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Introduction

There is a need in many areas of synchrotron radiation science for an optical system capable of producing an achromatic sub-micron focus. Of immediate interest at the Advanced Light Source are micro-focusing systems for hard x-ray Laue diffraction (μ-diffraction) and for soft x-ray photoelectron spectroscopy (μ-XPS). Despite the different photon energy ranges, many factors have led us to develop achromatic focusing systems based on mirrors in the Kirkpatrick-Baez (K-B) configuration for both applications.

In μ-diffraction, our aim is to produce a system in which strain can be measured in an arbitrarily oriented micro-crystal in a thin film. The use of zone-plate focusing while ensuring high spatial resolution requires monochromatic light, and would have necessitated the difficult task of constructing a diffractometer with a sub-micron sphere of confusion. Without prior knowledge of micro-crystal orientation, it would also require scanning through a large angle range or a large energy range to find suitable reflections, requiring in the latter case a large longitudinal motion of the sample to track the zone plate focus. In both cases mechanical alignment would be problematic and initial orientation determination would be slow. In the case of a white beam method, orientation is determined directly from the Laue pattern using prior knowledge of the crystal structure. Strain can then be determined by measuring the energy of a unique set of reflections, either by direct measurement of a diffracted beam with a crystal analyzer, or by insertion of a zero displacement monochromator into the incident beam. We have chosen the latter option based on a 4 bounce monochromator using two channel cut crystals upstream of the K-B mirror pair [1]. From the crystal orientation and crystal structure we know the energy of each Laue spot in the un-strained case. Strain is detemined by measuring the precise energy difference from the un-strained case for a small number of reflections.

In the case of μ-XPS, we wanted to develop a system in which we could rapidly tune the photon energy from around 270 eV to 1300 eV, to take advantage of the variation in cross section of the materials of interest (carbon, nitrogen, oxygen and fluorine 1s, transition metal 2p through to the rare earth 3d edges), and to use the change in photoelectron scattering length to enhance and sometimes to avoid surface sensitivity. In this case, restrictions of the sample environment with in-situ optical microscopy, micro-focused ion beam etching, large-wafer handling, and a large-aperture electron analyzer required a minimum distance of 5 cm between the sample and optics [2]. This would have been difficult with a zone plate system, and would have required the use of many interchangeable zone plates with different focal lengths to accomodate the required range of photon energies.

Mirrors can be formed in a number of ways, for example from a capillary [3,4], a single toroidal or elliptical surface [5,6], or by a combination of surfaces, such as the Kirkpatrick-Baez (K-B) mirror pair [7]. Although around 1-μm spatial resolution has been obtained with ring shaped ellipsoids in the soft x-ray region[8], the relatively low aperture and the extreme problems of obtaining a low-scatter finish on the internal surface made us avoid this option. Excellent spatial resolution has been obtained with capillary optics [9], but at the price of a relatively small collection aperture, with flux-density gains typically being a few hundred. However, the combination of the ultra-low divergence of third-generation undulator sources with K-B pre-focusing optics may make this an attractive option in the future [10]. The K-B mirror system with plane elliptical surfaces offers excellent possibilities for a large collection aperture and high spatial resolution, but with the significant problem that near-perfect elliptical surfaces have to be fabricated. In this report, we describe a novel approach to achieving near-perfect bending of flat substrates into the required elliptical shape, and report on two mirror systems for μ-diffraction and μ-XPS, that have produced a spatial resolution of 0.78 μm and 1.6 μm respectively.

Elliptical bending

Figure 1 shows the general scheme of the K-B mirror system. The two mirrors are elliptical in the tangential direction and plane in the sagittal direction and are mounted in a crossed configuration. The convergence angle onto the sample can have a maximum value of the critical angle of reflection; this would correspond to a situation where a ray near the object side of the ellipse would be travelling almost parallel to the surface, and at the image end it would strike near the critical angle. In practice, several practical considerations such as the allowed magnification and curvature change usually restrict the aperture to a smaller value. Conservation of phase space requires for a certain image size s' and convergence angle f' combined with a defined source size s, that the collection angle be given by f=f's'/s. For example, in the case of μ-diffraction in beamline 10.3.2 at the ALS [11], we vertically image the source at 31m to a focus at 0.5 m. With a vertical emittance of 6 x 10^{-11} m·rad and a vertical beta function of 1.46 m, we would expect a source size of 22 μm (FWHM) and an image size of 0.37 μm (FWHM). In order to have good reflectivity for a platinum reflector up to 11 keV, we have used a grazing angle of 5.8 mrad, and a convergence angle of 1.9 mrad. This means that the vertical acceptance from the source is 32 μrad, or at 31 m, a physical aperture of 0.98 mm and a mirror length of 165 mm. In the horizontal case, we have a source size of 245 μm (FWHM) (beta x = 0.85m, emittance = 6 x 10^{-9} m·rad at 1.9 GeV, energy spread = 8 x 10^{-4}), an object distance of 31.4 m, an image distance of 0.1 m, and an expected source size of 0.78 μm (FWHM). In this case therefore, the source acceptance is 6 μrad, or at 31.4 m, a physical aperture of 0.19 mm and a mirror length of 33 mm. The reflectivity of each mirror is around 0.85, so we could expect a flux density gain of 4.7 x 10^5 if the mirrors focus perfectly.

We have chosen to produce elliptical surfaces by elastic bending of initially flat substrates using the application of unequal couples. This approach, originally used for producing collimators [12] has the great merit that flat substrates can be easily made to the required tolerances and also can be measured to very high precision by optical interferometry. A multilayer mirror K-B system based on a similar approach has produced a spatial resolution of around 1 μm at 8.5 KeV [13]. In the case of μ-diffraction however, we had to use much smaller grazing angles for specular reflection and required a collection angle as large as possible; this necessitated active mirror lengths of approximately 20 and 4 times those used in [13], while keeping the same figuring accuracy. The allowable slope deviation of the surface from the ideal is simply set by the angular size of the source. In the case of the parameters of an ALS bending-magnet source given above, we have vertical and horizontal angular sizes of 0.7 μrad (FWHM) and 7.8 μrad (FWHM) respectively. Taking into account angle-error doubling on reflection and a desire to have an image broadening no greater than half of the real image size, this sets a requirement for the slope errors to be a maximum of 0.18 μrad (FWHM) and 2.0 μrad (FWHM). Although small, these tolerances are well within the capabilities of optical polishers for relatively short flat substrates.

The mechanisms we have developed for producing highly accurate bending are all based on the application of unequal couples using springs. A schematic of one type of mechanism is shown in Figure 2. In this case, weak springs attached at each end of the mirror are anchored to a base at one end and to a slideway at the other. Moving the slideway to the left (F) deforms the springs into opposed S shapes, which apply equal and opposite couples to the mirror and bend the mirror into a circular shape. To apply unequal couples, the beam is pushed on the neutral axis (G), which would increase the right hand couple and decrease the left hand couple. One of the great merits of applying the couples through weak springs is that the extension of the spring can be large, so the couples can be applied with high accuracy using only relatively coarse actuators. In addition, the change in couple caused by thermal expansion mismatch of the mirror to the base is effectively eliminated. Expressing the moment in terms of the applied couples, the simple beam bending equation can be re-written as,

$$EI_0\frac{d^2y}{dx^2}=\frac{C_1+C_2}{2}-\frac{C_1-C_2}{L}x$$

where E is the modulus of elasticity, I is the moment of inertia of the beam, C_1 and C_2 are the applied couples, y is the vertical displacement and x is the distance along the beam from the middle. It can be seen, therefore that the sum of couples is responsible for a fixed curvature term, and the difference of couples is responsible for a term that varies linearly with displacement. These correct the optical aberrations of defocus and aperture defect (coma). However, for the extreme ranges of curvature needed for high aperture highly demagnifying micro-focusing systems, it is necessary to include many more optical aberration terms with higher power dependences on x. This can be done by varying the moment of inertia of the beam as a function of x. The moment of inertia is given by $I=bh^3/12$, where b is the width of the beam and h is its thickness. In this case, we chose to vary b, as a change in width is easy to produce by controlled grinding. The same effect can be produced by changing h, which can be conveniently done for metal mirrors by wire electric-discharge machining. Details of this approach, as well as the fundamental equations of beam bending, can be found in [14].

Systems for μ-diffraction and μ-XPS

Figure 3 shows the arrangement of the μ-diffraction system installed in beamline 10.3.2 at the ALS. Beam enters from the left, is reflected from the long vertical focus mirror, passes through an image plate, and is horizontally focused by a shorter mirror 100 mm from the focus. The vertical focus mirror is made of ULE glass and the springs are attached to blocks that were glued with epoxy to the ends of the beam. It is essential to glue to the ends of the beam rather than the base, as any shrinkage of the glue will produce forces perpendicular to the beam, and these cannot produce bending. The glass substrate was edge-shaped to produce the correct variation of moment of inertia, giving a variation of 3 mm in comparison to a center width of 42 mm. Details of the construction of the vertical focus mirror can be found in [15]. The horizontal focus mirror uses a more elaborate spring system in which the main couple is applied by "S" springs, and piezo-driven screws drive much weaker cantilever springs to provide a fine adjusting mechanism. The system shown has a piezo-driven cleaved GaAs crystal at the focus that allows knife edge measurements of the focus size to be recorded. Normally this location is occupied by a sample centered in a two-axis goniometer that positions an x-ray CCD camera for recording diffraction patterns.

As an example of the performance of the mirror systems, Figure 4 shows the beam size recorded for 2/3 illumination of the vertical focus mirror. The beam size is 0.78 μm (FWHM), approximately twice the calculated value. At positive positions, we can see an asymmetry possibly caused by a small error in the difference of the couples. In addition, outside ± 2s of the Gaussian fitted beam, we see additional intensity that falls off almost linearly with position. This background is due to scattering from the mirrors and needs to be reduced by improved optical polishing techniques. In the horizontal direction, we have measured a beam size of approximately 1.6 μm at 2/3 aperture. The gain in flux density is therefore 5.0 x 10^4 in comparison to the 4.7 x 10^5 for perfect mirrors. This difference reflects the use of 2/3 aperture and a factor of two increase in beam size in each direction over the expected demagnified source size. However, this gain in conjunction with a bending-magnet brightness at 10 KeV of 6 x 10^{14} photons/sec·mm^{-2}·mrad^{-2}· 400 mA· 0.1% band for standard 1.9 GeV operation is sufficient for a wide range of thin-film diffraction studies.

Over the next few months, we will continue to develop the techniques of microfocusing using K-B mirrors, and then the system will be transferred to a dedicated beamline, 7.3.3. This beamline differs from 10.3.2 in that we are using a toroidal mirror to focus the source to a pair of slits at the front of the x-ray hutch. We can then choose the "source" size and therefore the appropriate demagnification. This also allows us the advantage of imaging a hard-edged source object, as well as enabling us to have a linear trade-off between flux and resolution simply by changing the slit width.

We have also developed a similar system for XPS [2,16]. This again uses optics to form an intermediate focus at a pair of slits, and a K-B mirror pair focuses at nominal 20 : 1 (v) and 41 : 1 (h) demagnification to a 1-μm focus. The object and image distances are (4.0m, 0.2m) and (4.1, 0.1m) for the vertical and horizontal focus mirrors respectively. The full optical lengths are 50 mm (h) and 100 mm (v), and we currently run with lengths of 33 and 55 mm, respectively. A grazing angle of 1.6° and a platinum coating are used to ensure good reflectivity to 1300 eV. The grazing angle is five times that of the μ-diffraction system, so the radius of curvature is approximately five times less. In the case of the horizontally focusing mirror, we have a central radius of 7 m. To reduce stress to the same as the μ-diffraction horizontal-focus mirror, the substrate would have to be five times thinner (2 mm) and consequently would not be stiff enough to polish flat to the required level. As the stress in the μ-diffraction mirror is already high, the only solution is to use a different material. In this case 17-04 PH precipitation-hardened steel was used, with the superpolish directly applied to the steel [17]. Of a total 13 of mirror substrates to date, all have had a finish in the range 2 - 3 Å rms. The deviation from the desired elliptical shape for both mirrors used in our current system is less than 3 μrad rms, and with improved substrates we now have, this should reduce significantly.

The actuator for the vertical-focus μ-XPS mirror is shown in Figure 5. The springs in this case are cantilevers with the lower end pivoted to and attached to slideways and are bolted at the other end to the mirror through a polished interface. The beam passes between the center pair of bolts. The whole double-mirror arrangement is integrated in an ultra-high vacuum system, and has in-vacuum step motors to adjust the couples and the longitudinal position. With the first-generation mirrors currently installed, we have achieved a focus size of < 2 μm in each direction. The system is routinely used at this resolution for scanning XPS at high data rates, primarily dedicated to the needs of the semiconductor industry. One reason for the high data rate is that the entire vertical emission of an ALS bending magnet at 1 keV can be accepted by a mirror system and compressed to 1μm without geometric loss due to the small source size. Including the reflectivity of each mirror (0.7 each), the flux density increase for the aperture used was

1.7×10^5. In order to test the stability of the system, a spare mirror assembly was baked to 140°C for 4 days in its bent state; no change in elliptcal shape could be detected at the μrad level using a long trace profiler (LTP). The performance of the μ-XPS system is presented in [18]

Summary and future directions

There is a need for in-situ measurement with x-rays and dynamic adjustment. So far we have used a variant of the Foucault knife test to assess the deviation of the surface from the required elliptical shape, but aperture scanning techniques in which the local slope is measured using either a scanning slit or an array of holes are promising avenues to solve this problem. A scanning slit arrangement has recently been used at ESRF for this purpose, with a slope measuring precision of better than 25 nrad (rms), and has been successfully applied to alignment of a K-B mirror system [19]. Ultimately we will be limited by the perfection of the initially flat substrate, but this can be overcome to a large extent by correcting the width or thickness of the substrate to compensate the deviations from flatness or for residual bending errors.

Kirkpatrick-Baez elliptical mirror systems have been built which produce spot sizes around 1 μm and flux density gains of 5×10^4 for μ-diffraction and 1.7×10^5 for μ-XPS. With a modest investment in alignment techniques and in procuring flatter substrates, we can expect to see the spatial resolution improve to < 0.5 μm in the near term. The use of directly polished steel for a substrate material should also open up many new opportunities for high performance optics. Finally it should be noted that if near perfect elliptical surface can be made, the diffraction limited resolution of mirror systems can be extremely good. In the case of the mirrors used in this work, the diffraction limit for the μ-diffraction system is 33 nm at 10 KeV, and for the μ-XPS system is 43 nm at 1 KeV.

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Figure Captions

Fig. 1

General arrangement of a Kirkpatrick-Baez mirror focusing system. A cleaved crystal knife blade is used to cut the beam in order to measure beam size.

Fig. 2

General arrangement of an 'S' spring mirror bender. F controls the sum of couples and G the difference in couples.

Fig. 3

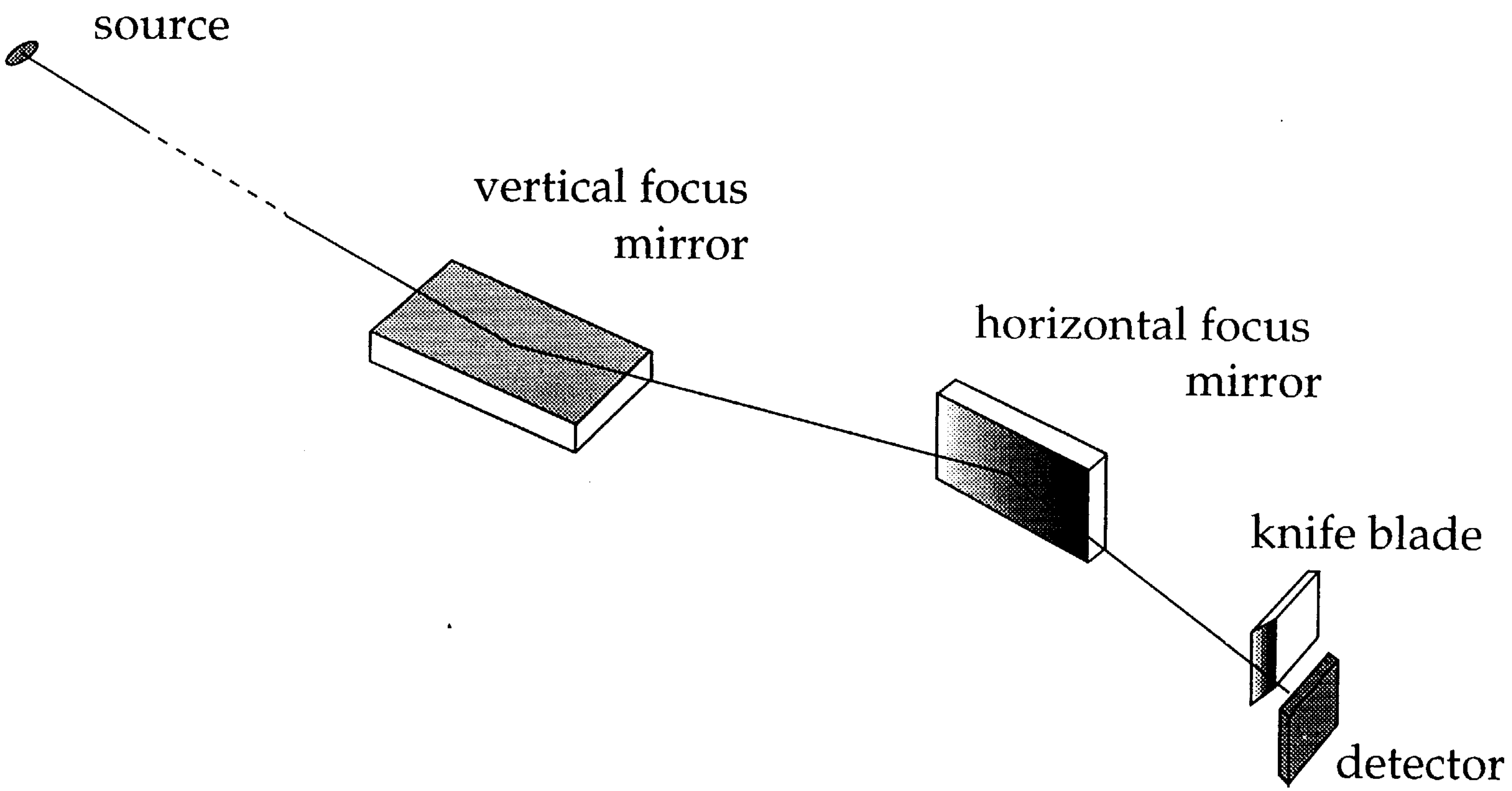
μ-diffraction K-B mirror pair. Light enters from the left, passes through slits, is vertically focused, passes through a hole at the center of an image plate and is horizontally focused. A piezo controlled knife edge is used for measuring the beam size.

Fig. 4

The measured vertical beam size in the μ-diffraction system. The FWHM is 0.78 μm. The non-gaussian intensity at + 1 to + 3 μm is probably residual coma. The wings are probably due to scattering from the mirror. 56% of the beam is within the gaussian profile.

Fig. 5

μ-XPS vertical focus mirror. The mirror bending is performed with cantilever springs mounted to motor driven slideways. The mirror is steel, and the superpolish is applied directly to the steel surface. Center radius is 14 m.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knife blade
detector

Figure 1

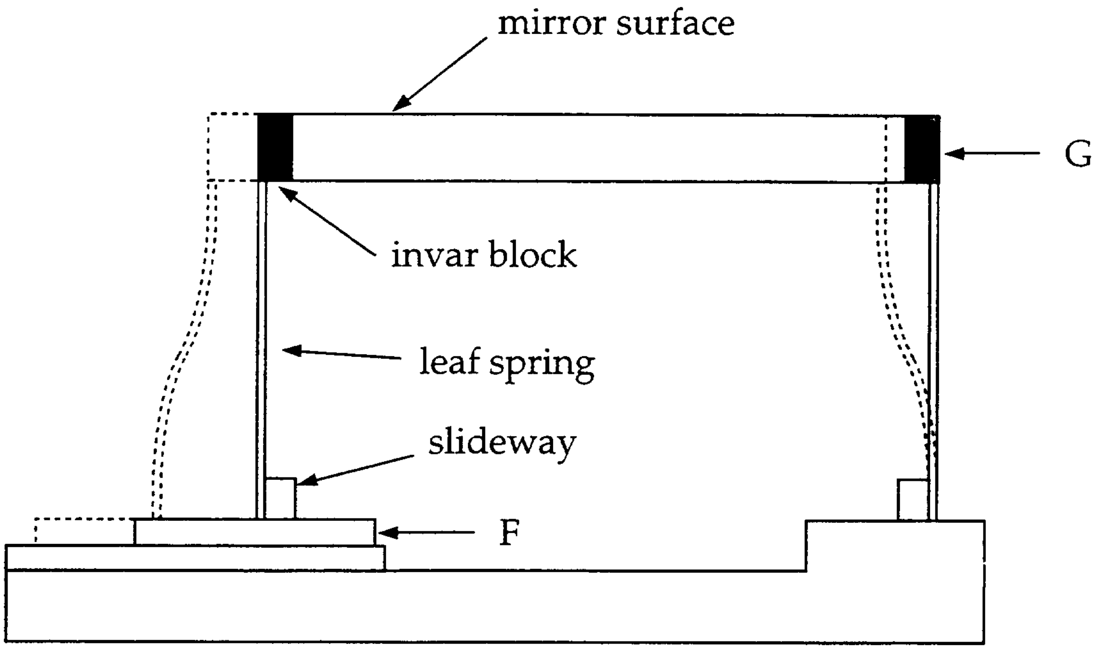
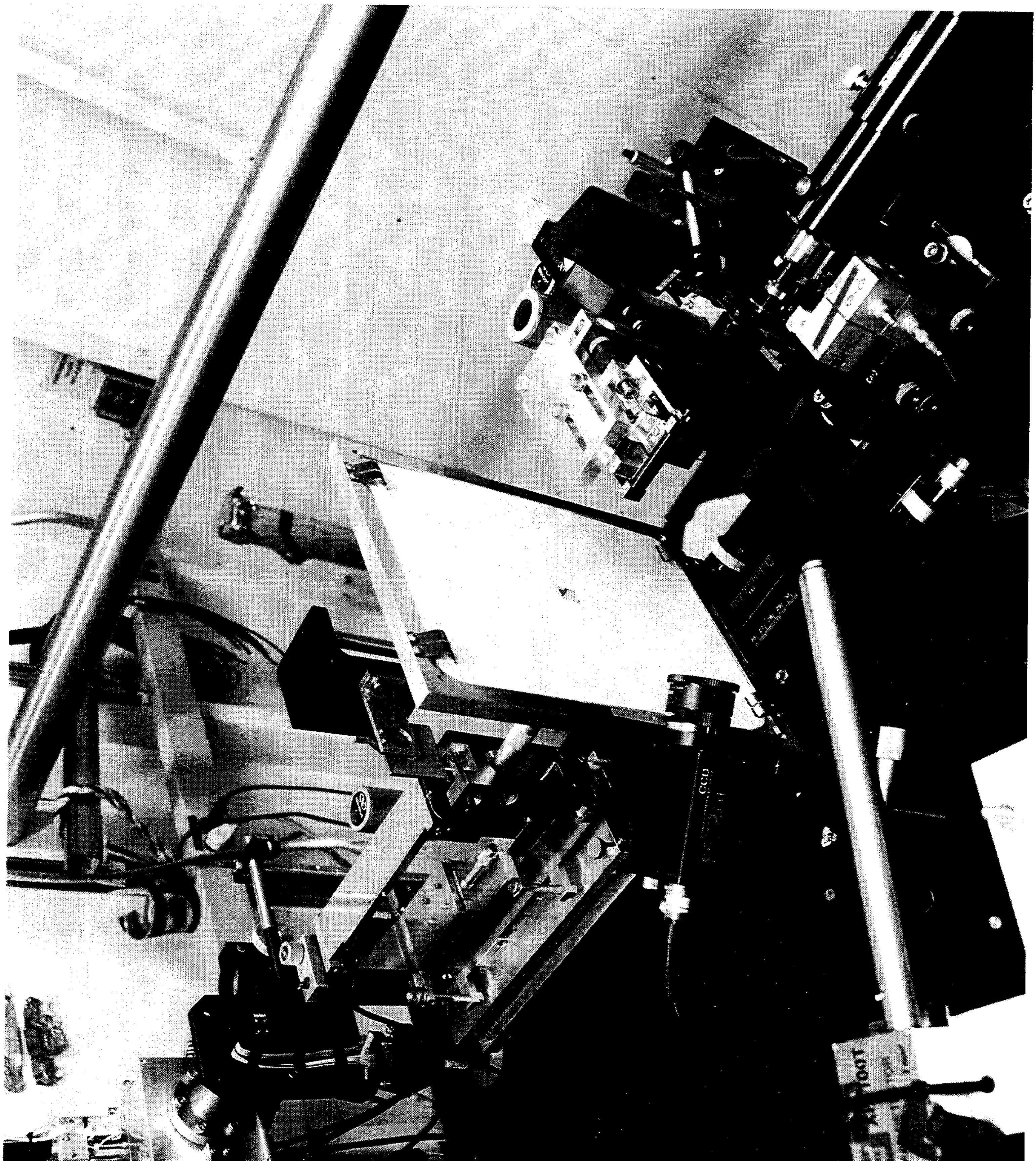


Figure 2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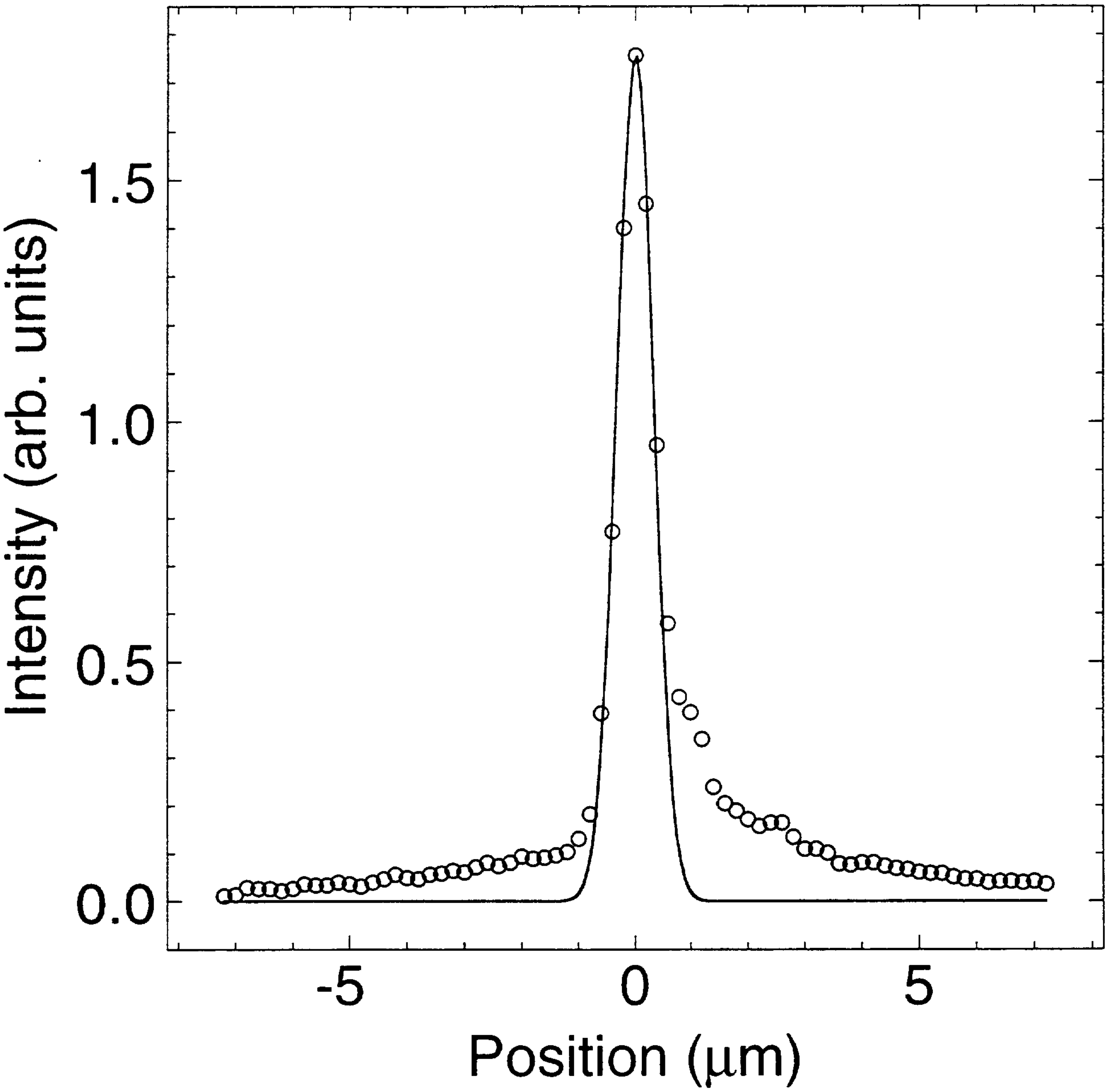

Figure 4