LAPORATORY EXPERIMENT ON MAGNETIC RECONNECTION AND TURBULENCE

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Abstract

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 $(n, T, v, j, \rho)$, and waves $(\delta n, \delta B, \delta E)$ have been developed. Quasi-stationary reconnection is observed and understood, to first order, by fluid models but, upon closer inspection, modified by kinetic effects (anisotropic in $f(v)$, microinstabilities, space charge fields). Spontaneous disruptive instabilities of a current sheet are observed when $V_{de}$ approaches $V_{the}$. Inductive voltages form double layers where energetic particles are formed. The conversion of stored magnetic energy into particle kinetic energy is studied by a controlled interruption of the plasma current. The disrupted current sheet self-consistently cascades into small scale current structures (loops, filaments) which evolve into spatial turbulence. The magnetic field energy is dissipated anomalously fast while the plasma is energized and waves are generated.

1. Introduction

Magnetic field line reconnection is important in space and fusion [1]. It explains how changes in magnetic field topologies and energy conversion processes occur in highly conducting plasmas. Reconnection involves a breakdown of the frozen-in condition between field and fluid which 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) which 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 ($j = \nabla \times B$) and, according to fluid theory, with Ohm's law ($E + v \times B = \eta j$). The magnetic field associated with the plasma current provides a potential energy source which 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 ($V_{de} \rightarrow V_{th}$).

Fundamental questions in space plasmas (solar flares, magnetic substorms) deal with the conversion of magnetic field energy into particle kinetic energy [2]. However, in fusion (tokamaks) the importance of reconnection by tearing modes lies in the associated transport processes. Particles and thermal energy are redistributed due to formation of magnetic islands. Enhanced radial losses and possibly catastrophic current disruptions may arise. In both fusion and space, one is interested in the dynamics of the magnetic topologies and the role of turbulence in modifying the effective fluid properties. Extensive

Magnetic Reconnection and Turbulence, M.A. Dubois et al. Editor
(Editions de Physique, Orsay, 1985)
theoretical work and computer simulations exist in both fields, but experimental observations of reconnection processes are mostly indirect. Current sheets in solar plasmas cannot be resolved remotely (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 the objective of the present [3] and of previous [4-6] laboratory experiments. In the UCLA experiments, 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. Its properties are carefully diagnosed using modern digital data processing techniques. The following sections describe the experiment, the observations of stable and unstable current sheets.

2. Experimental Setup

Figure 1 shows a schematic picture of 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. 1(b) is uniform, quiescent, essentially collisionless, and highly reproducible in pulses of duration \( t_p = 5 \text{ msec} \) repeated every \( t_r = 2 \text{ sec} \). The plasma may be immersed in a uniform axial magnetic field of variable strength \( B_0 = 0 \ldots 100 \text{ G} \). For the reconnection experiments, a time varying \( (t_{\text{rise}} = 100 \text{ usec}) \) magnetic field is applied transverse to the plasma column \( (|B_1| = 0 \ldots 20 \text{ G}) \). This field is produced by pulsing currents \( (I_{\text{plate}}) \) through two parallel-plate electrodes adjacent to but insulated from the plasma column. All return currents flow coaxially on the cylindrical metallic chamber wall which is not shown for purpose of clarity. In vacuum, the transverse field topology \( B_{\perp}(x,z) \) contains an X-type neutral point on the axis of the device. However, when the space between the plates is filled with plasma, a secondary current is induced anti-parallel to the plate current. This induced plasma current \( (I_{\text{plasma}}) \) flows preferentially near the X-point but is so large \((\sim 1000 \text{ A})\) that the vacuum field topology is greatly modified. A neutral sheet and O-type neutral points may arise.

Detailed plasma diagnostic tools are employed in conjunction with a high-speed digital data processing system. Vector magnetic fields \( B_r(r,t) \) are obtained in situ with a movable probe at up to 4000 spatial locations \((\Delta r \approx 2 \text{ cm})\) and 1000 temporal points \((\Delta t = 100 \text{ msec})\). From repeated measurements statistical averages are formed \((\text{mean, standard deviation, correlations})\). Distribution functions are measured with a modified retarding potential analyzer [7] which filters particles through a passive microchannel plate and thereby obtains high directional sensitivity \( (\Delta \Omega/4\pi \approx 10^{-3}) \). 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 \( f(v_r,\theta,\phi) \) are time resolved to within a few microseconds. Ensembles averages yield fluctuations in velocity space. Measurements of such multi-dimensional functions produce large data flows \((N > 10^9 \text{ numbers})\) which can only be handled by digital techniques. The analog traces are therefore digitized with 100 MHz, 32 K, 8 bit A-D converters, evaluated on-line with an array processor and a VAX 11/750 computer linked to a Cray computer for further analysis. Besides particles and fields, plasma waves are investigated. Frequency spectra \((10^3 < f < 10^{10} \text{ Hz})\) and wavevectors \( k \) are measured using two-point cross correlation techniques.
3. Reconnection at a Neutral Sheet

The magnetic field topology during the time of external plate current rise is shown in Fig. 2(a) [8]. Whereas in 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 ( \( \rightarrow \rightarrow \)). This topology is that of the classical neutral sheet [9] which arises when the induced plasma currents slow down the penetration and reconnection of magnetic fields at the field reversal region. The result is a pile-up 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 \( J = \nabla \times B / \mu_0 \). The dashed region of largest current density indicates the shape of the current sheet which is nearly uniform in y direction. The thickness \( \Delta z = 5 \, \text{cm} \) is in the range between the electron Larmor radius \( (r_{ce} = 1 \, \text{cm}) \) and the ion Larmor radius \( (r_{ci} = 60 \, \text{cm}) \). The current is dominantly carried by electrons which are freely accelerated in the null region and drift in its vicinity with \( v_d = E \times B_{i}' / B_{i}^2 \ greater than \ v_{ion} \). The current sheet widens when a magnetic field component \( B_y \) 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 [10], the rate of flux transfer across the separatrix is measured by the inductive electric field \( E_y \) along the separator \((-\partial \phi / \partial t = V, \phi = \int \nabla \phi \cdot d\mathbf{r}, V = \int E_y \cdot d\mathbf{r}, E_y = -3A_y / \partial t \). However, the assumption of axial uniformity \( (\partial / \partial y = 0) \) and absence of space charge electric fields is an unrealistic simplification. From measurements of the plasma...
Fig. 2. (a) Measured ensemble averaged vector magnetic field \( \vec{B}_1(x,z) \) at a fixed time \( t = 27 \) µsec and position \( y = 137 \) cm showing a classical neutral sheet topology.

(b) Contours of constant current density \( j_y = (\nabla \times \vec{B})_y / \mu_0 \). The dashed region of maximum current density indicates the typical shape of the current sheet.

Fig. 3. Schematic view of the axial electric field components in the plasma. The applied inductive electric field \(-\vec{A}_y\) due to the increasing sheet current \( I_S \) is opposed in the plasma by a space charge electric field \(-\nabla \phi_\rho\). The net line-integrated voltage along the plasma column is \( |V_1| - |V_2| = 20 \) Volt, the remaining inductive voltage (≈ 80 V) drops off at the cathode sheath.
potential (Fig. 3) we observe that a space charge electric field \( \mathbf{E}_S = -V_0 \mathbf{E}_p \) 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. In the absence of electron supply the inductive field would be completely cancelled by the space charge field, the current would be negligible, and the reconnection would proceed as in vacuum. However, in the present case of a strong current source (cathode) and high conductivity a nonzero net Ohmic electric field \( (E_y < 0.1 \, \text{V/cm} = nJ) \) penetrates the plasma.

While the space charge field partially shields out the inductive field over a major part of the plasma volume, it cannot do so everywhere since \( \int \mathbf{E}_S \cdot d\mathbf{r} = 0 \). The plasma potential is found to drop sharply at the cathode sheath. There, most of the inductive voltage \( V = -\dot{\phi}/\dot{t} \) drops off and energizes the particles. Electrons with energy equal to the cathode supply plus the reconnection voltage \( (\sim 100 \, \text{V}) \) are injected into the plasma of lower thermal energy \( (\sim 10 \, \text{eV}) \). The resultant distribution functions are non-Maxwellian, as will be shown below.

Space charge electric fields also develop self-consistently in the direction perpendicular to the neutral sheet. For example, in Fig. 4 the observed ion flow in the transverse \( x-z \) plane is shown. It 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 which 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 \( \rho \dot{\mathbf{V}}/\dot{t} \) with the total force density \( j \times B - \mathbf{V}_p \) [11]. The presence of fluctuating electric and magnetic fields causes an effective drag on the ions which 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 separatix [12].

Further investigations of the fluid properties have been concerned with the electrical resistivity \( \rho \) which is important for energy dissipation, reconnection rates, and current disruptions [13]. From an analysis of the generalized Ohm's law the effective resistivity 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.

![Fluid Velocity](image)

**Fig. 4.** Transverse ion flow \( \mathbf{v}_i(x, z) \) normalized to the local sound velocity \( c_s = (kT_e/m_i)^{1/2} \). The characteristic fluid flow during reconnection is established, i.e., vertical inflow toward the neutral sheet and horizontal outflow at high velocities \( (v/c_s)_{\text{max}} = 0.6 \). Note that the driving \( j \times B \) force acts on the electrons while the ions are accelerated via space charge electric fields.
Analysis of the particle distribution functions and waves provide a better understanding of the causes for the anomalous fluid behavior. Figure 5a-c summarizes the measurements of the electron distribution function in the current sheet in one, two, and three-dimensional velocity space, respectively. The electron flux vs. energy observed along the *z* direction (Fig. 5a) reveals the presence of a tail of high energy electrons streaming away from the cathode. These electrons are accelerated at the cathode sheath by a potential given by both the discharge supply voltage (*V* = 40 Volt) and the reconnection voltage (*V* = 70 V). Two-dimensional flux measurements yield the distribution function \( f(v_e, v_i) = f(v_e, v_i) \) 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 \( f(v_e, v_i, v_n) = \text{const.} \), one of which is shown in Fig. 5c. These data depict an increasing resolution the anisotropy of the electron distribution in the current sheet. The tail electrons are mainly accelerated by the reconnection electric field which, due to space charge effects, has been distributed non-uniformly along the separator. Such field localizations are likely to occur also at non-uniformities in density, conductivity, cross-section or magnetic fields. The consequence of localized reconnection fields is the production of runaway particles which modify transport coefficients (e.g., resistivity, heat flow), cause spatial non-uniformities (anisotropy is confined to the current sheet [14]), and can drive various kinetic microinstabilities.

Observations of turbulence in the current sheet are summarized in Fig. 6. Low frequency density fluctuations exist as broadband turbulence up to the ion plasma frequency. With two probes cross-spectral functions \( c_{12} = \langle \delta n, \delta n \rangle / \omega \) are measured and the dispersion \( \omega = kc \) is identified. The turbulence consists of ion acoustic modes driven unstable by the relative drift between electrons and ions \( (v_d > c_s) \) in a plasma with \( T_e > T_i \). Ion sound turbulence is likely to be responsible for the anomalous increase in the plasma resistivity [13] and electron heating [12]. A second spectrum of electrostatic fluctuations is found near the electron plasma frequency \( (f = fpe \lesssim 12 \text{ GHz}) \). 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 which are observed outside the plasma with horn antennas [16]. The current sheet is also a source of magnetic fluctuations. Magnetic noise exists up to a few electron cyclotron harmonic frequencies \( (\omega_{ce} = \omega_{pi}) \). Below \( \omega_{ce} \) cross-spectral function measurements of the vector magnetic field fluctuations have shown that the fluctuations consist of many oblique whistler modes [17]. Above \( \omega_{ce} \) magnetic fluctuations can be carried by the energetic streaming electrons without corresponding to eigenmodes of a Maxwellian plasma [18].

4. Current Sheet Disruptions

While the previous observations described the properties of quasi-stationary reconnection, the present section deals with impulsive reconnection events which involve rapid changes in field topology and plasma properties. As indicated in Fig. 7, two types of disruptions have been studied: spontaneous and controlled disruptions. Spontaneous disruptions arise when the current in the center of the neutral sheet is raised, which is accomplished by biasing the central part of the end anode positively [19]. When monitoring the collected current \( I_a \) to this center electrode, one finds at increasing current densities \( (v_d/v_e > 0.3) \) spontaneous, impulsive \( (\Delta t \lesssim 10 \mu \text{sec}) \) current interruptions. On repeated reconnection pulses, the disruptions are random in timing and amplitude (except for the first partial disruption). The cause for these current interruptions has been inferred from both the global circuit properties and the local plasma properties. During the current loss the plasma potential
Fig. 5. Characteristics of the electron distribution in the current sheet.
(a) Electron flux vs. energy as detected along the \( \pm y \) direction with a directional velocity analyzer schematically shown in the insert. A large flux of energetic electrons opposite to \( E_y \) is observed.
(b) Distribution function in two velocity dimensions, \( \log f(v_y, v_z) \). Cuts through \( \log f(v) \) show \( F_1 = \log f(v_y, 0) \), \( F_1 = \log f(0, v_z) \) and a contour plot \( \log (v_y, v_z) = \text{const} \). A second contour plot shows the rms fluctuations in the distribution function while the upper traces refer to ensemble average values. Note the tail in \( f(v) \) and enhancements of fluctuations due to the anisotropy.
(c) Distribution function in three-dimensional velocity space is displayed as surfaces of \( f(v_x, v_y, v_z) = \text{const} \). Shown is a surface \( f(v)/f(0) = 2 \times 10^{-3} \) which cuts through the high energy tail and shows its rich structure. Moment calculations and instability criteria have been evaluated [15].
Fig. 6. Summary of observed microinstabilities in the current sheet.
(a) Ion acoustic turbulence spectrum and dispersion.
(b) Electron plasma wave and microwave emissions near \( \omega = \omega_{pe} \) vs.
time showing enhancements during reconnection.
(c) Frequency and wavevector spectrum of magnetic fluctuations
identified as whistler wave turbulence [17].
in the perturbed current channel rises to a value (~ 100 V) much larger than the dc potential (~ 30 V) applied to the end plate. This large potential increase is due to an inductive voltage \( \frac{d\phi}{dt} = L \frac{dI_a}{dt} \) associated with the current drop. Spatially, the enhanced plasma potential drops off in a sharp transition (\( \phi_Y = 5 \text{ mm} \approx 100 \lambda_p \)) to the ambient value (\( \phi_p = 10 \text{ V} \)), i.e., a potential double layer is formed where the current is disrupted and the neutral sheet tears. The disruption is localized to the center of the current sheet and the disruption on axis causes an enhanced current to the surrounding anode such that the total plasma current remains constant. The mechanism for the disruption is believed to be a positive feedback between inductive effects and plasma thinning in the current channel. For example, the rising plasma potential causes an expulsion of ions, hence a density loss and further current drop which in turn amplifies the potential increase. During this explosive current instability, magnetic field energy is released and converted at the double layer into particle kinetic energy. The energy first resides in particle beams but subsequent beam-plasma instabilities transfer some of the directed energy into waves and heat. Bursts of Langmuir waves due to fast electrons and magnetosonic waves excited by fast ions are observed.

Many of the observed phenomena have been considered in models of magnetic substorms or solar flares. High energy particles are often associated with inductive electric fields [20]. Localized acceleration by parallel electric fields are considered in auroral physics [21]. Electromagnetic emissions from solar flares are ascribed to the presence of runaway electrons. Redirected current flows upon current disruptions are known from the magnetotail and auroral current system. However, many fundamental questions remain open. For example, when the stored magnetic field is embedded in a highly conducting plasma at which rate can the energy be released upon a current disruption? The dynamics of unstable current systems is a rather open subject. In order to address some of these questions, we have controlled the current sheet disruption in time and space, as shown in Fig. 7. It is then possible to obtain from repeated point measurements the evolution of fields, currents, and particles.
After establishing a well formed current sheet, a magnetic switch is activated which produces a thin slab of normal magnetic field $B_z$ preventing the electron flow between cathode and anode. The switching is performed rapidly ($\Delta t = 3$ μsec) compared with the Alfvén transit time across the plasma ($t_A > 30$ μsec) so as to distinguish subsequent magnetic field propagation and dissipation processes. The total plasma current may be disrupted with high reproducibility.

The magnetic field diagnostic has been further perfected. All three vector components $(B_x, B_y, B_z)$ are measured with a probe which moves in three dimensions recording the field at about 4000 spatial locations $(x, y, z)$ versus time digitized in typically 1024 time increments ($\Delta t = 100$ nsec). Appropriate software has been developed so as to display field lines in three dimensions, an example of which is shown in Fig. 8. It displays the reverse field topology for the case of an added component $B_y = 6$ G = const. at two times, prior to the disruption ($t = -0.6$ μsec) and after the disruption ($t = 6$ μsec). The contribution to the magnetic field by the plasma current changes while that of the plate currents and the solenoidal $B_y$ remain constant. While the field lines indicate the change in the direction of $B$ the magnitude can be displayed as a contour plot. Figure 9 shows the magnetic energy density $|B|^2/2\mu_0$ before and after the disruption. When integrated over the volume, one finds that the stored magnetic energy is released within $\Delta t = 5 \ldots 10$ μsec, which is shorter than the propagation time of Alfvén waves to the boundaries ($\Delta t = 25$ μsec). Thus the field energy is dissipated rather than convected away by waves.

A possible mechanism for the anomalously fast magnetic energy dissipation lies in the evolution of the current system. By calculating the local current density $j = \nabla \times B/\mu_0$ and fitting field lines through this vector field, one can follow the space-time variation of the disrupted current flow as is shown in Fig. 10. Before the disruption, $t = -0.6$ μsec, 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 current loops and filaments. This process of cascading from large to small scale structures lowers the effective magnetic Reynolds number $(R_m \ll 1)$ and enhances the magnetic diffusion. The plasma resistivity may also be enhanced by instabilities associated with the current flow across magnetic field lines driven by local inductive electric fields.

The current flow changes from a two-dimensional sheet to a fully three-dimensional inhomogeneous pattern. This becomes obvious from Fig. 11, which shows the current density lines in the plasma volume seen from three different angles. The linkage of currents and associated flux produces a magnetic helicity which has been evaluated. Calculating from first principles the vector potential $A$ from the current density $j$, one obtains, together with the known magnetic field $B$, the total magnetic helicity $K = \int A \times B \, dV$. Its time dependence is depicted in Fig. 12. The rapid rise of helicity due to onset of disruption is followed by a diffusive decay similar to that of the magnetic energy. In the present case their temporal variations are governed by the electron fluid.

A careful analysis of the plasma properties during the disruption still has to be performed. Presently, it is known that the electrons are heated and, locally, energetic electron tails are generated. Due to energy losses from the unconfined plasma, the particle energy increase is expected to be smaller than the magnetic energy density loss. Ions are energized at the plasma boundaries since the plasma potential rises during the current disruption. Large amplitude waves also convect energy out of the system. For example, the density ejection across the magnetic switch steepens into a large amplitude electrostatic shock wave, as shown in Fig. 13. It interacts with the tail ions of the ambient plasma and thereby transfers some of the original magnetic energy into ion kinetic energy.
Fig. 8. Magnetic field lines in three dimensions $B(x,y,z)$ when a constant field component $B_y = 6 \, \text{G}$ is applied along the neutral line. The current disruption changes the reconnection topology to a curl-free X-point with added $B_y$.

Fig. 9. Magnetic energy density $B^2/2\mu_0$ vs. $(x,z)$ before and after the disruption. The magnetic energy associated with the plasma current is dissipated anomalously fast.
**FIELD LINES**

\[ \mathbf{J} = \mathbf{v} \times \mathbf{B} / \mu_0 \]

**Fig. 10.** Field lines for the current density vector \( \mathbf{j}(x,y,z) \) at different times of the current disruption. The initially \( t = -0.6 \mu\text{sec} \) laminar current sheet cascades during the disruption into small scale current loops and filaments. Due to the triggered disruption the spatially random pattern is highly repeatable from pulse to pulse.

**Fig. 11.** The three-dimensional nature of the disrupted current flow is demonstrated by viewing the current density lines at different angles in the plasma volume. Currents flow both along and across \( B \).
Fig. 12. Magnetic helicity of the plasma current system increases during the disruption indicating flux linkage due to circulating current loops.

Fig. 13. The energization of plasma by the current disruption leads to a mass ejection which steepens into a shock wave and propagates through the ambient plasma. Probe traces show ion flux vs. time at different positions along direction of shock propagation.

5. Summary

The present laboratory experiment has demonstrated some of the basic aspects of reconnection at a neutral sheet. Narrow current sheets governed by electron currents are observed. While fluid models may correctly describe the slow evolution of fields and flows, there are also kinetic effects important for understanding the reconnection process. These are space charge electric fields leading to localized particle accelerations, anisotropic velocity space distributions and associated microinstabilities which change the classical transport properties. When large current densities \(v_{de} \rightarrow v_{the}\) are approached
more violent instabilities arise whereby magnetic energy is impulsively converted into kinetic particle energy via formation of nonstationary double layers. During rapid current disruptions the "frozen-in" magnetic fields of the plasma currents are dissipated anomalously fast. The mechanism appears to be the observed cascading of a laminar current sheet into small scale current filaments and loops of high spatial turbulence.

Acknowledgments

The authors gratefully acknowledge support from the U. S. National Science Foundation under grants NSF ATM 84-01322, PHY 84-10495, and AFOSR contract F19628-85-K-0003. We also appreciate Mr. L. Xu's help with the computer system.

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