SIMULTANEOUS MEASUREMENT OF ELECTRON BEAM SIZE AND DIVERGENCE WITH AN UNDULATOR

B. X. Yang and A. H. Lumpkin

ANL/APS/ASD, Argonne, IL 60439, USA

4/5/99

Future Light Source Workshop

Why do we need single shot diagnostics capability?

- Photo cathode gun drive laser has inherent fluctuation
- SASE output is very sensitive to the energy, emittance, length, peak current and other details of the electron bunch

How do we use the single shot information?

- Help tuning up the light source: from the accelerator to wiggler
- Pass the information to user shot-by-shot, which will be important to the interpretation of their experimental data.

New challenge

- Fast acquisition of data
- Fast processing of data (shorter that drive laser duty cycle)
- High charge sensitivity (~ 1 nC)

HOW, WHERE AND WHAT

Single bunch characterization (1 nC)

- Interceptive (commissioning of accelerators)
- *Noninterceptive (operational)**

Where do we need them?

- In acceleration
- *In compression chicane*
- *After acceleration*
- *In wiggler*
- *End of wiggler*

What beam properties do we need to know?

- *Transverse position (x, y)*
- *Transverse direction (x', y')*
- *Transverse size* (σ_x, σ_y)
- *Divergence* ($\sigma_{x'}$, $\sigma_{y'}$)
- *Energy centroid (E)*
- *Energy spread* (σ_E)
- Phase (τ)
- Length (σ_τ)
- Emittance (ε)

As invisible as possible

* Places where diagnostics undulator may be useful.

Why do we measure e-beam property with undulator radiation?

(1) Non-intrusive logging of every bunch delivered to user wigglers (sensitivity goal ≈ 1 nC?)

(2) High photon flux makes single bunch / single pass measurement possible

(3) Obtain the beam divergence and size simultaneously

(4) Measure the emittance independent of lattice Twiss parameters

Ref: Bingxin Yang and Alex H. Lumpkin, PAC-99

APPROXIMATE MEASUREMENTS AND "SYSTEMATIC ERRORS"

(Qualitative)

(1) **Approximate beam divergence measurement:** Far from the source, the monochromatic x-ray beam cross section is dominated by e-beam divergences.

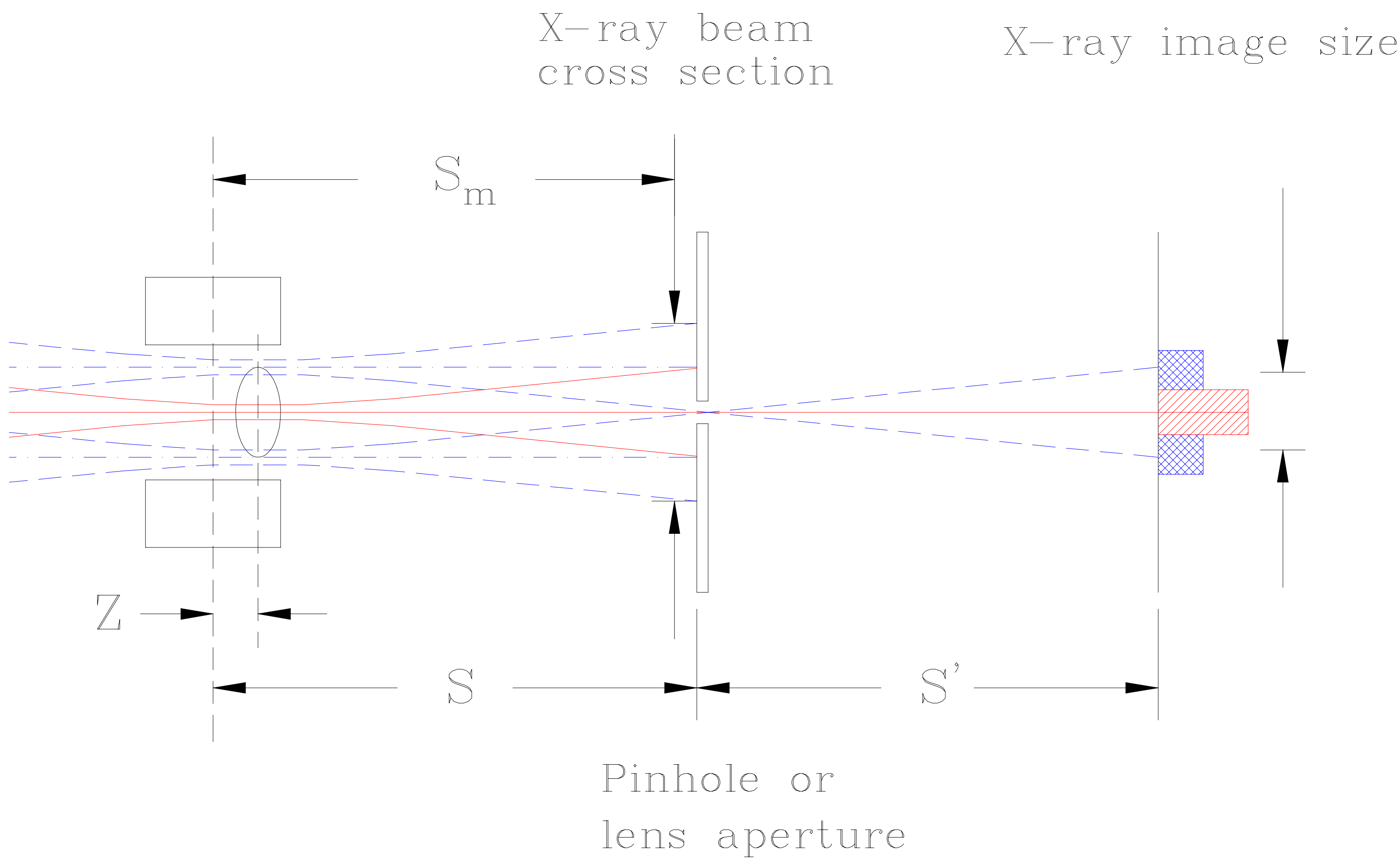
- *Off-axis electrons increases apparent beam divergence*

(2) **Approximate source size measurement:** Pinhole camera or other imaging optics measures the apparent source size.

- *Collimated radiation from off-axis electrons decreases apparent source size ("Systematic error" for any optics with small apertures: zone plate, mirror, lens, etc.)*

APPROXIMATE MEASUREMENT AND "SYSTEMATIC ERRORS"

(Schematic)



APPROXIMATE MEASUREMENT AND "SYSTEMATIC ERRORS"

(Quantitative / Geometric Optics)

Effective divergence from x-ray beam cross section

$$S_m{}^2 \sigma_{x',eff}{}^2 = \left(S_m - Z\right)^2 \sigma_{x'}{}^2 + S_m{}^2 \sigma_m{}^2 + \sigma_{x0}{}^2$$

Effective beam size from pinhole camera (or any small aperture optic)

$$\sigma_{x,eff}{}^2 = \frac{S^2\left(\sigma_{x'0}{}^2 + \sigma_\gamma^2 + \dfrac{Z^2}{\beta_0{}^2}\sigma_\gamma^2\right)}{\sigma_{x'0}{}^2 \left(S - Z\right)^2 + \sigma_\gamma^2 S^2 + \sigma_{x0}{}^2} \sigma_{x0}{}^2$$

Product of the two effective measurements

$$\varepsilon_{x,eff} = \sigma_{x,eff} \sigma_{x',eff} = \varepsilon \sqrt{\frac{\beta_0{}^2 + \left(S_m - Z\right)^2 + S_m{}^2 \dfrac{\sigma_m{}^2}{\sigma_{x'}{}^2}}{\beta_0{}^2 + \left(S - Z\right)^2 + S^2 \dfrac{\sigma_\gamma^2}{\sigma_{x'}^2}} \cdot \left(1 + \frac{\beta\sigma_\gamma^2}{\beta_0 \sigma_{x'}^2}\right)}$$

Nearly complete cancellation of error for $S \approx S_m$.

EXPERIMENT

An undulator optimized for beam diagnostics

- **Short period undulator: 1.8 cm $\times$198 period**
- **Low power : 25.9 keV @ 30 mm gap, < 1 W x-ray power**
- **Low divergence : 2.6 μrad**
- **Low field error: rms slope error < 1 μrad**

Monochromator optics optimized for divergence measurement

- **Direct imaging of unmasked undulator beam: Interpretation straightforward**
- **Single crystal monochromator: Avoid artifacts associated with double crystal monos**
- **Short distance (0.5 m) from crystal to scintillator screen: Minimize effect of heat-induced crystal distortion**
- **Thin silicon crystal (0.3 mm) can be used in Bragg (400) or Laue (220) reflection: Allow substantial hard x-ray flux to pass for source size measurement**

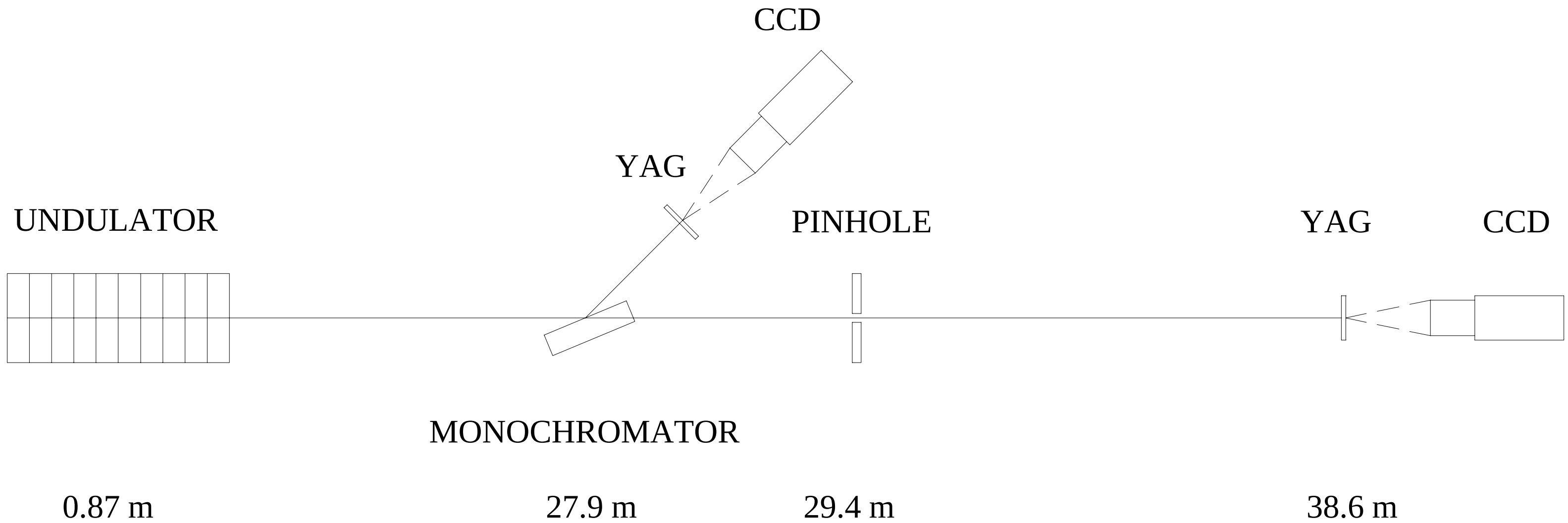
Pinhole Camera for source size measurement

- Pro: Simple optics, no distortion from optical elements
- Con: Diffraction limit ~ 40 μm for 3:1 geometry (~ 20 μm for 1:1 geometry)

Beam line parameters

- Monochromator: Si (400), contact cooling, θ ≈ 10.2°, in S/S chamber with 1 mm Be-window from 2θ = 8° to 90°, located @ 27 m from ID
- Detector: YAG crystal 0.5 mm thick + 7:5 reducing optics + SONY CCD camera, located @ 27.5 m

- Pinhole slits: water cooled 6 mm tungsten blades, located @ 28.5 m, 25 μm × 25 μm
- Detector: YAG crystal (0.17 mm) + Navitar zoom lens + SONY CCD camera @ 37.4 m
- M = 0.32



Measured beam sizes and calculated ones
(ε = 8.2 nm·rad and 1% coupling)

Location	*x*		*y*	
	Measured	Expected	Measured	Expected
35-ID divergence (μrad)	22 ± 1	22	3.2 ± 0.2	5.2
35-ID beam size (μm)	350 ± 10	368	34 ± 7 [2]	16

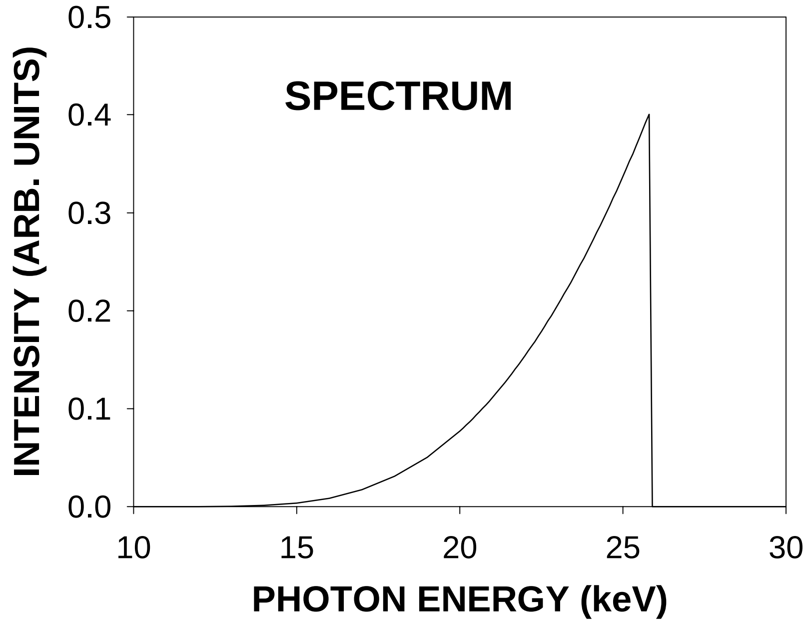
[1] Instrument resolution was not subtracted.
[2] The ID pinhole camera is dominated by slits diffraction in the vertical direction.

Multiplying ID source size and divergence:

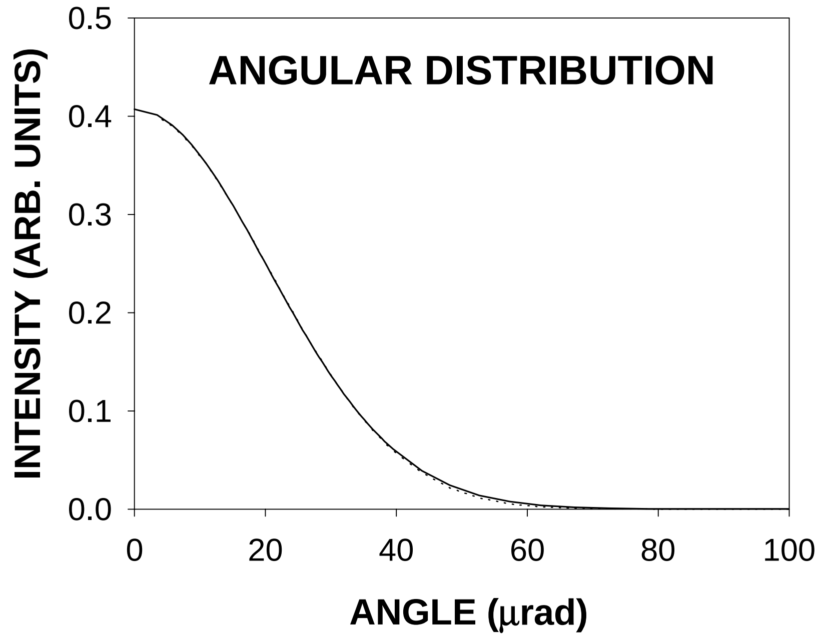
$$\varepsilon_x = 7.7 \pm 0.5 \text{ nm·rad}$$

$$\varepsilon_y = 0.11 \pm 0.03 \text{ nm·rad}$$

$$\chi = 1.4\%$$



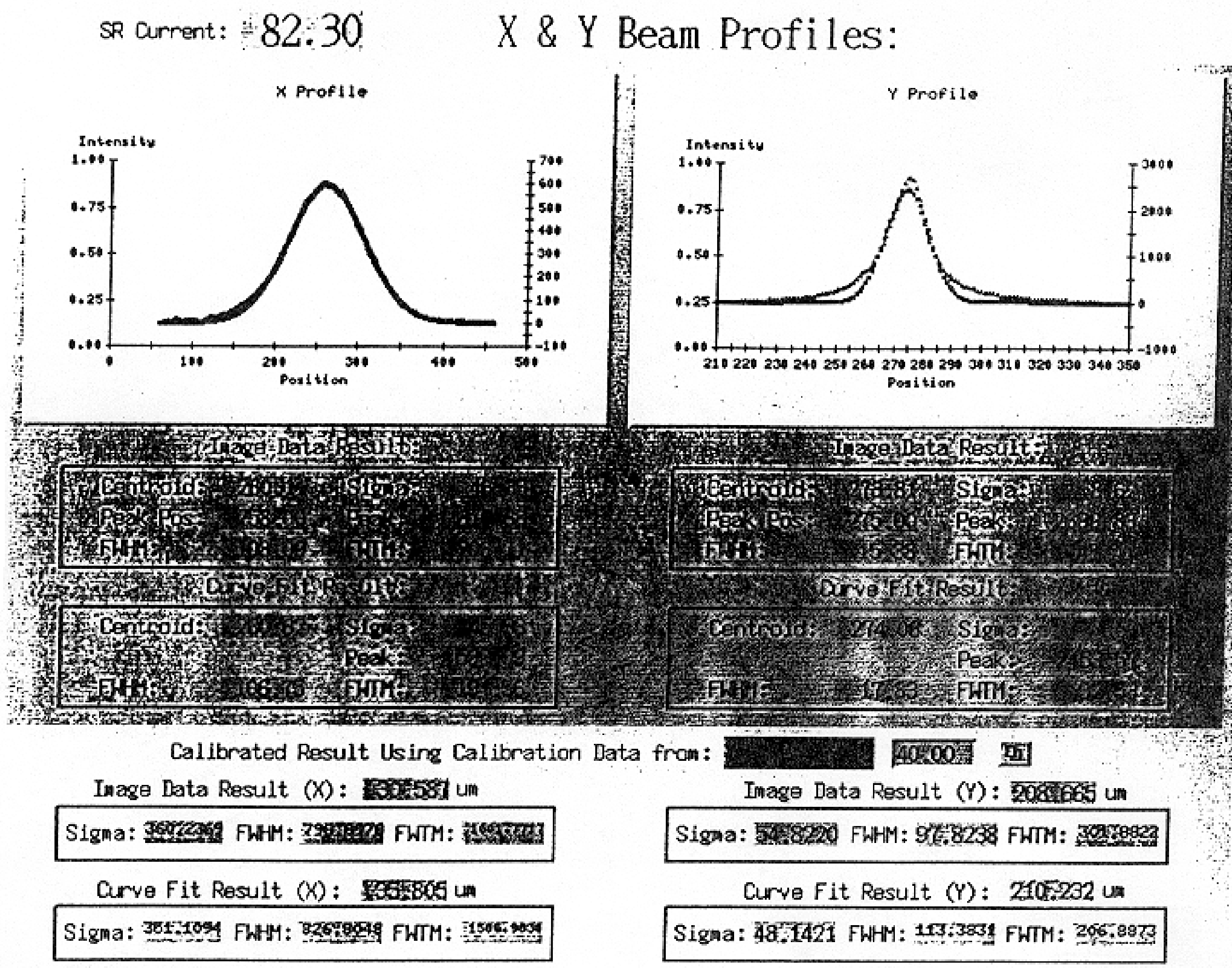
The calculated x-ray spectrum downstream of the silicon monochromator crystal



The calculated x-ray angular distribution downstream of the silicon monochromator crystal. It has a nearly perfect Gaussian shape (σ_{γ} = 20 μrad).

Dec 11, 1998

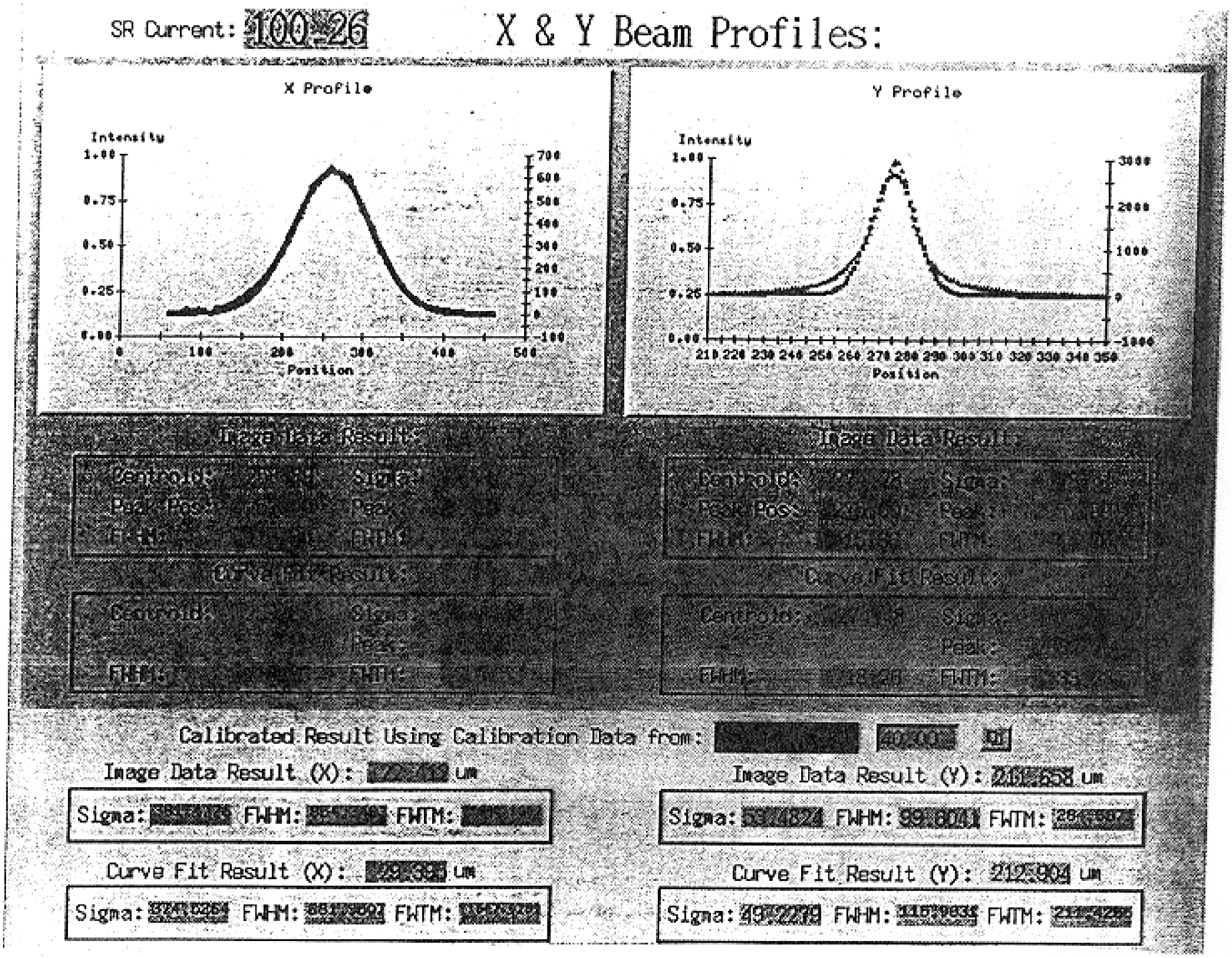
13:30:15



Integrated intensity profile derived from digitized pinhole camera images: **Source Size** measurement (screen capture). Left is for horizontal profile and the left vertical. The horizontal beam size comes back to normal (same as triplet fill) as current decays.

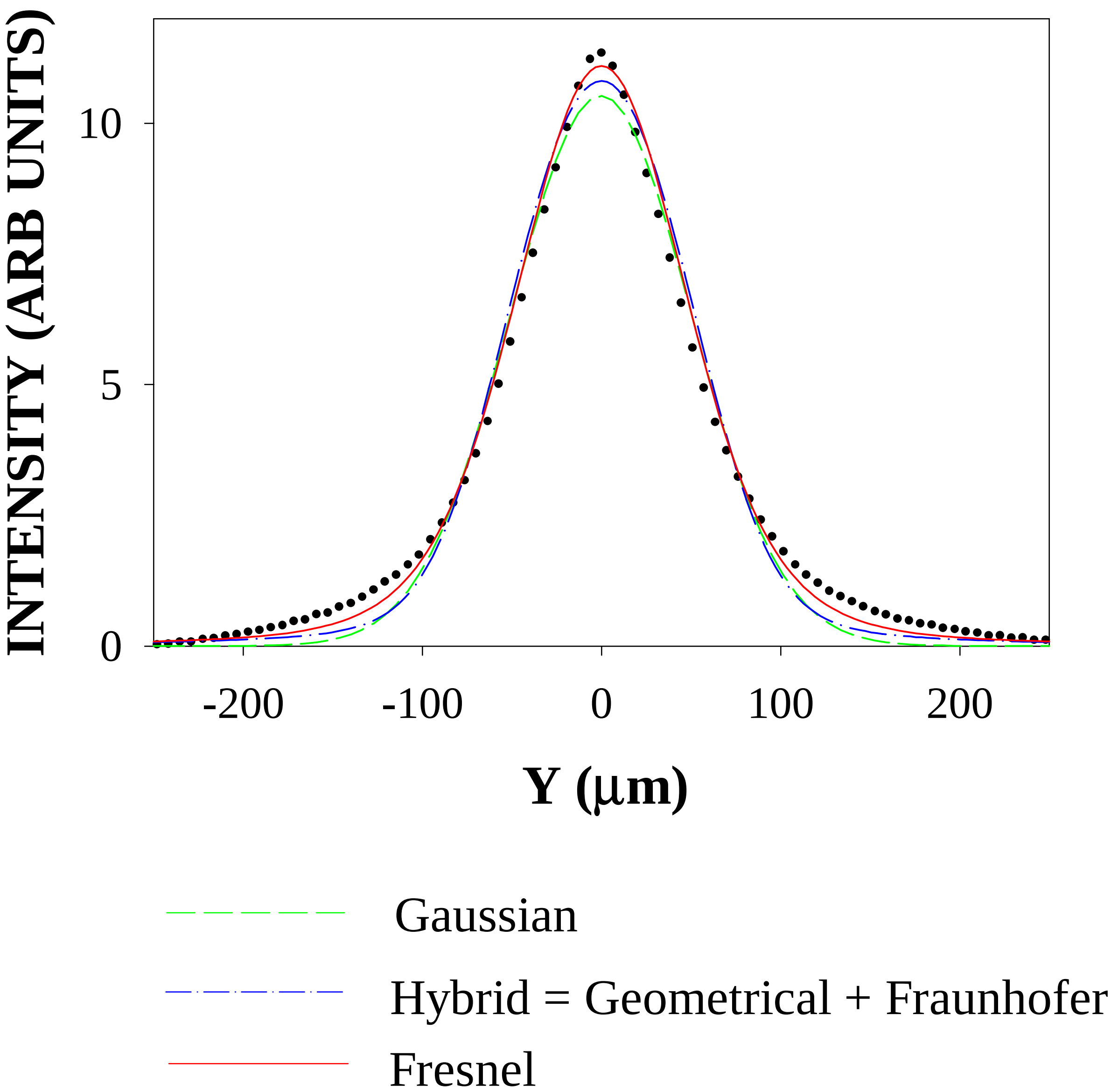
Dec 11, 1998

10:28:20



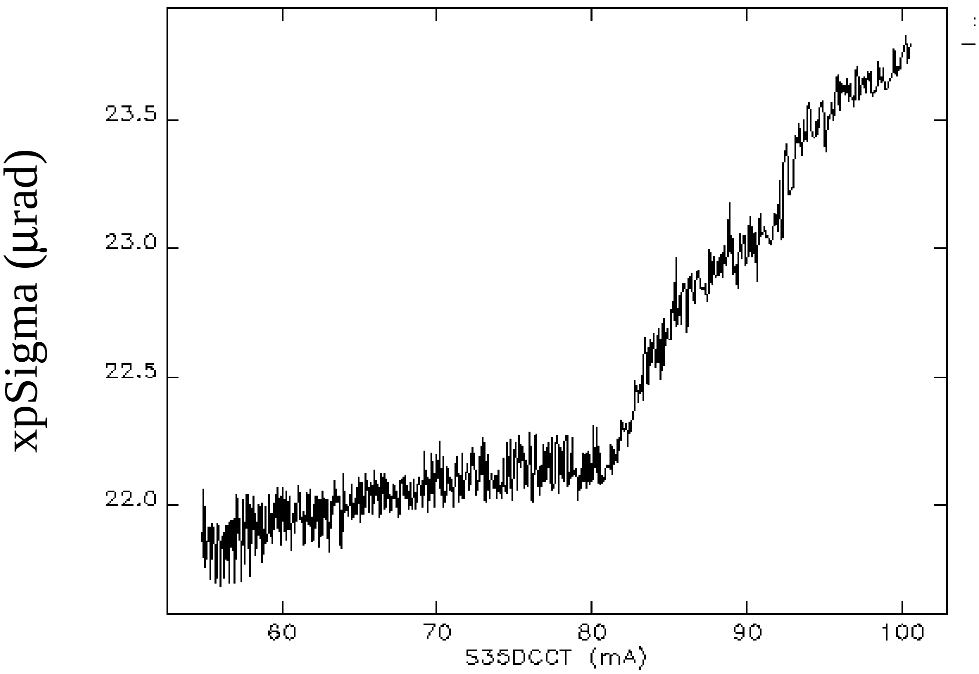
Integrated intensity profile derived from digitized pinhole camera images: **Source Size** measurement (screen capture). Left is for horizontal profile and the left vertical. The horizontal profile is nearly Gaussian in shape. The vertical profile has pronounced central peak and significant side lobes (attributed to Fresnel diffraction). The rates for acquiring images and fitting the profiles are 30 Hz.

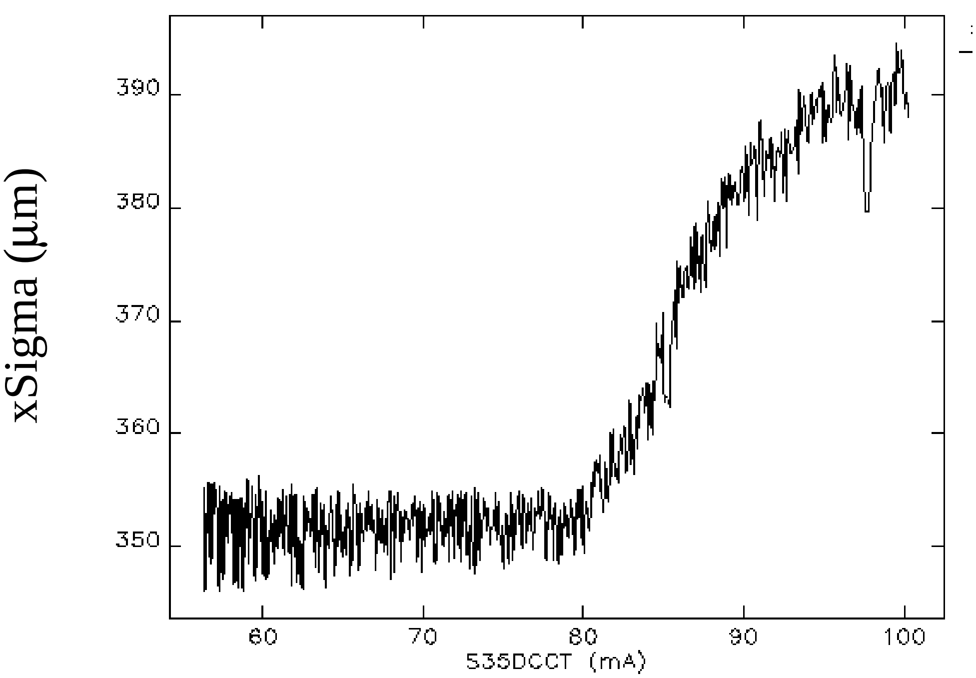
INTEGRATED VERTICAL INTENSITY PROFILE SHOWS FRESNEL DIFFRACTION SIGNATURE



ADVANCED PHOTON SOURCE

Data logged for 12 hours @ 1-minute interval
(Plotted as function of current)

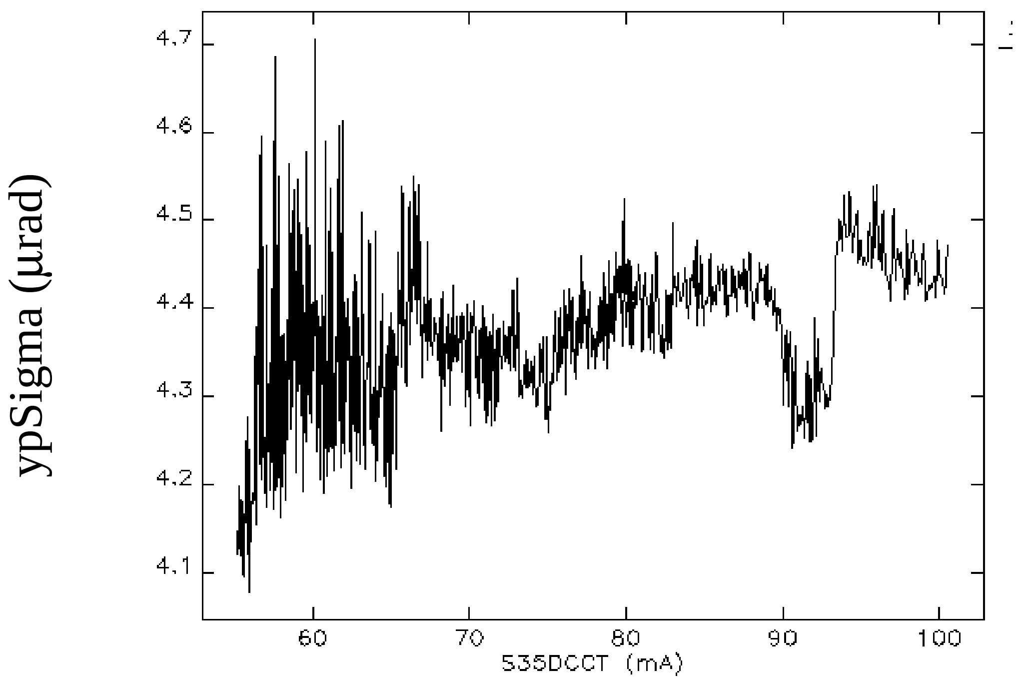


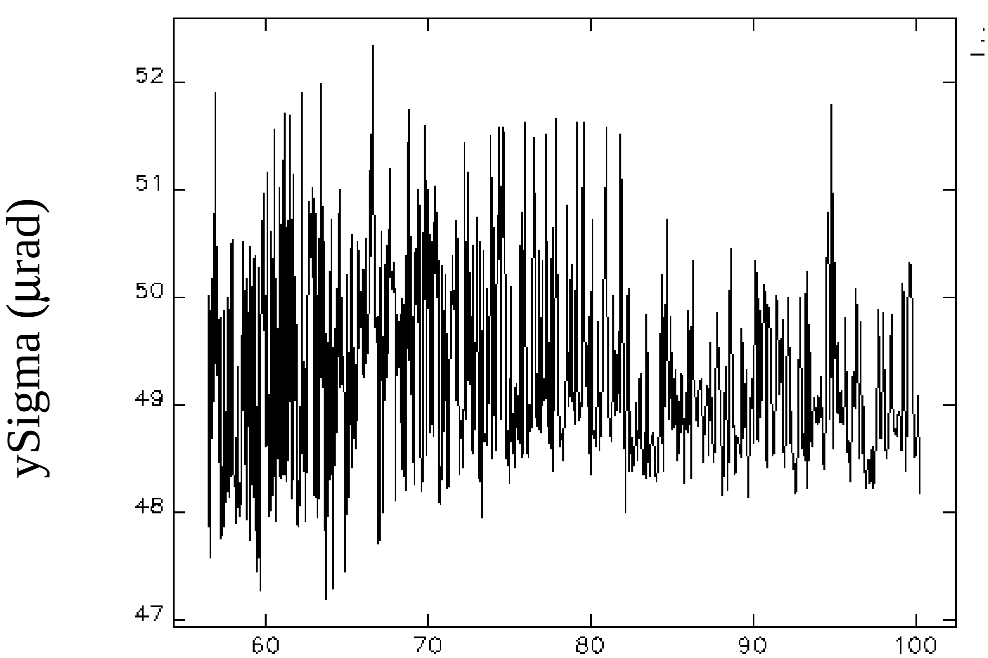


Current (mA)

ADVANCED PHOTON SOURCE

Data logged for 12 hours @ 1-minute interval
(Plotted as function of current)





Current (mA)

SUMMARY

(1) By combining a **thin-crystal monochromator** and **a pinhole camera** with a suitable undulator source, we have demonstrated experimentally that both electron beam divergence and size can be measured simultaneously. The current rate of measurement is limited by the speed of the camera/digitizer at about 30 Hz.

(2) While the lattice function and the properties of the undulator radiation can significantly affect either measured effective beam divergence or size, their **product remains a good measure of emittance**, robust against fluctuations of lattice α- and β-functions.

(3) We have presented experimental evidence showing that the **Fresnel diffraction** is valid and important in understanding x-ray pinhole camera data. Its introduction also pushes the resolution limit below that of the current, hybrid model by ~30%.