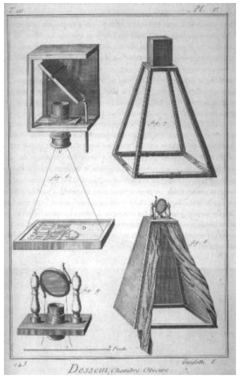
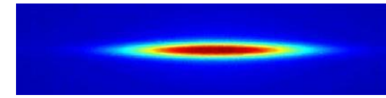


Pinhole Cameras – Operation and Analysis

US Particle Accelerator School
January 14-18, 2008

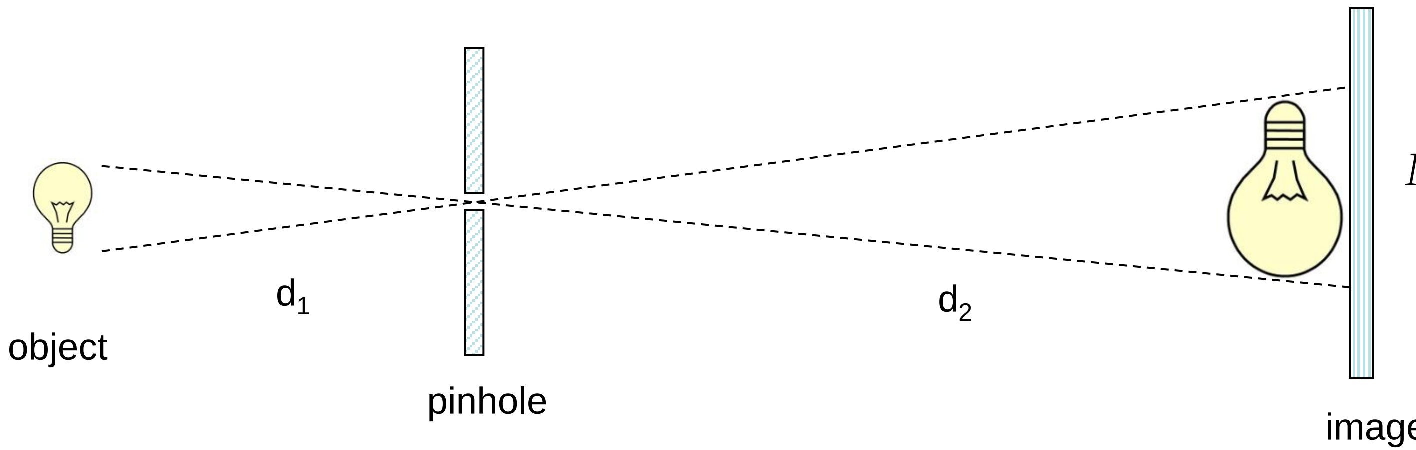


- Use x-rays to minimize diffraction effects

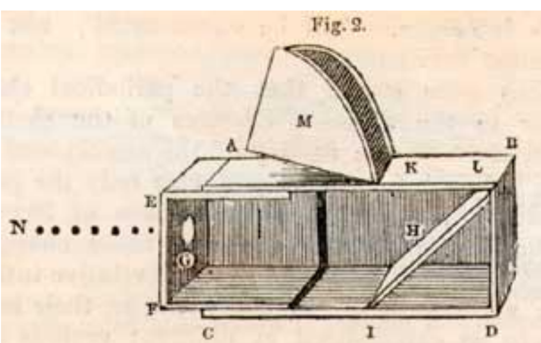
- Reflective/refractive optics not available

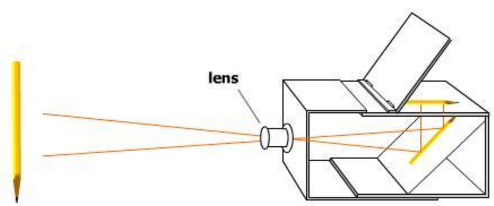
- Simple components

Camera Obscura

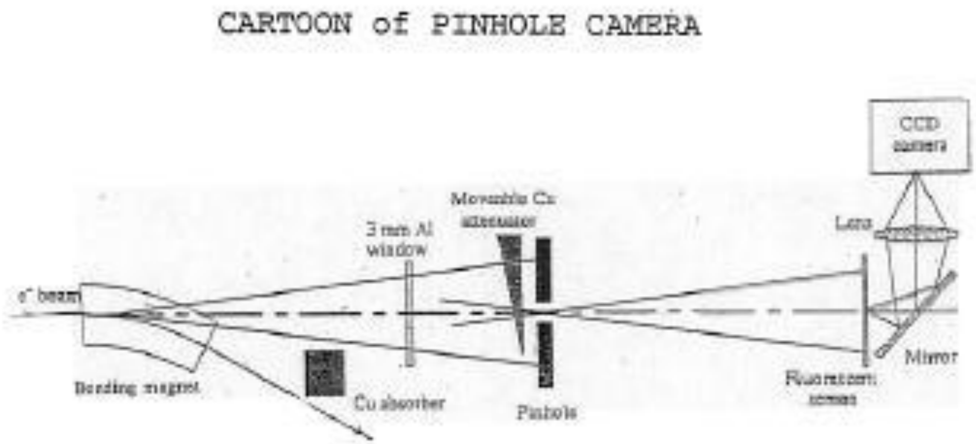


$$M = \frac{d_2}{d_1}$$

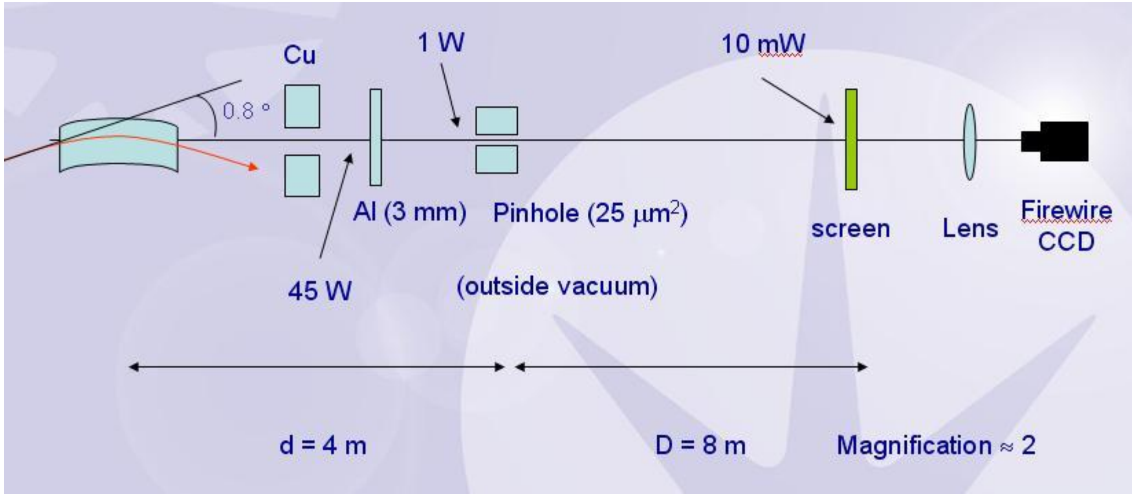




X-ray Pinhole Camera - Schematic

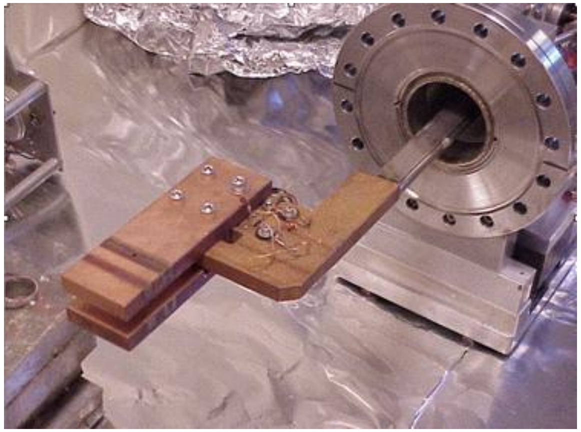


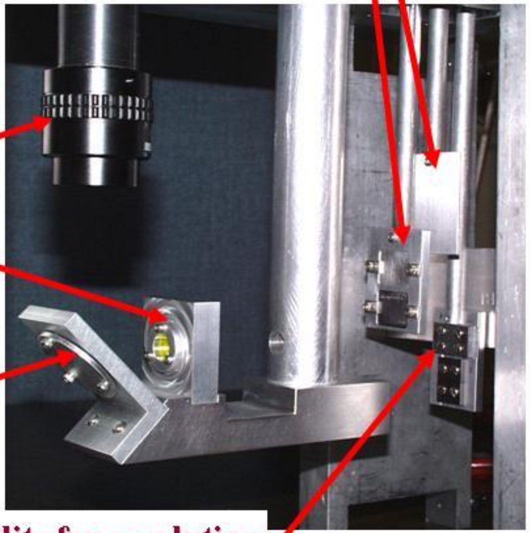
SPEAR circa 1975



DIAMOND circa 2005

SPEAR3 Pinhole, Filters, YaG Screen and Camera





What does the Pinhole Camera See?

1. Horizontal Plane

- Electron beam distribution

$$\rho(x,x') = \frac{1}{2\pi\varepsilon_o} e^{-(\gamma_o x^2 + 2\alpha_o x x' + \beta_o x'^2)/2\varepsilon_o}$$

- Photon beam distribution

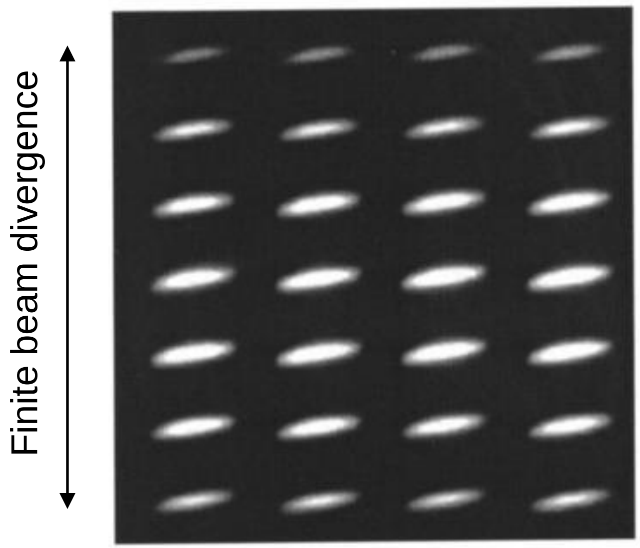
$$\rho(x,x') = \frac{1}{2\pi\varepsilon} e^{-(\gamma\, x^2 + 2\alpha x x' + \beta\, x'^2)/2\varepsilon}$$ (new Twiss, new ellipse)

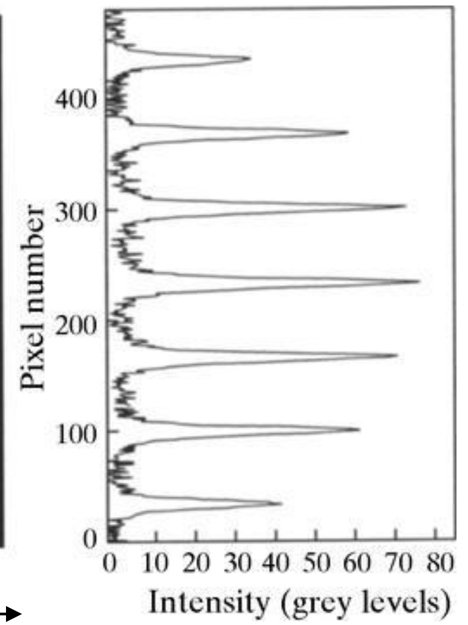
Searchlight sweeping across pinhole integrates over x'

$$\rho(x) = \frac{1}{\sqrt{2\pi\beta\varepsilon}} e^{-x^2/2\beta\varepsilon}$$ (simple result)

where $\beta\varepsilon = \beta_o\varepsilon_o + (\eta_o\delta)^2$ ⟶ fit to Gaussian, compute ε_o

BESSY-II Pinhole Array
(Peatmann and Holldack)

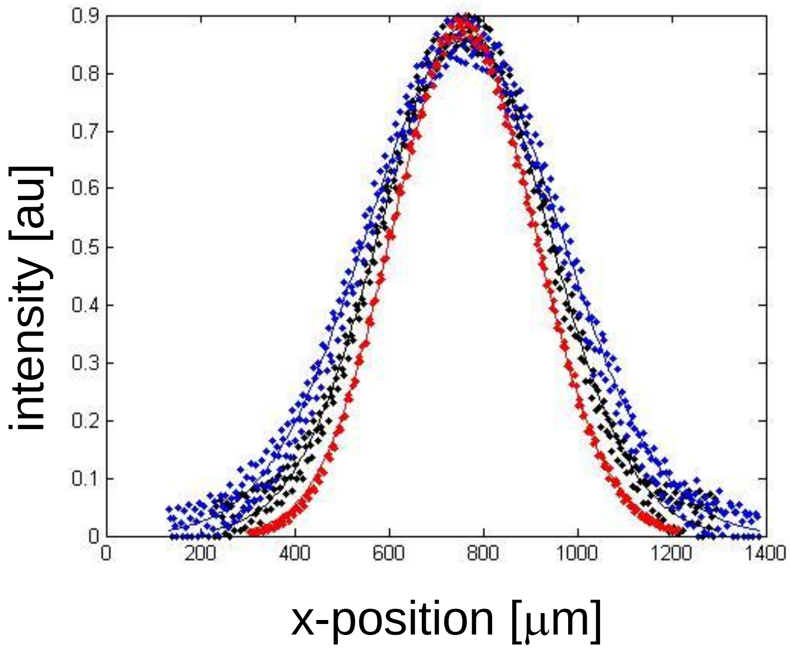




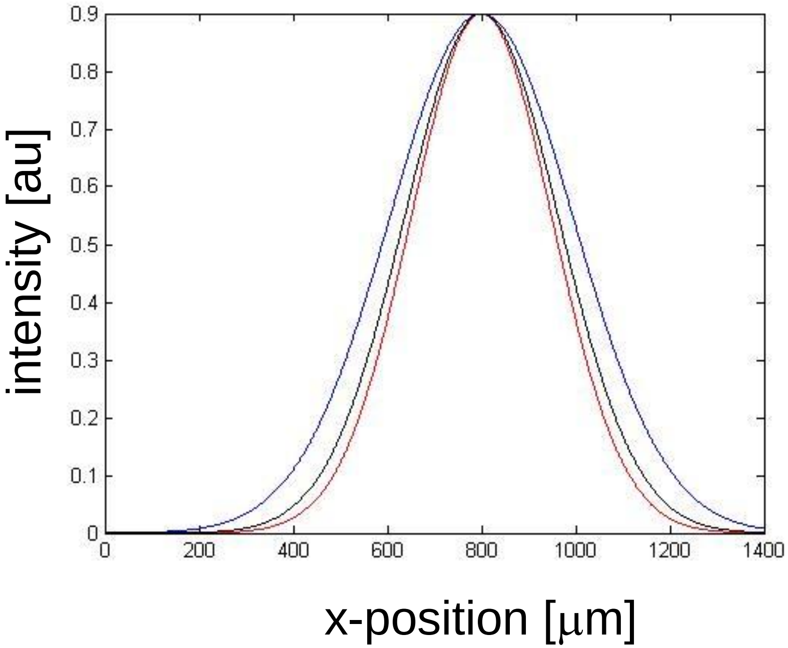
Constant Image Intensity

SPEAR3 Example – three different operational modes

Measurement



Theory

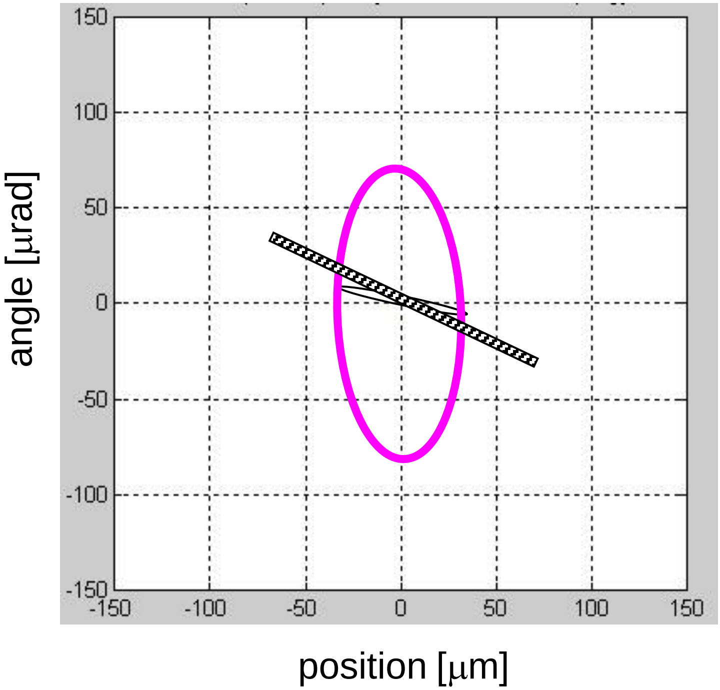


What does the Pinhole Camera See?

2. Vertical Plane

- Sweeping searchlight no longer integrates over angles

- Pinhole projected onto source casts a 'shadow' in phase space: $y' = \frac{y}{d_1}$



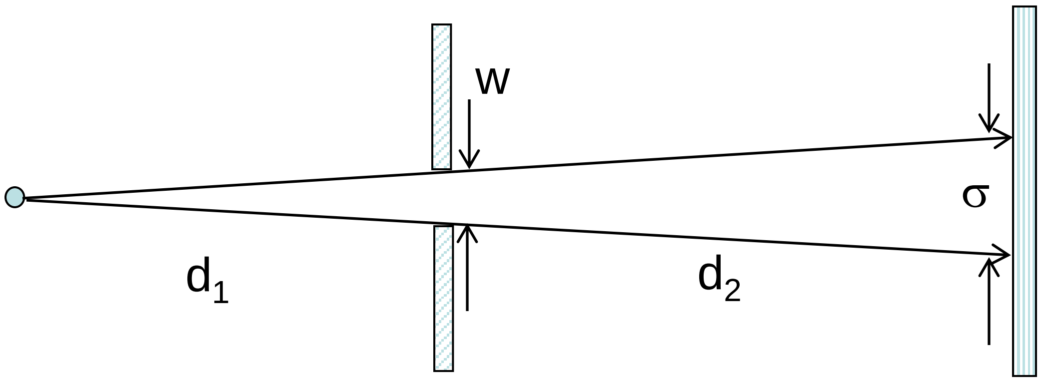
$$\left(\gamma y^2 + 2\alpha y y' + \beta y'^2\right)/2\varepsilon \rightarrow \frac{y^2}{2\varepsilon\beta}\cdot\left\{1+\left(\alpha - \frac{\beta}{d_1}\right)^2\right\}$$

$$(\varepsilon\beta)_{eff} = \frac{\varepsilon\beta}{1+F}$$

$$\rho(y_i) = Ae^{-y_i^2/2(\varepsilon\beta)_{eff}}$$

at the screen
(neglecting diffraction)

What size pinhole?



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

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

If the pinhole is small, diffraction dominates...

Evaluating the Source Size

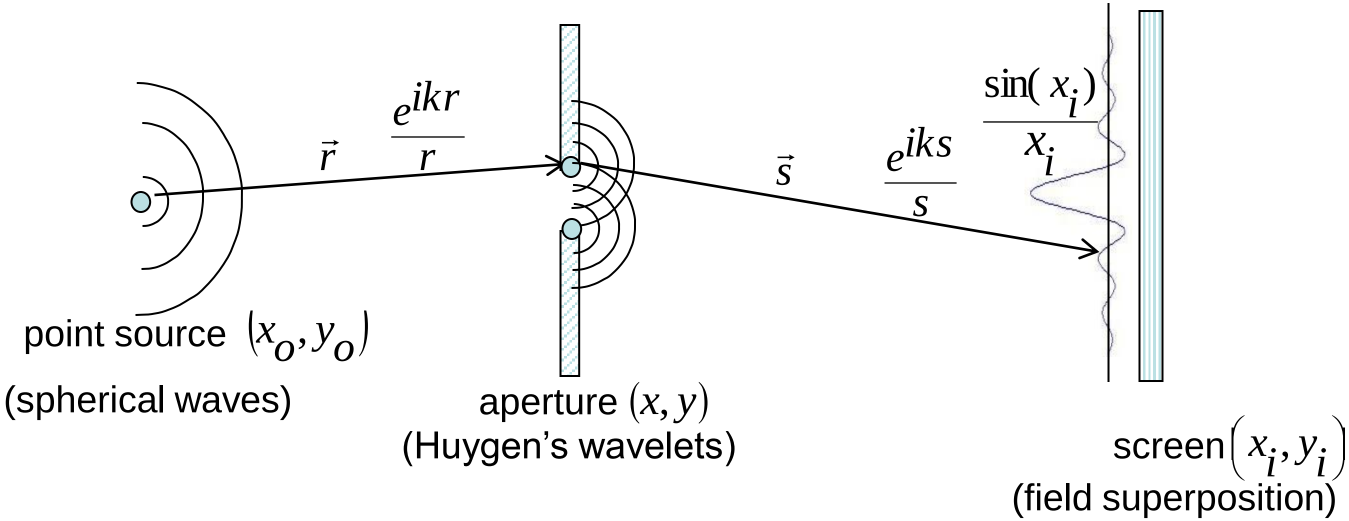
$$\left(\sigma_{image}\right)^2 = \left(\frac{\sigma_{source}}{demag}\right)^2 + \left(\sigma_{blur}\right)^2 + \left(\sigma_{diffraction}\right)^2$$

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

L_1 Source – pinhole 2.34 m
L_2 Pinhole - screen 1.2 m
Demagnification 1.95:1
W pinhole size 63 μm

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

Diffraction Effects – monochromatic beam



$$F(x_i\,|\,x_o, y_i\,|\,y_o) = \frac{B}{\lambda rs} \iint_{aperture} e^{ik(r+s)}\,dx\,dy$$

Point Source Diffraction (cont'd)

$$F = \iint_{aperture} e^{ik(r+s)} dxdy$$ field integral over pinhole aperture

$$= U_x V_y$$ retangular aperture - surface integral is separable

$$I_x = \text{intensity} = U_x^* U_x$$

$$I_y = V_y^* V_y$$

expand 'r' and 's' to 2nd order - the field integrals look like

$$U_x = \int_{x-aperture} \exp ik \left\{ \frac{(x_o - x)^2}{2d_1} + \frac{(x_i - x)^2}{2d_2} \right\} dx$$

Distributed Source Field Pattern

$I(x_i|x_o) = \text{intensity} = U^*U$ is for a point source

- Integrate again over the source distribution

$$I(x_i) = \int \rho(x_o) \cdot I(x_i|x_o) dx_o$$

where $\rho \sim e^{-x^2/2\sigma_x^2}$ (Gaussian distribution)

- Jack reduced the double integral to a single integral

emittance image

$$I(x) = \int_0^1 \frac{e^{-Az^2}}{z} \cdot \sin Bz(1-z) \cdot \cos Cxz \cdot dz$$

A, B and C are physical system parameters

‘Polychromatic’ Diffraction

Sands-121

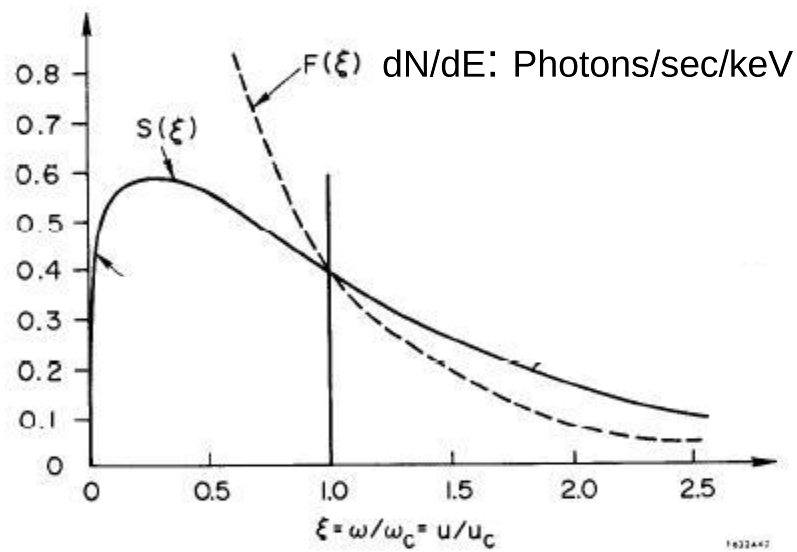
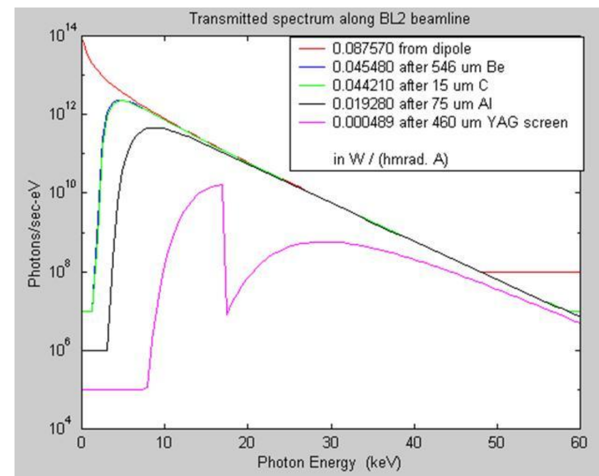


FIG. 42--Normalized power spectrum S and photon number spectrum F of synchrotron radiation.

spectrum at screen



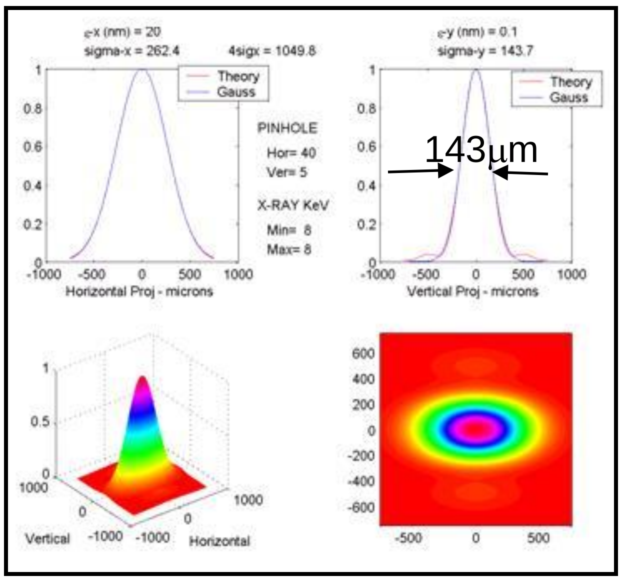
C. Limborg - SSRL

- ➢ Integrate intensity pattern over photon spectrum

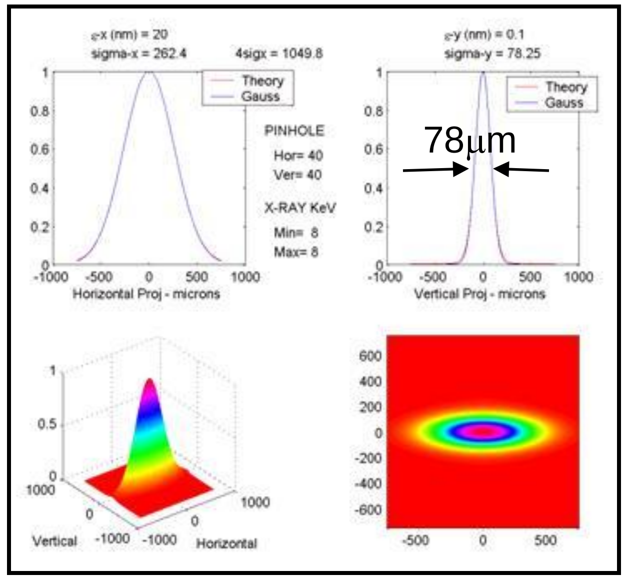
Putting it all together...

fresnel.m valid from geometric to diffraction regimes

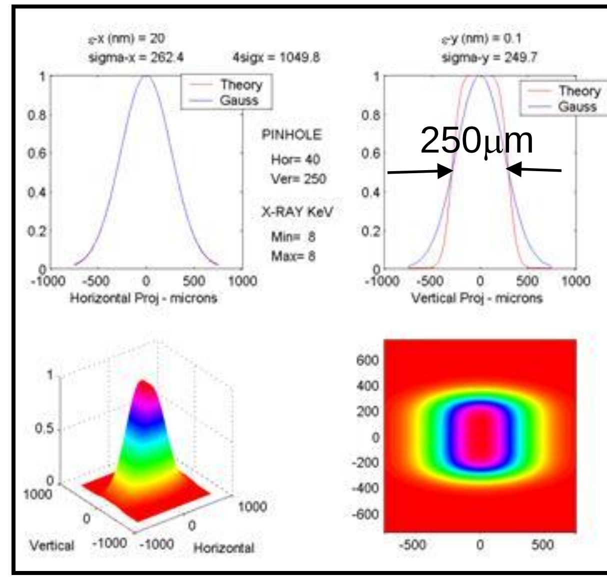
A_y=5 micron
(diffraction)



A_y=40 micron
(optimum)



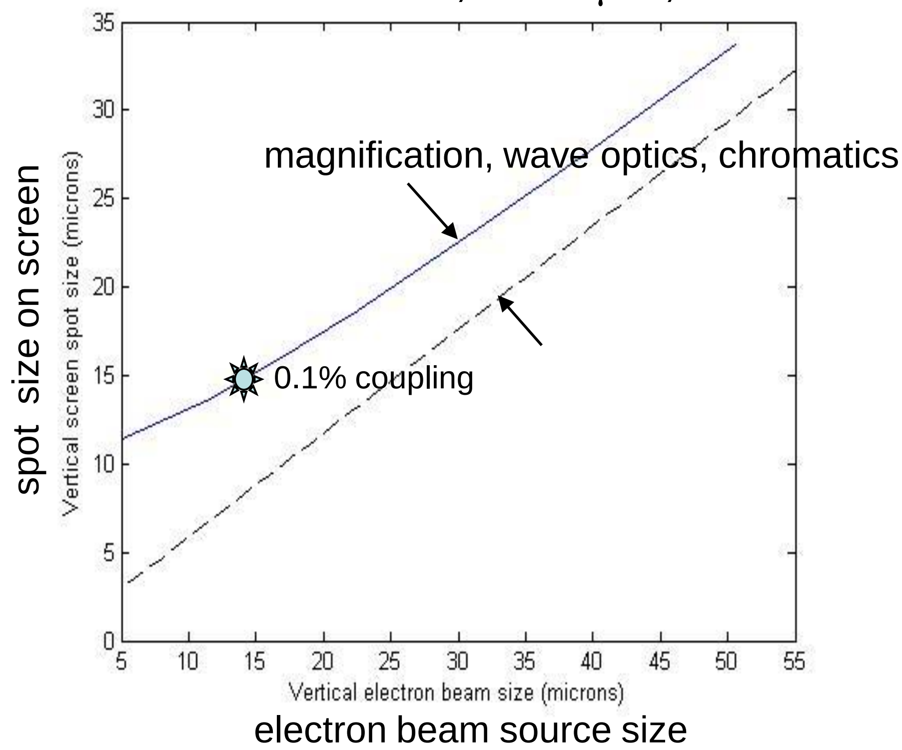
A_y=250 micron
(geometric)



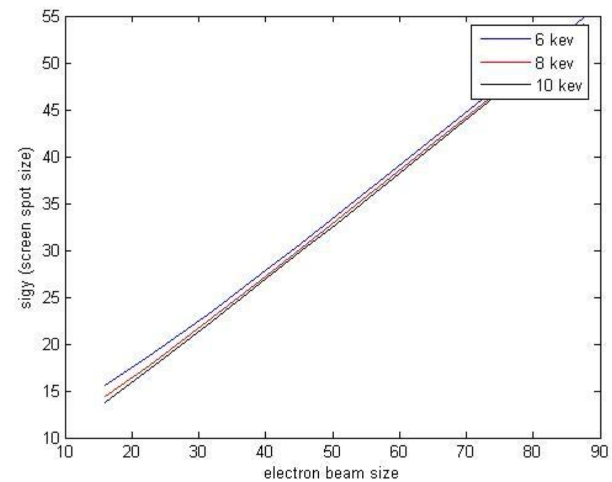
J. Bergstrom - CLS

Application to measurement

SPEAR3: M=0.6, w=30μm, 8keV



hardening of the spectrum



Summary

- Pinhole cameras effective in the x-ray regime

- System construction fairly straight-forward

- Power loading considerations

- Optimize aperture size

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

- Effective for measuring small spot sizes