NUKLEONIKA 2001;46(1):21–25

X pinch as a source for X-ray radiography

Sergej A. Pikuz,
Tatyana A. Shelkovenko,
Vera M. Romanova,
Daniel B. Sinars,
David A. Hammer,
Simon N. Bland,
Sergej V. Lebedev

Abstract This article describes several applications and methods using the X pinch as a source of X-ray radiation for the radiography of dense plasma objects. These methods, in general, do not use pinholes, and instead take the advantage of the small size (<1 mm, and in some cases <3 μm) and a short X-ray emission duration (<1 ns) of the radiation source produced by an X pinch. Two of these methods, monochromatic and direct point-projection backlighting, are discussed. Experimental images of exploding wires and wire arrays obtained on the BIN, XP, and MAGPIE generators using these techniques are presented. Also included are detailed measurements made on the XP generator of the emission characteristics of X pinches using different wire materials.

Key words wire array • X pinch • X-ray imaging • X-ray radiography • Z-pinch

S. A. Pikuz[✉], T. A. Shelkovenko, V. M. Romanova
P.N. Lebedev Physical Institute,
Leninsky pr. 53, Moscow, 117924, Russia,
Fax/Tel.: 1-607/ 2555162, Fax: 1-607/ 2553004,
e-mail: pikuz@lps.cornell.edu

D. B. Sinars, D. A. Hammer
Laboratory of Plasma Studies, Cornell University,
369 Upson Hall, Ithaca NY, 14853, USA

S. N. Bland, S. V. Lebedev
The Blackett Laboratory, Imperial College, London SW7 2BW, UK

Received: 16 November 2000, Accepted: 29 December 2000

Introduction

Recent experiments [2, 6, 7, 13–16] have shown that X-ray radiography of high density plasmas is an effective diagnostic method for studying exploding wires or imploding wire arrays. Two methods of radiography, monochromatic and direct point projection X-ray radiography, were designed and used to investigate wire or wire array explosions on the pulsed power generators listed in Table 1. For point projection (i.e., no pinhole) X-ray radiography the size and duration of the X-ray source are important, because they directly determine the spatial and temporal resolution of the imaging system. In this article we describe measurements of these parameters for the bright spots (intense X-ray emission regions) formed in the X pinch depicted most simply in Fig. 1a, and discuss the performance of two backlighting techniques using X pinch X-ray sources.

Methods of X-ray radiography using the X pinch as a source of radiation

In 1994 at the P.N. Lebedev Institute and Cornell University a new technique for imaging dense plasmas, monochromatic X-ray radiography, was studied [11, 12]. Using this technique, shadow images of bright plasma or test objects were obtained with high spatial and temporal resolution using a single spectral line from a separate plasma. The principal scheme of monochromatic radiography is shown in Fig. 2a. In these experiments, an X pinch was used as the X-ray radiation source and a spherically bent mica crystal was used as a crystal mirror to form the X-ray shadow image of the object. The X pinch is a variant of a Z-pinch made using two or more fine wires which cross

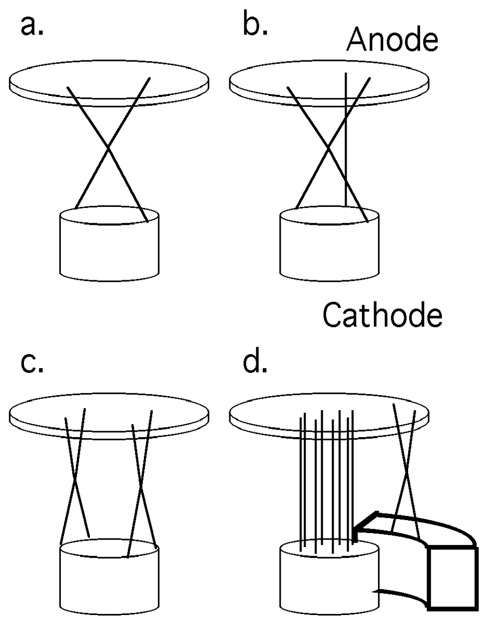

Fig. 1. Schematic diagrams of X pinch experimental arrangements. a. – one X pinch in a diode; b. – one X pinch with shunt wire in a diode; c. – two or three X pinches in a diode; d. – one, two or three X pinches in the return current circuit.

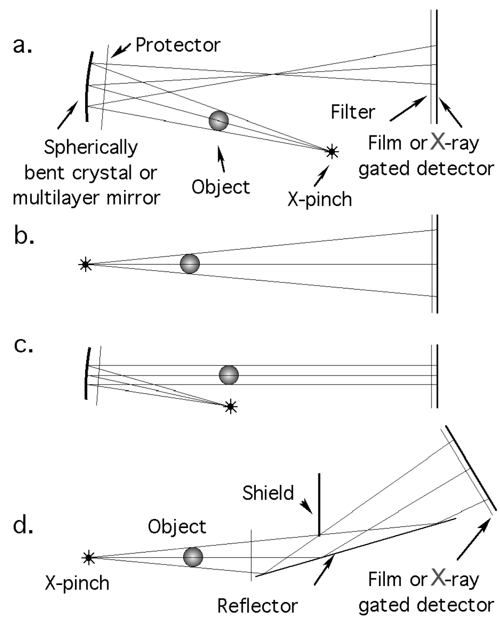

Fig. 2. Configurations for X-ray radiography using an X pinch as a sources of radiation. a. – monochromatic X-ray radiography; b. – point-projection radiography; c. – imaging with a parallel beam of X-ray radiation; d. – point-projection imaging using soft X-ray radiation.

and touch at a single point (Fig. 1a). The X pinch is placed as the load of pulsed power generator and typically driven with a pulsed current of a few hundred kA. Detailed descriptions of the monochromatic backlighting technique can be found in [11, 12]. In the monochromatic backlighting scheme using X pinches, we note that the spatial resolution of the method is dominated by the quality of the mica crystal, so it is important to use high-quality crystals. The best spatial resolution obtained with a test object on BIN generator was about 4 μm (Fig. 3). The source size in this case determines the spectral range of the radiation involved in forming the image. The small size of the X pinch source (<1 mm) implies a maximum relative spectral range ($\Delta\lambda/\lambda$) not more than 10^{-3}. This range is comparable to the width of a single X-ray spectral line. The mica crystal and properly placed shields in the monochromatic scheme provide an effective spectral and spatial filtering of the radiation from the object plasma, so that the brightness of the X pinch X-ray source needs to be greater than the object brightness only in the bandwidth of the spectral line being used. Therefore, it is possible to use this method for studying plasma objects many orders of magnitude more powerful than the X-ray backlighter source.

While monochromatic X-ray radiography is very promising for studying bright plasma objects, the doubly-curved crystals used are somewhat expensive and can be damaged by an energetic object plasma in some cases. For this reason, it may be desirable to use direct X-ray radiography to study object plasmas of lower brightness than the X-ray source, such as an exploding wire or wire array. A simple method of direct radiography is shown in Fig. 2b. It requires a point source of X-ray radiation because the spatial resolution of this method depends on the size of the X-ray source. In this method, it is possible to project a high-resolution shadow image of a dense plasma directly onto an X-ray sensitive film. As we will demonstrate later, an X pinch can be ideal as a point source of X-ray radiation for this method.

In the initial experiments using an X pinch as a source of radiation for direct X-ray radiography at Cornell University (USA) [4, 5], the object (an exploding wire) was placed in the diode parallel to the X pinch as shown in Fig. 1b. The spatial resolution in these experiments was limited to 20 μm because the X pinch was not optimized for the purpose, owing to a wide energy range of X-ray radiation being used. To improve the spatial resolution, subsequent experiments in later years to optimize the performance of the X pinch were necessary.

For many years X pinches were studied at the P.N. Lebedev Institute as an interesting physical object and as a point source of radiation for different applications [3, 8, 9]. These experiments were continued at Cornell University with an

Table 1. X pinch backlighting experiments.

Pulser	Laboratory	Current	Pulse width	X pinch current	Scheme	Object	State
BIN	Lebedev	270 kA	120 ns	200 - 270 kA	Monochromatic	Wire	Done
XP	Cornell	470 kA	100 ns	150 - 470 kA	Direct	Wire	Done
					Monochromatic	Wire array	Done
MAGPIE	Imperial	1.2 MA	250 ns	100 - 250 kA	Direct	Wire	Done
	College				Monochromatic	array	Planned

emphasis on studying the X pinch as a source of X-ray radiation for point-projection radiography [10, 14]. The X pinches were placed in different locations in the diode or the return current circuit of the pulsed power generator, as shown in Fig. 1, and the quality of the images obtained was investigated. To obtain multiple shadow images of an object at different times, two or more X pinches could be loaded in parallel. (The time of the X-ray emission from an X pinch could be delayed by increasing the diameter of the wires used for the X pinch). The best spatial and temporal resolutions have been obtained with two X pinches used in parallel as the load of the XP pulsed power generator (see Table 1). The images shown in Fig. 4 were taken using two 25 μm Nb X pinches. The radiation used to make these images was limited to the 2.5–5 keV range by using a 12.5 μm Ti filter. These images, using optimized X pinch parameters, clearly demonstrate wave-optics-limited resolution, in some cases as good as 2–4 μm.

The technique of X pinch point-projection radiography was used to study imploding cylindrical wire arrays on the MAGPIE generator [6] at Imperial College. This generator had significantly different current pulse parameters (Table 1) than that used previously on the XP or BIN generators. The experimental set-up is shown in Fig. 5a. The X pinch was installed in one of the four return current posts. On the basis of previous experiments [12, 14, 15], X pinches composed of 15–25 μm Mo and 15–50 μm Al wires were used. By positioning the line-of-sight of the X pinch and X-ray shields along the edge of the cylindrical array, images of several wires at the array edge could be recorded and radiation from the implosion of the wire array on axis was prevented from reaching the film. Spatial and temporal resolutions of ~5 μm and <1 ns have been demonstrated. For example, fine structure with a typical scale of 10–15 μm was observed in titanium wires (Fig. 5b).

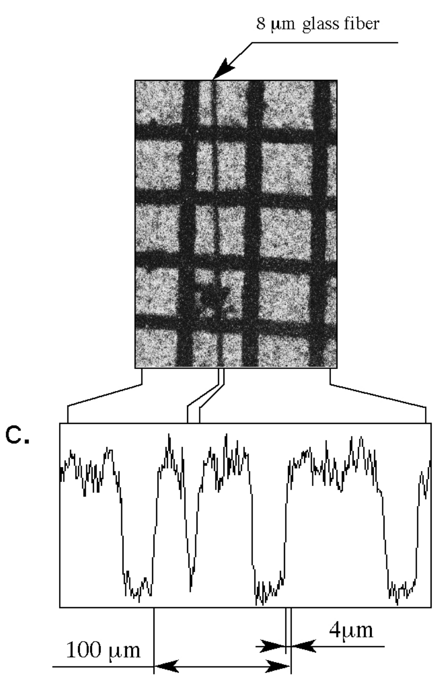

Fig. 3. Shadow image and densitogram of a stainless steel grid and an 8 μm glass fiber in the 6.343 Å radiation from Al XII ions obtained on the BIN generator using a mica crystal with R=100 μm.

X pinch emission characteristics

The principal factors determining the spatial resolution in point-projection radiography are the size (and possibly the structure) of the brightest region of the X-ray source, the imaging geometry, and the imaging wavelengths used. Refraction, reflection, and diffraction effects certainly play a role in this, as illustrated in Fig. 4a. Typical experiments studying exploding wires used a magnification of 4–10, and in these experiments the spatial resolution was limited to 3–6 μm by diffraction (depending on the wavelengths and distances used). An example of this is shown in Fig. 4b. To reduce the diffraction limit, radiographs of static test objects were made with magnification 90–120 by bringing the object closer to the X pinch. The result of doing this is shown in Fig. 4c. The spatial resolution of many of the images recorded in recent experiments was close to the diffraction limit for the wavelengths used. Thus, it is necessary that size of the X-ray source must be much less than 3 μm and may be even less than 1.3 μm obtained in the experiments with high magnification. Experiments were made to directly measure the size and structure of the time-integrated emission from X pinches. These experiments used a 5 μm diameter pinhole camera and a linear Bragg-Fresnel lens [15] to study radiation in the 1.5–6 keV band. The minimum measured source sizes (3–6 μm) corresponded to the resolution limits of these diagnostics.

Several experiments were made to measure the duration and temporal profile of the X-ray bursts from X pinches on the XP generator. The first experiments measured radiation in the 1.5–6 keV band using a set of fast diamond PCDs with different filters and a Tektronix TDS694C oscilloscope (10 GS/s). For X pinches composed of Mo wires, for exam-

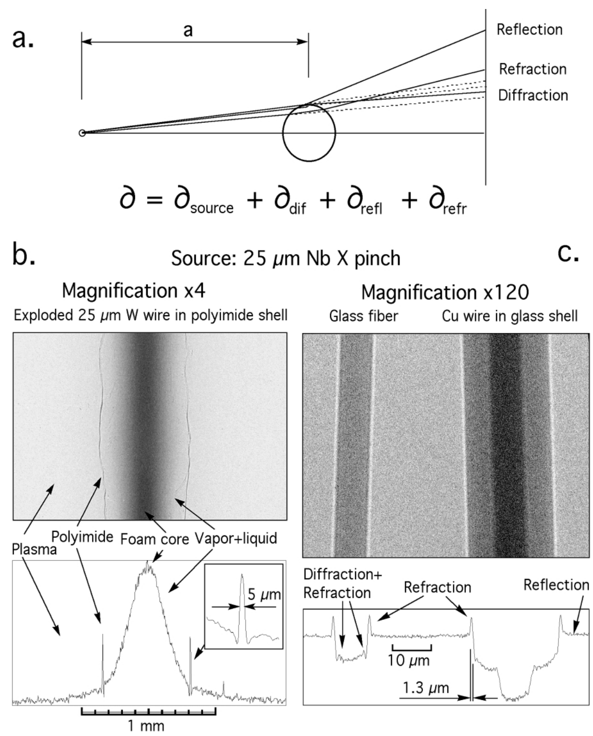

Fig. 4. a. – Diagram demonstrating how diffraction, reflection, and refraction effects can alter the image of the object; b. – Point-projection radiographic image and densitogram of an exploding 25 μm W wire in a polyimide shell (magnification ×4); c. – High-magnification (×120) point-projection radiograph of 8 μm glass fiber and 8 μm Cu wire in a glass shell, along with a densitogram of each object, showing the effects of diffraction, refraction and reflection.

ple, the full width at half-maximum (FWHM) of the radiation pulse was about 250 ps, the minimum time resolution of that system. Further experiments were carried out using a Kentech X-ray streak camera to measure the direct X-ray emission. Using speeds as fast as 15 ns for the full sweep (3.5 cm) and a 120 μm entrance slit width, pulse durations less than the resolution limit of the instrument (100 ps) were observed for Mo X pinches in the energy bands typically used in our experiments for imaging.

To investigate the line and continuum X-ray radiation emitted from X pinches, time integrated spectra were recorded on film using a convex KAP spectrograph and a focusing spectrograph based on a spherically bent mica crystal. Time resolved spectral measurements were later obtained by using the Kentech X-ray streak camera with the focusing spectrograph. Two general types of X-ray burst spectra were observed – spectra with weak continuum radiation and narrow, intense line radiation, and spectra with intense continuum radiation and broadened spectral lines. The bursts with intense continuum radiation gave high quality shadow images with the best spatial and time resolution when also used for radiography. When bursts with a weaker continuum radiation were used to make shadowgraphs, the quality of the shadowgraphs was not as good. As an example, typical Ne-like time-resolved Mo spectra obtained in these experiments are shown in Fig. 6 for the case of two 25 μm Mo X pinches in the diode. From the spectra it is possible to see the different intensities of line and continuum radiation for different bright spots of the X pinch. (For simplicity, spectra emitted from bright spots of the one of X pinches are shown in Fig. 6.) Bright spot #3 has intense lines and weak continuum radiation, bright spot #2 has an intermediate intensity of continuum and line radiation and bright spot #1 has intense continuum and weak (in comparison with bright spots #2 and 3) line radiation. Densitograms of the hot spot #1, shown in Fig. 6b, demonstrate shorter duration (~100 ps) of the continuum radiation than the line

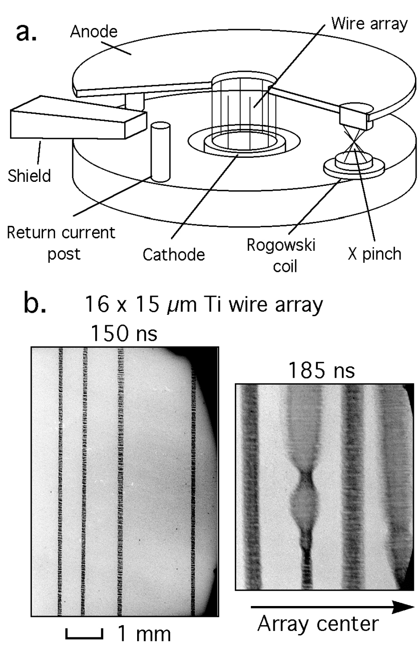

Fig. 5. a. – Configuration for X-ray point-projection radiography on MAGPIE; b. – Point-projection radiograph images of 16×15 μm Ti wires array showing the high spatial resolution of the method.

Table 2. X pinch bright spot parameters.

Size	<1 – 3 μm
X-ray burst duration	< 0.1 – 0.3 ns
Electron temperature	~ 0.8 – 1.5 keV
Electron density	> 10^{22} cm^{-3}
Radiated energy (3.5 – 5eV)	~ 0.1 J
Volume power density	> 10^{21} W/cm^3
Surface flux	> 10^{16} W/cm^2

radiation (300–600 ps). Only the bright spot #1 yielded a high quality image. Taking into account the absorption of the filters and the film sensitivities, we conclude that the smallest spot sizes, which yield the highest quality images, are achieved using continuum radiation from the X pinch. Initial estimates of the X pinch bright spot parameters using the results obtained from these experiments are presented in Table 2. (Not all of the data have been analyzed as yet.)

Conclusions

In summary, the X pinch is a very useful X-ray source for radiography. X pinch sources provide the possibility of using a very small wavelength range in monochromatic X-ray radiography to obtain spatial resolution as good as 4 μm. In direct point projection radiography, 1–10 μm spatial resolution and subnanosecond time resolution were obtained. The two methods, monochromatic and point-projection X-ray radiography, and the wide range of current and time requirements for X pinch sources, allow diagnostics based on X pinches to be used with a wide range of object plasma parameters. These and two additional schemes, shown in Fig. 2c [1] and 2d can expand possible applications of this method to the investigation of gas-puff

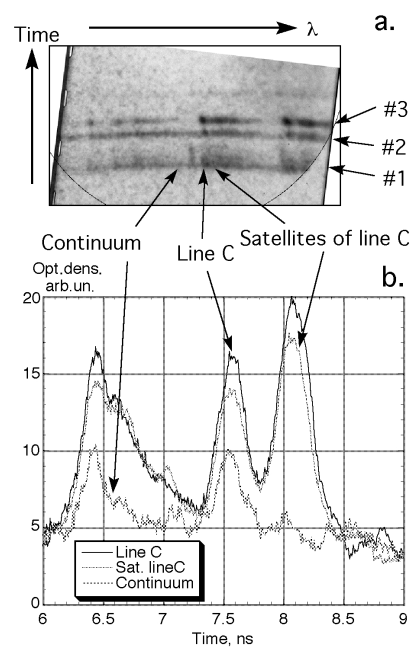

Fig. 6. a. – Time resolved spectra emitted by one of two 25 μm Mo X pinches in the diode, showing different parameters of bright spots of the X pinch; b. – Densitogram of bright spot #1, showing different time duration of continuum and line radiation emitted by this bright spot.

plasmas, plasma focus loads, the structure of biological objects, etc.

Experiments to study the later stages of the pinching of a plasma focus load using X-ray point-projection radiography are being planned now in IFPLM (Poland). Because of the extremely long pinching time of a plasma focus load (several μs) compared to that of pulsed power generators, an auxiliary pulsed power generator (100–150 kA, 100 ns) can be used as a separate driver for the X pinch X-ray source in these experiments.

Acknowledgments This research was supported in part by DOE Grant No. DE-FG02-98-ER54496 and in part by Sandia National Laboratories, Albuquerque, Contract No. BD 9356.

References

1. Faenov AY, Mingaleev AR, Pikuz SA, Pikuz TA, Romanova VM, Skobelev IY, Shelkovenko TA (1993) Generating collimated intense monochromatic beams of soft X-ray radiation from an X-pinch in the wavelength region 0.4–1.0 nm by means of spherical crystal mirrors. Quantum Electron 23:394–396
2. Gus'kov SY, Ivanenkov GV, Mingaleev AR, Pikuz SA, Shelkovenko TA, Hammer DA (1998) Temporal evolution of the hydrodynamic instability of the boundary between the dense core and the plasma corona during nanosecond explosion of wires. JETP Lett 67:559–566
3. Ivanenkov GM, Mingaleev AR, Pikuz SA, Romanova VM, Shelkovenko TA (1996) Experimental study of X-pinch dynamics. Plasma Phys Rep 22:363–378
4. Kalantar DH (1993) An experimental study of the dynamics of X-pinch and Z-pinch plasmas. PhD dissertation, Cornell University
5. Kalantar DH, Hammer DA (1993) Observation of a stable dense core within an unstable coronal plasma in wire-initiated dense Z-pinch experiments. Phys Rev Lett 71:3806–3809
6. Lebedev SV, Beg FN, Bland SN et al. (2000) Effect of core-corona plasma structure on seeding of instabilities in wire-array Z-pinches. Phys Rev Lett 85:98–101
7. Lebedev SV, Beg FN, Bland SN et al. (2000) X-ray backlighting of wire array Z-pinch implosions using X pinch. Rev Sci Instrum 72:671–673
8. Pikuz SA, Bryunetkin BA, Ivanenkov GV et al. (1993) X-pinch plasma as an optical pumping source for X-ray lasers. Quantum Electron 23:201–206
9. Pikuz SA, Bryunetkin BA, Ivanenkov GV et al. (1994) Radiative properties of hot dense X-pinch. J Quant Spectrosc Radiat Transfer 51:291–302
10. Pikuz SA, Romanova VM, Shelkovenko TA, Hammer DA, Faenov AY (1995) Spectroscopic investigations of the short wavelength X-ray spectra from X-pinch plamas. Phys Scripta 51:517–521
11. Pikuz SA, Shelkovenko TA, Greenly JB, Dimant YS, Hammer DA (1999) Multiphase foamlike structure of exploding wire cores. Phys Rev Lett 83:4313–4316
12. Pikuz SA, Shelkovenko TA, Romanova VM, Hammer DA, Faenov AY, Dyakin VA, Pikuz TA (1995) Monochromatic X-ray probing of an ultradense plasma. JETP Lett 61:638–644
13. Pikuz SA, Shelkovenko TA, Romanova VM, Hammer DA, Faenov AY, Dyakin VA, Pikuz TA (1997) High-luminosity monochromatic X-ray backlighting using an incoherent plasma source to study extremely dense plasmas. Rev Sci Instrum 68:740–744
14. Shelkovenko TA, Pikuz SA, Mingaleev AR, Hammer DA (1999) Studies of plasma formation from exploding wires and multiwire arrays using X-ray backlighting. Rev Sci Instrum 70:667–670
15. Shelkovenko TA, Sinars DB, Pikuz SA, Chandler KM, Hammer DA (2000) Point projection radiography using an X pinch as the radiation source. Rev Sci Instrum 72:667–670
16. Sinars DB, Shelkovenko TA, Pikuz SA, Greenly JB, Hammer DA (2000) Exploding aluminum wire expansion rate with 1–4.5 kA per wire. Phys Plasmas 7:1555–1563