Application of a refractive bubbles-in-capillary x-ray lens to *X* pinch experiments

S. A. Pikuz,[a)] V. E. Asadchikov,[b)] K. M. Chandler, D. A. Hammer,[c)] Yu. I. Dudchik,[d)] N. N. Kolchevsky,[d)] F. F. Komarov,[d)] M. D. Mitchell, A. V. Popov,[e)] T. A. Shelkovenko,[a)] R. A. Senin,[b)] I. A. Suloev,[e)] and A. V. Vinogradov[a)]
Laboratory of Plasma Studies, Cornell University, Ithaca, New York 14853

(Presented on 11 July 2002)

A new type of x-ray refractive lens, the refractive bubbles-in-capillary lens (RBC lens), for plasma diagnostics is presented. The lens consists of a glass capillary filled with a large number of biconcave microlenses. The fabrication technique for the lens is described. It is shown that the microlenses have a spherical shape and can focus x-ray radiation with photon energies $E > 4$ keV. Ray-tracing and analytical calculations of lens properties have been performed and have predicted high efficiency and good spatial resolution for RBC lenses. Real lenses were tested using Cr $K\alpha$ x-ray radiation ($\lambda = 2.29$ Å), and spatial resolution of about 10 μm was obtained. In plasma experiments, x-ray radiation from a Ti *X* pinch ($\lambda = 2.62$ Å) was focused by a lens with 35 bubbles in a 100 μm diam capillary (focal length of about 8 cm) to a spot with diameter less than 6 μm. The shape of the hot plasma could be seen. Possibilities for RBC lens applications to plasma measurements are discussed. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1537863]

I. INTRODUCTION

The search for new types of imaging devices in the x-ray spectral band is important for measurements of small-size, hot plasma sources such as the *X* pinch and the dense core of laser driven inertial confinement fusion targets. Imaging in the spectral band $\lambda < 5$ Å with extremely good spatial resolution (~1 μm or better) is required for detailed studies of the internal structure of those plasmas.

Simple and inexpensive pinhole cameras have diffraction limits of several μm, and also have limited luminosity. X-ray optical elements such as Fresnel and Bragg–Fresnel (BF) lenses built to work in the soft x-ray band are very expensive. Furthermore, Fresnel lenses do not work very well in the short wavelength band ($\lambda < 5$ Å) and BF lenses are difficult to align. Grazing incidence refractive optical instruments (for example, the Kirkpatrick–Baez microscope) are ineffective for hard radiation and have a very small field of view. Bent crystal mirrors have good characteristics and have been successfully used in plasma experiments, but they are also expensive and have some limitations in experimental arrangement.

Here we describe an attempt to use the refractive properties of matter for x rays to create optical elements suitable for imaging. Refractive elements have been used for concentrating x-ray synchrotron radiation and have shown high x-ray collection efficiency.

The new type of x-ray lens to be discussed here is called the refractive bubbles-in-capillary lens (RBC lens). It is made by filling a glass capillary with a long string of biconcave microlenses, i.e., air bubbles in plastic. The microlenses are found to have a spherical shape in test samples, and can focus x-ray radiation with energies >4 keV. The attenuation is unacceptably large for energies below 4 keV.

The complex refractive index, n, of a medium may be written[1]

$$n = 1 - \delta - i\beta, \tag{1}$$

where $1-\delta$ is the real part of the refractive index and β is the factor related to the absorption of x rays. Far from absorption edges, the value of δ is inversely proportional to the square of the photon energy, E. In the keV x-ray spectral band, it is in a range 10^{-5}–10^{-7}. For example, in glass δ is about 7×10^{-6} for $E = 8$ keV. The focal length F of a biconcave spherical lens is determined by

$$F = R/2\delta, \tag{2}$$

where R is the radius of the lens. For x rays, the focal length is rather large (10–50 m) even for submillimeter lens radii. To reduce the focal length of the lens, a compound refractive lens was first proposed for x rays with energies of 5–30 keV by Snigirev *et al.*[2,3] Their concept consists of a large number (10–100) of biconcave lenses made of low *Z* materials (such as beryllium, carbon, aluminum, or plastic). A lens of this type was first realized as a linear sequence of orthogonal cylindrical holes in a plastic block. It was tested in a synchrotron[2] as a collimator for hard x-ray radiation. The focal length of such a lens is determined by

$$F = R/2\delta N, \tag{3}$$

where N is the number of lenses.

a)Permanent address: P. N. Lebedev Physical Institute, Leninskii Prospect 53, Moscow 119991, Russia.
b)Permanent address: A. V. Shubnikov Institute of Crystallography, Leninskii Prospect 59, Moscow 117333, Russia.
c)Electronic mail: dah5@cornell.edu
d)Permanent address: Institute of Applied Physics Problems, Kurchatova 7, Minsk 220064, Belarus.
e)Permanent address: IZMIRAN, Troitsk, Moscow region 142092, Russia.

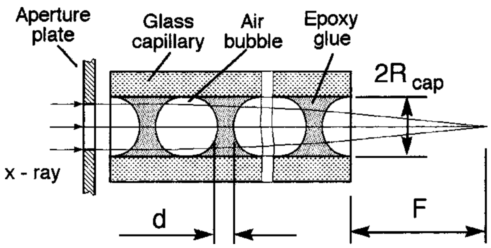

FIG. 1. Schematic diagram of an RBC lens.

The idea of a refractive x-ray lens was advanced in other work that led to the development of microcapillary lenses.[4,5] These were applied on a synchrotron to focus 18 keV photons[4] and as an objective lens for an x-ray microscope.[5] The main goal of the present work was to use a lens of this type for softer x-ray radiation ($E=3-8$ keV, or $\lambda=1.5-4$ Å).

II. LENS CONFIGURATION AND FABRICATION TECHNIQUE

The refractive-bubbles-in-capillary lens (RBC lens) design is shown in Fig. 1. The lens is realized as a chain of biconcave plastic microlenses inside a glass capillary. Lens fabrication is based on the tendency of a liquid to bead in a capillary to develop concave ends because of surface tension forces. Various liquids or polymers can be used as the lens material.

The chain of lenses was produced by blowing air bubbles into a glass capillary filled with liquid epoxy glue (see Fig. 2). Compressed air was delivered into the capillary by a thin metal pipette, forming bubbles inside the liquid. The growth of each bubble was followed visually. When the surface of a bubble reached the inner wall of the capillary, the pipette was moved along the capillary to a position a few μm from the previous bubble, and the process was repeated, as illustrated in Fig. 2. The liquid between two bubbles thus prepared assumes a shape similar to a biconcave lens. This technique does not have any restrictions on the number of lenses other than that due to the attenuation of the x rays passing through the total lens. Using this method 100–500 microlenses can be made from industrial epoxy in a glass capillary with radius $R_{cap}=0.1-0.5$ mm.

Obviously, the efficiency of the RBC lens is strongly dependent on the x-ray absorption, which is determined by the total amount of the lens material along the ray path. As such, an important parameter is the individual microlens thickness d. It was found for the epoxy used here that the dependence of the minimum thickness on capillary size follows a linear relationship,

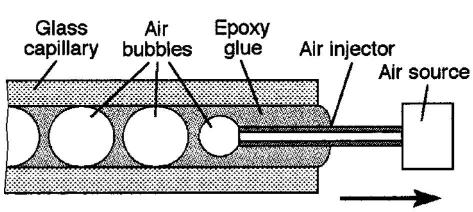

FIG. 2. Illustration of how an RBC lens can be made.

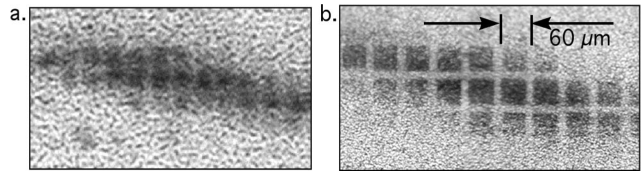

FIG. 3. Images of the 60 μm period mesh with ×1 (a) and ×3 (b) magnification using an x-ray tube as a source of radiation.

$$d_{min}=0.12\,R_{cap}+d_0, \tag{4}$$

where $d_0=13\,\mu$m. This relationship is valid for epoxy lenses in glass capillaries with radii between 50 and 1000 μm. The shape of the lens surface is not typically spherical, but in small diameter capillaries, optical measurements of lens shape indicate that it deviates little from being spherical with a radius close to the capillary radius.

III. LENS MODELING AND TESTING

Lens properties were studied theoretically, analytically, and numerically by ray-tracing and full-wave simulations. Ray-tracing calculations show a diameter for the focal spot two orders less than the diffraction limit determined as $a_{dif}=1.22\lambda F/2R$, indicating a low level of spherical aberration in the geometric optics limit. Full-wave simulations using the parabolic method equations[6] gave results close to the diffraction limit of about 0.6 μm for a 50 μm diam lens and the radiation of the Cr $K\alpha$ spectral line ($\lambda=2.29$ Å).

An RBC lens with focal length $F=9$ cm and capillary diameter 200 μm was tested using Cr $K\alpha$ x-ray tube radiation. Images of a mesh with period 60 μm were obtained with magnification 1 and 3, and spatial resolution of about 10 μm was demonstrated (see Fig. 3).

IV. APPLICATION IN *X* PINCH EXPERIMENTS

Experiments with *X* pinches as the source of 3–8 keV x rays were carried out with an RBC lens consisting of a 100 μm diam capillary in an 800 μm diam glass tube with 35 microlenses (see Fig. 4). The average thickness of the microlenses was about 50 μm, and it varied from 21 to 60 μm. The minimum value of d was close to the value predicted by formula (4). The total length of the lens was 8 mm. Epoxy with the chemical formula $C_{100}H_{200}O_2N_3$ and a density of 1.08 g/cm^3 was used to make the lens. For photons with energy 5.4 keV, the absorption coefficient is 20 cm^{-1}, $\delta=8.3\times10^{-6}$, and focal length $F=8.6$ cm. Lens transparency along the axis was $T=0.03$.

A refractive lens is not achromatic. Therefore it is beneficial to narrow the spectral band used for imaging. The total length of the epoxy along the lens axis was about 50 μm times 35, or 1.75 mm. Assuming absorption is mainly due to carbon, and using known absorption data, we have calculated the lens transmission in the spectral band of interest to us, $\lambda=1-5$ Å. Data for 2.2 g/cm^3 carbon was used, but the thickness of the absorbing medium was decreased from 1.75 to 0.86 mm to account for the reduced density. The resulting lens transmission as a function of wavelength is shown in Fig. 5(a) as curve 1. In experiments, 12.5 μm Ti

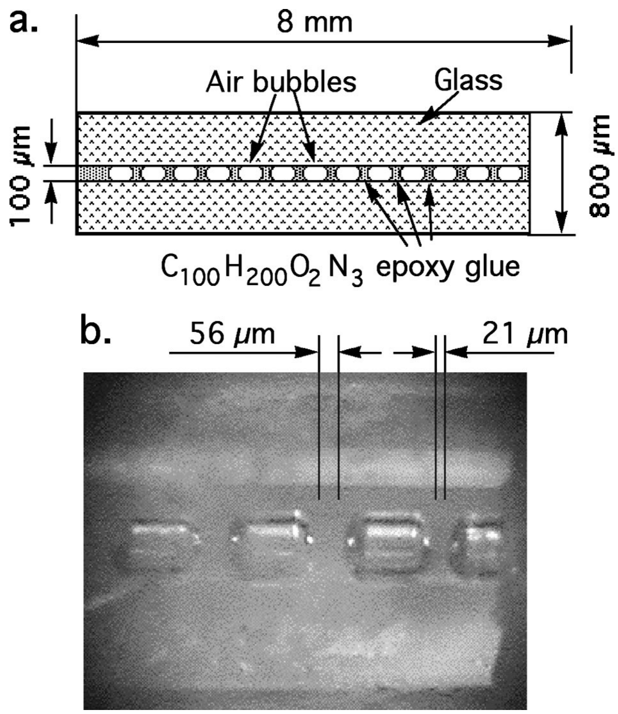

FIG. 4. (a) The design of the RBC lens used for the experiments reported in this article. (b) A photograph of the lens obtained with an optical microscope.

filters, with transmission given by curve 2 in Fig. 5(a), were used for film protection from visible light. The net transmission, taking into account both the lens and the filter is given as curve 3, which shows that the spectral bandpass is mostly below about 1.7 Å, but has a transmission window between 2.4 and 4+, just above the Ti K edge. Images were recorded on two pieces of Kodak DEF films, one behind the other. Lens efficiency curves taking into account DEF film sensitivity are presented in Fig. 5(b). These curves were calculated for the front film and three radiation spectra: constant intensity across the spectral band; a Planckian spectrum with $T_e = 800$ eV; and a Planckian spectrum with $T_e = 600$ eV. For back film, the lens efficiency curves are almost the same except the peak in the Ti transparency window ($\lambda = 2.5$ Å) is eliminated. The maximum transmission for $T_e = 800$ eV lies near 1.55 Å or $E = 8$ keV. Taking into account $\delta \sim E^{-2}$, the focal length for x rays of this energy is about 18 cm. However, for $T_e = 600$ eV, we have the maximum of the transmission efficiency in the Ti K window (just below 5 keV)

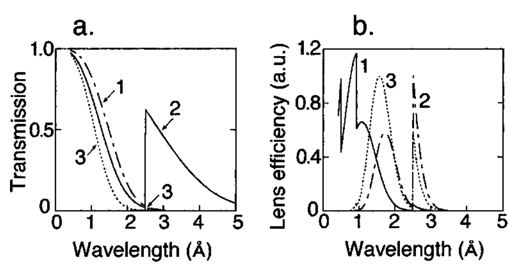

FIG. 5. (a) Transmission of the lens (1), a 12.5 μm Ti filter (2), and the combination of the two of them (3). (b) Lens efficiency for a "flat" spectrum (1), a Planckian spectrum with 600 eV temperature (2), and a Planckian spectrum with 800 eV temperature (3).

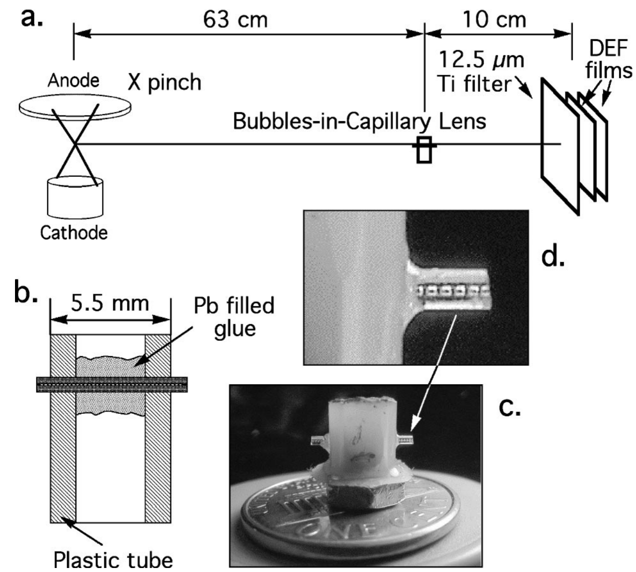

FIG. 6. (a) Experimental arrangement for testing the RBC lens using X pinch radiation. (b) Method of mounting the RBC lens in a plastic tube. (c) Photograph of the RBC lens in the plastic tube. (d) Enlargement of the protruding portion of the lens.

and a focal length of about 7 cm. This makes it clear that a measurement of the source structure with an RBC lens will require severe reduction of the spectral bandwidth of a broad bandwidth source.

The RBC lens described above has been tested using X pinches as a source of x-ray radiation in the configuration shown in Fig. 6(a). To avoid problems in alignment, a geometry with demagnification was chosen. The lens was mounted 63 cm from the source and radiation was recorded on film 10 cm away, corresponding to a focal length of 8.6 cm. The intent was to see if the lens was able to focus x-ray radiation in our case or not, and if there would be sufficient lens efficiency to obtain a clear image on the film. With a demagnification of about 6, alignment using a small red laser (laser pointer) was adequate.

The lens was mounted in a piece of plastic tube filled with lead-contained glue in order to block direct transmission of radiation to the film [see Fig. 6(b)]. The plastic tube was glued to a small nut and placed on an optical stage. Photographs of the RBC lens are shown in Figs. 6(c) and 6(d).

V. RESULTS

A four-wire 37 μm diam Ti wire X pinch was the source of radiation. Figure 7 shows pinhole images of the X

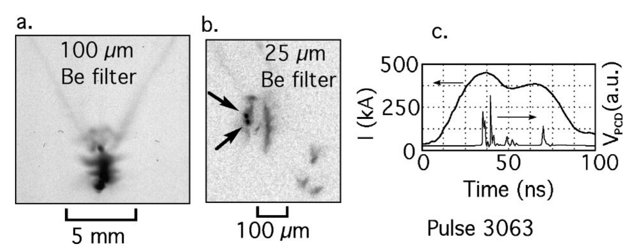

FIG. 7. Time-integrated x-ray images of the X pinch obtained using pinhole cameras with 80 μm (a) and 5 μm (b) pinhole diameters and (d) PCD signal using a Ti 12.5 μm filter.

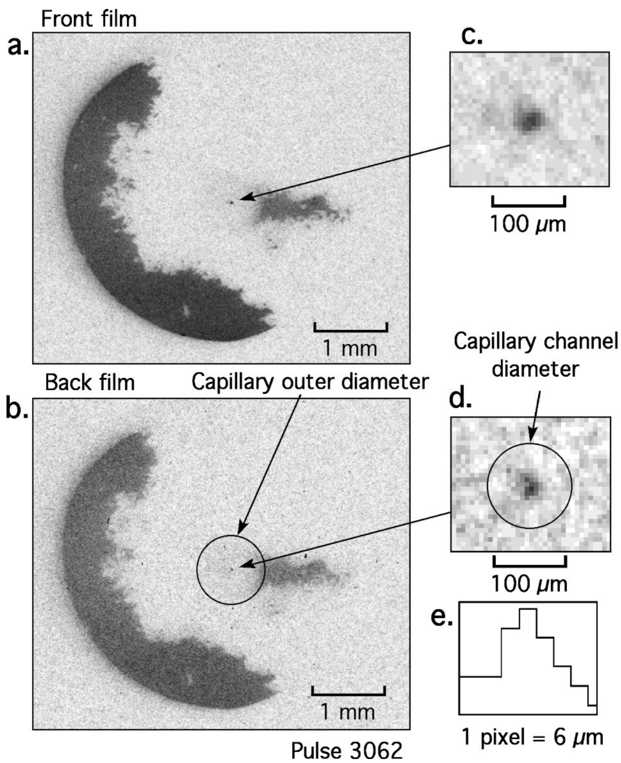

FIG. 8. Images of 4-wire Ti *X* pinch (wire diameter 37 μm) obtained using a RBC lens on the front (a) and back (b) pieces of DEF film. Enlarged fragments of the images in (a) and (b) are shown in (c) and (d), respectively. An optical density profile horizontally across the middle of the circle in (d) is shown in (e).

pinch. Photoconducting diode (PCD) signals are presented in Fig. 7(c). The *X* pinch had a complex structure with several bright spots in the pinhole images, corresponding to the number of x-ray peaks in the PCD signals. Two emission spots separated by 15–20 μm had the highest brightness and are seen in the high resolution pinhole camera image. The RBC-lens images on the two DEF films from the same test are shown in Fig. 8. The images were scanned and their contrasts adjusted separately in Photoshop, so the intensities of the images in the figure do not correspond to film densities, However, the film densities did not differ greatly from each other before adjustment. The images on the two films have similar size but are different in detailed structure. That could be because of the different spectral bands of radiation involved in image formation on the front and back films and different focusing properties of the lens, both of which are discussed above. For example, the He-like Ti radiation at $\lambda = 2.61$ Å can reach the front film only. The size of the central spot on the back film appears to be less than 1 pixel (6 μm) of the scanner used for image development. That means that the tested RBC lens has a resolution of 6 μm or better and we can expect high quality images in a geometry with high magnification. However, some kind of narrow-band filter must be used. For example, a flat crystal might be placed between the lens and the film.

ACKNOWLEDGMENTS

This work was supported in part by DOE Grant Nos. DE-FG03-98DP00217 and DEF02-98ER54496.

[1] A. G. Michette, *Optical Systems for Soft X-Rays* (Plenum, New York, 1986).
[2] A. Snigirev, V. Kohn, I. Snigireva, and B. Lengeler, Nature (London) **384**, 49 (1996).
[3] B. Lengeler, C. G. Schroer, M. Richwin, J. Tummler, M. Drakopoulos, A. Snigirev, and I. Snigireva, Appl. Phys. Lett. **74**, 3924 (1999).
[4] Yu. I. Dudchik and N. N. Kolchevsky, Nucl. Instrum. Methods Phys. Res. A **421**, 361 (1999).
[5] Y. Kohmura, M. Awaji, Y. Suzuki, T. Ishikawa, Yu. I. Dudchik, N. N. Kolchevsky, and F. F. Komarov, Rev. Sci. Instrum. **70**, 4161 (1999).
[6] Yu. Kopylov, A. V. Popov, and A. V. Vinogradov, Opt. Commun. **118**, 619 (1995).