Pinhole Cameras – Operation and Analysis

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Beam Diagnostics Using Synchrotron Radiation: Theory and Practice
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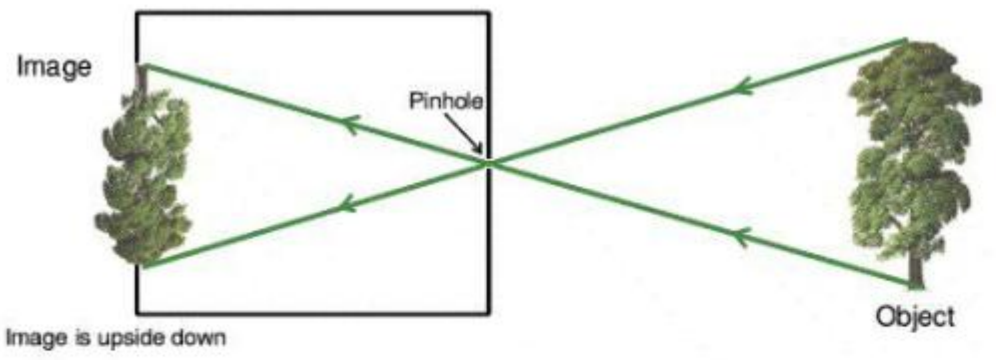
Small beams need to be measured

- Low-emittance beam at 3rd generation light sources and HEP accelerators (ILC damping ring, superB, ERL, SLS /SOLEIL /Diamond /SSRF /ALBA /PETRA-III /NSLS2 etc…)
- Horizontal emittance ~ 1 nm.rad, vertical emittance ~ 10 pm.rad
- Typical beam size < 10um vertically (100um horizontal)
- Q: How to measure such a small beam?
  - Visible light image of synchrotron radiation (diffraction > 50um)
  - Wire scan, laser wire (minutes for a full scan, 1-D)
  - Interferometer (~10um resolution)
  - Vertical beam size from π-mode radiation
  - X-ray pinhole (simple, ~5um resolution)
  - Fresnel zone plate (x-ray imaging of monochromatic beam, used at ATF, Spring-8 etc.)
  - X-ray refractive optics (monochromatic light, complicated)

First Observation of Pinhole Image

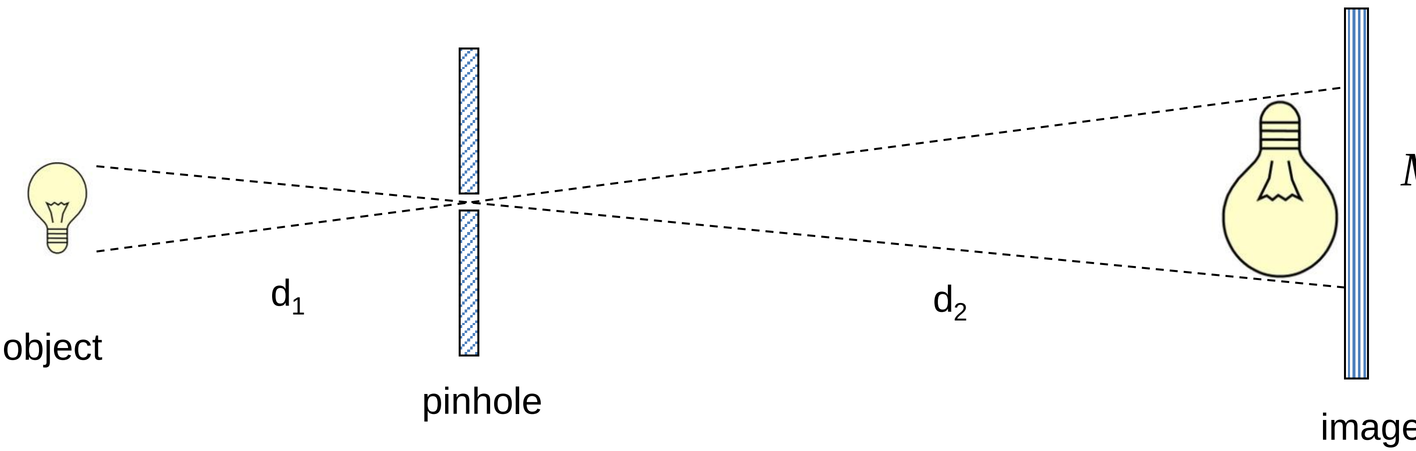
"景到（倒），在午有端，与景长，说在端"《墨经》

The image is upside down, because of the pinhole in the wall.

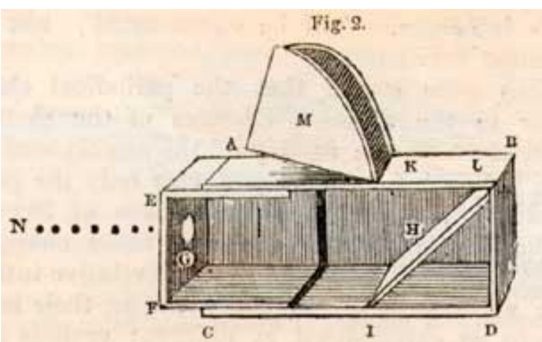


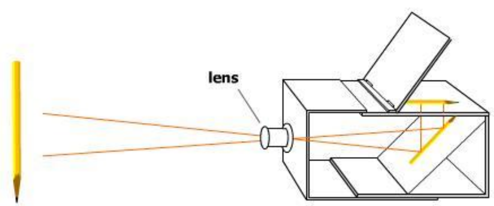
墨子 (468-376 B.C.)

Camera Obscura

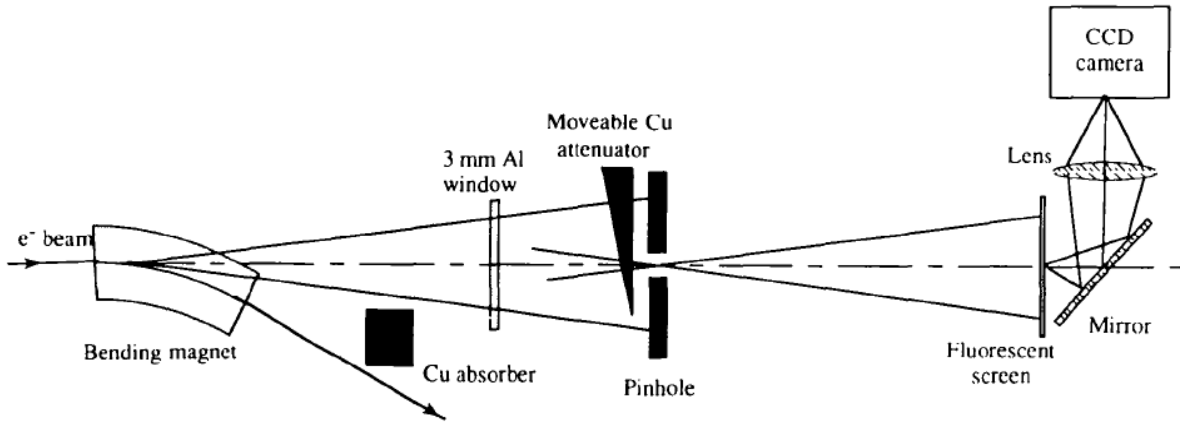


$$M = \frac{d_2}{d_1}$$

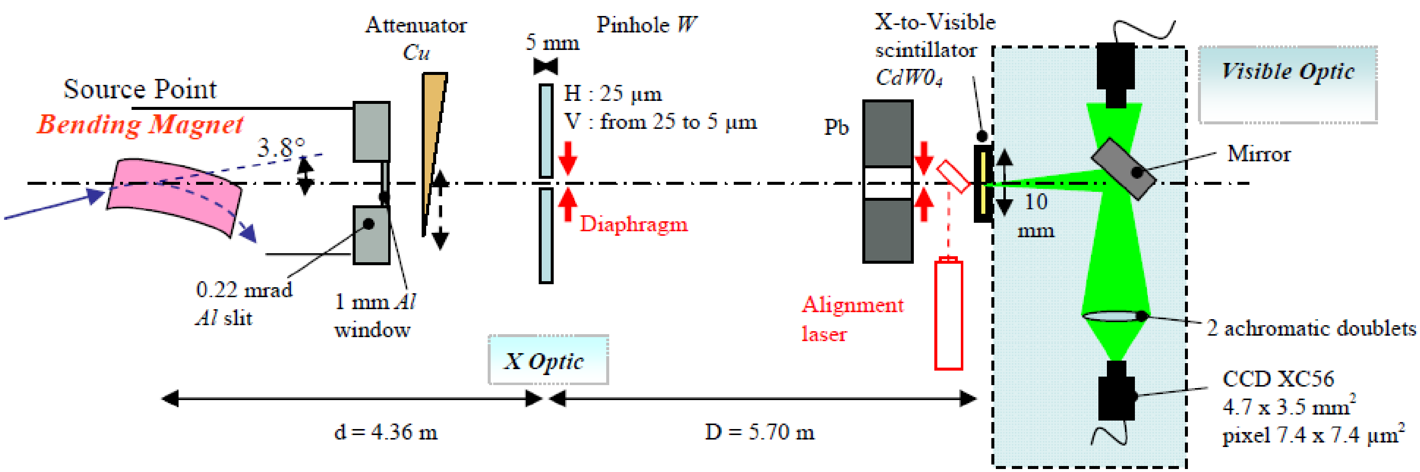




X-ray Pinhole Camera - Schematic

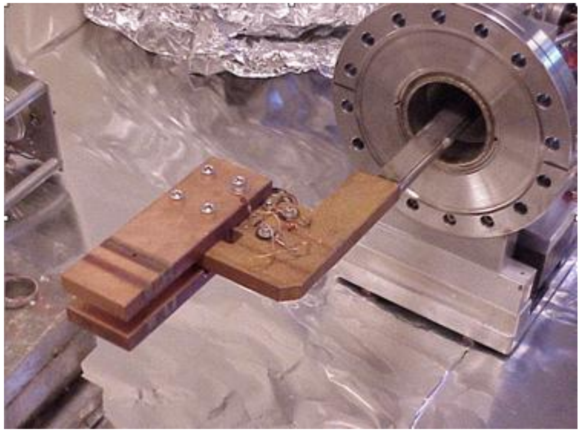


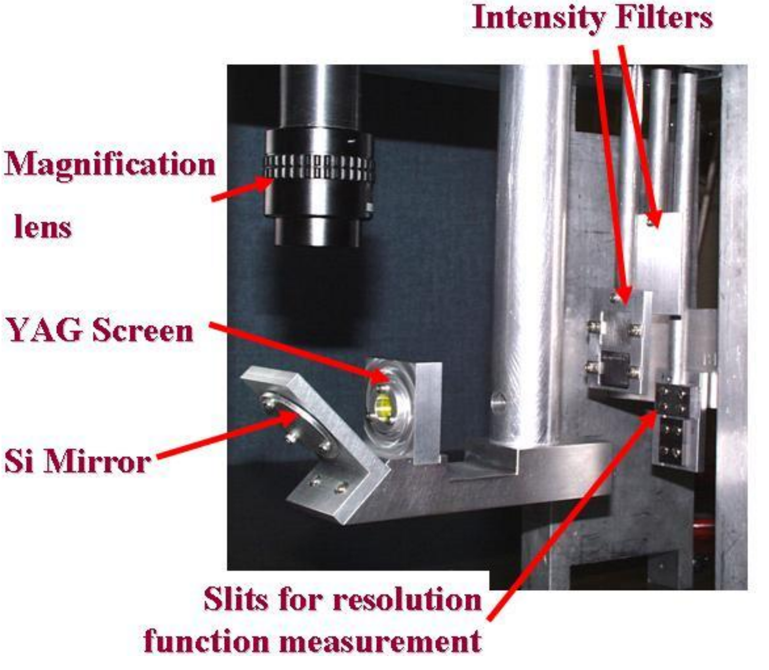
SPEAR



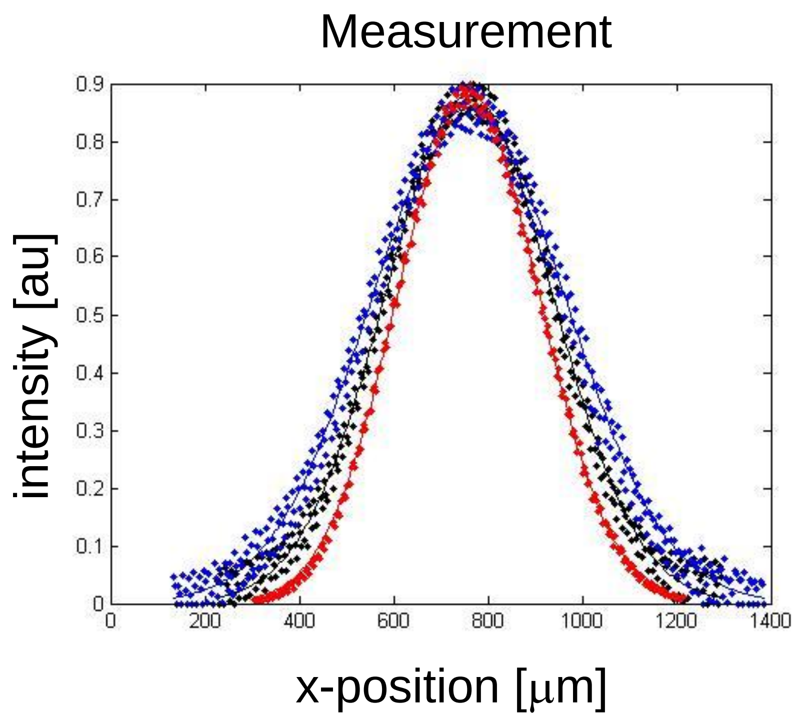
Soleil

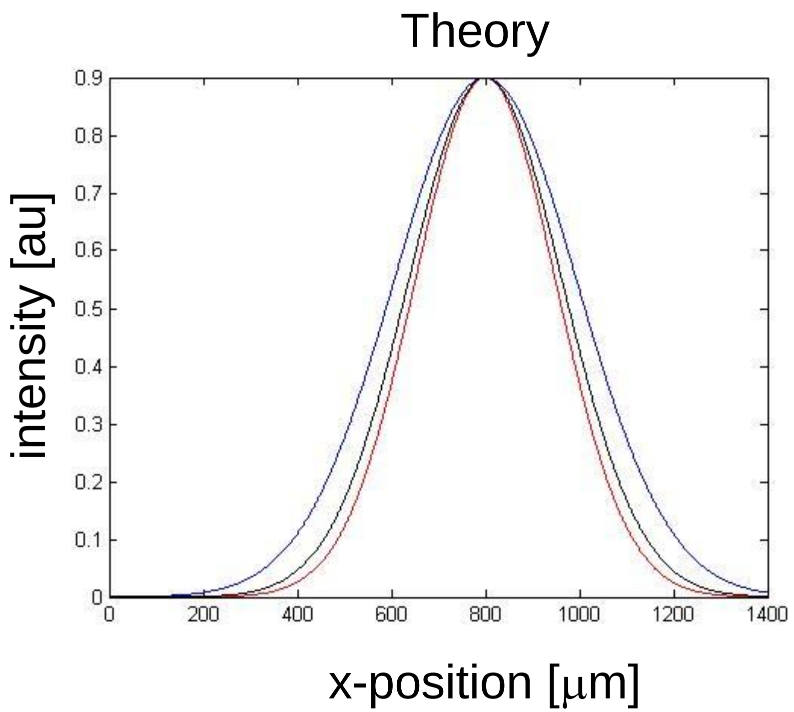
SPEAR3 Pinhole, Filters, YAG Screen and Camera

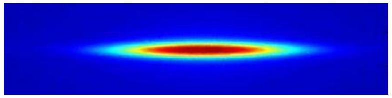




SPEAR3 pinhole results





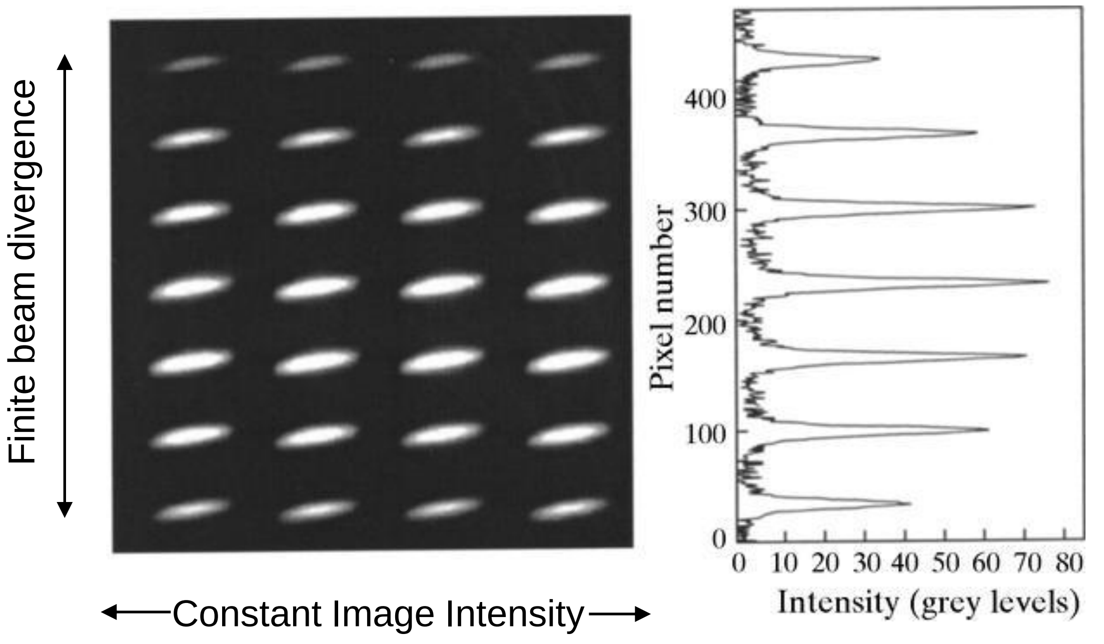


Three optics available:
- Low emittance
- Achromatic
- Low-alpha

$$\sigma_x^2 = \beta_x \varepsilon_x + \left(\eta \frac{\Delta E}{E} \right)^2$$

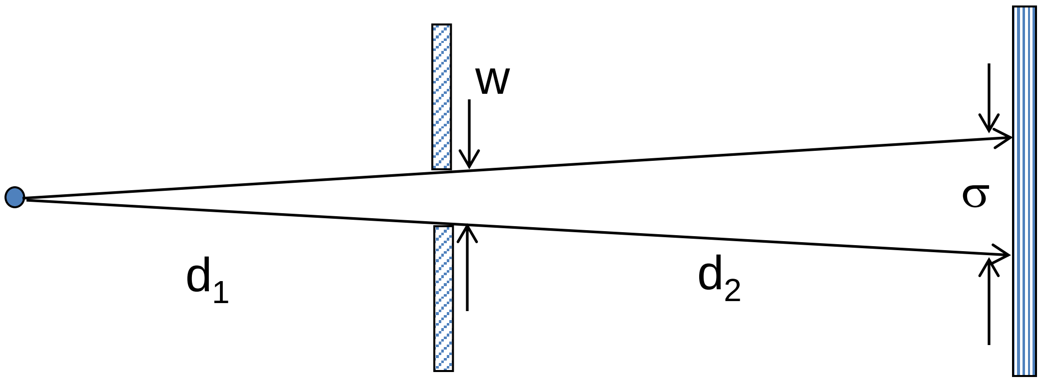
$$\sigma_y^2 = \beta_y \varepsilon_y$$

BESSY-II Pinhole Array



Used at ALS and ASP as well
Beam size & divergence

Optimize the pinhole size



If the pinhole is large, ray-optic ‘spread’ dominates

$$\sigma \approx \frac{w \cdot (d_1 + d_2)}{d_1}$$

Geometric error

If the pinhole is small, diffraction dominates...

Diffraction error

Other measurement errors include: Screen, CCD camera and chromatic error etc

Optimize the pinhole size (cont')

$$\left(\sigma_{image}\right)^2 = \left(M \cdot \sigma_{source}\right)^2 + \left(\sigma_{blur}\right)^2 + \left(\sigma_{diffraction}\right)^2$$

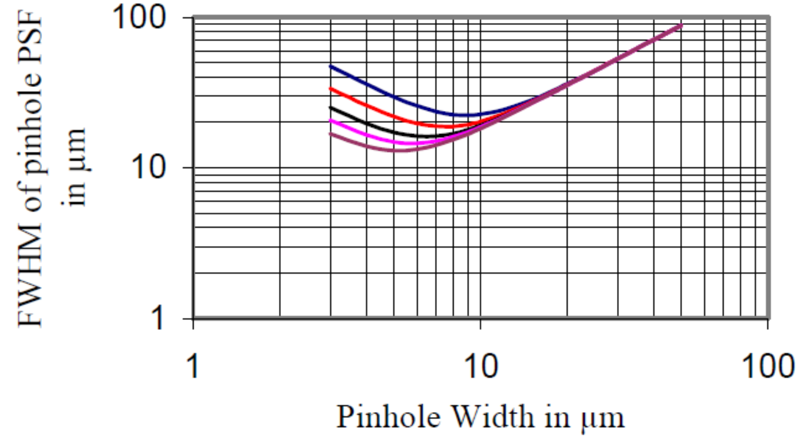
$$\sigma_{blur} = \frac{w}{\sqrt{2\pi}} \frac{\left(L_1 + L_2\right)}{L_1}$$

$$\sigma_{diffraction} = \frac{\sqrt{12}}{4\pi} \frac{\lambda L_2}{w}$$

L_1 Distance from source point to pinhole
L_2 Distance from pinhole to screen
$M=L_2/L_1$, magnification factor
W pinhole size

Optimize the pinhole size (cont')

Different curve corresponding to different filters



Geometric error:

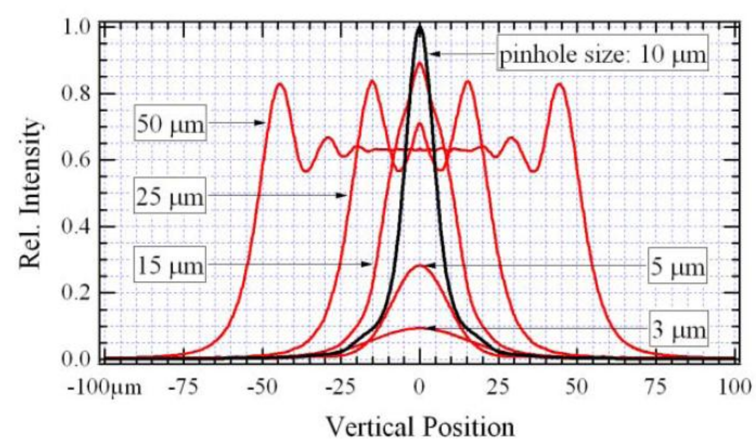
$$Wg_{FWHM} = a\,(D+d)/D$$

Diffraction error:

$$Wdiff_{FWHM} = 1.10\ 10^{-6}\ d/(a^*E)$$

a – pinhole width
d – distance from source point to pinhole
D – distance from pinhole to screen
E – photon energy in eV unit

SRW PSF simulation



‘Polychromatic’ Diffraction

Sands-121

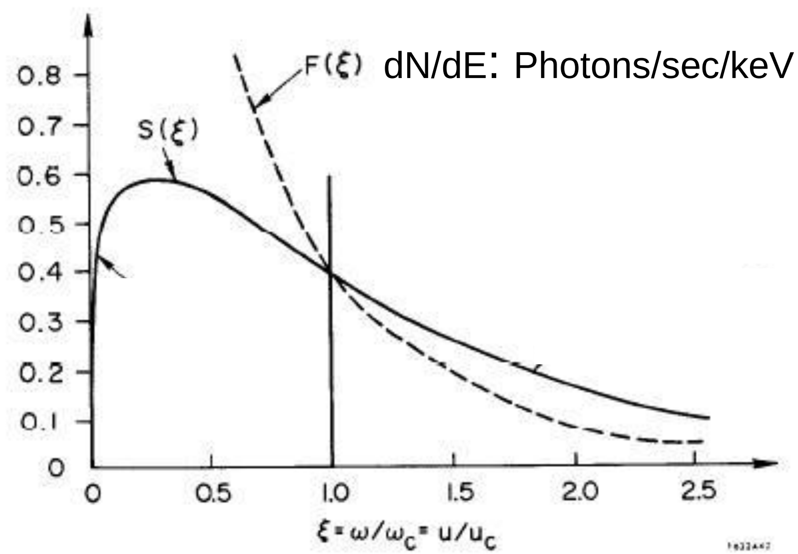
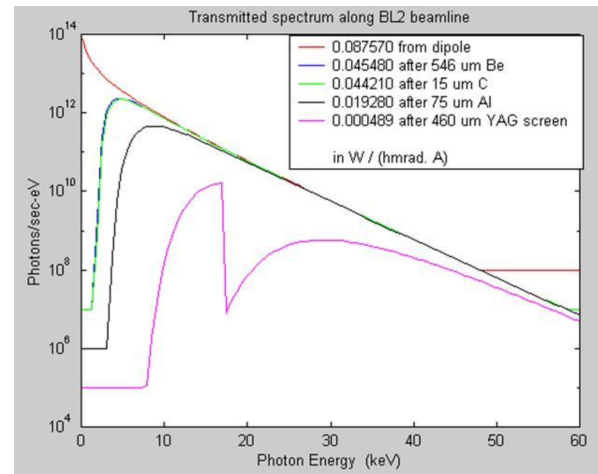


FIG. 42--Normalized power spectrum S and photon number spectrum F of synchrotron radiation.

spectrum at screen



C. Limborg - SSRL

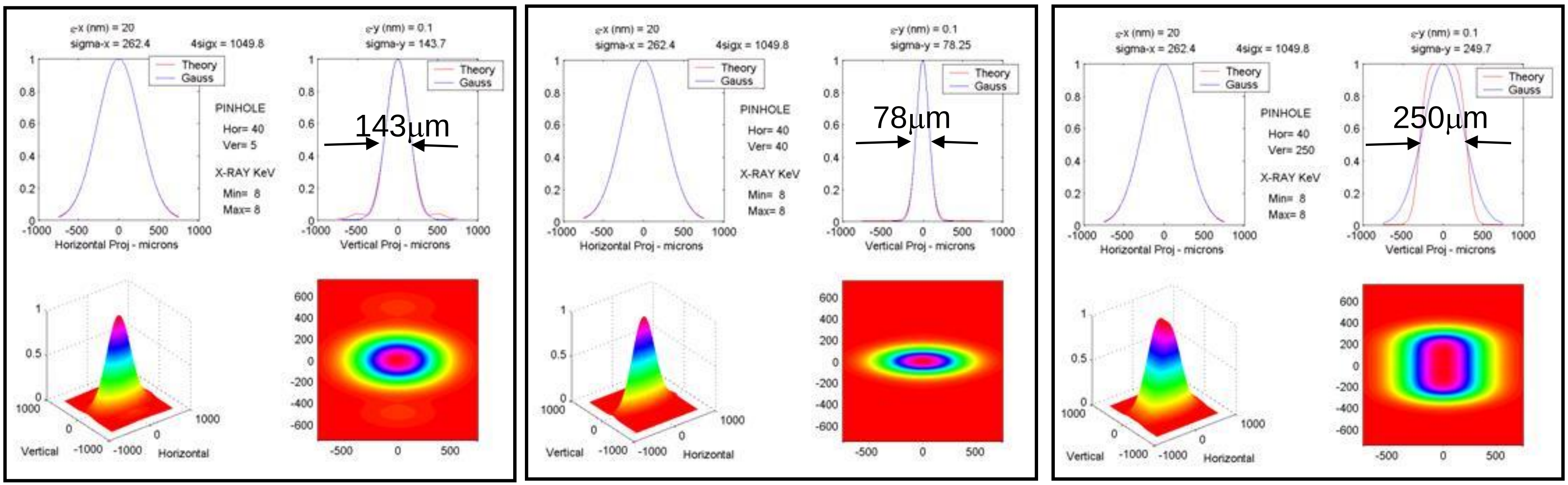
- Integrate intensity pattern over photon spectrum

PSF Calculation

Putting it all together…

fresnel.m valid from geometric to diffraction regimes

A_y=5 micron (diffraction) | A_y=40 micron (optimum) | A_y=250 micron (geometric)



J. Bergstrom - CLS

SRW, SPECTRA etc. can do the similar job

Phosphor screen error

Table 1: Width of the PSF (r.m.s) of the X-ray camera with several screens (in μm). The error is given by the standard deviation of the fitted width per line on the digital image.

Thickness (μm)	P43	$CdWO_4$	LuAG
5	6.2 ± 0.39	-	-
100	-	7.45 ± 0.45	-
200	-	8.45 ± 0.45	8.70 ± 0.45
400	-	-	10.0 ± 0.45
500	-	13.5 ± 0.45	-

Diamond, screens compare

To select the screen:

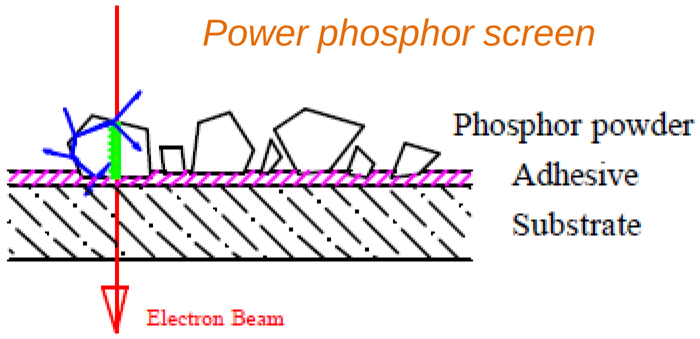
– Spatial resolution

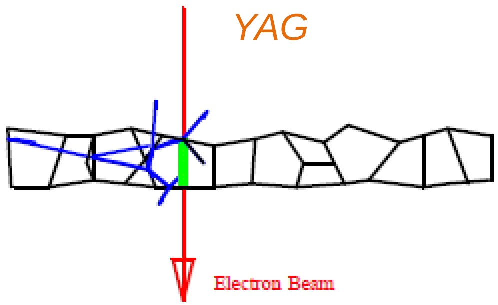
– Time response (decay time, 70ns for YAG:Ce)

– Photon yield of the screen

– Emission wavelength

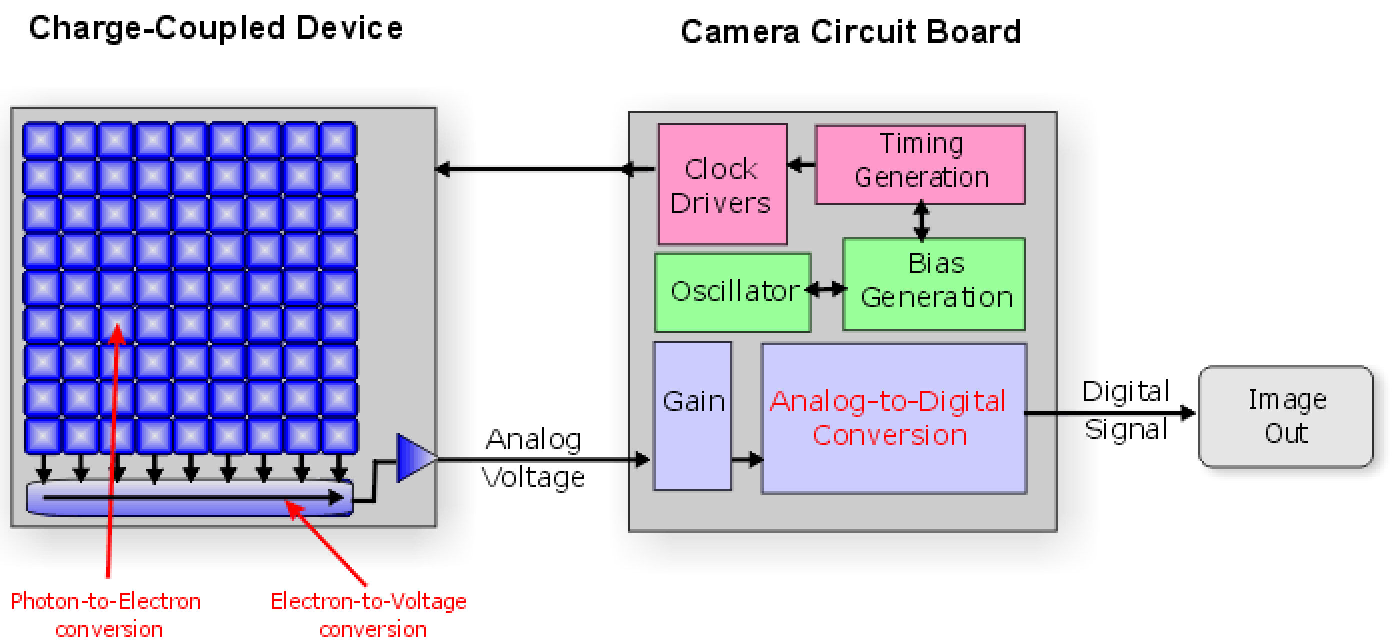
– Radiation damage etc.





CCD error

CCD – Charge Coupled Device



Finite pixel size (Flea2, 4.65 x 4.65µm pixel size)
Spilling to neighbors due to spilled charge or scattered radiation

$$\sigma_{ccd} \approx 0.3 + spill\_fraction, [pixels]$$

Screen and CCD errors are negligible if the pinhole magnification factor is large

Summary

- Pinhole cameras effective in the x-ray regime (~5μm resolution)

- System construction fairly straight-forward

- Power loading considerations

- Optimize aperture size

- Data analysis relies on comparison of model with measurement
  fresnel.m

- Relative high exposure time due to small aperture (fast measurement needed for injection transient and machine physics)