Magnetic Field Line Reconnection Experiments

2. Plasma Parameters

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Detailed measurements of density, temperature, and potentials of a laboratory plasma undergoing magnetic field line reconnection are reported. The plasma column \( n = 10^{13} \text{ cm}^{-3}, T_e = 5 \text{ eV}, B_B = 20 \text{ G} \) is subject to a time-varying transverse magnetic field with X-type neutral point \( (B_{\text{max}} = 100 \text{ G}, \Delta t = 100 \mu s) \). Time- and space-resolved probe measurements show rapid electron heating giving rise to further ionization up to neutral burnout. Density and temperature exhibit strong spatial nonuniformities in all directions as well as significant temporal fluctuations. The plasma potential increases in the direction of the induced electric field, indicating the presence of axial space charge separation. Electrostatic fields also develop perpendicular to the applied fields and can exceed the latter in magnitude. The knowledge of the basic plasma parameters is essential in explaining the observed magnetic field configurations, plasma flows, and resistivity, which are described separately.

INTRODUCTION

Most laboratory experiments on magnetic field line reconnection [Andersen and Kunkel, 1969; Baum and Bratenahl, 1980; Ohyabu et al., 1974; Syrovatski et al., 1973; Zakakashvili et al., 1978; Irby et al., 1979] have been performed in pinches, i.e., fast, high-density discharges of relatively small dimensions which are difficult to diagnose internally with good time and space resolution. Similarly, the research on tearing modes in tokamaks, which is closely related to the physics of reconnection, is limited by diagnostic difficulties, e.g., internal magnetic field topologies are inferred from external measurements or indirectly from X-ray data [von Goeler et al., 1974; Mirnov and Semenov, 1977]. Observations of reconnection phenomena in space from satellites [Frank et al., 1976; McPherron, 1979] present the most direct measurements but suffer from other problems: from a single spacecraft passing once through a reconnection region, the three-dimensional time-dependent phenomena cannot be mapped. Thus a detailed picture of plasma and field properties in reconnection events has not yet been obtained.

We have designed a new laboratory experiment with the purpose of performing detailed measurements on reproducible reconnection events. It differs from previous work by its large scale length, long time scale, fast repetition rate, and digital data analysis. Time- and space-resolved measurements of the magnetic field topologies in three dimensions have been presented in the first paper on this work, subsequently referred to as part I [Stenzel and Gekelman, this issue]. Here we wish to show complementary results on the basic plasma properties, i.e., density, temperature, and potential. These data are essential in understanding the self-consistent behavior of the coupled system. Subsequent analyses of plasma acceleration, resistivity, and dissipation depend on the knowledge of these first-order plasma parameters.

Since the experimental setup and measurement techniques have been described earlier, we will give only a brief account of the specific diagnostics used in this part and then present the measurement results.

DIAGNOSTICS

Density and temperature in this experiment are in a parameter range \( n = 10^{13} \text{ cm}^{-3}, T_e < 15 \text{ eV} \) suitable for Langmuir probe diagnostics [Chen, 1965]. The magnetic fields are small \( (B_B = 20 \text{ G}) \) so that probes can be built smaller than an electron Larmor radius \( (r_{\text{L}} \approx 5 \text{ mm}) \) but large compared with the Debye length \( (\lambda_D = 0.03 \text{ mm}) \). Typically, planar Langmuir probes of 3-mm diameter are used and aligned with their surface normal parallel to the axis, although the orientation angle has only a small effect on the saturation currents. The probes are inserted radially with shafts which form a right angle with respect to the induced electric field. This is important because otherwise the observed potentials at the end of the probe shaft would differ from the ones at the probe tip. These differences are clearly observed when one compares the traces from radial and axial probe whose probe tips are at the same location.

Electron density \( n \), temperature \( T_e \), and plasma potential \( \phi_p \) are calculated from the I-V probe characteristic which is swept out rapidly (2 \mu s/division) compared with the time scale of the experiment \( (T = 200 \mu s) \). Typical probe traces are shown in Figures 1a and 1b. The two sets of traces show the currents to two identical back to back collectors of a differential probe, one collecting current from the +y direction, the other from the −y direction, both driven simultaneously with the same linear voltage ramp. From the current difference the net plasma current density and electron drift velocity can be determined. Here, however, the current average \( J = (J_+ + J_-)/2 \) is formed so as to cancel the drift effects for determining \( n \) and \( T_e \).

The pictures in Figures 1a and 1b show a superposition of 10 traces from consecutive magnetic field pulses, indicating the fluctuation level in time and from shot to shot. The fluctuation amplitude varies with spatial location and time within the pulse ranging from \( (\delta n/n)_{\text{rms}} \approx 20\% \) at early times (Figure 1a, \( t_s = 25 \mu s \)) to \( (\delta n/n)_{\text{rms}} \approx 2\% \) at late times (Figure 1b, \( t = 160 \mu s \)) or prior to the pulse. Because of the significant fluctuation effects ensemble averages over typically 10 events are formed prior to evaluating the probe traces.

The data acquisition and evaluation is performed digitally. Using an 8-bit, 20-MHz analog-to-digital converter, the probe traces are digitally averaged and stored in the memory of a minicomputer (M11 2/28, 32 k words). A typical replay of a digitized 10-shot average probe trace is shown in Figure 1c. From such curves a computer program finds the plasma potential from the ‘knee’ (drop in \( dI/dV \)), the temperature \( T_e \), from a least squares fit to ln \( I(V) \), and the density from the electron saturation current and \( T_e \). The evaluation of the
The data discussed in the present paper were taken from one data run under identical conditions as for the magnetic field measurements in part 1, Figures 7, 8, and 11-16. We will present first the space-time variations for the density, then the electron temperature, and finally the plasma potential.

Electron Density

The density measured in the x-z plane at $y = 84$ cm at several discrete times prior to and during the rise of the external current is displayed in Figure 2 as contour maps, $n_{e,0} = \text{const}$, and as three-dimensional graphs $n_{e,0}$. Figures 2a and 2e show the density profile of the background plasma before the application of the magnetic field pulse. The density is relatively uniform [$n = (0.6 \pm 0.2) \times 10^{12}$ cm$^{-3}$] across the axial bias magnetic field ($B_d = 20$ G) over most of the cross section ($20 \times 50$ cm$^2$) between the metal plates. Weak density gradients exist dominantly in the z direction which has a shorter distance to the boundaries ($H = 32$ cm) than the x direction ($2R = 150$ cm).

At $t = 25$ µs after the application of the magnetic field pulse the density (Figures 2b and 2f) has been dramatically changed in both magnitude and distribution. The average density has essentially doubled; locally it has increased by up to a factor of 4. Strong local density gradients have developed with scale lengths ($n/\sqrt{n} = 5$ cm) much smaller than the distances to the closest boundaries. It is interesting to note that the density increase is much smaller in the central region where the neutral sheet is formed than in the surrounding regions with $B_z = 0$.

The initial density increase cannot arise from plasma flows alone, since the time scale for flows is too long and there is no reservoir of plasma to account for a possible particle inflow. Further observations in different axial planes confirm that there is a net particle increase. Thus ionization must account for the density increase. The enhanced ionization arises mainly from heating of the bulk electron distribution, to be discussed below, rather than an increase in the cathode emission of energetic electrons which amounts to $\Delta I / I \approx 20\%$.

The density increase is most pronounced at early times ($0 < t < 25$ µs). Measurements in intervals of $\Delta t = 20$ µs show that the subsequent variations in the average density are relatively small ($<n_e> = 1.5 \times 10^{12}$ cm$^{-3}$ at $t = 40$ µs, $1.4 \times 10^{12}$ cm$^{-3}$ at 60 µs). Since the electron temperature remains elevated, the rate of particle production must drop, indicating the ‘burnout’ of available neutrals inside the plasma volume. Thus while at early times the density profile may be governed by ionization phenomena, subsequently the nearly fully ionized plasma is dominated in its dynamics by particle flows.

Comparison between Figures 2b and 2c ($t = 80$ µs) shows that the density maxima around the neutral sheet have spread out, raising the density in the corners of the measurement plane. These profile modifications are qualitatively consistent with the observed ion flow across the separatrix which exhibits the classical ion acceleration in $\pm z$ direction in the plane of the neutral sheet, to be reported in part 3. The ion outflow also leads to a decrease in the average density.

At later times ($t = 195$ µs), when the magnetic field topology...
Fig. 2. Density profiles \( n_{x,y} \) at \( y = 87 \) cm for various times \( t \) with respect to the start of the magnetic field pulse displayed as contour plots (Figures 2a–2d) and three-dimensional views (Figure 2e–2h). The density varies by \( \Delta n = 10^4 \) cm\(^{-3}\) between adjacent contours. Value and location for density maxima (DENMAX) and minima (DENMIN) are given as well as the spatially averaged densities (DEN). The origin \( x = 0, z = 0 \) is at \( x' = 26 \) cm, \( z' = 11 \) cm; the conductor plates are at \( z = \pm 16 \) cm. The scales in Figures 2d and 2h apply to the other corresponding boxes as well. The initially uniform plasma (Figures 2a and 2e) develops large density inhomogeneities in the reconnection process. The neutral sheet is at a density minimum (Figures 2b and 2f), while the magnetic island coincides with a density maximum (Figures 2d and 2h).

has changed from an \( X \) point to an \( O \) point, the density profile is again modified, as shown in Figures 2d and 2h. Plasma has been accelerated into the elliptical magnetic island, forming a density maximum in the center of the plane. The peak density is smaller than at early times due to a decrease in electron temperature and the slow inflow of neutrons injected at the chamber wall at \( x = \pm 75 \) cm.

The density profile is not only modified in the transverse direction but also axially along the bias magnetic field. This is demonstrated in Figure 3, which shows in Figure 3a and 3b density contours in two \( x-z \) planes separated axially by \( \Delta y = \pm 15 \) cm around \( y = 87 \) cm. The data are obtained by sweeping two identical Langmuir probes simultaneously so as to be able to observe instantaneous differences in the plasma parameters. The normalized density difference \( \Delta n/n \) shows not only large instantaneous values but also a significant mean value when averaged over an ensemble of 10 shots, as done in Figure 3. Figure 3c displays the density difference \( \Delta n/n \) between the data of Figure 3a and 3b which were all taken at the same time, \( t = 60 \) \( \mu s \). The measurement indicates maximum density variations of \( \Delta n/n \approx \pm 66\% \) located mainly near the edges of the plane. The corresponding axial density gradient scale length \( L_z = n/\sqrt{\Delta n} \approx 45 \) cm is, however, considerably longer than the minimum transverse length \( L_x = n/\sqrt{\Delta n} = 5 \) cm, in-
been spatially averaged over the $x$-$z$ plane. This is more clearly visible in Figure 4, which displays $(n)$ measured in three widely spaced planes $(y = 37, 87, 137 \text{ cm})$ at different times $t$. Although initially $(t < 0)$ the density is low and uniform, it rapidly rises during the magnetic field pulse, establishing at $t \approx 40 \mu s$ an axial gradient pointing toward the cathode $(n/n_{e}(t) \approx 250 \text{ cm})$. It is interesting to note that the ionization reaches burnout faster $(t \approx 25 \mu s)$ in the center of the device than near the cathode $(t \approx 40 \mu s)$, indicating again that the cathode does not supply the energetic electrons for this process. Since the axial density profile is not related to the temperature profile (to be shown in Figure 6), it may reflect the initial distribution of neutrals in the chamber.

The observation of an axial density gradient has several important implications. First, the induced axial electric field will cause space charge separation along the density gradient. The resultant electrostatic field is observed and will be discussed in connection with plasma potential measurements. Second, the density gradient gives rise to fluid motions. Axial ion flows are observed and will be presented separately in part 3. Finally, axial current continuity implies an increase in electron drift velocity with decreasing density. A higher level of turbulence and electron heating can be expected in the direction toward the end anode.

**Electron Temperature**

The electron temperature evaluated from the same probe traces which yield Figures 2 and 3 is shown in Figure 5. The temperature is displayed as contours of constant $T_e$ (0.6 eV change per contour) in the transverse $x$-$z$ plane at different times $t$ prior to and during the magnetic field pulse. Initially, the unperturbed background plasma (Figure 5a) has a highly uniform temperature distribution over most of the transverse plane $(T_e \approx 5.8 \text{ eV } \pm 10\%)$. However, during the rise of the magnetic field $(0 < t < 80 \mu s)$, a spatially nonuniform temperature profile develops with local heating up to $T_e \approx 14 \text{ eV}$. The strongest heating does not occur in the middle of the neutral sheet but displaced in $\pm x$ direction on the sides of the sheet where current and density also maximize. At early times

indicating that the density inhomogeneities consist of axially elongated structures. Even though $L_z \gg L_x$, the axial density profile modifications produced by applying time-varying magnetic fields to the plasma are very pronounced when compared with the conditions prior to the field pulse shown in Figure 3d.

Besides the local density inhomogeneities, Figure 3 also shows a significant axial gradient in the density $(n)$ which has

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Fig. 3. (a), (b) Density contour plots $n_{e}(x,y)$ in two axial planes $y = 72 \text{ cm}, 102 \text{ cm}$ at $t = 60 \mu s$ showing radial and axial gradients; $\Delta n = 10^{3} \text{ cm}^{-3}$ between adjacent contours, $x = x' - 26 \text{ cm}, z = z' - 11 \text{ cm}$. (c) Axial density variations $\Delta n/n = (n_{e}(102) - n_{e}(72))/0.5(n_{e}(102) + n_{e}(72))$ calculated from Figures 3a and 3b. Adjacent contours are spaced by 10%. Local maximum (DN/NMAX), minimum (DN/NMIN) and spatial average $(DN/N)$ are given. (d) Axial density changes $\Delta n/n$ prior to the magnetic field pulse indicating the nearly uniform initial axial density profile. Scale applies to all boxes.

Fig. 4. Axial variations of the density $(n)$ spatially averaged over transverse planes at different times $t$ with respect to the start of the magnetic field pulse $(t = 0)$. During the first quarter cycle (Figure 4a, $0 < t < 100 \mu s$) the density gradient is maintained by ion flow toward the cathode. Ionization accounts for the initial density rise; transverse and axial ion flows cause the subsequent density decay. In the second quarter cycle (Figure 4b, $100 < t < 200 \mu s$) the density gradient still points toward the cathode due to the slow ion motion $(v_i \approx 2 \times 10^6 \text{ cm/s})$. 
Fig. 5. Electron temperature profiles $T_e(x, z)$ at $r = 87$ cm at different times $t$ before and during the magnetic field pulse. Adjacent contours are spaced by $\Delta T_e = 0.6$ eV. Spatial averages ($\langle T_e \rangle$), maxima (TEMAX) and minima (TEMIN) are given. (x = x' = 26 cm, z = z' = 11 cm). All scales are identical to those given in Figure 5c. The initially uniform temperature distribution (Figure 5a, $\Delta T_e/\langle T_e \rangle = 20\%$) develops strong inhomogeneities in the presence of the neutral sheet (Figure 5c, $\Delta T_e/\langle T_e \rangle = 200\%$) with temperature maxima near the sheet edges but not in the center. For the magnetic island (Figure 5f) the temperature maximizes at the origin of the O point.

When the magnetic field topology changes from X- to O-type neutral point ($t > 100$ $\mu$s), the current and temperature profile are also modified. As shown in Figure 5f, the electron temperature now exhibits a maximum near the plasma center where the magnetic island is located (see Figures 10 and 11 in part 1). Because of the smaller currents involved at this time (see Figure 13, part 1) the temperature increase is lower than in the initial phase.

While Figure 5 described the transverse temperature profile, Figure 6 summarizes the axial dependence of the temperature $\langle T_e \rangle$ averaged over the transverse cross section. Prior to the magnetic field pulse ($t = -35$ $\mu$s) the temperature shows a very small decrease in $y$ direction ($\langle T_e \rangle/\langle T_e \rangle = -15$ $\mu$s). During the rise of the applied current ($0 < t < 30$ $\mu$s) the temperature increases in $+y$ direction, i.e., electrons are heated as they move toward the end anode in response to the applied electric field. During the reverse direction of the field (e.g., at $t = 120$ $\mu$s) the temperature gradient reverses. Temperature and density gradients do not balance.

For the present plasma parameters ($n = 1.5 \times 10^{12}$ cm$^{-3}$, $T_e = 8$ eV) the classical electron mean free path is $l = \nu_e/\nu_{ee} = 90$ cm. Thus one might expect electrons to accelerate freely to
energies \( eE_l \approx 90 \text{ eV} \), where \( E \) is the applied electric field \( (E_{\text{max}} = 1 \text{ V/cm}) \). Observations from probe traces (e.g., Figure 1) show strong order zero runaway electrons but Maxwellian distributions with \( kT_e \ll eE_l \). This apparent discrepancy, noted already in earlier experiments \( [\text{Strykovskii et al., 1973}] \), is resolved here by the observation of space charge electric fields.

Langmuir curves were also taken close \((\Delta y = 1 \text{ mm})\) to the mesh anode which itself is 2 cm from the cathode surface. No tail of high-energy electrons was observed during the reconnection process. The boundary formed by the anode cathode gap is not a source of the spatially anisotropic electron distribution.

**Plasma Potential**

The evaluation of the Langmuir probe traces also yields the plasma potential, which is the basic parameter for determining electrostatic fields. Plasma potential measurements are very difficult to perform in dense laboratory plasmas because of the large saturation currents involved and in space plasmas because of lack of a suitable reference potential. The present measurements fill the data gap which exists in this area.

Figure 7 shows the plasma potential in the \( x-z \) plane at \( y = 87 \text{ cm} \) from the cathode \((y = 0)\). At \( t = -35 \mu \text{s} \), prior to the start of the magnetic field pulse (Figure 7a) the potential is quite uniform \((\Delta \phi_p/\phi_p \approx \pm 18\%)\) and has a positive average value \( \langle \phi_p \rangle \approx 12 \text{ V} = 2kT_e/e \) with respect to the grounded mesh anode and end plate. These conditions are typical for a uniform, nearly collisionless discharge plasma (electron mean free path \( \approx \) plasma dimensions). At \( t = 25 \mu \text{s} \) during the pulse (Figure 7b) the potential has increased to \( \langle \phi_p \rangle \approx 52 \text{ V} \) and exhibits spatial variations of up to \( \Delta \phi_p \approx 14 \text{ V} \). However, near the end anode the plasma potential has to be close to ground potential, since a sizable electron current \((i_e \approx 1000 \text{ A})\) flows to ground. Thus the large positive plasma potential in the middle of the plasma implies an axial potential gradient which, as will be shown below (Figure 8), is not concentrated in a narrow sheath but distributed throughout the plasma. The axial electrostatic field \( E_x = -\partial \phi_p/\partial x \), points in the direction opposite to the induced field \( E_i = -\partial A_i/\partial t \), and both are of comparable magnitude \((E_i \approx E_x)\). The observation of this space charge field is very important in the analysis of plasma acceleration, resistivity, and dissipation, to be discussed subsequently in parts 3 and 4.

The transverse potential gradients are as important as the axial ones. The contour map of Figure 7c provides an expanded scale \((1 \text{ V/contour})\) a detailed view of the transverse potential profile. One can observe a correlation between regions of large positive potentials (e.g., \( x' = 8 \text{ cm}, z' = 8 \text{ cm} \), and \( x' = 48 \text{ cm}, z' = 10 \text{ cm} \)) with large temperatures (see Figure 5b) and high densities (see Figure 2b, f), i.e., high pressures \( p = nkT_e \). Away from these pressure islands the potential drops off in a short distance, resulting in large transverse electrostatic fields \( E_x = -\nabla \phi_p \left( |E_x| \approx 3 \text{ V/cm} > E_i \right) \). These fields accelerate the essentially unmagnetized ions (ion Larmor radius \( r_p \approx 50 \text{ cm} \) at \( kT_e = 1 \text{ eV}, B = 20 \text{ G} \)) and give rise to transverse electron Hall currents (see Figure 12b in part I). The relative drift between electrons and ions is a possible cause of microinstabilities considered to be of great importance in reconnection regions \([\text{Hartenstel}, 1978]\).

Measurements of the plasma potential in three widely separated planes reveal the space-time variation of the electrostatic fields. In Figure 8 the potential \( \langle \phi_p \rangle \) averaged over transverse planes is plotted versus axial position \( y \) at different times \( t \) of the magnetic field pulse. Essentially no potential gradients exist prior to the pulse. While the induced electric field \( E_i = -\partial A_i/\partial t \) points in the \(-y\) direction \((0 < t < 100 \mu \text{s})\), a space charge electric field \( E_x = -\nabla \phi_p \) develops in the \(+y\) direction. The linear axial potential profile implies \( E_x = \text{const} \) throughout the plasma. The magnitude of \( E \) \((\approx 0.4 \text{ V/cm} \text{ at } t = 25 \mu \text{s}) \) is smaller but of the order of \( E_i \) \((\approx 0.6 \text{ V/cm} \text{ at } t = 25 \mu \text{s}) \). In time the space charge field varies in magnitude and direction with the applied field (see, e.g., Figure 2b in part I).

Thus as shown in Figure 8b, the potential gradient reverses for...
Fig. 8. Axial dependence of the plasma potential ($\phi_p$) averaged over transverse planes at different times $t$ before and during the magnetic field pulse. The potential gradient implies a nearly uniform space charge electric field $E_i = -\Delta \phi_p$, which opposes the induced field $E_i = -\partial A/\partial t$, is of comparable magnitude, and changes sign from first quarter cycle (Figure 8a, $\partial A/\partial t < 0$) to second Figure 8b, $\partial A/\partial t > 0$). Note that $E_i$ is not given by the pressure gradients (see Figures 4 and 6).

$t \geq 100 \mu s$. During the first quarter cycle (Figure 8a) the end anode is near ground potential and draws the induced electron current ($I_e \approx 1000 A$); during the second period (Figure 8b) the gridded anode adjacent to the cathode draws electrons, while the solid end anode collects ions. From Figures 4, 6, and 8 it is also clear that the axial electrostatic field is not given by pressure gradients $E_i = (\nabla n T_{ei})/ne$ but by induced space charge separation effects. Although the pressure gradient would give rise to ion drifts away from the cathode, the net electric field (induced plus space charge) points toward the cathode for $0 < t < 100 \mu s$; hence ions flow into the high density regions thereby enhancing or maintaining the axial density gradient (Figure 4).

CONCLUSIONS

The present experimental results give a detailed account of the plasma properties in a dynamic reconnection experiment. They are an essential counterpart to the magnetic field measurements of part 1. Several major results have been obtained.

First, the presence of a space charge electric field opposing the induced electric field has previously neither been considered nor observed due to diagnostic difficulties. If space charge effects are discussed, they are usually assumed to be localized near the end electrodes [Frank, 1976]. The presence of space charge fields has important implications on plasma resistivity and dissipation. For example, it explains, in part, the discrepancy between the frequently quoted high plasma resistivity calculated from the induced field alone [Baum et al., 1973] and the low electron heating observed. Space charge electric fields are also crucial to the acceleration of particles and explain partially the highly inhomogeneous ion flows and electron currents observed. In the presence of induced electric fields, space charge fields are not given by pressure gradients.

Second, significant electron heating has been observed, which implies an energy transfer from the applied magnetic field to particles. Density and temperature profiles become spatially highly inhomogeneous. The largest heating does not occur in the center of the neutral sheet but near its edges where significant normal field components exist. The temperature rise appears to be limited by inelastic collision processes, initially ($0 < t \lesssim 30 \mu s$) ionization of residual neutrals ($\sim 15$ eV/collision), subsequently excitation of line radiation ($\sim 12$ eV/collision). Although we have shown only ensemble averaged data, there are significant fluctuations from shot to shot and within each shot (see, e.g., Figure 1a). Thus the inhomogeneities and fluctuations in the plasma properties are quite similar to those observed on satellites when crossing the magnetosheath [Frank et al., 1976].

While the present paper gives a detailed account of the electron properties, the acceleration and heating of ions will be discussed in part 3 together with a careful account of forces and anomalous drag processes. The important subject of energy transfer from magnetic fields to particles, waves, radiation, etc. will be addressed later in part 4.

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REFERENCES

Stenzel, R. L., Experiments on current-driven three-dimensional ion...


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