Measurement of the electron temperature distribution in a Z pinch by the laser absorption method

G. S. Sarkisov[1)]
P. N. Lebedev Physics Institute, Russian Academy of Sciences, 117924 Moscow, Russia

B. Etlicher
LPMI, Laboratoire du CNRS, Ecole Polytechnique, 91128 Palaiseau, France

(Submitted 4 September 1995; resubmitted 6 October 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **62**, No. 10, 775–782 (25 November 1995)

A new method is proposed for measuring the electron temperature in the interior region of a Z pinch. The method is based on laser probing of the plasma with simultaneous measurement of the absorption and interference phase shift profiles of the probe radiation inside the Z pinch. It is shown that the opaque region which appears in the pinch in laser-probing experiments is related to the absorption of radiation and not to the refraction of the radiation by transverse gradients of the electron density (as previously believed). The refraction of the laser radiation does not exceed the angular aperture of the recording optics and cannot influence the formation of the opaque region in the image of the central part of the pinch. It is shown that the laser radiation transmitted through the Z pinch has a high degree of coherence, which makes it possible to perform interferometry of the absorption region. In experiments with Z pinches formed by exploding a 20-μm-aluminum wire with a ~250-kA, 50-ns current pulse, electron densities and electron temperatures $\sim 1.4 \times 10^{20}$ cm^{-3} and ~530 eV, respectively, were produced at the neck of the pinch. © *1995 American Institute of Physics.*

A series of methods has now been developed for measuring the plasma temperature in a Z pinch. X-ray spectroscopy methods are most widely used. Fairly complete reviews of this subject can be found in Refs. 1 and 2 . Of laser diagnostics methods, the most highly developed method is the Thompson light-scattering method[3] which yields information about the local values of the electron temperature and density.

A unique method for measuring the electron temperature of a plasma by means of laser radiation was proposed in Ref. 4 . To investigate a two-component, strongly interacting laser plasma with electron density $\sim 10^{20}$ cm^{-3} and electron temperature ~2–6 eV, it was suggested that simultaneous time-resolved measurements of the absolute plasma radiation and the absorption of the laser probe radiation be performed. However, this method of measurement has serious limitations. The plasma temperature distribution is assumed to be uniform and the experimental plasma must be in the form of a flat slab. Such serious limitations make the method proposed in Ref. 4 for measuring the temperature very exotic and inapplicable to Z pinches.

Laser probing methods have not been previously employed for obtaining information about the interior region of a Z pinch, because in probing a Z pinch a so-called zone of opaqueness for the laser radiation appears. This happens for three reasons: absorption of the laser radiation, refraction of laser radiation by the transverse gradients of the electron density, and reflection of light from the critical electron density ($n_e > 10^{21}$ cm^{-3}). It was usually assumed that refraction predominates because of steep electron density gradients, which make laser probing of the central region of the pinch virtually impossible. In this case the only possibility of penetrating into the volume of the pinch is to use ultraviolet radiation for probing, since the angle of refraction is a quadratic function of the wavelength. In Ref. 5 it was shown, however, that when the axial region of a Z pinch produced by electrical explosion of thin metallic wires carrying a 50-ns, 250-kA current pulse is porbed with the second harmonic of Nd laser radiation ($\lambda = 532$ nm), laser absorption predominates. The measurements showed that the light intensity is approximately 10–20 times lower in the region of absorption, and it was found that a copper wire 20 μm in diameter was not vaporized for the entire first half-period of the current. In laser probing of a Z pinch the most likely mechanism for absorption of electromagnetic radiation is inverse bremsstrahlung. In this case, the absorption coefficient K is proportional to $n_e^2/T_e^{3/2}$. Simultaneous measurements of the absorption and interference phase-shift profiles thus make it possible to reconstruct the local electron temperature distribution in the central region of a Z pinch (assuming that the region is axisymmetric).

For characteristic laser probe intensities $\sim 10^7 - 10^8$ W/cm^2 and plasma parameters $n_e \sim 10^{18} - 10^{20}$ cm^{-3} and $T_e \sim 100$ eV the main light absorption mechanism is inverse bremsstrahlung (because of electron-ion collisions). For a thermal distribution of the ions and a Maxwellian distribution of electrons, the expression for the absorption coefficient has the form[6]

$$K = 8.73 \times 10^{-30} \; \lambda^2 \frac{n_e^2 Z \; \ln \Lambda}{T_e^{3/2} (1 - n_e / n_c)^{1/2}}, \tag{1}$$

where K is the absorption coefficient in cm^{-1}, λ is the wavelength in cm, n_e and n_c are the electron density and the critical electron density in cm^{-3}, T_e is the electron temperature in eV, Z is the ion charge, and $\ln \Lambda$ is the Coulomb logarithm.

When the probed plasma is axisymmetric, the Abel transformation can be used to reconstruct the local distribution $K(r)$ of the absorption coefficient. Similar analysis of the corresponding interference pattern makes it possible to reconstruct the local electron density $n_e(r)$ distribution $K(r)$ and, therefore, the local distribution of the electron temperature $T_e(r)$ from Eq. (1).

The absorption of the laser radiation propagating tnrough the plasma is attributable to the local absorption as follows:

$$\ln(I/I_0) = -\int^L K dl, \tag{2}$$

where I/I_0 is the change in the intensity of the laser light after passage through the plasma, and L is the optical pathlength.

To obtain the radial distribution of the electron density, it is necessary to perform simultaneously interference measurements which give the phase shift of the diagnostic beam along the line of sight:

$$\delta = 4.46\times 10^{-14}\lambda \int^{L} n_e dl, \tag{3}$$

where δ is in the lines, λ and L are measured in cm, and n_e is measured in cm^{-3}.

We employ the following expression to calculate the Coulomb logarithm (for $T_e < 1$ keV):

$$\ln \Lambda = 23 - \ln(Z n_e^{1/2} T_e^{-3/2}), \tag{4}$$

where n_e is in cm^{-3}, and T_e is in eV.

We assume that the condition of local thermodynamic equilibrium is satisfied in the region of the neck. Tthe approximate expression presented in Ref. 7 can then be used to calculate the ion charge as a function of the electron density and the electron temperature:

$$I(Z+1/2) = T_e \ln(6\times 10^{21} T_e^{3/2}/n_e), \tag{5}$$

where I is the ionization potential in eV, T_e is the temperature in eV, and n_e is given in cm^{-3}.

The experiment was performed on the GAEL (Ecole Polytechnique) high-current generator[8] with the following parameters: maximum current strength 250 kA, pulse width at half-maximum 50 ns, voltage 0.5 MV, and power 0.1 TW. The load consisted of an aluminum wire 20 μm in diameter, placed in a 10-mm cathode-anode gap in the generator. The plasma was probed with a powerful, actively Q-switched Nd:YAG laser (QUANTEL NG-24). The output energy of the laser, which consisted of a 3-ns generator and three amplifiers, was equal to 1 J. The second harmonic of the laser radiation, obtained by nonlinear conversion in a KDP crystal with a conversion factor of 25%, was used to probe the plasma. In summary, the probing radiation had the following parameters: wavelength 532 nm, pulse width 3 ns, and pulse energy 250 mJ. The scatter in the synchronization of the laser radiation with the current pulse in the GAEL generator did not exceed 5 ns.

Figure 1 shows a three-channel diagnostics complex, which makes it possible to obtain simultaneously the absorption,[9] shadow, and interference images of the plasma. The angular aperture of the optical system was equal to ~0.2 rad, the spatial resolution was equal to ~20 μm, and the temporal resolution was equal to ~3 ns (the temporal resolution depends on the duration of the probing laser pulse). A visualizing diaphragm 7 was used to match the coordinates of the three images. The lens 5 transferred the image of the plasma into the plane of the visualizing diaphragm 7, after which the lens 8 transferred the intermediate image of the plasma, together with the image of the diaphragm 7, to the photodetectors in the absorption, shadow, and interference channels 13, 14, and 15, respectively.

The absorption image[5] is a standard shadow image of the plasma, obtained by reducing severalfold the size of the neutral filters in front of the photodetector. The image region on the CCD camera, where the laser beam did not undergo absorption, is satured

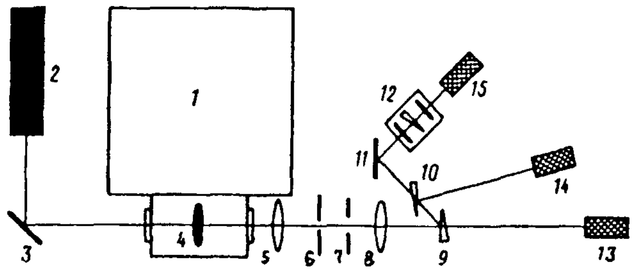

FIG. 1. Optical layout of a three-channel diagnostics complex for measuring the temperature in Z pinches. *1* — GAEL high-current generator; *2* — Nd:YAG laser; *3* — dielectric mirror; *4* — plasma; *5, 8* — lenses; *6* — object spatial filter; *7* - visualizing diaphragm; *9, 10* — 2° glass wedge; *11* — Al mirror; *12* — polarization shearing interferometer; *13, 14, 15* — CCD cameras in the absorption, shadow, and interference channels, respectively.

and the central region of the pinch (not transparent in standard shadow photography) is transparent to green light. If the dynamic range of the photodetector is sufficiently large, the shadow image of the plasma will also be an absorption image. However, since the dynamic range of the photodetector is not large enough in our case and since the external view of the absorption image of the plasma differs substantially from the shadow image, we shall henceforth call images of this type "absorbograms." The external view of an absorbogram looks more like the image of a pinch obtained with a pinhole camera.

A polarization shearing interferometer 12, which consists of an entrance film polarizer, a 3° calcite wedge, and an exit film polarizer, was used in the diagnostics apparatus. The calcite wedge divides an incident wave into two beams with orthogonal linear polarizations and separates them by angle. Two images of the plasma, shifted relative to one another in the radial direction, are thus formed in the recording plane 15. Because of the presence of the exit polarizer, both beams have identical polarization and equidistant interference fringes, which are perpendicular to the shearing direction, appear in the region where the beams are superimposed. The ratio of the intensities in the interfering beams can be changed by rotating the exit polarizer. This procedure is very important for performing interferometry of the absorption zone in a Z-pinch.

Spatial and frequency filtering of the radiation were used to eliminate the influence of the characteristic emission of the plasma. A narrow ($\sim$1 mm) slit oriented perpendicular to the axis of the Z pinch was used for spatial filtering. This made it possible to decrease substantially the intensity of the characteristic radiation from the plasma and thus to direct to the photodetector the unrefracted probe radiation and the probe radiation which has been refracted in a direction perpendicular to the symmetry axis of the pinch, along which the macroscopic gradients of the electron density are oriented. Frequency filtering was performed using interference filters placed in front of the photodetectors. The photodetectors consisted of CCD cameras (Philips NXA1050/05), calibrated with the help of a stepped attenuator in the probing laser radiation.

It is important to know the degree of coherence of the laser radiation which passes through the absorption region. Is it sufficiently high for performing reliable interferom-

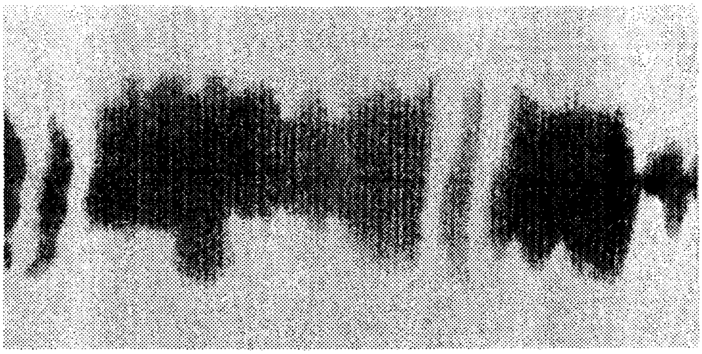

FIG. 2. Differential interferogram of the absorption region in a Z pinch. The interferogram was obtained by superimposing two absorption images of the plasma which were shifted with respect to one another in the axial direction. A trace of the unevaporated wire is visible along the axis of the interferogram.

etry of the interior region of a Z pinch? A special experiment was performed to clarify this question. A differential interferogram of the absorption region of the Z pinch is shown in Fig. 2. This interferogram was obtained by superimposing two absorption images of the plasma which were shifted relative to one another in the axial direction. This image clearly shows that the degree of coherence of the light which has undergone absorption in the central part of the pinch is high. The degree of interference modulation varied from $\sim$90% in the absence of the plasma down to $\sim$25% after the light has passed through the region of absorption in the pinch. This is sufficient for localizing the coordinates of the maxima and the minima of the interference fringes. A shadow from the unvaporized wire is visible along the axis of the pinch.

Figure 3 shows a shadowgram, an interferogram, and an absorbogram of a Z pinch formed by the explosion of a 20-μm aluminum wire. Probing was performed 55 ns after current flow started (7 ns before x-ray emission appeared). In this shot the plasma was axisymmetric, and the x-ray radiation was recorded in the form of a single pulse. To reconstruct the absorption coefficient, it was sufficient to employ a shadow image of the plasma, since the entire drop in the intensity of the probe radiation did not exceed the dynamic range of the CCD camera.

The most difficult part was the reconstruction of the interference phase shift in the central region of the pinch, since the ratio of the intensities of the interfering beams changed substantially in the radial direction. By rotating the exit polarizer in the interferometer it was possible to superimpose on the region of the image in one beam the unperturbed region of the other beam, whose initial intensity was several times lower than that in the first beam. This, of course, decreased the contrast of the fringes in the peripheral part of the pinch, but in the process it provided in the absorption region a contrast of the interference fringes which was acceptable for recording. The phase shift was reconstructed by the differential method using *a priori* information, obtained immediately before the shot, about the coordinates of the undisturbed fringes. This procedure made it possible to reduce the rms error of the deviation of the fringes to the 0.05 level of a line. This is very important for measuring small phase shifts.

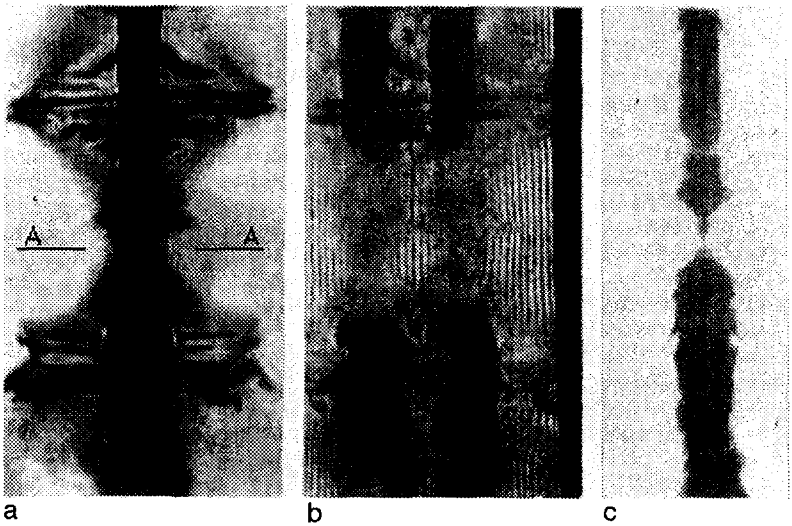

FIG. 3. Shadow, interference, and absorption images of a Z pinch formed by exploding a 20-μm aluminum wire. The probing was performed 55 ns after the current started to flow and 7 ns before x-ray emission appeared. The current strength was equal to 180 kA.

The results of the reconstruction of the local radial distributions in the section $A-A$ at the neck of a Z pinch are illustrated in Fig. 4: the absorption coefficient $K(r)$ and electron density $n_e(r)$ (Fig. 4a), electron temperature $T_e(r)$ and thermal pressure $p(r)$ (Fig. 4b), ion charge $Z(r)$ and Coulomb logarithm $\ln\Lambda(r)$ (Fig. 4c), and a temperature histogram of the mass distribution in the pinch (Fig. 4d). In reconstructing the distributions we assumed that the condition of local thermodynamic equilibrium is satisfied in the region of the neck. The electron density, temperature, and pressure reach a maximum at the center of the pinch and have the following values: $n_e=1.4\times10^{20}$ cm^{-3} ($\pm20\%$), $T_e=530$ eV ($\pm30\%$), and $p=0.12$ Mbar ($\pm35\%$). The linear density of the thermal energy of the electrons in the pinch is equal to ~540 mJ/cm. The linear mass density in the pinch is equal to ~0.11 μg/cm, which is only ~1.3% of the linear mass density of a 20-μm aluminum wire, which is equal to ~8.5 μg/cm. These data show that substantial mass is displaced along the axis of the pinch. Since the magnetic flux is frozen in, this displacement of the plasma should probably also result in the displacement of current out of the pinch, as demonstrated in Ref. 10 , where measurements showed that the current flowing through the pinch does not exceed 2% of the current flowing through the high-density region of the pinch. We see from the histogram in Fig. 4d that ~79% of the mass in the pinch has a temperature as high as 100 eV and only ~3.4% of the mass has temperatures in the range 400–500 eV.

A calculation of the angle of refraction on the radial electron density gradients in a plane perpendicular to the symmetry axis of the pinch showed that the angle does not exceed 1.3°, which is much less than the angular aperture ~10° of the recording optics. Apparently, in our case this is the largest angle of deflection of the probe radiation, since

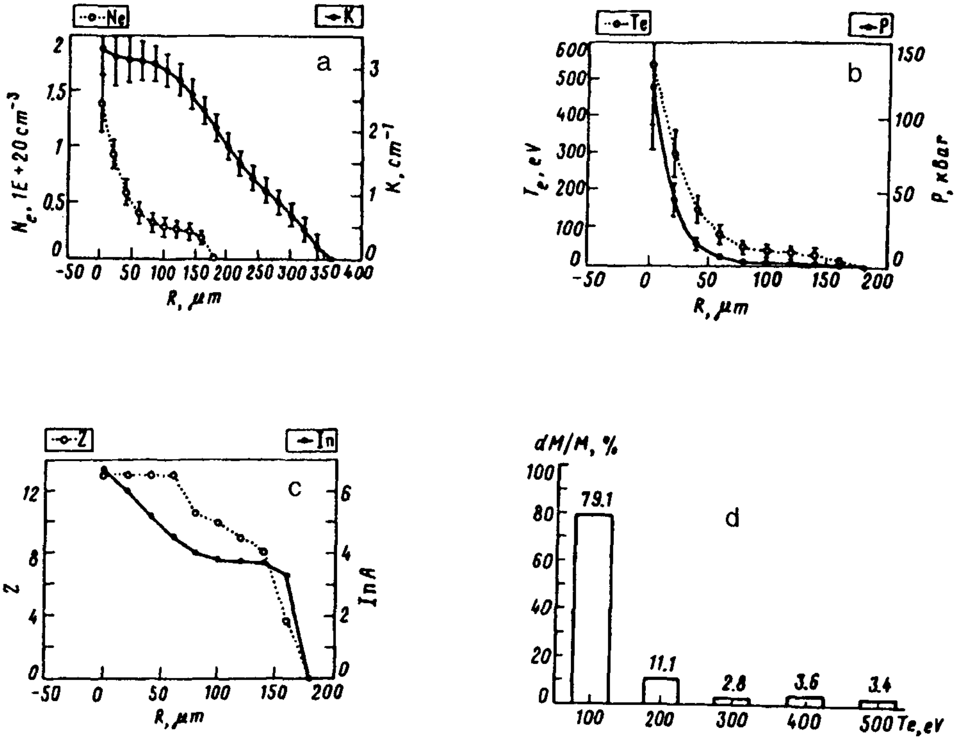

FIG. 4. Local distributions in the Z pinch in the section $A-A$: absorption coefficient and electron density (a), electron temperature and thermal pressure (b), ion charge and Columb logarithm (c), and temperature histogram of the distribution of the relative mass of the plasma (d).

the density in the other regions of the plasma is much lower and, correspondingly, these regions cannot produce significant refraction of the laser radiation.

Few words are in order about the correctness of using at the neck of a Z pinch the model of local thermodynamic equilibrium (LTE). It is well known that the LTE model gives somewhat higher values of Z than other models of equilibrium. This will accordingly give electron temperatures which are too high. How large is this overestimation? Comparing the LTE calculations and the calculations performed using a more accurate collisional-radiative model (for an optically transparent medium)[11] gives for Al ions a charge Z which is higher no more than 15–20%. It follows from Eq. (1) for the absorption coefficient that the corresponding overestimation of the temperature will not exceed 10–15%, which falls within the range of the measurement error, as one can see from a plot of the electron temperature distribution in Fig. 4b. The main errors in the measurement of the electron temperature are associated with the measurement of the phase shift and the absorption coefficient, the double Abel transformation procedure and, of course, the assumption that the plasma is axisymmetric.

In summary, we have proposed a new and unique method for measuring the electron temperature distribution in the interior region of a Z pinch with high spatial ($\sim$20 μm) and temporal ($\sim$3 ns) resolutions. It was shown that the angle of refraction of the probe radiation is rather small (not more than 1.3°), and the change in the intensity of the light in the central region of the pinch is associated exclusively with the absorption of light. The coherence of the radiation passing through the central region of the pinch remains sufficiently high for interferometry. Analysis of the experimental results for a Z pinch formed by exploding a 20-μm aluminum wire with a 250-kA, 50-ns current pulse, made is possible to reconstruct the radial distributions of the plasma parameters in the region of the neck. At the moment of probing the maximum values of these parameters were as follows: electron density 1.4×10^{20} cm^{-3}, electron temperature $\sim$530 eV, thermal pressure $\sim$0.12 Mbar, linear density of the thermal energy $\sim$540 mJ/cm, and linear mass density $\sim$0.11 μg/cm. The procedure proposed by us makes it possible to produce a two-dimensional picture of the temperature in a Z pinch and to observe the evolution of the temperature in the chosen radial section with high spatial and temporal resolutions.

The results presented in this letter radically expand the possibility of laser probing of Z pinches. It is possible to talk confidently about a "renaissance" of laser diagnostics of dense plasma. Multichannel laser methods of diagnostics of dense plasma make it possible to perform contact-free measurements in the entire volume of a Z pinch and to reconstruct local distributions with high spatial and temporal resolution — electron density, magnetic-field induction, current strength, current density, electron drift velocity, magnetic pressure,[10] electron temperature, ion charge, thermal pressure, linear densities of the mass and thermal energy, and quantities derived from them.

We thank S. Attelan and C. Rouille for assisting in the experiments and V. T. Tikhonchuk for a useful discussion of the results.

This study was supported by contracts EC ##SC1*-CT91-0728, ETCA/CEG ##420/115/01, and DRET ##92/134.

1)e-mail: Sarkisov@ldp.fian.msk.su

1 V. A. Boiko, A. V. Vinogradov, S. A. Pikus *et al.*, J. Sov. Laser Res. **6**, 85 (1985).
2 E. V. Aglitskiĭ, V. V. Vikhrov, A. V. Gulov *et al.*, *Spectroscopy of Multicharged Ions in Hot Plasma* [in Russian], Nauka, Moscow, 1991, pp. 163–202.
3 J. Sheffield, *Plasma Scattering of Electromagnetic Radiation*, Academic Press, New York, 1975.
4 K. J. Kearney, A. N. Mostovych, and J. A. Stamper, Rev. Sci. Instrum. **61**, 3596 (1990).
5 G. S. Sarkisov, B. Etlisher, S. Atelan, and K. Ruie, JETP Lett. **61**, 555 (1995).
6 T. W. Johnston and J. M. Dawson, Phys. Fluids **16**, 722 (1973).
7 Yu. P. Raĭzer, Zh. Éksp. Teor. Fiz. **36**, 1583 (1959) [Sov. Phys. JETP **9**, 1124 (1959)].
8 F. Wessel, B. Etlicher, and P. Choi, Phys. Rev. Lett. **69**, 3181 (1992).
9 G. S. Sarkisov, B. Etlicher, C. Rouille, and S. Attelan, Preprint LPMI 2987, Ecole Polytechnique, 1994.
10 G. S. Sarkisov, B. Etlicher, S. Attelan *et al.*, JETP Lett. **61**, 485 (1995).
11 V. I. Oreshkin and V. V. Loskutov, Preprint No. 9, Tomsk Scientific Center of the Siberian Branch of the USSR Academy of Sciences, 1990.

Translated by M. E. Alferieff