

Microbeam generation with capillary optics (invited)

Donald H. Bilderback

Cornell High Energy Synchrotron Source and School of Applied and Engineering Physics, Cornell University, Ithaca, New York, 14853

Daniel J. Thiel

Cornell High Energy Synchrotron Source and Department of Biochemistry, Cell and Molecular Biology, Cornell University, Ithaca, New York 14853

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Grazing incidence x-ray optics for microbeam generation can be classified into five types: ellipsoidal mirror, Wolter mirror, monocabillary concentrator, microchannel array, and polycapillary concentrator. These components each have their own properties, yet they are closely related. Each optical component is at a different stage of development. Ellipsoidal mirrors are based on a mature technology and at 1/10 magnification should yield 10- μm -diam beams. Optics based on replicate Wolter mirrors are capable of producing beams on a 1–10 μm scale with high gain. Monocabillary concentrators are producing beam sizes of less than 0.1 μm . On a larger scale, polycapillary concentrators, and microchannel arrays are promising microbeam components. Ray tracing programs exist in different forms for some of these components. Prototype capillary optics have been tested, but as a whole, the manufacturing methods could be significantly improved with further investments in time and effort. All of these optical designs show great promise for intensifying a beam in a small area if they can be adequately perfected. This is the great challenge before us. © 1995 American Institute of Physics.

I. INTRODUCTION

The generation of small-sized x-ray beams ranging from 100 μm down to 20 nm in diameter opens opportunities in many scientific fields. X-ray optics based on the total external reflection of x rays from smooth surfaces are capable of generating beams over this range of size scales. In this paper, we review the various grazing-incidence efforts worldwide that have substantial promise for intensifying a synchrotron radiation beam by making it smaller, and we highlight the similarities and differences between the optics based on small bore tubes. First, we briefly review several results of Fresnel theory which form the physical basis for the optics, then we describe the current understanding and state-of-the-art in fabrication of these components that operate in the hard x-ray range from 5 to 30 keV. When coupled to synchrotron or other kinds of x-ray sources, capillary optics will continue to have a wide impact on application areas such as x-ray crystallography, x-ray astronomy, fluorescence, tomography, spectroscopy, high-pressure diffraction, medical imaging, etc.

II. OPTICAL PRINCIPLES AND THE DESIGN OF OPTICS

All of the developments in grazing incidence x-ray optics discussed in this paper rely on the principle of total reflection of x rays from a smooth surface. From the point of view of optics design, the two most important consequences from Fresnel theory are that the reflection process is specular (or mirrorlike), Fig. 1, and that the reflection process can be very efficient if the x rays are reflected from a relatively smooth surface at less than the critical angle ($\theta_c = 3.2$ mrad at 10 keV for a silicon surface and θ_c scales with x-ray energy as $1/E$), Fig. 2. X rays incident on a reflecting surface

are deflected (by an angle of 2θ) into a new direction. This is a key step in being able to fabricate optics that can condense or focus an x-ray beam to a smaller beam size, for instance. If the glancing angle is small compared to the critical angle, then the efficiency of reflection is near unity; hence, it becomes possible to conceive of highly efficient optics where the x rays undergo multiple reflections instead of just one reflection per optical element as is the case for a classical x-ray mirror design. The calculated reflectivity for a single reflection from a smooth silicon surface is 98.2% at 1/2 of the critical angle of 3.2 mrad (see the arrow in Fig. 2). Thus a perfect optical component with ten bounces would have a throughput of approximately $0.982^{10} = 0.834$ or 83%! Therefore, it is reasonable to consider x-ray optics based on multiple bounces if all other loss mechanisms can be controlled.

With some imagination and the help of various ray tracing programs, one can readily explore new optical designs, including those based on drawn glass capillary tubing, metalized replicate optics made from polished mandrels, etc. However, the step that greatly hinders the current implementation of many of these ideas is the imperfect nature of the different optical manufacturing processes. It has only been in the last five to ten years that fabricating and testing methods for large scale (20–150 cm long) figured mirrors have been



FIG. 1. Schematic of an x ray incident on a smooth surface at angle θ reflecting specularly.

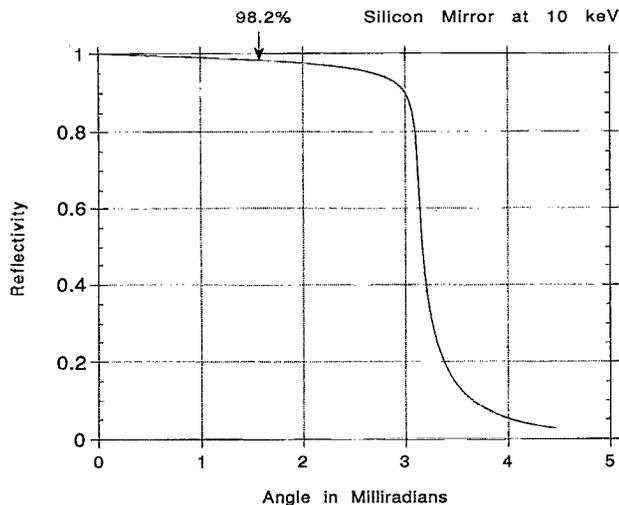


FIG. 2. Computed Fresnel reflectance for a silicon mirror with 10 keV x rays. At half the critical angle of 3.2 mrad, the reflectance is still 98.2% (see the arrow).

developed to the point that they do not spoil the brilliance of the latest generation of synchrotron light sources. It is now possible for opticians to figure an ellipsoidal mirror, for instance, with slope errors (departure from ideal curvature) of less than several microradians and a surface roughness of 1–3 Å rms. By way of contrast, for current optics based on glass tubing or replication methods, fabrication methods are in a reasonable demonstration stage but there is still much room to optimize the various manufacturing processes.

III. CLASSIFICATION OF GRAZING-INCIDENCE OPTICS INTO FIVE TYPES

We next summarize the underlying optical concepts of these optical devices and then examine their current state of development.

We have classified the different types of optics, Fig. 3, into five different categories: ellipsoidal mirror, Wolter mirror, moncapillary concentrator, microchannel arrays, and polycapillary concentrator. There may be other ways of classifying the type of optics, but in the present case it is helpful to see similarities among the different types of optics and also to discover the unique features of each kind of optic.

In Fig. 3(a), a conventional toroidal or ellipsoidal mirror is placed in a highly demagnifying manner.¹ An image of the source is formed in the image plane scaled by the magnification, $M = F_2/F_1$ where F_1 and F_2 are the distances from the optic to the source and image, respectively.

A conventional ellipsoidal mirror is not considered to be a capillary optic. If a revolution about the SI axis in Fig. 3(a) is made, a Wolter² type of mirror is achieved [Fig. 3(b)]. Wolter mirrors have been employed by the astronomy community as a compact way to build space telescopes for x-ray imaging. Such a mirror is just a segment of an ellipsoid of revolution. By reducing the inner diameter to the scale of a millimeter, the mirror begins to take on the shape of a cap-

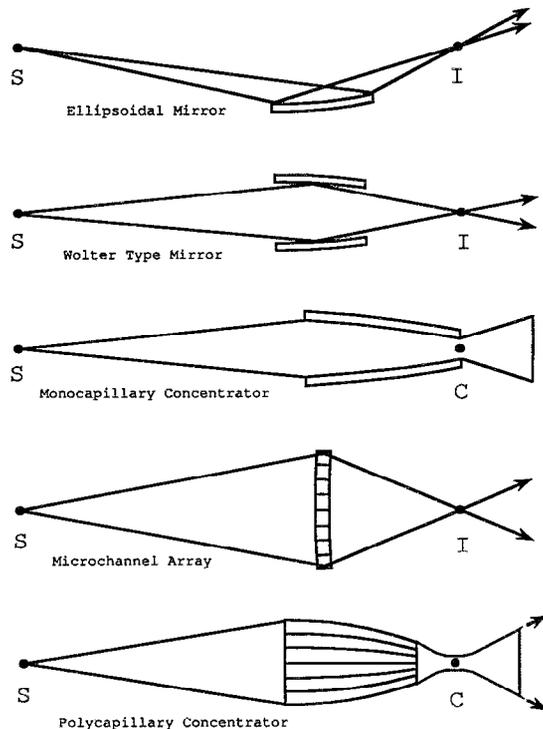


FIG. 3. Total reflection optics for microbeam generation showing cross sections of (a) ellipsoidal mirror, (b) Wolter-type mirror, (c) moncapillary concentrator, (d) microchannel array, and (e) polycapillary concentrator. S is the x-ray source point and I or C denote the point of maximum beam intensification for imaging optics (I) or concentrating optics (C).

illary, a tube with a small bore. Just like the ellipsoidal mirror, this type of mirror images the source, and the focus is at some distance from the end of the optic.

By extending its length and perhaps reducing its inner diameter the Wolter mirror is essentially transformed into a moncapillary concentrator, Fig. 3(c). Here the x rays are concentrated to their highest intensity just at the tip of the capillary tube. Because the x rays are scrambled in direction as they pass through the concentrator, this class of optics is referred to as a nonimaging or concentrating optic.

The first three components illustrated in Fig. 3 consist of one reflecting surface. It is possible to consider other configurations, ones in which multiple reflecting surfaces or capillaries are involved. We classify these optics into two further categories, microchannel arrays, Fig. 3(d), and polycapillary concentrators, Figure 3(e), depending on whether the length of the capillaries are short or long compared to their diameter.

By suitably curving a microchannel array, asymmetric focal lengths can be obtained suitable for intensifying the x-ray beam. A microchannel array may be an imaging optic if it is composed of either a series of nested, short Wolter mirrors or an array of short, square holes. Other microchannel configurations, such as round channels, result in optics which display concentrating characteristics.

If the length of the tubes are extended so that multiple bounces take place in the channels, then a polycapillary concentrator is obtained. Unlike the moncapillary concentrator,

this device intensifies the beam at some distance beyond the tip of the optic. In contrast to the four prior optical devices, this one can concentrate x rays over a range of angles as large as 40 times the critical angle as long as the x rays are guided along a gentle curve and the incidence angle of each bounce does not exceed the local critical angle.

So far it is not clear whether concentrators are capable of producing higher x-ray intensities than imaging x-ray optics as is the case for optics concentrating solar (visible) light.³

In the following sections we will discuss the specific stage of development for all of these five optical devices starting with ellipsoidal mirrors.

IV. ELLIPSOIDAL MIRROR

For an undulator source of radiation at the European Synchrotron Radiation Facility (ESRF), a $10\ \mu\text{m} \times 10\ \mu\text{m}$ beam size is expected from an ellipsoidally figured mirror⁴ operating with a magnification of 1/10. Typically these mirrors are 20–100 cm in length, 4–10 cm in width, and are generally doubly curved. The radius of curvature in the plane of reflection is generally on the scale of kilometers and, perpendicular to this plane, on the scale of a few centimeters. These commercially available mirrors have been installed on many synchrotron beamlines and can be produced in nearly perfect form, but the costs of manufacture are usually rather high. The ellipsoidal mirror technology is relatively mature compared to the other optics components that remain to be discussed.

V. WOLTER MIRRORS

Wolter-type mirrors are another class of devices with potential to provide high-intensity microbeams. The current methods employed to fabricate larger-scale ellipsoidal mirrors are not capable of forming Wolter-type mirrors with inner diameters as small as 1 mm. It may be possible, however, to polish diamond turned mandrels on a sewing needlelike scale and then to replicate the optics (Aoki,⁵ Hudec,⁶ Uhlmer.⁷) Such an optic⁸ operating with a magnification of 1/13 achieved a $1.6\ \mu\text{m} \times 34\ \mu\text{m}$ beam size in Photon Factory in experiments where a source pinhole of $16\ \mu\text{m}$ diam was employed. The $34\ \mu\text{m}$ horizontal width was much larger than expected based on simple geometrical concerns and is attributed to the modest surface roughness obtained from the replication process.

Arndt⁹ and Hudec *et al.*⁶ have proposed building a 26-mm-long single bounce ellipsoidal optic (smallest diameter 0.39 mm, largest diameter 0.73 mm) to work at a magnification of 1/30 consisting of a gold reflecting surface supported by an electroformed metal shell. In conjunction with a microfocus x-ray tube source, this group hopes to achieve beam sizes in the range of 2–10 μm at 8 keV.

Wolter mirrors are very much in the developmental stage, but show promise if the manufacturing techniques can be further optimized.

VI. MONOCAPILLARY CONCENTRATORS

In Fig. 4, it is shown schematically how an x-ray beam can be squeezed to smaller dimension as it reflects multiple



FIG. 4. Two-dimensional simulation of an x-ray beam undergoing two bounces from the bottom and top walls of a parabolic tapered monocalipillary. The beam intensity is highest just at the position of the fine needlelike tip.

times from the tapered inside wall of a hollow tube. Because we are only addressing optics which increase the intensity of the incident x-ray beam, studies using untapered, straight capillaries will not be mentioned. With tapered capillaries, intensity gains as high as 700 000 may be possible if imperfections in the glass fabrication process do not limit the performance of the optic.¹⁰

In spatially resolved x-ray fluorescence experiments at Hasylab, capillaries have been employed with tip openings down to $0.1\ \mu\text{m}$.^{11,12} A $0.8\text{-}\mu\text{m}$ -diam beam has been produced at Hitachi by employing a microfocus x-ray source along with a tapered capillary in order to measure the strain and elemental composition of electronic circuits on a highly spatially resolved fashion.¹³ At CHESS, tapered capillaries fabricated from leaded glass of 3–10 cm length^{14–18} have produced beam sizes from 50 nm to $20\ \mu\text{m}$. The capillary optics have been tested with 5–25 keV x rays and a gain as high as 960 at 6 keV has been observed with a capillary whose transmission was 2%.¹⁶ Using a 1.6% bandwidth multilayer monochromator, a flux of 10^6 x rays/s at 12.3 keV was measured through the $0.1\ \mu\text{m}$ tip opening of this same capillary. In other experiments, tapered capillaries have also been used to concentrate “white” radiation produced by a bending magnet.

Various other groups are now becoming active in using tapered capillaries for microfocusing. At the ESRF, tests are presently being made with capillary optics on an undulator beamline.¹⁹ At the Advanced Photon Source (APS), efforts are underway to produce the most intense beams possible on a $1\ \mu\text{m}$ scale with these optical elements.²⁰ A second APS group aims to provide small, intense beams of various sizes for general use at the APS.²¹ In summary, monocalipillary optics have been employed in a few experiments although the fabrication process has yet to be fully optimized.

VII. MICROCHANNEL ARRAYS

Microchannel arrays consisting of small round or square holes have some promise of being useful for creating microbeams of x rays.^{22–24} Figure 5 shows how x rays can be directed from point to point with a curved array of holes. With a 2-mm-thick Varian microchannel plate²² and a hole size of $10\ \mu\text{m}$, a gain in flux/area of 20 was observed at the point of concentration with the microchannel plate (as compared to having no microchannel plate present). A $20\text{-}\mu\text{m}$ -diam microfocus $\text{Cu } K_{\alpha}$ source of x rays was employed for these tests. The x-ray microbeam community is waiting for the next developmental step, a test with synchrotron radiation incident upon an array of square holes that can create a highly demagnified beam.

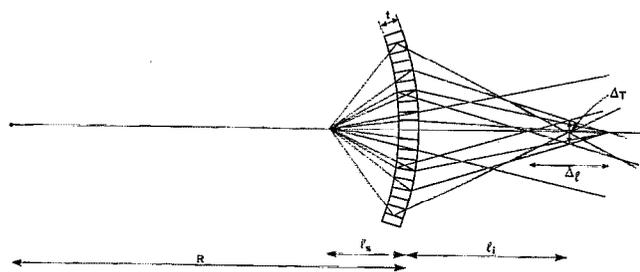


FIG. 5. Ray diagram showing possible paths for meridional rays of a microchannel array of holes. The lens equation for this device is $1/l_s - 1/l_t = 2/R$. The transverse magnification, $M_T = l_t/l_s$. The dimension of the condensed beam, D , [$D_{\text{Transverse}} = d(M_T + 1)$, $D_{\text{longitudinal}} = t(M_T + 1)$] involves the thickness of the plate, t , and the diameter of the channels, d . (The figure is taken from Ref. 22.)

VIII. POLYCAPILLARY OPTICS

The last class of optical components to be discussed here is the tapered polycapillary. For microbeam generation on the large scale of 50–100 μm , the polycapillaries are of much shorter length than an equivalent monocapillary concentrator and therefore it is interesting to investigate their capabilities. Figure 6 shows a lengthwise cross section of a single strand of a hexagonal shaped tubing that contains 336 glass channels, each 17 μm in diameter and that has been tapered to condense the x-ray beam to smaller dimension. Ray tracing studies show that high efficiency is achieved if the x rays are redirected to the point of concentration in a single bounce by either a linear or parabolic steering section followed by a linear taper region to further guide and compress the beam. A gain in intensity of a factor of 5 was measured for this polycapillary optic when tested with 6 keV x rays on an unfocused CHESS bending magnet beamline.²⁵ A beam size of 68 μm was observed 6 mm beyond the tip of the optic, Fig. 7. The observed x-ray transmission of this component was 24%.

Larger polycapillary devices have been formed by grouping together single-stranded polycapillary tubes into bundles.^{26,27} Figure 8 shows both a photograph and design schematic of such an optic. The actual device was tested in

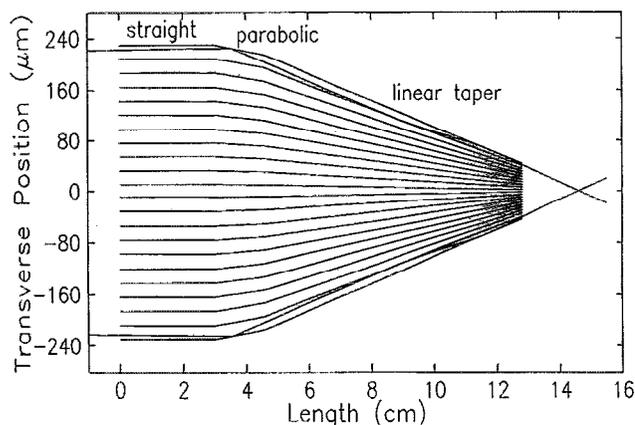


FIG. 6. Longitudinal cross section of ideal polycapillary array with two rays traced to the point of concentration. (The figure is taken from Ref. 25.)

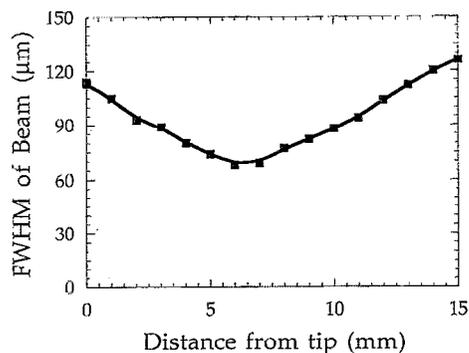


FIG. 7. Measured beam diameter vs distance from the tip of a polycapillary optic. The x-ray beam achieved its maximum concentration at a point 6 mm beyond the small tip of the optic. (The figure is taken from Ref. 25.)

the collimating mode where a source of CuK_α radiation (8 keV) was placed near the small end, collecting 7.2° of angular spread. Ray tracing simulations of the actual device suggest that a 20-fold gain in intensity should be possible with a beam size of 80 μm full width at half-maximum on a synchrotron beamline when this component is reversed to operate in a condensing mode. At the time of this writing, this experiment has not yet been conducted.

IX. CONCLUSION

Microbeam grazing-incidence optics can be placed into five categories: ellipsoidal mirror, Wolter mirror, monocapillary concentrator, microchannel array, and polycapillary concentrator. The ellipsoidal mirror technology is mature and is used to generate beams down to a 10 μm scale. Wolter rep-

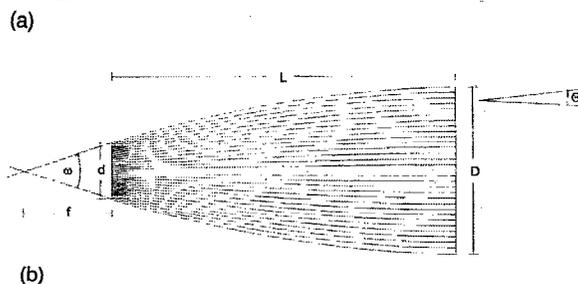
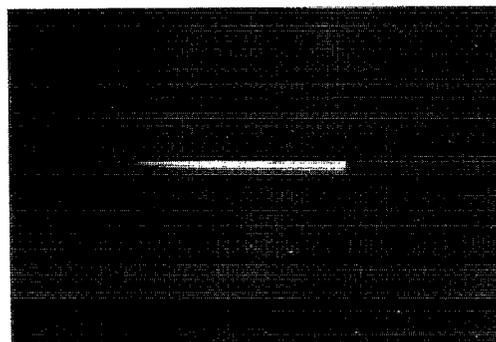


FIG. 8. (a) Photograph of a large polycapillary optic fabricated by assembling many single-stranded polycapillary tubes and drawing the bundle. (b) A design schematic is also shown. For a particular application, parameters of $D=6.3$ mm, $d=1.9$ mm, $L=119$ mm, $f=15$ mm, and $\omega=7.2^\circ$ were selected and a corresponding polycapillary optic fabricated. (The figure is taken from Ref. 27.)

lica mirrors have the potential to achieve 10 μm sizes at lower cost. Monocapillaries have made small diameter beams of $<0.1 \mu\text{m}$ with high gains in intensity. On a larger scale, microchannel arrays have been used for both collimating and condensing x-ray beams, but not yet at synchrotron sources. Also, on a size scale of $>50 \mu\text{m}$, polycapillaries have generated higher-intensity beams. All of these optical designs show potential for improvement if fabrication techniques can be adequately perfected. This is the challenge before us.

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