

## **POLYCAPILLARY KUMAKHOV OPTICS: A STATUS REPORT**

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### **ABSTRACT**

The Center for X-Ray Optics at the University at Albany, founded to pursue the development of capillary x-ray and neutron optics, has grown rapidly since its establishment less than four years ago. Quantitative characterization of these optics from 1 keV to 45 keV was reported here in 1993. In this report, a summary of the current status of this effort will be described in the context of activities at the Center for X-Ray Optics.

### **INTRODUCTION**

Polycapillary x-ray and neutron optics were invented by Muradin A. Kumakhov of the Kurchatov Institute of Atomic Energy in Moscow in the mid 1980's.<sup>1,2,3</sup> In November 1990 the Center for X-Ray Optics (CXO) was established by Walter M. Gibson at The University at Albany as part of an agreement with Kumakhov to jointly develop the new technology. At the same time the Institute for Roentgen Optical Systems (IROS) was formed in Moscow to carry on the work there, and a company, X-Ray Optical Systems, Inc. (XOS) was formed to commercialize the new technology. In a series of agreements that involved the Kurchatov Institute, where much of the initial work was carried out, and Soviet, Russian, and Moscow city governmental bodies, IROS became part of the Moscow branch of the World Laboratory<sup>4</sup> in order to facilitate movement of people and materials between the three collaborating bodies and also to allow existing and future intellectual property to be protected by patents inside and outside Russia. In the light of subsequent events and turmoil in the former Soviet Union, these arrangements have proven to be propitious.

Establishment of collaborations with leaders in a variety of application areas has provided an

Figure 1. Multifiber neutron lens, photo courtesy of X-Ray Optical Systems, Inc.

Figure 2. Transmission of 12 cm. long polycapillary fibers with 13-17  $\mu\text{m}$  channel size.<sup>21</sup>

## CENTER FOR X-RAY OPTICS

Figure 3. Current activities at CXO, University of Albany.

effective approach for the introduction of capillary optics into science, medicine and industry. During the months of April, May and June 1991, Kumakhov and Gibson visited numerous university and governmental research centers, describing the new technology. This technology, termed Kumakhov Optics in honor of its inventor, consists of bundles of hollow glass capillary tubes designed to collect and guide x-rays and neutrons. An optic constructed from polycapillary fibers is shown in Figure 1. The guiding of x-rays occurs due to the total external reflection of x-rays from smooth solid surfaces.<sup>5</sup> Kumakhov optics technology builds upon experimental and theoretical studies of this phenomenon<sup>6,7</sup> and on previous demonstration of the guiding of x-rays through straight and curved glass capillary fibers<sup>8,9,10,11,12,13</sup> and of neutrons through neutron guides.<sup>14</sup>

Some of the inspiration for this new technology came from studies of ion channeling in single crystals, particularly the deflection of very high energy ion beams in elastically bent single crystals. Kumakhov and Gibson were involved with, and became acquainted through, ion channeling studies. Kumakhov is particularly well known for his proposal and theoretical description of "channeling radiation" which accompanies channeling of electrons and positrons in single crystals.<sup>15,16,17</sup> Much of the intuition that has guided the development of Kumakhov optics has come from the experience gained through ion channeling research. In particular, the algorithm that is used for effective modeling of the motion of neutrons and x-rays in capillary channels was taken from ion channeling simulations.<sup>18</sup>

A broad range of potential applications for Kumakhov capillary optics were described in 1992,<sup>19,20</sup> and quantitative characterization from 1 keV to 45 keV was reported in 1993.<sup>21</sup> Measured polycapillary fiber transmission is in excess of 70% at 15 keV and better than 50% over the entire range from 1 to 45 keV, as shown in Figure 2. At this time, progress in capillary optics is being advanced with a variety of projects in basic research and applications development. The first commercial sale, in 1993, (of a neutron focusing lens) has begun to open the way for widespread access to this new technology. The present status of this effort will be described in the context of activities at the Center for X-Ray Optics at the University at Albany. The current research areas of the Center are summarized in Figure 3; in the remainder of this report we will briefly review these activities.

### **BASIC STUDIES**

#### **SCATTERING THEORY AND SURFACE MORPHOLOGY**

The penetration depth of grazing incidence x-rays into glass is less than 10 nm. Thus the surface properties of the capillaries are critical in determining the performance of the optics. Theoretical studies indicate that surface roughness of greater than 0.5-1 nm rms will effectively eliminate transmission.<sup>22</sup> Theoretical analysis of the effects of adsorbed and deposited surface films have also produced interesting results. Coating of the capillaries with low density carbon, beryllium, or plastic films could reduce the detrimental effects of oxygen absorption<sup>23</sup> and surface roughness over a broad energy range.<sup>24</sup> The increase

Figure 4. Normalized theoretical transmission of a 10 cm long, uniformly bent borosilicate glass polycapillary with 17  $\mu\text{m}$  channels, and 1 nm rms roughness, with (from lowest) no coating, and 20 nm coatings of carbon, beryllium, and polycrystalline nickel. Figure 5. Schematic and computer screen from automated capillary measurement system.<sup>26</sup>

in transmission for a uniformly bent polycapillary is shown in figure 4. In addition, coating capillaries with selected metals could increase the critical angle for reflection and therefore the capture angle for incident radiation. Nickel-58 is particularly attractive for neutron optics applications. In collaboration with the advanced thin film synthesis and characterization program at the University at Albany, the use of chemical vapor deposition (CVD) techniques are under investigation for the production of coated capillary optics. Theoretical analysis of wave nature effects at long wavelengths is also producing interesting results.

As a result of the theoretical studies, it is clear that analysis of actual capillary surface structure and composition is important for understanding capillary performance. Measurements of surfaces by atomic force microscopy (AFM), and x-ray photoelectron spectroscopy (XPS) are underway. X-ray transmission as a function of length is also an indicator of capillary quality, and has been found to vary enormously with manufacturing technique.<sup>21</sup> Defect analysis in individual capillaries found to have low transmission is also underway.

#### **ENVIRONMENTAL AND RADIATION EFFECTS**

The stability and lifetime of capillary optics are important in considering potential applications. It was discovered relatively early that drawing even high purity water into the capillary channels, followed by removal in an oven or vacuum system, reduces transmission dramatically. This is presumably a result of etching of the surface with the associated introduction of surface roughness. Acetone and some organic solvents do not have the same catastrophic effect.<sup>25</sup> In order to test the sensitivity of capillary optics to water vapor, a series of controlled tests has been performed. An essential part of any study of the effects of environmental factors or radiation exposure on capillary optics is the ability to achieve reliably reproducible measurements of x-ray transmission. A computer automated test station was developed which produces better than 1% accuracy for these measurements.<sup>26</sup> The schematic set-up and a computer screen displaying a spectrum and four axes scan are shown in figure 5. Capillaries previously measured on this test stand were exposed to controlled humidity levels and elevated temperatures. Capillaries 10 cm in length, with 17  $\mu\text{m}$  channel size, demonstrated only 20% loss in transmission after exposure to 98% humidity at 90°C for 1 week.<sup>27</sup>

Some applications of capillary optics involve very high radiation exposure. These include focusing of synchrotron radiation beams, capture of intense divergent x-rays to produce a collimated or focused beam, and selection and focusing of slow neutrons in the presence of an intense fast neutron and gamma ray background. In addition, heating may occur under conditions of very high photon intensity, especially with synchrotron sources.

Figure 6. Gain in a double crystal diffraction set-up with prototype multifiber lens, relative to slit collimation of given angular width.<sup>34</sup>

subjected to high intensities of focused 1 keV x-rays at the Center for X-Ray Lithography (CXRL) synchrotron facility at the University at Wisconsin showed a decrease in transmission only after 700 kJ/cm<sup>2</sup> of exposure. At this dose it was also possible to observe slight darkening of the borosilicate glass, in correspondence with the expected color center formation. Both the transparency of the glass and the transmission efficiency were recovered after annealing in vacuum at 300 °C. There have been extensive studies of defect formation during irradiation of insulating materials by ionizing radiation. Most of these studies were concerned with color center formation and other bulk defects. There have not been systematic studies of the nature and quantity of surface defect formation. X-ray transmission loss in polycapillary fibers may be one of the most sensitive indicators of such effects because the multiple reflections magnify the effect of small surface structural changes.

### **MULTILAYER OPTICS**

Extension of capillary optics to energies higher than 100-200 keV will require channel dimensions much smaller than 1 μm. Komorov et al. have suggested that one way to achieve very small spacing with good control is to use alternating layers of low and high density materials.<sup>28</sup> In such systems the x-rays would propagate in the low density layers and be reflected at the interface between the two materials. In addition to permitting higher photon energies, such multilayer structures also provide possibility for mode selection. Theoretical analysis of novel thin film multilayer optics in a variety of geometries is an ongoing area of research.<sup>29</sup> Fabrication of planar multilayer optics is also a subject of collaboration with the advanced thin film synthesis and characterization program at the University at Albany.

### **X-RAY ASTRONOMY**

Measurements of the distribution and spectra of medium and high energy galactic x-ray sources is important for identification of black hole candidates and separation from the more numerous neutron stars. In addition, high energy resolution will permit study of isotopic ratios used to study nucleosynthesis in supernova remnants. Multifiber polycapillary optics provides the possibility to extend the energy range to 100 keV, increase the sensitivity, and decrease the focal length, weight, and cost of spectral measurements compared to existing or proposed astronomical x-ray concentrators.<sup>30</sup> The reduced weight and short focal length of a polycapillary based concentrator also makes possible balloon or sounding rocket based measurements of the hard x-ray spectrum of intense extra solar sources such as Cygna-1.<sup>31</sup> The small critical angle for high energy x-rays (1 mradian at 30 keV) limits the field of view of a polycapillary based concentrator, which provides good suppression of background but requires a stable and accurate pointing platform.

### **MATERIALS ANALYSIS APPLICATIONS**

In order to assess the radiation hardness of capillary optics, a systematic study is underway at the Center for X-Ray Optics in collaboration with X-Ray Optical Systems, Inc. These studies will be reported in detail separately.<sup>27</sup> Capillary optics are remarkably robust. For example, beam intensities at the Cornell CHESS facility sufficient to shatter a microscope slide or to produce a crater in a lead (Pb) block had little effect on a group of polycapillary fibers. It is likely that the apparent insensitivity of polycapillary fibers to beam heating is due to the thin walled polycapillary structure, which results in lower thermal gradients. Fibers that were

Figure 7. Schematic of monolithic focusing optic.<sup>19</sup>

Figure 8. Measured and simulated transmission through a prototype monolithic optic at 8 keV.<sup>35</sup>

Some of the most promising applications for capillary optics involve improving the sensitivity, resolution, or throughput of materials analysis techniques by improving the collection and control of x-rays or neutrons.

#### **DIFFRACTION APPLICATIONS**

The efficiency of crystal diffractometry from a standard rotating or fixed anode source can be improved by collection of x-rays in a collimating capillary optic. Collimating optics can be constructed of either polycapillary fibers guided through metal screens, or as a monolithic tapered capillary structure. The former, multifiber lens construction, is at the more advanced state of development. Such optics are appropriate where relatively large beam sizes are desired.

Measurements have been reported previously for an early prototype multifiber collimating optic.<sup>32</sup> In the first study, x-rays from a standard fixed x-ray source were collimated and then diffracted from a single crystal. The diffracted beam intensity was increased by about 4.5 compared to the intensity without the lens when a circular collimator defined the acceptance from the source. However, if a slit collimator was used, there was no advantage obtained with the lens for single crystal diffraction measurements. A similar conclusion was observed when this lens was used to examine secondary x-rays produced by bombarding metal targets with a focused synchrotron beam.<sup>33</sup> The transmission efficiency of this prototype optic was only about 6%, less than expected from transmission measurements made with individual capillaries, indicating the necessity for improved polycapillary fiber fabrication and screening.

A similar, prototype collimating lens was the subject for a second diffraction study, reported in detail in this proceedings.<sup>34</sup> In this work, the conditions for optimization of double diffraction measurements without a collimating lens were determined. For double diffraction measurements with a standard laboratory line source, a gain of 5 was obtained with the lens compared to an optimized no lens condition, as shown in figure 6. This gain was obtained even though the overall transmission efficiency of the lens was low (4%) due to nonuniform capillary transmission. The gain was also reduced because of apparent misalignment of the capillaries at the output. However, even a gain as low as five could potentially reduce data collection times from forty hours to a single shift.

Based on the experience gained with these two prototype lenses, and on advances in design, fabrication and testing, an improved multifiber polycapillary lens for diffraction applications is now under construction. At the current stage of understanding and control, this type of collimating lens is the one most likely to become widely available in the near future and to be compatible with existing electron bombardment static or rotating anode laboratory x-ray sources.

#### **MICRODIFFRACTION**

Another type of polycapillary collimator for diffraction applications is a monolithic assembly of tapered capillaries in which the individual capillary channels are close packed along their length, as shown schematically in Figure 7. For small samples such as those used for protein structure determinations, this type of collimator is preferred. Monolithic optics are at an earlier stage of development than the multifiber collimators discussed above. However, measurements with a prototype lens show a gain of about 35 for small sample diffraction applications relative to using a small (.25 mm diameter) spot source of x-rays without a collimating lens.<sup>35</sup> It is apparent from this and earlier<sup>36</sup> studies that careful control of the shape of the optic during fabrication is vital. Simulations agree quite well with actual lens performance if the real shape of the lens is taken into account, as shown in Figure 8. A systematic investigation of methods to reproducibly control the shape and quality of monolithic optics is now underway.

At the present time it is likely that such lenses will be relatively small in diameter (<1 cm) and will thus be inefficient with standard laboratory x-ray sources, particularly line sources. In fact, because of Liouville's theorem, which says that the density of states in phase space (brightness) cannot be increased,<sup>37</sup> it is necessary to use a very small x-ray source in order to get maximum benefit from any collimating optic with a small output diameter. Measurements are currently underway at CXO with a very bright, small x-ray source. It is expected that the use of monolithic collimating optics with such a source will produce very intense quasiparallel beams. This will be particularly important for protein structure determination.

### **X-RAY MICROANALYSIS**

It is possible to use polycapillary optics to focus as well as to collimate x-rays. Indeed, the first Kumakhov Lens was used to focus x-rays from a divergent source to a 1 mm spot with an increase in x-ray intensity as high as 3300 times compared to the intensity at the same distance from the source without the lens.<sup>2</sup> In addition to capturing and focusing x-rays from a divergent source, parallel x-ray or neutron beams can also be focused.

At the present time, the most straightforward focusing optic utilizes multiple polycapillary fibers guided through thin screens. However, the spot size for such multifiber focusing lenses will not be much less than 500  $\mu\text{m}$ . This is because, even with perfect alignment of individual fibers, the spot size cannot be less than the fiber diameter. It is impractical to make the polycapillary fibers smaller than 0.3-0.4 mm and still retain the strength and rigidity needed to guide them accurately. In spite of this focal spot size limitation, multifiber polycapillary focusing optics are still the technology of choice for many applications, such as x-ray concentrators in astrophysics studies, and neutron focusing for neutron analysis.

In principle, monolithic polycapillary optics can be used to focus x-rays to much smaller spot sizes than multifiber polycapillary optics. In this case, if perfect alignment is achieved, the focal spot size can be nearly as small as the individual channel diameters at the output of the lens. This is similar to the use of single tapered capillaries to focus synchrotron radiation<sup>38</sup> except that the output of many channels can be added together with a resultant increase in x-ray intensity. In fact, gain has been shown for a single tapered polycapillary fiber.<sup>39</sup> There is an additional possible advantage for such a focusing optic compared to a single tapered capillary. Since virtually all of the channels are curved as well as tapered, x-rays can be guided to the focal spot while undergoing reflection from only the concave (positive) curved surface of the capillary channel. If the curvature is perfectly uniform (circular), the incidence angle then remains constant and does not increase with each reflection as with a single tapered capillary.

The transmission efficiencies of focusing lenses are even more dependent on precise shape control than are the collimating lenses discussed above. However, the transmission of prototype collimating lenses used in reverse, to focus parallel x-ray beams, have been measured and can be compared to simulated results. One such transmission measurement with a prototype collimating lens leads to a predicted gain of twenty if this rather imperfect optic were used in focusing synchrotron radiation.<sup>40</sup> Focusing of divergent radiation from a point source using a monolithic optic has also been demonstrated.<sup>41</sup>

### **XPS and XRF**

The requirements for application of focusing optics for scanning x-ray microanalysis techniques such as photoelectron spectroscopy (XPS) are currently being analyzed. Such a focusing optic could also be used for x-ray fluorescence (XRF). Ultimately, it is planned to use one monolithic polycapillary optic to focus x-rays to a small spot and a second optic to collect secondary x-rays for energy or wave-length selective analysis. This will make possible three dimensional, non-destructive micro XRF analysis, as shown in Figure 9.<sup>19</sup>

Figure 9. Sketch of microfluorescence experiment, showing that the overlap of irradiation and collection volumes would yield three dimensional spatial resolution.<sup>50</sup>

Figure 10. Neutron focusing. Top: Intensity distribution of neutrons at focal spot. Bottom: Intensity distribution near exit of lens.<sup>47</sup>

### **X-Ray Microtomography**

Another exciting potential application of polycapillary collimating optics is microtomography. In addition to a very bright, highly collimated x-ray beam, this will require a high resolution imaging detector which can measure diffracted or fluorescent beam patterns in real time and a powerful computer and program to do the reconstruction, also in real time. Although development projects are ongoing with two different solid state x-ray imaging technologies at CXO, implementation of this possibility must await the realization of these components.

### **NEUTRON ANALYSIS**

Neutrons undergo highly efficient reflection from smooth solid surfaces at small angles of incidence, in the same manner as x-rays. Thus, the same type of geometrical optics that applies for x-rays leads to the guiding and focusing of neutrons with Kumakhov capillary optics. Since the critical angle for total external reflection for thermal neutrons corresponds, for silica based glasses, to about that of 30 keV x-rays, only relatively slow neutrons can be controlled by polycapillary optics. An additional limitation is the absence of point sources for slow neutrons. Thermal (or colder) moderators, for either reactors or accelerators, produce extended sources, emitting neutrons with a range of angular distribution from each point. This results in reduced capture efficiency in each capillary channel. However, the lack of availability of other neutron focusing optics with high gain makes polycapillary neutron optics particularly attractive.

Measurements with multifiber polycapillary lenses have shown neutron flux gains of 1 to 2 orders of magnitude. Measurements with the earliest prototype neutron focusing lens, shown in figure 10, showed an intensity increase larger than had been achieved by any other technique. However, the same type of transmission irregularities and alignment difficulties that had been experienced with x-ray collimating prototype lenses were apparent.<sup>42,43,44</sup> A second, improved neutron focusing lens was constructed at XOS. This lens exhibited a spot size and gain very close to that predicted by simulation calculations. Current techniques for the manufacture of polycapillary fibers and construction of multifiber lenses should thus allow accurate fabrication of additional custom optics for many neutron and x-ray applications.

Focused neutron beams are potentially important for materials studies, including depth profile analysis<sup>45</sup> and small angle neutron scattering.<sup>46,47</sup> Multifiber polycapillary optics can also be used to provide deflection of neutron beams in much shorter distances than possible with current neutron guides. This will provide separation from fast neutron and gamma ray background and will allow multiple experiments to be run from existing thermal or cold neutron beam guides.

## **MICROELECTRONICS APPLICATIONS**

### **X-RAY LITHOGRAPHY**

A potential application of capillary optics is x-ray lithography using intense laboratory point sources. If it becomes possible to produce quasiparallel beams of x-rays with the required intensity, uniformity, macro parallelism, and point-to-point micro divergence in a stepper with a footprint, configuration, vacuum requirement and cost comparable to existing optical steppers, the effect on the microelectronics industry could be dramatic. Not only could smaller feature sizes be obtained due to the shorter wavelength of x-rays, but the small scattering cross-section, the extended depth of field, the lower cost and granularity (ability to incorporate x-ray steppers into existing production facilities without extensive modification) of such a system make this approach very attractive.

Measurements of capillary optics at wavelengths appropriate for proximity x-ray lithography (about 1 keV) are complicated by the need for a vacuum environment due to the high cross-section for air absorption. However, preliminary studies with single polycapillary fibers are encouraging, as shown in figure 11.<sup>48</sup> In addition, modeling simulations of a complete collimating optic indicate that the required performance is theoretically achievable, as shown in figure 12. The growing ability to equal simulated behavior with actual data in multifiber polycapillary systems also provides encouragement for this application.

### **X-RAY TOPOGRAPHY**

A possible application for multifiber polycapillary optics which would take advantage of the ability to achieve a large quasiparallel beam output size is the x-ray topographic screening of semiconductor wafers and thin film structures for voids, slip planes, strain or other defects. The feasibility of this application is being investigated at the Center for X-Ray Optics.

Figure 11. Measured transmission of bent polycapillary at 1 keV, 33 cm (upper curve) and 5 cm (lower curve) from source.<sup>48</sup>

Figure 12. Theoretical transmission from multifiber lens designed for lithography.<sup>48</sup>

## **MEDICAL APPLICATIONS**

Perhaps the most important of the applications of polycapillary x-ray and neutron optics is in medicine.<sup>49,50</sup>

### **MEDICAL IMAGING**

Hanging on a wall in the seminar room of the physics building of the University at Albany is a radiographic image of "Roentgen's wife's hand," taken very shortly after the discovery of x-rays. Nearly one hundred years later, and despite the advent of ultrasound and MRI, x-ray imaging is still the most widely used medical imaging modality. Its low cost and ease of use is critical for mass screening, for example in cancer detection.

#### **Mammography**

Mammography is a particularly important screening modality. Breast cancer is the leading cause of cancer death among American women aged 20 to 54, and three quarters of all breast cancers occur in women with none of the currently identified risk factors. At the same time, mammography is a particularly difficult imaging problem, because early detection of cancer relies on the identification of extremely subtle density differences and tiny microcalcifications. The need for high contrast requires the use of relatively low energy x-rays (20 keV), which have a high cross-section for interaction with the tissue. However, this same interaction results in Compton scattered photons making up about half of the intensity at the film plane. Failure to suppress this random fog of scattered photons results in a badly degraded image.

Scatter rejection is conventionally achieved by the use of "grids" of lead strips aligned with the source interposed with a low density material. Design of the grid is a trade off between improved scatter rejection and absorption of primary x-ray dose to which the patient has already been exposed. The low angular acceptance of capillary x-ray optics, due to the small critical angle for reflection, provides the potential for extremely efficient scatter rejection with relatively high primary transmission. Extensive measurements of capillary performance at mammographic energies have been performed.<sup>51</sup> Measurements with a prototype optic yielded calculated scatter transmissions of less than 1%.<sup>52</sup> Other preliminary measurements with a small optic bundle showed nearly ideal contrast enhancement.<sup>53</sup>

Another application of the optic to mammography is the matching of the image to a digital detector. One existing technology for digital detection is the use of computed radiography (CR) photostimulable phosphor plates. These can be used in existing radiographic units in place of film/screen cassettes. However, the resolution of the plates is about a factor of two too low for mammography. Magnification of the image onto the plate by increasing the air gap between plate and patient causes an unacceptable increase in the blurring of point objects due to the finite source size. One application of polycapillary x-ray optics which is currently being investigated is the use of a tapered monolithic optic to simultaneously reject scatter and magnify the image without increase in geometric blur, as sketched in figure 13.

A second common digital imaging modality is the use of a fused fiber optic following a phosphor screen to demagnify the resulting visible light image for recording with CCD technology. The use of capillary x-ray optics to demagnify the x-ray image in connection with direct imaging x-ray detectors may be more efficient and would avoid the loss of resolution in the optical conversion process. This a major new program of study at CXO.

#### **Chest Radiography**

Scatter rejection is also important in other medical imaging modalities, including chest and abdominal radiography. These modalities, however, employ higher energy x-rays, from 60-120 kVp. The use of capillary optics in these areas depends on measurements of capillary performance at those energies. A test station equipped with a microfocus source capable of operation to 100 keV, and the additional shielding and collimation required at those energies, has recently been installed at the Center.

#### **Angiography**

Another aspect of capillary optics, energy filtration due to the energy dependence of the critical angle, has been exploited by XOS in the investigation of the possibility of producing a high intensity source for digital energy subtraction angiography.<sup>54</sup>

Figure 13. Capillary optic magnification "grid" for mammography. Figure 14. Neutron focusing for BNCT. Bottom figure shows reduction of blur with optic compared to air gap magnification without optic<sup>52</sup>

## **MEDICAL THERAPY**

### **Boron Neutron Capture Therapy**

Boron Neutron Capture Therapy (BNCT) is an experimental cancer treatment modality. It is based on selective delivery of a boronated pharmaceutical to cancerous tissue followed by irradiation with thermal neutrons.<sup>55</sup> Thermal neutrons have a high cross-section for interaction with boron with the resultant production of energetic alpha and lithium particles. These reaction products have a short range in tissue and a high relative biological effectiveness. Thermal neutrons are therefore very effective at killing boronated cells while sparing healthy, unboronated tissue. However, the effective range for the thermal neutrons themselves in tissue is approximately 1-4 cm. For this reason, a large body of current BNCT research is devoted to the development of epithermal neutron beams which could penetrate to deep tissue, thermalizing on the way. However, capillary neutron optics might provide an effective way of delivering concentrated thermal neutrons to a tumor site directly, as shown in figure 14. The highly directional nature of the beam would increase the ease of delivery to an intraoperative site. The optics would also allow for greater distances and therefore enhanced shielding between the neutron source and the patient and medical personnel, and also filtration of gamma and high energy neutron components from the beam. The center is participating in a measurement and modeling effort to determine the feasibility of an integrated BNCT delivery system.

### **Orthovoltage X-Ray Therapy**

Conventional x-ray radiation therapy is currently performed with high energy x-ray or gamma radiation. The patient is exposed to multiple parallel beams, produced with slit collimators, with an intersection at the tumor. High energy photons are chosen to minimize the absorbed skin dose relative to the dose at the tumor, although energies as low as 150 keV are employed in the orthovoltage modality. The choice of energy to reduce the skin dose is necessary because in an unfocused beam the intensity is necessarily higher at the point of entry than at the tumor site. Use of focusing capillary optics at energies around 100 keV may be feasible and might substantially increase the tumor dose relative to the skin dose. An investigation into this modality is dependent on the same high energy x-ray measurements described in the chest radiography section.

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