Performance study of polycapillary optics for hard x rays

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In order to investigate the feasibility of using Kumakhov capillary x-ray optics for high energy x-ray applications, measurements have been performed on the behavior of capillary optics from 10 to 80 keV. Transmission efficiencies of straight polycapillary fibers of different types have been measured as a function of source location and x-ray energy. The measurements are analyzed using a geometrical optics simulation program, which includes roughness and waviness effects. Despite the low critical angle for total external reflection at high energies, capillary x-ray optics appear promising for many hard x-ray applications. Transmission measurements at high energies have also proven to be a very sensitive tool in capillary quality analysis.

I. INTRODUCTION

Capillary x-ray optics use total external reflection to guide x-rays through tiny glass tubes. A polycapillary fiber is a capillary bundle with hundreds or thousands of hollow channels. Figure 1 shows a cross section of a polycapillary fiber. X-ray beams can be bent, focused, or collimated by a carefully curved capillary array. Systems involving the use of a large number of capillary channels for shaping x-ray beams were first suggested by Kumakhov and his collaborators in 1986. Unlike some other x-ray devices, such as multilayer mirrors, zone plates, or phase gratings, capillary optics have a broad energy and angular bandwidth. Such systems have potential usefulness in many applications, including x-ray lithography, medical imaging, crystallography, and astronomy.

Capillary performance measurements and simulation analyses are very important in both capillary manufacture and application research. The properties of polycapillary x-ray fibers at medium energies (8–20 keV) for applications such as crystal diffraction and mammography have been extensively measured and reported. As the technology develops, it may be possible to extend the range of usefulness to applications which require higher energy x-rays, such as chest radiography, x-ray orthovoltage therapy, x-ray astronomy, and nondestructive testing in industrial applications. In this article we will present measurement results for a variety of straight capillaries in the energy range from 10 to 80 keV. The results were analyzed using a geometrical optics simulation program which is discussed in Sec. III. Transmission obtained in this energy range for straight capillaries shows the potential to extend applications up to 80 keV. The analysis indicates waviness and bending are more harmful to the transmission of high energy than lower energy x-rays. This will make it more difficult to guide high energy x-rays with curved capillaries, and also provides a challenge in manufacturing that may limit applications. In this work, we also show that the transmission source scans at low energy are sensitive to surface roughness and bending, so transmission measurements will be very useful in capillary quality analysis.

II. BASIC PRINCIPLE

Capillary x-ray optics use multiple total external reflections to guide grazing incidence x-rays in an array of tiny hollow glass tubes. X-ray photon energies are much larger than the electron plasma energies of glasses, which are tens of electron volts. In this regime, the index of refraction of glass can be simply approximated by

\[ n^2 = \frac{\varepsilon}{\varepsilon_0} \approx 1 - \frac{\omega_p^2}{\omega^2}. \]  

where \( n \) is the index of refraction, \( \varepsilon \) is the dielectric constant of the glass, \( \omega \) is the photon frequency, \( \omega_p \) is the plasma frequency of the material and \( \varepsilon_0 \) is the dielectric constant of vacuum.

Since the plasma frequency, \( \omega_p \), for glass is small compared with the photon frequency, \( n \) is slightly less than unity. Therefore, x-rays traveling in vacuum or air can be totally externally reflected from smooth glass surfaces.

Using Snell’s law, the largest grazing angle for which total external x-ray reflection occurs is the “critical angle” \( \theta_c \), and

\[ \sin \left( \frac{\pi}{2} - \theta_c \right) = n \sin \left( \frac{\pi}{2} \right). \]

Thus

\[ \theta_c \approx \frac{\omega_p}{\omega}. \]

For the glass used in the experiments described here, this becomes

\[ \theta_c = \frac{30}{E(\text{keV})} \text{ mrad}, \]

where \( E \) is the photon energy in keV. For example, the critical angle is 3 mrad (0.17°) for 10 keV photons and 0.3 mrad for 100 keV photons.
III. THE GEOMETRIC SIMULATION

A. Geometric algorithm for the simulation

X-ray transmission through hollow glass capillaries is simulated by tracing a large number of x rays through the capillary. The geometric algorithm previously discussed has been extended to higher energies. In addition, in this work the model includes capillary surface quality effects, such as roughness and waviness effects. Results from this code applied to capillaries at low energies agree with the results from previous code.

The geometric algorithm is basically a two-dimensional approximation. Because of the small critical angle, the velocity of the photon along the capillary axis is nearly equal to \( c \), the velocity of the light. The trajectory of an x ray can be reduced to the two-dimensional motion of a classically accelerated particle which bounces around inside the capillary cross section. Figure 2 shows the transverse motion of an x ray in a straight capillary. Although the cross sections of capillary channels in the polycapillary fibers are roughly hexagonal, the shape of the cross section was approximated as a circle in the simulation for simplicity. For a uniform curved capillary, the x ray can be considered as a moving particle with a centripetal acceleration opposite the bending direction. The path of an x ray moving in a curved capillary is shown in Fig. 3. Here we suppose the fiber is bending in the direction opposite to the y direction. If an x ray bounces off the capillary wall at \( t=0 \), it will hit the wall again at a time \( t \) given by the conditions

\[
\begin{align*}
x(t) &= x(0) + v_\gamma t, \\
y(t) &= y(0) + v_\lambda t + \frac{1}{2} a t^2, \\
x(t)^2 + y(t)^2 &= r^2,
\end{align*}
\]

where

\[
a = \frac{c^2}{R},
\]

\( r \) is the radius of the capillary channel, \( R \) is the bending radius, and \( c \) is the velocity of light. At each collision, the transverse velocity changes from \( v_0 \) to \( v \), given by

\[
\begin{align*}
\mathbf{r} \cdot \mathbf{v} &= -\mathbf{r} \cdot \mathbf{v}_0, \\
\mathbf{r} \times \mathbf{v} &= \mathbf{r} \times \mathbf{v}_0,
\end{align*}
\]

where \( \mathbf{r} \), \( \mathbf{v}_0 \), and \( \mathbf{v} \) are shown in Fig. 4(a).

B. Reflectivity and the roughness correction

For a perfectly smooth reflecting surface, the reflectivity \( R^0(\theta) \) for x rays with small incidence angle \( \theta \) is
where absorption and Compton scattering included in Eq. (8) in this work was proposed by Bittel and Kimball.\textsuperscript{15}

When an x-ray strikes the glass surface at less than the critical angle for total reflection, surface roughness produces both diffuse scattering, for which the reflected angle can be either larger or smaller than the corresponding incident angle, and transmission into the glass. These decrease the specular reflection coefficient by a roughness correction due to the diffuse reflected x-rays which continue down the capillaries was ignored in the simulation. Even though this overestimates the roughness correction, our calculation shows that the effect of roughness is small, especially for higher energy x-rays.

D. Waviness correction

Capillary surface oscillations with wavelengths shorter than the capillary length and longer than the wavelength of the roughness are called waviness. The detailed shape of waviness is unknown. Its average effect can be considered as a random tilt of the glass wall, so that the grazing angle of the photon is changed by a random amount after each bounce, as shown in Fig. 4(b). Let the incident angle be \( \theta \), and the reflected angle be \( \theta' \). Then

\[
\theta' = \theta + \delta \theta,
\]

where \( \delta \theta \) is a random number between \(-\Delta \theta_{\max}\) and \(\Delta \theta_{\max}\) if \(\theta \geq \Delta \theta_{\max}\). The maximum random tilt angle \(\Delta \theta_{\max}\) is an adjustable parameter which depends on the waviness of the capillary. To keep \( \theta' \) positive, \( \delta \theta \) is taken to be a random

\[
\eta' = \theta' / \theta_c, \quad p = 2D/\theta_c, \quad D = c/\omega_p,
\]

\(\theta\) is the glancing angle, \(\theta'\) the scattering angle, which is smaller than \(\theta_c\), \(\theta_c\) is the critical angle, \(s\) is the correlation length, \(p\) is the penetration path length, and \(D\) is the glancing angle penetration depth. \(Z^2\) is the mean-square displacement of the rough surface from the ideal surface. The values of \(\omega_p\) and \(\theta_c\) are calculated from Eqs. (1)–(3) and tabulated values of the indices of refraction.\textsuperscript{11} The parameters \(p\) and \(D\) can be calculated from \(\omega_p\) and \(\theta_c\) according to Eq. (15).

Some of the diffusely scattered x-rays could still have incident angles less than the critical angle and continue to be transmitted down the capillary. The distribution of diffusely scattered x-rays is given by

\[
\frac{dR_D}{d\eta'} = \eta' \eta^2 f^2 \frac{8}{\pi} \frac{\varphi}{1 + \varphi^2 (\eta' - \eta^2)^2}.
\]

The contribution to transmission due to the diffusely scattered x-rays which continue down the capillaries was ignored in the simulation. Even though this overestimates the roughness correction, our calculation shows that the effect of roughness is small, especially for high energy x-rays.

C. Waviness correction

The transverse velocity change of a photon on a reflection, \(v_0\) is the incident velocity and the \(v\) is the reflected velocity.
number between $-\theta$ and $\Delta \theta_{\text{max}}$ when $\theta < \Delta \theta_{\text{max}}$. Since a photon with an incident angle smaller than $\Delta \theta_{\text{max}}$ has a larger chance to experience an angle increase than an angle decrease, this is physically reasonable.

In the simulation, changing of the grazing angle is the same as changing $v_\perp$, the transverse photon velocity as shown in Fig. 4, since

$$\theta = v_\perp / c,$$

where $c$ is velocity of light. $v_\parallel$ does not contribute to the grazing angle. We assume that $v_\parallel$ does not change. After the reflection the transverse velocity of the photon is

$$v'_\perp = -v_\perp + \delta v, \quad v'_\parallel = v_\parallel,$$

where $\delta v$ is $\delta \theta \cdot c$.

D. Profile correction

Capillary profile error whose wavelength is longer than the capillary length can be approximated as uniform bending. This results in a nonzero acceleration, $a$, in Eq. (6).

E. Simulation parameters

In summary, the adjustable parameters in the simulation are the correlation length, $s$, and root-mean-square displacement of the rough surface, $\delta$, in the roughness correction, the maximum tilt angle, $\Delta \theta_{\text{max}}$, in the waviness correction, and the bending curvature, $R$, in the profile correction. It is very difficult to determine all these parameters in one simulation since they all decrease the transmission. Fortunately, we have found that the roughness effect is important only for low energy x rays, with almost no effect for x rays with energy of more than 40 keV. At the same time, waviness and very small bending can effect the high energy x rays significantly without greatly affecting the low energy x rays. By using transmission source scan curves over the whole energy range, we found it possible to determine the effects of all these parameters. An example simulation analysis is presented in Sec. VI.

IV. EXPERIMENTAL APPARATUS

The experimental setup is shown in Fig. 5.

A. Source

The x-ray generator used in the experiment is a low current Microfocus MS50 with a 50 $\mu$m spot size, tungsten target, and a maximum operating voltage of 100 kV$_p$. The source head is mounted on a stage which can be moved in the two directions transverse to the x-ray beam. In order to reduce the background of scattered x rays, this movable source is enclosed in a 6-mm-thick lead box with a 4 x 7 in. aperture in the front. The source to fiber distance is about 1 m. In the measurements for photons with energy higher than 40 keV, a 5-mm-thick aluminum plate is used as a filter between the source and the fiber to remove the low energy photons, and reduce the dead time of the detector.

B. Pinhole

A pinhole through 1 mm of lead and 1 mm of tungsten (attached together), with a diameter smaller than the outer diameter of the fiber, is placed 1 mm away from fiber at the entrance end. The pinhole is attached to a 2-mm-thick lead shield and is adjustable on a tilt stage to make the axis of the pinhole parallel to the x-ray beam. The pinhole diameter is 200 $\mu$m, which is much smaller than the metal thickness. The pinhole and lead shield together block scattered x rays and leakage around the outside of the fiber. The lead shield is on a stage which can be translated in two directions perpendicular to the fiber. The pinhole is smaller than the fiber but still covers hundreds or more channels. Its small size was chosen not only to avoid leakage around the fiber and reduce dead time in the detector, but also to keep the source–fiber distance as small as possible while keeping the photon entrance angle at the edges of the pinhole less than the critical angle.

C. Fiber

The fiber is held straight by a finely machined groove in an aluminum plate and is covered by iron powder to prevent x-ray leakage around the fiber. The aluminum plate is also mounted on a stage which can be translated in two orthogonal directions transverse to the beam. All stages are mounted on rail carriers which can be moved along the beam direc-
tions. Five kinds of capillaries, listed in Table I, were measured. The outer cross sections and channels of all five capillaries are roughly hexagonal.

D. Detector

The detector is a high purity germanium detector with about 200 eV resolution at 5.9 keV and 550 eV at 122 keV. The detector is placed behind the fiber. The distance between the source and detector is fixed to keep air absorption constant. Motion control and data collection are all controlled with a small microcomputer.

V. EXPERIMENTAL TECHNIQUE

A. Alignment

For the initial measurements of capillary transmission, it was important to verify that the fiber was aligned with the pinhole, and that no leakage was being detected. This was determined by scanning the fiber in two dimensions, with source, pinhole, and detector fixed. An example of the resultant intensity profile is shown in Fig. 6. The small sharp peak...
behind the main peak is due to leakage between the fiber and metal plate. When the fiber is returned to the location of the main maximum, it is centered on the pinhole and the leakage is avoided. This is verified by fixing the location of the fiber and scanning the source. A plot of intensity versus source location is shown in Fig. 7. The plotted intensity has had a small fluorescence and detector background subtracted. The fluorescence background is highest between 40 and 50 keV and is less than 5% of the signal at all energies. The intensity is shown for seven different energy windows, each approximately 2 keV in width. The intensity plots are narrower for the higher energy windows, as expected due to the smaller critical angles. This behavior would not be observed if the detected signals were due to leakage through a small hole. The scan curves also establish the position of optimum source alignment.

B. High angle background subtraction

The total transmission is defined as the ratio of counts detected with and without the fiber with fluorescence and detector background subtracted. At energies larger than 50 keV, the total transmission consists of transmission through the channels, which drops rapidly as the source is moved off axis, plus a background signal from photons which cut through the glass at angles above the critical angle. This high angle background offset, which can be seen in Fig. 7, is about 2% at 59 keV and 5% at 80 keV for a 136-mm-long type 3 fiber. Measured offsets at several energies are plotted in Fig. 8 along with the theoretical values,

$$T_e = e^{-L(1-f)\mu \rho},$$

FIG. 11. (a) Simulated source scan curves for fiber C at 10 keV with different roughness corrections are compared with the experimental data. The figure shows that the scan curve is sensitive to the roughness at this energy. (b) Simulation of transmission vs source displacement for three values of roughness correction length. The roughness height was varied to compensate. (c) Simulated source scan curves at 68 keV for fiber C with different roughness corrections are compared with the experimental data, showing that the scan curve is less sensitive to the roughness at this energy than at 10 keV.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Outer diameter (mm)</th>
<th>Channel size (µm)</th>
<th>Open area</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Borosilicate</td>
<td>0.5</td>
<td>12</td>
<td>65%</td>
<td>105</td>
</tr>
<tr>
<td>2</td>
<td>Lead glass</td>
<td>0.5</td>
<td>12</td>
<td>52%</td>
<td>95</td>
</tr>
<tr>
<td>3</td>
<td>Borosilicate</td>
<td>0.75</td>
<td>22</td>
<td>50%</td>
<td>136</td>
</tr>
<tr>
<td>4</td>
<td>Borosilicate</td>
<td>4</td>
<td>12</td>
<td>55%</td>
<td>130</td>
</tr>
<tr>
<td>5</td>
<td>Borosilicate</td>
<td>0.3</td>
<td>4–5</td>
<td>55%</td>
<td>105</td>
</tr>
</tbody>
</table>
where $T_c$ is the high angle transmission, $f$ is the fractional open area of the fiber, $l$ is the length of the fiber, $\mu$ is the mass absorption coefficient, and $\rho$ is the density of the glass. The theoretical curves are calculated using tabulated values for the attenuation coefficients as a function of energy.\textsuperscript{16} The channel transmission is defined as the total transmission minus the background offset. The transmission results presented later are all channel transmission which have been corrected for high angle offset and fluorescence background.

VI. MEASUREMENT RESULTS AND ANALYSIS

A. Experimental results and simulation analysis

Transmission of a number of different fibers was measured in the energy region of 10–80 keV. The transmission versus source scans were recorded at each energy. The transmission results are shown in Fig. 9 along with their simulation curves. Before explaining the experimental results, the results of the simulation program for a type 3 capillary, fiber C, will be discussed. This analysis is very helpful in understanding the results. As mentioned earlier, the simulation has a number of adjustable parameters, which fortunately can be separated. It is shown next how this separation is done.

1. The roughness effect

The detailed analysis of the effect of roughness on the transmission spectrum and source scan curves, which follows, shows that roughness is not the main factor which causes the transmission drop at higher energies. However, the source scan curve is sensitive to roughness at low energies.

Simulation of the transmission spectrum for fiber C with and without roughness corrections are compared with the experimental data in Fig. 10. For a perfect capillary the transmission spectrum is flat, since the distance between the source and the fiber is large enough to ensure that every photon which hits the glass wall has a grazing angle smaller than its critical angle. Figure 10 shows that the transmission spectrum with a very large roughness correction, 5 nm, is still flat. The roughness of the capillaries glass surface, as measured by atomic force microscopy, is usually under 1 nm.\textsuperscript{17} This result indicates that the transmission spectrum is not sensitive to roughness. Roughness alone could not explain the transmission drop at high energies.

The transmission drop is related to both surface reflectivity and the number of reflections that the photon undergoes through the channel, i.e., the transmission, $T \times R^n$, where $R$ is the reflectivity, and $n$ the number of bounces. For a straight capillary, the average number of bounces the photon experiences is small, usually less than 2. Thus the roughness has only a small effect on this simulation. On the other hand, the transmission scan curve at 10 keV shown in Fig. 11(a), where photons experience more than 20 reflections for large source displacements, does sense the roughness. In Fig. 11(a), simulations with and without roughness corrections are compared with the experimental data. These simulations...
vary the correlation length, it is fixed at 6 nm. Because of the lack of sufficient data to determine the correlation length, the chosen value of correlation length, 6 μm, may result in a slight underestimate of absolute roughness in the simulations. However, the relative roughness, and the insensitivity to roughness at high energies, will be unchanged by corrections to the correlation length.

Returning to Fig. 11(a), which has \( s = 6 \) μm, the simulation with 0.5 nm for \( z \) fits the experimental data quite well. It is definitely overcorrected when \( z = 1.0 \) nm. The same simulations are also carried out at 68 keV, where the width of the curve is narrower than that at 10 keV because of the smaller critical angle. Photons also experience fewer bounces on average. As shown in Fig. 11(c), simulations with \( z \) as large as 1.0 and 2.0 nm could not fit this data. Knowing that 1.0 or 2.0 nm roughness is definitely too large at 10 keV, we can determine that the roughness correction by itself is not sufficient at high energy to reproduce source scan measurements. Other effects need to be considered. These are bending and waviness.

2. Waviness and bending effects

While slight roughness does not significantly affect the transmission efficiency at high energy, as seen in Fig. 10, a slight bending can dramatically reduce the transmission of high energy photons because of the small critical angle. A comparison between experimental data and simulations with different bending is shown in Fig. 12(a). The figure shows that the simulations with bending alone did not fit the experimental data well, which indicates that bending is not the only factor which causes the high energy transmission to drop. However, from Fig. 12(a), we can see that the range of the bending radius must be larger than 100 m to give the observed transmission at the highest energy (80 keV).

In Fig. 12(b), simulations with waviness corrections with \( \Delta \theta_{\text{max}} \) set at 1 and 2 mrad, which is comparable to the critical angle, are compared with the experimental data. Figure 12(b) shows that simulations with waviness alone do not fit the experimental data. This is because the waviness correction changes the reflected angle, not the profile. In fact the capillary is still considered to be perfectly straight, so those photons which have few reflections will not be significantly affected by waviness. In Figs. 12(a) and 12(b), roughness is not included, because it has little effect on the transmission spectra.

Finally the waviness and bending are combined by increasing the bending radius \( R \), roughly determined in Fig. 12(a), and adding a waviness parameter, \( \Delta \theta_{\text{max}} \). Several trials are shown in Fig. 13. Model 2 has too much bending and not enough waviness; Model 3 has too much waviness and not enough bending; Model 1 is the best fit. Roughness is also included in those simulations, with \( z \) equal to 0.5 nm, which is the best fit in Fig. 11(a).
3. Verification with the transmission scan curve

To verify the correctness of the three fitting parameters, \( z \), \( \Delta \theta_{\text{max}} \), and \( R \), simulations using the best fit parameters are compared to the source scan experimental data at 10 and 68 keV in Figs. 14(a) and 14(b). Figure 14(a) shows that the scan curve simulation at 10 keV, with the roughness determined in Fig. 11(a), and the additional bending and waviness determined in Fig. 13, can still fit the data fairly well. (Sometimes a small modification is necessary on the roughness correction after bending and waviness are added.) This means bending and waviness have less effect on the low energy scan curve than does the roughness. On the other hand, the 0.5 nm roughness required at low energies could not make the scan curve simulation fit the data well at 68 keV, as was illustrated in Fig. 11(b). After introducing the bending and waviness correction the simulation fits well in Fig. 14(b). This means the bending and waviness do have significant effect at high energies, where the roughness is not important. The simulation without waviness is also plotted at both energies. Although it still fits nicely at 10 keV in Fig. 14(b), it does not fit the data at 68 keV in Fig. 14(b), indicating that waviness is significant at high energies. The source scan simulation with the three fixed parameters are plotted along with the experimental data in Fig. 15 for four more photon energies. They all fit fairly well.

4. Explanation of experimental results

The best fit parameters for the four simulations shown in Fig. 9 are given in Table II. Reexamining Fig. 9, the channel transmission for fiber A shows a rapid drop for energies above 30 keV. This is a type 1 capillary which is thin (~500 \( \mu \)m in diameter) and flexible, and therefore difficult to keep straight in the measurement apparatus. Table II shows that the simulation requires more bending and waviness for this

\[ \begin{array}{|c|c|c|c|c|}
\hline
\text{Fiber No.} & \text{Type} & \text{R} (\text{m}) & \Delta \theta_{\text{max}} (\text{mrad}) & z (\text{nm}) & s (\mu\text{m}) \\
\hline
A & 1 & 105 & 0.4 & 0.7 & 6 \\
B & 2 & \ldots & \ldots & \ldots & \ldots \\
C & 3 & 125 & 0.35 & 0.5 & 6 \\
D & 4 & 110 & 0.285 & 0.8 & 6 \\
E & 5 & 28 & 0.2 & 0.7 & 6 \\
F & 4 & 90 & 0.45 & 0.8 & 6 \\
\hline
\end{array} \]

\[ \text{FIG. 15. Simulated source scan curves, compared with experimental data at four different photon energies. Parameters are: } R=125 \text{ m}, \Delta \theta_{\text{max}}=0.35 \text{ mrad}, s=6 \mu\text{m}, \text{ and } z=0.5 \text{ nm.} \]

\[ \text{FIG. 16. Transmission spectrum of fiber F (exposed), compared with that of fiber D (unexposed). Fiber F and fiber D are the same capillary type and the same length. The lines are simulated results. The simulations use the same roughness parameters, } z=0.8 \text{ nm and } s=6 \mu\text{m.} \]
fiber than that of fiber C or D. Any slight bend is more significant at high energies, where the critical angles are smaller. Transmissions for fiber C and fiber D are nearly flat up to 60 keV. As noted in Table I, these two capillaries have larger outer diameters, so they are more rigid and easier to keep straight. Even though these two fibers have lower fractional open areas than fiber A, their transmissions exceed that of fiber A at energies above 30 keV. The simulation also requires smaller waviness and bending correction for these two capillaries. Fiber E is a type 5 capillary which is thinner than type A, but its transmission is flat to 40 keV. The reason for this is that this fiber has small channel size which reduces the sensitivity to waviness and other profile errors. Table II shows that this fiber has a larger bending correction than the type A fiber because of its flexibility, but still has better high energy transmission. However, the small channel size also results in more reflections being needed for a photon to traverse the fiber and may also introduce other defects such as closed channels. This is why the transmission is only 40% under 40 keV although the open area is around 55%.

The high measured transmissions and the simulation results show that the quality of the capillaries is quite good. The surface roughness is low, and bending curvature is more than 110 m for type 3 and type 4 capillaries. It is hopeful that we can further improve the high energy transmission performance of capillaries by decreasing the channel size and making them more rigid.

Also shown in Fig. 9 is the channel transmission for polycapillaries made from leaded glass. The leaded glass considerably reduced the high angle transmission, which is a benefit for applications requiring angular discrimination. However, as a result of the poor quality channels and high absorption of lead, the channel transmission of those fibers is poor over the whole energy range.

B. An analysis of radiation damaged capillary

The measured transmission spectra and source scans provide sensitive tools for analyzing capillary quality. This method was used to analyze the effect of radiation damage on fiber F which is the same type and length as fiber D.

Radiation damage has been observed after a very large dose of x-ray exposure. It was found that prolonged exposure to synchrotron white beam radiation can cause measurable fiber bending for a thin fiber. This bending can be removed by annealing and can be reduced by holding the fiber rigid during exposure. Fiber F had 1.8 MJ/cm² exposure before the current measurements. There is no measurable bending or other visible damage.

The transmission spectrum and its simulation for fiber F are compared with an unexposed capillary of the same type, fiber D in Fig. 16. Parameters for the roughness correction were determined by scan curve fitting on the unexposed fiber (see Fig. 17). The measured data for the exposed fiber shows a significant transmission drop above 30 keV and below 10 keV. Because the aligned transmission spectrum is insensitive to the roughness, the roughness parameter for the exposed fiber can be set the same as the unexposed fiber for this figure. The simulation indicates that the exposed capillary has more bending and waviness. The bending curvature was changed from 110 to 90 m and the waviness changed from 0.285 to 0.45 mrad. Although these profile changes have a significant effect on the transmission, they are still very small and not apparent. The transmission drop below 10 keV cannot be explained by this simulation.

In Fig. 17, the scan data and simulations at 10 keV are compared for fiber F and fiber D. The two simulations use the same roughness correction. Waviness parameters are as determined by the transmission spectrum fitting. The two experimental scan curves almost overlap. The simulations...
for them used the same amount of roughness correction. Simulations with different roughness corrections for the exposed capillary are plotted in Fig. 18, which shows that 0.3 nm roughness increase will cause a noticeable change in the source scan curve at 10 keV. Thus it is believed the roughness change of exposed capillary is small. To summarize, exposure to a large dose of radiation causes increased waviness and bending in the exposed capillary, but little roughness increase.

VII. CONCLUSIONS

Transmission efficiencies which are fairly flat out to 60 keV, and in excess of 30% at 80 keV, have been measured for borosilicate glass polycapillaries. A geometric simulation with roughness, waviness, and bending correction works quite well in explaining the transmission spectrum. According to the simulation, slight waviness and bending in the capillary channel profiles is particularly harmful for high energy photons because of the smaller critical angle at high energies. Roughness becomes less important as the energy is increased. It is expected that the transmission can be further increased by increasing the rigidity and straightness of the fiber and reducing the channel size. A concern for borosilicate glass capillaries is that high energy photons which are not reflected can cut through the glass wall instead of being absorbed. This background transmission is only 5% for a 13.6-cm-long fiber even at 80 keV, but could be a problem in application where absorption of even low levels of scattered x rays is critical. The high absorption of leaded glass has advantage in preventing scattered x rays, but unfortunately it also produces low transmission. Use of thicker or longer optics may be possible for these applications. Transmission spectra and transmission source scan curve measurements also have been found to be a very sensitive tool for capillary quality analysis.

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16. The NNDC online data service, Brookhaven National Lab Nuclear Data Center. (Remote host address: bnlnd2.dne.bnl.gov).