Monochromatic x-ray probing of an ultradense plasma

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The ultradense plasma of an exploding wire has been studied by a new method of monochromatic x-ray probing. This method makes it possible to obtain shadow images of bright plasma objects in individual spectral lines at a high spatial resolution. The method also relaxes the requirements on the radiation source. The method uses x-ray elements with mica crystals bent to a spherical surface shape with a radius of 100–250 mm. Images of the explosion of an aluminum wire have been obtained in the $1s^2$–$1s3p$ spectral line ($\lambda = 6.6343$ Å) of the He-like ion Al XII. The experimental results confirm that there is a low-density plasma corona, which arises in the initial stage of the discharge through the wire, and that there is also a dense core, which exists at the axis of the pinch during the discharge. © *1995 American Institute of Physics.*

The method of x-ray probing[1–3] of dense and ultradense plasmas is one of the most effective diagnostic methods for studying the state of a compressed target in laser-fusion problems and also in research on the compression of various liner systems with pinch discharges. There have been suggestions that x-ray lasers be used for these purposes (Ref. 4, for example), but these suggestions have yet to be realized in the hard part of the spectrum. The source of the probe radiation has been either an auxiliary target bombarded by an auxiliary laser (see, for example, Refs. 5–7 and a review[8]) or an X-pinch parallel to the main discharge.[3] In the case of a point radiation source, shadow projection is used to obtain an image of the object under study; if the source is instead extended, x-ray microscopy in some version or other is used. In most of the methods which have been tested for x-ray probing, nonmonochromatic radiation from the probe source has been used, and a high spatial resolution has been achieved through the use of pinhole cameras.

Layouts using various crystals have recently been used for selecting the probe radiation against the background of intense emission from the objects under study.[5,9] In all cases, however, the power required to create the sources of the probe radiation has been

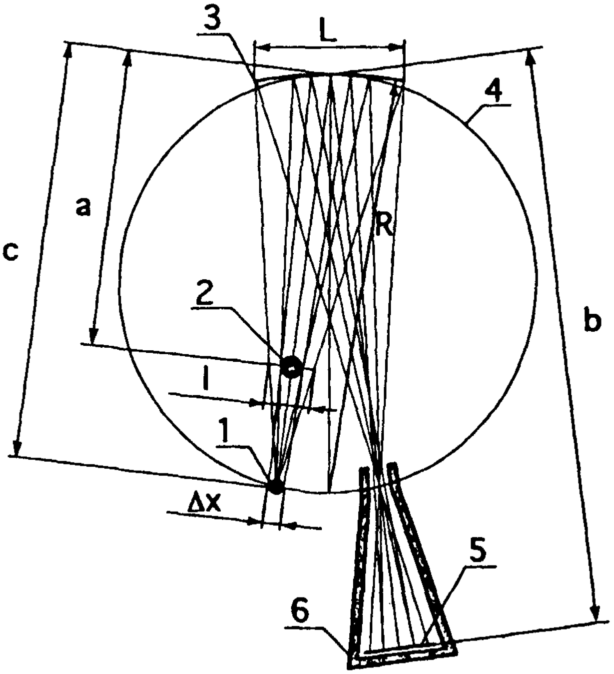

FIG. 1. Layout for the monochromatic probing. 1—Radiation source; 2—plasma under study; 3—spherical bent crystal; 4—Rowland ring; 5—radiation detector (photographic film); 6—shield.

comparable to the power expended on heating the plasma under study, and the luminosity of the system has decreased sharply as the spatial resolution has improved. A serious disadvantage of most of the probe methods which have been used previously is a small field of view, which makes these methods useless for studying large plasma formations, e.g., high-power pinches with liner loads.

In this letter we are reporting the use of a new method for monochromatic x-ray probing. This method makes it possible to obtain shadow images of bright plasma objects in individual spectral lines at a high spatial resolution. This method also permits a substantial relaxation of the requirements on the radiation source. The method furthermore has a field of view measured in centimeters, so it can be used to study essentially any plasma object.

The primary distinctive feature of this new probing method is that it exploits the ability of a crystal bent into a spherical surface shape to form images of objects in x rays. The crystal works as an ordinary optical spherical mirror whose reflection has a high spectral selectivity.

Figure 1 is a schematic diagram of the experimental layout. Radiation source 1 is on a Rowland ring 4 with a radius $R/2$ (R is the radius to which crystal 3 is bent). The source is positioned in such a manner that the Bragg condition $2d\sin\theta = m\lambda$ is satisfied. Here λ is the wavelength of the radiation from the source, d is the interplanar distance in the crystal, and θ is the glancing angle made by the radiation with the surface of the crystal. The object under study, 2, is positioned between the source and the crystal, at a distance $f<a<2f$, where $f=c/2=(R/2)\sin\theta$ is the focal length of the spherical mirror in the meridional plane. A shadow image of the object is formed in the plane of the detector or photographic film (5), at a distance b from the crystal. This distance is determined from the lens formula $1/a+1/b=1/f$. With the source near the axis of the curvature of the crystal, the sagittal focus can be assumed to coincide with the meridional focus and to be equal to the radius of the Rowland ring, $R/2$, so we have $b=aR/(2a-R)$. The spatial resolution in terms of the object in this method is essentially independent of the size of the source, being determined only by aberrations of the spherical mirror and the diffraction properties of the crystal.

The size of the source determines the interval of radiation wavelengths which are involved in shaping the image: $\Delta\lambda/\lambda=(\Delta x/R)\cot\theta$. Since the angle θ is close to the normal, and the actual dimensions of the source, Δx, are no greater than 1–2 mm, the wavelength interval for crystals with $R\approx 100$–500 mm does not exceed $(0.3$–$2)\times 10^{-3}$ Å. These figures lie within the width of an individual spectral line. The choice of spectral line of course requires an angle θ in the interval 82–88°. This requirement imposes certain restrictions on the choice of the material and properties of the source of the radiation. In the present study we used mica crystals ($2d=19.94$ Å). Mica reflects radiation fairly well in many orders (in practice, from the first to higher than the fifteenth). As a result, the selection of spectral lines is substantially increased, and the capabilities of the method are extended. The crystals were bent into a spherical surface shape with radii of 100, 186, and 250 mm by a special technique, which leads to a surface finish of nearly optical quality.[10] The wavelength range could be expanded in the long-wave direction (30–100 Å) by using a multilayer mirror as the optical element. The interplanar distance in such a mirror would be determined by the fabrication procedure and could be selected to suit the task at hand.

The size of the working field of view, l, is determined by the relative positions of the source, the object under study, the size of the crystal used, and the magnification k: $l=L/2(l-l/k)$. In the case of a high magnification, the size of the working field of view is half the aperture of the crystal, L. The crystals which we used had dimensions of $(10$–$15)\times(35$–$50)$ mm. The field of view was measured in centimeters, at least in one direction.

Since all the radiation from the source is focused into a fairly small spot near the Rowland ring, the radiation detector can be effectively shielded from intrinsic emission from the object under study and also from other types of radiation present in the experiments, e.g., in high-current Z-pinches. A shield with an aperture whose diameter is on the order of the size of the source can be installed.

In this layout, there is effective spectral and spatial filtering of the intrinsic emission from the plasma under study. The source of the probe radiation can thus have a total intensity much lower than the intensity of the object under study. The only condition which must be met is that the surface brightness of the source exceed the surface brightness of the object within one spectral line. Since the probe source can be extremely small, the power required to create this source can be several orders of magnitude lower than the power expended on heating the plasma under study.

Experiments on x-ray probing of plasmas were carried out at the XP high-current pulse generator of Cornell University (Ithaca, New York),[3] with a current of 350 kA through the load at the peak of a pulse 100 ns long. The radiation source was an X-pinch produced by the explosion of crossed aluminum wires 37.5 μm in diameter in the vacuum diode of the generator (Fig. 2a). The probing system, with a mica crystal bent to a spherical surface shape with a radius of 186 mm, was tuned to the $1s^2-1s3p$ emission line of the He-like ion Al XII, with a wavelength $\lambda = 6.6343$ Å (with an angle $\theta \approx 86°$ in the third order of reflection). The dimensions and shape of the radiation source were monitored by an x-ray microscope[11] with a spherical mica crystal with $R = 250$ mm. Figure 2b shows an image of the source in the light of the same spectral line to which the probe system was tuned.

We studied the explosion of an individual wire connected in a discharge circuit in parallel with the conductor carrying the return current. The part of the current which flowed through this wire was small, no more than a few kiloamperes. This current corresponds approximately to the initial stage of the explosion of the wire in a high-current nanosecond Z-pinch.[12] Figure 2, c and e, shows shadow images obtained in experiments on the explosion of aluminum wires 37.5 and 15 μm in diameter (these wires are marked by arrows 2). A mesh with a period of 400 μm and a wire similar to that under study, but not connected in the discharge circuit, were used to adjust and monitor the focusing in the plane of the object (this mesh and wire are marked by arrows 1). In the explosion of a wire 37.5 μm in diameter we observed a plasma filament ≈ 400 μm in diameter with a dense core of smaller diameter. This structure of the filament may be due to the presence of a sheath of evaporated material which had been adsorbed by the surface of the wire. Such material is always present in experiments unless special measures are taken to eliminate it. The dense core apparently corresponds to the wire material itself. The absorption profile implies that only a small fraction of this material evaporates. In the experiments with the thinner wire (15 μm in diameter) it was possible to observe material evaporated from the surface in the initial stage of the discharge, which expanded a distance on the order of 1 mm from the wire by the time of the probing (50 ns after the beginning of the current pulse). The diameter of the plasma filament formed in the explosion of the wire corresponds to the diameter of the dense core in Fig. 2c.

The results of these experiments confirm that there is a low-density plasma corona, which arises in the initial stage of the discharge through the wire and which has a substantial effect on the formation of the dense pinch. An effect of this sort was first observed in a comparison of observations of the final stage of a pinch in the explosion of wires in their "natural state" and of wires which were subjected to a special cleaning before the explosion.[13] At that time, no direct proof of the existence of a corona was found, since the density of the corona was low, and the corona could not be detected by ordinary optical methods.

We should point out that a laser plasma is a fairly convenient source of probe radiation in this method. In some test experiments to check the spatial resolution, the plasma was heated by illuminating an aluminum target with a neodymium laser (10 J, 2 ns). Figure 3 shows a shadow image of a mesh with a period of 100 μm in the $1s^2-1s3p$ line of the He-like ion Al XII. The spatial resolution was estimated from the

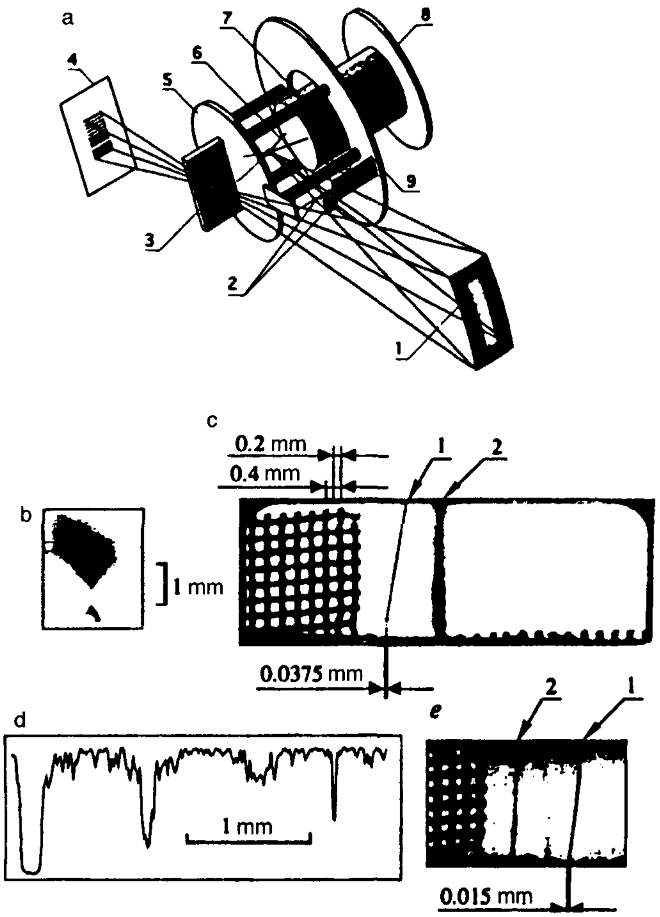

FIG. 2. a: Layout of an experiment in which an X-pinch is used as radiation source. 1—Spherically bent mica crystal; 2—object under study (a mesh, an exploding wire, and a wire not connected to the discharge circuit); 3—screen; 4—photographic film; 5—anode; 6—load of the X-pinch (crossed wires); 7—cathode; 8—high-voltage electrode; 9—ground electrode. b: Image of the source in the $1s^2-1s3p$ emission line of the He-like aluminum ion, obtained with the help of an x-ray microscope. c, e: Shadow images of the object during the explosion of wires 37.5 and 15 μm in diameter. d: Densitometer trace of a shadow image from the explosion of a wire 15 μm in diameter.

sharpness of the edge of the mesh. It was better than 10 μm with a field of view of 3 $\times 7$ mm.

This new method of high-resolution, monochromatic x-ray probing of plasmas which we have proposed and tested in the present study can serve as an alternative to the use of short-wave lasers in many situations. The spatial resolutions achieved experimentally are not surpassed by those which have been achieved by other methods, while in terms of other parameters this new method has clear advantages.

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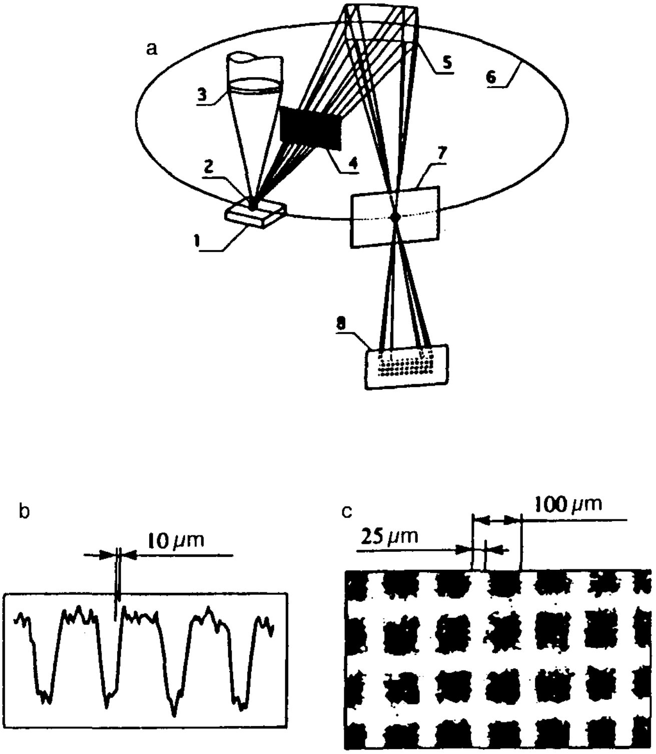

FIG. 3. a: Layout of an experiment to test the spatial resolution, with a laser plasma used as radiation source. 1—Target; 2—plasma; 3—lens; 4—test object; 5—spherically bent mica crystal; 6—Rowland ring; 7—shield; 8—photographic film. b, c: Densitometer trace and shadow image of the test object.

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[1] M. H. Key, R. G. Evans, and D. J. Nicholas, Preprint/Rutherford Lab. NRL-78-0202, 1978, p. 21.

[2] D. T. Attwood, IEEE J. Quantum Electron. **QE-14**, 12, 909 (1978).

[3] D. H. Kalantar and D. A. Hammer, Phys. Rev. Lett. **71**, 3806 (1993).

[4] A. G. MacPhee, G. F. Cairns, M. H. Key *et al.* in *Central Laser Facility of Rutherford Appleton Laboratory, Annual Report 1994*, RAL-94-042.

[5] G. Bayer, D. Billon, M. Decroisette *et al.*, in *Laser Interaction and Related Plasma Phenomena*, ed. by H. Schwarz, H. Hora, M. Lubin, and B. Yaakobi (Plenum, New York, 1981), Vol. 5, p. 595.

[6] C. Yamanaka, S. Nakai, Y. Kato *et al.*, in *Laser Interaction and Related Plasma Phenomena*, ed. by H. Schwarz, H. Hora, M. Lubin, and B. Yaakobi (Plenum, New York, 1981), Vol. 5, p. 541.

[7] D. T. Attwood, N. M. Ceglio, E. M. Campbell *et al.*, in *Laser Interaction and Related Plasma Phenomena*, ed. by H. Schwarz, H. Hora, M. Lubin, and B. Yaakobi (Plenum, New York, 1981), Vol. 5, p. 432.

[8] H. G. Basov, Yu. A. Zakharenko, A. A. Rupasov *et al.*, *Diagnostics of Dense Plasmas* [in Russian] (Nauka, Moscow, 1989), Ch. 7, p. 10.

[9] D. A. Goodman, A. Ridgeley, A. MacPhee, and T. A. Hall, in *Annual Report to the Laser Facility Committee* (1991) RAL-91-025, p. 27.

[10] A. Ya. Faenov, S. A. Pikuz, A. I. Erko *et al.*, Phys. Scr. **50**, 333 (1994).

[11] A. Ya. Faenov, S. A. Pikuz, T. A. Pikuz *et al.*, *X-ray Science and Technology*, 1995, in press.

[12] A. Bartnik, G. V. Ivanenkov, L. Karpinskiĭ *et al.*, Fiz. Plazmy **16**, 1482 (1990) [Sov. J. Plasma Phys. **16**, 857 (1990)].
[13] A. Bartnik, G. V. Ivanenkov, L. Karpinskiĭ *et al.*, Kvant. Élektron. (Moscow) **21**, 181 (1994) [Quantum Electron. **24** (1994)].

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