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AUTHOR(S): Gene H. McCall

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los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

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X-RAY IMAGING IN THE LASER-FUSION PROGRAM*

Gene H. McCall
University of California
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

Imaging devices which are used or planned for x-ray imaging in the laser-fusion program are discussed. Resolution criteria are explained, and a suggestion is made for using the modulation transfer function as a uniform definition of resolution for these devices.

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Introduction

Imaging of x-rays has been proposed as a way of improving the resolution of microscopes by using short wavelengths to reduce the diameter of the diffraction-produced blur circle. The difficulty of fabricating optical elements to sufficiently small tolerances has made these proposals impractical, and the development of the electron microscope has made them largely unnecessary. X-ray imaging, therefore, has been mainly confined to situations where the x-rays themselves are of significance. High resolution instruments have been used for astronomical observation,[1] but until the beginning of the laser-fusion program the instruments used for the observation of x-rays emitted by laboratory plasmas were rather crude pinhole cameras.

Inertially confined plasmas produced by laser compression are characterized by densities ranging from 10^{-4} to 10^{4} times solid density, time scales as short as 1 ps, distance scales as short as 1 μm, and temperatures of a few keV. Optical probing of the high density region by a back-lighting source or the observation of the self-emission of the plasma, therefore, requires the imaging of x-rays with photon energy of, at least, several keV. Although a spatial resolution of 1 μm and a time resolution of 1 ps will utimately be necessary, significant measurements have been made with instruments which have resolutions as poor as 10 μm and 30 ps. In the following discussion, the characteristics of devices which have been used for laser fusion diagnostics will be given.

X-Ray Pinhole Camera

The simplest imaging device in use is the x-ray pinhole camera shown schematically in Fig. 1. In the geometric optics limit, two points separated by a distance, a_s, at the source (assumed small) are separated at the film by a distance given by:

$$\frac{a_s}{d_s} = \frac{a_f}{d_f} \qquad (1)$$

or

$$a_f = a_s\, d_f/d_s. \qquad (2)$$

The quantity, d_f/d_s, is therefore, the magnification, M, of the camera. Rays from a single source point passing through the pinhole of diameter, D, subtend an angle, D/d_s, and make an extended spot on the film whose diameter is

$$B = D(d_s+d_f)/d_s \qquad (3)$$

or

$$B = D(1+M). \qquad (4)$$

Alternatively, a point on the film projects as a circle at the source with a diameter

$$B_s = D(1+M)/M. \qquad (5)$$

If $M \gg 1$, which is usually the case in laser fusion applications, then

$$B_f \approx D, \qquad (6)$$

and the resolution of a pinhole camera is said to be equal to the pinhole diameter.

It should be noted that this definition of resolution can not be compared directly with the Rayleigh criterion for the resolution of an optical system.

This definition of pinhole resolution assumes that two points are resolved when the image of one is completely outside the image of the other. The Rayleigh criterion, on the other hand, assumes that two points can be resolved when there is considerable overlap in their images. One could conclude, then, that for certain source distributions the effective resolution could be smaller than the pinhole diameter by as much as a factor of two.

This example illustrates the difficulty of defining the resolution of an x-ray imaging device in terms of the usual definition for an optical system. The spatial extent and the intensity distribution of the image of an x-ray point source is usually determined by the geometry, surface accuracy, and surface finish of the x-ray imaging device rather than by diffraction. Comparisons of quoted resolutions for different types of imaging devices are, therefore, meaningless within, approximately, a factor of two unless great care is taken in understanding the various definitions of resolution.

The pinhole camera is, however, not free from diffraction effects. The half-angle for the central disc of the Fraunhofer diffraction pattern[2] is

$$\theta = 1.22\ \lambda/D. \tag{7}$$

For the pinhole camera of Fig. 1, the corresponding spot radius referred to the source is

$$r_d = 1.22\ \lambda d_s/D. \tag{8}$$

For typical laser fusion applications, $\lambda = 8$ Å, $d_s = 1$ cm, and $D = 5$ μm,

$$r_d \cong 2\ \mu m \tag{9}$$

which is of the order of the pinhole diameter.

A rough estimate of the resolution can be obtained by adding the geometric and diffraction resolutions in quadrature to give

$$R = \sqrt{D^2 + (1.22\ \lambda d_s/D)^2} \tag{10}$$

which can be minimized to give the optimum pinhole diameter for a given source distance. This diameter is

$$D_{opt} = \sqrt{1.2\ \lambda d_s} \tag{11}$$

and the corresponding resolution is

$$R_{opt} = \sqrt{2.4\ \lambda d_s}. \tag{12}$$

For a source distance of 1 cm, the optimum pinhole diameter is 3 μm and the resolution is ∿ 4 μm.

For these pinhole cameras, however, Fresnel diffraction[2] applies rather than Fraunhofer diffraction. Terrell[3] has done diffraction calculations which show that optimum resolution is obtained for $M >> 1$ when the source Fresnel number

$$F = D^2/4d_s\lambda \simeq 0.6. \tag{13}$$

The resolution in this case is approximately equal to D. For the case above,

$$D_{opt} = 3\ \mu m \simeq R. \tag{14}$$

The pinhole camera has been used with success in many laser compression experiments. The resolution obtained with other imaging devices has not yet exceeded that obtained with pinhole cameras, although other techniques have advantages which will be discussed below. High resolution imaging requires small pinholes, but the pinhole substrate must be thinner than a pinhole diameter.

Therefore, high resolution pinhole cameras are restricted to low energy x-rays, and for laser fusion plasmas the high energy background may obscure the image unless the high energy photons are removed. Also, the solid angle subtended by a typical pinhole is $\sim 10^{-7}$ sr, which limits the available intensity. The ease of alignment and low cost, however, will make the pinhole camera a useful device even after higher resolution instruments are available.

Parallel Bore Collimators[4]

A nonfocusing device which has seen little use but which has advantages in certain situations is the parallel-bore collimator shown in Fig. 2 A tube of radius, r, and length, ℓ, will accept x-rays from a cone which has an apex angle, $4r/\ell$. The resolution of a set of parallel tubes can then be as small as $4r(d_s + \ell/2)/\ell$, where d_s is the distance to the source. A microchannel plate consists of parallel tubes having a diameter of approximately 10 μm, and a plate can be fabricated with a length of approximately 1 cm. For a source distance of 5 mm the resolution is 30 μm. Although the resolution of this device is rather poor, it has the advantage that microchannel plates are made of lead glass, and high energy x-rays can be imaged.

Coded Aperture Imaging[5]

Another imaging technique which is related to pinhole imaging is that of coded aperture imaging. A set of apertures is placed in a specified geometric arrangement in a plate which is opaque to x-rays. The apertures can be a simple set of pinholes at random positions in the plate such that the individual pinhole images overlap on the film. For N pinholes, the intensity at the film is, approximately, N times that of a single pinhole, but because the individual images overlap, processing is required to reconstruct the image. The resolution obtained from aperture arrays of any shape is, in general, equal to the smallest linear dimension of an aperture, and, as in the case of the pinhole camera, diffraction must be considered for high resolution, and small aperture, arrays.

Two major problems, other than fabrication, exist for these instruments, those of reconstruction methods and signal-to-noise ratio. Ceglio[6] at LLL has used a zone plate as a coded aperture to produce images having, approximately, 8 μm resolution. The zone plate device can be reconstructed using a He-Ne laser beam incident on the film, while other methods require digital processing and substantial computer time. Nonlinearities in the film response, however, produce an image which maintains the shape of the object but not necessarily the intensity distribution. For accurate density measurements additional processing may be required.

Although the image intensity may be increased by a factor of $\sim 10^5$ over that of a pinhole camera with the same resolution, the reconstructed image will, in general, have a poorer signal-to-noise ratio than a single pinhole image unless the number of apertures is large. A new development in this area has been made by Fenimore and Cannon[7] at Los Alamos who have found that aperture distributions exist for which the unfolding process is noise free.

Coded apertures have diffraction limitations similar to those of pinholes, and Eq. 10 can be used to obtain a rough estimate of the resolution by replacing the pinhole diameter by the smallest linear dimension of an aperture.

Grazing Incidence Optics[8]

The devices described above all use the properties of apertures to produce geometric images of a source. All of them suffer from diffraction problems at longer x-ray wavelengths, and all are required to be placed near the source to achieve optimum resolution. Devices employing grazing incidence reflection which approximate lenses or mirrors do not have these inherent problems although fabrication problems may be quite severe for some configurations.

Total external reflection of x-rays from heavy metals occurs when x-rays of photon energy, E, are incident on a heavy metal surface at a grazing angle θ_g such that

$$E(\text{keV}) < 4/\theta(\text{degrees}). \tag{15}$$

To calculate the reflectivity for low energy x-rays it is necessary to include the effect of absorption edges, but for a photon energy of ~ 1 keV and a grazing angle of 1 to 2 degrees, a reflectivity of 0.7 cm can be achieved with nickel surfaces. Optical elements which use grazing incidence reflection, typically, have two reflecting surfaces which give a reflectivity of 0.5 over a broad range of wavelengths, but, obviously, care should be taken in interpreting images from broad band sources if an absorption edge of the reflector material lies near the wavelength range of interest.

Kirkpatrick Microscope[9]

The problem of designing grazing incidence optical elements which have simple shapes that can be fabricated to sufficiently high tolerance was solved by Kirkpatrick by employing two cylindrical elements with their axes perpendicular to each other. A version of this system, designed by Seward and Palmieri,[10] which has been used quite successfully at LLL to produce images having a resolution in the 3 to 5 μm range is shown in Fig. 3. The perpendicular cylinders provide imaging in the directions orthogonal to their axes, but, as one would expect, the system has rather large aberration. This problem was successfully solved for the LLL microscope by using a sma-l aperture and by keeping the magnification small. The solid angle of the system is, approximately, that of a pinhole camera which has the same resolution, but the system can be operated at a large distance from the target while a high-resolution pinhole camera must be within one centimeter of the source, as mentioned above. The advantage of large separations should not be minimized in laser fusion applications where experimental solid angle is costly and damage from target debris is possible.

Wolter Microscope[11,12]

The optical system which is currently believed to have the best possibility for achieving a resolution of 1 μm at magnifications as high as 50 is that described by Wolter. This system consists of a coaxial, confocal, ellipsoid-hyperboloid pair as shown in Fig. 4. Wolter showed, analytically, that this system is free of coma for points near the axis and for rays which strike near the intersection of the surfaces if the Abbe sine condition is satisfied at the intersection line. This requirement implies that the angle of incidence for a ray striking the hyperboloid is the same as the angle of incidence for the second reflection at the ellipsoid. It has been found, however, that the angles can differ by approximately 20 percent with no significant effect on the resolution.[13] Systems of this type have been used successfully as x-ray telescopes where the ellipsoid is replaced by a paraboloid.[12]

The resolution of the Wolter microscope for laser fusion applications is determined entirely by surface scatter and figure errors rather than by aberrations which are characteristic of the optical system. If the figure of the element of Fig. 4 is assumed perfect, and if the surfaces are assumed to scatter x-rays according to a random Gaussian distribution which has an angular spread, $\Delta\theta$, the spot size referred to the source resulting from scatter is

$$r_s = d_s \, \Delta\theta. \qquad (16)$$

Surfaces have been produced with scatter angles as small as 25 μrad (5 arc sec), which implies that the maximum distance that can be used for a Wolter microscope which has 1 μm resolution and is made with current fabrication methods is 4 cm.

in general, the resolution is determined by the slope error of the surface which can be the result of a figure error or the result of high spatial frequency surface irregularities. These problems are discussed more fully in Ref. 13. Figure 5 shows an x-ray image produced by a Wolter microscope which was fabricated by diamond-point machining. The resolution is 25 μm, but it is important that no optical polishing has been done on this element.

A disadvantage of the Wolter system is its limited depth of field. For a 1 degree grazing angle the practical depth of field is, approximately, 40 μm, while the transverse field of view may be ~ 400 μm. The axial position of the microscope should then be accurate to ± 10 μm with respect to the center of the target. If a visible source is used for alignment, the axial extent of the visible focal spot will greatly exceed the required alignment tolerance because of diffraction. However, using resonant detection techniques it is possible to determine the center of the diffraction spot to better than 1 percent.

Definition of Resolution

Reference was made above to the problem of defining the resolution of x-ray imaging systems. Values have been quoted for the resolution of various systems, but although these numbers may have some meaning for determining the limit of usefulness of a particular instrument for a particular type of image, they are of little use for comparing different types of instrument. Images of grids, for example, give a subjective resolution which is always smaller than that determined by simple criteria, and grid images made by a 5 μm pinhole appear to have a resolution of, approximately, 3 μm. The radius of the circle containing a given fraction of the energy emitted by a point source is easy to calculate and measure, but grazing incidence optics usually produce point source images which have a sharp central peak and broad low-intensity wings. Encircled energy measurements, then, give a poor indication of the response of the system to an extended source. The complete point-spread function for an instrument indirectly specifies the instrument response to a general source, but it is tedious to measure or calculate.

A quantity which is frequently quoted for optical instruments and is relatively easy to measure and calculate is the modulation transfer function (MTF), which is the modulation as a function of spatial frequency of the image of a source which has a sinusoidal variation of intensity with position. Resolution can be defined as the inverse of the spatial of the spatial frequency for which the MTF has a value of 0.05 , which corresponds to the Rayleigh criterion for a diffraction limited system.[3] Such a criterion would remove much of the confusion which results when different types of instruments are compared.

Conclusion

Current devices used for x-ray imaging in the laser-fusion program have achieved a spatial resolution of 3 to 5 μm. The prospect for development of higher resolution instruments is such that a Wolter microscope having a resolution of 1 to 2 μm will be deployed within the next 6 months to one year. In the future, diamond-point machining of Wolter elements should make these instruments readily available at low cost.

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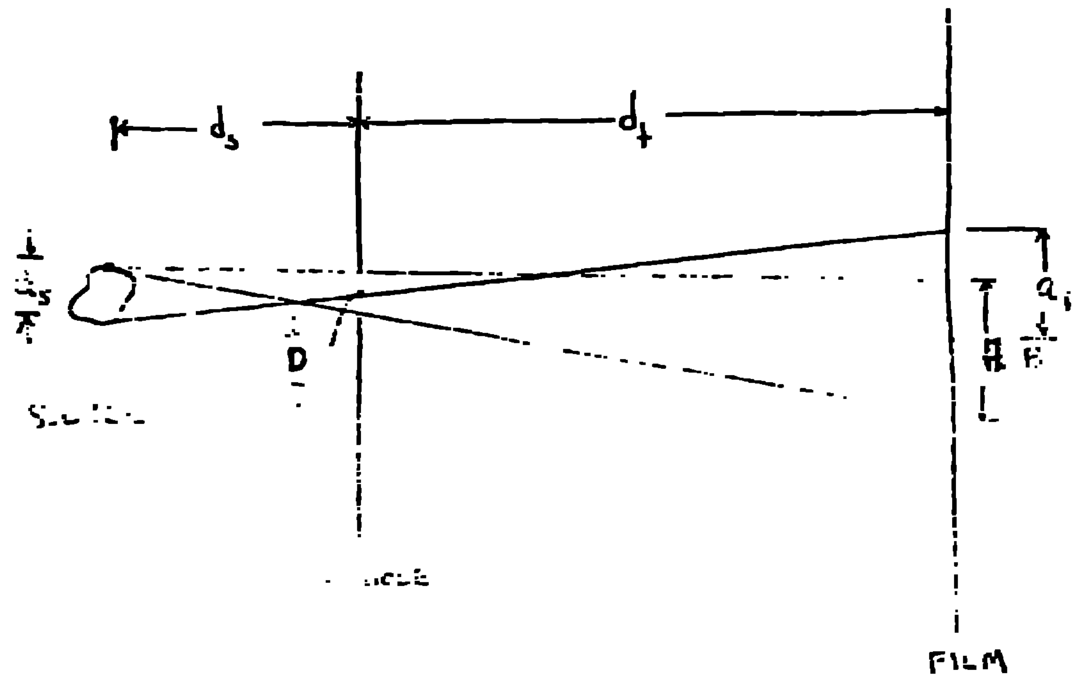
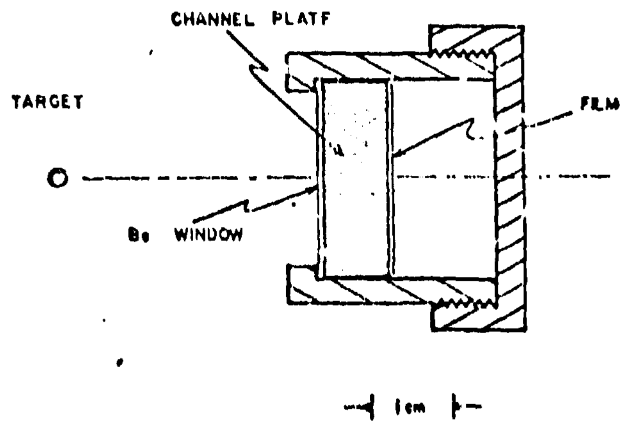
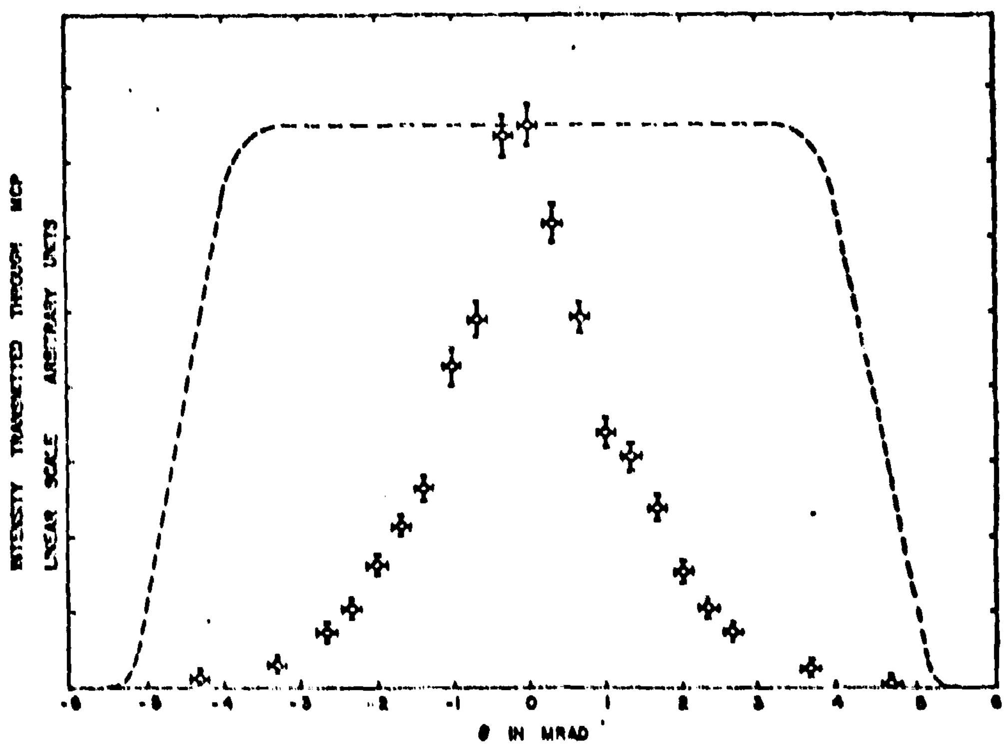


d_s
d_f
a_s
a_i
D
FILM



CHANNEL PLATE
TARGET
FILM
Be WINDOW
1cm



INTENSITY TRANSMITTED THROUGH MCP
LINEAR SCALE ARBITRARY UNITS
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
θ IN MRAD

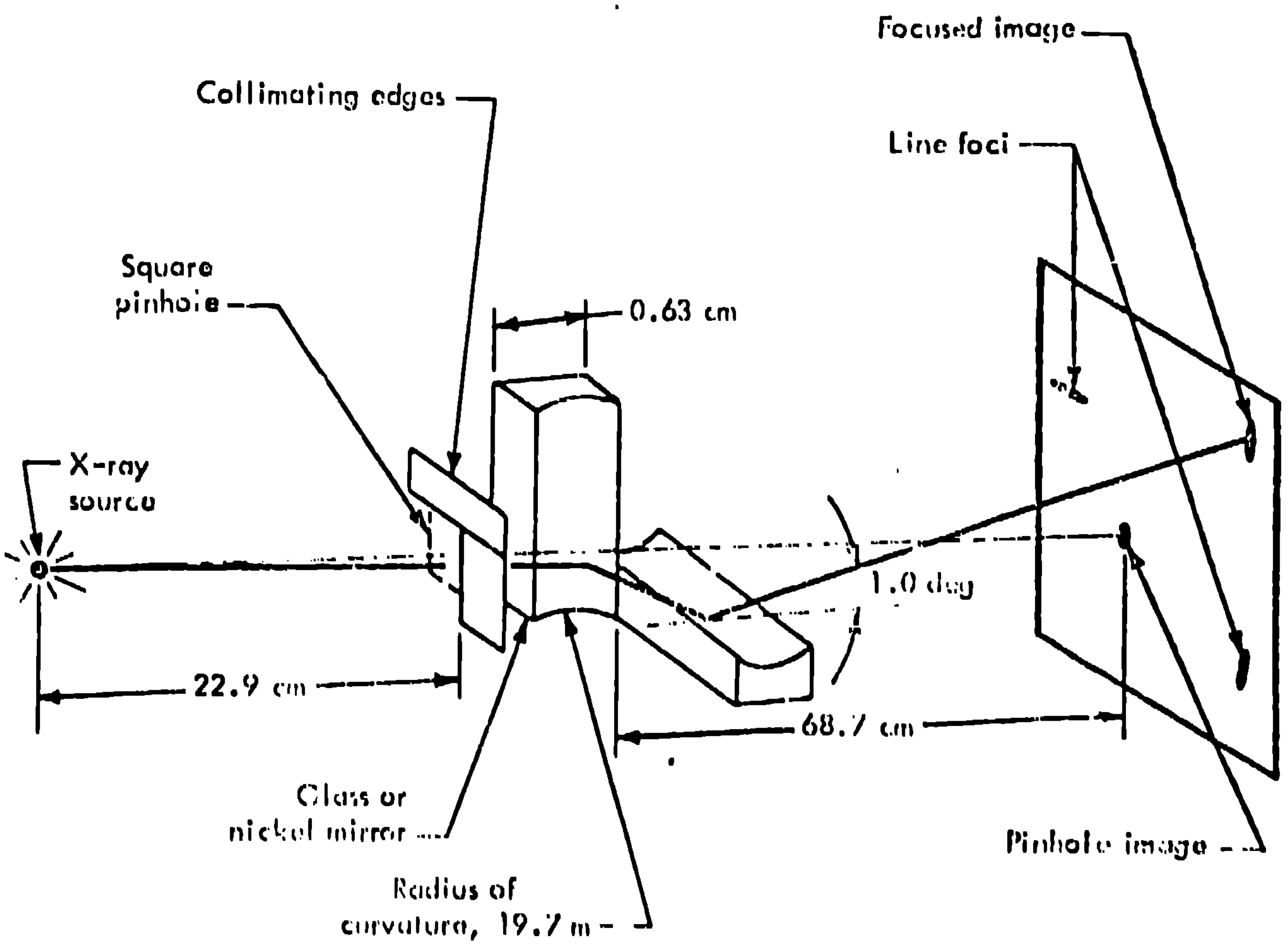
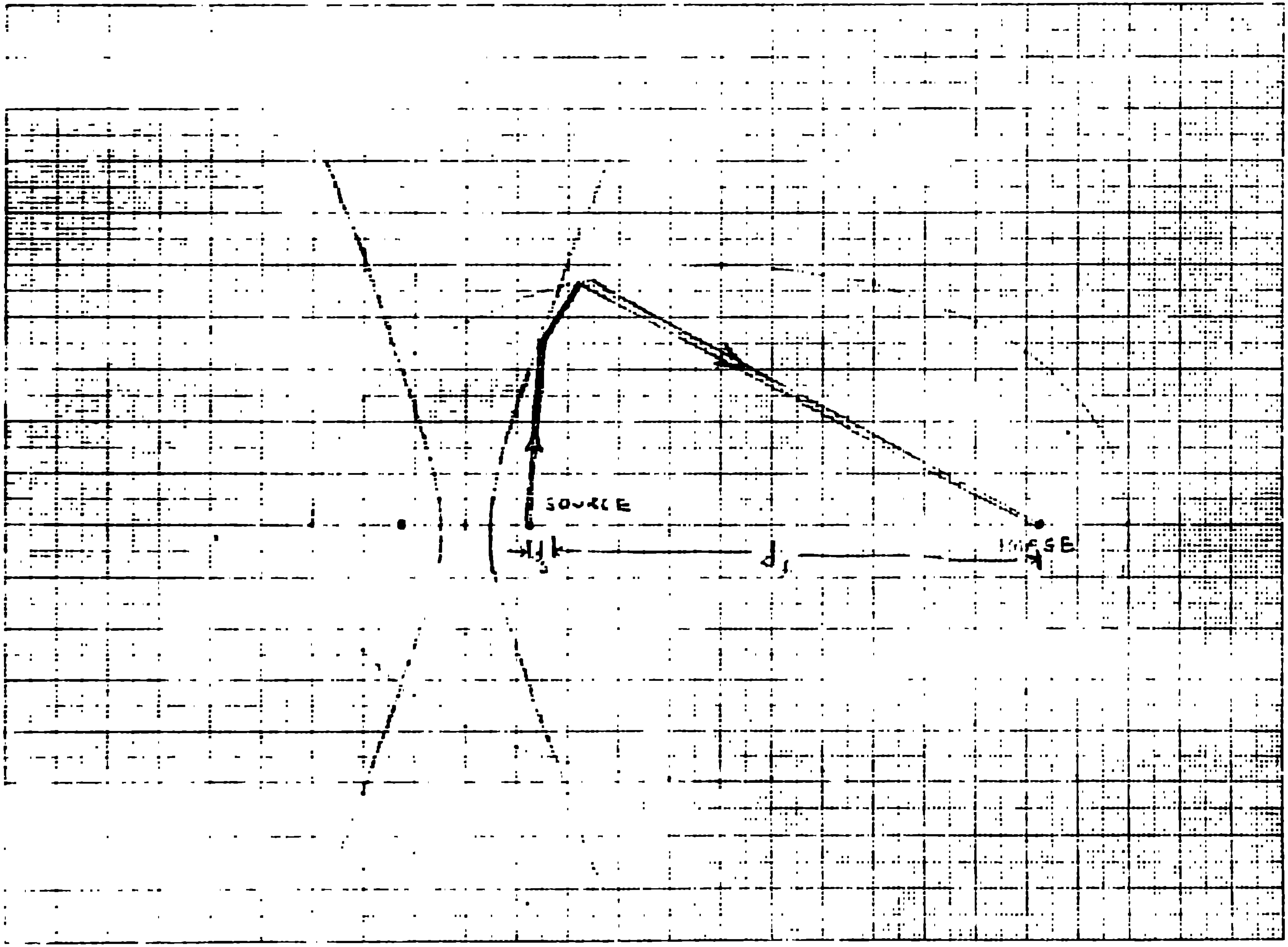

Focused image
Collimating edges
Line foci
Square pinhole
0.63 cm
X-ray source
1.0 deg
22.9 cm
68.7 cm
Glass or nickel mirror
Pinhole image
Radius of curvature, 19.7 m

Fig 2



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