Change in the magnetic field configuration during the explosive destruction of a current sheet

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The configuration of the magnetic field of a current sheet is determined from experimental data, and the magnetic reconnection is studied. The reconnection occurs in two stages: a nearly steady stage and an explosion. The explosion, which results from the onset of the anomalous resistance, changes the magnetic-field configuration of the sheet, redistributes the current, and generates pulsed electric fields.

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Current sheets and the associated magnetic-reconnection effects play an important role in astrophysics and in the physics of laboratory plasmas.[1,2] An experimental study of the internal magnetic-field configuration of current sheets can reveal the details of the development of the sheet and, especially, the processes responsible for its destruction.

We produced a plane current sheet in an approximately steady, two-dimensional magnetic field $\mathbf{B} = h\{y; x; 0\}$ with a null line Oz and with a gradient $h = 600$ G/cm in a preexisting plasma with a density $N_e \cong 10^{15}$ cm^{-3}, by applying a voltage pulse $U_z \simeq 15$ kV to an interelectrode gap 40 cm long.[3] The electric current flowing parallel to the null line excited two-dimensional plasma flows in the (x, y) plane,[4] which gave rise to a current sheet: a region with a large x dimension ($2\Delta x \gtrsim 6$ cm) and a short y dimension ($2\Delta y \lesssim 1$ cm), in which the current is concentrated[5] and in which the plasma density is much higher than in the surroundings.[6] The magnetic field was measured simultaneously with six magnetic probes at the surface of the sheet, at $y_1 = 6$ mm and $z = 150$ mm; three of the probes (at $x = 0$, 10, and 23 mm) measured the component (B_x) tangent to the sheet, and three (at $x = 5$, 17, and 29 mm) detected the component normal to the sheet (B_y; see Fig. 1). These measurements were used to determine the positions of the magnetic lines of force at various times (Fig. 3) and to calculate the average current density over the thickness of the sheet (Fig. 2). The current in the sheet, i.e., the current flowing in the region $0 \leqslant x \leqslant 3$ cm, was found through an integration, $J_s = \int_0^3 I(x)dx$. Its value at each time was compared with the total current J_t, which was measured independently with a Rogowski loop outside the chamber (curve IV in Fig. 2).

Several assumptions were made in the analysis of the data. For the most part, these assumptions dealt with the symmetry of the sheet, and they agree with experimental results obtained independently. The magnetic field of the sheet was assumed to be two-dimensional in all stages, with the vector potential $\mathbf{A} = A\mathbf{e}_z$:

$$\mathbf{B} = \operatorname{rot} A\mathbf{e}_z = \left\{ \frac{\partial A}{\partial y}; \ -\frac{\partial A}{\partial x}; \ 0 \right\}. \tag{1}$$

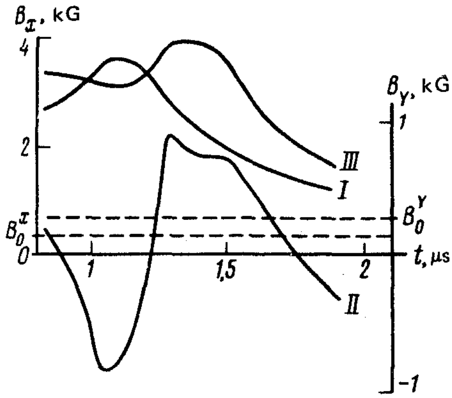

FIG. 1. Time dependence of the magnetic field measured at the surface of the current sheet. I–B_x at $x = 0$; II–B_y at $x = 5$ mm; III–B_x at $x = 23$ mm. The dashed lines show the level of the nearly steady magnetic field (before the current sheet begins to form).

The equation for a magnetic line of force is then

$$A = \text{const}\,, \tag{2}$$

and the magnetic flux between the lines of force A_1 and A_2 for a unit interval along the z axis is

$$\Phi = A_1 - A_2 \;. \tag{3}$$

The sheet was assumed to be symmetric with respect to the $z = 0$ and $y = 0$ planes, so that the magnetic fields can be measured and the calculations carried out in a single quadrant, $x > 0, y > 0$. It also follows that $\mathbf{B} = B_y \cdot \mathbf{e}_y$, $B_x = 0$ at $y = 0$ and $\mathbf{B} = B_x \cdot \mathbf{e}_x$, $\mathbf{B}_y = 0$ at $x = 0$. For each fixed time the values of $A(x, y)$ required for determining the positions of the lines of force, (2) (Fig. 3), were found by calculating the magnetic fluxes in (3) and using (1). In the region $0 \leqslant y \leqslant 6$ mm, we assumed a linear y dependence of the field component tangent to the sheet: $B_x(x_1, y, t) = h(x_1, t)y$. In the gaps between the probes the values of B_x and B_y were found by interpolation.

It can be seen from Fig. 3 that the magnetic field of the formed sheet (0.9 μs; solid curves) is quite different from the original field (dashed curves); the tangential component B_x has strengthened, and the normal component B_y has weakened. In other words, the excess magnetic energy has increased. At $x = 0, y = 0$, there is a null line of the X type, where the separatrices intersect. The separatrix makes an angle ~13° with the x

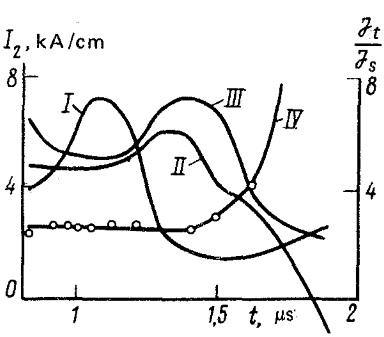

FIG. 2. Time evolution of the current density in the sheet, averaged over the thickness of the sheet. I–x = 0–5 mm; II–x = 10–17 mm; III–x = 23–29 mm. IV–Ratio of the total current in the chamber (J_t) to the current in half the sheet (J_s), found from the magnetic measurements.

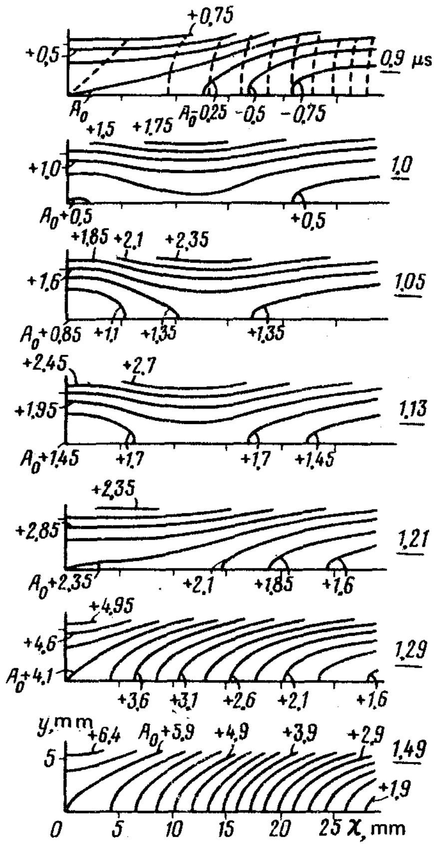

FIG. 3. Configuration of the magnetic field of the sheet at various times. Adjacent lines of force differ by $\delta A = 0.25$ kG • cm.

axis, in contrast with 45° in the original field. The current distribution over the sheet is essentially uniform, with $I(x) \cong 5$ kA/cm.

To learn about the magnetic reconnection in the sheet, we consider the changes in the positions of the magnetic lines of force in (2). For two-dimensional fields the change in A is described by the equation

$$\frac{\partial A}{\partial t} + (\mathrm{v}\ \nabla) A = \nu_m \Delta A , \tag{4}$$

where $\nu_m = c^2/4\pi\sigma$, σ is the local conductivity, $\Delta A = -4\pi/c\, j$, and j is the current density. On the line $x = 0, y = 0$ we have $\mathrm{v} = 0$ from the symmetry, and the change in A^0 is caused exclusively by ohmic dissipation; i.e.,

$$A^0(t_1) = A^0(t_0) + \int_{t_0}^{t_1} \nu_m(t)\ \Delta A^0(t)\ dt. \tag{5}$$

On the basis of (5) we can apply a "through enumeration" to the lines of force at successive times. As long as the direction of the current j^0 remains the same, A^0 increases over time, and the lines of force in the quadrant under study move, on the average, in a single direction: from top to bottom and from left to right in Fig. 3. Lines with large values of A concentrate near the surface of the sheet, while lines with smaller values of A reconnect within the sheet; then they are carried away along the x axis by the plasma flow, or they dissipate in the sheet. For estimates of $A^0(t)$ we used both the plasma conductivity $\overline{\sigma}(t)$ found from the voltage-current characteristics of the discharge, and averaged over the current region, and an argument regarding the direction in which the lines of force move.

In the interval 0.9–1.05 μs, the magnetic reconnection occurs most intensely in the region $1 \leqslant x \leqslant 1.5$ cm, where an X-type null line appears. This effect causes a redistribution of the current in the sheet: In the central part of the sheet the current increases (Fig. 2), the sign of the B_y component changes (Fig. 1), and a region with closed lines of force encircling the null line of the O type forms (Fig. 3; 1.0, 1.05, and 1.13 μs). The current at the center of the sheet reaches a maximum at 1.05 μs, and the configuration with closed lines of force is defined best at this time. There is then a relative increase in the reconnection rate at the center, and as a result the O-type null line gradually transforms into an X-type null line, with separatrices squeezed against the x axis (Fig. 3, 1.21 μs). Up to this moment the reconnection occurs comparatively slowly (this is the nearly steady stage), although it is a complicated process, apparently because of an inhomogeneity of the conductivity over the width of the sheet. Indications of the reconnection are seen, however, only in the internal structure of the magnetic field of the sheet, which contains no lines of the X and O types; the field configuration outside the sheet remains essentially constant.

In the time interval 1.21–1.29 μs, there is a radical change in the magnetic field configuration: The normal (B_y) component increases sharply at the center of the sheet, while B_x simultaneously decreases (Fig. 1); the current at the center of the sheet drops to less than half its value, while the current at the periphery increases (Fig. 2). Now the magnetic field contains an X-type null line with a field gradient three times the initial gradient (Fig. 3, 1.29 μs). These facts are evidence of a current redistribution within the sheet. It can be seen from curve IV in Fig. 2 that roughly half of the total current is concentrated in half of the sheet ($x > 0$) up to 1.4 μs; this result confirms the conclusion that there is a redistribution of the current in the sheet without any substantial change in its symmetry during the time interval 1.2–1.4 μs. The significant increase in the magnetic flux intersecting the x axis at 1.29 μs can be explained only on the basis of a sharp increase in the magnetic reconnection rate at the center of the sheet, since the lines of force continue to move in the same direction. The smallest possible change in A^0 can be used to estimate the electric field in the reconnection region $E \gtrsim 300$ V/cm, and the conductivity, $\sigma^0 \lesssim 10^{13}$ s^{-1}; this conductivity turns out to be an order of magnitude lower than the average conductivity over the sheet at this time. The apparent reason for the sharp local decrease in the conductivity is a threshold in the evolution of small-scale instabilities, with a transition of the central part of the current sheet to a turbulent state. The impulsive reconnection of magnetic fields that occurs here causes a rapid expansion of the region of reduced current density; the greater part of the current is ejected at a velocity $v_x \sim 2 \times 10^7$ cm/s to the edges of the sheet (Fig. 2). This ejection destroys the sheet and causes a substantial change in the magnetic field configuration (Fig. 3, 1.29 and 1.49 μs).

As a rule, this explosive destruction of the sheet begins at the center of the sheet, i.e., where the current density is highest, even if this region contains an O-type null line (Fig. 3, 1.05, and 1.13 μs). This circumstance confirms that the destruction of the sheet results from a local increase in the anomalous resistance after a threshold is reached; the destruction cannot be explained on the basis of the tearing-mode instability,[7] which may possibly be seen in the nearly steady stage of the magnetic reconnection (Fig. 3; 0.9, 1.0, 1.05 μs). These experimental results thus furnish a basis for choosing among the several mechanisms for the macroscopic destruction of a current sheet which were discussed in Refs. 1 and 2.

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