X-Ray Imaging with Compact Kirkpatrick-Baez Microscopes

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Abstract

X-ray imaging is needed to diagnose inertial confinement fusion (ICF) implosions. For example, radiography using an x-ray backlighter target allows the size, symmetry, and density of both the compressed core and surrounding shell to be determined. One means of imaging ICF target x-ray emission is a compact Kirkpatrick-Baez (KB) microscope. Before a KB microscope is used, the KB optic must have its best focus location and resolution determined. Test exposures were taken with an electron-beam-generated x-ray source. The test target was a copper grid with 25.4 µm diameter wires and a reference hole to align different exposures. A PV-Wave program was written to efficiently take lineouts across the image. These lineouts graph the film density of the shadows created by the mesh grid. Measurements of the edge response of the shadows were subsequently used to determine the best focus positions in the images, as well as the point spread function near best focus. The calibrated mirror pairs will assist the continued development of a 16-image KB microscope.

Introduction

Inertial confinement fusion (ICF) may one day provide mankind a nearly unlimited source of energy. In the ICF process, high-intensity laser beams are used to uniformly compress thermonuclear-fuel-bearing targets, filled with deuterium and tritium fuel.[1] The subsequent ablation of the target leads to an implosion confined by inertia, allowing the fuel to be driven to

extremely high temperatures (in excess of 1.5×10^7 K) and extremely high densities (~100 g/cm^3), comparable to conditions found at the center of the sun.

The fusion of a deuteron and a triton results in the creation of an energetic alpha particle and a neutron. The alpha particles can deposit their energy in the compressed fuel, resulting in additional fusion reactions. This process can produce a propagating thermonuclear burning region that gives off an enormous amount of energy. The ultimate goal of inertial confinement fusion research is to achieve ignition, a condition where the energy given off by the reactions is greater than the amount of energy required to initiate the fusion process. The National Ignition Facility (NIF) in Livermore, California hopes to become the first fusion facility to attain ignition in the laboratory.[2]

To support the NIF, the Laboratory for Laser Energetics at the University of Rochester carries out fusion-related experiments on its OMEGA[3] and OMEGA EP[4] lasers. OMEGA is a 60-beam ultraviolet laser system with an output of 30 kJ of energy in 1 nanosecond, corresponding to a power of 30 TW (30×10^{12} W), typically used to irradiate a 1 mm diameter target. The laboratory's second laser system, OMEGA EP, is capable of picosecond (10^{-12} s) laser pulses with an on-target energy of approximately 1 kJ for two of its four beams, thereby operating at a power output of ~ 1 PW (10^{15} W).

When the laser beams compress the target, an assemblage of charged particles, called a plasma, is formed. When the plasma is sufficiently heated (~10^7 K), it emits x rays. An imploding ICF target emits x rays during illumination by the laser beams and at stagnation when the kinetic energy of the plasma is transformed into thermal energy. The inner core of the fusion reaction gives off high-energy x rays, which are able to penetrate the plasma with their extremely

short wavelengths of 1 to 10 Å. The x rays emitted by the target are subsequently studied to obtain information about conditions in the target.

To study the fusion process, x-ray imaging is used to obtain critical information on the absorption of radiation, transfer of energy, and hydrodynamic behavior. In addition, with the ability to obtain the spectra of x rays emitted from the fusion plasma, x-ray imaging allows the approximation of core temperatures and the estimation of the size, symmetry, and density of both the fusion center and the surrounding imploding shell. These are all crucial diagnostics in assessing the performance of the target implosion and the process of laser fusion.

X-ray radiography uses an x-ray source and either photographic film or image plates to capture the penetrating radiation. To create images of inertial confinement fusion phenomena and study the conditions in the compressed cores, good spatial resolution and high energy sensitivity are needed. Instruments used for imaging nuclear fusion often include pinhole cameras and KB microscopes.[5]

A KB mirror pair and a pinhole camera assembly are shown in Fig. 1. The mirror pair is 17 mm long, 4.5 mm thick, and has a radius of curvature of approximately 26 m. The pinhole cameras used to image the OMEGA fusion target consist of a 10 μm hole. The delicate pinhole is placed on top of two collimators made of tungsten, an element noted for its high density. Then, the pinhole is covered with a beryllium shield that blocks unwanted soft x rays and only allows the desired x rays through. Finally, a third collimator is placed onto the beryllium shield. This collimator filters the x rays that go through to the pinhole and ensures that these rays are traveling parallel to the hole's entrance. A cover is then put onto the pinhole apparatus to protect the camera from any debris or damage from the laser plasma.

At LLE, in addition to the reliable and relatively inexpensive pinhole camera, the KB microscope often provides better resolution and better images of the ICF reaction. First developed in 1948, KB microscopes can image high-energy x-ray sources with the necessary resolution and sensitivity.[6] The KB microscope (Fig. 2) is a reflection system that makes two-dimensional images by using a pair of spherical, concave mirrors whose centers of curvatures are perpendicular to each other. Each mirror focuses in one plane, so two mirrors positioned perpendicularly will focus in two planes, thus forming a two-dimensional image.

As shown in Fig. 2, a baffle is often used in conjunction with a KB mirror pair to act as a field stop. Rays that reflect off both KB mirrors are the ones that form the desired two-dimensional image; those rays are the ones desired on the film. Rays that reflect off only one mirror will image in one dimension but are stopped by the baffle.

Each mirror has a high radius of curvature and follows the focus equation[6]

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

where p is the distance of the mirror to the object, q is the distance of the mirror to the image, R is the radius of curvature of the mirrors, and i is the grazing angle of the rays. Due to the high radius of curvature of the mirrors, the KB microscope reflects rays at small grazing angles. These small grazing angles are necessary for x-ray reflection, because the rays will only form images when the angle of incidence is less than one degree.

Rays reflected off the KB microscopes form images with high resolution, about 3 μm, and high sensitivity, up to 9 keV. These properties, along with its small size and strong reflectivity, make the KB microscope suitable for inertial confinement fusion experiments. The

pinhole camera often has limited resolution due to the diffraction caused by the pinhole and is susceptible to damage because it must be in close proximity to the target.[5]

On the OMEGA laser, the KB microscopes have two perpendicular pairs that form four mirror pairs.[7] The compact microscope design allows the instruments to take four images of the target for each exposure. In addition, the KB microscopes can be modified to better accommodate the type of experiment being run. Often, multilayer coatings are used to increase reflectivity and increase the distance the microscope can be away from the object being imaged, meaning the microscope can be placed where it will not be damaged.[8] Another modification frequently used is the framing camera, which, when attached to the microscope, allows it to take multiple, time-gated images. The framing camera creates time resolution differences between the images, allowing images to be taken in time intervals of approximately 100 picoseconds.[9]

Currently, a 16-image KB microscope, shown in Fig. 3, is being developed at the University of Rochester's Laboratory for Laser Energetics.[10] The innovative design will allow 16 images to be taken during one exposure, as opposed to the traditional 4. For the continued development of this design, mirror pairs needed to be characterized and tested. To calibrate and test the KB microscopes to be used on OMEGA and OMEGA EP, the Laboratory for Laser Energetics has an x-ray diagnostics laboratory.

Experiments

To take the x-ray exposures, the apparatus must be positioned with precision. To do so, a height gauge was used, as shown in Fig. 4. The KB optic must be the same distance from the mesh grid, positioned at the tip of the pointer, and the baffle. For this experiment, the distance from the grid to the optic and distance from the optic to the baffle were set to be 180.00 mm. To ensure this exact distance, a pointer was placed onto the optic that had a tip that was 180.00 mm

from the optic. Thus, when this pointer tip touched the mesh grid, this would indicate that the grid was 180.00 mm from the optic. For the optic to baffle distance, adjustable machine parts were used in combination with the height gauge to place the baffle onto the KB chassis 180.00 mm from the optic.

For test exposures in the diagnostics laboratory, a mesh grid made of copper is used, shown in Fig. 5. The grid consists of 25.4 μm (0.001 in) diameter wires spaced 50.8 μm (0.002 in) apart. The mesh also has a reference hole that allows the images taken to be aligned with each other. Consequently, the reference hole allows for the determination of the position in the image relative to the same point in space.

Images were obtained using an electron-beam generated x-ray source housed in a vacuum chamber (Fig. 6). An electron-beam current, generated using a high voltage supply, is directed onto a metal target with an adjustable magnetic field, causing x rays to be emitted. Soft x rays less than 3 keV cannot transmit through air, and so the chamber is sealed and pumped down to low pressure conditions (~10^{-6} Torr), allowing x rays to travel through the apparatus un-attenuated. After the x rays pass through the mesh grid and vacuum, the rays will travel through the KB microscope chassis. The chassis holds the KB optic and focuses the x rays formed by reflections off the KB mirror pairs onto Biomax-MS film, which records an image of the mesh grid. The film is exposed for a sufficient amount of time (~30 mins) to obtain an image upon development of the film. The film is subsequently digitized using a photomicrodensitometer, and the exposure allows for analysis of the optical characteristics of the KB mirror pair, including the best focus location, reflectivity, and resolution.

To generate the electron beam, current is passed through a thick tungsten filament, which, when heated, will subsequently go through thermionic emission and emit a stream of electrons.

The electrons are accelerated by a negative voltage (typically 10 to 20 keV) through the anode hole and directed by a pair of dipoles onto the desired metal target. A current through a coil at the magnets creates a magnetic field that focuses the beam. A target wheel on the x-ray generator apparatus rotates different metal targets into position, and each metal target results in different x-ray characteristics for the exposures because each metal has a unique x-ray emission.

The system parameters of the x-ray generator are variable and can be changed by a controller box with software controls. For this experiment, the bending current and the focus coil current of the magnets were 21 mA and 100 mA respectively. The electron beam current was set to 21 mA, while the filament current to create the beam was 19 A. The accelerating voltage was 14 kV. The pressure inside the target chamber was 6 x 10^{-7} Torr. The electron beam position was monitored with a digital camera.

For the experiment, a half-hour exposure was taken on Kodak Biomax-MS x-ray sensitive film with a 2 mm baffle behind the KB mirror pair. The film was developed with standard chemical processing, and the subsequent image was digitized with a Perkin-Elmer microdensitometer.[11]

A program, FWHMlineout (see Appendix), was written in PV-Wave[12] and used to analyze the image. In PV-Wave, a lineout of the image is taken that shows the film density of the image along a row or column of the mesh grid. This lineout is averaged over the space between the wires and median filtered to reduce noise. The resulting values are used to measure the width of the shadows of the wires. Measurements are taken across the lineout at each wire shadow. The resulting values are a measure of the KB-mirror-pair resolution as a function of position.

An exposure (Fig. 5) was taken using a single compact Kirkpatrick-Baez microscope. Both vertical and horizontal lineouts were taken from the image and used to find the best focus location and resolution of the image.

First, the image was rotated to follow the grid lines. This rotation was optimized by using perpendicular vertical lineouts along a horizontal line to ensure that the shadows lined up correctly, as depicted in Fig. 7. Since the shadows correctly line up with each other, this means that the vertical perpendicular lineouts match each other, meaning that the grid lines are straight and perpendicular. This graph is also used to set the lower and upper bounds of the following lineout, which is the number of pixels the lineout will be averaged over.

To perform additional calculations on the image, the magnification of the exposure must be determined. First, the known dimensions of the grid are used to find the actual length across 10 of the wires, which is 0.508 mm. Then, the length across 10 wires on the image is measured with PV-Wave, shown in Fig. 8, which is 6.62 mm. The magnification M is given by

$$M = \frac{q'}{p'} \tag{2}$$

where q' is the image size and p' is the object size. The magnification is calculated to be 13.03 horizontally. The same process is done in the y-direction. The vertical length across 10 wires of the image is measured to be 6.45 mm, meaning the magnification vertically is 12.70.

The shadows of the wires seen in Fig. 8 are also used to determine the resolution. The lineout's edges are measured as a function of position, and this edge response serves as a measure of resolution along the lineout. One edge response measurement is shown in Fig. 9. Narrower edges indicate better resolution, while wider edges indicate poorer resolution. The

graph of the edge width as a function of position is shown in Fig. 10, with edge width on the y-axis. The best focus position is where the width is smallest, shown in Fig. 10 to be approximately 8 μm. Ideally, as shown by ray tracing, the edge width at best focus would be 0 μm; however, due to imperfections on the mirrors and diffraction, it cannot be achieved.

At the best focus position, the derivative of the edge response curve (an example is given in Fig. 9) is taken to determine the point spread function[13] (PSF), which serves as a measure of resolution. The better the resolution, the narrower the edge width will be at best focus, meaning the edge width will have a steeper slope. With such a steeper curve, the derivative will have a higher peak, in turn causing the PSF to be narrower and have a smaller full-width-at-half-maximum (FWHM). The PSF at best focus is shown in Fig. 11. This is seen to have a FWHM of ~6 μm. This is a measure of the best resolution of this compact KB mirror pair.

Conclusions

Kirkpatrick-Baez (KB) mirror pairs are used at the University of Rochester's Laboratory for Laser Energetics to image x rays emitted by laser plasmas. To image the phenomena more efficiently, a 16-image KB optic is being developed. Mirrors must first be characterized and calibrated prior to constructing the 16-image optic. An electron-beam generated x-ray source was used to take exposures on Biomax MS film, and a digitizer was used to format the image for analysis in PV-Wave. The mirror pair apparatus was determined to have a magnification of approximately 13. In addition, the KB mirrors had their best focus position determined by measuring the edge widths of the image shadows, and the resolution at this best focus position was calculated to be ~6 microns as the FWHM of its point-spread function.

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Appendix. FWHMlineout.

```
;Title: FWHMlineout.pro
;Author: Andrew Chun
;Date: 2010 August 6
;Description: FWHMlineout creates a plot of edge response as a function of position.
This data can subsequently be used to determine the resolution of a Kirkpatrick-Baez
mirror pair, in addition to finding where the mirror is in the best focus. The program
also creates a point spread function to determine the full-width at half-maximum and
resolution at best focus.
;Usage:
;       FWHMlineout, img, rimg, rdeg, pixsize, mag, width, splotrange, fxvals, fwhm,
ofile
;            where
;                   img       =       input array
;                   rimg      =       rotated array
;                   rdeg      =       returned rotation angle
;                   pixsize   =       size of pixels in microns
;                   mag       =       magnification of mirrors
;                   width     =       width of mesh grid wires in microns
;                   splotrange =       number of pixels subplot of absolute value of
derivative grpah will show (recommend 60 for 20 micron pixels, 120 for 10 micron
pixels)
;                   fxvals =       position of middle of edge shadows
;                   fwhm      =       value of edge shadow widths
;                   ofile     =       path to desired output file for results
PRO FWHMlineout, img, rimg, rdeg, pixsize, mag, width, splotrange, fxvals, fwhm, ofile

;Adjusting for different pixel sizes
       adj= 20/pixsize

;Rotating image
       s= size(img)
       window, 0, xsize= s(1)/2, ysize= s(2)/2
       loadct, 16
       tvscl, congrid(img, s(1)/2, s(2)/2, /interp)
       print, "click mouse on left and right portion of a line"
       cursor, ax1, ay1, /device, /up
       cursor, ax2, ay2, /device, /up
       rdeg= atan(ay2-ay1, ax2-ax1)*!radeg
       print, "rdeg", rdeg
       rimg= rot_int(img, rdeg)
       tvscl, congrid(rimg, s(1)/2, s(2)/2, /interp)

;Establishing subimage to work with
       print, "click mouse on bottom left and upper right corner of desired subimage"
       cursor, sx1, sy1, /device, /up
       cursor, sx2, sy2, /device, /up
       simg= rimg(sx1*2:sx2*2, sy1*2:sy2*2)
       window, 0, xsize= (sx2-sx1), ysize= (sy2-sy1)
       tvscl, congrid(simg, sx2-sx1, sy2-sy1, /interp)

;Plotting horizontal lineout
       print, "click mouse on center of left box, best focus box, and right box"
       cursor, bx1, by1, /device, /up
       cursor, bx2, by2, /device, /up
       cursor, bx3, by3, /device, /up
       window, 1
       plot, findgen(61*adj)+(by2*2-(30*adj)), avg(simg(bx2*2-(5*adj):bx2*2+(5*adj),
by2*2-(30*adj):by2*2+(30*adj)), 0), xstyle= 1, xrange= [by2*2-(30*adj),
by2*2+(30*adj)], linestyle= 0, title= "Lineout", xtitle= "Pixel Number", ytitle= "Film
Density * 800"
       oplot, findgen(61*adj)+(by2*2-(30*adj)), avg(simg(bx1*2-(5*adj):bx1*2+(5*adj),
by1*2-(30*adj):by1*2+(30*adj)), 0), xstyle= 1, xrange= [by2*2-(30*adj),
by2*2+(30*adj)], linestyle= 1
       oplot, findgen(61*adj)+(by2*2-(30*adj)), avg(simg(bx3*2-(5*adj):bx3*2+(5*adj),
by3*2-(30*adj):by3*2+(30*adj)), 0), xstyle= 1, xrange= [by2*2-(30*adj),
by2*2+(30*adj)], linestyle= 3
```

```
;Rotation checking loop
        ans= "string"
        WHILE ans NE 'y' DO BEGIN
                print, "is this rotation angle satisfactory? (y/n)"
                read, 'answer = ', ans
                        IF ans EQ 'n' THEN BEGIN
                                print, "by how many degrees should the rotation angle be
adjusted?"
                                read, 'answer = ', r
                                rdeg= rdeg + r
                                print, rdeg
                                rimg= rot_int(img, rdeg)
                                simg= rimg(sx1*2:sx2*2, sy1*2:sy2*2)
                                wset, 0
                                tvscl, congrid(simg, sx2-sx1, sy2-sy1, /interp)
                                print, "click mouse on center of left box, best focus box,
and right box"
                                cursor, bx1, by1, /device, /up
                                cursor, bx2, by2, /device, /up
                                cursor, bx3, by3, /device, /up
                                window, 1
                                plot,     findgen(61*adj)+(by2*2-(30*adj)),     avg(simg(bx2*2-
(5*adj):bx2*2+(5*adj), by2*2-(30*adj):by2*2+(30*adj)), 0), xstyle= 1, xrange= [by2*2-
(30*adj), by2*2+(30*adj)], linestyle= 0, title= "Lineout", xtitle= "Pixel Number",
ytitle= "Film Density * 800"

                                oplot,    findgen(61*adj)+(by2*2-(30*adj)),    avg(simg(bx1*2-
(5*adj):bx1*2+(5*adj), by1*2-(30*adj):by1*2+(30*adj)), 0), xstyle= 1, xrange= [by2*2-
(30*adj), by2*2+(30*adj)], linestyle= 1
                                oplot,    findgen(61*adj)+(by2*2-(30*adj)),    avg(simg(bx3*2-
(5*adj):bx3*2+(5*adj), by3*2-(30*adj):by3*2+(30*adj)), 0), xstyle= 1, xrange= [by2*2-
(30*adj), by2*2+(30*adj)], linestyle= 3
                        ENDIF
        ENDWHILE

;Setting upper and lower bounds to average over
        print, "click mouse on lower and upper bounds in that order"
        cursor, cx1, cy1, /data, /up
        cursor, cx2, cy2, /data, /up

;Plotting lineout
        xvals= (bx3*2)-(bx1*2)
        yvals= median(avg(simg((bx1*2):(bx3*2), (cx1):(cx2)), 1), 3)
        window, 2
        plot, findgen(xvals)+(bx1*2), yvals, xstyle= 1, xrange= [bx1*2, bx3*2], title=
"Lineout", xtitle= "Pixel Number", ytitle= "Film Density * 800"

;Adjusting plot with energy cutoff
        print, "what is the desired energy cutoff for this lineout?"
        read, "answer = ", ecut
        eyvals= yvals-ecut
        plot,   findgen(xvals)+(bx1*2),   eyvals,   xstyle=  1,   xrange=  [bx1*2,  bx3*2],
ystyle= 1, yrange= [0, 1500], title= "Lineout", xtitle= "Pixel Number", ytitle= "Film
Density * 800"

;Energy cutoff checking loop
        ans= "string"
        WHILE ans NE 'y' DO BEGIN
                print, "is this energy cutoff satisfactory? (y/n)"
                read, 'answer = ', ans
                        IF ans EQ 'n' THEN BEGIN
                                print, "by how much should the energy cutoff be adjusted?"
                                read, 'answer = ', e
                                ecut= ecut + e
                                print, ecut
                                eyvals= yvals-ecut
                                wset, 2
                                plot,   findgen(xvals)+(bx1*2),   eyvals,   xstyle=  1,   xrange=
[bx1*2,  bx3*2],  ystyle=  1,  yrange=  [0,  1500],  title=  "Lineout",  xtitle=  "Pixel
Number", ytitle= "Film Density * 800"
                        ENDIF
        ENDWHILE
```

```
;Initializing and using loop to find full-width at half-maximum points with respective
to position
        i= 0
        fxvals= fltarr(1000)
        fwhm= fltarr(1000)
        ix= 0
        s2= size(eyvals)
        index= findgen(2000)
        x= fix(width*mag/pixsize)
        WHILE ((ix+splotrange) lt s2(1)) DO BEGIN
                window, 3
                plot,   index(ix:ix+splotrange),   eyvals(ix:ix+splotrange),   xstyle=  1,
xrange= [ix, ix+splotrange], ystyle= 1, yrange= [0,1500], title= "Lineout", xtitle=
"Pixel Number", ytitle= "Film Density * 800"
                print, "click mouse on top of the edge of the lineout peak. Use left
click to record data. Use right click to skip data"
                cursor, ex1, ymax, /data, /down
                print, "click mouse on bottom of the edge of the lineout peak. Use left
click to record data. Use right click to skip data"
                cursor, ex2, ymin, /data, /down
                IF (!mouse.button EQ 1) THEN BEGIN
                        fxvals(i)= ((((ex1+ex2)/2)*pixsize)/mag)/1000
                        fwhm(i)= (ex2-ex1)*pixsize/mag
                        i= i+1
                ENDIF
                ix= ex1+x-(10*adj)
        ENDWHILE
        fxvals= fxvals(0:(i-1))
        fwhm= fwhm(0:(i-1))

;Plotting full-width at half-maximum as a function of position
        window, 4
        plot,  fxvals,  fwhm,  psym=  4,  title=  "Resolution",  xtitle=  "Position  (mm)",
ytitle= "Edge Response (Microns)", xstyle= 1, xrange= [0, 1.5], ystyle= 1, yrange= [0,
20]

;Plotting error bars with averaged x values and fwhm values
        n= i/2
        n= fix(n)
        n= n*2
        i= 0
        xavg= fltarr(1000)
        yavg= fltarr(1000)
        err= fltarr(1000)
        REPEAT BEGIN
                xavg(i)= (fxvals(i)+fxvals(i+1))/2
                yavg(i)= (fwhm(i)+fwhm(i+1))/2
                err(i)= yavg(i)-fwhm(i)
                i= i+1
        ENDREP UNTIL i EQ (n-1)
        xavg= xavg(0:i)
        yavg= yavg(0:i)
        err= err(0:i)
        window, 5
        plot,  xavg,  yavg,  psym=  4,  title=  "Resolution",  xtitle=  "Position  (mm)",
ytitle= "Edge Response(Microns)", xstyle= 1, xrange= [0, 1.5], ystyle= 1, yrange= [0,
20]
        oploterr, xavg, yavg, err, 4

;Saving results to an output file
        openw, 1, ofile
        FOR j= 0, i DO BEGIN
                printf, 1, xavg(j), yavg(j), format= "(F8.2, F8.2)"
        ENDFOR
        close,1
```

```
;Plotting the point spread function
        print, "where is the best focus location? (mm)"
        read, 'answer = ', bf
        bf= bx1*2+(((bf*1000)*mag)/pixsize)
        window, 6
        plot,   median(avg(simg(bf-(30*adj):bf+(30*adj),   cx1:cx2),   1),   3),   title=
"Lineout", xtitle= "Pixel Number", ytitle= "Film Density * 800"
        print, "click mouse on one edge of the lineout peak"
        cursor, fx1, fy1, /data, /up
        print, "click mouse on other edge of the lineout peak"
        cursor, fx2, fy2, /data, /up
        a= median(avg(simg(fx1-(30*adj):fx2+(30*adj), cx1:cx2), 1), 15)
        b= median(avg(simg(fx1-(30*adj)+1:fx2+(30*adj)+1, cx1:cx2), 1), 15)
        window, 7
        plot,    findgen((fx2+(30*adj))-(fx1-(30*adj))*pixsize/mag),   smooth(abs(a(fx1-
(30*adj):fx2+(30*adj))-b(fx1-(30*adj):fx2+(30*adj))),   5),   title=   "Point   Spread
Function", xtitle= "Pixel Number", ytitle= "Film Density * 800 / Pixel Number"
        print, "click mouse on desired peak"
        cursor, hx, hy, /data, /up
        plot,    findgen((hx+20)-(hx-20)*pixsize/mag),   smooth(abs(a(hx-20:hx+20)-b(hx-
20:hx+20)), 5), title= "Point Spread Function", xtitle= "Position (microns)", ytitle=
"Film   Density   *   800   /   Pixel   Number",   xrange=   [(hx-20)*pixsize/mag,
(hx+20)*pixsize/mag], xstyle= 1

;Calculating the full-width at half-maximum
        print, "click mouse on peak of subimage"
        cursor, xmid, ymax,/ data, /up
        plots, [hx-20, hx+20], [ymax*0.5, ymax*0.5]
        print, "click mouse on full-width at half-maximum points"
        cursor, gx1, gy1, /data, /up
        cursor, gx2, gy2, /data, /up
        fwhm= (gx2-gx1)*pixsize/mag
        print, "fwhm (microns)", fwhm

END
```
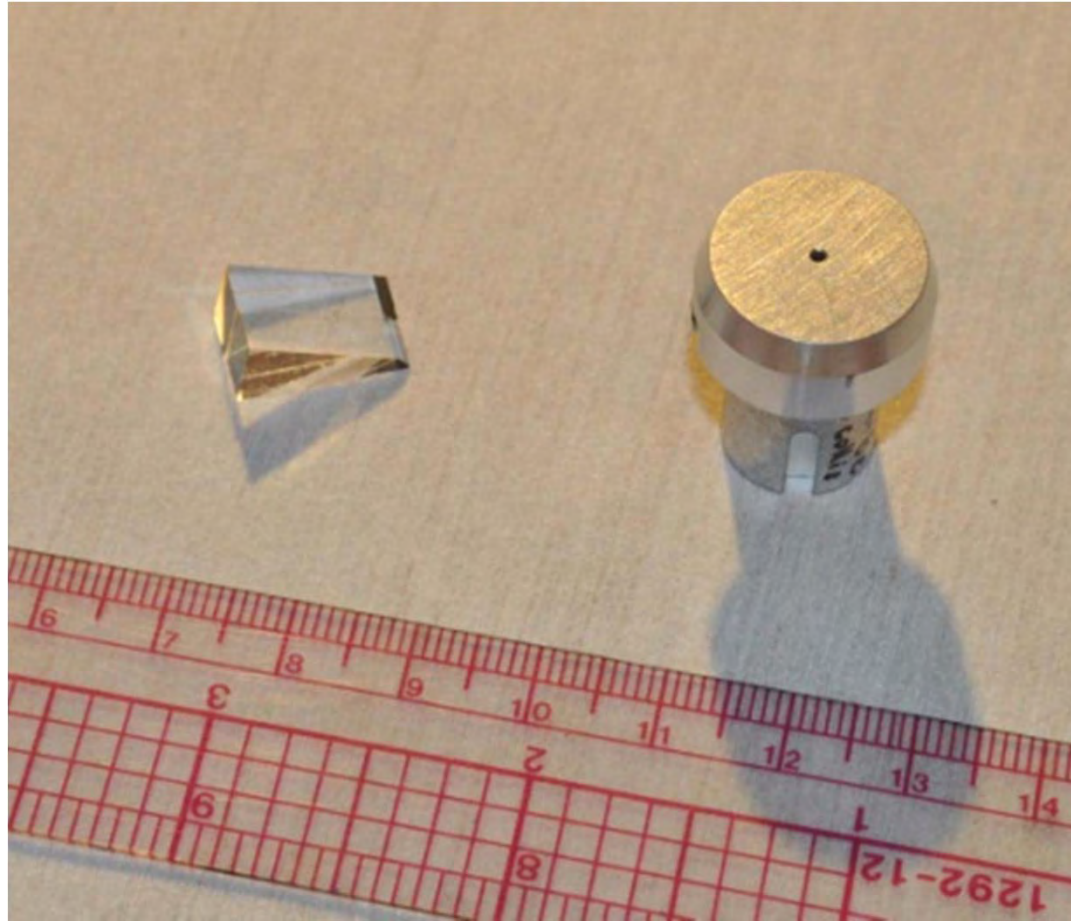
Figure 1. *Kirkpatrick-Baez mirror pair (left) and pinhole camera (right).*
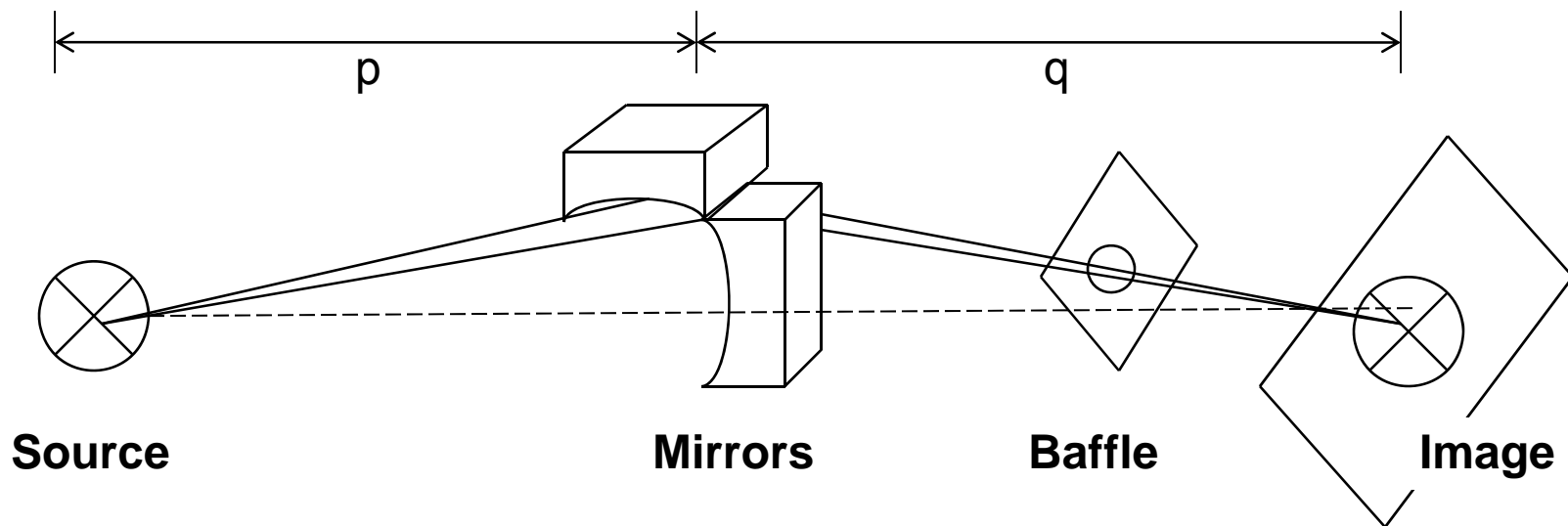
Figure 2. *Kirkpatrick-Baez mirror pair perpendicularly crossed. Each mirror will focus in a different dimension, so rays that reflect off both mirrors will form two-dimensional images. A baffle is also used to filter out the 1-dimensional images and straight-through x rays.*
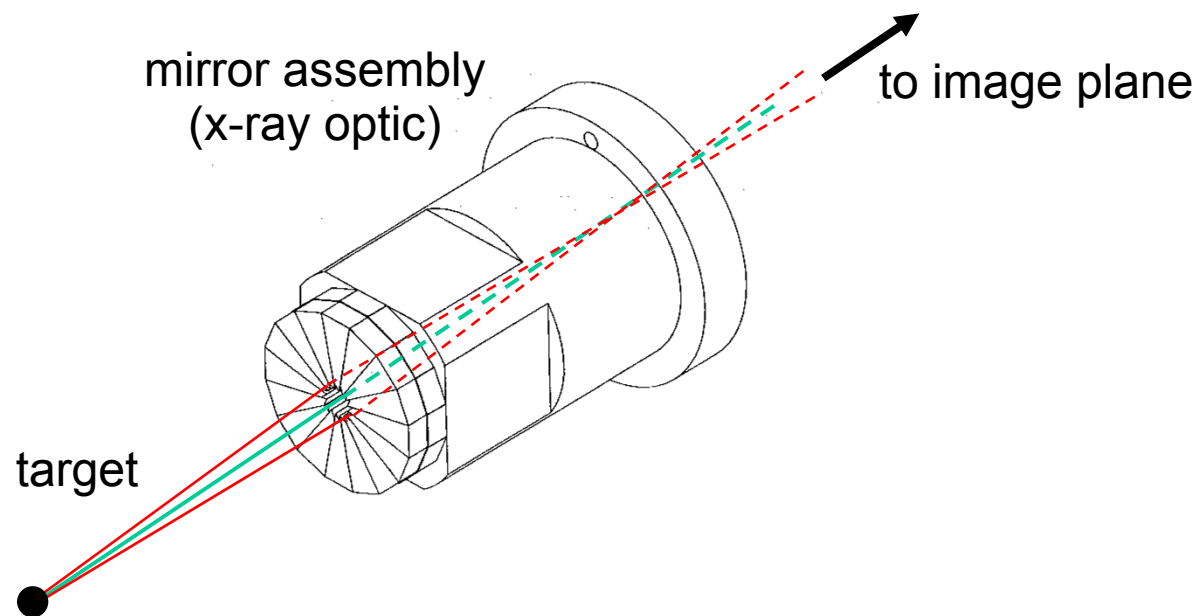
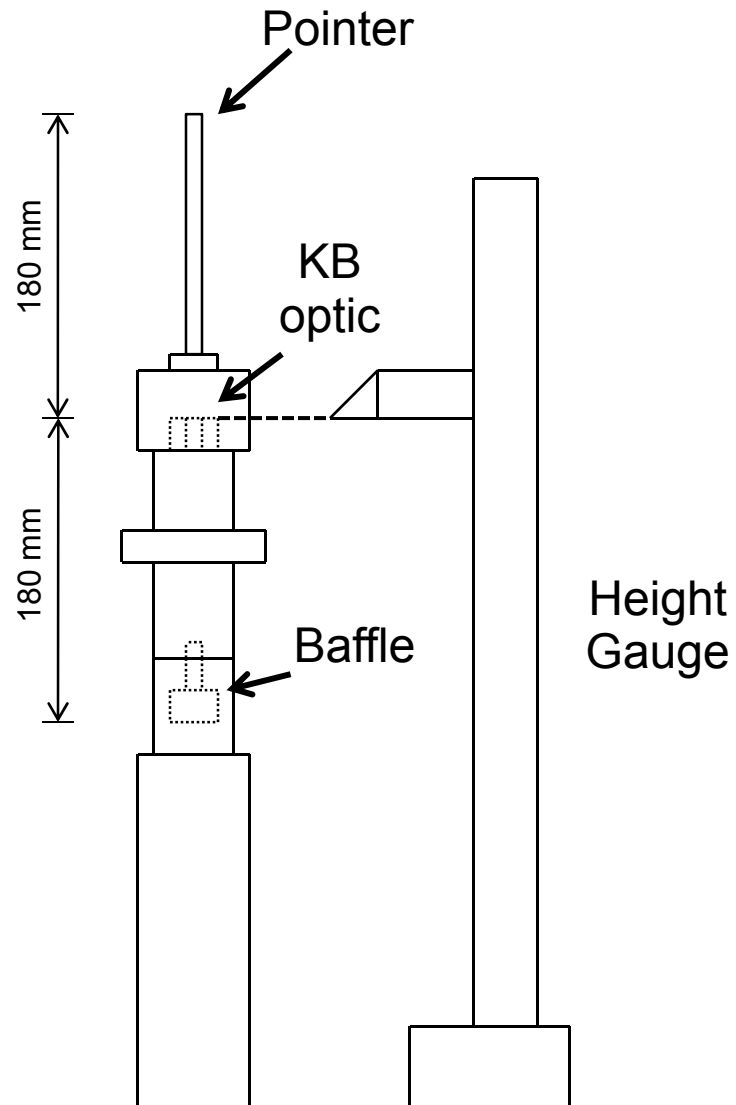**Figure 3.** *Design of the 16-image Kirkpatrick-Baez microscope. The microscope uses 16 mirror pairs to take 16 images for each exposure.*

Figure 4. *Kirkpatrick-Baez microscope precisely positioned with a height gauge. The pointer and the baffle are set 180 mm away from the Kirkpatrick-Baez optic.*
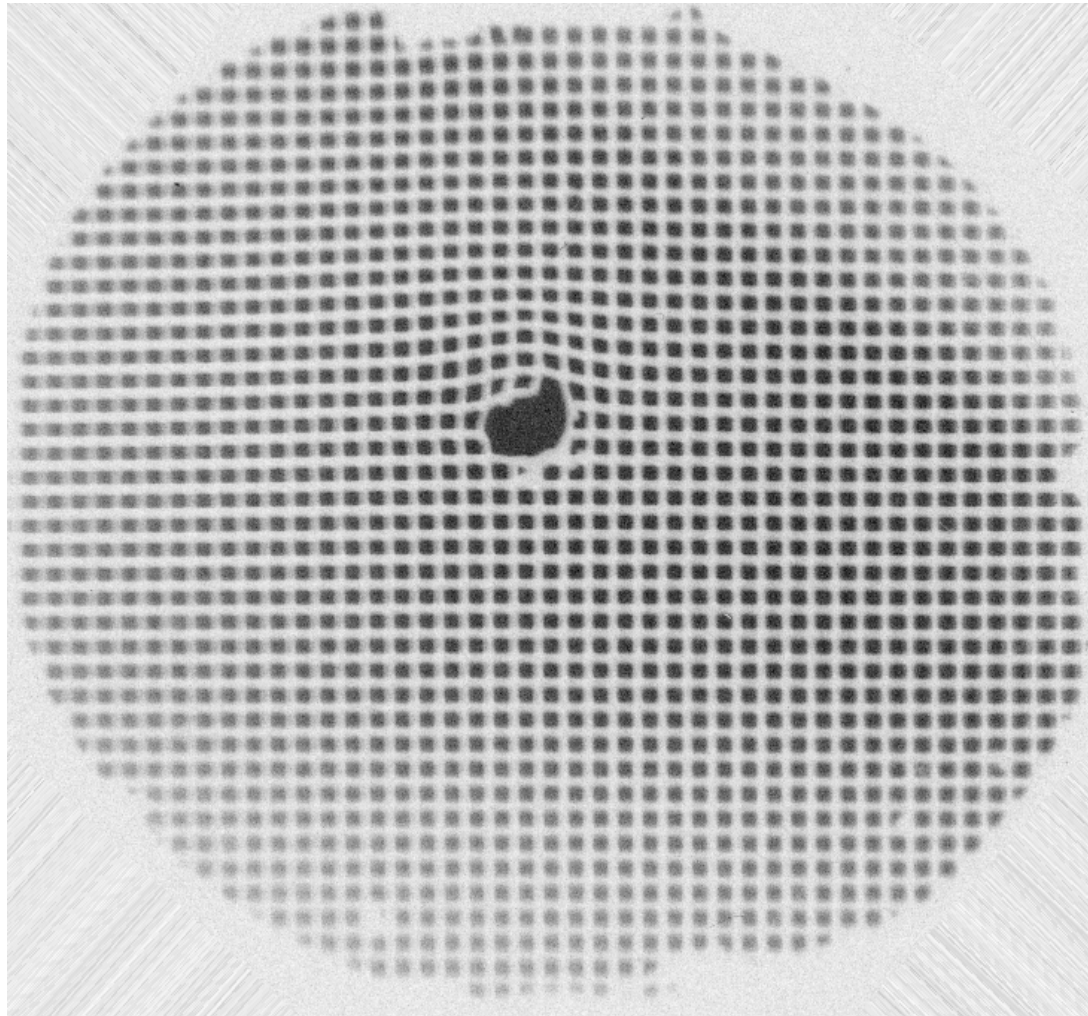
Figure 5. *KB microscope image of a copper mesh grid target. The target has 25.4 μm diameter wires spaced 50.8 μm apart. A reference hole is made for alignment purposes.*
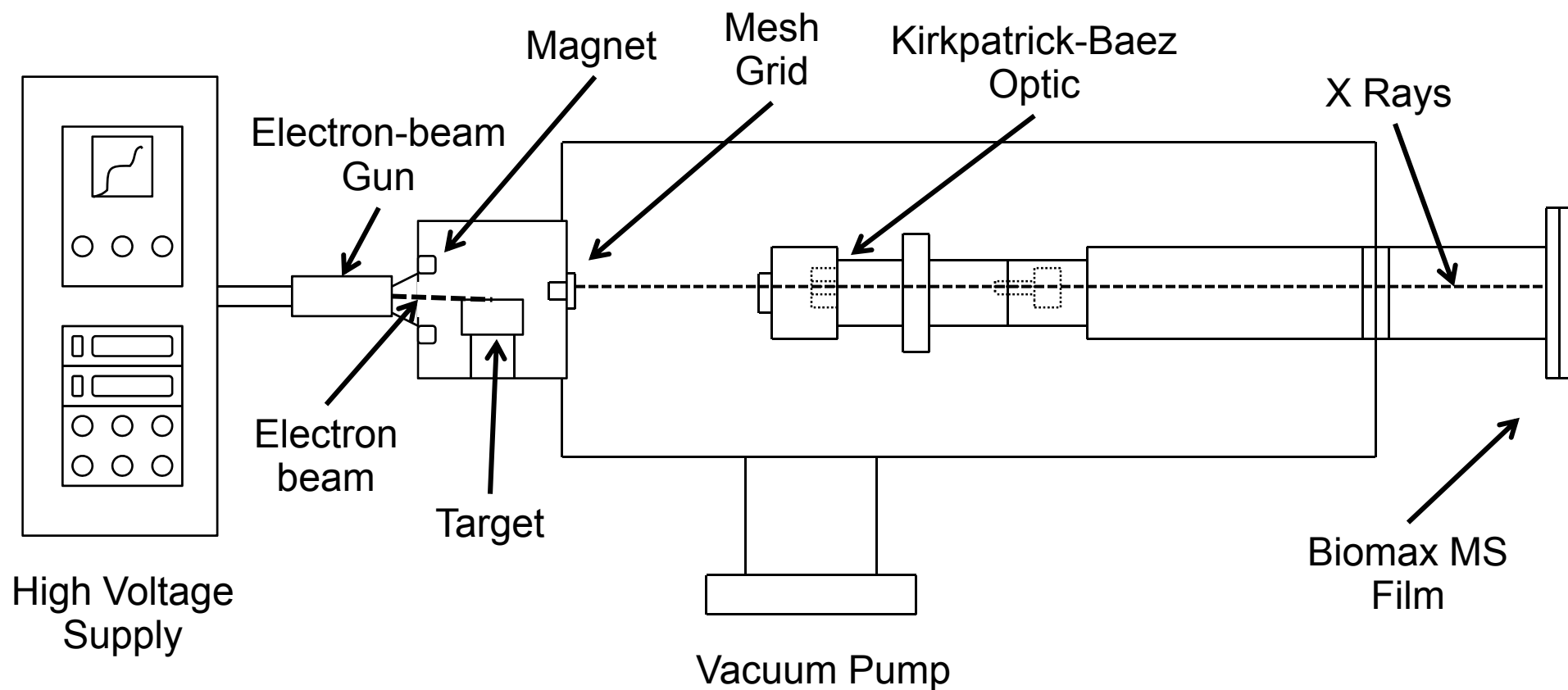
Figure 6. *Apparatus for testing the KB microscope. An electron beam is deflected onto a metal target, which when heated emits x rays. The x rays go through the Kirkpatrick-Baez microscope chassis to expose film at the end of the apparatus.*
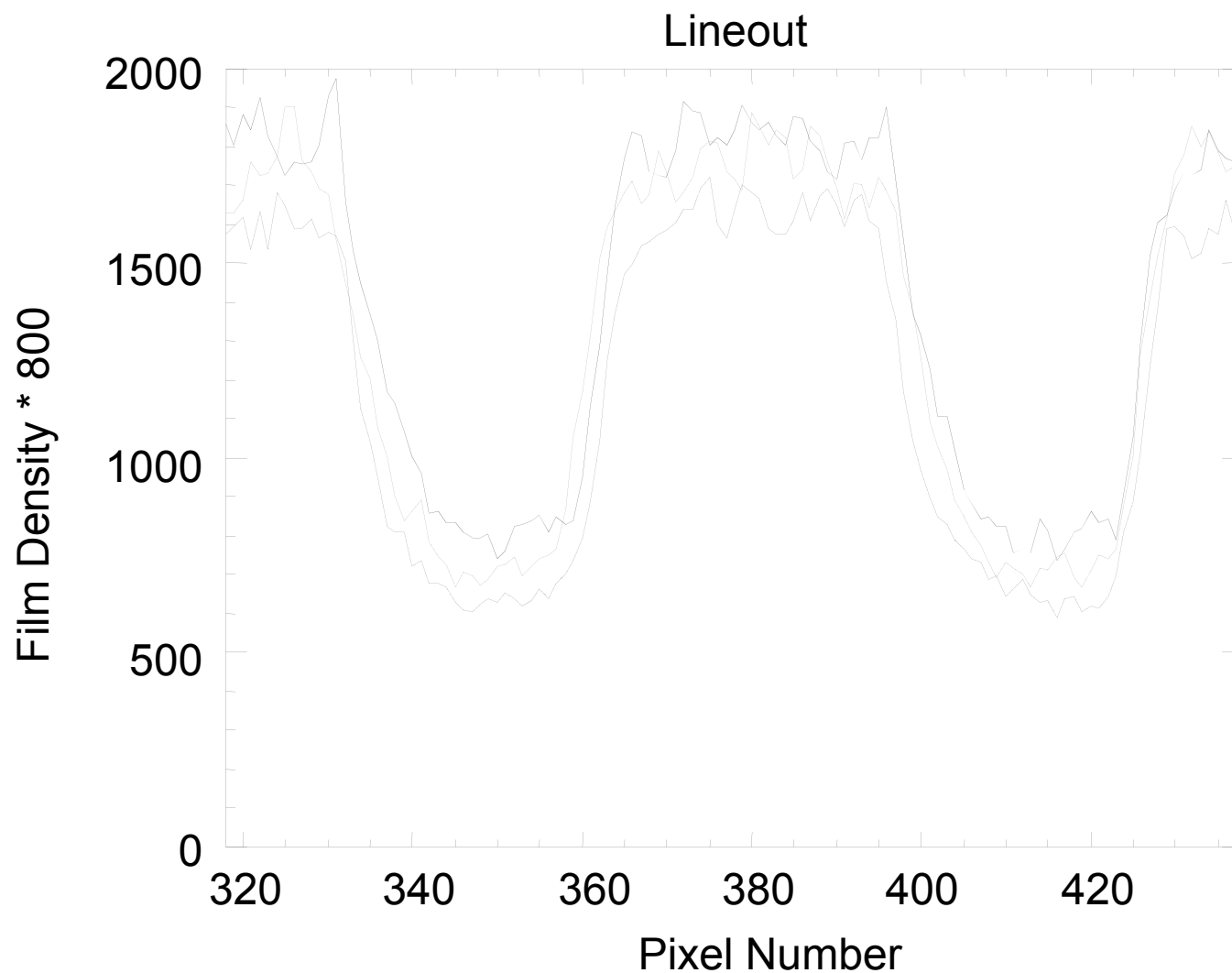
Figure 7. *Optimized rotated image is achieved by comparing vertical lineouts at different horizontal positions. The best rotation angle occurs when the shadows of the wires are aligned.*
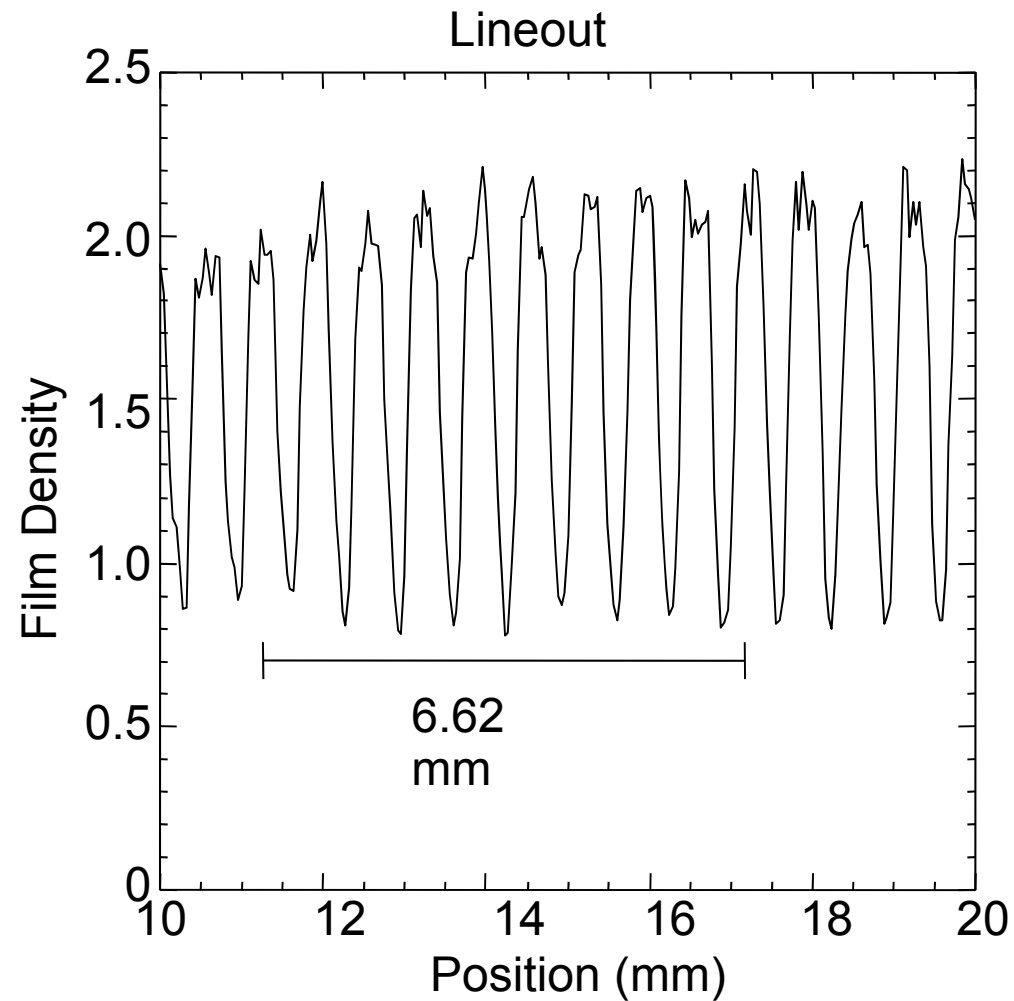
Figure 8. *Measurement of 10 shadows of horizontal lineout. The image length of 10 wires is compared to the actual length to determine the magnification.*
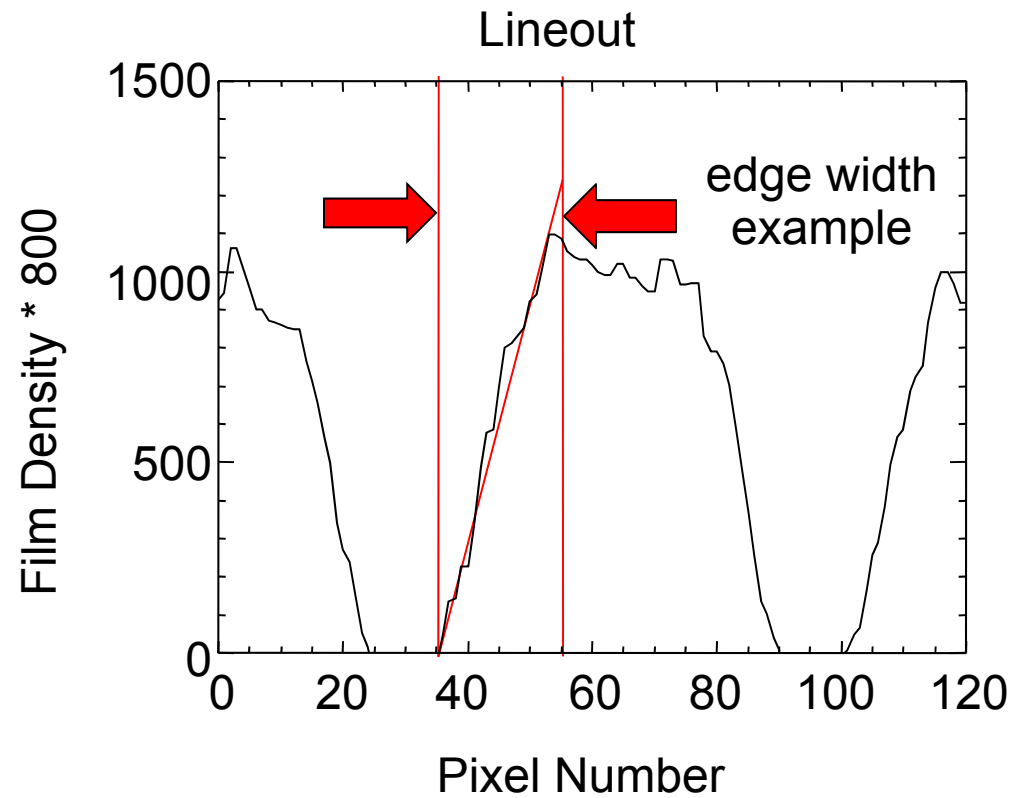
Figure 9. *Example of edge width response. The edge widths are measured across the lineout to determine the best focus position and resolution.*
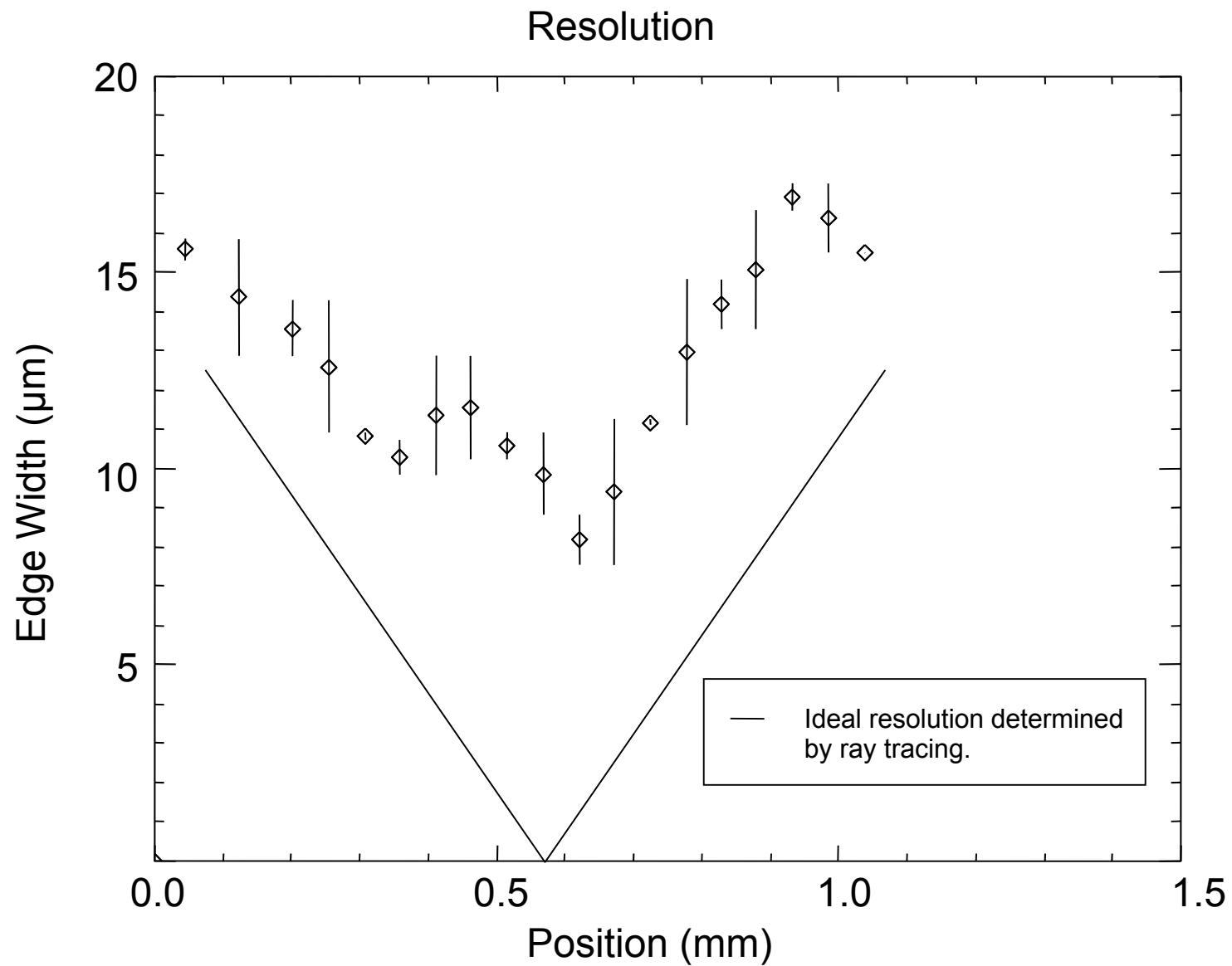
Figure 10. *Measurements of the edge response across a lineout. Diffraction and imperfections of the mirrors prevent the ideal resolution from being obtained.*
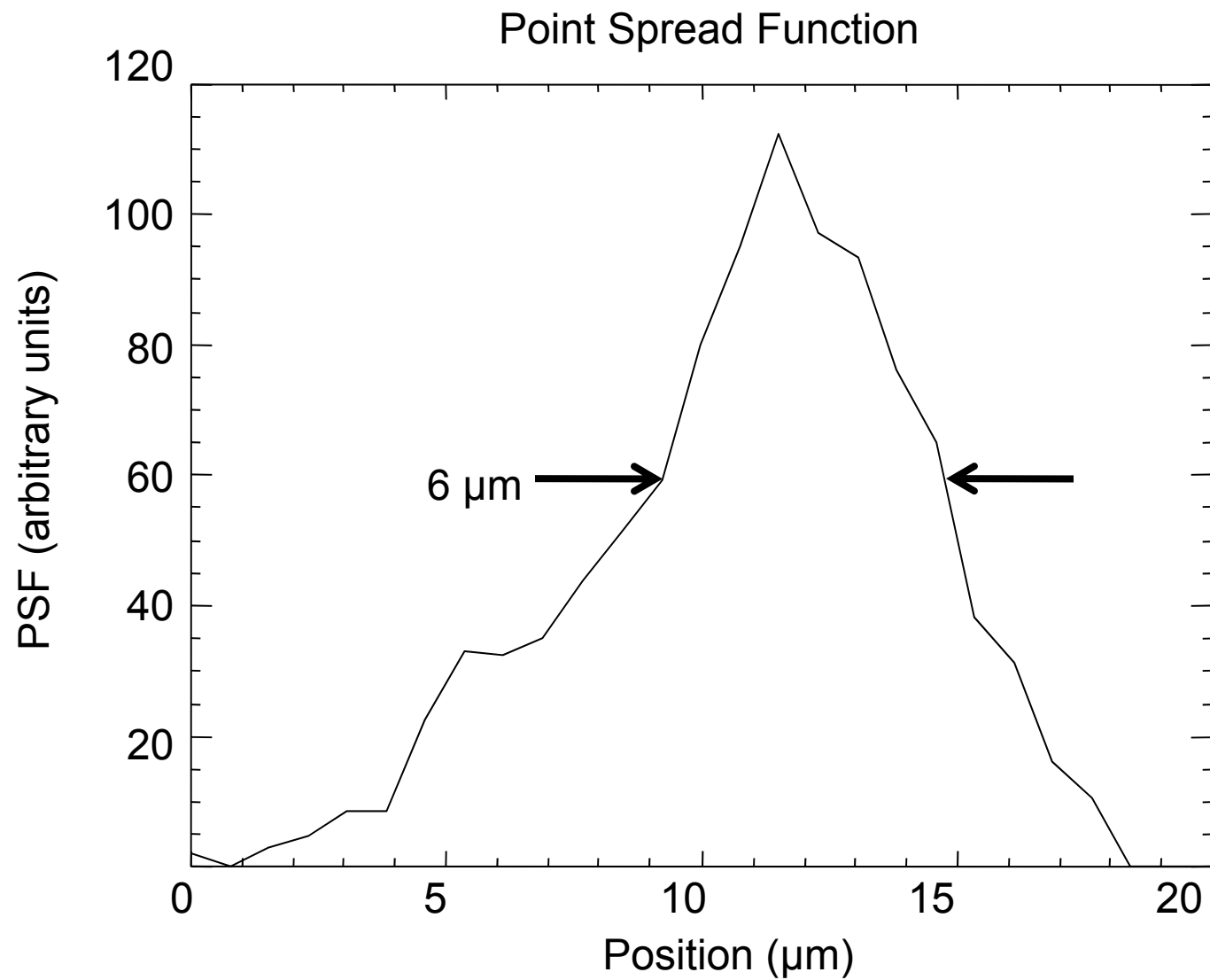
Figure 11. Point spread function determined from the best focus edge response.