Local pulsed plasma heating and destruction of a current sheet

N. P. Kiriĭ, V. S. Markov, and A. G. Frank
Institute of General Physics, Russian Academy of Sciences, 117942, Moscow

(Submitted 8 June 1992)
Pis'ma Zh. Eksp. Teor. Fiz. **56**, No. 2, 82–86 (25 July 1992)

The heating of the plasma ions of a current sheet is definitely not monotonic. The rate at which the ion thermal energy increases may be an order of magnitude greater than the average rate of Joule heating over the sheet thickness. The plasma heating is associated with the formation of a magnetic island at the center of the sheet. A scenario of a rapid destruction of the sheet after a comparatively lengthy metastable stage of the evolution is outlined.

1. The search for physical mechanisms which would cause a rapid destruction of a current sheet after a comparatively lengthy metastable stage in the evolution of the sheet has attracted interest to the thermal conditions in a sheet. Analysis of the magnetic field configuration, the distribution of electric current, and the distribution of the electron density shows that these properties remain essentially unchanged during the metastable stage of the evolution of the sheet, up to the point at which the pulsed phase of magnetic reconnection begins.[1] Several factors indicate a progressive increase in the plasma temperature.[2–5] It was found in Ref. 6 that the highest observed temperatures, $T_e \simeq 100$ eV and $T_i \simeq 200$ eV, are reached just before the disruption of the metastable stage and the beginning of the pulsed phase of magnetic reconnection. The evolution of T_e within the current sheet was later analyzed in Ref. 7.

In this letter we are reporting a first study of the evolution of the ion temperature in the plasma of a current sheet. We have observed that the temperature rise can occur in two steps, which differ substantially in duration and also in heating rate. A study of the spatial characteristics of the plasma emission in various spectral lines has revealed that the electron temperature is very nonuniform. There are distinct hot spots inside the sheet. Analysis of the internal magnetic structure of the sheet has established, for the first time, that there is a correlation between the formation of a magnetic island at the center of the sheet and the intense plasma heating which subsequently destroys the sheet.

2. The experiments were carried out in the TS-3 device,[1,5] in which a plane current sheet was produced by exciting an electric current in a plasma along the null line of a 2D magnetic field. The initial gradient of the quasisteady magnetic field was 600 G/cm; the initial plasma density was $N_e^0 \simeq 10^{15}$ cm^{-3}; and the working gas was helium. The maximum plasma current was $J_z = 50$ kA; the half-period was $T/2 = 3.2$ μs. The current sheet, with a length $\Delta z = 40$ cm, had the following transverse dimensions: a width $2\Delta x \simeq 8$–9 cm and a thickness $2\Delta y \simeq 1$ cm. The current density was $j_z = 4$–6 kA/cm^2. The magnetic field near the surface of the sheet was $B_x \simeq 5$–6 kG. The electron density in the sheet was $N_e^{\mathrm{sh}} = (1-1.5)\times 10^{16}\ \mathrm{cm}^{-3}$. The plasma pressure in the sheet was balanced by the magnetic pressure from the exterior, where the electron density was $N_e < 10^{15}\ \mathrm{cm}^{-3}$. In other words, the relation $(T_e + T_i/\bar{z}_i) \simeq 40$–$60$ eV held in the sheet.

We used a two-channel spectroscopic apparatus[6,5] and magnetic probes at the surface of the sheet.[8,5] In the measurements of the shapes of spectral lines, one of the two optical channels was used as a monitor. It measured the intensity of the spectral line OVI 5290.6 Å. The time $\tau = 0$ (3 in Fig. 1) corresponds to the maximum OVI intensity (in contrast with the actual time t, which is reckoned from the beginning of the current flow in the plasma; Fig. 2).

The ion temperature (Fig. 1a) is found from the shapes of spectral lines whose broadening is due to the Doppler effect under the given experimental conditions. Comparison of the profiles of two spectral lines of the same ion, the Doppler profile of CIV 5812 Å and the Stark–Doppler profile of CIV 4658 Å (Fig. 1b), makes it possible to trace the evolution of the nonequilibrium electric fields.[6,9]

3. Figure 1a shows the temperatures of the various ions (T_i) and the temperature of the helium atoms (T_a) versus the time τ. From $\tau = -1.2$ to $-0.2\ \mu$s, the temperature T_i increases progressively from 45 to 80 eV. The values found for T_i from the broadening of CIII, CIV, and HeII (for $\tau < 0.4\ \mu$s) are the same, while the temperature T_a does not exceed 10 eV. In other words, the HeI emission comes from the region outside the current sheet. Over this comparatively long stage we have $dT_i/dt \simeq 60 \pm 20$ eV/μs; i.e., the rate of increase of the energy density of the ions is $dW_i/dt = \frac{3}{2}[d/dt(N_e T_i/\bar{z}_i)] = (0.9$–$0.45)\times 10^{24}\ \mathrm{eV/(cm^3\cdot s)}$ (for an effective ion charge $\bar{z}_i = 1$–2). This figure represents a significant fraction (0.6–0.3) of the specific rate of current dissipation averaged over the sheet thickness: $\bar{p} = \overline{j^2/\sigma} \simeq 1.4\times 10^{24}\ \mathrm{eV/(cm^3\cdot s)}$. The difference is a consequence of electron heating[6,7] and the energy loss, due primarily to the longitudinal electron thermal conductivity.

4. The difference in the way the two CIV spectral lines broaden (Fig. 1b) indicates that electric fields are important in shaping the profile of the line CIV 4658 Å. It follows from theoretical calculations[9] that the broadening detected cannot be explained by interparticle fields and is instead due to nonequilibrium, low-frequency electric fields $\langle E \rangle \simeq 50 \pm 10$ kV/cm at $-1.0 < \tau < -0.2\ \mu$s. In other words, the turbulence level during the metastable stage of the evolution of the current sheet is $\eta = \langle E^2 \rangle / 8\pi N_e k(T_e + T_i/\bar{z}_i) \simeq 10^{-3}$.

5. The second stage in the evolution of the ion temperature begins at $\tau \simeq -0.2\ \mu$s: T_i increases extremely rapidly, to $\simeq 300$ eV, so that we have $dT_i/d\tau \simeq (2 \pm 0.4)\times 10^{-3}$ eV/μs (Fig. 1a). The values found for T_i from the broadening of the spectral lines of various multiply charged ions (CIV, NV, and OVI) are in agreement, within the 30% errors. The profiles of these lines are Gaussian. Their relaxation times, which characterize the momentum loss and the temperature equalization for the specified ions in the plasma of the current sheet ($N_e \simeq 1.5\times 10^{16}\ \mathrm{cm}^{-3}$, $\bar{z}_i \simeq 2$), do not exceed 0.1 μs. On this basis it can be asserted that Fig. 1 accurately reflects not only the maximum values of T_i but also the time evolution of T_i. In the interval from $\tau = -0.2 + 0.2\ \mu$s, the values found for T_i from the broadening of the CIII 4647.4 Å

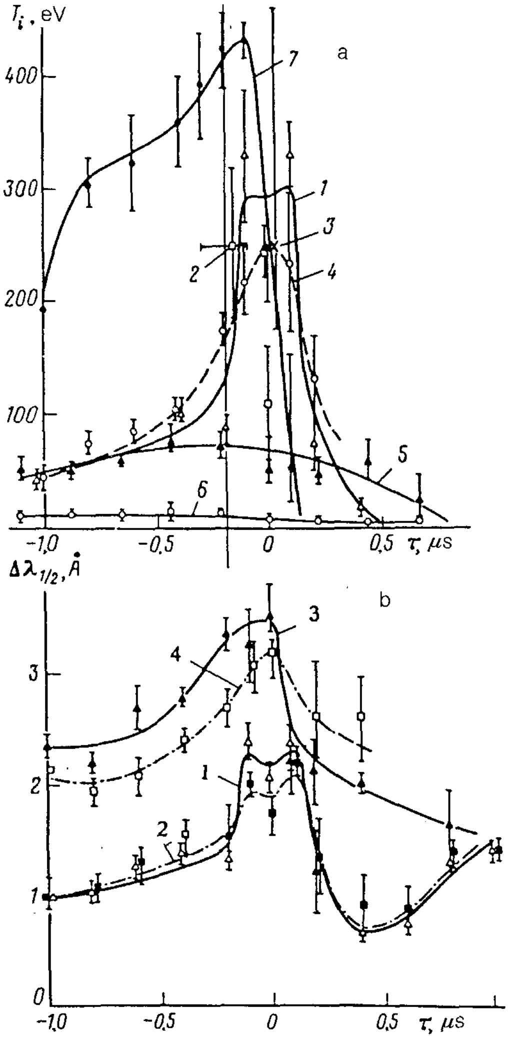

FIG. 1. a: Temperatures of the ions and atoms in the central part of the current sheet as a function of the time τ. The temperatures were determined from half-widths of several spectral lines. *1*—CIV 5812 Å; *2*—NV 4620 Å; *3*—OVI 3811.4 Å; *4*—HeII 4685.7 Å; *5*—CIII 4647.4 Å; *6*—HeI 6678.2 Å; *7*—time evolution of the magnetic field component tangential to the sheet surface, B_x. Each point is an average over three to five working pulses of the device. b: Time evolution of the half-widths of spectral lines of the triply charged carbon ion. *1, 2*—CIV 5812 Å ($3s-3p$); *3, 4*—CIV 4658.3 Å ($5gfd-6hgfd$). Curves *1* and *3* were recorded at an amplitude of the monitor signal roughly twice that for curves *2* and *4*.

line do not increase; in fact they decrease slightly. In other words, the sharp increase in T_i and T_e during the second stage of the heating also leads to a significant increase in the temperature gradients.

Over the interval from $\tau = -0.2$ to -0.1 μs, the rate of increase of the ion energy density, $dW_i/dt \simeq 2\times 10^{25}$ eV/(cm$^3\cdot$s), is considerably higher than the specific

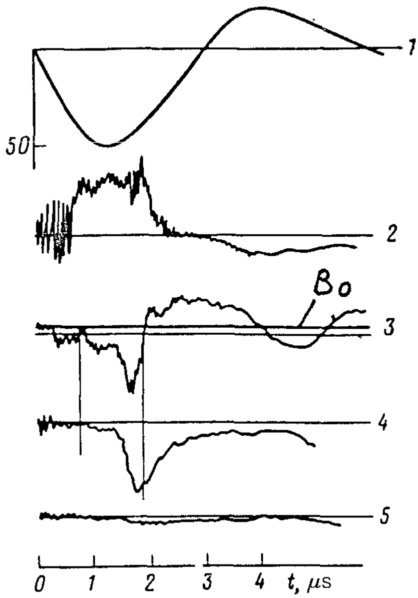

FIG. 2. Several properties versus the time t. *1*—Total plasma current J_z; *2, 3*—the magnetic field components B_x and B_y at the surface of the current sheet; *4*—intensity of the emission in a spectral line of the quadruply charged nitrogen ion, NV 4620 Å; *5*—continuum intensity.

rate of current dissipation, averaged over the sheet thickness, $\bar{p} \simeq 2 \times 10^{24}$ eV/(cm^3·s). This disbalance exceeds a factor of 10, when we allow for the simultaneous and extremely rapid increase in T_e (Refs. 6 and 7). If follows that the rapid increase in T_i and T_e during the second stage of the heating cannot occur over the entire thickness $2\Delta y$ of the current sheet, but it apparently could occur in regions of relatively small size: "hot spots."

6. The correlation which we find between the rapid plasma heating and the formation of a magnetic island at the center of the sheet—a configuration with closed field lines—supports this hypothesis. Specifically, the emission in the NV spectral line, which is evidence of an increase in T_e and then in T_i (Fig. 1a), appears at the time at which the magnetic field component normal to the surface of the current sheet, B_y (Fig. 2), reverse. In other words, this emission appears at the same time as the local increase in the current density at the center of the sheet and the conversion of the X-type null line into an O-type null line.[8] It may be that the subsequent compression of the plasma in these regions leads to a local increase in the plasma thermal energy, particularly when the likely decrease in the thermal conductivity is taken into account.

7. As can be seen from Fig. 3, the emission in the OVI and CIV spectral lines at $\tau = 0$ comes primarily from the central part of the sheet, from a region no greater than $2\delta x \simeq 1$–1.5 cm in size. The HeII emission has a local minimum here. Accordingly, the plasma with the highest values of T_e and T_i and with $\bar{z}_i > 2$ is localized in specifically this region, whose size is close to the sheet thickness $2\Delta y$ and also close to the size of the magnetic island.[8] The spatial resolution of the measurements of the emission distribution (Fig. 3) and that of the magnetic measurements was ~ 0.7–1 cm, so this hot region might actually be considerably smaller yet.

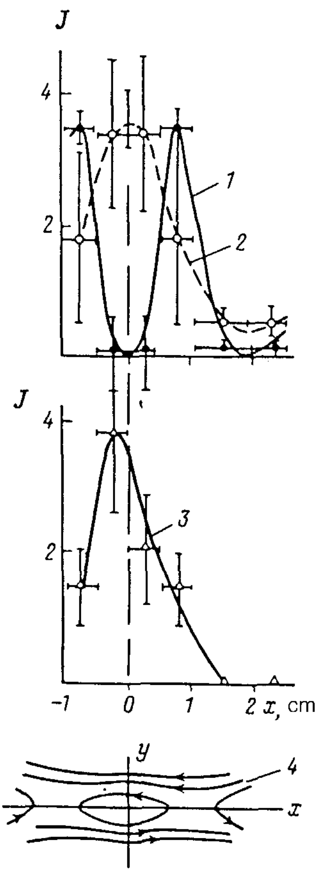

FIG. 3. Distribution of plasma emission over the width of the sheet (the X axis) in spectral lines. *1*—Line of the singly charged helium ion, 4685.7 Å; *2*—line of the triply charged carbon ion, CIV 5812 Å; *3*—line of the quintuply charged oxygen ion, OVI 5290.6 Å; *4*—magnetic structure at the center of the current sheet (a schematic diagram of a magnetic island).

8. Over the time interval from $\tau = -0.2$ to 0 μs, we observe an increase in the nonequilibrium electric fields (Fig. 1b), which reach $\simeq 100$ kV/cm (Ref. 9). This increase occurs at essentially the same time as the increase in T_e and T_i. The turbulence level is again $\eta \simeq 10^{-3}$, so—despite the increase in $\langle E \rangle$—the plasma turbulence apparently cannot be regarded as the direct cause of the macroscopic destruction of the current sheet.

9. The pulsed local heating of the plasma, in contrast, is the most likely reason for the termination of the metastable stage of the evolution and for the beginning of the destruction of the sheet. On the basis of the experimental results presented above, one might suggest the following scenario for this process. A local maximum of the electric current arises in the central part of the current sheet during the metastable stage, and a system of closed magnetic field lines forms. This configuration constitutes a magnetic island, in which the plasma is heated, slowly at first and then extremely rapidly, probably because of a compression of the medium. The increase in pressure disrupts the transverse equilibrium of the plasma in the magnetic field. A sort of thermal microexplosion occurs and causes the plasma to expand at the velocity of sound. This process initiates a redistribution of the current and a rapid reconnection of the oppositely directed magnetic field lines through the current sheet, i.e., the pulsed phase of magnetic reconnection (Fig. 1a; the sharp decrease in B_x at $\tau = -0.1 \pm 0.05$ μs). The change in magnetic field topology gives rise to electrodynamic forces, which account for the region of intensified magnetic reconnection and reduced electric current density to propagate rapidly along the surface of the current sheet, from its middle toward its edges. This change in topology also causes a further expansion of the plasma and, ultimately, the macroscopic destruction of the current sheet.

We are deeply indebted to S. Yu. Bogdanov and D. T. Kiselev for assistance in this study.

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Translated by D. Parsons