Detection of a "cold core" in a *Z*-pinch formed in a wire explosion

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A "cold core" exists in the plasma of a fast, high-current Z-pinch formed in the explosion of a thin wire. The experimental results were found by probing the plasma with a 3-ns laser pulse at a wavelength of 532 nm. The experiments were carried out with the help of a high-current source with a pulse length ~50 ns and a maximum current ~250 kA. The results indicate that most of the wire remains unevaporated over essentially the entire first half-period of the current pulse. © *1995 American Institute of Physics.*

Research on the Z-pinch formed during the explosion of a wire serving as the load of a high-current source has attracted much interest because of the effort to achieve controlled fusion, the effort to develop bright sources of x radiation, and research on the possible development of an x-ray laser. The possibility that a substantial part of the wire remains unevaporated during the explosion of a 20-μm copper wire and during the current flow through the resulting plasma was first raised by Aranchuk *et al.*[1] Their argument was based on an analysis of integrated pinhole photographs and the absence of any significant relationship between the power and energy of the emission, on the hand, and the wire diameter, on the other. The lack of such a relationship was evidence that the discharge used only a small fraction of the initial mass of material. It was established that the current flows through a low-density, relatively hot outer part of the pinch which constitutes a small fraction of the mass per unit length of the pinch. The inner part of the pinch remains dense and relatively cool.[2] Bobrova *et al.*[3] showed theoretically that, when the plasma thermal conductivity is taken into account, there can be an equilibrium heterogeneous state in a Z-pinch with a dense, cool core and a rarefied, hot corona. The corona would be formed by a small fraction of the mass per unit length, through which nearly all the current flows.

On the other hand, we should mention a paper by Kalantar and Hammer,[4] who assert that more than 50% of the initial mass of the material goes into the plasma corona upon the explosion of a 25-μm aluminum wire. Those results were found from experiments involving projection x-ray probing of the plasma of an exploding wire with the help of an *X*-pinch. Shadow photography of the outer boundary of the plasma was carried out in parallel, in the light from a nitrogen laser ($\lambda = 337$ nm). The shadow photography showed that the plasma boundary is subject to a substantial $m = 0$ instability. The x-ray probing showed that there is a stable, dense plasma core 200–300 μm in diameter, which does not transmit radiation in the interval 4–5 keV. Whether there is an unevaporated part of the wire in the pinch process thus remained an open question.

As we know, three basic effects oppose penetration of probing laser light into a Z-pinch: refraction of the light by the transverse gradients of the electron density, reflection of the light from the critical surface of the electrons (when the laser frequency is comparable to the plasma frequency), and absorption of the light in the plasma. The most common opinion is that refraction plays a dominant role. In other words, as the laser light passes through the plasma, it is deflected significantly away from its original propagation direction, because of large radial gradients of the electron density. The light does not fall in the capture angle of the optical detection system. An opaque plasma region arises on the image of the pinch in this case and detracts significantly from the information content of the laser diagnostics. As the angular aperture of the detection system is increased, the refraction limitations are obviously reduced. If an electromagnetic wave from the visible range is to be reflected from the critical surface of the electrons, the electron density must exceed $\sim 10^{21}$ cm^{-3}. Such densities can apparently be achieved only in the neck, and then only for a short time. The absorption coefficient of the plasma increases with increasing electron density and with decreasing plasma temperature. We have used laser light at a wavelength of 532 nm to probe the plasma of a Z-pinch produced in the explosion of a wire. The angular aperture of the optical detection system was ~0.2 rad. The results showed that no limitations are imposed by reflection of the probe light from the critical electron surface or by the pronounced refraction of the light (more than 0.1 rad in our case); the only point of importance is absorption of the light by the plasma.

The experiments were carried out with the help of the GAEL high-current source with a water forming line (Ecole Polytechnique),[5] with the following parameter values: a maximum current of 250 kA, a pulse length of 50 ns at half-maximum, a voltage of 0.5 MV, and a power of 0.1 TW. The load was a copper wire 20 μm in diameter in the gap between the cathode and the anode of the apparatus, which was 10 mm wide.

The plasma was probed with a high-power QUANTEL NG-24 Nd:YAG laser with active Q switching. The output energy of this laser, which consisted of a 3-ns source and three amplifiers, was 1 J. The plasma was probed with the second harmonic of the laser, generated by nonlinear conversion in a KDP crystal with a conversion coefficient of 25%. The probe light thus had the following parameter values: 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 apparatus within 5 ns.

We studied the plasma with the help of a three-channel diagnostic complex, which was capable of obtaining shadow, Schlieren, and interference images of the plasma simultaneously. The angular aperture of the optical system was ~0.2 rad, and the spatial resolution ~20 μm. Spatial and frequency filtering of the light was used to eliminate the effect of intrinsic emission by the plasma. For the spatial filtering we used a narrow (~1-mm) slit oriented perpendicular to the axis of the Z-pinch. The approach made it possible to significantly lower the level of intrinsic emission from the plasma (since the plasma emits into a solid angle of 4π) and to pass to the photodetector the probe light which has not undergone refraction and also the light which has been refracted in the direction perpendicular to the symmetry axis of the pinch. The macroscopic gradients of the electron density are directed along this symmetry axis. For the frequency filtering we

FIG. 1. Absorbogram of a Z-pinch formed in the explosion of a 20-μm copper wire at the beginning of x-ray emission. 1—Region of saturation of the signal at the CCD detector; 2—region of light absorption; 3—shadow from the part of the wire which has not evaporated.

used interference filters in front of the photodetector. As the photodetectors we used CCD cameras (Philips NXA1050/05 576×604 with an optical-fiber input). These cameras were calibrated with the help of a step attenuator in the light of the probe laser. The optical layout of the experiments is described in detail in Ref. 6.

Figure 1 shows an absorption image of a Z-pinch formed in the explosion of a 20-μm copper wire by a 200-kA current. The beginning of x-ray emission from the plasma is detected at the time at which the plasma was probed. This absorption image is an ordinary shadow image of the plasma, obtained with neutral filters in front of the photodetector causing an attenuation by a factor of a few units. The part of the image at the CCD camera in which the laser beam does not undergo absorption is in a state of saturation, and the central region of the pinch (which does not transmit in ordinary shadow photography) turns out to transmit green light. Along the axis of this absorbogram we can see a shadow from the unevaporated wire. When the photodetector has a sufficiently large dynamic range, it is possible to simultaneously detect shadow and absorption images of the plasma with the same detector. However, since the outside diameter of the absorption image of the plasma is quite different from that of the shadow image, we will refer to images of this type below as "absorbograms."

Figure 2 shows an inverted surface of the distribution of the relative intensity of the laser light on an absorbogram. Along the axis of the pinch we see the track of the unevaporated wire. Radial cross sections of the surface correspond to the distribution of the integral absorption coefficient for the laser light. These measurements showed that the absorption of light in the plasma results in a reduction of the light intensity by a factor of 10–20 under our experimental conditions.

Figure 3 shows a series of four absorbograms of the Z-pinch of 20-μm copper wires recorded in various shots. These absorbograms correspond to different probing times, from -7 ns to $+10$ ns with respect to the beginning of the x-ray emission. In all four cases we see an image of the unevaporated wire. Before the x-ray emission begins, the plasma tends to assume an axisymmetric shape; constrictions and swellings form. Once the x-ray emission begins, we see a disruption of the symmetry of the Z-pinch and the formation of radial gaps in the plasma.

Simple estimates show that a plasma corona with a degree of ionization of 2–3 and an average electron density $\sim 10^{19}$ cm^{-3} over the corona can be produced by evaporating only ~ 1 μm of material from the surface of the wire. This amount of material would not

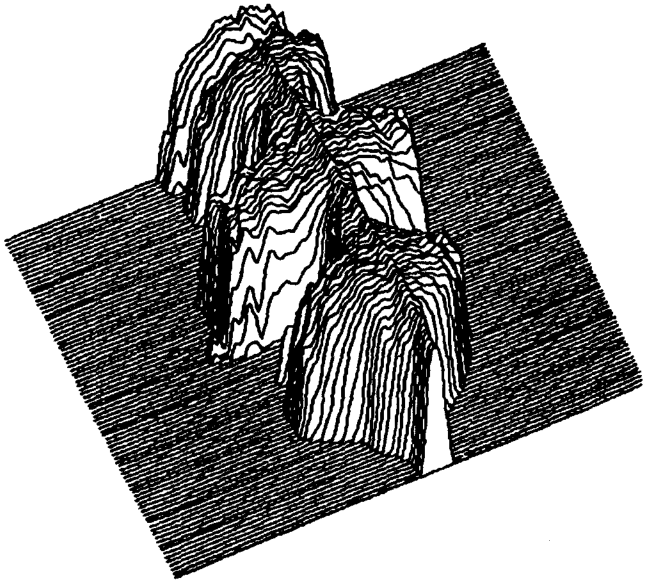

FIG. 2. Inverted surface of a distribution of the intensity of laser light which has undergone absorption in a Z-pinch.

exceed ~3% of the mass of the wire (an increase in the charge of the ions in our estimate would lead to a decrease in the fraction of the mass which has evaporated). Complete evaporation of the material apparently occurs at later times. This estimate confirms the results of Ref. 7, where it was shown that the cleanliness of the wire surface has a strong effect on the experimental results.

In summary, the results of this study show that a plasma shell arises in experiments

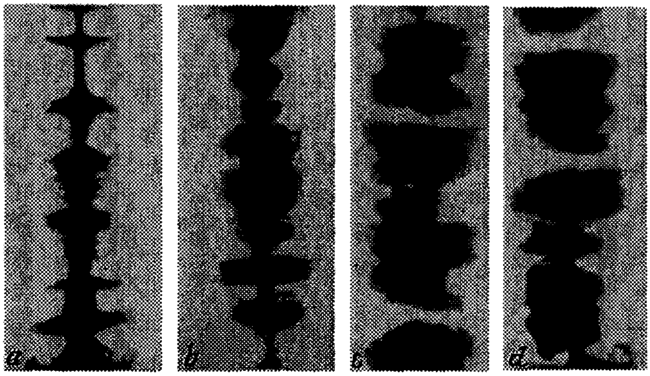

FIG. 3. Absorbograms of a Z-pinch formed in the explosion of a 20-μm copper wire. These absorbograms were recorded in different shots and correspond to different probing times with respect to the beginning of the x-ray emission. a) -7 ns; b) 0 ns; c) $+5$ ns; d) $+10$ ns.

with wires as the result of the surface explosion of a very small fraction of the initial mass of material. The current is then shunted by the low-density plasma, and the subsequent ablation of the wire results from a transfer of energy from the zone of Joule heating in the current shell by electron thermal conductivity and radiation. Complete evaporation of the wire occurs either in regions in which necks form and in which the temperature and the pressure rise sharply, or at later times, which are of no interest to the physics of Z-pinches. The unevaporated part of the wire serves the role of a "cold core" in the current flow through a Z-pinch. This cold core limits the rise of the plasma temperature, because the Joule heat and the radiation from the current shell are expended on ablation and ionization of the wire material.

We should point out that using laser light to probe the inner region of a Z-pinch plasma adds substantially to the possibilities for the diagnostics of dense plasmas. For example, a Schlieren image of the absorption zone makes it possible to visualize the structure of the gradients of the electron density of the inner part of the pinch. The simultaneous recording of absorbograms and interferograms of the plasma makes it possible to reconstruct a spatial distribution of the electron temperature and the pressure of the inner region of the Z-pinch.

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