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Observation of Interference Effects at the Focus of an X-ray Lens

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During an experiment on synchrotron radiation focusing with a capillary lens, an interference structure was observed at the focal spot of the lens, despite the fact that the lens capillary diameter is about a million times greater than the wavelength of the X-ray photons (600 μm and 8 Å, respectively). The width of the central peak is close to the capillary diameter. At the same time the synchrotron radiation concentration increased by more than one hundred times. Analysis shows that the capillary lens acts in many respects as a macroscopic crystal. The observed effect is accounted for by wave theory. This phenomenon may have important practical effects in many fields.

Keywords: X-ray lenses; capillary lenses; focusing; interference effects.

1. Introduction

Lately, a number of reports concerned with capillary X-ray and neutron lenses have appeared (see, for example, *Science*, 1991; *New Scientist*, 1991; *Science News*, 1992; *McGraw-Hill Yearbook of Science and Technology*, 1993). These capillary lenses were originally proposed by one of the authors (Kumakhov, 1986). They are systems consisting of bent glass capillaries or polycapillaries in which the photons or neutrons undergo multiple reflections (Figs. 1*a* and 1*b*). As a result, Kumakhov lenses can effectively transform divergent radiation into a quasi-parallel beam, focus radiation, turn it through large angles and cut off the hard part of the spectrum (Kumakhov, 1986; Kumakhov & Komarov, 1990; Kumakhov & Sharov, 1992; Chen *et al.*, 1992). The results of capillary lens investigations are summarized in a special issue of the journal *Optics of Beams* (1993). In other recent work using tapered capillaries (Bilderback, Hoffman & Thiel, 1994) substantial gains in X-ray intensity have been achieved.

The mechanism of operation involves a channeling effect arising from penetration of charged particles into the crystal at small angles to the main atomic rows and planes, and is well known in physics. These particles 'feel' an average potential of an atomic chain or plane, rather than a separate atom. Thus, particles move into so-called crystallic channels (microchannels). In the case of capillary optics, we have photons channeling in macrostructures. However, in both cases there is a definite symmetry in cross section. A unit cell of the capillary macrostructure used in the experiments reported here is given in Fig. 1(*d*).

The increase of synchrotron radiation density obtained with Kumakhov lenses was first demonstrated by our group on synchrotron S-60 at the Lebedev Institute of Physics, Moscow (Kolomitzev, Nikitina, Murashova, Fedorchuk & Yakimenko, 1993). The lens used in these experiments belongs to the fourth generation of X-ray capillary optics. It was manufactured from glass monocapillaries by using technology developed at the Institute for Roentgen Optical Systems, such that the diameters of the capillaries are tapered uniformly along the lens length from entrance to exit. The diameters at the entrance and the exit are 1 mm and 600 μm, with wall thicknesses of 150 and 100 μm, respectively. The number of capillaries is 615 ± 5. The open area of the lens is 70%; the lens length and focal length are 45.5 and 40 mm, respectively.

2. Experimental and theoretical results

X-rays having energies within a narrow band were selected from the broad incident spectrum by a filter, passed through the lens, and then recorded on a film (Fig. 2). All elements of the system were placed in a vacuum chamber at a pressure of not greater than 5×10^{-6} Torr. The chamber design allowed radiation to be recorded at different distances (0–60 mm) from the lens exit. The synchrotron radiation was focused from $\sim$300 mm^2 area at the lens entrance to a spot of diameter $\sim$3 mm.

The measurements consisted of two runs. The first was performed with a monochromatic X-ray beam with a photon energy of $\sim$1 keV (wavelength 12.4 Å). The X-ray pattern obtained on a film at the focal plane is presented in Fig. 3(*a*). The results of a theoretical calculation (see Fig. 3*b*) with the same parameters as in the experiment show the creation of a certain structure in the focal spot. The results do not indicate any smearing of the spot at the focal plane. It is seen from these pictures that the focal spot has a particularly pronounced structure of bright interference maxima. The overall size of the focal spot is given by d_f

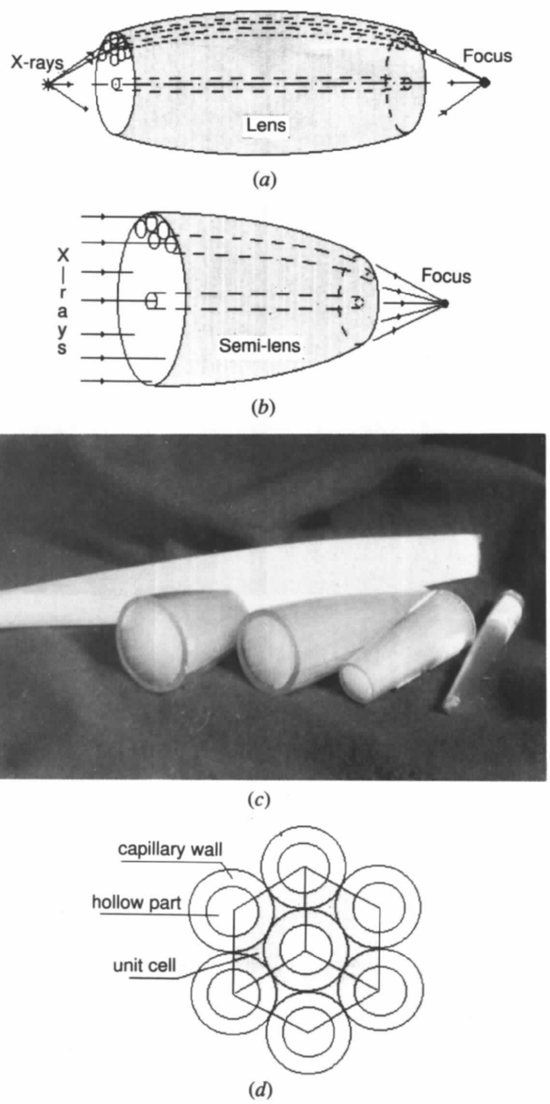


Figure 1
(*a*) Illustration of a capillary lens for collecting X-rays from a divergent source and focusing them onto a small spot. (*b*) Illustration of a capillary semi-lens for focusing X-rays from a parallel beam. (*c*) Photograph of lenses and semi-lenses of the fourth generation. (*d*) The unit cell of the capillary lens in a general case. The diameter of the hollow part changes from 1 mm at the entrance of the semi-lens to 0.6 mm at the exit; the wall thickness decreases correspondingly from 0.15 to 0.1 mm.

$= d_c + 2f\theta_c$ (d_f is the diameter of the focal spot, d_c is the capillary diameter at the lens exit, f is the focal distance, and θ_c is the critical angle), and is ~3 mm for our case. But the width of the focal central maximum, as seen in both the experiments and the theoretical calculations, is ~600 µm, *i.e.* about one-fifth of the diameter estimated above. Some differences in the images may be explained by uncertainties in the experimental measurement, and by the differences between the cross sections of the capillaries used in the experiment (hexagonal) and in calculations (circular cross section assumed). Preliminary analysis shows that in the central peak the radiation density increases by a factor of more than 100. Results of a detailed analysis will be published separately.

To check these results a second experiment was carried out. In this experiment a synchrotron radiation beam with energy ~1.5 keV (wavelength 8.3 Å) was used. Changes in the observed picture caused by the closing of definite sections of the lens end have been investigated. The results of measurements and theoretical calculations for the case with a closed sector (with an angle of 90°) are presented in Fig. 4. The patterns obtained confirm that the interference at the focal spot is a consequence of X-ray 'diffraction' within the lens, since the interference structure observed with a mask opaque to radiation (closed sector) overlaps a classic shadow of the mask.

It might be thought surprising that an interference phenomenon is observed when the periodic structural dimensions (channel diameters and capillary wall thicknesses) greatly exceed the wavelength of the transmitted radiation (for 1.5 keV photon energy the capillary diameter/wavelength ratio is about one million). However, if we consider the fact that monochromatic plane waves incident on the lens entrance are transported by channels with differing curvature, then at the exit we obtain a set of waves with various phase fronts. It is necessary to note that this set is a hexagonally symmetric one, because the lens has axial symmetry. Those waves arriving in phase at the same point on the focal plane are intensified, while those out of phase are suppressed, resulting in an interference pattern. This phenomenon is analogous to X-ray diffraction in crystals.

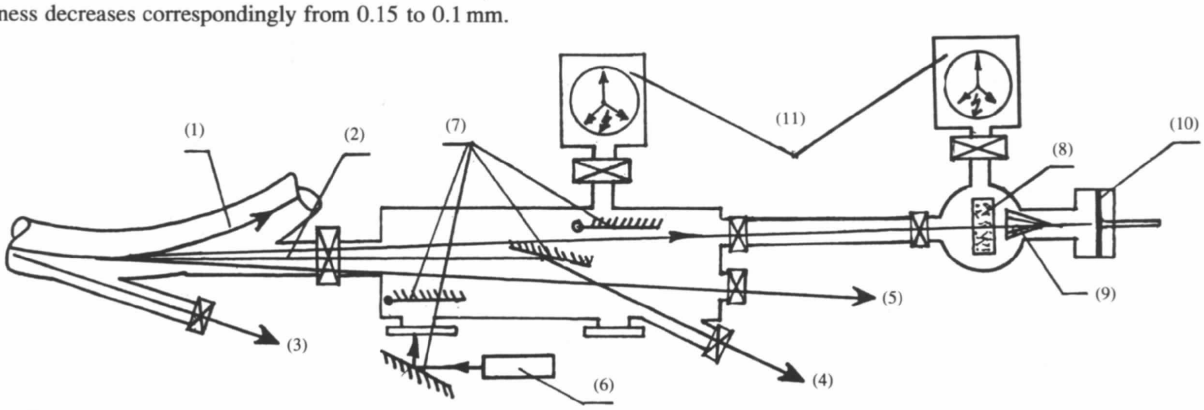
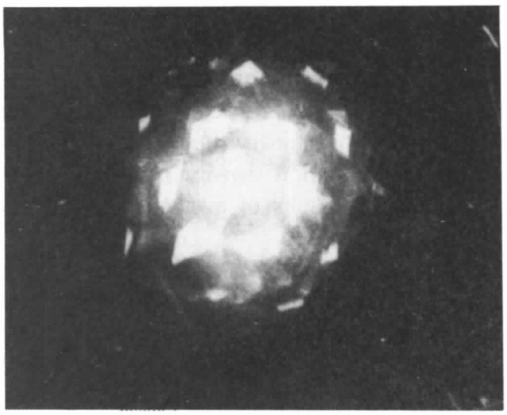
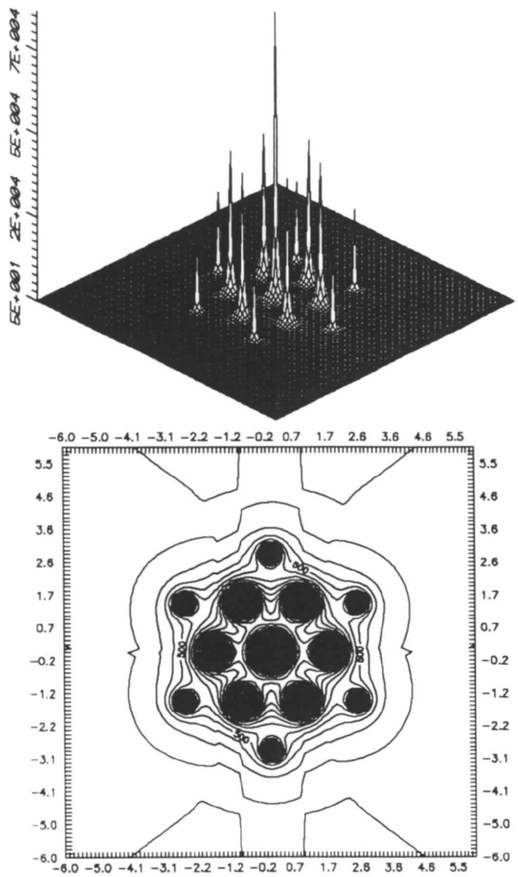


Figure 2
Layout of the experimental station for the investigation of lens focusing properties on S-60: (1) electron orbit; (2) synchrotron radiation; (3), (4), (5) beamlines for time-resolved, VUV-atomic and solid-state spectroscopy; (6) laser; (7) mirrors; (8) filter; (9) lens; (10) film holder; (11) high-vacuum pumps.

For a description of the observed phenomenon, a certain analogy between photon trajectories in capillaries, and channeled particles in a crystal, can be used. In both cases trajectories are close to periodic ones. In addition, the capillary packing in our lens has axial symmetry, similar to

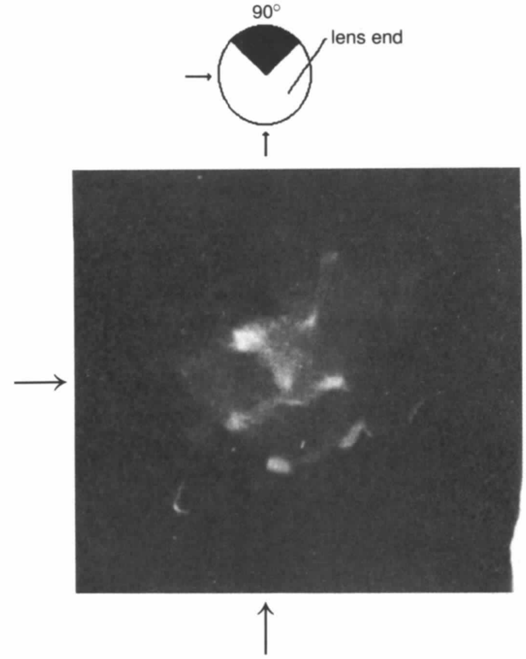


(*a*)

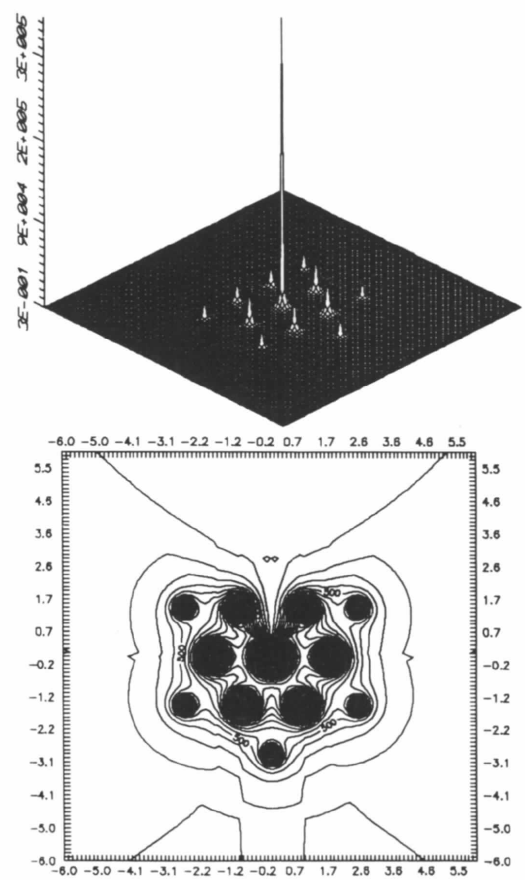


(*b*)

Figure 3
(*a*) Photograph of the X-ray film image at the focal plane at a distance of 40 mm from the lens exit. The bright-spot size is ~3 mm. Energy of synchrotron radiation used is ~1 keV. (*b*) Results of a theoretical calculation on the formation of the focal spot. The distance from the lens exit is 40 mm, the synchrotron radiation beam energy is 1 keV. The intensities on the *z* axis are given in arbitrary units, the scale of the (*x*,*y*) coordinates is 1:0.3 mm.



(*a*)



(*b*)

Figure 4
(*a*) Photograph of the X-ray film image at the focal spot of the lens, which is closed partly by a sector of 90°. The bright-spot size is ~2.5 mm, the energy of the synchrotron radiation was ~1.5 keV. (*b*) Results of the theoretical calculation of the focal-spot structure for the pertinent experimental parameters [see (*a*)]. The presentation is as in Fig. 3(*b*).

that for many crystal structures. Therefore, we have adapted the wave theory used to describe the interference structure arising from the channeling of electrons through crystals (Dabagov & Ognev, 1988*a*,*b*). Calculations are based on a solution of the wave equation for the wavefunctions $E(\omega,\mathbf{R})$ of incident photons

$$\Delta E + \omega^2 n^2 E = 0,$$

where $\Delta = \partial^2_i/\partial\mathbf{R}^2_i$, ω is a photon energy, and $n = n(\omega,\mathbf{R})$ is a refractive index depending on the photon energy and coordinates. It is assumed in the calculations that capillary systems are strictly packed periodical structures with channels for photon transmission and that the parameters of these channels (diameter, wall thickness, curvature radius) change between the system entrance and exit. Details of this theory, applied to the case of the X-ray lens, will be published elsewhere.

To understand the physics, let us consider channeling of photons with a wavevector of $\mathbf{k} \equiv (k_\perp,k_\parallel)$ into a capillary with radius of curvature R_i (ith layer of the capillaries). At small glancing angles θ, the change of $k_\parallel$ under reflection from a capillary wall is negligibly small and the changes in the transverse wavevector $k_\perp \simeq k\theta$ $(\theta < \theta_c)$ are more significant. The transverse wavelength will greatly exceed a longitudinal wavelength $\lambda_\perp = \lambda/\theta >> \lambda$, and therefore is closer to typical dimensions in the capillary lens. It is for this reason that interference effects are possible.

It is important to note that most of the focused radiation is concentrated in the central peak. Existing technology allows us to make capillary sizes on a micrometer and submicrometer level. This means that it is possible to obtain a very high concentration of radiation for a very small size spot, which is difficult to achieve by other means. This new effect may find interesting applications in microscopy, in element analysis, in biology, in scientific instrument design, *etc*., and should thus prove useful for many researchers.

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