Observation of a current-loss effect at the neck of a Z-pinch formed in the explosion of a wire

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The plasma of a Z-pinch has been studied by a Faraday-rotation method. The current at the neck decreases sharply, to a level no more than 2% of the total current through the pinch, which is ~ 100 kA. The plasma is produced in the explosion of a 25-μm Al wire, used as the load of a high-current source. The experimental results force a radical revision of ideas regarding the mechanism for the formation of a neck. Qualitative features of the phenomenon agree with electron MHD. © *1995 American Institute of Physics.*

The sharp self-focusing of energy at the necks of Z-pinches has attracted much interest in connection with the possibility of producing plasmas with high temperature and densities. All the existing models for the development of the neck assume that the focusing of energy results from an increase in the pressure of the magnetic field of the linear current in inverse proportion to the square of the radius. However, there are no experimental data which confirm or refute this scenario for the development of a neck in a Z-pinch. A study of the spatial distribution of magnetic fields near the neck of a pinch would resolve this question.

The most informative method for studying the spatial structure of magnetic fields in a dense plasma is one based on the Faraday magnetooptic effect. Faraday diagnostic methods have been used in studies of the structure of magnetic fields in a plasma focus,[1] in a vacuum spark,[2] and in a high-current Z-pinch formed in the explosion of deuterated polyethylene by a current ~ 3 MA at the Angara-5-1 facility.[3] Those papers, however, did not report data on the magnetic-field configuration near the neck. The study we are reporting in the present letter makes it possible to resolve this question.

The Faraday magnetooptic effect is a rotation of the polarization plane of a plane-polarized electromagnetic probe wave as it propagates along the magnetic field lines in a plasma. Simultaneous measurements of the angle through which the polarization plane is rotated and of the interference phase shift of the probe light make it possible to establish the average value of the projection of the magnetic induction along the probing line.[4] If the plasma under study is axisymmetric, one can reconstruct the local distributions of the magnetic field and of the electron density by means of an Abel transformation.[4]

To study the structure of the magnetic fields and the electron density we use the principle of three-channel polarization interferometry, which involves the simultaneous production of Faraday, shadow, and interference images of the plasma.[4] A joint analysis of the Faraday and shadow images reveals the distribution of the angle through which the polarization plane rotates, with allowance for absorption and refraction of the probe light. One can work from the shift of the interference lines from their unperturbed positions to reconstruct the distribution of the phase shift.

The experiments were carried out at the GAEL high-current sources (Ecole Polytechnique) with a current of 250 kA, a pulse length of 50 ns, a voltage of 0.5 MV, and a power of 0.1 TW. The load was an Al wire 25 μm in diameter in a 10-mm gap between the cathode and anode of the device.

For the optical measurements we used a high-power QUANTEL NG-24 Nd:YAG laser with active Q switching. The output energy of the laser at the fundamental frequency was 1 J. The light from the laser was converted into the second harmonic through nonlinear conversion in a KDP crystal with a conversion coefficient of 25%. The probe light thus had a wavelength of 532 nm, a pulse length of 3 ns, and an energy of 250 mJ. The laser light was synchronized with the current pulse of the GAEL device within 5 ns.

To study the distributions of the magnetic fields and the electron density in the Z-pinch plasma, we assembled a three-channel polarization interferometer, which made it possible to simultaneously produce Faraday, shadow, and interferences images of the plasma. The three images were brought into coincidence with the help of a visualizing diaphragm near the intermediate image of the plasma. A slit diaphragm at the focus of the first lens, oriented perpendicular to the axis of the Z-pinch, made it possible to eliminate the effect of spontaneous emission of the plasma on the measurement results. The probing light which did not undergo refraction and also the light which was refracted in the plane perpendicular to the pinch axis, along which the macroscopic gradients of the electron density were directed, passed through a diaphragm. An additional decrease in the spontaneous emission of the plasma was achieved with the help of interference filters in front of the photodetectors. These photodetectors were CCD cameras calibrated with the help of a stepped attenuator in the light of the probe laser. The optical layout of the apparatus and a detailed description of the apparatus are given in Ref. 5.

Figure 1 shows Faraday, shadow, and interference images of the plasma. The load here was a 25-μm Al wire. The plasma was probed during the current rise, 13 ns before the beginning of x-ray emission. The value of the load current at the time of the probing was ~ 100 kA according to electrical measurements. On the image we can clearly see the neck which is formed. The Faraday effect is seen most prominently in the region of plasma ejection, but we will discuss the results of a reconstruction of the magnetic field and the electron density in cross sections A (100 μm from the neck along the pinch axis) and B (near the neck).

Figure 2a shows results of a reconstruction of the magnetic induction and the electron density in cross section A. The magnetic field reaches 460 kG at a distance of 400 μm from the pinch axis. The electron density reaches a maximum of 5×10^{18} cm^{-3} at a distance of 270 μm from the pinch axis. These results show that the maximum current in cross section A is limited to a diameter of 800 μm and has a value of 90 kA, in good agreement with the results of electrical measurements. Figure 2, b and c, shows results of a reconstruction of the interference phase shift (b) and of the angle through which the

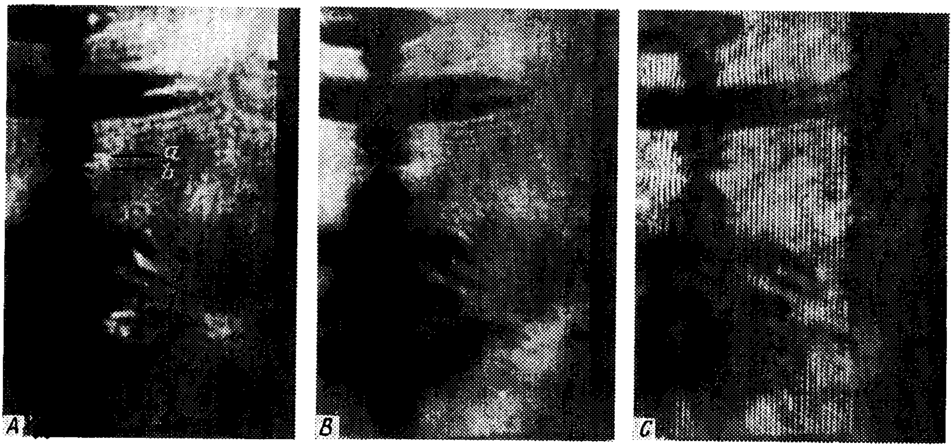

FIG. 1. Faraday (A), shadow (B), and interference (C) images of the plasma of an exploding 25-μm Al wire at the time at which a current of 100 kA is flowing through the wire and also at a time 13 ns before the beginning of x-ray emission.

polarization plane rotates (c) in cross section B. The distribution of the rotation angle is purely noisy with a noise amplitude $\alpha = \pm 0.05°$. The interference phase shift is of a signal nature, with a maximum value $\delta \sim 0.3$ of a line at a distance $\sim 50\ \mu$m (this figure corresponds to an average electron density $\sim 3 \times 10^{18}\ \mathrm{cm}^{-3}$). We can estimate an upper limit on the average magnetic field:[4]

$$B = 0.56 \cdot \alpha / \delta \sim 90\ \mathrm{kG},$$

where α is in degrees, and δ in lines. Correspondingly, the current does not exceed 2 kA; i.e., it is less than 2% of the total current.

A special method was devised to reliably reconstruct such small values of the interference phase shift. This method is based on a differential analysis principle which makes use of *a priori* information on the initial position of the unperturbed interference lines. Just before a working shot of the apparatus is released, there is a shot of the probe laser of the interference channel of the three-channel polarization interferometer. The unperturbed interferogram formed in this manner is stored in computer memory. After a working shot, the coordinates of the maximum and the minimum along the selected cross section of the interferogram of the Z-pinch are compared with the corresponding coordinates in a complementary cross section of the unperturbed interferogram. This approach makes it possible to keep the error in the reconstruction of the phase shift at a level of ~ 0.03 of a line. The coordinates of the two interferograms are reconciled with the help of a visualizing diaphragm. This method makes it possible to avoid errors associated with imperfections of the optical elements of the diagnostic complex.

Figure 3 shows a 2D distribution of the interference phase shift (a) reconstructed through an analysis of a large number of radial cross sections on the interferogram at steps of 25 μm along the axis, along with a corresponding fragment of a shadow image (b) of the neck region. On the phase image we can see the onset of a radial plasma

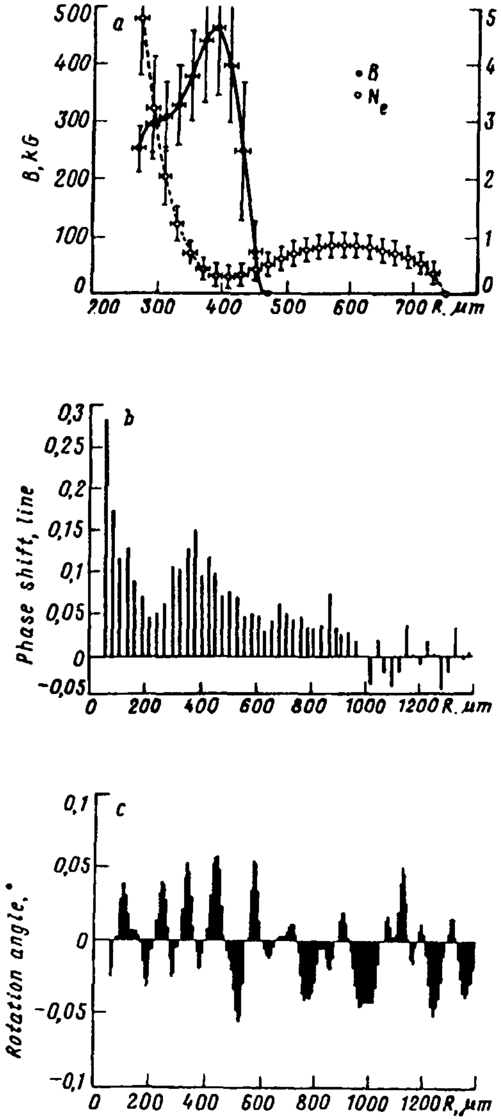

FIG. 2. Distributions of the magnetic field and the electron density (a) in cross section *A* and of the interference phase shift (b) and the angle through which the polarization plane is rotated (c) in cross section *B*.

ejection directed away from the center of the pinch toward its periphery. This plasma ejection can apparently explain the switching of the current to the low-density peripheral plasma.

A surprising effect was observed experimentally: The magnetic field near the neck is essentially zero, and the corresponding fraction of the current does not exceed ~2%. This result is in total contradiction of the standard scenario,[6–9] according to which plasma flows out of the neck as the result of an elevated magnetic pressure, and the magnetic field is strengthened because of a compression of plasma with a frozen-in magnetic field.

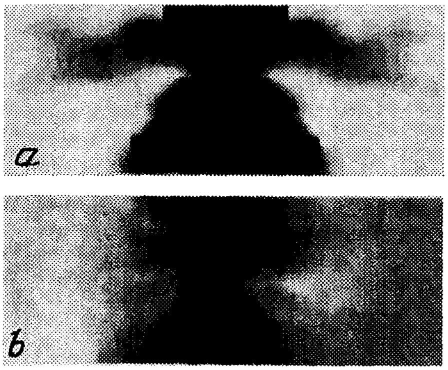

FIG. 3. Two-dimensional distribution of the interference phase shift in the neck (a) and corresponding fragment of a shadow image (b), which demonstrates a radial ejection of plasma from the periphery of the pinch.

Note, however, that the standard scenario was worked out for a plasma which is described by single-fluid MHD, in which the primary mechanism for the evolution of the magnetic field is a convective motion of the plasma, which is indistinguishable from a motion of ions in this approximation. However, the validity of MHD is limited to large numbers of electrons per unit length,[9] $N_e > M_i c^2 / Ze^2$. For deuterium this condition corresponds $N_e > 10^{17}$ cm^{-1}; for doubly ionized aluminum it corresponds to $N_e > 3 \times 10^{17}$ cm^{-1}. In modern fast pinches which start with a small radius, this condition is rarely violated, even if one assumes that the entire wire evaporates. Interference measurements of the electron density at the neck of an exploding wire[10] show that the number of electrons per unit length under our experimental conditions is on the order of $N_e = 10^{15}$ cm^{-1}, i.e., far outside the range of applicability of single-fluid MHD, but clearly within the range of applicability of electron MHD $(m_e c^2 / e^2 < N_e < M_i c^2 / Ze^2)$. In electron MHD, the current velocity is greater than the Alfvén velocity, and the primary mechanism for the evolution of the magnetic field becomes convection of the magnetic field by the electron current.[9] This extremely important mechanism was first discussed for semiconductor plasmas.[11,12] For a qualitative explanation of our experiments, it is sufficient to recall that in the first approximation of electron MHD the current flows along lines of $n_e r^2 =$ const (Ref. 13). It follows from this relation that the current and the magnetic field are carried by convection out of regions with a low number of electrons per unit length (the neck), in contradiction of the standard single-fluid picture but in agreement with our experiments (Fig. 3). This mechanism has been invoked previously to explain the stabilization of the neck region of pinches with a large initial value of the number of electrons per unit length.[9] Actually, this stabilization frequently occurs as the number of electrons per unit length decreases to the threshold for the applicability of MHD, but there has been no prediction of the observed picture, although the formulas from which the current-loss effect follows directly were written.

One is naturally led to ask the following question: If the current moves away from the neck, what mechanism pushes plasma out of the neck? A partial answer to this question was given in the theory of plasma opening switches[13,14] on the basis of the electron MHD resistance:

$$R[\Omega] = 15u/c,$$

where $u=I/(\pi r^2 n_e e)$ is the average current velocity in cm/s, I is the current in amperes, r is the neck radius in centimeters, and e is the electron charge in coulombs. It follows from this formula that with decreasing value of the number of electrons per unit length in the plasma, $\pi r^2 n_e$, the electron MHD resistance increases rapidly, and a thermal explosion occurs. Under our experimental conditions, this process terminates in an essentially complete loss of current from the neck.

In summary, the results of these measurements of the structure of the magnetic field in the neck of a Z-pinch formed during the explosion of a 25-μm aluminum wire force a radical revision of the existing picture of the neck formation. Qualitative features of the phenomenon agree with electron MHD.

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[1] S. Czekaj, A. Kasperczuk, R. Miklaszewski *et al.*, Plasma Phys. and Control. Fusion **31**(4), 587 (1989).
[2] V. A. Veretennikov, A.E. Gureĭ, S. N. Polukhin *et al.*, Fiz. Plazmy **16**, 818 (1990) [Sov. J. Plasma Phys. **26**, 475 (1990)].
[3] A. V. Branitskiĭ, V. D. Vikharev, A. G. Kasimov *et al.*, Fiz. Plazmy **18**, 1131 (1992) [Sov. J. Plasma Phys. **18**, 588 (1992)].
[4] T. Pisarchik, A. A. Rupasov, G. S. Sarkisov, and A. S. Shikanov, Preprint 135, FIAN, Moscow (1989); J. Sov. Laser Res. **11**, 1 (1990).
[5] G. S. Sarkisov, B. Etlicher, C. Rouille, and S. Attelan, Preprint LPMI 2986, Ecole Polytechnique (1994).
[6] A. C. Kolb, Rev. Mod. Phys. **32**, 74 (1960).
[7] V. F. D'yachenko and V. S. Imshennik, *Reviews of Plasma Physics*, ed. by M. A. Leontovich (Consultants Bureau, New York, 1980), Vol. 8, p. 164.
[8] V. V. Vikhrev and S. I. Braginskiĭ, *Reviews of Plasma Physics*, ed. by M. A. Leontovich (Consultants Bureau, New York), Vol. 10, p. 251.
[9] V. V. Yan'kov, Fiz. Plazmy **17**, 521 (1991) [Sov. J. Plasma Phys. **17**, 305 (1991)].
[10] G. S. Sarkisov, B. Etlicher, C. Rouille, and S. Attelan, Preprint LPMI 2987, Ecole Polytechnique (1994).
[11] A. I. Morozov and A. P. Shubin, Zh. Éksp. Teor. Fiz. **46**, 710 (1964) [Sov. Phys. JETP **19**, 484 (1964)].
[12] V. I. Bryzgalov and A. I. Morozov, Zh. Éksp. Teor. Fiz. **49**, 1789 (1965) [Sov. Phys. JETP **22**, 1223 (1965)].
[13] K. V. Chukbar and V. V. Yan'kov, Zh. Tekh. Fiz. **58**, 2130 (1988) [Sov. Phys. Tech. Phys. **33**, 1293 (1988)].
[14] P. V. Sasorov, JETP Lett. **56**, 599 (1992).

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