Abstract: A laboratory experiment on the problem of magnetic field line reconnection in plasmas has been performed. Comprehensive measurements of the magnetic field topologies as well as the plasma dynamics have been performed. The formation of neutral magnetic sheets, tearing, island formation and magnetic turbulence will be shown first. Then, the force density and ion acceleration have been measured. An anomalous ion collision frequency \( \nu^* / f_{pi} \) has been derived from these quantities and found to be large, \( \nu^* / f_{pi} \cali{<} 0.5 \), when turbulence is present. Finally, detailed time-dependent measurements of the total electric field and current density vectors have been made in the large (35\( \times \)85\( \times \)200 \( \text{cm}^3 \)), weakly collisional (\( \nu_{ei} / \omega_{pe} = 10^{-4} \)) argon plasma (\( n_0 = 10^{12} \text{ cm}^{-3} \), \( T_e = 10 \text{ eV}, T_i = 6 \text{ eV}, \beta = 1 \)). The evolution of a broad (\( \lambda = 35 \text{ cm} \)), thin (\( \Delta z = 3 \text{ cm} / \omega_{pe} = 1.5 \text{ cm} \)) neutral current sheet is seen to coincide with an increase in the calculated resistivity. The resistivity is found to be spatially inhomogeneous with average values exceeding the classical resistivity by one order of magnitude and locally by two orders.

1. Introduction

The reconnection of magnetic field lines at neutral points in plasmas is a problem of fundamental interest in both space plasmas\(^1\) (e.g. solar flares, magnetic substorms) and in fusion plasmas (tokamaks, reverse field configurations). Unfortunately, in these areas direct in-situ measurements are very difficult to perform. We have, therefore, built a large basic research laboratory plasma to explore the physics of reconnection processes in detail\(^2\).
The crucial aspects which the work is addressed to are the self-consistent magnetic field topologies inside a high beta plasma, particle heating and acceleration, anomalous resistivity and fluctuation phenomena, and the energy transfer processes from magnetic fields to particles.

2. Experimental Setup and Measurement Techniques

The experiment is performed in a linear device in which a large (1 m diam., 2 m length) uniform, low pressure ($10^{-4}$ Torr Argon) discharge plasma is produced with an oxide coated cathode. The pulsed plasma ($n_e \approx 10^{12} \text{cm}^{-3}$, $T_e \approx 10^5$, $T_i = 5$ to $15 \text{ eV}$) is immersed in a constant uniform axial bias magnetic field ($B_0 = 20 \text{ G}$, $\beta = 1$). A time-dependent (sinusoidal) transverse magnetic field is established by pulsing an axial current ($I_s \leq 50 \text{ kA}$, ~100 μsec rise time) through two parallel aluminum plates located on either side of the plasma column. In vacuum, the transverse field topology is quadrupole-like exhibiting an X-type neutral point in the middle between the sheets. With plasma, however, currents are induced ($I_p > 1000 \text{ A}$) which modify the magnetic fields until a self-consistent current and field pattern evolves.

The magnetic field is measured point-by-point with small magnetic loop probes. At each of the typically 300 points in the transverse $x$-$z$ plane the time history of the vector components is recorded digitally. Subsequently, at a given time, the spatial field pattern is assembled in the form of vector fields or contour maps. The time can be chosen in 1 μsec intervals from typically 300 quantization steps. All three vector components have been recorded in three orthogonal directions. Thus, the complete time space history of the magnetic field is known.
3. Experimental Results

Magnetic Field Topologies

During the rise of the applied magnetic field opposing plasma currents are induced which slow down the flux transfer across the separatrix. Whereas in vacuum the separatrix intersect at right angles, in the plasma it has two contact points joined by a common line along which $B = 0$. This neutral sheet (in 3 dimensions) predicted to develop self-consistently$^3$ is observed in our experiment and shown in Fig. 1. The sheet of length to thickness ratio $\Delta x/\Delta z > 10$ is found to be stable against tearing for $\geq 4$ Alfvén transit times from metal plates to neutral sheet. The thickness $\Delta z$, defined by the half
width of the current sheet $J_y = (\nabla \times \mathbf{A})_y$ approaches the inertial limit ($\Delta z = 3 c/\omega_{pe}$).

**Figure 2:** Tearing of the vertical neutral sheet. $\mathbf{B}_\perp(x,z)$, unit vectors.

A different field topology is observed when the applied current decreases in time and the induced plasma current flows parallel to it. A vertical neutral sheet is formed which rapidly tears and forms magnetic islands as shown in Fig. 2. The O-points coalesce to form a single large magnetic island at the time when the externally applied current crosses zero. Fig. 3 depicts the field lines for the O-type neutral point topology.

**Figure 3:** Field topology of a large magnetic island. Vector potential $A_y = \text{const.}, \Delta A_y = 7.5 \times 10^{-8}$ Vsec/cm per contour.
The complete time evolution of the magnetic field topology has been displayed in the form of a computer generated movie. It displays real data and is not a simulation. Detailed discussions of the field topologies are given in a recent publication.4

Thus, we have observed the self-consistent formation of neutral sheets and tearing processes in a large laboratory plasma. Although the present data represent ensemble averages over many shots we have also seen strong magnetic turbulence in neutral regions which can lead to random magnetic islands with strong effects on particle transport.

Plasma Dynamics

The plasma pressure, nkTe, has been measured with the use of rapidly swept Langmuir probes inserted into the neutral sheet of a plasma undergoing reconnection. At seven separate times within the reconnection event, the plasma potential, density and electron temperature are determined from computer evaluation of a ten shot ensemble average. This is done at several hundred locations on a plane transverse to the device axis. The data displayed in Fig. 4 is the plasma pressure nkTe at t = 40 μs.

![Contour plot of plasma pressure](image)

**Figure 4:** Plasma pressure, $2.5 \times 10^{-7}$ joules/cm$^3$ - contour. x,z, in cm. t corresponds to two Alfvén transit times; t = 0 is start of current rise.
The pressure peaks on either side of the neutral sheet (see Fig. 1). Similar displays of the electron temperature indicate corresponding temperature peaks at values of 14 eV and spatial average values of 8 eV. The initial electron temperature average was 5 eV and highly uniform throughout the plane.

**Fluid Force**

The force on a fluid element $\mathbf{f} = \mathbf{J} \times \mathbf{B} - \nabla p$ may be evaluated from the pressure, $\mathbf{B}$ measured from orthogonal pickup loops and $\mathbf{J} = \nabla \times \mathbf{a}$. A vector force field is shown in Figure 5a. It is fully developed 25 $\mu$s after the experiment begins.

![Diagram](image)

**Figure 5**: a). Fluid force density $t = 60 \mu s$, $<f> = 1.6 \times 10^{-7}$ joule/cm$^4$. b). Ion flow unit vectors $t = 80 \mu s$, $<v> = 10^{-1} c_s$, $3 \times 10^{-3} <v/c_s < 6 \times 10^{-1}$. 
Ion Motion

Ion flow fields were measured using miniature orthogonal ion collectors at 1024 time steps and on the spatial grid shown above. The probes were sensitive to $\dot{\mathbf{v}}/c_s$. The flow pattern does not track with the force density but takes time to develop. The velocity flow field shown at $t = 80 \mu s$ (Fig. 5b) is displayed as unit vectors because of its large spatial variation. At earlier times the pattern contains many whorls and eddies.

In a collisionless plasma the ions would accelerate in accord with the force density $\mathbf{a} = \mathbf{F}/m_i$. That this is not observed indicates the ions are subject to a large drag.

Ion Drag

From stored data the ion acceleration $\mathbf{a} = \mathbf{d}/dt (x,z,t)$ is evaluated. The electric field which gives rise to this can be calculated $\mathbf{E}_1 = \mathbf{m} \mathbf{d}\mathbf{v}/ne dt$ as well as $\mathbf{E}_2 = \mathbf{J} \times \mathbf{B} - \mathbf{Vp}/ne$. These two terms may be combined to evaluate the anomalous ion collision frequency $\nu^* = \frac{e(\mathbf{E}_1 - \mathbf{E}_2)}{mv}$ which is shown in Figure 6.

![Collision Frequency/Fpi T = 25.00 us](image)

Figure 6: Effective ion collision frequency $\nu^*/f_{pi}$, $t = 25 \mu s$.

$\frac{\nu^*}{f_{pi}} = 0.1, 10^{-3} < \nu^*/f_{pi} < 0.7$. 
\( \nu^* \) is normalized to the ion plasma frequency which is also calculated at each spatial position. The effective collision rate is highest in the center of the reconnection region. Drag on the ions prevents their free acceleration until \( t > 50 \mu \text{s} \) at which time \( \nu^* \) has dropped by more than a factor of two, and is no longer peaked in the neutral sheet. Drag is thought to arise when ions are moving through electrostatic turbulence generated by space-charge separation between magnetized electrons and unmagnetized ions. The charge fluctuations are coupled via the electrons to the magnetic field lines which absorb the ion momentum change and transfer it to the boundaries of the device. The scattering is not isotropic so that \( \nu^* \) is strictly a tensor whose diagonal and off-diagonal components have also been calculated. Their time-space variation is similar to the one discussed above.

**Resistivity and Dissipation**

One of the critical questions in the problem of magnetic field line reconnection is the plasma resistivity which determines dissipation and size of the diffusion region. By carefully measuring the relevant terms of the generalized Ohm's law in a controlled laboratory experiment, the resistivity \( \eta = \frac{E_{\text{tot}} \cdot \mathbf{J}}{J^2} \) and dissipation \( \mathcal{P} = \frac{E_{\text{tot}} \cdot \mathbf{J}}{J} \) have been calculated.

The total electric field parallel to the bias magnetic field \( (B_y = 20 \text{ Gauss}) \) and perpendicular to the pulsed magnetic field is given by

\[
E_{11} \pm \mathbf{B}_\perp \times \mathbf{B}_\perp + \frac{1}{ne} \mathbf{V}_{11} (nkT_e) - \frac{1}{ne} (\mathbf{J}_\perp \times \mathbf{B}_\perp) = \eta \mathbf{J}_{11}. 
\]

The applied electric field \( E_{11} = -\partial \mathbf{A}/\partial t \) and the space charge field \(-\mathbf{V}_p \neq 1/ne \mathbf{V}_{11} (nkT_e) \) have been measured simultaneously\(^5\). The space charge field is found to be spatially nonuniform, having components both anti-parallel and perpendicular to the applied field, and can locally exceed the applied field strength. The \( \mathbf{v} \times \mathbf{B} \) term is also measured but its contribution is negligibly small \( (v = c_s << v_e) \).

The induced plasma current closes externally; the large oxide coated
cathode resupplies electrons collected at the end of the device. The current density $\mathbf{J}$ is measured by using a small (3 x 4 mm$^2$) double-sided Langmuir probe. The sum and difference signals of the collected electron saturation current yield the average density and the net drift speed, respectively. The axial current density maximizes along the neutral sheet region ($J_y \text{ max} = 1.8 \text{ amp/cm}^2$) and is generally 5 - 10 times larger than the transverse currents (Fig. 7).

By measuring the time-varying magnetic flux with loop probes, all three spatial components of the pulsed field are measured. The current density derived from the Maxwell Eq. $\mathbf{J} = \mathbf{V} \times \mathbf{B}/\mu_0$ is found to agree with the direct measurements.

![Figure 7: Axial plasma current density $J_y(x,z)$. The contour spacing is 0.125 amp/cm$^2$; $t = 40$ μsec; $y = 87$ cm. $J_y,\text{max}(30,14) = 1.9$ amp/cm$^2$.](image)

The resistivity grows to anomalously large values in 30 - 40 μsec (Alfvén transit time $\tau_a = 20$ μsec). It remains high as long as the transverse magnetic fields continue to rise ($0 < t < 80$ μsec). The Ohmic dissipation $E_{\text{tot}} \cdot \mathbf{J} = \eta J^2$ is found to be greatest where $|\mathbf{J}|$ is largest (Fig. 8). Electron heating is observed, with the average electron temperature rising up to 4 times its initial value.
Figure 8: Ohmic dissipation $P(x,z) = \frac{E_{\text{tot}} \cdot J}{y^2}$. The contour spacing is 0.02 watt/cm$^3$; $t = 40$ µsec; $y = 87$ cm. $P_{\text{max}}(42,14) = 0.25$ watt/cm$^2$.

The spatially averaged resistivity is seen to increase with the average plasma current density. However, the resistivity itself maximizes in regions of low $|J|$ (Fig. 9), in contrast to the assumption $\eta \propto |J|^2$ made in recent computer models$^6$.

Figure 9: Ratio of calculated resistivity to local Spitzer value. Contour intervals are 10 units; $t = 40$ µsec; $y = 87$ cm. $\langle n \rangle = 18.1 \, \eta_{\text{Sp}}$, $\eta(8,14) = 145 \, \eta_{\text{Sp}}$. 
4. Conclusions

The plasma current system associated with magnetic field line reconnection is seen to evolve self-consistently with an anomalously high resistivity, which in turn leads to energy dissipation via Joule heating. This power is largest in regions of maximum $|\mathbf{J}|$. The local resistivity does not maximize in regions of large $|\mathbf{J}|$, i.e. with an imposed electric field a region of high resistivity implies a small current density. Joule heating, line radiation from excited argon ions, and ionization account for most of the energy losses. Significant low frequency fluctuations are observed and conditions for ion sound and electron drift cyclotron instabilities are satisfied ($v_D \approx 0.1 v_e >> c_s$).

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References: