Magnetic Field Line Reconnection Experiments
1. Field Topologies

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A laboratory experiment on the reconnection of magnetic field lines in plasmas has been performed. A large-volume stationary plasma is produced and a time-varying magnetic field is applied to it. In vacuum the field exhibits an \(X\)-type neutral point on axis. Because of the time variation, plasma flows across the separatrix and currents along the separator are induced. The plasma currents modify the magnetic field topology. Flat neutral sheets are observed when flux is transferred across the separatrix into regions of common flux. Forced tearing and magnetic island formation occur in the return phase of the flux. An axial magnetic field is applied along the neutral line. This first part of the report mainly deals with the magnetic field topologies, but subsequent reports will present observations of plasma properties, anomalous resistivity, particle heating, and acceleration.

INTRODUCTION

The reconnection of magnetic field lines in plasmas is one of the key problems in solar terrestrial physics. For a long time it has been considered as a possible mechanism for generation of fast particles in solar flares and magnetospheric substorms [Dungey, 1953]. Numerous authors have proposed theoretical models, which have been reviewed recently by Vasyliunas [1975]. Various computer simulations have been performed in support of the theoretical models [Ugai and Tsuda, 1977; Hayashi and Sato, 1978]. Observations from spacecraft [Frank et al., 1976; McPherson, 1979] generally confirm the existence of fast particles near regions of neutral points, but the data collected from a single observation point are inadequate to obtain a conclusive picture of the large-scale processes.

Finally, efforts have been undertaken to model reconnection processes in controlled laboratory plasmas. Pioneering work by Andersen and Kunkel [1969] and by A. Bratenahl and co-workers [Bratenahl and Teatet, 1970; Baum and Bratenahl, 1977] stimulated a number of investigations on reconnection processes in pinch-type plasmas [Syrovatkii et al., 1976; Ohayu et al., 1974]. A striking feature of these experiments was a current interruption resulting in strong particle acceleration. Because of the difficulties in diagnosing high-density transient plasmas a fully detailed picture of the reconnection processes in these plasmas has not yet emerged.

In the present work a new attempt is made at understanding reconnection processes in a laboratory plasma [Stenzel and Gekelman, 1979]. Since the main advantages in modeling space plasma phenomena in the laboratory are diagnostic access, repeatability, and parameter control, we have chosen a parameter regime which optimizes these features. The optimum density is \(n_e \approx 10^{12} \text{ cm}^{-3}\), the characteristic size \(L \approx 1 \text{ m}\) \(\beta \sim c/\omega_p\), the magnetic field \(B \approx 20 \text{ G}\) such that \(\beta = n_kT/(B^2/2\mu_0) = 1\). Such a laboratory plasma has been developed by the authors by carefully scaling up hot cathode discharge devices [Stenzel, 1976]. These possess most of the desirable properties of a good laboratory device: The parameters are uniform and stable and can be varied over a wide regime. The plasma properties are diagnosed internally with small probes which provide excellent spatial and temporal resolution without causing serious perturbations of the system. The time scale of the pulsed reconnection experiment lends itself to digital data acquisition. The repetition rate is sufficiently high \((\tau_{\text{rep}} \approx 2 \text{ s})\) such that a large amount of detailed information is obtained in a reasonably short time interval.

In the experiment an initially stationary uniform plasma is produced to which a time-varying magnetic field is applied. The latter has antiparallel field lines with an \(X\)-type neutral point in the center. The time scale during which the applied magnetic field rises is larger than the Alfvén transit time from boundaries to the neutral point but short compared with the resistive diffusion time for the corresponding distance. The magnetic Reynolds number is \(R_m \approx 20\). While the electrons are strongly magnetized, the ions remain essentially unmagnetized. Ideal MHD theories model the reconnection process by considering a resistive region containing an \(X\) point or neutral sheet surrounded by a perfectly conducting plasma. Fluid flows into this ‘diffusion’ region carrying frozen influx with it; fluid and reconnected flux subsequently leave. This experiment models the dynamic reconnection processes within and close to the diffusion region. The critical questions to which this experiment is addressed are the magnetic field topologies and the plasma dynamics including heating and acceleration, anomalous resistivity, and fluctuations.

The self-consistent interaction between plasma and magnetic field leads to a complicated space-time dependence of all parameters. We have attempted to measure all important physical quantities in this experiment. Without such a complete data base, erroneous interpretations of the plasma dynamics are easily possible. Because there is such a wealth of data, we wish to break up the subject into four parts. This first paper deals with the magnetic field topology. It will also provide a detailed description of the experimental setup and measurement techniques. In the second part [Gekelman and Stenzel, this issue] we present the plasma properties in space and time, i.e., density, temperature, and potentials. The third part will deal with particle accelerations and flows. Direct measurements of electron and ion drifts have been performed. The force balance between pressure and magnetic forces is investigated. In the fourth part the plasma resistivity and dissipation will be analyzed. From direct measurements of electric fields and currents the resistivity is determined and found to be anomalously large and current dependent. The dissipated power can be accounted for by excitation, ionization, electron and ion heating, and fluid acceleration.
In this first part we shall show the self-consistent formation of a neutral magnetic sheet when magnetic flux is transferred across the separatrix. The thickness of the neutral sheet approaches the inertial limit; the width exceeds the thickness by an order of magnitude. No tearing of the current sheet is observed within approximately five Alfvén transit times. The induced plasma current does not exhibit disruptions. Thus it is possible to follow the field topologies throughout the period of external magnetic field rise and decay. The observed transition from neutral sheets to X and O points will be presented. Important quantities such as the current distribution, vector potential, and induced electric fields will be derived from the magnetic field measurements.

**Experimental Setup**

The experiments are performed in a large linear discharge plasma shown schematically in Figure 1. Using a 1-m-diameter, indirectly heated, oxide-coated cathode with adjacent mesh anode, a dc discharge is generated in argon at a gas pressure $p_0 = 2 \times 10^{-4}$ torr. The plasma column is radially confined by a constant uniform axial magnetic field $B_0 = 20$ G. Typical plasma parameters are density $n_e \approx 10^{15}$ cm$^{-3}$, temperature $kT_e \approx 10 \text{kT_e} = 5$ eV. While the cathode is heated continuously ($P_e \approx 50 \text{ kW heater power}$), the discharge is pulsed repetitively (5 ms on, 1 s off) so as to avoid thermal runaway of the cathode due to the large discharge power ($P_{dis} \approx 50 \text{ V} \times 1500 \text{ A} = 75 \text{ kW}$). The space charge limited electron emission of the cathode is highly uniform; hence the plasma parameters are essentially constant ($\Delta n/n < 10\%$) for $\sim 80$ cm across $B_0 = B_{r0} \hat{e}_r$, and $\sim 200$ cm along $B_0$. The temporal reproducibility from pulse to pulse is excellent ($\Delta n/n < 5\%$). The pulse length is sufficient to reach steady state plasma conditions at which time the reconnection experiments are initiated.

Transverse to the axial bias magnetic field $B_{r0}$, a pulsed magnetic field $B_z(x, z, t)$ is established whose geometry is sketched in Figure 2a (the magnetotail coordinate system has been adopted here). In vacuum the field topology exhibits an X-type neutral point on axis ($x = z = 0$). The dashed separatrix divides the outer common flux from the two inner cells with private flux encircling each conductor. The field is produced by passing two identical currents ($0 < I_\perp < 25$ kA) axially through two parallel aluminum plates of dimensions in width 74 cm, length 175 cm, spacing 32 cm, and thickness 1 cm. The plates are parallel to the plasma column, but the cathode emission is arranged so as to produce plasma only in the volume between the plates. The plate current returns through the metallic chamber walls (5-cm-thick aluminum) to the current sources. The skin depth of the pulsed current is much smaller ($\sim 2$ mm) than the thickness of the metallic conductors.

The time dependence of the plate current or transverse magnetic field is shown in Figure 2b. The waveform corresponds to the current dependence in a damped LC (inductance-capacitance) circuit. The power supply consists of two 10 kV, 80 $\mu$F capacitor banks which are discharged via ignitrons, damping resistors, and air core transformers into the essentially inductive plate system. The supply delivers up to 50

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*Fig. 1.* Schematic view of the plasma device and some diagnostics.

*Fig. 2.* (a) Cross-sectional view of the device showing the transverse magnetic field geometry without plasma. The applied current $2I_\perp$ flows in a coaxial system where the center conductor consists of two parallel plates. (b) Time dependence of current $I_\perp$ and voltage $V_z$ applied to each plate.
kA, 500 V to the water-cooled plates at a pulse repetition time of 2 s.

Figure 3 shows an electrical block diagram which summarizes the essential components of the experiment. When the space between the plates has been filled with a uniform discharge plasma, the plate current is pulsed on. During the first period of current rise, an inductive electric field $-\partial A/\partial t$ is generated along the plasma column. This field drives a plasma current $I_p$ which is dominantly carried by electrons drifting from the cathode to a grounded end plate terminating the plasma column. The current closes via the chamber walls to the cathode, which emits as many electrons as are collected at the end plate so as to maintain space charge neutrality. Thus the plasma current is an induced or secondary current in response to the primary current in the plate system. The plasma current $I_p$ flows in the direction opposite to the plate current $I_o$, so that the penetration of magnetic flux through the plasma is slowed down. This results in a change of the magnetic field topology; for example, the curl-free neutral X point of the vacuum field becomes a thin neutral sheet in a plasma. It is the purpose of the experiment to investigate the self-consistent field topologies and the plasma dynamics in this reconnection process.

In the second phase, when the applied plate current decreases in time, the electric field is reversed. No current flows to the end plate. However, circulating currents are observed, and the field topology is fundamentally different from that in vacuum, exhibiting an O-type neutral point rather than an X point. When the polarity of the applied waveform is reversed, the current flow in the second phase is as described earlier for the first phase. In the absence of the induced electric field the plasma current along the column is negligible. The discharge current flows between cathode and grid anode rather than to the end plate [Stenzel, 1978].

Measurement Techniques

The laboratory experiment is designed to optimize the diagnostic access to the plasma. The parameter regime allows us to insert probes into the plasma without significant perturbations of the plasma or damage to the probes. The large scale lengths yield good spatial resolution. The long time scale provides for good temporal resolution. The vacuum chamber is equipped with approximately 50 ports so that the plasma is accessible from all directions.

All the basic parameters of the experiment are carefully monitored and maintained stable. Discharge voltage and current, gas pressure, etc., and pulsed magnetic fields are measured digitally to within 0.1% accuracy. Before taking data the cathode is fully activated and operated for several days so as to ensure stable operation. The stable lifetime of the cathode coating exceeds 100 pulses or ~5 weeks of continuous operation. It is coated and reactivated within 1 week.

The plasma properties are diagnosed with Langmuir probes. The I-V characteristic is swept within approximately 5 μs, converted with a fast analog-to-digital converter (20 MHz) and evaluated on-line with a minicomputer (MIK 11/2B). Density, electron temperature, and plasma potential are found from a single plane probe. Using two identical probes back to back, the current density or relative drift velocity is found from the difference in the electron saturation currents. Using two probes spaced by a distance Δx, the difference in plasma potential yields the electrostatic field $E = -\nabla \phi = -\Delta \phi / \Delta x$. The density obtained from probe measurements agrees favorably with values obtained independently from a 10-GHz microwave interferometer and from dispersion measurements of whistler waves. The Langmuir probe traces are swept prior to and at different times during the magnetic field pulse so as to follow the temporal variations of the plasma parameters.

The ion temperature is obtained from retardation grid ion velocity analyzers. Ion drifts are found analogous to electron drifts from the difference in saturation currents to two analyzers or negatively biased plane Langmuir probes. Since the ion drift is a vector, three orthogonal pairs of differential ion collectors are mounted at the end of a probe so as to obtain direction and magnitude of the local fluid drifts.

The magnetic field is measured with magnetic loops and Hall probes. The latter are used only in the absence of plasma in order to calibrate the loop probes. In the presence of the hot cathode the probes assume temperatures as high as 400°C at which only the loop probes can operate. These consist of 0.1-mm-diameter anodized aluminum wire toroidally wound as 50 turn coils with 5-mm major, 1-mm minor poloidal

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Fig. 3. Electrical block diagram showing applied voltage and current ($V_x$, $I_x$) in the primary circuits and induced electric field ($-A_x$) and secondary current ($I_p$) which flows through the plasma between cathode and end anode and closes through the chamber wall.

Fig. 4. Block diagram for the magnetic field measurements using magnetic loops and a digital data acquisition system.

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Fig. 5. Peak magnetic field $B_0(x)$, flux per axial length $\psi_{x0}$, and vector potential $A_x(x)$ along the x axis in the absence of plasma. For comparison the width of the conductor plates and the chamber inner radius $R$ are also indicated. $I_{pmax} = 17$ kA, $y = 87$ cm.
radius. As shown in Figure 4, two orthogonal electrostatically shielded loops are arranged at the end of the probe shaft which can be rotated by 90° around its axis so as to determine also the third component of the magnetic field vector. The probe can be scanned along the horizontal position $x$ at different vertical positions $z$ so as to determine point by point the field distribution in a transverse plane $y = \text{const}$. By inserting the probe into different radial ports the three-dimensional field distribution $B(r, t)$ can be composed from data of the various transverse planes.

The magnetic loop signals are time integrated and recorded at a given position versus time. With fast analog-to-digital converters the time dependence is quantized in up to 1024 increments, and the data are stored digitally with 8-bit accuracy. Since the reconnection process involves shot-to-shot fluctuations, an ensemble average over typically 10 pulses is performed. These average time dependences of the three field components are recorded at about 300 points in the transverse plane. On a large computer (CDC 7600) the data matrix is evaluated to yield, for example, spatial vector plots of the magnetic field at different times. Other useful operations such as spatial differentiation and integration to obtain currents and vector potentials are also performed. The ion flow velocity is analyzed in the same way as the magnetic field. Both data sets can be combined in order to calculate Hall fields $\mathbf{v} \times \mathbf{B}$. These in turn are combined with electric field and current data to yield the plasma resistivity. Thus a detailed picture of plasma and field properties in space and time is obtained. It forms the basis for understanding the complicated plasma dynamics in a reconnection process.

Fig. 6. Comparison of the magnetic field topologies in vacuum (Figures 6a-6c) and in plasma (Figures 6d-6f) at $t = 40 \mu s$. (a) and (d) Unit vector fields indicating the local direction of $\mathbf{B}_z$. Solid line indicates separatrix. (b) and (e) Contours of constant magnitude $|\mathbf{B}_z|$. Inside the central contour $\mathbf{B}_z = 0$, increasing at 0.5 G/contour in Figure 6b, 2 G/contour in Figure 6e. (c) and (f) Three-dimensional display of the field strength for an X point and neutral sheet topology, respectively. Argon $3 \times 10^{-6}$ Torr, $y = 87$ cm, $I_{\text{ion},\text{max}} = 17$ kA.

Fig. 7. Comparison of transverse (Figure 7a) and longitudinal (Figures 7b and 7c) time-varying magnetic field components at $t = 40 \mu s$, $y = 87$ cm, $I_{\text{ion},\text{max}} = 17$ kA. (a) $B_{z,\text{max}} = 15.3$ G at $x = 26$ cm, $z = -18$ cm. (b) $B_{x,\text{max}} = 2.2$ G at $x = -14$ cm, $z = -11$ cm. (c) Contours of constant $B_x$ are dotted for $B_x > 0$, solid for $B_x < 0$, and vary by 0.25 G/contour. Note that there is also a dc magnetic field component $B_y = 20$ G.
Figure 8. Transverse magnetic fields $B_z(x, z)$ at three different axial positions $y$ showing the spatial development of the neutral sheet at a given time $t = 55 \mu s$. (a), (b), (c) Unit vector fields $B_x/B_y$. (d), (e), (f) Contours of constant $|B|$, with $\Delta B = 1.25 \text{ G/contour}$ and $B = 0$ in inner closed contour. $I_{\text{max}} = 17 \text{ kA}$.

EXPERIMENTAL RESULTS

In order to describe the magnetic field topology $B(r,t)$ one has to display three vector components as a function of three spatial coordinates and time, possibly for different plasma parameters. We shall have to separate this problem into several steps. First, the spatial dependence will be discussed starting out with one component versus one coordinate, then two components in a plane. Second, the time dependence of the dominant components will be described. Finally, the time dependence of current density and flux calculated from the magnetic fields will be shown.

Spatial Field Properties

In order to compare the magnetic field topologies in plasma and vacuum we start out with the vacuum field properties.

Figure 5 shows the $x$ dependence of the field strength $B_z(x)$, the common flux per axial length $\psi(x) = \int_{x'} B_z(0, x) dx'$, and the vector potential $A_x = \int_{x'} B_z(0, x') dx'$, where $R$ is the radius of the vacuum chamber. In the present flat plate geometry most of the flux ($\sim 72\%$) is outside the volume between the plates. Hence the induced electric field $E_{\text{ind}} = -\partial A/\partial t$ shows relatively small variations in the region of interest.

The two-dimensional field distribution $B_z(x,z)$ is shown in Figures 6a–6c in vacuum and, for comparison, with plasma in Figures 6d–6f. The top graphs show the local direction of the magnetic field, displayed as unit vector fields. The middle graphs present the magnitude $|B|$ as contours of constant field strength. And at the bottom the field strength is shown in a three-dimensional view. In the absence of plasma the field exhibits an $X$-type neutral point in the transverse field components near the geometric center of the parallel plate system. Close to the null point the field is similar to that of a quadrupole, $B(r, \phi) = \mu_0 I r/(\pi a^2) [\sin 2\phi, + \cos 2\phi x_3]$, where $a$ is the characteristic distance from the currents, $I$, to the neutral point. The separatix ($x = \pm \pi/4, \pm 3\pi/4$) intersects at right angles, satisfying $\nabla \times B = 0$. The field strength increases linearly with distance $r$ from the neutral point, i.e., the magnitude contours are circles, $r = \text{const}$. With increasing distance, $r$ the approximation breaks down, and the field is governed by the exact current distribution on the plates. We find essentially antiparallel field lines near the plates, vertical fields $B_z$ in the symmetry plane $z = 0$, and a gradient in $|B|$ mainly in the $x$ direction. As the plate current increases in time, the vacuum field geometry is essentially unchanged except for small shifts in the location of the $X$ point due to current imbalance in the two plates. The field strength varies in time proportional to the applied current.

In the presence of plasma the field topology and field

![Figure 9](image-url)
strength are drastically changed due to the induced plasma currents. Even though the plasma currents \( I_s \) are small compared with the plate current \( I_p = 10 f_p \), the field modifications are strong, since the vacuum fields are relatively small between the plates. Figures 6a–6f show the observed fields inside the plasma at a time when the plate current rises. As predicted by the classical picture of merging [Dungey, 1953], the antiparallel horizontal field lines flatten near the neutral region. The separatrix now intersects along a line rather than a point, indicating a topological change from a first- to second-order contact point. The arrow plots are unit vectors; they do not indicate magnitude. Along the sheet the magnitude of the transverse field \( B_{\perp} \approx 0 \) (which is consistent with a neutral sheet within the limit of measurement reduction, \( 1 \times 10^{-1} \) G). The contour plot (Figure 6e) shows that the field vanishes over a broad central region of width to height ratio \( \Delta x/\Delta z \approx 35 \) cm/3 cm \( > 10 \). The width of the neutral sheet \( \Delta z \) defined as half width at half maximum of the current density profile, \( J_z = (1/\mu_o) (\nabla \times B)_z \), can be as narrow as \( \Delta z = 1.5 \) cm, corresponding to a few collisionless skin depths, \( c/\omega_p \approx 0.6 \) cm, which is considered to be the narrowest width of a current channel. The probe diameter is 1 cm; the instrumental width caused by this sets the spatial scale. The neutral sheet, which is also visible as a trough in Figure 6f, remains stable against tearing for \( \sim 80 \) µs or four Alfvén transit times from plates to neutral sheet. The formation of a neutral sheet occurs self-consistently as a result of the induced plasma currents. No other external fields or currents are imposed to synthesize a sheath configuration [Spruit, et al., 1976].

In Figure 6 we have presented two components of the magnetic field, i.e., the projection of the total field \( \mathbf{B} = (B_x, B_y, B_z) \) into the x-z plane. The third component, \( B_z \), consists of the uniform constant bias magnetic field \( B_z = 20 \) G, and a time-varying field \( B_{\perp} \) created by plasma currents flowing in the x-z plane. Figure 7 shows at a given time (\( t = 40 \) µs) and axial position (\( y = 87 \) cm, \( y = 0 \) at cathode) both transverse (Figure 7a) and axial (Figures 7b and 7c) field components. It is apparent that the time-varying axial component is small compared with either the static axial component or the average transverse field. The sign of \( B_z(t) \) changes spatially, but dominantly, \( B_{\perp} \) is located in the same direction. The observation of \( B_{\perp} \) indicates the presence of transverse currents \( J_z \), which will be shown later (Figure 12b).

While Figures 6 and 7 show the three vector components \( (B_x, B_y, B_z) \) in two dimensions (x, z), we now complete the spatial picture by showing the dependence on the remaining axial coordinate \( y \). Figure 8 displays the dominant transverse fields \( B_x \) (x, z) in three x-z planes at a distance \( y = 37, 87, \) and 137 cm from the cathode. The plate electrodes extend from \( y = 13 \) cm to \( y = 188 \) cm. The first plane is located at a distance \( \Delta y = 24 \) cm from the end of the plates which is less than the vertical plate separation (\( H = 32 \) cm). Presumably due to fringing field effects and the proximity to the cathode, a neutral sheet has not yet developed, and the field geometry resembles that of a flattened X point. However, at \( y = 87 \) cm, and especially at \( y = 137 \) cm, well-developed neutral sheets are observed. To first order, the axial variations in the central region of the plates are negligible compared with the transverse gradients. However, there is some tendency for the neutral sheet to flatten and to lengthen in x direction with increasing distance from the cathode. This may be related to the fact that for large \( y \) values only field lines with \( B_z = 0 \) (note \( B_{\perp} = 20 \) G) lead to the cathode, while others spiral around the plates through vacuum. Thus strong field-aligned currents can only flow in the neutral sheet region. In fact, experiments with larger axial bias fields show less pronounced neutral sheets also in the middle plane.

**Temporal Field Properties**

The current through the metal plates, \( I_p \), and hence the applied magnetic field, vary in time (see Figure 2b). The plasma currents \( I_p \), driven by the induced electric field \( -\partial A/\partial t \) change in response to the applied currents \( I_p \propto -\partial A/\partial t \propto -\partial I/\partial t \). Hence the total magnetic field, which can be viewed as a superposition of the fields of two current systems, changes in configuration and strength with time. The difficulty in predicting the resultant field lies in the complicated behavior of the plasma as a conductor, i.e., its fluid character, anisotropies, and nonlinearities. We have therefore investigated the field topology as a function of time. The transverse fields \( B_{\perp} (x, z) \) are of primary interest. In Figures 9–11 some characteristic field patterns are shown which are selected from the typically \( 2^\text{nd} \) time steps generated digitally in each data run.

Traditionally, most of the attention has been focused on the initial phase during which the current \( I \) rises linearly in time. If the rise time could be made long in terms of the Alfvén transit time, a steady state flow across the separatrix would, in principle, be achieved, but in practice there is a limit for the peak current (here \( \sim 50,000 \) A) and hence for the rise time (here approximately five Alfvén transit times). Other experiments [Baum and Bratenahl, 1977] the relevant time span can also be limited by the available plasma to flow across the separatrix. Thus in our experiment we are observing dynamic reconnection events rather than steady state conditions.

Figure 9b shows the observed field topology during phase I, the rise of the external current, sketched not to scale in Figure 9a. It is characterized by the long thin neutral sheet described earlier. It develops within one to two Alfvén transit times (~20 µs) and remains relatively unchanged until the external current reaches its maximum. Near the current peak, denoted as phase II, the neutral sheet becomes shorter and thicker un-
Fig. 11. Temporal change of the field topology from a magnetic island (phase V in Figure 9a) into a neutral sheet (phase VI). The display includes linearly scaled vector fields \( \mathbf{B}_x(x, z) \) (Figures 11a–11f), unit vector fields \( \mathbf{B}_x/B_z \) (Figures 11a–11e) which enhance the field structure near the nulls, and contour maps \( B_z = \text{const} \) (Figures 11g–11i). The O point (Figures 11a, 11d, and 11g) flattens into an elongated island (Figures 11b, 11e, and 11h) which eventually approaches a sheet with two adjacent flat \( X \) points (Figures 11c, 11f, and 11i). Here \( y = 137 \) cm, \( I_{\text{imax}} = 17 \) kA, 1.25 G/contour.

til it assumes the shape of a nearly curl-free \( X \) type neutral point (see Figure 9c). Phenomenologically, this transition is explained by the vanishing of the inductive electric field, hence plasma currents near the peak of the plate current. When the latter decreases the electric field reverses sign and grows again. Plasma currents are now induced to flow in the same axial direction as the plate currents. Whereas in the first phase the plasma currents inhibited the flux transfer from private to common flux cells, they now slow down the reverse flux transfer. This process leads to the formation of a neutral sheet elongated in the \( z \) direction, shown in Figure 9d and denoted as phase III. This vertical neutral sheet is considerably broader than the earlier horizontal sheet. It also exists only for a relatively short period of time and then is forced to tear into \( O \) and \( X \) points.

The tearing process occurring in phase IV is demonstrated in Figure 10. Initially one (Figure 10b) or two (Figure 10a) magnetic islands are formed which rapidly coalesce into a single growing island (Figure 10c). The associated \( X \) points are pushed vertically out of the observation region, presumably into the surface of the metal plates. The 'forced' tearing process is readily understood if one considers the temporal decrease of the plate current and the increase of the plasma current (see Figure 9a). Tearing occurs when the \( O \)-type fields of the plasma currents dominate over the \( X \)-type fields of the plate currents. In fact, when the plate current goes through zero denoted as phase V, the magnetic field exhibits only closed field lines linked with the plasma currents. This \( O \) point topology is essentially depicted in Figures 11a, 11d, and 11g.

After the zero crossing, the plate current increases again but now in reverse direction. This result in an increase of the horizontal and a decrease of the vertical field components, forming an elliptical island elongated in \( x \) direction (Figures 11b, 11e, and 11h). Two \( X \) points move in toward the elongated \( O \) point (Figures 11c, 11f, and 11i). The long flat island finally collapses into a neutral sheet. Its length extends over nearly the entire plane of measurement (\( \Delta x \approx 50 \) cm). The topology is the same as in Figure 9b, but the field directions are reversed.

If the external current would continue to oscillate, the field topologies would repeatedly go through the cycle described above. However, the actual circuit has a strongly damped current waveform, so that subsequent cycles are not comparable with initial ones. Furthermore, the two plate currents are difficult to keep balanced in time, which causes vertical asymmetries in the field pattern noticeable in Figure 11.

Currents, Flux

From the measurement of the local time-varying magnetic fields one can obtain by spatial differntiation the plasma current density \( \mathbf{J} = \nabla \times \mathbf{B}/\mu_0 \) and, by integration, the flux \( \psi = \int \mathbf{B} \cdot d\mathbf{a} \) and vector potential \( \nabla \times \mathbf{A} = \mathbf{B} \) whose time derivative yields the induced electric field \( \mathbf{E} = -\partial \mathbf{A}/\partial t \). These quantities are important in describing reconnection processes and will be discussed here, since they are based on magnetic field measurements. For example, we will show quantitatively the excess flux building up as a result of the slower merging rate in plasmas than in vacuum. Additionally, more detailed data on currents and electric fields will be presented later in con-

Fig. 12. Calculated current density \( \mathbf{J} = \nabla \times \mathbf{B}/\mu_0 \). (a) Axial current distribution displayed as contours \( J_x = \text{const} \) in increments of 0.2 A/cm²/contour. Characteristic values: minimum \( J_x(17 \) cm, \(-1 \) cm) = \(-1.68 \) A/cm², maximum \( J_x(25 \) cm, \( 5 \) cm) = \( 0.195 \) A/cm², spatial average \( \langle J_x \rangle = 0.58 \) A/cm², position \( y = 137 \) cm, time \( t = 55 \) ms. (b) Perpendicular current density \( J_z(x, z) \) at \( t = 40 \mu s, \ y = 87 \) cm. Characteristic values: maximum \( J_z(-12 \) cm, \( 9 \) cm) = \( 0.27 \) A/cm², average \( \langle J_z \rangle = 0.09 \) A/cm², \( I_{\text{imax}} = 17 \) kA.
show reasonable agreement in waveform and absolute values, confirming that the plasma current is axially continuous. However, when the applied current decays, the induced electric field and plasma current reverse sign. Since the end anode does not emit electrons, its current is negligibly small. The axial plasma current observed in the middle of the device is assumed to be closed via transverse ion currents flowing to the metal plates. Because of the relatively large surface area of the plates the ion loss current can account for the positive axial electron current. The experiment has also been run with reverse polarity of the applied current. Consequently, the induced plasma currents are smaller in the first quarter cycle and larger in the second when the electron current closes via the end anode.

The magnetic flux through a surface area $S$ is given by $\psi = \oint_S B \cdot da$, where $da$ is a surface element with normal parallel to $B$. Since the time-varying magnetic field is dominantly transverse and independent of $y$, it is sufficient to consider the flux per axial length $\psi' = \psi / y = \int (-B_z dz + B_x dx)$. Conventionally, the flux in our field geometry can be classified into two groups: (1) private flux associated with field lines encircling each conductor plate, and (2) common flux encircling both plates. Since all field lines are confined to within the cylindrical chamber wall of radius $R$, the common flux can be found from $\psi'_c = \int_0^{2\pi} B_x dx$, the private flux from $\psi'_p = \int_0^{r/2} B_z dz$, where $H$ is plate spacing, and the total flux is $\psi' = \psi'_c + \psi'_p$. The vector potential $A$ defined by $B = \nabla \times A$ has an axial component given by $A_x = \int (-B_z dz + B_x dx)$ with $\partial A_x / \partial y = 0$. The line integration starts appropriately at the chamber wall where the magnetic field rapidly goes to zero due to the surface return currents. Thus the vector potential on the separator is identical with the common flux, $A_x(0,0) = \psi'$. The time derivative of the vector potential yields the induced electric field $E_x = -\partial A_x / \partial t$.

The induced electric field along the separator $E_x(0,0)$ is measured with a loop probe consisting of two parallel wires along the x axis and a short wire in y direction ($\Delta y = 4$ cm) at $x = 0$. The open loop voltage measured just outside the chamber wall yields $E_x = V_0 / \Delta y$. By time integration the vector potential or flux is found. Typical measurement results both in vacuum (subscript v) and with plasma (subscript p) are shown in Figure 14. The induced electric field (Figure 14a) is smaller when the plasma current rises and larger when it decays in comparison with the fields in vacuum. The difference is due to the flux change associated with the plasma current. The connected with the subjects of anomalous resistivity and dissipation.

The axial current density profile $J_y(x, z)$ corresponding to the neutral sheet topology (Figure 8c) is shown in Figure 12. The current flows mainly in a sheet of half width at half maximum $\Delta z = 3.5$ cm corresponding to seven collisionless skin depths ($c/\omega_{pe} = 0.5$ cm). This value represents an upper limit, since the observed width is broadened by the spatial response of the magnetic probe ($\Delta z = 1$ cm) and by averaging over fluctuations from pulse to pulse. Current channels as narrow as $\Delta z = 1.5$ cm have been observed and reported earlier [Stenzel and Gekelman, 1979]. It is interesting to note that the current density generally exhibits two maxima near the ends of the neutral sheet rather than a single peak in the middle. The narrow current channel as well as the magnitude of the peak current density ($J_y = -1.7$ A/cm$^2$) imply that the current is carried by electrons. The corresponding relative electron drift velocity for a Maxwellian distribution with $T_e = 5$ eV is calculated to be $v_{de}/v_e = 0.08$. Outside of the current channel there are regions of reverse currents, but when averaged over the plane of measurement, the current density is nonzero ($<J_y> = -0.58$ A/cm$^2$), implying that a net current is induced as schematically shown in Figure 3. This current is also measured independently at the end anode. A comparison between the two separate current measurements will be presented in Figure 13. Figure 12b shows direction and magnitude of the transverse current density $J_z = (J_x, J_y) = (-\partial B_y / \partial z, \partial B_x / \partial x) / \mu_0$, with $B_x$ from Figure 7 and $\partial B_y / \partial y = 0$ according to Figure 8. The transverse currents are partly Hall currents ($J_z = B_x$) and partly the projection of field-aligned currents in the x-z plane. On the average the transverse current density is small; yet locally it may not be negligible compared with the axial current density.

Since the magnetic field strength and topology change in time, the current and its distribution also vary temporarily. Here we will only show the time variation of the total plasma current which is calculated by integrating the current density $\langle \nabla \times B \rangle / \mu_0$ over the cross section between the metal plates. For comparison, Figure 13 also shows the measured current flowing between the end anode and ground. During the rise of the applied current in the metal plates the induced plasma current is negative, i.e., flows toward the cathode opposite to the electron drift. The two independent current measurements

Fig. 13. Axial plasma current $-I_y$ versus time determined from magnetic field measurements and from the externally measured end anode current (bold line). Here $I_{e\text{max}} = 17$ kA.
mon flux shown in Figure 14b is smaller with plasma currents than without. The private flux shows a corresponding excess of flux as long as the plasma current flows in the opposite direction to the plate current ($t \approx 80\ \mu s$). When the plasma current reverses direction, the common flux is larger and the private flux smaller than in vacuum. However, since the field topology changes from $X$ to $O$ point, the original distinction of the two flux groups can no longer be made. The full time behavior of the 'private' flux $\psi'_{p0} = \int_{-H/2}^{0} B_{x0,0,0} \, dz$ is shown in Figure 15 and demonstrates the above described behavior.

The complete spatial dependence of the vector potential is obtained by adding to the common flux $\psi' = A_{0}(0,0)$ an incremental potential $\Delta A_{y}(x,z) = \int_{0}^{z} B_{d,0,0} \, dx = \int_{z}^{0} B_{d,0,0} \, dx$. While the first contribution was shown in Figure 14, the second one is given in Figure 16. The contour map of $\Delta A_{y}$ (Figure 16a) shows quantitatively the distribution of the vector potential. Furthermore, since lines of constant $A_{y}$ represent magnetic field lines ($dx/dz = B_{y}/B_{z}$) and the line spacing is a measure for the field strength ($B = \nabla \times A_{y}$), the display is an alternate but equivalent description of the field properties compared with, e.g., Figures 6a and 6b. Sign and magnitude of $\Delta A_{y}$ are best shown in the three-dimensional display of Figure 16b. The surface has a saddle point at the origin $[\Delta A_{y}(0,0) = 0]$. The potential increases toward the current-carrying plates and decreases most rapidly in $\pm x$ direction toward the chamber wall where $A_{y} = 0$. However, in the presence of the magnetic island the potential surface exhibits a maximum at the $O$ point, i.e., the center of the plasma current profile.

**DISCUSSION AND CONCLUSION**

The present laboratory experiment offers a unique possibility to investigate in detail the dynamic interaction of magnetic fields with plasmas. In this first part we have concentrated on the magnetic field measurements. A major result was the observation of a neutral sheet which developed self-consistently upon compressing flux through an $X$-type neutral point. The evolution of this field topology is long been postulated to occur in solar flares and the magnetosphere [Dungey, 1953], although there the flux dynamics is thought to be caused by plasma flows rather than time-varying currents. We also observed the forced tearing of field lines when the self-generated fields by plasma currents dominate over the externally applied fields. Such a formation of magnetic islands can conceivably also occur in space when plasma flows change in time. The field topology in this experiment is strictly three dimensional, although in the central regions of the long conductor plates the transverse fields are an order of magnitude larger than the axial time-varying fields.

From the magnetic field measurements a number of important quantities have been evaluated. The current density is found, and the resultant total plasma current confirmed by end plate current measurements. The vector potential and induced electric field have been determined. Currents and electric and magnetic fields will later on be used to calculate energy flows ($E \times H$), stored energy ($B^{2}/2\mu_{0}$), dissipation ($E \cdot J$), resistivity ($E/J$), and acceleration ($J \times B$). Thus the magnetic field measurements provide the most important data in the reconnection problem. However, it has to be complemented by measurements of the plasma properties in order to examine the transfer of magnetic to particle energies.

It should be pointed out again that the present data represent ensemble averages over 10 pulses per point, i.e., several thousand pulses per plane. Thus only the repetitive part of the events is displayed, and fluctuations are averaged out. Magnetic field fluctuations are significant near neutral regions, and it is conceivable that instantaneously, the neutral sheet has far more structure than displayed here. Fluctuations in the current density are more pronounced than those in the magnetic field, since the latter is an integral value over the current distribution. However, no impulsive interruptions of the plasma current have been observed, which seems to be a characteristic feature of inverse pinch devices. A careful study of the fluctuation phenomena will be performed in the future.
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