LBL-36133
LSBL-236
UC-410

HIGH-BRIGHTNESS BEAMLINE FOR X-RAY SPECTROSCOPY AT THE ADVANCED LIGHT SOURCE*

R. C. C. Perera and G. Jones

Advanced Light Source
Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

D. W. Lindle

Department of Chemistry,
University of Nevada, Las Vegas,
Las Vegas, NV 89154

August 1994

Paper presented at the 5th International Conference on Synchrotron Radiation Instrumentation, Woodbury, New York, July 18-22, 1994

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*This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division, of the U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

DISCLAIMER

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R. C. C. Perera and G. Jones
Advanced Light Source,
Lawrence Berkeley Laboratory,
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D. W. Lindle
Department of Chemistry,
University of Nevada, Las Vegas,
Las Vegas, NV 89154-4003

Abstract

Beamline 9.3.1 at the Advanced Light Source (ALS) is a windowless beamline, covering the 1-6 keV photon-energy range, designed to achieve the goals of high energy resolution, high flux, and high brightness at the sample. When completed later this year, it will be the first ALS monochromatic hard-x-ray beamline, and its brightness will be an order-of-magnitude higher than presently available in this energy range. In addition, it will provide flux and resolution comparable to any other beamline now in operation. To achieve these goals, two technical improvements, relative to existing x-ray beamlines, were incorporated. First, a somewhat novel optical design for x-rays, in which matched toroidal mirrors are positioned before and after the double-crystal monochromator, was adopted. This configuration allows for high resolution by passing a collimated beam through the monochromator, and for high brightness by focusing the ALS source on the sample with unit magnification. Second, a new "Cowan type" double-crystal monochromator based on the design used at NSLS beamline X-24A was developed. The measured mechanical precision of this new monochromator shows significant improvement over existing designs, without using positional feedback available with piezoelectric devices. Such precision is essential because of the high brightness of the radiation and the long distance (12 m) from the source (sample) to the collimating (focusing) mirror. This combination of features will provide a bright, high resolution, and stable x-ray beam for use in the x-ray spectroscopy program at the ALS.

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Introduction

Beamline 9.3.1 at the Advanced Light Source (ALS) is a windowless beamline, covering the 1-6 keV photon-energy range. The beamline is designed to achieve the goals of high energy resolution, high flux, and preservation of the high brightness from third generation synchrotron radiation (SR) sources like the ALS. This beamline will provide flux and resolution (10^{11} ph/s in ≤ 0.5 eV bandpass) comparable to those of any other beamline now in operation. The brightness will be an order-of-magnitude higher than presently available in this energy range. The anticipated beam size is about 0.4 mm in diameter.

For the ALS, operating at 1.5 GeV, the approximate vertical opening half-angle of the radiation at the critical energy is:

$$1/\gamma = m_e c^2 / E = 0.34 \text{ mrad}$$

The vertical electron beam size is at its smallest value at all bend magnet 2 (BM 2) and BM 3 positions in the storage ring lattice. The bend magnet field is B = 1.069 T. The critical energy is given by:

$$\varepsilon_c(\text{keV}) = 0.665\, E^2\,(\text{GeV})\, B(\text{T}) = 1.60 \text{ keV}$$

The ALS storage ring has a natural rms horizontal emittance[1] of 3.4×10^{-9} mrad and a 10% emittance ratio into the vertical direction. The electron beam emittances are:

$$\varepsilon_h = 3.4 \times 10^{-9} \text{ mrad}, \ \varepsilon_v = 3.4 \times 10^{-10} \text{ mrad}$$

In BM 3 the horizontal and vertical beta functions (β_h and β_v) take the values 0.8545m and 1.4575 m, respectively,[1] and the horizontal dispersion, D_h, is 0.0944. The relative momentum spread, $\Delta p/p$, is 8×10^{-4}. Hence the rms photon beam dimensions are:

$$\sigma_h = [\varepsilon_h \beta_h + (D_h\, \Delta p/p)^2]^{1/2} = 93\ \mu\text{m}$$

and

$$\sigma_v = (\varepsilon_v \beta_v)^{1/2} = 22\ \mu\text{m}.$$

The electron beam emittances and photon beam dimensions taken together completely define the source.

Optical Design

The optical layout of the ALS beamline 9.3.1 is shown in figure 1. The first mirror (M1), located 11.75 m from the source, collimates the beam vertically and horizontally from bend magnet 9.3. The second mirror (M2), located 15.50 m from the source, focuses the beam vertically and horizontally onto the sample at 27.25 m from the source. The two-crystal monochromator will be located 13.63 m from the source. This configuration allows for high resolution and high brightness by passing a collimated beam through the monochromator, and by focusing the ALS source on the sample with unit magnification. The optical design used at NSLS beamline X-24A, the brightest source of x-rays presently available in this spectral range was not good enough to preserve the high brightness of ALS. The maximum horizontal acceptance of BL 9.3.1 is 8 mrads, but smaller horizontal acceptance of bend magnet radiation can be used to minimize the dominant mirror (spherical) aberrations. A detail study of the optical design of this beamline is presented elsewhere.[3] A summary of the ray tracings of the beamline will be presented in the next section.

The sagittal and tangential radii of both toroidal mirrors (M1 and M2) are the same. The sagittal (minor) radius is 0.2585 meters and the tangential (major) radius is adjustable from 1000 meters to ∞ (flat) in increments of 1% (approx.) by elastically bending the mirror. The nominal tangential radius of the mirror is 2136 meters when the mirror is positioned such that the glancing incidence angle for the principle ray is 11 mrads.

The best configuration to combine the action of two mirrors has been studied by several authors.[2] The configurations used in BL 9.3.1 radically violate the Abbe´ sine condition, because the angle to the axis increases at the outgoing side, when the angle to the axis decreases on the incoming side. But, this design results in approximate cancellation of the spherical aberrations originating from the non-unity magnification values used in the design of the beamline. This effect was first observed during the initial ray tracing studies performed to determine the optimum optical layout for this beamline.

I. Ray tracing the beam line

In principle, the optical properties of a beamline can be analytically described. With matrices, each corresponding to an optical element, operating on a representation of the beam in four-dimensional phase space (two position and two angular coordinates), the net effect of an optical system can be determined. Since these calculations are generally very complex, a more practical approach is to use the ray-tracing method based on the propagation of randomly generated rays of equal amplitude, weighted with appropriate distribution functions.

The x-ray optics ray tracing program[4] SHADOW, based on the geometrical optics tracings of the rays propagating through an optical system formed by sequential surfaces, was used. The ALS BM3 source was modeled assuming random (Monte Carlo) distributions in both real and momentum space. The parameters used in generating the BM3 source using SHADOW are presented in Table 1 and the cross-section of the synchrotron radiation source at the waist of the BM3 is shown in Fig. 2. Ray tracing of the imaging system for a acceptance of 4 mrad bendmagnet radiation was performed. Fig. 3 shows the image plane computed by the ray tracing program, neglecting the figure errors of the two mirrors. The rms beam dimensions at the image plane, shown in figure 3, are $\sigma_h = 108\mu m$ and $\sigma_v = 33\ \mu m$, compared to $\sigma_h = 93\ \mu m$ and $\sigma_v = 22\ \mu m$ at the waist of the bendmagnet source, which indicates that the image quality is extremely good.

If the M2 mirror shown in figure 1 is rotated by 180° along the beam axis, the two toroidal mirrors are configured to obey the sine condition. The ray tracing performed on such an optical system showed that the final image is highly abberated and beam dimensions are $\sigma_h = 206\ \mu m$ and $\sigma_v = 626\ \mu m$. This illustrate that the dominant aberrations (spherical) would not be improved by satisfying the sine condition, which led into a detailed study of aberration - canceling schemes for SR beamline mirror systems.[5]

II. Figure errors

Figure errors in the optical components need to be minimal to preserve the high brightness of the ALS. The two mirrors in ALS BL 9.3.1 will have a slope error deviation from best-fit sphere of 5 μrads or better (including thermal distortions) over a frequency range of 5 mm to the size of the clear aperture. The errors of the mirror surfaces were modeled with a sine wave with origin at the center of the mirror. Slope errors were considered only in the tangential directions, as the saggital slope errors have a negligible effect, due to the forgiveness factor. For worst-case RMS displacement of 5 μrads and ripple wavelengths of 0.1, 1.0, and 10 cm, the ray tracings were performed. As expected, σ_h remained unchanged, and the resulting σ_v for the three cases are 169, 168, and 183 μm, respectively.

III. Power Loading

When operating at 1.5 GeV and 400 mA, the ALS produces 37.2 kW of total bend magnet power, distributed over the 2π radians. Therefore, in BL 9.3.1, when accepting 8 mrads of bend magnet radiation, receive 47.4 watts. The first mirror and first crystal in the monochromator accept most of this power. The first mirror will nominally be operating between 11 and 14 mrads of grazing incidence. The power absorbed by the optical components in the beamline were calculated using SHADOW for the worst case (8 mrads of acceptance) for 11 and 14 mrads of grazing incidence of M1. The first mirror will absorb 11.7 to 19.4 watts, whereas the first crystal will absorb 35.4 to 28.0 watts, respectively. The power absorbed on the M1 is distributed over a 9.5 cm by 80 cm area of the mirror. Based on this analysis and other thermal calculations, M1 is not cooled, but the first crystal in the monochromator needs to be cooled.

Monochromator

A new "Cowan type" double-crystal monochromator based on the design[6,7] used at NSLS beamline X-24A was developed. The measured mechanical precision of this new monochromator shows significant improvement over existing designs, without using positional feedback available with piezoelectric devices. Such precision is essential because of the high brightness of the radiation and the long distance (12 m) from the source (sample) to the collimating (focusing) mirror. Design details and the measured performance of the monochromator are presented elsewhere.[8]

Conclusion

We have designed a windowless beamline at ALS, covering the 1-6 keV photon-energy range, to achieve the goals of high energy resolution, high flux, and high brightness at the sample. When completed later this year, it will be the first ALS monochromatic hard-x-ray beamline providing flux and resolution comparable to any other beamline now in operation. The brightness will be an order-of-magnitude higher than presently available in this energy range. To achieve these goals, two technical improvements, relative to existing x-ray beamlines, a somewhat novel optical design for x-rays, in which matched toroidal mirrors are positioned before and after the double-crystal monochromator, was adopted, and a new "Cowan type" double-crystal monochromator based on the design used at NSLS beamline X-24A was developed. The beamline 9.3.1 at ALS will provide a bright, high resolution, and stable x-ray beam for use in the x-ray spectroscopy program at the ALS.

Acknowledgments

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. We would like to thank P.L. Cowan for his help and encouragement in designing the beamline and E.M. Chow for assistance in ray tracing the optical system.

TABLE 1: Source Description of ALS Bend Magnet 3.

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Random Source.
Generated total         5000 rays.
Source assumed TRIDIMENSIONAL.
Source Spatial Characteristics: GAUSSIAN
                     Sigma X :  0.92 E-04 m    Sigma Z :  0.22 E-04 m
Depth:  SYNCHROTRON SOURCE.
+++++++++++++++++++++++++++++++++++++++++++++++++++++++

Source Emission Characteristics
Distribution Type: SYNCHROTRON
Distribution Limits.                X :  4.0 mrad
                                    Z :  1.0 mrad
Magnetic Radius =    4.81 m.      Beam Energy =   1.5 GeV.
Distance from Waist.     X:  0                    Z:  0
Polarization Used: SR TOTAL
+++++++++++++++++++++++++++++++++++++++++++++++++++++++

Source Photon Energy Distribution: BOX DISTR
from Photon Energy:   1000 eV to 10000 eV
+++++++++++++++++++++++++++++++++++++++++++++++++++++++
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FIGURE CAPTIONS

1. A schematic diagram of the beamline 9.3.1 at ALS.

2. The cross-section of the synchrotron radiation source at the waist of the ALS BM3 modeled by the ray-tracing program SHADOW.

3. The image at the sample computed by SHADOW neglecting figure errors of the two mirrors.

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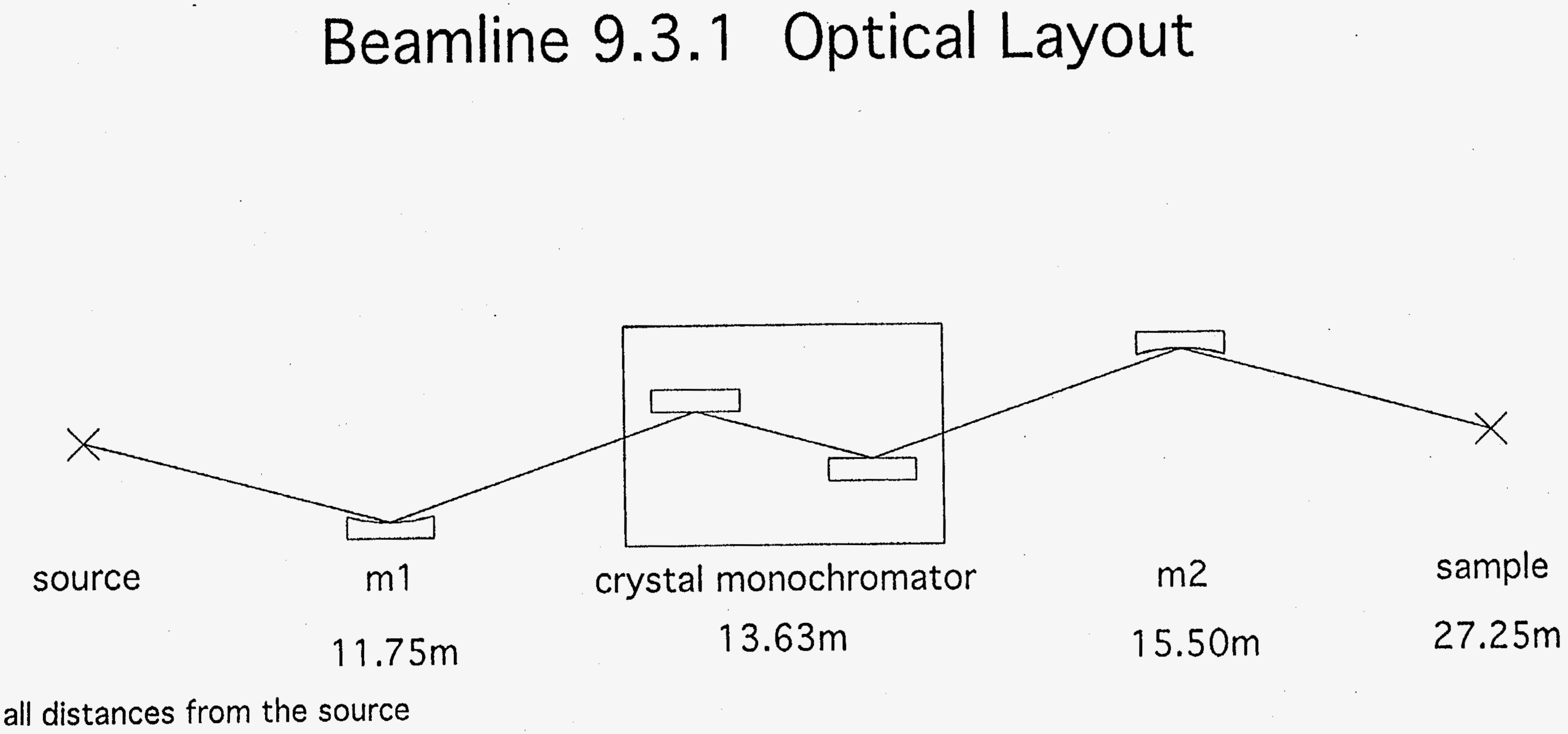
Beamline 9.3.1 Optical Layout
source
m1
11.75m
crystal monochromator
13.63m
m2
15.50m
sample
27.25m
all distances from the source

Fig. 1

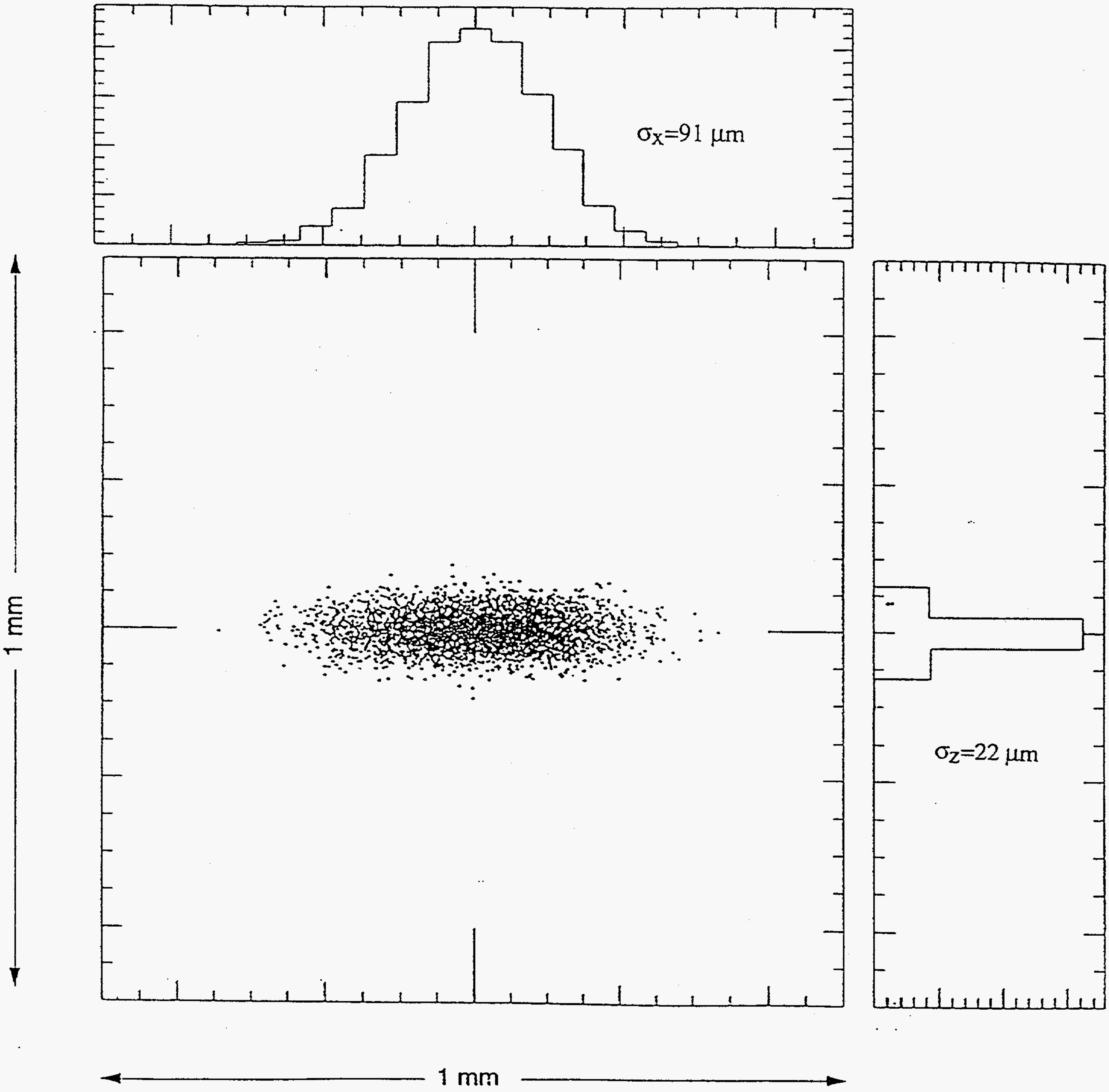

Fig. 2

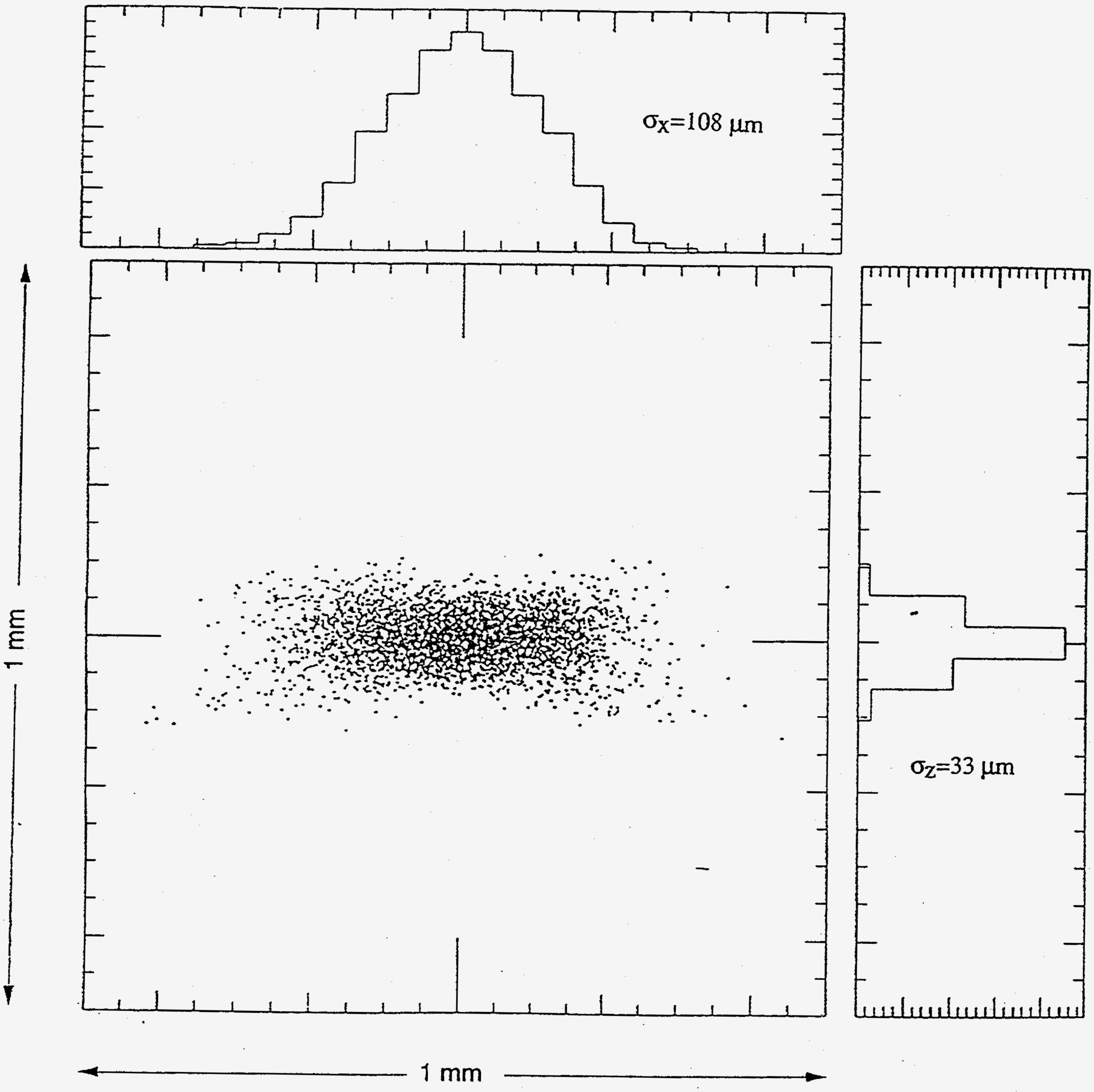

Fig. 3.