Integration of X-ray Microscope Elements to a High-Speed Framing Camera Format

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Abstract

Compact x-ray mirrors have been positioned so as to form multiple images in a high-speed framing camera format. The angles at which the mirrors lie are altered by glass shims. The image offsets are set by positioning the mirrors using a multiple stepper-motor table positioning system. The mirror assembly has been tested in the x-ray diagnostic laboratory using electron-beam-generated x rays. Successful alignment of the images will allow for use of high-speed framing cameras in conjunction with the microscope elements to diagnose plasmas formed by the OMEGA laser system.

Introduction

Inertial confinement fusion (ICF) attempts to produce an ignited plasma by compression of a deuterium-tritium target using high-intensity laser beams. The OMEGA [1] laser system at the University of Rochester's Laboratory for Laser Energetics (LLE) is used to create high temperature plasmas (> 1 keV) via ICF. The plasma conditions of the compressed target, such as the density, shape, and size, can be assessed through imaging.

X rays in the energy range from ~0.1 to ~10 keV are emitted by the laser-heated plasma. X-ray imaging systems are used in the OMEGA target chamber to space resolve the emission from the plasma.

The principle means of imaging in use at LLE consist of either pinhole arrays [2] or Kirkpatrick-Baez (KB) [3] microscopes. When combined with a framing camera [4] the x-ray emission is also time resolved. The pinhole arrays and KB microscopes serve to magnify the image, while the framing camera serves to record time-resolved images. Time resolution of ~30 ps is achievable with framing cameras. Framing cameras usually are used with pinhole arrays, though development of KB image arrays is desired.

X-ray Imaging

Figure 1 shows a KB mirror pair and an assembled pinhole camera. The pinhole camera is the simpler of the two, and is modeled similarly to a visible-light pinhole camera, although on a much smaller scale. Figure 1 shows a single pinhole used for imaging on OMEGA, whereas framing cameras use an array of ~10 μm laser-drilled holes. The resulting inverted image from the x rays passing through the holes is recorded on the opposite side, using either a framing camera as mentioned above, or an x-ray sensitive detector. Due to the simplicity of the pinhole array, this method is relatively inexpensive and can produce images with moderate resolution (~15 μm for a 10 μm pinhole). However, this resolution limits the ability to distinguish smaller features in the plasma. As an example, the center of a target imploded by OMEGA is ~30 μm in diameter. This is only 2 resolution elements if the resolution is 15 μm.

KB microscopes can improve on pinhole camera resolution with resolution as high as ~3 μm. The KB x-ray microscope consists of mirror pairs each of which produces a single image. One design uses sixteen pairs, providing sixteen images of the plasma emission [5]. When coupled with a framing camera these KB mirror pairs can provide time-separated images.

KB X-Ray Microscopes

The Kirkpatrick-Baez x-ray microscope was developed by Kirkpatrick and Baez in 1948 [3]. KB microscopes have been used at LLE to image laser-generated plasma x-ray emission since the 1980's, originally on the 24-beam OMEGA laser system and more recently on the 60-beam OMEGA laser [6]. A Kirkpatrick-Baez microscope consists of perpendicular, spherical, concave mirror pairs (Figure 2) designed so that the planes of focus for each mirror are combined. When x rays reflect off both mirrors a two-dimensional image is formed.

As shown in Figure 2, only x rays that reflect off the mirror pairs will contribute to the two-dimensional image. To prevent other x rays that reflect off one or none of the mirrors in a pair from reaching the image plane, a baffle is used in conjunction with the mirror pairs. With the baffle in place, only x rays that reflect off both mirrors in the pair create the image.

Each mirror in the pair obeys the focus equation

$$\frac{1}{p}+\frac{1}{q}=\frac{2}{R\sin(i)}, \tag{1}$$

where p is the source-to-mirror distance, q is the mirror-to-image distance, R is the radius of curvature of the mirror, and i is the angle of incidence of the x rays (Figure 3). The image is magnified by an amount $M=q/p$. As i becomes small, $\sin(i)$ approaches $\tan(i)$, which is equivalent to $\Delta x/p$, where Δx is the perpendicular distance from a mirror to the optical axis.

When p is assumed a fixed quantity (~180 mm on OMEGA) and q is rewritten as Mp (for a magnification M), it is possible to verify R. R was verified to be between 25 and 30 m for the mirrors in use. The angle i on the mirrors is ~0.7 degrees, which is necessarily small, since x rays in the energy range of interest will not reflect unless the angle is small [7].

A schematic of a KB mirror pair is seen in Figure 4. A mirror in a mirror pair on the 16-image KB microscope measures 17 mm long (if the triangle is extended) and 4.5 mm thick. The pair subtends an angle of 22.5 degrees, or 1/16 of a complete circle. The top ~3 mm of a mirror are cut to a 45 degree angle, so that the two mirror surfaces in the pair are perpendicular. To increase the reflectivity of the mirrors, metallic coatings are used on each individual mirror, on the perpendicular face. Ir is used, as it provides the best reflectivity of x rays at the highest energies. Each mirror departs from a perfect flat by 97 nm (0.1 μm) in the curved direction.

The mirror pairs in one 16-image KB optic design are assembled in a 16-mirror-pair arrangement, with all pairs touching [Figure 5(a)], so as to make a spherical arrangement in the center [8]. This uniform distribution of mirrors, when combined with a circular framing camera design, can produce circular sets of 16 images, separated by ~100 ps, with a temporal resolution of ~80 ps [8]. These times are limited by the unusual design of the circular framing design, as the speed of the pulse (which captures the image) running through the strip (~c/2) and the diameter of the image (76 mm) determine the time frame in which images can be taken.

A new design of KB microscope has been proposed [Figure 5(b)], such that it continues to take 16 images at a time, but instead of focusing on a circular framing camera, the mirrors are spaced such that they focus on a rectangular array. The image points are 9 mm apart, and located on four framing camera strips, each 5.6 mm wide. These camera strips allow for much more closely spaced time-gated images (60 ps), and these strips can have up to a 30 ps time resolution. Figure 5(b) only shows 12 of the 16 mirrors of the new design, as two-plane tilts will have to be implemented for the final four mirrors, as four more mirror pairs will not fit in this design on the optical base.

Figure 6 shows the array of points and the framing camera strips. It also shows, as an overlay, the image circle that the 16-image KB microscope would produce without shifts to the mirror pairs. Four mirror pairs need to be shifted onto the outermost circle, eight to the middle circle, and four to the innermost circle, to create the 4 by 4 grid of images.

Figure 7 shows the shift necessary for a mirror pair on the existing 16-image optic design to result in the desired layout. If the image needs to be moved by a distance δx' on the image plane (from the unshifted circle to the appropriate new circle), and the image plane is treated as a concave surface with a large radius of curvature, the angle that the mirror needs to be tilted is determined by

$$\Delta\theta = \delta x' / (p + q) . \tag{2}$$

For the mirror pairs on the proposed model [5], operating at M=9.2 to function properly on the OMEGA laser system, the values of Δθ are 0.596, 0.352, and 0.200 degrees for the outer, middle, and inner circle tilts, respectively. Furthermore, the mirrors would have to be moved outward from the center by an amount

$$\delta x'' = \frac{\delta x'}{(M+1)} , \tag{3}$$

or 1.88 mm, 1.10 mm, and 0.63 mm respectively.

This is made difficult, however, by the aberrations caused by the movement and tilt of the mirrors. As seen in Figure 8, the resolution drops off dramatically when the mirrors are off focus by even 0.4 mm. Further aberration occurs due to mis-tilting because the error in tilt of the mirror is doubled in the image placement error.

Experiments

To create a 16-image KB microscope such that the images fall onto four image strips, the mirrors must be tilted and placed with precision. The x-ray microscope chassis available in the x-ray laboratory was configured to operate at a magnification of 12.85 which is different than the case of M=9.2 given in ref. [5]. Only four mirror pairs (two outer, two middle) were included on the test assembly, to test that one row of images could be produced. Small wedges were used to produce the tilts (Figure 9). The wedges were made by using Huntsman Araldite 1253 Epoxy [9] to hold two glass slides together over a pre-measured distance of 50 mm, with plastic shims on one end of the slides to create the correct angle. The wedges were measured by taking the inverse tangent of the difference of the height of the slides at the thin end and the 50 mm mark divided by 50 mm (see brown triangle in Figure 9). The angles of the wedges produced measured 0.401 and 0.516 degrees, while the angles calculated for the outer and middle circles for M=12.85 are 0.408 and 0.520 degrees. The differences between the desired and measured angles are 0.007 and 0.004 deg respectively.

The mirror assembly apparatus can be seen in Figure 10. To center and appropriately move the optical base, three stepper-motor tables were assembled on top of each other. A micropositioner stage was also used. Two tables were set up to move perpendicularly to each other in the horizontal plane, and the third was a rotary stage. All three stepper tables were combined with stepping motors, giving a precision of 1/10,000th of an inch (2.54 microns) and 1/100 of a degree on the flat and rotating tables, respectively. To hold the optical base in place, a metal plate was constructed that allowed the base to rest securely on the assembly stage. To view the assembly at a magnification, a Panasonic Video Camera was held above the stage using an apparatus comprising aluminum rods and 90-degree clamps. The camera lens was fitted with a correction lens ~20 mm away from the top of the optic, and provided an image of the assembly at a magnification of 153 resulting in a ~10 micron resolution on a connected display. A sliding positioner was set up on one side of the stage, with two aluminum rods holding a rod with a three-axis micropositioner stage. The sliding stage acted as a rough positioner, while the micropositioner stages were used for precise movements when close.

To assemble the mirror pairs, a fence was made out of a glass base and glass slides; one slide was used to line up the mirror bases, and a stack of glass slides acted to insure the mirrors were also at the correct angle when assembled. UV cured epoxy was used to bond the mirrors. Curing was accomplished by exposing the epoxy to UV light for ~10 sec. The tilted wedges were attached to the mirror pairs in this fashion as well.

Vacuum grease was then used to hold the mirror pairs (with wedges) to an aluminum plate that attached to the micrometer stages at the end of the rough slider. The stepper-motor tables were then rotated and displaced such that the crosshairs of the viewing camera was directly above the point at which the mirror pair was desired. The rough slide was moved until the mirror pair was visible on the viewing screen. Then, the micrometer stages were used to center the mirrors in place directly to the crosshairs, such that the mirror pair was then in the correct place. A precisely placed mirror pair can be seen in Figure 10. UV epoxy was used to attach the mirrors to the base. The micropositioner was then backed away from the optic. The stepper motor tables were then rotated to the correct angle and displaced to the correct radius for the next mirror pair, and the process was repeated for the remaining mirrors. The vacuum grease was then cleaned from the top of the mirror pairs using acetone. The final test optic is seen in Figure 11.

Results

The assembled KB microscope mirror pairs were tested in the LLE X-Ray Laboratory. Figure 12 shows a schematic of the x-ray testing device. Five exposures of a Cu 25 μm mesh were taken. Figure 13 shows one sample exposure. The three images seen are not in a straight line as desired. One mirror-pair image is not visible on the images, likely due to a large tilt error introduced in the assembly process. Table 1 shows the placement error of the mirror pairs on the base. These numbers, when multiplied by the magnification 12.85, result in the error in the image due to the misplacement. Small placement errors during assembly demonstrate that only ~1 mm of image error is due to misplacement. Angle error thus accounts for the majority of the image error. If the error due to misplacement is assumed to be 1 mm, then the remaining error is contributed by wedge construction error. The angle error can be calculated using the following formula,

$$\Delta i = \frac{\delta x'}{2pM}, \tag{4}$$

where (See Figures 3 and 7) Δi is the angle error, δx′ is the distance the image is away from where the ideal image would be, p is the distance from the object to the mirror, and M is the magnification (12.85) for this experiment. Given the image positions as seen in Fig. 13, the inferred shim errors are between 0.06 and 0.02 degrees. This additional error (compared to 0.007 and 0.004 deg) was likely made during assembly, and was likely due to misalignment of the mirror pairs with the optic base. As the micropositioner was a flat surface and the mirrors had a tilted shim on them, it is likely that the mirror pairs were not placed flat on the optic base, thus contributing to the error of the images.

Conclusions

KB mirror pairs were assembled in a high-speed framing camera format, such that a single column of images was to appear when exposed to x rays. Accurate wedges were built using glass slides and epoxy to better than the desired angular accuracy (~0.01 deg). A test assembly with these glass wedges was performed to measure the relative placement of the images produced by the tilted KB mirror pairs. The images were found to be mislocated with respect to the desired positions by much greater than 1 mm (~10 mm) indicating a very large tilt error. Since the wedges were accurately manufactured it is likely that an error in tilt was introduced in assembly. This error may have also been introduced by radial placement errors. The tilt error needs to be lower than 0.01 degrees to assure properly placed images. Once the alignment problem is solved, high-speed framing cameras coupled to KB optics promise to provide a significant enhancement to LLE capabilities.

Acknowledgements

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Table 1. Table showing the mirror pair locations, ideal tilt angles, as-built angles, and as-measured angles of the four mirror pairs. Also included is the angle and radius where each pair was placed, as well as the placement error of each pair.

		Tilt Angle (degrees)			Optical Base Placement		Placement Error
Mirror pair	Assignment	Ideal	As Built	Measured	θ (degrees)	R (mm)	δR (mm)
1	Outer	0.408	0.393	0.401	45.00	4.39	0.131
2	Middle	0.520	0.509	0.516	18.43	4.74	0.013
3	Middle	0.520	0.509	0.516	-18.43	4.74	0.033
4	Outer	0.408	0.393	0.401	-45.00	4.39	0.098

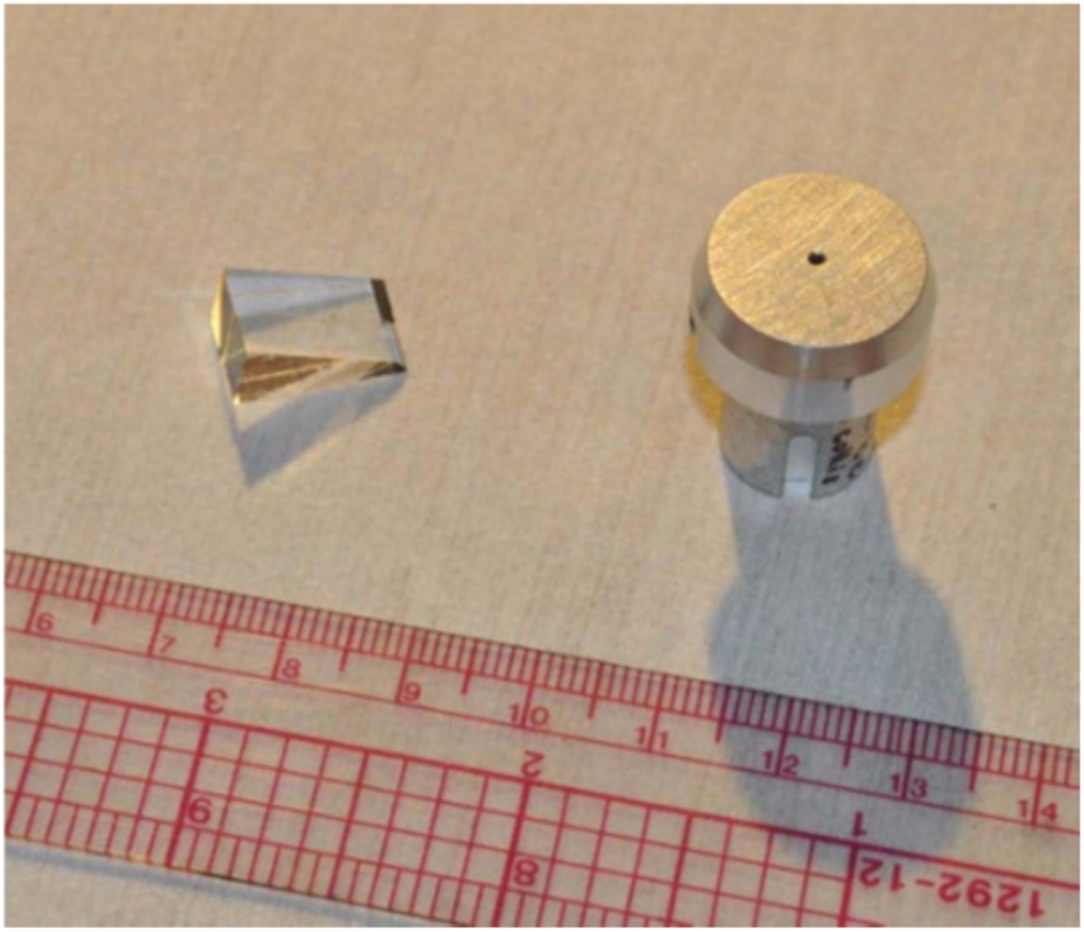

Figure 1. Photograph showing a KB mirror pair (left) and a pinhole camera (right). The two x-ray reflecting surfaces are located on the right of the mirror pair, at the tip of the wedge, and are mutually orthogonal.

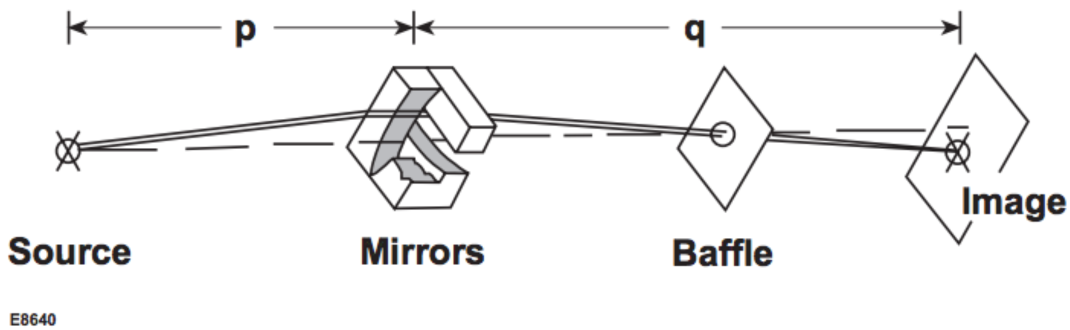

Figure 2. Schematic of a combination of two KB mirror pairs, perpendicularly arranged such that the image is in focus, such that the mirrors are the correct distance from the source *p* and distance from image *q*. A baffle is also in place to prevent unfocused x rays from appearing on the image plane. (This figure appears as Fig. 1 in ref. [8]).

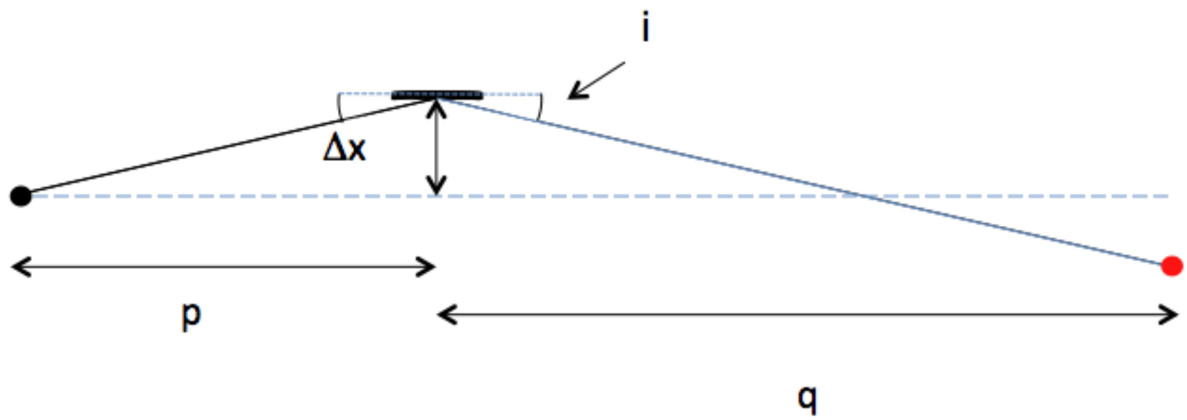

Figure 3. Side view of x rays reflecting off a focused KB mirror. Δx is the distance from point of reflection to optical axis, *p* is the distance from object to point of reflection, *q* is the distance from point of reflection to image, and *i* is the angle of incidence of the x rays off the mirror.

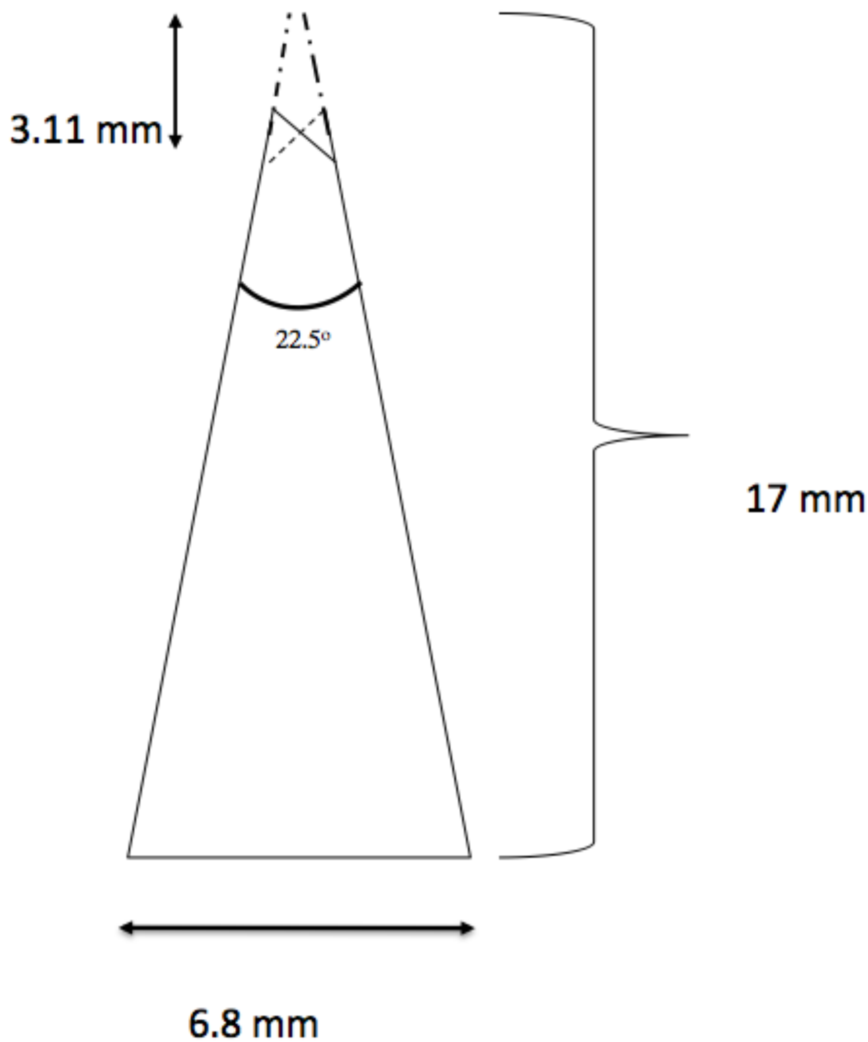

Figure 4. Diagram of a single KB mirror pair viewed edge on, with a continuation of the triangle (dash-dot) after it has been cut, to demonstrate the original length of 17 mm.

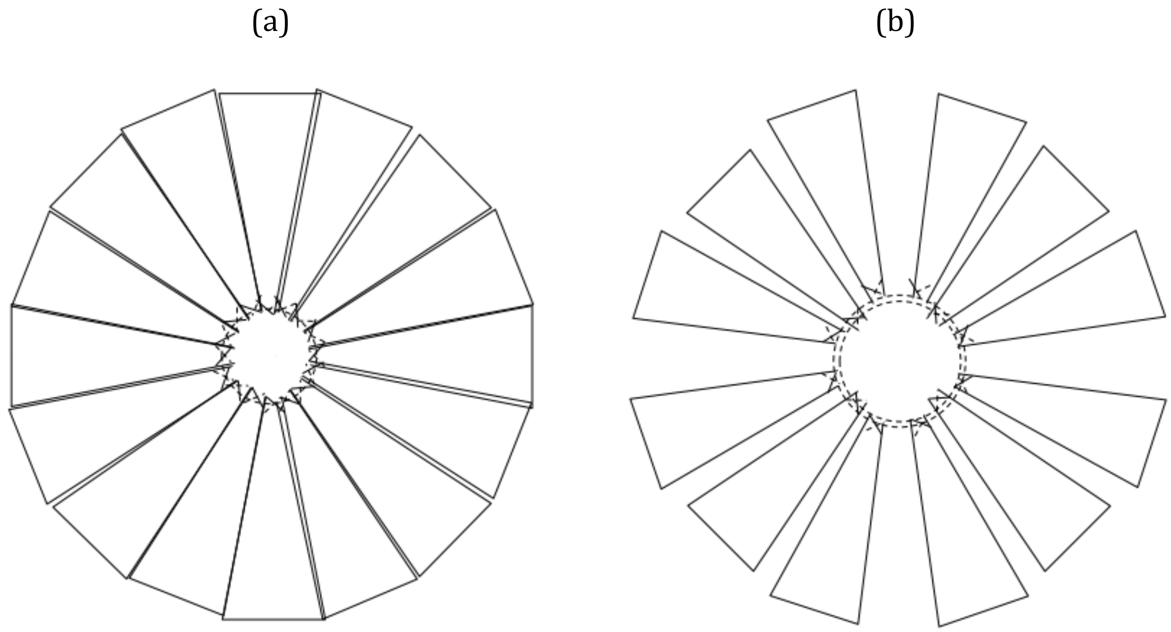

Figure 5. Schematic of two arrangements of KB mirror pairs on an optical base. (a) 16 uniformly spaced mirror pairs that produce a ring of 16 images; (b) 12 out of a set of 16 mirror pairs proposed to produce a rectangular array of images.

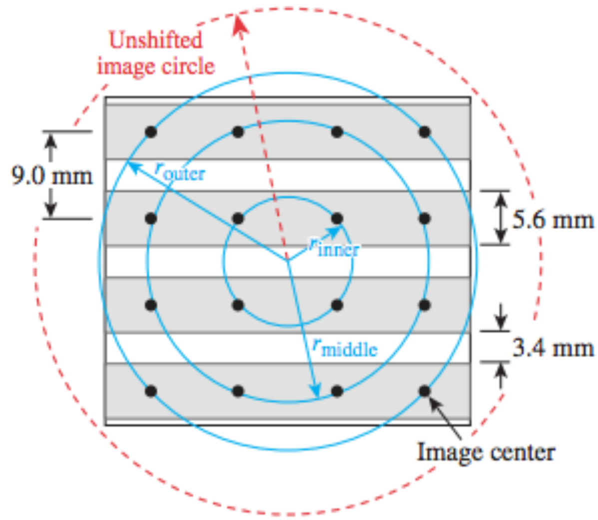

Figure 6. Schematic of a 4-strip framing camera, with three concentric circles overlaid to show how images would be arranged. (This figure appears as Fig. 6 in ref. [5]).

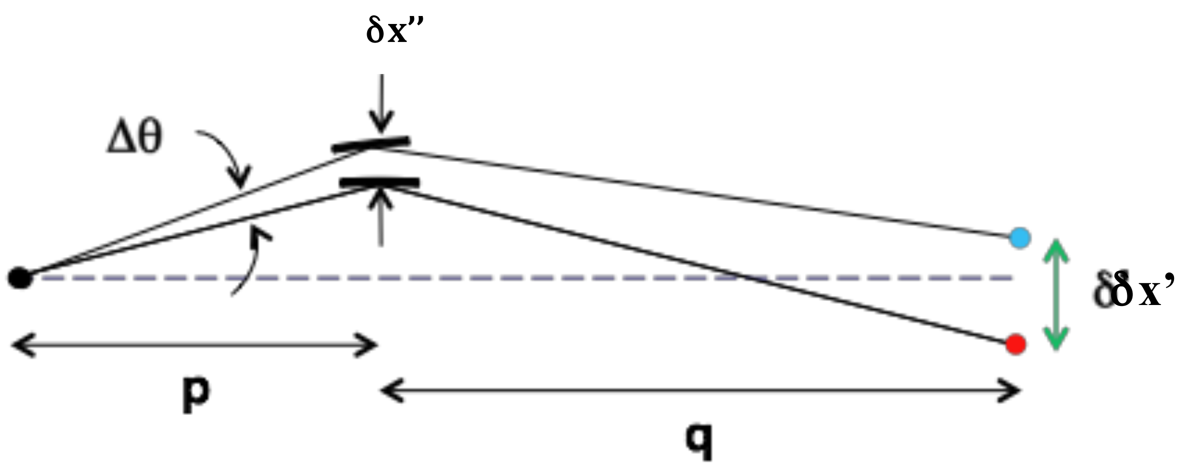

Figure 7. Side view of a tilted mirror and the effect on the image location. Δθ is the change in angle, *p* is the distance from object to mirror, *q* is the distance from mirror to image, δx'' is the mirror's change in distance away from the optical axis, and δx' is the resulting change in the image location.

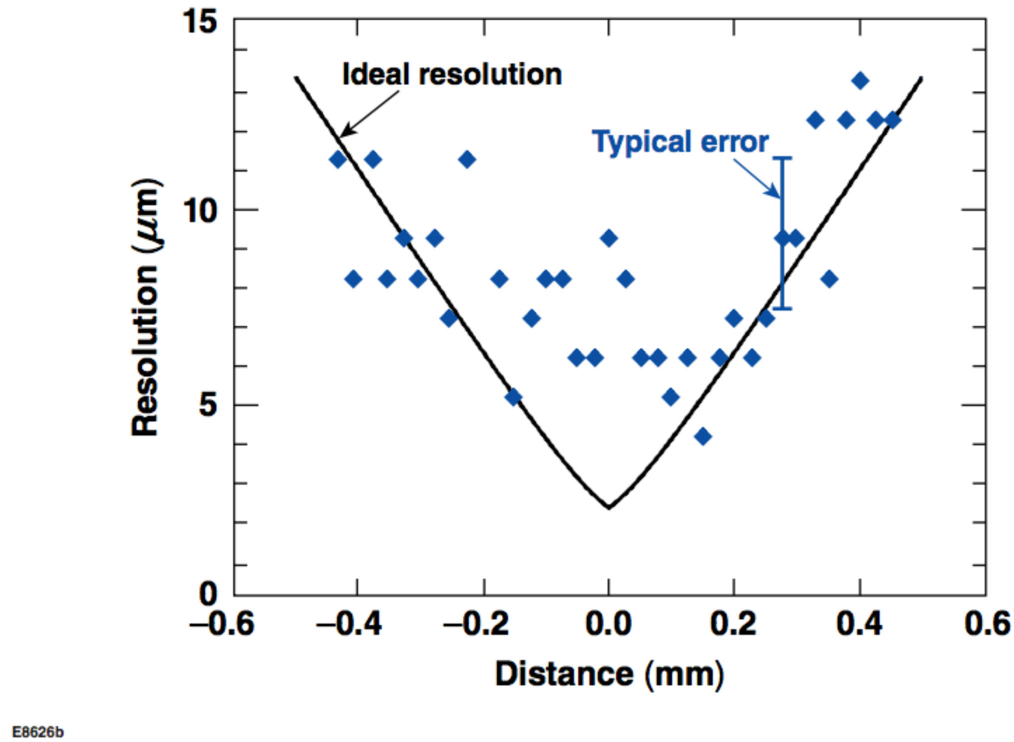

Figure 8. Chart showing the decrease of resolution as distance error increases from the ideal case. (This figure appears as Fig. 4 in ref. [5]).

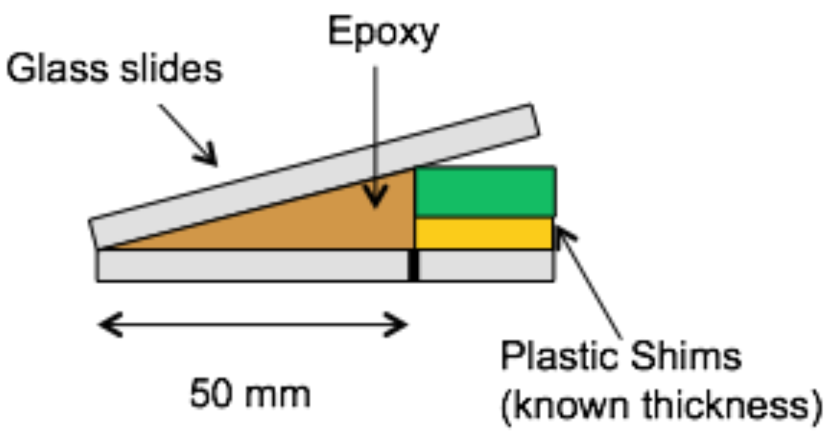

Figure 9. Diagram showing an exaggeration of the wedge assembly. The shims are typically ~15 mm thick.

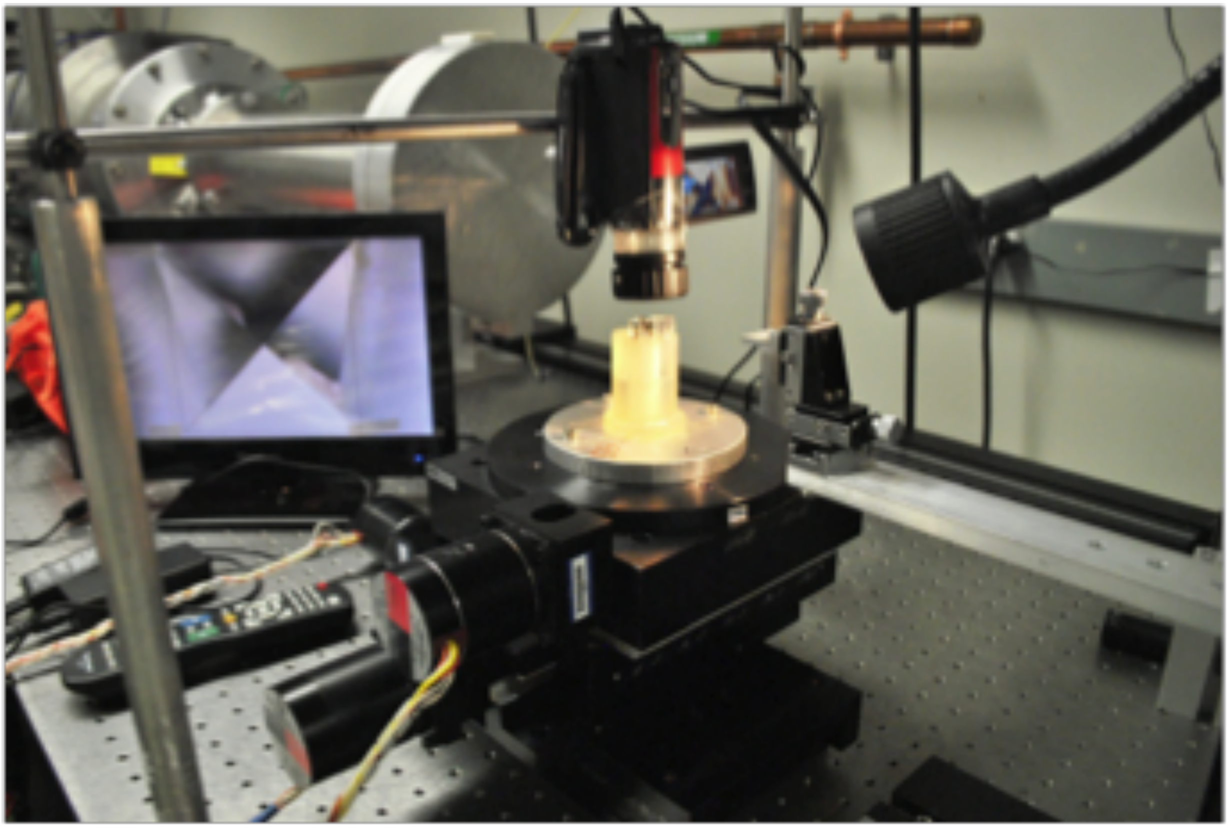

Figure 10. Photograph of the experimental set up. The sliding stage can be seen in the lower right, the light source in the upper right. The viewing screen, with the mirror pair at the crosshairs, can be seen far left. The optical base is seated on the stepper-motor tables in the middle, and the video camera sits above it, with the attached magnifying lens.

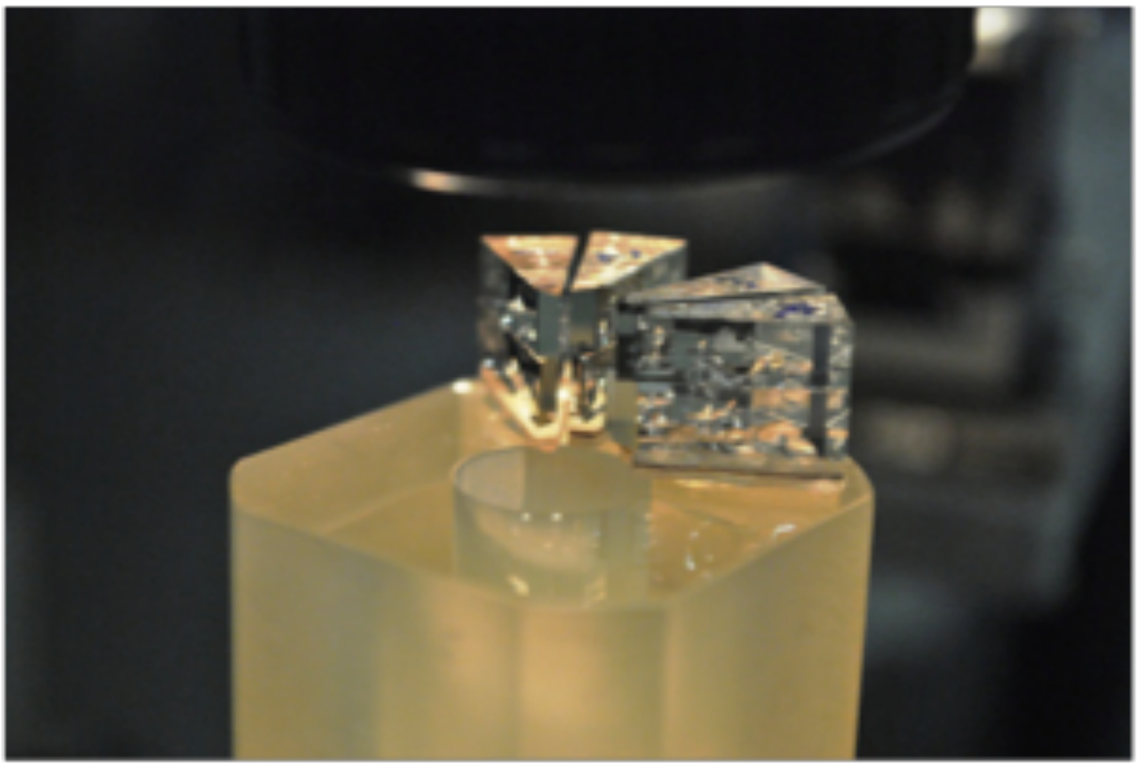

Figure 11. Photograph showing the final test optic. The mirror pairs are fastened to the optical base using UV-cured epoxy.

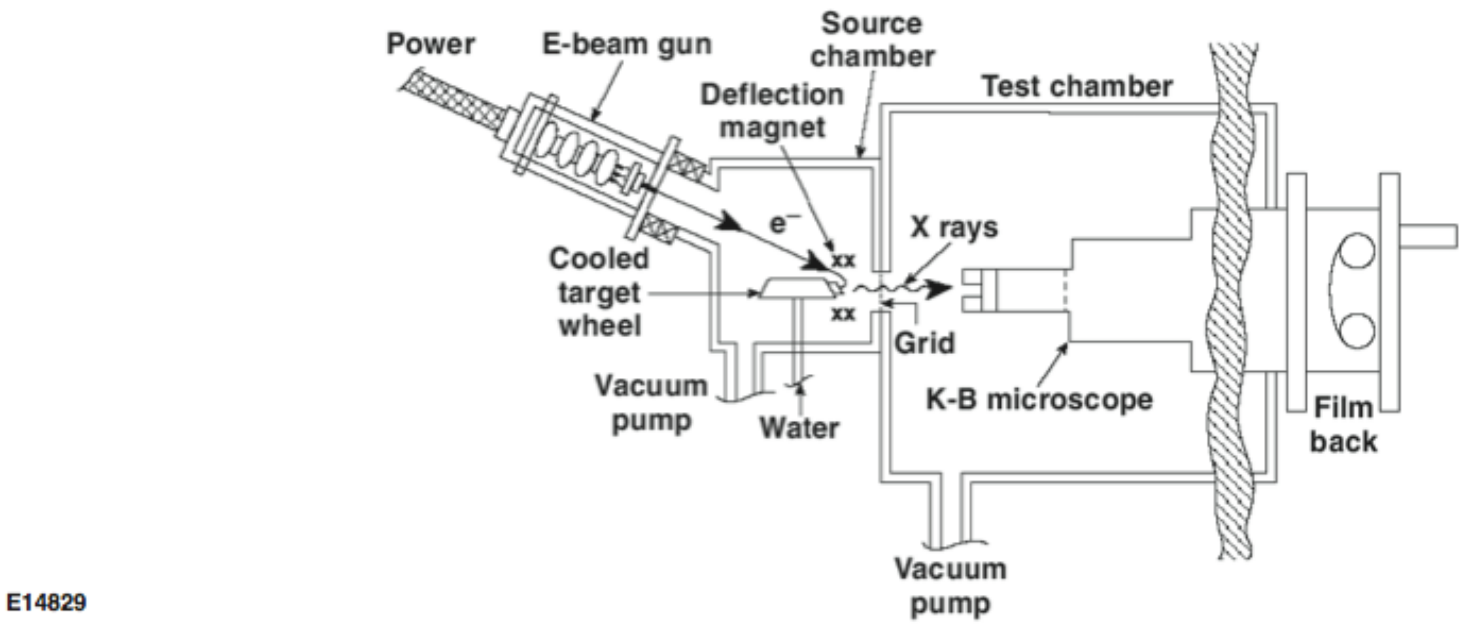

Figure 12. Schematic of the X-ray testing chamber. The e-beam from the upper left hits a copper target (middle left), and the resulting x-rays are aimed into the test chamber.

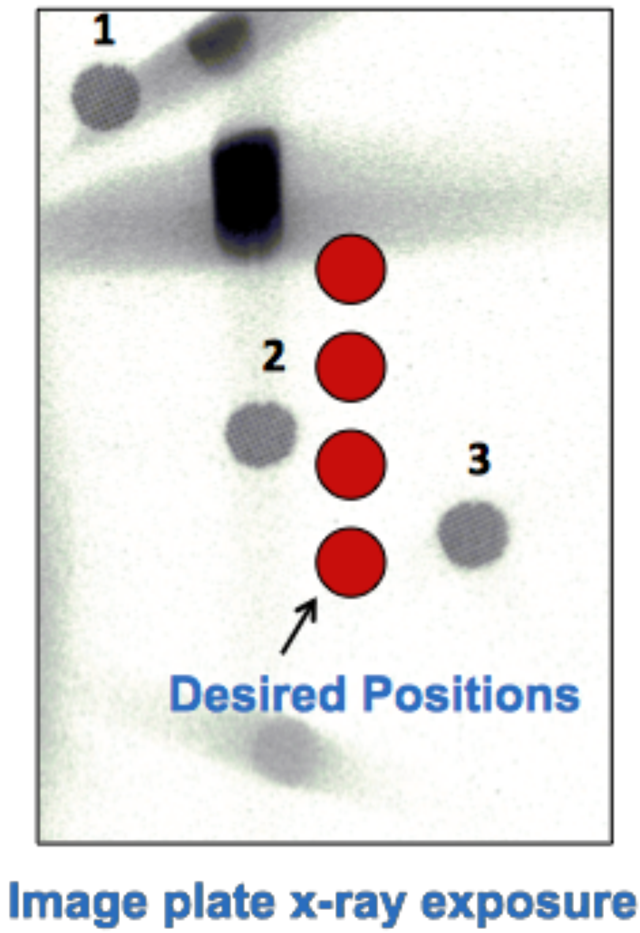

Figure 13. Image from the test x-ray exposure film pack. The ideal locations are overlaid in red, showing the significant error in the locations of the resulting images (1, 2, and 3). The desired positions' centers are separated by 9 mm.