Observation of accelerated-particle fluxes emerging from a current sheet across a strong magnetic field

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Fast electrons moving along the surface of a plane current sheet in the direction perpendicular to the direction of the current have been detected during the pulsed stage of magnetic reconnection for the first time. Whether electrons can escape from the sheet is determined by the overall magnetic field configuration.

Syrovatskii[1] has shown on the basis of the concept of a current sheet that magnetic energy can be converted into other types of energy, including accelerated-particle fluxes. In the present letter we are reporting an experimental study of the possible motion of fast particles over large distances from the region of direct acceleration. We share how this process is related to the magnetic field configuration of the current sheet.

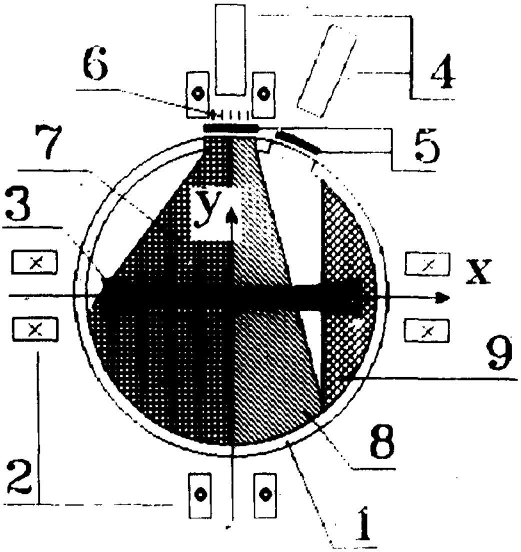

FIG. 1. Experimental layout. *1*—Vacuum chamber; *2*—conductors which produce the quadrupole magnetic field; *3*—current sheet; *4*—scintillation detectors; *5*—auxiliary filters; *6*—collimator; *7*, *8*—halves of the regions from which x radiation is detected, for two orientations of the collimator; *9*—half of a region in which x radiation appears.

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A plane current sheet was formed during a high-current direct discharge in a magnetic field with a null line.[2] We determined the magnetic configuration of the current sheet.[2] The accelerated electrons were detected by virtue of their x-ray bremsstrahlung with the help of three scintillation detectors. Two of these detectors were outside the vacuum chamber, at the center of the discharge gap, in the plane perpendicular to the null line. They were positioned at angles of 90° and 60° from the surface of the sheet. They detected the x radiation which escaped through mica windows (Fig. 1). The third detector was inserted into the chamber from its end and was positioned behind a grid electrode outside the discharge gap.

Depending on the formation conditions, the magnetic configuration of the current sheet in the metastable stage of its evolution can be of two types: either similar to the configuration of the original field, with an X-type null line at the center of the sheet and with several separatrices squeezed against the X axis (Fig. 2a; an open configuration), or a closed configuration with field lines looping the entire sheet, as in Fig. 2c. The latter configuration results from an overcancellation of the magnetic field component normal to the surface, B_y, near the edges of the current sheet. The pulsed stage of magnetic reconnection is manifested in either case by a rapid decrease in the field

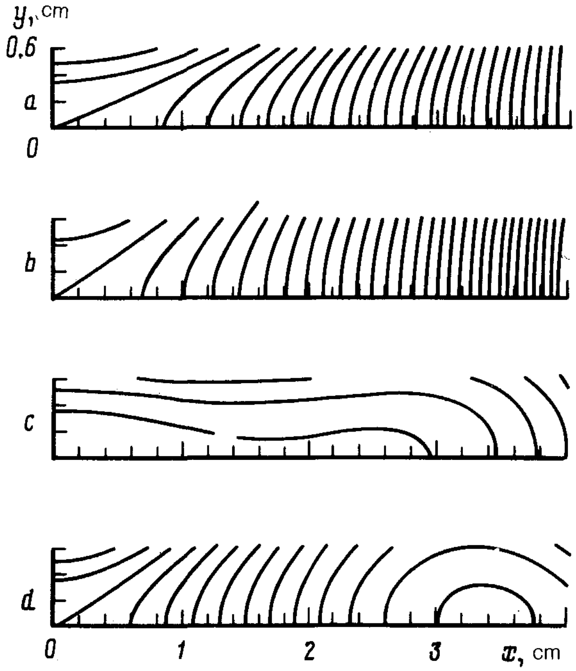

FIG. 2. Configuration of magnetic field lines of the current sheet. Shown here is one-quarter of the XY plane. *a,c*—Metastable stage of magnetic reconnection; *b,d*—pulsed stage of magnetic reconnection. *a,b*) Open magnetic configuration, Ar, $h_0 = 2.3$ kG/cm, $E_z = 250$ V/cm, P $= 6\times10^{-3}$ torr; *c,d*) closed magnetic configuration, He, $h_0 = 0.6$ kG/cm, $E_z = 250$ V/cm, P $= 2.5\times10^{-2}$ torr.

component B_x, an increase in B_y, the induction of an electric field E_z, and the acceleration of electrons[2-4] (Figs. 2b and 2d and Figs. 3a and 3b.)

In the open configuration, the x radiation is detected simultaneously by the three detectors and takes the form of brief bursts, which are correlated with a structural feature on the $U_z(t)$ curve, i.e., with the pulsed stage of reconnection (Fig. 3a). This correlation is seen most clearly in Fig. 3. The positions of the sources of the x radiation detected by the side detectors was determined with the help of a multislit collimator. The field of view of the detector was changed with the orientation of the collimator (Fig. 1). When the wall regions were excluded, the signal decreased by a factor of greater than ten (Fig. 3c); i.e., the x radiation appeared far from a null line, apparently at the walls of the vacuum chamber. The electrons accelerated in the pulsed stage of magnetic reconnection thus left the nonadiabatic region—a small neighborhood of the null line, with a size[5] $\delta < 0.1$ cm—moving across the magnetic field a distance on the order of 5 cm, and escaped from the current sheet.

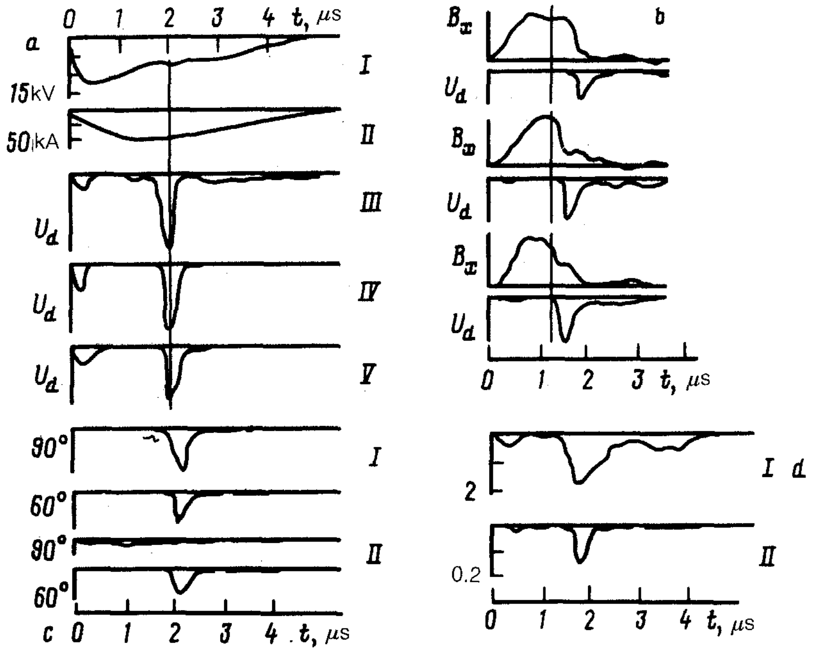

FIG. 3. *a*: Oscilloscope traces of (I) the voltage across the discharge gap, (II) the plasma current, (III) the signal from the end detector, and (IV, V) the signals from side detectors. *b*: Oscilloscope traces of the signals from a magnetic probe which detects B_x (the magnetic field component near the null line) and the x radiation from a detector at an angle of 90° from the surface of the sheet. Three different cases are shown. *c*: Oscilloscope traces of the signals from the side detectors. I—The diaphragm does not limit the field of view along the width of the sheet; II—it does limit the field of view along the width of the sheet. The detector at an angle of 60° is used as a monitor. *d*: Change in the shape of the signal from the side x-ray detector as the density of the absorbing filter is increased I—Without auxiliary filter; II—with an auxiliary filter consisting of 50 mg/cm^2 of Al. Ar, $P = 10^{-2}$ torr. *a,c*) $h_0 = 2.3$ kG/cm; *b,d*) 2.6 kG/cm. *a*) $E_z = 250$ V/cm; *b*) 190–250 V/cm; *c,d*) 190 V/cm.

The characteristic energy of the x radiation was determined by a filter method. The amplitude ratios of the signals detected from the various filters were compared with corresponding ratios calculated for three different spectra: $I \sim \exp(-E/T_0)$, $I \sim E^{-\gamma}$, and $I \sim \delta(E - E_0)$. All three of these spectra can fit the experimental ratios satisfactorily, within the experimental error, with the values $T_0 \approx 1$ keV, $\gamma \approx 6$, and $E_0 \approx 7$ keV. The hardest radiation was detected at the beginning of the pulsed stage (Fig. 3d). The value $E_0 \sim 7$ keV corresponds to a maximum electron energy $E_{\max} \sim 10$ keV. Under the assumption that the electrons are accelerated by the induced field E_z, we find $E_z \sim 500$ V/cm. This value does not contradict the value $E_z \geqslant 360$ V/cm from Ref. 3. In other words, the induced electric field which arises in the pulsed stage of magnetic reconnection could explain the observed electron energies. On the other hand, one cannot rule out the further possibility that electrons are accelerated in turbulent electric fields.[2,3]

In regimes in which a closed magnetic configuration forms, the pulsed stage of reconnection is clearly expressed (cf. Figs. 2c and 2d) and is accompanied by the excitation of an induced field[2] E_z; the end detector detects x radiation. The side detectors, in contrast, do not detect x radiation, even when their sensitivity is raised by a factor of 100. Under these conditions the accelerated electrons thus escape from the current sheet exclusively along the null line and cannot escape along the surface of the sheet to its lateral edges.

In summary, fluxes of fast electrons moving along the surface of a current sheet in the direction perpendicular to the current direction have been detected for the first time. It has been shown that the escape of electrons from the current sheet in this manner is made possible by the overall magnetic field configuration. There are grounds for suggesting that differences in the magnetic field configuration of current sheets can explain the differences in the efficiency at which particles are accelerated and heated in processes of a flare type.

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