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2.B X-Ray Imaging with Kirkpatrick-Baez Microscopes

This article describes the design, testing, and use of Kirkpatrick-Baez (KB) x-ray microscopes on OMEGA. These microscopes consist of grazing-incidence mirror pairs arranged to reflect and focus x rays, thereby providing images of the x-ray-emitting region. KB microscopes are one of several practical devices that can be used to focus and collect x rays. Simpler x-ray-imaging devices are the pinhole camera and cameras involving coded-aperture (typically Fresnel zone-plate) techniques.[1] These, however, do not use x-ray optics. The KB microscope[2] and its axially symmetric relative, the Wolter microscope,[3,4] both use the principle of grazing-incidence reflection of x rays to form images of the x-ray-emitting region.

The KB microscope was originally conceived and developed by Kirkpatrick and Baez in 1948.[3] In this device, shown in Fig. 46.18, the meridianal rays from a point p are reflected from a mirror surface and form an image at q. For a source-to-mirror distance of d and a mirror-to-image distance of D, the requirement for focusing is given by

$$1/d + 1/D = 2/R\sin i = 1/f. \tag{1}$$

Since only the meridianal rays (i.e., the rays in the plane of Fig. 46.18) are focused by one such mirror, to obtain images of two-dimensional objects, two such mirrors are placed with their normals perpendicular to each other (along x and y) and perpendicular to the source-mirror direction (z-axis). This allows the unfocused sagittal rays of the first mirrors, which are then the meridianal rays of the second mirrors, to be focused. The principal contributions to aberrations of this system are obliquity and spherical aberration.[5]

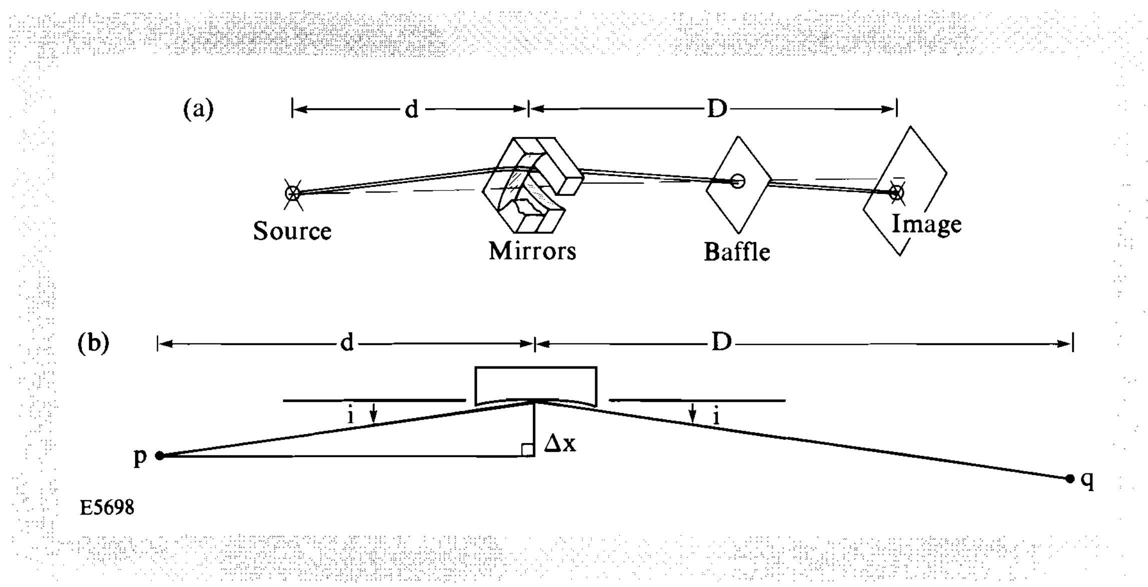

Fig. 46. 18
Schematic of the LLE KB microscope optical assembly (a) and focusing geometry (b).

KB Microscope Development at the Laboratory for Laser Energetics (LLE)

The mirrors of the LLE KB microscope are constructed of Cervit, a glass with a low coefficient of expansion. The assembly of the optical components has been accomplished as follows:[6] The mirrors were cut to shape with their surfaces given a sufficient polish to enable optical contacting to be accomplished at a later stage. Next, the mirrors were arranged on a spherical polishing table, where they were given a radius of curvature of approximately 30 m. Subsequent to initial polishing, the mirrors were given a final surface finish by repeated hand polishing until the surface roughness was <10 Å. This step caused slight changes in the radius of curvature of the mirrors, so that the final focus of the x-ray microscopes had to be determined by actual measurements. The final assembly procedure required that the components of the KB microscope be optically contacted together. The precision of the assembly of the mirror components of the microscope is such that an alignment of better than 1 arc sec is maintained between the mirror normals. This ensures that the amount of misfocus is negligible when compared to spherical aberration and obliquity.

Both nickel-coated and gold-coated KB mirrors have been prepared by the evaporative method. The calculated reflectivities, assuming 0.7° grazing angle, are shown in Fig. 46.19. Both curves include transmission through a 25-μm-Be light shield, which is typical. The nickel-coated mirrors are seen to have a high efficiency at low energies but have a cutoff energy of ~4.5 keV. The gold-coated mirrors, on the other hand, do not have as high an efficiency as the nickel-coated mirrors but have a response that extends out to 7 keV.

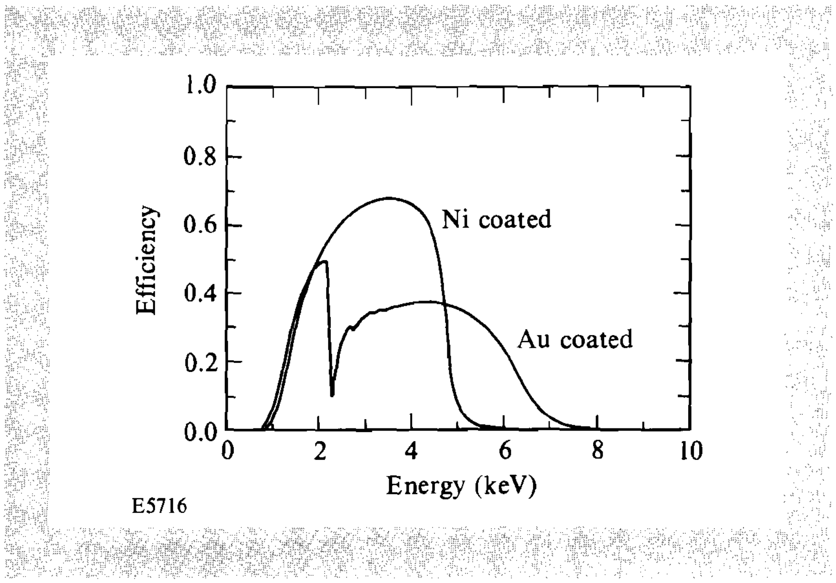

Fig. 46.19
Calculated reflection efficiency of the nickel-coated and gold-coated KB microscopes. Both curves assume an 0.70° grazing angle and include transmission through 25.4 μm of Be, which is used as a blast shield.

KB Microscope Testing

A facility has been assembled at LLE for testing and characterizing KB microscopes. The facility (Fig. 46.20) consists of a two-chamber vacuum system for housing the x-ray microscope and a high-flux electron-beam-generated x-ray source. Both chambers are pumped to an initial vacuum pressure of ~0.1 mTorr by a roughing pump. The chambers are then pumped

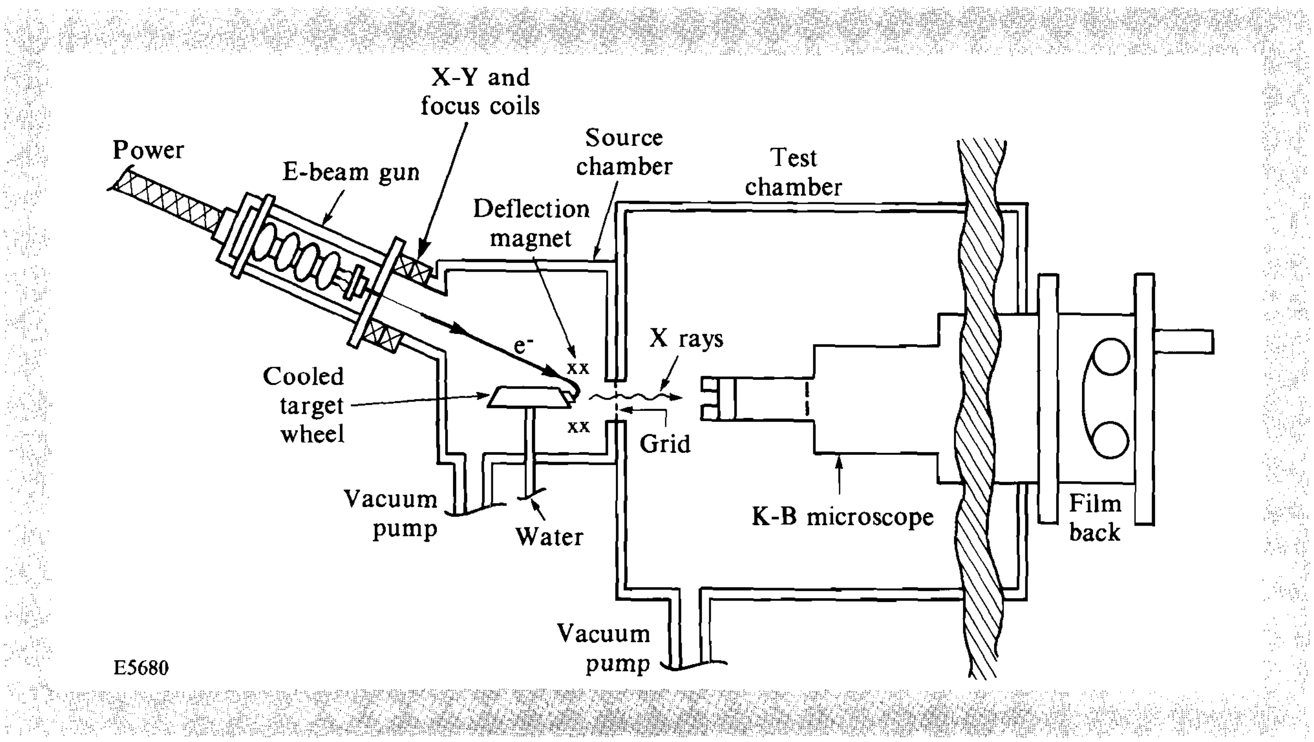

Fig. 46.20
Schematic of the KB microscope testing facility.

to a high vacuum (<10^{-6} Torr) by separate ion pumps, a 500-l/s-capacity pump for the main chamber and a 50-l/s-capacity pump for the x-ray source chamber. X rays are generated by causing an electron beam to strike a metal target positioned inside the source chamber. The electron beam gun is a modified Pierce type.[7] It creates a beam of electrons that can be focused to a spot <1 mm in diameter. The e-beam gun, controls, and power supplies were originally built and sold commercially as a welding device. To direct the e-beam so it strikes the target at the desired position, the operator adjusts the current to the x-y deflection coils and the bending magnet (Fig. 46.20). Positioning is accomplished visually by aligning the fluorescing spot the e-beam creates on the surface of the target with the previously aligned crosshair of an inspection microscope (not shown in Fig. 46.20). This inspection microscope has been prealigned so that its crosshair and the x-ray microscope are both pointed at the same place on the target wheel. The beam spot size is then adjusted by changing the current supplied to the focusing coil so that an area source of x rays is created. The e-beam gun can be operated at up to 15 kV and 30 amps. Actual beam current depends on specific settings, 10 mA is a typical example. The e-beam is directed onto the source wheel containing several metallic targets on a water-cooled base. Aluminum, iron, and silicon targets are typically used in tests. A summary of typical operating conditions and settings is given in Table 46.II.

Table 46.II: Test chamber x-ray source.

Type	Electron beam, modified Pierce electron gun
	Water-cooled target wheel with focus coil and x and y deflection fields
Power supply:	0–15 kV
	0–30 amp dc
Filament:	Tungsten
Targets:	Al, Fe, Si, . . .
Typical settings:	8 kV, 17 amp, 10-mA filament current
Bending magnet:	Fe with induced field ~ 10–20 Gauss
Film types used:	Kodak 2495 and Kodak DEF
Exposure time:	10 min to 2 h

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Figure 46.21 shows images obtained on test exposures of a Ni-coated KB microscope. Figure 46.21(a) shows an exposure taken of x rays transmitted through a wire mesh consisting of 25-μm wires on 50-μm spacings when the microscope was arranged at a magnification of ~5.2. Variations in the brightness are caused by spatial variations in the intensity of the e-beam at the target plane. Also, variations in the image quality can be seen to be a function of position in the image. An image of the same grid [Fig. 46.21(b)] was taken at a magnification of 11.0. Again image quality is a function of position in the image.

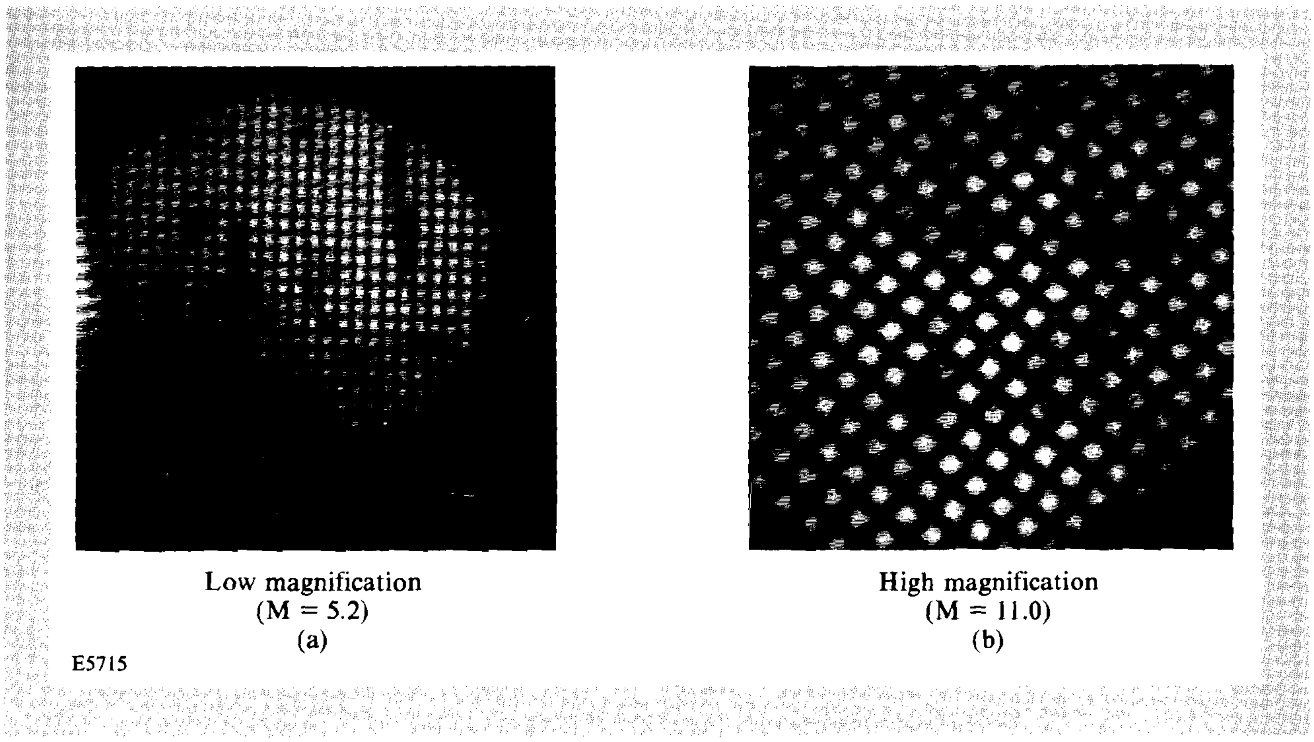

Fig. 46.21
Exposures of back-lit 25-μm wire mesh at magnification of 5.2 and 11.0.

The variation of image quality versus position was analyzed by digitizing the images of Fig. 46.21 and subsequent computer analysis. Lineouts are taken along the axes of the wire mesh. By measuring the width of the shadow of each wire, the resolution at that point in the image plane of the microscope is determined. Figure 46.22 shows plots of the resolution for the Ni-coated KB at both magnifications. We see that the best resolution obtained is ~5 μm and that the field of view is ~500 μm.

The depth of field of the KB microscope was investigated by taking exposures of the wire mesh and varying the mirror-to-film distance D. Figure 46.23 shows a plot of the best resolution obtained from each such distance as a function of change in D. The best resolution is obtained at the optimum focal position. This determination of the optimum value of D serves to characterize the focus equation [Eq. (1)], since for a fixed source-to-mirror distance d and an optimized value of D, the value of the product $R\sin i$ can be inferred. The depth of field of the KB microscope is seen to be ~1 mm.

Summary

The KB microscopes have been used on the OMEGA target chamber for a number of years.[8,9] Originally, two microscopes with nickel-coated mirrors each provided four independently filtered images from the four corners of the mirror assembly [see Fig. 46.18(a)]. The microscopes were placed to view target x-ray emission from two nearly perpendicular views. Testing of the KB microscopes confirms early measurements that the

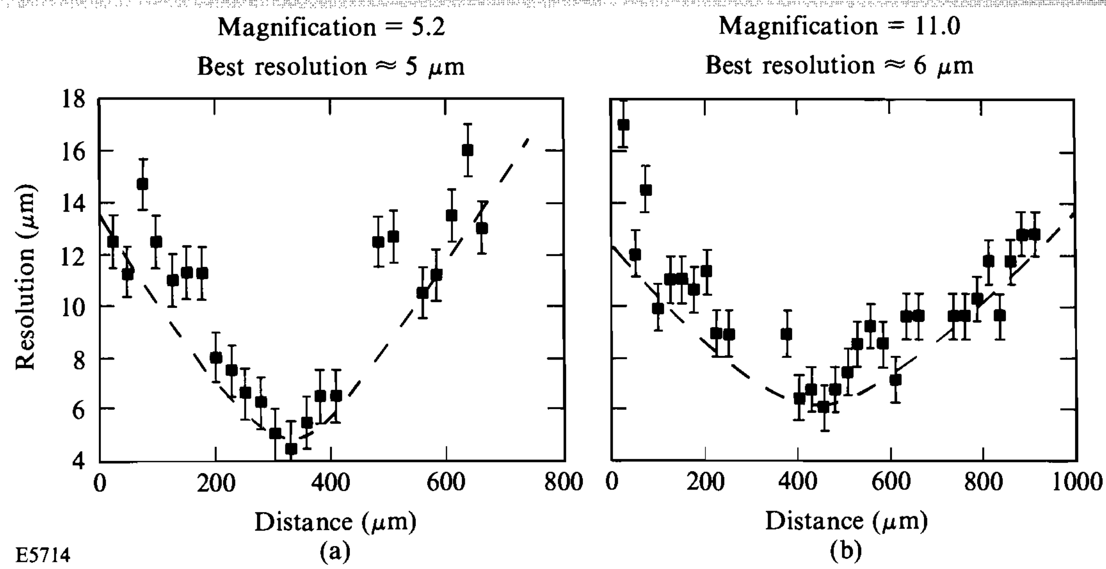

Fig. 46.22
Plots of the resolution versus position as determined from the images of Fig. 46.21.

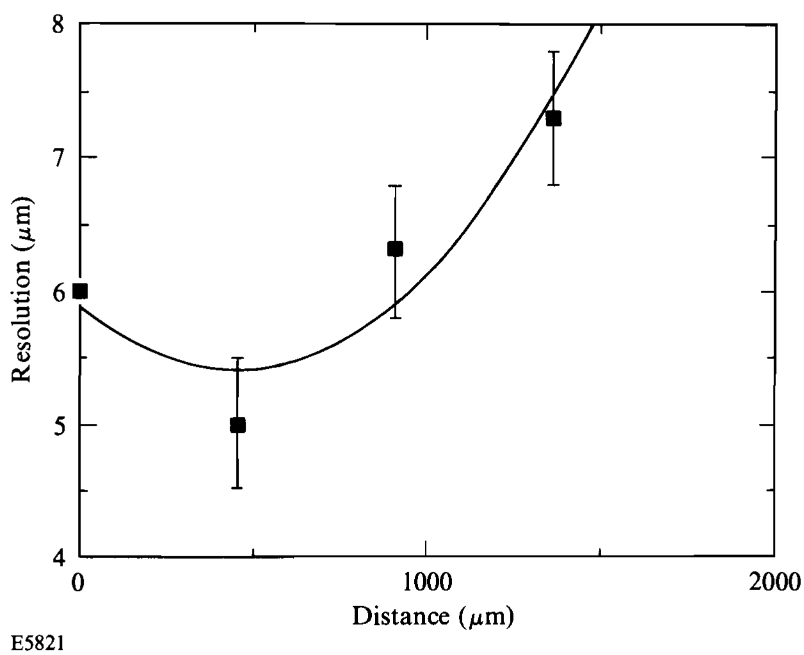

Fig. 46.23
The depth of field and optimum focus are determined by adjusting the mirror to image plane D.

optimum resolution is ~5 μm and that the field of view and depth of field are ~500 μm and ~1 mm, respectively. Recently a new KB microscope assembly with gold-coated mirrors has been completed. The resolution of the Au-coated mirrors allows imaging of x rays up to ~7 keV. This microscope has also been configured with a transmission grating placed at the baffle [Fig. 46.18(a)] in order to obtain imaged spectra of implosion cores. Work on analyzing spectra from dispersed core images is now in progress.[10] The current existing complement of KB microscopes and their parameters are summarized in Table 46.III.

Table 46.III: OMEGA KB microscope parameters.

Ni-coated mirror microscopes:	2
Au-coated mirror microscopes:	1(with transmission grating)
Grazing angle:	~0.7°
Magnification:	5–12
Solid angle:	$\sim 3 \times 10^{-7}$ sr
Sensitive range:	1–7 keV
Number of images:	4/microscope
Film:	Kodak 2495 and Kodak DEF

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ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy Division of Inertial Fusion under agreement No. DE-FC03-85DP40200 and by the Laser Fusion Feasibility Project at the Laboratory for Laser Energetics, which has the following sponsors: Empire State Electric Energy Research Corporation, New York State Energy Research and Development Authority, Ontario Hydro, and the University of Rochester.

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