma the null region is extended along a separatrix with two contact points, described by two opposing horizontal \(Y\)'s \((\rightarrow \leftarrow\)). This topology is that of the classical neutral sheet\(^9\) that arises when the induced plasma currents slow down the penetration and reconnection of magnetic fields at the field reversal region. The result is a pileup of flux although, in contrast to a superconductor, the shielding is incomplete and reconnection does take place.

In Fig. 2b a typical current density profile is shown, obtained by calculating \(\mathbf{j} = \nabla \times \mathbf{B} / \mu_0\). The dashed region of largest current density indicates the shape of the current sheet, which is nearly uniform in the \(y\) direction.

The thickness \(\Delta z \approx 5 \text{ cm}\) is in the range between

$E_i = -\nabla \phi_i$ builds up in the direction opposite to the applied inductive electric field. The net electric field is reduced to a value consistent with the electron supply and plasma resistivity and is of order 1/10 the inductive electric field.

Space charge electric fields also develop self-consistently in the direction perpendicular to the neutral sheet. For example, in Fig. 2c, the observed ion flow in the transverse $x$-$z$ plane is shown. The ion flow exhibits the characteristic fluid flow during reconnection, which is driven by the $j \times B$ force. This body force acts on the current-carrying electrons that set up a space charge electric field and accelerate the unmagnetized ions until a common fluid flow is established. The evolution of the classical fluid flow at a neutral sheet has been studied in detail by comparing the measured acceleration $\rho \delta v / \delta t$ with the total force density $j \times B - \nabla p$.\textsuperscript{10} The presence of fluctuating electric and magnetic fields causes an effective drag on the ions and has to be added to the average force densities. The fluid flow does not generate a density maximum on axis. Density and temperature maximize at the edges of the current sheet near the two contact points of the $Y$-shaped separatrix.\textsuperscript{11}

Further investigations of the fluid properties have been concerned with the electrical resistivity $\eta$, which is important for energy dissipation, reconnection rates, and current disruptions.\textsuperscript{12} From an analysis of the generalized Ohm's law, the effective resistivity $\eta$ is obtained and found to be at least one order of magnitude larger than the classical resistivity, to exhibit large spatial variations and to vary with current density as expected from current driven microinstabilities. This spatial dependence is shown in Fig. 3. Here $\eta = J \cdot E$, where $E = -\nabla \phi - \partial A / \partial t$, was measured with a specialized probe, and $J = 1/\mu_0 \nabla \times B$.\textsuperscript{8}

In two-dimensional reconnection models,\textsuperscript{8} the rate of flux transfer across the separatrix is measured by the inductive electric field $E_i$, along the separator $(-\partial \phi / \partial t = V \times B_i / B_i^2 > v_{ion}$. The current sheet widens when a magnetic field component $B_i$ is present along the separator. In this three-dimensional case, which will be depicted later, the electrons remain magnetized and carry axial current while drifting along $B_i$.

In two-dimensional reconnection models,\textsuperscript{8} the rate of flux transfer across the separatrix is measured by the inductive electric field $E_i$, along the separator $(-\partial \phi / \partial t = V \times B_i / B_i^2 > v_{ion}$. The current sheet widens when a magnetic field component $B_i$ is present along the separator. In this three-dimensional case, which will be depicted later, the electrons remain magnetized and carry axial current while drifting along $B_i$.
The magnetic field topology shown in Fig. 2, as well as the other parameters discussed so far, are ensemble averages. In the vicinity of the neutral sheet, considerable fluctuating components of the fields $(\delta B_i / B_i - 1, \delta B_i / \phi - 0.05)$ reflecting wave activity have been observed. By correlating the signals from a pair of electrostatic probes tuned to monitor $\delta \Phi$ at a fixed frequency within the broadband turbulence $(f \leq f_p)$, the cross-spectral function (CSF), $C_{12}(\Delta y)$, may be obtained. The distance between maxima in Fig. 4a is the wavelength. By measuring $\lambda$ as a function of the frequency the dispersion $\omega = k c_s$ is identified. The turbulence consists of ion acoustic modes driven unstable by the relative drift between electrons and ions $(v_\parallel >> c_s)$ in a plasma with $T_e > T_i$. Ion sound turbulence is likely to be responsible for the anomalous increase in the plasma resistivity and electron heating.

The current sheet is also a source of magnetic fluctuations. Magnetic noise exists up to a few electron cyclotron harmonic frequencies $(\omega_{ce} \sim \omega_p)$. The cross-spectral function in this case is a tensor produced by correlating the three components of $B$ for the reference and movable probe. In contrast to Fig. 4a, the cross-spectral function is a complex pattern due to the spatial interference of many wavenumbers at a given frequency. The three-dimensional wavenumber spectra at $f = 1$ MHz is shown in Fig. 4b for a single component $(B_{11}', B_{22}')$ of the Fourier transform of CSF tensor into $k$ space. Each dot represents an observed random wave, and the size of the dot is proportional to the wave amplitude. All the modes lie within two surfaces that are the whistler wave dispersion

$$\left( \frac{k c_s}{\omega} \right)^2 = \frac{\omega_p^2}{\omega (\omega, \cos \theta - \omega)}$$

for the maximum density and minimum magnetic field $(B_e \approx 10 \text{ G})$ within the region probed.

All the possible modes are expected to fill the volume between these surfaces. Finally, a test of the random waves moving along the axial field showed the waves to be right circular polarized. In addition to these electromagnetic whistlers and ion sound waves, a second spectrum of electrostatic fluctuations is found near the electron plasma frequency $(f = f_p \approx 12 \text{ GHz})$. These are Langmuir waves excited by the stream of high-energy electrons. They scatter the tail electrons and transfer some of the tail energy into the main body. By mode conversion on density gradients and by scattering off density fluctuations, Langmuir waves couple to electromagnetic waves that are observed outside the plasma with horn antennas.

Analysis of the particle-distribution functions and waves provides a better understanding of the causes for the anomalous fluid behavior. Figure 5a-c summarizes measurements of the electron distribution function in the current sheet in one-, two-, and three-dimensional velocity space, respectively. The electron flux versus energy observed along the $\pm y$ direction (Fig. 5a) reveals the presence of a tail of high-energy electrons streaming away from the cathode. These are electrons accelerated at the cathode sheath by a potential given by both the discharge supply voltage $(V = 40 \text{ volts})$ and the reconnection voltage $(V = 70 \text{ volts})$. Two-dimensional flux measurements yield the distribution function $f(v_x,v_y) = f(v_x,v_y)$ (assuming isotropy in $v_x,v_y$) shown in Fig. 5b as a topographical map and a contour map. Finally, in three dimensions the distribution can be displayed as a set of nested surfaces of constant value $f(v_x,v_y,v_z) = 1$ constant, one of which is shown in Fig. 5c. These data depict, with increasing resolution, the anisotropy of the electron distribution in the current sheet. The tail electrons are mainly accelerated by the reconnection electric field that, due to space charge effects, has been distributed nonuniformly along the separator. Such field localizations are likely to occur also at nonuniformities in density, conductivity, cross section, or magnetic fields. The consequence of localized reconnection fields is the production of runaway particles that modify trans-

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**Figure 4**—(a) Ion acoustic dispersion relation measured using cross-spectral function techniques. (b) Three-dimensional wavenumber spectrum of magnetic fluctuations. The experimentally observed modes (dots with radius proportional to mode amplitude) are bounded by whistler wave dispersion curves at $\omega = 1$ MHz.
port coefficients (e.g., resistivity, heat flow), cause spatial nonuniformities (anisotropy), and can drive various kinetic microinstabilities.

The electron distribution function was analyzed using an anisotropy test that indicates that it is prone to a parallel whistler instability. The measured phase velocities of the Doppler shifted whistlers \( v - \omega / k \) falls into the range of the observed tail. In addition, the reduced parallel distribution function \( g(v) = \int f(E) dE \) exhibits a positive slope satisfying the criteria for Langmuir stabilities.

**CURRENT SHEET DISRUPTIONS**

While the previous observations described the properties of quasistationary reconnection, the present section deals with impulsive reconnection events that involve rapid changes in field topology and plasma properties. Two types of disruptions have been studied: spontaneous and controlled. Spontaneous disruptions arise when the current in the center of the neutral sheet is raised and are accomplished by biasing the central part of the end anode positively. The cause for these current interruptions has been inferred from both the global circuit properties and the local plasma properties. They result in the production of double layers within the current sheet.

A second class of current disruption is caused by interruption of the entire plasma current. Such experiments can locally model the interruption of the cross-tail current. It is conjectured that the redirected currents may result in auroras at the earth’s poles. In any event, the investigation of a current-sheet breakup addresses some fundamental questions. If the stored energy is embedded in a highly conducting plasma, at what rate can the energy be released during a disruption? How does the magnetic field topology change? The dynamics of unstable current systems is an open subject.

After establishing a well-formed current sheet, a magnetic switch is activated producing a thin slab of normal magnetic field \( B_z \), preventing the electron flow between cathode and anode. The switch itself consists of a set of fine (0.02 mm) copper wires (Fig. 1c) placed midway between the oxide-coated cathode and grounded anode of the device. The current switch-off is performed rapidly (\( \Delta t \approx 3 \mu s \)) compared with the Alfvén transit time across the plasma (\( t_A \geq 30 \mu s \)) so as to distinguish subsequent magnetic field propagation and dissipation processes. The total plasma current may be disrupted with high reproducibility.

All three vector components of \( B \) are measured throughout the volume of the plasma between the wire array and the anode at 4000 spatial locations and 1024
time steps. The field measured at each position is an en-
semble average over five pulses of the device. The vol-
ume measurement takes about a week (at a 1 Hz repeti-
tion rate) and is only possible because the source is ex-
tremely stable. The total magnetic field in this case is
that due to the currents in plates at the plasma bound-
aries, the plasma current, and a constant axial field
\(B_A = 6 \text{ G}\). There is also a stray magnetic field (\(B_s\))
due to the switch, that drops off rapidly (over a few cm)
in the \(y\) direction.

The transverse magnetic field energy density in a plane
midway between the switch and anode is shown in Fig.
6. Before the disruption, a neutral sheet is observed near
\(z = 0\). Shortly after the disruption, \(E^2 / 2\mu_0\) looks the
same as it does in vacuum. When integrated over
the volume, one finds that the stored magnetic energy dis-
appears within \(\Delta t = 5 \cdots 10 \mu\text{s}\), which is shorter than
the propagation time of Alfvén waves to the boundaries.

By calculating the local current density
\(j = \nabla \times B / \mu_0\) and fitting field lines through this vec-
tor field, one can follow the space-time variation of the
interrupted current flow as is shown in Fig. 7. Before the
disruption, \(t = -0.6 \mu\text{s}\), the current flows in a laminar
sheet along the \(-y\) direction. As the electron inflow at
the left \(x-z\) plane is inhibited by the magnetic switch, the
current begins to circulate within the plasma volume
forming a spatially random pattern of small-scale cur-
et loops and filaments as well as decays. The magnetic
fields associated with these currents cancel, giving rise
to \(X\)-point topology for the transverse magnetic field.
This process of cascading from large- to small-scale
structures lowers the effective magnetic Reynolds num-
ber \(R_m \propto l\) and enhances the magnetic diffusion.

When the vertical magnetic field appears, the current
does not stop instantaneously. Its flow changes from a
two-dimensional sheet to a fully three-dimensional in-
homogeneous pattern. This may be seen in Plate IV-3,
which shows current flux tubes before and after the dis-
ruption. The tubes are calculated by specifying a flux
\(|J_f|\) and start point. The local direction of \(j\) is calcu-
lated and then an area such that \(|J_f| = j \cdot nda\). The
calculation proceeds by storage of points on the bound-
ary of the area and \(n\) advancing slightly along the local

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**Figure 6**—Magnetic energy density \(E^2 / 2\mu_0\) versus \((x,z)\) be-
fore and after the disruption. The magnetic energy associ-
ated with the plasma current is dissipated anomalously fast.

**Figure 7**—Field lines for the current density vector \(j(x,y,z)\) at different
times of the current disruption. The initially \(t = -0.6 \mu\text{s}\) lam-
inar current sheet cascades during the dis-
ruption into small-scale current loops and filaments. Due to the trig-
gered disruption, the spatially ran-
dom pattern is highly repeatable
from pulse to pulse.
Plate IV-3—Stereo pairs showing current flux tubes: (A) before and (B) during the disruption. Initially the tubes are parallel; they then veer and weave around each other as they avoid the switch.
direction of \( j \) and repeating until a boundary is reached or 1000 areas are stored. The flux tubes are presented as three-dimensional stereo pairs, best seen with the viewer provided in this book. Before the disruption, the current tubes are a set of parallel cylinders within the neutral sheet. Afterward, the currents can criss-cross past each other (Plate IV-3B), implying that the flux associated with them can now link. This flux linkage gives rise to a change in the magnetic helicity.

HELCITY GENERATION

The magnetic helicity is a pseudoscalar quantity that may be identified with the linkage of magnetic field lines. It is defined as the volume integral

\[
H = \iiint A \cdot B \, dV
\]

(2)

where \( A \) is the vector potential. For two untwisted magnetic flux tubes linked once \( H = \pm 2\Phi_1 \Phi_2 \), where \( \Phi \) is the flux in each tube and the sign depends upon the sense of linkage.\(^6\) Equation 2 is a special case of the integral \( \int z \cdot \nabla \times z \, dv \), which reflects the topology of \( \nabla \times z \). As shown by Berger and Field,\(^8\) the helicity can arise from twists and kinks within a single flux tube (internal helicity) and/or linkage and by knotting of separate flux tubes (external helicity). In ideal MHD, they are independently conserved. Taylor\(^9\) has conjectured that the helicity is conserved in highly conducting plasmas, although reconnection can take place and the magnetic topology can change. This would be a consequence of a transfer between internal and external helicity.

In the current disruption, the ions are not magnetized (Fig. 7); they may be considered as nearly fixed (\( V_{\text{Ar}} = 2 \times 10^5 \, \text{cm/s}, \Delta t = 10 \, \mu s \)). The magnetized electrons that carry all the current may be considered a resistive fluid. When currents decay, the helicity does also,\(^10\) according to

\[
\frac{dH}{dt} = -2 \iiint \eta \cdot B \, dv
\]

(3)

where \( \eta \) is the plasma resistivity. Conventional fluid theory is not applicable in this experiment because significant space-charge electric fields have been observed\(^3\) and it is possible that a theory for a single electron fluid may make other predictions.

Various schemes to inject helicity have been proposed for fusion devices to maintain a given magnetic configuration. They are equivalent to adding flux to the system (or the imposition of an electric field) to keep the current flowing.

The integral for \( H \) (Eq. 2) is over all space and therefore includes the current systems that give rise to the vector potential and field

\[
A(r) = \frac{\mu_0}{4\pi} \int \frac{j(r')}{|r - r'|} \, dr'
\]

(4a)

\[
B = \nabla \times A
\]

(4b)

In this case, the current consists of at least two contributions. Current is forced to flow through the plates that bound the plasma column and to return through the chamber wall. This produces a vector potential \( A_{\text{pl}} \) (\( p = \text{plate} \)) along the \( y \) axis and the vacuum \( \chi \)-point magnetic field in any \( x-z \) plane. There is an additional constant axial field (\( B_{\text{ax}} = 6 \, \text{G} \)) imposed by solenoidal coils that surround the chamber.

The plasma currents arise self-consistently as \( A_{\text{pl}} \) changes slowly on the time scale of the disruption (\( dt_{\text{plate}} \approx 80 \, \mu s \), \( dt_{\text{disrup}} \approx 5 \, \mu s \)). In addition, image currents are induced on the plates. Since the external circuit is not affected by the disruption, we evaluate the relative helicity\(^18\)

\[
H' = \iiint (A_{\text{pl}} + A_{\text{image}}) \cdot B_{\text{pl}} \, dv'
\]

\( A_{\text{pl}} \) is the vector potential, due to plasma currents, calculated from Eq. 4a.

The current is evaluated from the measured magnetic field, \( j = (1/\mu_0) \nabla \times B \). \( B_{\text{pl}} \) is then obtained from \( \nabla \times A_{\text{pl}} \). The image currents are obtained from the discontinuity of the tangential component of \( B_{\text{pl}} \) at the plates. To check the data evaluation, the vector potential \( A_{\text{pl}} \) was calculated and when added to \( A_{\text{pl}} + A_{\text{image}} \), the field lines and vector magnetic field of the neutral sheet (Fig. 2b) could be reproduced. The volume integrated over is sandwiched between the plates on top and bottom (\( |z| > 17 \)), the vacuum on the sides (\( |x| > 35 \)), and the magnetic switch (\( y = 0 \)) and anode (\( y = 66 \)).

The temporal dependence of \( H' \) is shown in Fig. 8; a rapid change (\( T \ll T_{\text{lifem}} \)) in the relative helicity occurs at the time of the disruption. Subsequently, the helicity relaxes toward its initial value as the neutral sheet

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**Figure 8**—The magnetic helicity as a function of time. The disruption occurs at \( \Delta t = 0 \). The neutral sheet was formed at \( t_0 = -30 \, \mu s \).
reestablishes itself. The change in helicity is accompa-
nied by changes in the field topology. Plate IV-4 shows
two flux tubes evaluated from the magnetic field due
to plasma current. The initial current (Fig. 7a) is pre-
dominantly along the device axis and the flux encircles
it. After the disruption, the geometry is so complicated
that the linkage can only be seen in stereoscopic views.
Plate IV-4B shows two flux tubes after the disruption.
Although the tubes have nearly common endpoints, one
of them (colored magenta) reverses in direction and loops
through the other (red). Not all pairs of flux tubes link;
in Plate IV-4C the pair simply spirals along in parallel.

A careful analysis of the plasma properties during
the disruption is in progress. Although possible, a measure-
ment of the plasma resistivity has not been made to see
if Eq. 3 is verified. Nevertheless, some conjectures con-
cerning the jump in helicity can be made. First of all,
it cannot be attributed to injection from the switch. The
field lines associated with the switch do not properly link
with those surrounding the plasma current flux tubes
(Fig. 9). The next (unlikely) possibility is that the change
in relative helicity on the other side of the switch is equal
and opposite to that in Fig. 8, thus conserving the total
helicity. A contribution to the helicity could come from
a change in wave activity caused by the current disrup-
tion. The helicity density carried by circularly polarized
waves
is
where \( B_\phi \) is the wave magnetic field
and \( k \) the wavenumber. If the current disruption de-
strays the whistlers within the current sheet, a helicity
transfer could occur, although these waves could only
account for a fraction (\(<5\%\)) of it \((B_\phi \sim 0.5 \, G, \langle \lambda \rangle \sim 10 \, cm)\). The electromagnetic wave spectrum,
however, extends to low frequencies\(^{13}\) and wavelengths
approaching the system size \((\lambda \sim 1 \, m)\). These were not
fully investigated; if polarized, they could carry consider-
able helicity. Finally, since kinetic effects are important
here, it is conceivable that whatever instability causes the
current filaments to snake about generates helicity as
well.

**SUMMARY AND CONCLUSIONS**

The first three sections of this paper were a brief re-
view of previously published work,\(^{11}\) written to orient
the reader to the geometry and plasma parameters in this
reconnection experiment. Once a neutral sheet is estab-
lished, a magnetic switch is used to disrupt the plasma
current. The magnetic field topology rapidly changes and
is accompanied by an abrupt jump in the helicity.

A review of these topological changes is summarized
in Fig. 10, which is arranged as a matrix. The first row
derpicts field lines generated from the data and projected
onto an x-z plane located 8 cm from the magnetic switch.
The second row is contours of the axial component of
the magnetic field \( B_\phi \), and the last row synthesizes this
with a view of some representative field lines in three
space. The vacuum condition (column 1) is the super-
position of an X-point (Fig. 10a) with a constant axial
field (Fig. 10b), which results in the sheared topology of
Fig. 10c. These fields are produced by currents in the
plates bounding the plasma (Fig. 1a) and solenoidal coils
on the device axis. The second two columns show the
magnetic field, \( B_\phi \), due to plasma currents only. Before
\((t = -7.6 \, \mu s)\) the current disruption the transverse field
lines are nested ellipses (Fig. 10d) and little axial mag-
netic field is generated from plasma currents. This is not
the case after the disruption (column 3, \( t = 4.8 \, \mu s)\) where
the transverse field strongly varies along \( y \) and consid-
erable axial field is generated. The total measured field
\((B_{\|} + B_{\perp} + B_{\image})\), shown in the final column, in-
dicates that the neutral sheet (Fig. 2a) has collapsed into
a distorted X-point. It is interesting that the axial field
in this case (Fig. 10k) does not show the structure ob-
served in Fig. 10h. This is because the axial magnetic
fields generated by image currents in the plates nearly
cancel those produced by plasma currents. One may
speculate that full or partial interruptions of the cross-
tail current could also generate "image current systems"
in highly conducting plasma near the plasma sheet enve-
lope. Finally, although the three-dimensional field con-
figuration differs from the vacuum case comparison of
Fig. 10c and 10k is not enough since the plasma cur-
rents depend on field gradients.

Although helicity has been measured indirectly in a
Spheromak experiment\(^{22}\) and estimated within the sol-
lar wind from the spectrum of magnetic turbulence,\(^{23}\)
this is, to the authors' knowledge, the first in situ mea-
surement from direct evaluation of \( A \) and \( B \). The com-
plete experimental database made it possible to show that
the helicity generation was accompanied by linkage of
magnetic flux tubes. The change in helicity occurs when
current flux tubes intertwine and may be accompanied
by a jump in resistivity (Eq. 3) or a large change in plas-
a turbulence. This would accompany the observed cas-
cade of the laminar current sheet into small-scale current
filaments and loops of high spatial turbulence.

It is apparent that a variety of complex interdepen-
dent processes has been observed in this laboratory experi-
ment and it is germane to ask if these have analogs in the
earth's magnetoait. An MHD description has been the
standard tool for a global description of the magnetos-
phere and recent computer simulations (see articles by
Walker and Ogino in this volume) have reproduced it.
This laboratory plasma cannot be described by a single
fluid MHD model. In the first place, the ion Larmor
radius (Fig. 1b) in argon is of order of the transverse
dimension between the plates on the plasma boundaries
The magnetic Reynolds number \((R_m = \mu_0 a L V_A)\),
where \( L \) = scale length, \( V_A = \text{Alfven velocity} \) is or-
ders of magnitude lower than in space \((R_m \approx 10 \, A, \, 25 \, \text{He})\), mainly because of the enormous scale lengths
up there. With this in mind, it is remarkable that the
magnetic field and fluid (ion) flow patterns observed in
the laboratory under quiescent reconnection conditions
(Fig. 2a,c) are what is classically predicted.

These experiments, however, are not meant to model
the magnetosphere, only the merging region. It is be-
coming evident from recent measurements\(^{24}\) that micro-
structure exists within the tail. Spacecraft particle
detectors can now measure distribution functions at
Plate IV-4—Stereoscopic pairs of magnetic flux tubes: (A) before; (B) 6.6 µs into the disruption, depicting tubes that link; and (C) two flux tubes at t = 6.6 µs that do not link. The origin defined by three arrows in the rear corner is at x = -21, y = -16, z = -11. The axis lengths are Δx = 42, Δy = 32, Δz = 22.
many angles in velocity space. The data are replete with ion conics, non-Maxwellian electron distribution functions with beam-like tails, and local heating. This, coupled with observations of large variations in $B_z$, cannot be described within an MHD framework. Regions of this type of activity in the tail exist over relatively small-scale lengths and the Reynolds number associated with them may not be large.

In this laboratory experiment, the neutral-sheet current is carried by electrons. A single fluid MHD model predicts otherwise for the tail and this has been the unproven belief of much of the space physics community until now. There is no reason, however, that electrons should not respond to $E_y$ along a neutral line. Recent analysis of asymmetries in distribution functions of both species obtained by spacecraft indicate this may be the case.

Several years ago, without the current accumulated wealth of satellite data, this laboratory experiment could only be superficially compared to what was then the model of the tail. It was assumed (perhaps with a sigh of relief) that the complexity observed in the laboratory would be ironed out in the highly conducting fluid in space. It is also true that as diagnostic techniques develop, structure previously averaged over always appears.

No claim is made that this laboratory experiment is a scaled-down version of the tail neutral sheet. In the first place the boundary conditions differ; secondly the spacecraft data are incomplete. However, a laboratory basic physics experiment can serve to stimulate fresh interpretation of signatures seen in space.

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