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Incidence Reflection Optics**

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X-Ray Microscopy Using Grazing Incidence Reflection Optics*

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The history of x-ray optics using grazing incidence reflection now dates back more than 50 years. One of the earliest works in the field was that of Ehrenberg and Jentsch in 1928.¹ Jentsch was probably the first to suggest focusing x-rays with a curved mirror by means of total external reflection. He discussed many of the problems of grazing incidence reflection, including surface roughness requirements and the acute astigmatism of spherical surfaces at grazing incidence. Jentsch also carried out experiments with grazing incidence x-ray optics. To avoid the astigmatism problem he used an axisymmetric optic, consisting of a glass tube with an internal diameter of 2.7 mm. There is, however, no record of the successful formation of images with this device. In later years, Ehrenberg went on to study grazing incidence reflection from flat and from bent glass surfaces.^{2,3} He also noted the effects of surface imperfections⁴ which resulted in broad wings on the line focus produced by the bent glass mirrors.

It was not until 1948 that the first two dimensional focused x-ray images were produced by Kirkpatrick and Baez⁵ using grazing incidence reflection. They avoided the problem of astigmatism at grazing incidence by crossing two cylindrical mirrors, each of which is focused in one of two orthogonal planes containing the optical axis. The effect is much the same as producing a 2-D image by crossing two cylindrical lenses.

The Kirkpatrick-Baez x-ray microscope has been an extremely successful imaging device, and is still used in many laboratories around the world. This success is largely due to the relative ease with which the required x-ray reflecting surfaces can be fabricated and to the high quality of the images produced.

mirrors can also be used without serious degradation of performance. Optical fabrication technology has advanced to the point that a nearly perfect surface can be produced over the tiny portion of the mirror actually used in image formation. Surface finishes better than 10 Å RMS are routinely produced on selected materials (fused silica, vitreous carbon, electroless nickel, silicon crystal, etc.). Absolute sagittal profiles with accuracies on the order of 100 Å/cm are frequently produced.

Figure 2 Kirkpatrick-Baez x-ray micrograph of a ball-in-plate target taken during the first full power (26 TW) target shot at the Shiva laser facility.

Many of the Kirkpatrick-Baez x-ray microscopes now in use are diffraction limited in the x ray portion of the spectrum. In fact, as Prince⁶ noted, a Kirkpatrick-Baez microscope with cylindrical mirrors can be optimized by adjusting the mirror length such that the geometrical aberrations of the mirror system are balanced by diffraction. This type of optimization typically produces resolutions on the order of one micron. In certain instances, resolutions of one half micron have been achieved.⁷

McGee has shown⁸ that by using surfaces with a cubic term, rather than purely cylindrical surfaces, geometrical aberrations can be reduced, mirrors lengthened, and resolution improved. Though useful for specialized applications, notably biological,

Figure 1 Each channel of a four channel Kirkpatrick-Baez x-ray microscope produces a focused double reflection image, two single reflection line foci and an unfocused spot from unreflected x rays. All four channels together, produce a pattern with four fold symmetry.

The cylindrical mirrors are nearly flat ($\approx 1 \mu\text{m}$ sagittal depth) and can be easily fabricated using conventional optical techniques. Shallow spherical

Figure 3 Ray diagram of a Wulfer Hyperboloidal-Ellipsoidal Axisymmetric x-ray microscope.

* Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

Figure 4 Hitter Axisymmetric, x-ray microscope fabricated from Diamond turned electroless Nickel on a steel substrate.

this increased resolution results in decreased field of view. For this reason, as well as increased cost and difficulty of fabrication, "cubic" surfaces have not been useful for laser fusion applications.

Figure 6 This streaked x-ray image of a laser irradiated gold disk (self emission at 270 eV) shows a constant velocity for the x-ray emission region while the laser intensity increases and decreases during the pulse. The FWHM of the x-ray emission region is only 15 μm during most of the pulse.

Figure 5 The Shiva x-ray backlighting system uses a Wfilter Axisymmetric x-ray microscope coupled to a soft x-ray streak camera and an optical alignment system.

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Figure 7 A 17 μm thick Aluminum slab was accelerated to 8×10^6 cm/sec by a 647 ps, 5.8×10^{14} W/cm² laser pulse and was observed using a Tantalum backlighter irradiated for 2.8 ns at 3.9×10^{14} W/cm². Self emission from the Aluminum sample slab is visible below the original disk location.

provide data immediately following each shot. Figure 1 shows the x-ray optical configuration of one channel of the four channel Kirkpatrick-Baez x-ray microscope configuration commonly used at LLNL.

As shown in figure 1, the 90° intersection produced by the crossed cylindrical mirrors lends itself to a square configuration. This forms an image from the x rays reflected at each corner. By choosing the grazing angles, reflecting materials, and filters carefully, an x-ray microscope can be made which produces images at four different x-ray energies along nearly the same line of sight. A factor of four or more can be spanned in x-ray energies passed by the various channels. This feature, together with the good definition of the energy channels ($E/\Delta E \approx 4$ to 5), makes these instruments extremely useful for laser fusion diagnostics. Kirkpatrick-Baez x-ray microscopes used to date in laser fusion applications have object distances of 25 to 40 cm and resolution in the 1 to 3 μm range. Magnifications have ranged from 3 to 8.

One of the major advantages of the Kirkpatrick-Baez x-ray microscope is that it produces a true focused image on film which can be developed and qualitatively evaluated in less than half an hour after a target shot. This capability often provides crucial information on target performance needed to properly set up the next target experiment. The relatively long object distances are dictated by the problem of blast damage during target irradiation: filters can be ruptured and mirrors damaged. However, as presently used, the Kirkpatrick-Baez x-ray microscopes can take pictures for months at a time without attention, except for changing film.

The Kirkpatrick-Baez x-ray microscopes have been fielded with channels ranging from 200 eV to 4.5 keV. Figure 2 is an x-ray photo of a ball-in-plate target irradiated at 26 TW during the first full power target shot on the Shiva laser facility.

While Kirkpatrick-Baez x-ray microscopes combine many of the features desired of a diagnostic, for some applications more solid angle is required than can be provided by an ordinary Kirkpatrick-Baez x-ray microscope. (Kirkpatrick-Baez x-ray microscopes typically have 10^{-6} to 10^{-7} steradian acceptance angles for laser fusion applications.) This need is now being filled by the Wulter axisymmetric x-ray microscope.

Figure 8 Vertical and horizontal scale lengths associated with various metrology devices and fabrication technologies are shown together with 1 arc second and 0.1 arc second tolerances required for advanced x-ray optics. The region with horizontal scale lengths between 100 μm and 10 mm, with vertical scale lengths of 5 - 50 $\text{\AA}$, is particularly difficult for optical fabrication work.

Figure 9 Random Device's slope scanner operates on the principle of the optical lever. It is capable of measuring slope errors of a few tenths of an arc second and displacements of 10 - 20 Å. It shows potential for improvement in sensitivity by an additional order of magnitude.

Wölter developed the idea of using axisymmetric mirrors made up of conic sections of revolution in 1952.^{11,12} His work was stimulated not only by Kirkpatrick and Baez, but also by Truitt,¹³ who in 1946 had successfully formed images using a paraboloid coated with a Barium Stearate crystal. Wölter also refers to Nahring's 1930 work¹⁴ on grazing incidence reflectivity and Schwarzschild's 1905 work on the conditions for aplanatic imaging systems. Interestingly, though Wölter apparently did not know about the work of Jentsch, he came to the same conclusion, that is, to use an axisymmetric grazing incidence reflector to avoid astigmatism in the imaging system. He also came to similar conclusions regarding surface roughness.

Figure 3 shows the geometry of a Wölter type I x-ray microscope. In this microscope a hyperboloid and an ellipsoid of revolution are combined such that they have a common focus (F1H and F1E). An object placed at the second focus of the hyperboloid (F2H) will then form a magnified virtual image of the object at the common focus of the hyperboloid and ellipsoid (F1H and F1E). The virtual image will then be refocused at the secondary focus of the ellipsoid (F2E), forming a magnified image of the object. In a practical Wölter microscope mirror, the ellipsoid may have a minor radius of 1 or 2 cm, while the major radius may be several meters or more. Only very small segments of the hyperboloid and ellipsoid are used, not more than a few centimeters in length along the optical axis.

Figure 4 is a photo of a recently fabricated Wölter x-ray microscope. The sagitta of these conic segments differ from straight cones by less than a micron. The requirements on the surface tolerances

are similar to the tolerances of a Kirkpatrick-Baez x-ray microscope; however, the area over which these tolerances must be met is 10's of square centimeters, rather than a few square millimeters. Furthermore, these tolerances must be met on a complex internal aspheric surface. Deviations in sagittal profile must be under 100 Å and the RMS surface roughness must be under 10 Å. Axisymmetric roundness of the mirror must be maintained to better than 0.5 µm.

Figure 10 The Clevite Profilometer is an inductive pickup diamond stylus device which is linear and reproducible to 70 Å.

Azimuthal slope errors must be held to a few arcseconds while longitudinal slope errors must be well under 1 arcsecond.

Figure 11 Comparison of Cleveite profilometer and Random Device's slope scanner measurements of a Wöhlert axisymmetric x-ray microscope mirror surface shows agreement at the $\pm 30 \text{ \AA}$ level for surface scale lengths greater than the $50 \text{ }\mu\text{m}$ spot size of the slope scanner.

Wöhlert realized that such tolerances might be difficult or impossible to meet on such a complex surface, and for many years no attempts to fabricate such mirrors were reported. Subsequently, interest in x-ray astronomy stimulated the modification and development of Wöhlert's design for astronomical purposes. In 1975, Palmeri and Seward¹⁶ suggested that a Wöhlert type I x-ray microscope might be applicable to the observation of high density laser fusion target implosions. Work was begun on a 9X and a 22X Wöhlert type I x-ray microscope design with fabrication being undertaken at LLNL and Random Devices, Inc.¹⁷ Later, a contract was let to the National Physical Laboratory in England through the Atomic Weapons Research Establishment, beginning a third parallel development effort. Los Alamos also began development work on a small Wöhlert x-ray microscope at Random Devices, Inc.¹⁸ At the time these contracts were let, the technology did not exist to fabricate the desired surface. Initially, two approaches were attempted:

1. Traditional grinding and polishing of electroless nickel on separate hyperboloidal and ellipsoidal aluminum substrates, and
2. and diamond turning of the entire mirror in electroless nickel on steel substrates.

Figure 12 The deviation from desired surface profile of the Wöhlert mirror recently finished by Random Devices compares favorably with the surface profile deviation of an early mirror finished at the Lawrence Livermore National Laboratory.

Later, the traditional grinding and polishing approach was dropped. Passive feedback was developed for the numerically controlled diamond turning machine to allow it to attain accuracies of 1 to 2

microinches (250 to 500 $\text{\AA}$). This is carried out by machining the mirror, then measuring the deviation of the mirror from the ideal contour and feeding the correction back into the diamond turning machine for the next cut. It was found necessary to polish the steel substrate to a 1000 $\text{\AA}$ finish in the region of the x-ray reflecting surface before electroless nickel plating and diamond turning. This avoids print through of the machining marks on the steel, onto the optical surface of the x-ray mirror during polishing. The diamond turned substrates were then turned over to the three different groups (LLNL, NPL, and Random Devices) for polishing.

Figure 13 The deviation of the new Random Devices fabricated Wöhlert mirror from circularity shows some periodic structure remaining from diamond turning.

Two 22X magnification Wöhlert mirrors of an early design were finished at LLNL several years ago and have been fielded at the Shiva laser facility during the past year in the streaked microscope system shown in figure 5. This system provides a spatial resolution of 4 to 5 μm over a field of view of up to 800 μm and a temporal resolution of 15 ps. The

Figure 14 The longitudinal slope errors on the ellipsoid and hyperboloid of the older Wöhlert mirror are random in nature with standard deviations of 16 and 13.2 arc seconds respectively.

spatial resolution is limited by the 100 μm resolution of the streak camera and the 22 $\times$ magnification of the x-ray mirror. The 2 μm resolution of the Wölter x-ray mirror does not contribute significantly to the overall spatial resolution of the system. The streaked x-ray microscope is also equipped with a collinear optical alignment system which allows alignment of the x-ray imaging device onto the target with an absolute accuracy of 5 to 10 μm . This is accomplished through the use of an optical lens with the same optical conjugates as the Wölter x-ray mirror. The lens and mirror are coaligned so the focal points overlap. A visible image of the target can then be viewed through a visible light alignment camera coupled to the x-ray streak camera.

Figure 15 The longitudinal slope errors of the ellipsoid of the Random Devices mirror are primarily random in nature with a standard deviation of 0.82 arc seconds.

The streaked Wölter x-ray microscope has been used to observe targets both in self emission and in transmission together with a laser driven x-ray backlighting source. This allows time resolved radiography of the dynamical behavior of the targets.

Figure 16 The longitudinal slope errors of the hyperboloid of the Random Devices mirror are also primarily random in nature with a standard deviation of 0.65 arc seconds. However, some periodic structure is evident from the peak at 1.2 arc seconds.

Figure 6 shows the time resolved x-ray self emission from a gold disk irradiated at 1×10^{14} W/cm^2 with a 6.4 ns laser pulse. This image is striking because the emitting plasma moves back toward the laser from the disk surface at nearly constant velocity, while the laser intensity increases and decreases during the pulse. It is also striking because the emitting region has a FWHM of only 15 μm . By the peak of the laser pulse, a cold region has developed between the emission region and the disk which is quite dark when viewed in the 270 eV photons with which this image was recorded.

Figure 17 The azimuthal slope error distribution of the Random Devices mirror shows considerable contribution from periodic surface structures with peaks in the distribution at 0.75 and 1.7 arc seconds. To analytically model the distribution a gaussian with a standard deviation of 2.8 arc seconds was used.

Figure 7 shows a backlit image of an aluminum slab which was accelerated by ablation resulting from direct laser irradiation. It attained a velocity of 8×10^6 cm/sec. The backlighter in this case was a Tantalum slab mounted at 45°, 1 mm away from the aluminum slab on the x-ray microscope line of sight. The Tantalum slab was irradiated with 10 of Shiva's beams temporally stacked to produce a 3 ns pulse. Both the self emission from the 600 ps laser drive pulse striking the aluminum sample and the 3 ns emission from the Tantalum backlighter are visible in the streaked image. The shadow of the moving slab is also visible sloping up to the left in the image.

The Wölter x-ray microscope now in use has adequate resolution but has substantial large angle scattering. Only about five percent of the energy incident on the x-ray microscope is contained in the central 50 μm (diameter) of the point spread function. To improve the throughput of the new Wölter mirror, the surface had to be substantially improved over the 250 Å peak to valley surface of the old mirror. This in turn required an improved understanding of the relation between fabrication techniques, metrology, surface profile, and the point spread function of the Wölter mirror.

Figure 8 shows the various vertical and horizontal scale sizes associated with the various fabrication, metrology, and physics processes related to x-ray mirror production and function. To produce a mirror one must first measure the deviation from the desired contour. Then, one must be able to control the machining and lapping processes to the accuracy required to produce the desired surface. This requires at least the accuracy in each of these steps which one wishes to ultimately obtain. A perfect x-ray surface would be one which had an

Figure 18 A Wölter mirror, perfect except for longitudinal ripples on one surface, will produce fans of radiation in planes including the optical axis. The fans of radiation cross on the optical axis producing a cylindrical $(1/r)$ singularity.

accuracy of $3 - 10 \text{ \AA}$ over the entire surface. This is clearly unattainable at present. A more realistic goal is a surface with $3 - 10 \text{ \AA}$ accuracy at horizontal scale lengths less than 0.5 mm , and a maximum slope error of 0.5 arcseconds for horizontal scale lengths of 0.5 mm or longer.

As one can see from figure 8, a number of problems must be faced in obtaining a surface with these specifications. Aspheric Diamond Turning, which is usually thought of as being a very accurate process, does not even come close to obtaining these tolerances. Thus, lapping must be used to improve the diamond turned surface. At short horizontal scale lengths, lapping and super-polishing appear to be able to meet these surface tolerances. At horizontal scale lengths longer than 1 mm , operator manipulation of the lap with rapid feedback from metrology, should be able to meet the surface specifications providing the required surface metrology is available. However, in the region between 0.1 and 3 mm , the physics of the lapping process still seems to present some uncertainties. This appears to be one of the more crucial horizontal scale length regions in the fabrication of grazing incidence x-ray reflecting surfaces.

As may be seen from figure 8, it is also quite difficult to obtain the required metrological accuracy to fabricate these surfaces. A few instruments, such as the Hetrodyne Interferometer, the Talysurf, and the Manosurf are capable of measuring to accuracies of $10 \text{ \AA}$ or better over scale lengths less than 1 mm . The Random Devices Slope Scanner can measure to an accuracy of 20 to $30 \text{ \AA}$ over scale lengths less than 1 mm and $60 \text{ \AA}$ over scale lengths less than 1 cm . The Random Devices slope scanner presently suffers from a number of technical difficulties, which appear to be correctable, and may

improve its resolution by as much as an order of magnitude, as well as greatly improving its stability. The Taly-Round appears to be able to make reproducible roundness measurements down to $25 \text{ \AA}$ for scale lengths longer than 0.5 mm . The Cleveite Profilometer can make measurements between $70 \text{ \AA}$ and $250 \text{ \AA}$ accuracy over a range of horizontal scale lengths of $2.5 \text{ \mu m}$ up to several inches. Another machine which shows a great deal of promise is the Stedman measuring machine at the National Physical Laboratory in England, which presently can measure to an accuracy of $160 \text{ \AA}$ down to horizontal scale lengths less than $50 \text{ \mu m}$. In the future, this machine may be improved to yield accuracies as good as $16 \text{ \AA}$.

Although a number of machines can make measurements of the vertical scale lengths required, only a few, and at the limits of their resolution, can reach the 0.5 arcsecond or better requirement in the range from 0.5 to 10 mm horizontal scale length. One of these devices is the Random Devices Slope Scanner, shown in figure 9. This machine operates on the principle of the optical lever. A carefully prepared beam of light is focused to a $50 \text{ \mu m}$ diameter spot on the optical surface to be measured. The deflection of the reflected beam is then twice the angular deviation of the surface. The mirror to be measured is mounted on a structure supported by air bearings. This allows the mirror to be moved in an arc very nearly matching the required curvature of the optical surface. The optical surface to be measured can also be rotated on an air bearing to make azimuthal scans of the surface. The deviation of the beam reflected from the surface is measured differentially by a set of PIN Diode Detectors. The difference of the two signals is divided by the sum to null out any fluctuations in the laser intensity, then integrated and recorded.

Figure 19 A Wölter mirror, perfect except for azimuthal ripples on one surface, will produce conical fans of radiation intersecting on the optical axis. This also results in a cylindrical $(1/r)$ singularity.

A typical scan of the surface of one of the Wölter mirrors takes about 20 seconds. It may be repeated quickly and easily to determine the stability and reproducibility of the system. One benefit of measuring the slope of the surface and integrating to obtain the profile, is that the system is insensitive to mechanical vibration. The optical scanner head itself is easily removable and polishing is carried out on the mechanical portion of the scanner by simply installing a small lapping mechanism. This is done without ever removing the mirror from the mechanical portion of the scanner. This whole process can be repeated as often as every half hour, if need be.

Figure 10 shows the Cleveite Profilometer, which measures the surface with a diamond stylus, using an inductive pick up. The Cleveite Profilometer has been calibrated in the Metrology Lab at LLNL, and appears to be accurate and reproducible to 70 Å.

Figure 11 shows a comparison of traces made on the same Wölter mirror surface with the Cleveite Profilometer and the Random Devices Slope Scanner. They appear to agree to 70 Å, when averaged over a 50 μ m horizontal scale length.

Figure 12 compares the longitudinal surface profile of the older Wölter mirror, with the surface profile of the new Wölter mirror, fabricated at Random Devices. The new mirror has a 30 Å RMS deviation from the ideal surface profile. The deviation from circularity of the hyperboloid of the new Wölter mirror is illustrated in figure 13.

Traces from the Random Devices Slope Scanner were digitized and reduced to slope error distributions. The older mirror had longitudinal slope distributions with standard deviations of 16 arc seconds for the ellipsoid and 13 arc seconds for the hyperboloid, as may be seen from figure 14.

Figures 15 and 16 show the longitudinal slope error distributions from the new Random Devices Wölter mirror. These have standard deviations of 0.82 and 0.65 arc seconds respectively.

Figure 17 is the azimuthal slope error distribution for the new mirror and has a standard deviation of 2.8 arc seconds. The measured distribution is, however, not completely random, and has correlation peaks at 0.75 and 1.7 arc seconds. The peak at 1.7 arc seconds corresponds to the ripples in figure 13, which have an approximate period of 4-5 mm.

Figure 20 The combined displacement, r , of a ray due to a displacement, x , caused by a longitudinal slope error, and a displacement, y , caused by an azimuthal slope error can be determined using the above geometry.

Figure 21 Comparisons of measured and theoretical point spread functions of the older Wolter Axisymmetric x-ray microscope show good agreement for both full and partial aperture operation.

One would like to be able to assemble this information into a theory which would predict the point spread function of the x-ray microscope. Such a theory can be developed from simple geometrical and statistical calculations. Figure 18 shows that a Wolter microscope which is perfect, except for longitudinal slope perturbations, will produce fans of radiation contained in planes, including the optical axis. These planes intersect on the optical axis and produce a cylindrical singularity, which is infinite on the axis.

On the other hand, if, as shown in figure 19, the mirror was perfect except for azimuthal slope perturbations, conical fans of radiation, which intersect on the optical axis, would be produced. This would again result in a cylindrical singularity, which would be infinite on the axis. However, when these types of perturbations are combined, the degenerate symmetry which allows the cylindrical singularities to be produced, is broken. This broken symmetry results in a finite value for the distribution on the optical axis.

Figure 22 The resolution of the Wolter x-ray mirror is measured with a 20 by 20 array of 2 μm diameter pinholes, spaced 50 μm apart.

Using the geometry shown in figure 20, a simple statistical calculation can be used to determine the probability, $P(r)$, of a given ray falling a distance r from the optical axis.

$$\int P(r) r dr = \int P(x) P(y|x) dx dy \quad (1)$$

$P(x)$ is related to the longitudinal slope error distribution. $P(y|x)$ is the probability of finding a ray at y , conditional on it having the coordinate x . We now define a few auxiliary formulae:

$$y = (d_0 (\tan \theta_g) - x) \tan \phi_T \quad (2)$$

$$x = d_0 \tan \alpha_T \quad (3)$$

$$\alpha_T = 2\sqrt{\sigma_1^2 + \sigma_2^2} \quad (\text{Longitudinal}) \quad (4)$$

$$\alpha_T = 2\sqrt{\alpha_1^2 + \alpha_2^2} \quad (\text{Azimuthal}) \quad (5)$$

$$a = \frac{r}{\alpha_T d_0 \tan \theta_g} \quad (6)$$

Where d_0 is the object distance, θ_g is the grazing angle, ϕ_T is the total azimuthal deflection of the ray, and α_T is the total longitudinal deflection of the ray. σ_T is the standard deviation of the longitudinal total deflection distribution. α_T is the standard deviation of the azimuthal total deflection distribution. σ_1 and σ_2 are the standard deviations of the hyperboloid and ellipsoid longitudinal slope error distributions, respectively. α_1 and α_2 are the standard deviations of the hyperboloid and ellipsoid azimuthal slope error distributions, respectively. a is a dimensionless variable. Using these formulae, it can be shown that:

$$P(r) r dr = \frac{4r dr}{\alpha_T \alpha_T d_0 \tan \theta_g} \frac{e^{-\frac{(r/d_0 \tan \theta_g)^2}{\alpha_T^2}}}{\sqrt{1+a^2}} f(a) \quad (7)$$

where

$$f(a) = 1 + \frac{a^2}{1 + 0.58 a^2 + 1.63 a^4} \quad (8)$$

Figure 23 A comparison of images of the pinhole array taken with the old and new Wölter mirrors shows the new mirror produces smaller images with less scattering than the older mirror, but that the wings of the point spread function are less symmetrical for the new mirror.

Using formulae 7 and 8, the FWHM can be shown to be: $\text{FWHM} \approx 7.5 \alpha_1 d_0 \tan \alpha_2$, where we have assumed that α_1 and α_2 are approximately equal. The Half Power Circle Diameter can be shown to be: $d_{1/2} = 2.7 \alpha_1 d_0$, where again we have assumed that α_1 is approximately equal to α_2 . Thus we find that the FWHM is related only to the azimuthal slope distribution, while the Half Power Circle Diameter is related only to the longitudinal slope error distribution.

Figure 24 We are currently building a Kirkpatrick-Baez x-ray microscope with multilayer (Barbee) x-ray mirrors.

At present, this theory is limited in that it relies only on geometrical optics. However, it can be shown that for the azimuthal perturbations, the conditions for geometrical optics are well satisfied. For the longitudinal perturbations, on the other hand, geometrical optics is only valid for long scale length perturbations and diffraction optics, such as described by Bennett^{19,20} and by Church,^{21,22,23} must be used for shorter scale

length perturbations. Both regimes occur in x-ray optics, and both effects must be included for a completely correct calculation. In the range where both effects are comparable, the results can be approximated by either. This change in the distribution of x-rays, caused by the longitudinal perturbations, will change the details of the wings of the point spread function. However, the central portion will be largely unaffected.

Figure 21 shows the measured and theoretical point spread functions for both full and partial aperture for the older Wölter microscope, whose distribution functions were given in figure 14. The agreement in these cases appears to be excellent. The point spread function was measured with an array of 2 μm diameter pinholes.

An electron micrograph of the array of two micron diameter pinholes is shown in figure 22. This pinhole array was backlit by a tungsten anode x-ray source for the point spread function measurements.

Figure 23 shows images of the pinhole array taken with both the old and the new mirror. Two interesting points will be noted here. The much greater scattering of the older mirror is obvious as a fuzzy background in the photograph taken with it. The new mirror shows much less scattering, but the image points are much less symmetrical. The greater symmetry of the image points of the old mirror are the result of statistical averaging. On the other hand, in the new mirror, the coherent defects, in particular, the azimuthal defects, have become comparable to the random defects, leading to the unsymmetrical image points.

I believe that this type of theory is particularly successful in calculating the central shape of the point spread function. With the inclusion of diffraction effects, it may be able to provide a good fit to the entire point spread function.

Figure 25 The use of multilayer x-ray mirrors produces good x-ray reflectivity with narrow bandpass at high energies and moderate grazing angles.

In summary, I see the Kirkpatrick-Baez microscopes maintaining their role as the workhorse of the x-ray imaging devices. This role is being extended with the development of a 22X magnification Kirkpatrick-Baez x-ray microscope with multilayer x-ray mirrors²⁴ as shown in figure 24, which can be installed in the x-ray backlighting system. As indicated in figure 25,²⁵ these mirrors can operate at large angles, high x-ray energies, and have a narrow, well defined x-ray energy bandpass. This will make them useful for numerous experiments. However, where a large solid angle is needed, the Wölter microscope will still be necessary and the technology needed to build them will be useful for many other types of x-ray optics.

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