Potential Diagnostics for the Next-Generation Light Sources *

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There is continued interest in developing a diffraction-limited soft or hard x-ray source. Candidate paths include the storage-ring-based free-electron laser (FEL) and the linac-based self-amplified spontaneous emission (SASE) FEL for the two regimes, respectively. As previously discussed, target beam parameters are $\sigma_{x,y} \sim 10$ μm, $\sigma_{x',y'} = 1$ μrad, and $\sigma_t \sim 1$ ps (0.1 ps for the linac case). We report the use of few- to sub-angstrom radiation emitted by a 7-GeV beam transitting a 198-period diagnostics undulator and a bending magnet to characterize the particle beam. A particle beam divergence as low as $\sigma_{y'} = 3.3$ μrad was measured using an x-ray monochromator. Additionally, a particle beam size of $\sigma_y < 45$ μm and bunch length of $\sigma_t = 28$ ps with 4-ps resolution were measured using an x-ray pinhole camera with a unique synchroscan and dual-sweep x-ray streak camera as the detector. The adjustable pinhole aperture was varied by more than a factor of 100 to assess spatial resolution and dynamic range issues in the system. These diagnostics demonstrations should scale to next-generation applications.

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I. Introduction

At the Rome FEL conference, it was suggested that the pursuit of next-generation light sources would involve the development of certain diagnostic capabilities as well [1]. In particular, targeted beam parameters for a diffraction-limited hard x-ray source are $\sigma_{x,y} \sim 10$ μm, $\sigma_{x',y'} \sim 1$ μrad, and $\sigma_t \sim 1$ ps and 0.1 ps for the storage-ring-based case and linac-based case, respectively. We report here measurements on the path to these objectives based on detecting few- to sub-angstrom x-ray synchrotron radiation (XSR) emitted by a 7-GeV e^+ beam as it transitted a 198-period diagnostics undulator as well as a separate dipole magnet. From the first source a particle beam divergence of $\sigma_{y'} = 3.3$ μrad was measured using an x-ray monochromator. From the second source a particle beam size of 10s of microns was measured, and a bunch length of 10s of ps with few-ps resolution was measured using a unique synchroscan and dual-sweep x-ray streak camera as the detector in an x-ray pinhole system.

II. Experimental Background

The Advanced Photon Source (APS) is a third-generation hard x-ray synchrotron radiation research facility. Its main particle beam parameters include a 7-GeV beam energy, 100-mA stored beam current, and a 8.2×10^{-9} m rad natural emittance. The measurement and monitoring of particle-beam quality is one of the operational requirements. In support of these tasks one of the 40 sectors in the ring has been dedicated to particle-beam diagnostics using both optical synchrotron radiation (OSR) and XSR. The push toward lower vertical coupling to enhance x-ray beam brilliance has also resulted in providing a test bed for techniques for measuring beam parameters in one plane relevant to next-generation sources. As shown in Table 1, vertical coupling of 1% implies few-μrad divergence and 0.1% coupling implies 1 μrad. The corresponding vertical beam sizes are 29 and 9 μm. As shown schematically in Fig. 1, our techniques include an x-ray pinhole system on one of the dipole sources in the ring and an x-ray monochromator on the diagnostics undulator. The adjustable pinhole based on a remotely controlled four-jaw aperture is located 10.1 m from the source resulting in a magnification of 1.67 at the photocathode (PC) of the x-ray streak camera. An important practical aspect of the set-up was the remote-controlled positioning of the camera using three stacked translation stages. These stages were under the camera mainframe and provided x-, y-, and z (t)-axis motion. This facilitated the alignment of the strip photocathode (6 mm (H) x 50 μm (V)) to the x-ray pinhole image field.

The Au photocathode provides sensitivity to radiation from at least 10 eV to 10 keV and has some efficiency at energies up to 20-25 keV. The soft x-rays are strongly attenuated by the Be windows in the transport. The x-ray tube is housed in a mainframe compatible with the plug-in units of the Hamamatsu C5680 series [2]. For these experiments the synchroscan plug-in provided the vertical (fast time) sweep and the M5679 unit the horizontal (slow time) sweep.

The insertion device (ID), or diagnostics undulator in this case, is a 198- period permanent magnet undulator specified by APS and fabricated by STI Optronics, Inc. [3]. It has a period λ_u = 1.8 cm and length L= 3.56 m. With a 7-GeV particle beam, the on-axis fundamental $\lambda \sim 0.5$ Å can be determined from Eq. (1) where λ_n is the harmonic wave number, λ_u is the undulator period, γ is the Lorentz factor, and K is the undulator deflection parameter:

$$\lambda_n(\theta) = \frac{\lambda_u}{n2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) \tag{1}$$

The projected on-axis cone angle σ_{po} from Eq. (2) is 2.6 μrad in the fundamental compared to the nominal 8-μrad divergence of the APS stored e^+ beam at the baseline 10% vertical coupling and for β_y = 10.1 m in the ID straight section:

$$\sigma_{p0} \cong \sqrt{\frac{\lambda}{2L}}. \tag{2}$$

Beam divergences were measured using an in-air monochromator based on a Huber goniometer, a Si (220) or Ge (440) crystal, a $CdWO_4$ converter crystal, and a charge-coupled device (CCD) camera. The converter crystal was located 36.5 m from the ID source point so that the divergence of the particle beam was the largest contributor to the ~26 keV x-ray beam image's transverse dimensions.

III. Experimental Results

In this section we discuss results on beam transverse size, bunch length, and beam divergence measurements whose values are relevant to future diffraction-limited sources.

Initial reports of our first direct measurements of the beam transverse size and beam bunch length using a unique synchroscan and a dual-sweep x-ray streak camera have been reported elsewhere [4]. However, the relevance to future fourth-generation light sources based on an FEL mechanism warrants reporting directly to this community as well. In Fig. 2, the focus mode of the x-ray camera is used to display a) the Hg light (UV) profile, b) the pinhole x-rays illuminating the Au PC, and c) the image from the off-axis photo cathode profile. The respective vertical full-width at half-maximum (FWHM) sizes are 4.5 ch, 9.1 ch, and 22.5 ch. The conversion factor in transverse dimensions is about 8 μm/ch and in the temporal domain of the fastest range is 0.3 ps/ch. The first two values illustrate the effects of the larger photo-electron energy spread on the static spread function for x rays (4b) compared to UV light (4a). The third value is attributed to imaging the full vertical profile of $\sigma_y \sim 45$ μm at the source (albeit with this 100 times less sensitive portion of the PC disk). The aperture was at 50×50 μm^2.

More recent data have been taken by varying the effective pinhole aperture from 20×20 μm^2 to 20×100 μm^2. The contribution to the system resolution by the aperture size was thus qualitatively assessed as shown in Table 2. By estimating the aperture's rms contribution to the observed size and subtracting the estimated camera limiting resolution of 12 μm in quadrature, the actual beam size of about $\sigma_y = 40$ μm was determined.

In Fig. 3 we show an example of a) a focus mode image and b) a synchroscan image with observed bunch length of 65 ps (FWHM) or 28 ps ($\sigma_{est.}$). The pinhole aperture was set at 100 μm (H) by 100 μm (V) with a magnification of about 1.6:1 for these data. On this streak deflection range the camera resolution is determined mostly from the focus mode image size to be $\sigma_{res} \sim 4$ ps. The fastest range available is about four times faster and implies 1 to 1.5 ps (σ) resolution. This same tube was previously tested with a UV laser at 2480 Å and $\sigma_{res} \cong 0.6$ ps was determined [5]. These numbers bound the expected performance for 2480 Å to ~ 1 Å. Streak images were also taken with the 10×10 μm^2 aperture at 80-mA stored beam, so this implies that with the aperture as in Fig. 3, a circulating single bunch involving current < 1 mA could be measured although single turn data from the dipole source seem unlikely. The dual-sweep feature was also demonstrated and data are reported in Ref. [4].

Analysis of the projected beam image from the diagnostics undulator in Fig. 4 leads to an implied vertical divergence of only 3.3 μrad with the horizontal divergence of 22 μrad. The vertical coupling was evaluated at 1.6% with a total natural emittance of 7.1 ± 0.9 μrad. The 3.3-μrad value is one of the lowest divergences directly measured to date on a storage ring. If this diagnostics undulator were used with a 15-GeV beam, the fundamental would be at 110 keV with an on-axis cone angle of about 1.2 μrad. It thus seems realistic to propose that one leg on the linac-based FEL array of beamlines should have such a diagnostics undulator. It is noted that these measurements were done with a 30-ms integration time in the CCD camera corresponding to an integrated charge of 2.4 MC. However, the gap was at 34 mm resulting in only 0.2 W in the fundamental. Scaling issues are readily addressed by closing the gap to 14 mm (6 mm) to gain a factor of 10^3 (10^4) increase in power for the source, using cryocooled or image-intensified CCDs to gain 10^2 to 10^3 in sensitivity, and using a low horizontal emittance as well. The combined factors of 10^6 to 10^7 in signal and detector options imply sensitivity to a single pulse (train) with $Q \leq 1$ nC total charge. This value is close to nominal fourth-generation light source (4GLS) designs. Further studies are planned with an in-vacuum monochromator recently installed in the beamline and eventually a cryocooled monochromator.

IV. Summary

In summary, we have used low vertical coupling in the APS storage ring and a unique set of diagnostics devices to generate and measure some beam parameters near prototypical of a diffraction-limited hard x-ray source or 4GLS. The unique x-ray streak camera and the diagnostics undulator are key, scalable devices that may ultimately be in the complement of diagnostics for an eventual next-generation light source facility.

V. Acknowledgments

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References

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Figure Captions

Fig. 1 A schematic of the APS diagnostics beamline. The x-ray pinhole and x-ray streak camera in the dipole source line are indicated as well as the monochromator on the undulator beamline.

Fig. 2 Focus mode images from the x-ray streak camera for a) Hg source illumination, b) x-rays on the Au PC, and c) x-rays on the "off-axis disk PC."

Fig. 3 X-ray streak camera images of the x-ray pinhole field in a) focus mode and b) synchroscan mode. The latter shows the time profile of 65 ps (FWHM) or 28 ps (σ) on the vertical display axis.

Fig. 4 Positron beam divergence data from the monochromator on the diagnostics undulator. The image (top) and the x- and y-profiles (bottom) imply $\sigma_{x'} = 22$ μrad and $\sigma_{y'} = 3.3$ μrad.

Table 1: APS Storage Ring Parameters in the Straight Section (for natural emittance ε = 8.2 nmrad)

Coupling	Parameter	Horizontal	Vertical
	Beta (m)	14.2	10.1
10%	$\sigma_{x,y}$ (μm)	325	87.0
10%	$\sigma_{x',y'}$ (μrad)	23	8.6
1%	$\sigma_{x,y}$ (μm)	340	29.0
1%	$\sigma_{x',y'}$ (μrad)	24	2.8
0.1%	$\sigma_{x,y}$ (μm)	341	9.0
0.1%	$\sigma_{x',y'}$ (μrad)	24	0.9

Table 2: Effects of Pinhole Aperture Size on the Observed Vertical Profile Size

Vertical Aperture Height + (μm)	Vertical Profile FWHM (μm)	Observed Vertical Profile σ_{est} (μm)	Actual Vertical Profile σ_{est} (μm)++
20	102	43	40.3
30	104	44.3	40.3
40	109	46.2	40.7
60	124	53	43.6

\+ The horizontal aperture size was held constant at 20 μm. The MCP gain was reduced as needed to compensate for the increased signal strength.

++ A camera contribution of about σ_{cam} = 12 μm to the limiting resolution was estimated, which was subtracted in quadrature with the aperture contribution.

Schematic of the S35 Sources and Beamlines

Top View

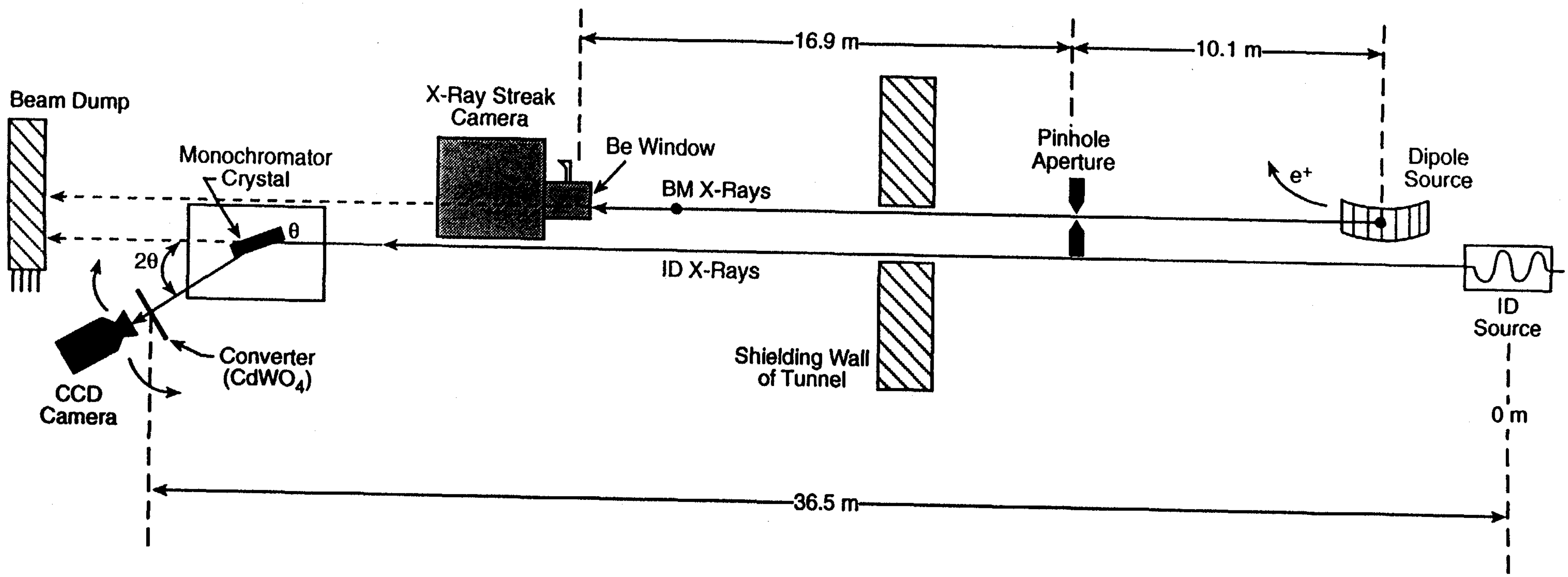

Fig. 1
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X-Ray Streak Camera Data
(Focus Mode)

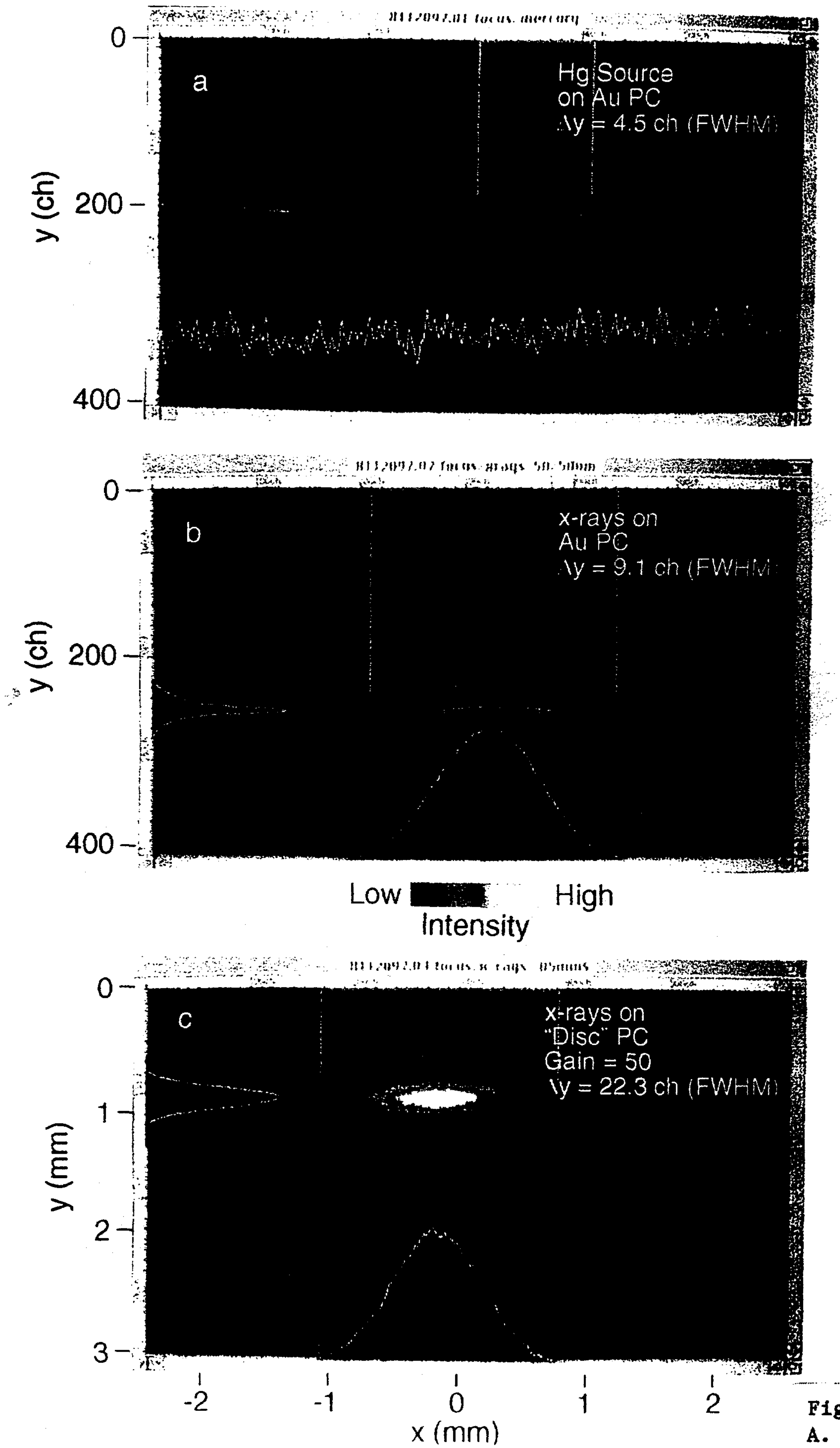

Fig 2.
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X-Ray Streak Camera Data
(Focus and Synchroscan Modes)

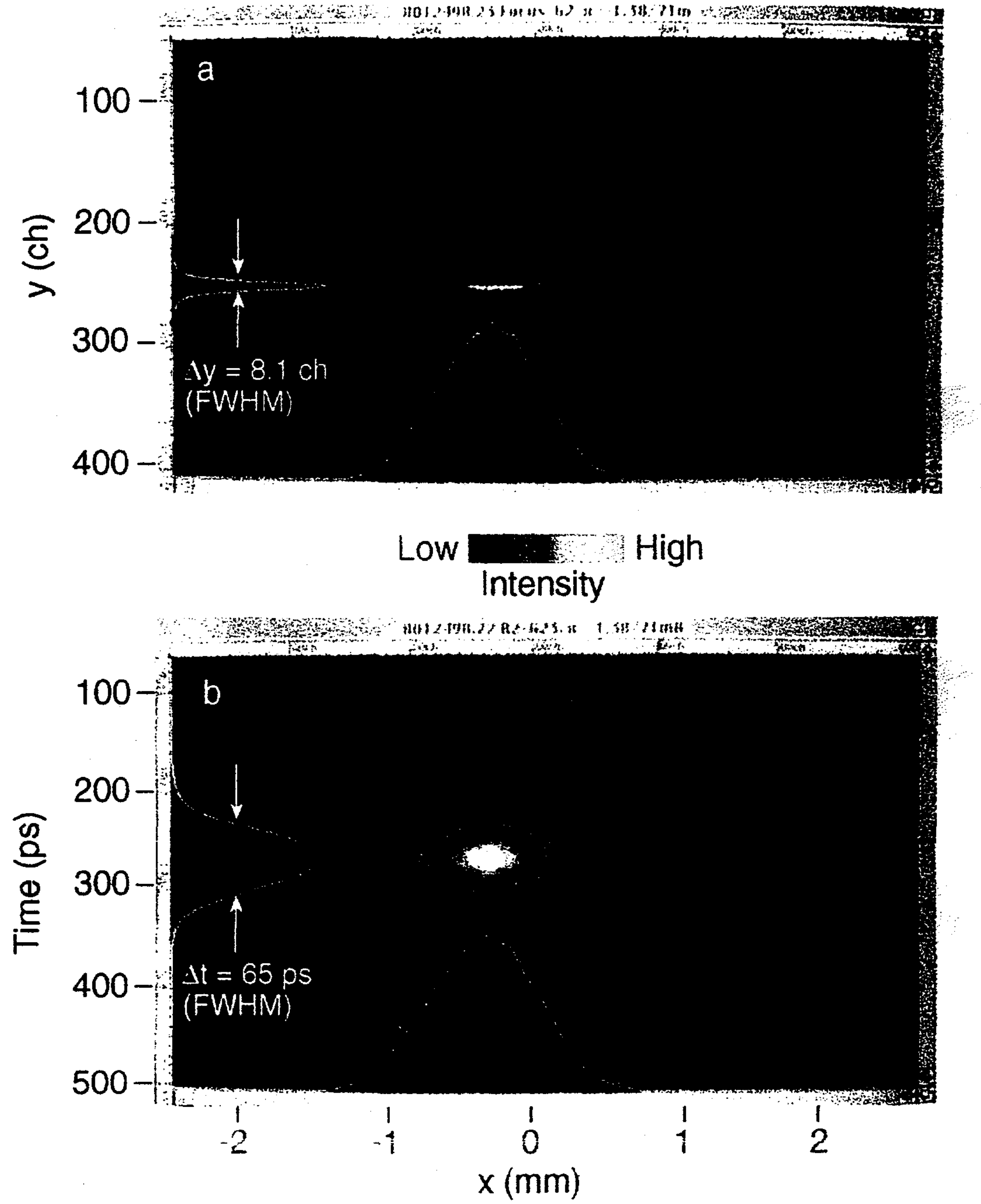

Fig 3.
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SR BEAM DIVERGENCE MEASUREMENT (35-ID)
(After minimizing vertical divergence @ 25 mA, 6/16/97 2:30 PM)

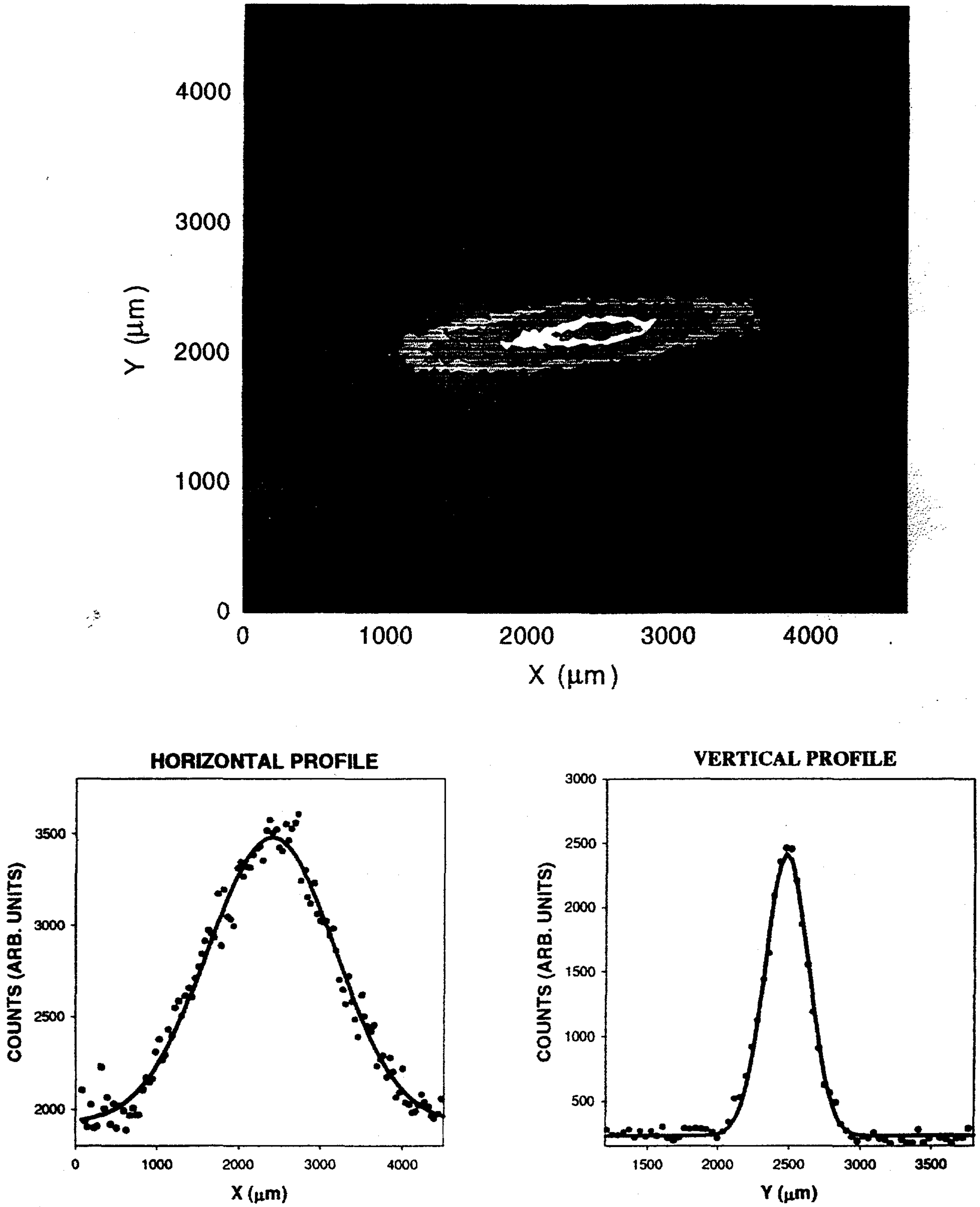

Fig. 4
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