Beam Diagnostics with Synchrotron Radiation – An Overview

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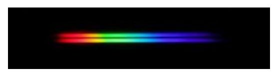
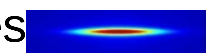
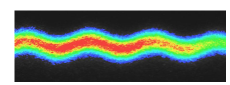
US Particle Accelerator School
January 18-22, 2010

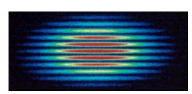
- Motivation

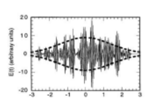
- Electron beam properties

- SR beam properties 

-Transverse imaging – cameras, pinholes, Fresnal lenses 

- Fast imaging – gated ICCD and streak cameras 

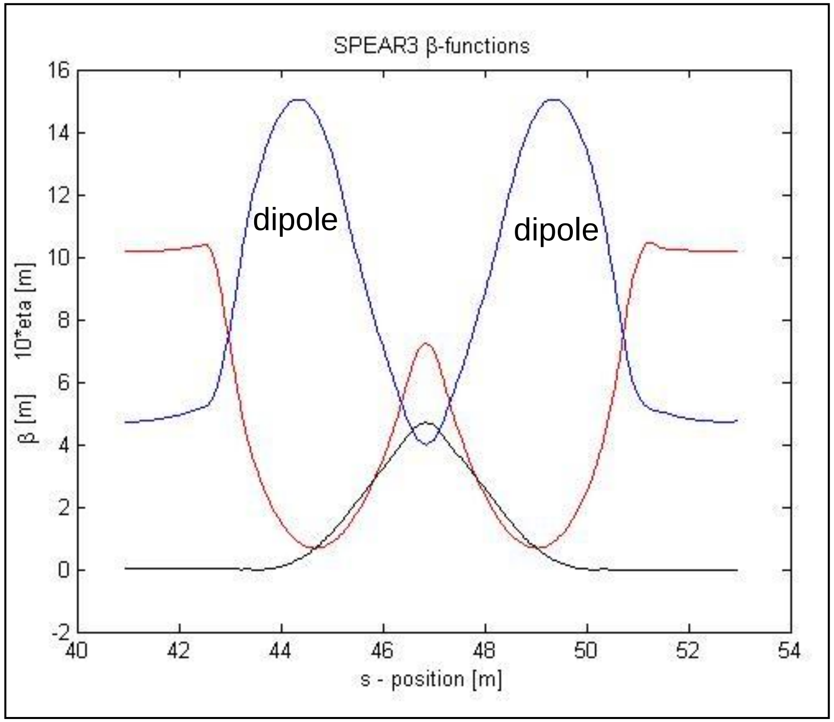
- Stellar Interferometer 

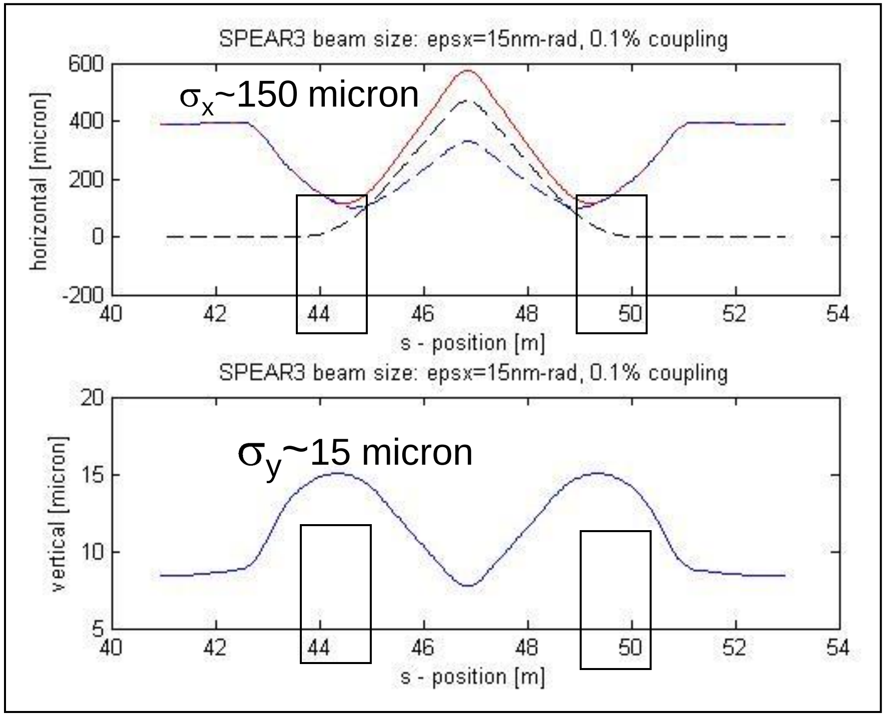
- Fluctuation measurements 

Motivations for SR diagnostics

- ‘eye’ into the accelerator
- faithful photon image reproduces electron beam distribution (x,y,z)
- optics verification, coupling, brightness
- impedance and instabilities
- other techniques less accurate (e.g. scraper, RMA)

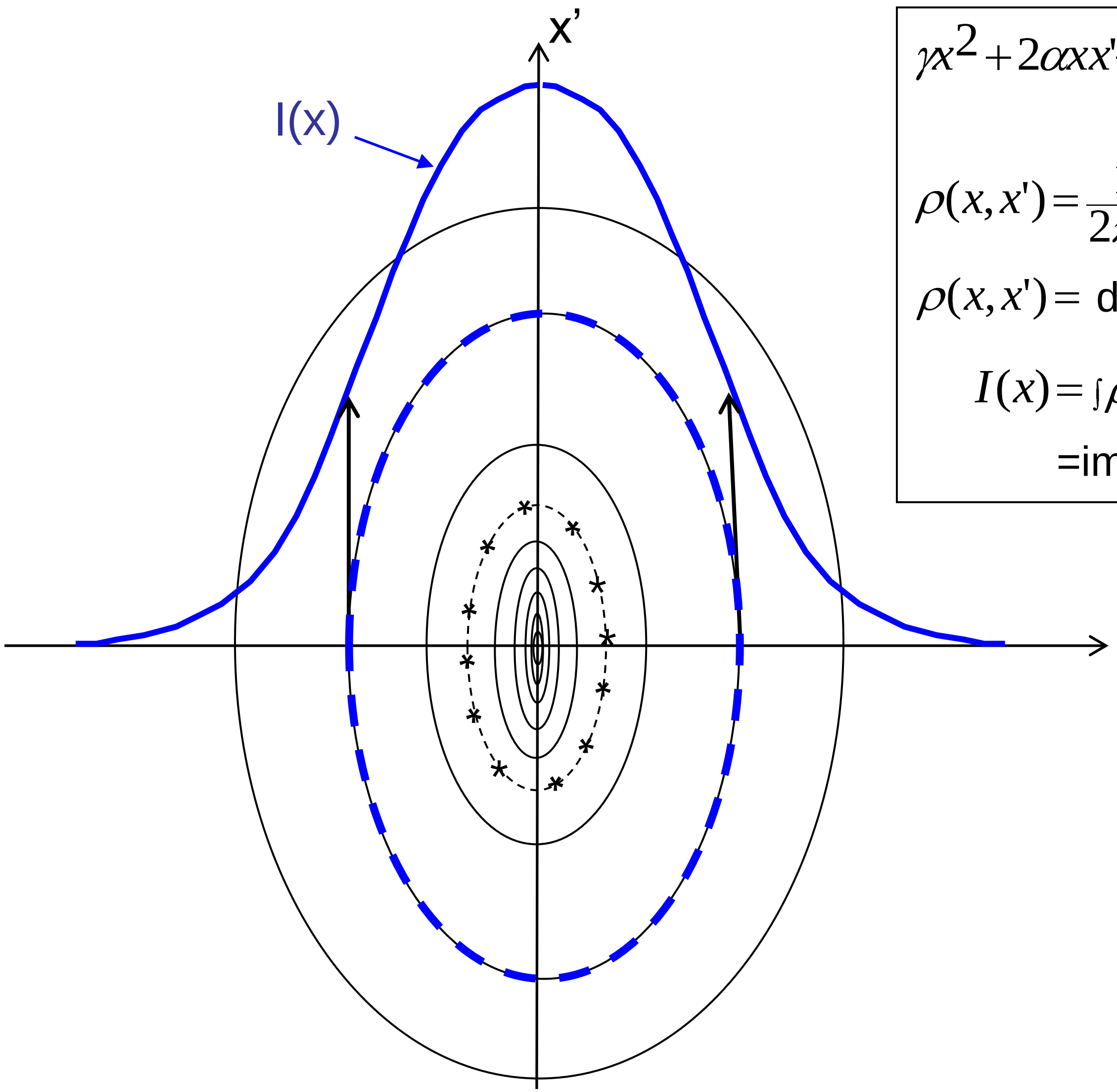
Electron beam properties: β-functions and beam size





Hofmann: chapter 13

Electron beam properties: Phase Space



$\gamma x^2 + 2\alpha x x' + \beta x'^2 =$ invariant oscillation amplitude

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

$\rho(x,x') =$ distribution in phase space

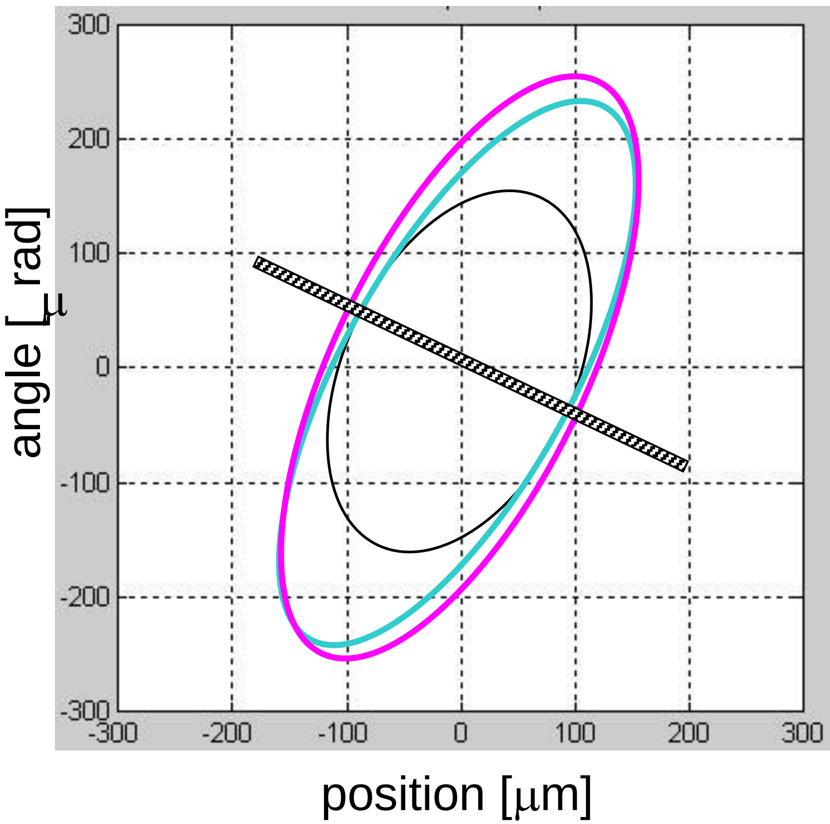
$$I(x) = \int \rho(x,x')dx' = Ae^{-x^2/2\varepsilon\beta}$$

=image projected on screen

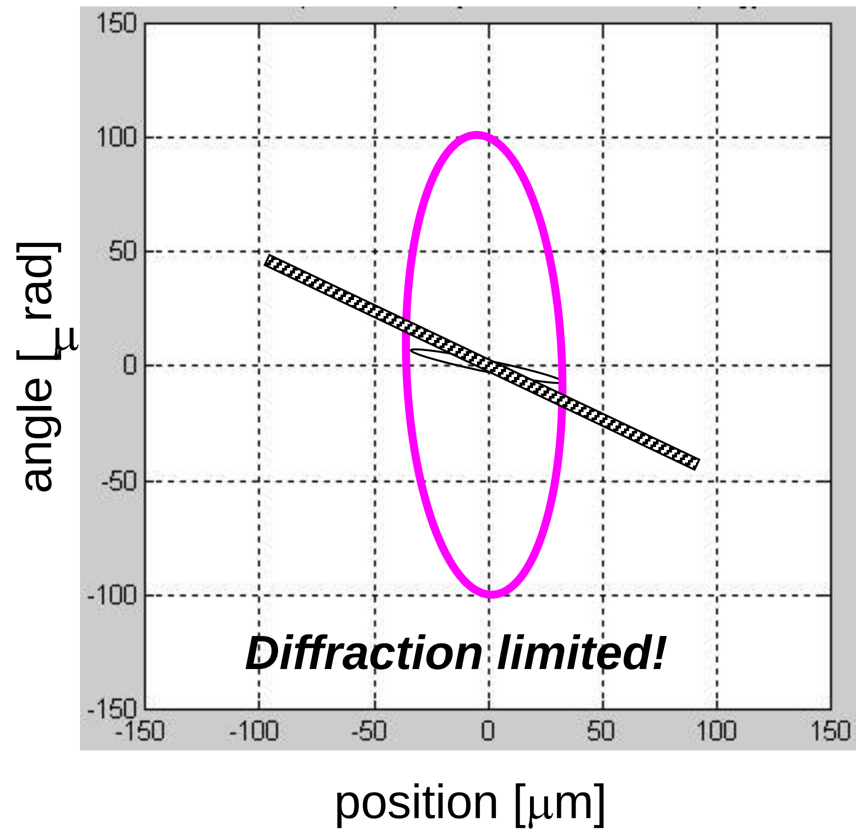
Hofmann: chapter 13

Photon beam properties: Phase Space

SPEAR3: Horizontal



SPEAR3: Vertical



$$\sigma_x^2 = \varepsilon_x \beta_x + (\eta_x \delta)^2$$

$$\sigma_{x'}^2 = \varepsilon_x \gamma_x + (\eta_x' \delta)^2 + \sigma_r{}^2$$

$$\sigma_y^2 = \varepsilon_y \beta_y + (\eta_y \delta)^2$$

$$\sigma_{y'}^2 = \varepsilon_y \gamma_y + (\eta_y' \delta)^2 + \sigma_r{}^2$$

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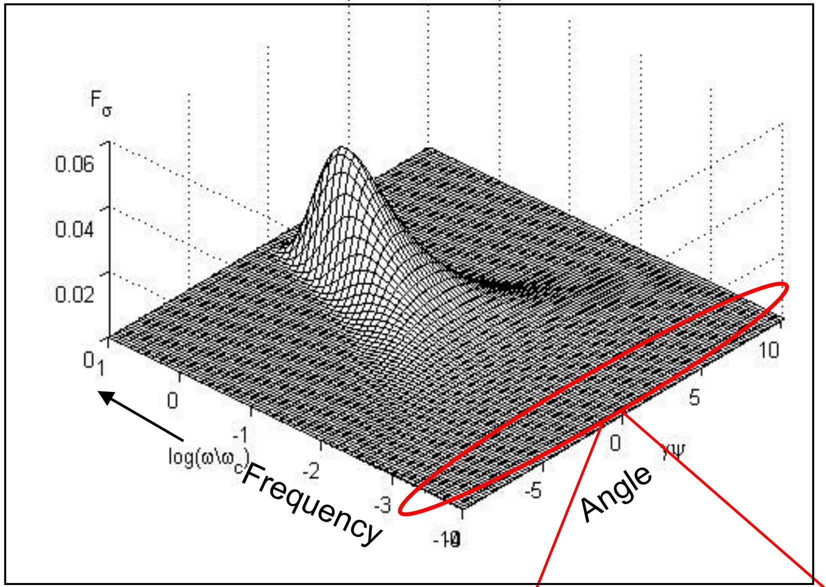
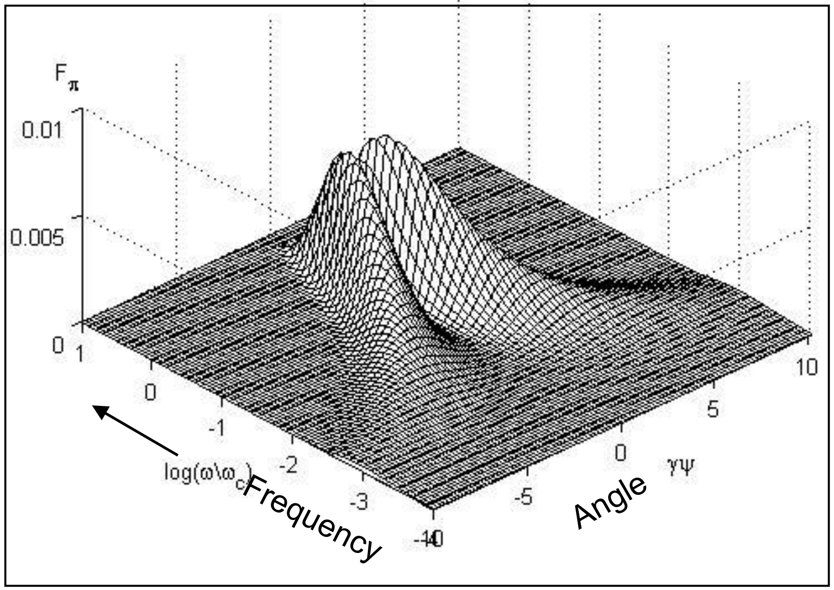
Photon beam properties: Angular spectral power density

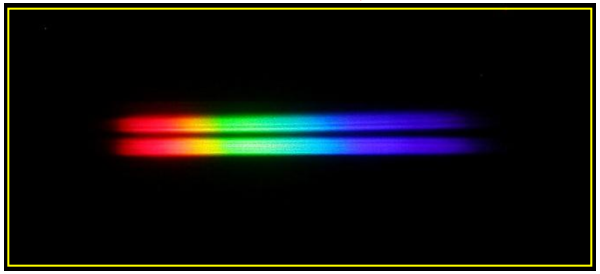
Horizontal Polarization

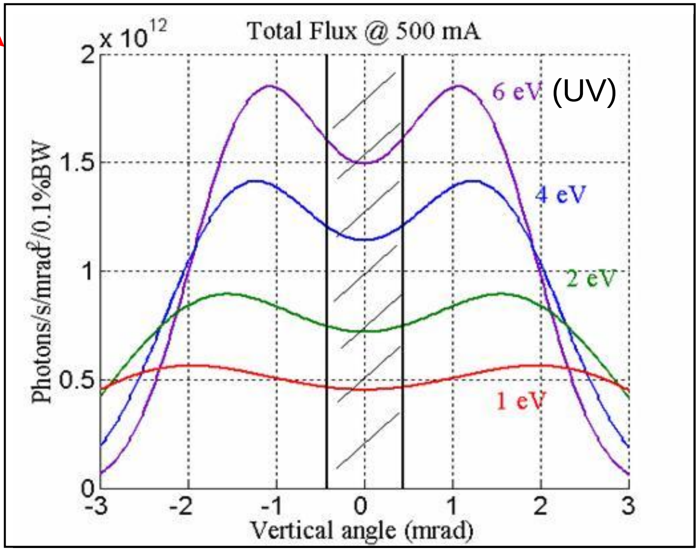


Vertical Polarization



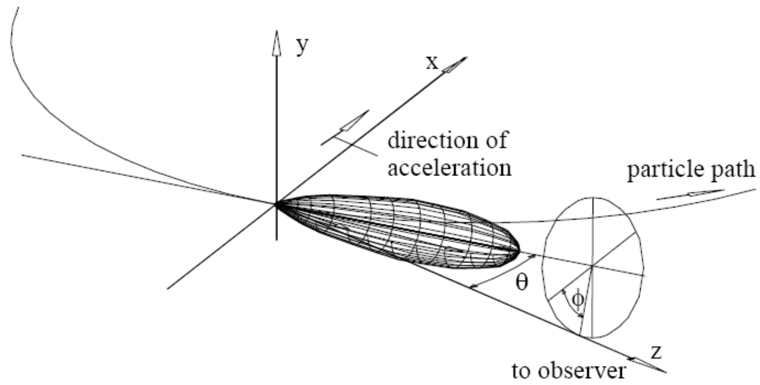
visible component



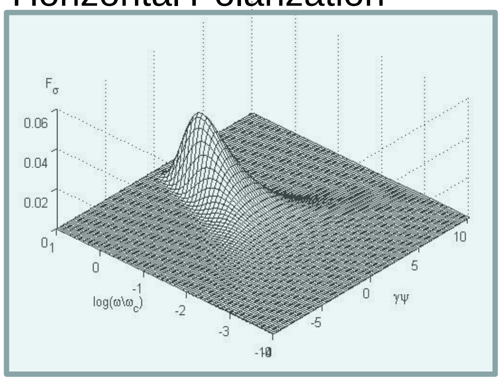


Hofmann: chapter 5

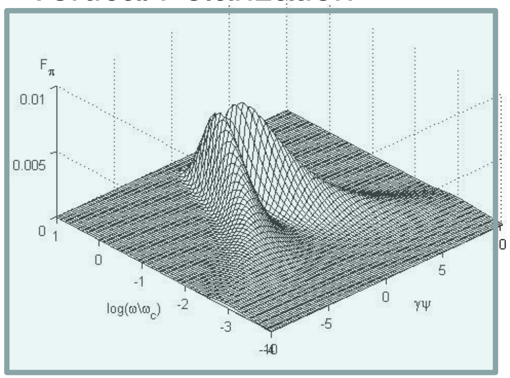
Angular spectral power density (Schwinger, 1946)



Horizontal Polarization



Vertical Polarization



$$F_{s\sigma}(\omega,\psi)=\left(\frac{3}{2\pi}\right)^3\left(\frac{\omega}{2\omega_c}\right)^2\left(1+\gamma^2\psi^2\right)^2K_{2/3}^2\left(\frac{\omega}{2\omega_c}\left(1+\gamma^2\psi^2\right)^{3/2}\right)$$

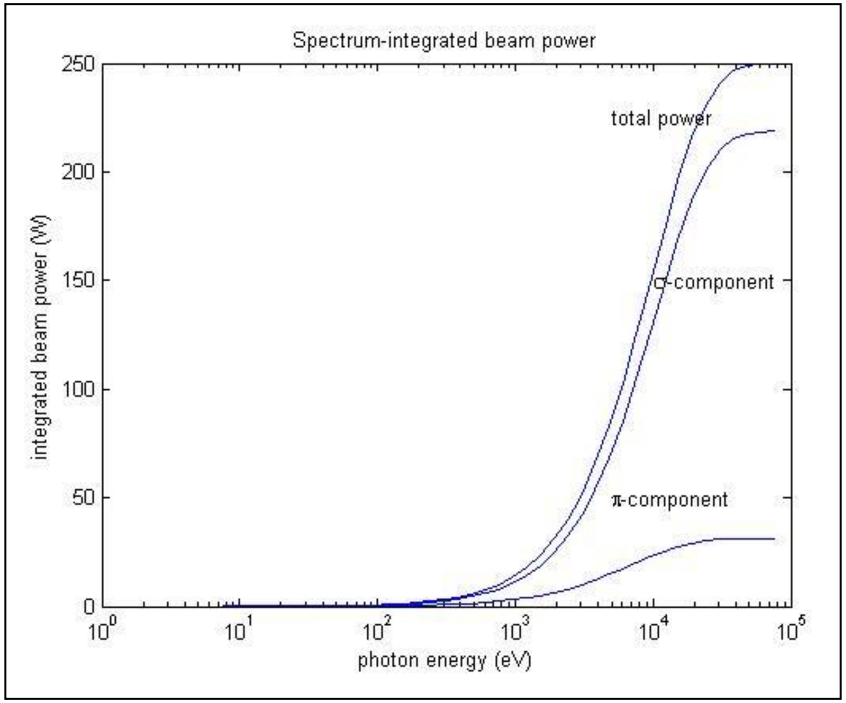
$$F_{s\pi}(\omega,\psi)=\left(\frac{3}{2\pi}\right)^3\left(\frac{\omega}{2\omega_c}\right)^2\gamma^2\psi^2\left(1+\gamma^2\psi^2\right)K_{1/3}^2\left(\frac{\omega}{2\omega_c}\left(1+\gamma^2\psi^2\right)^{3/2}\right)$$

Photon beam properties: Beam power

<u>Example</u>:
3 GeV and 200 ma current
P_{SR}~200kW (total)

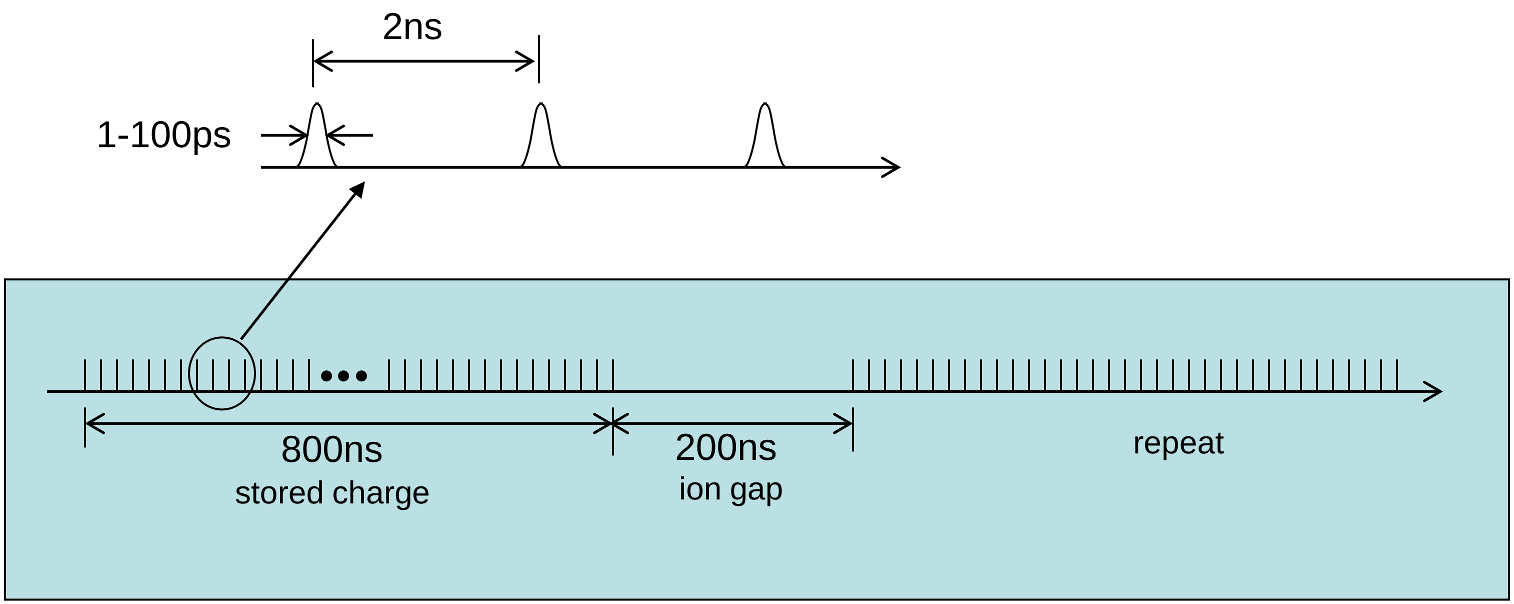
<u>visible beam line (1.5eV)</u>
25mm aperture at 5 m (5 mrad)
P_{SR}~150W
lucky to get 100μW visible
(Class I laser pointer)

<u>pinhole camera (15keV)</u>
25μm aperture at 5 m (5 μrad)
P_{SR}~100μW before filter

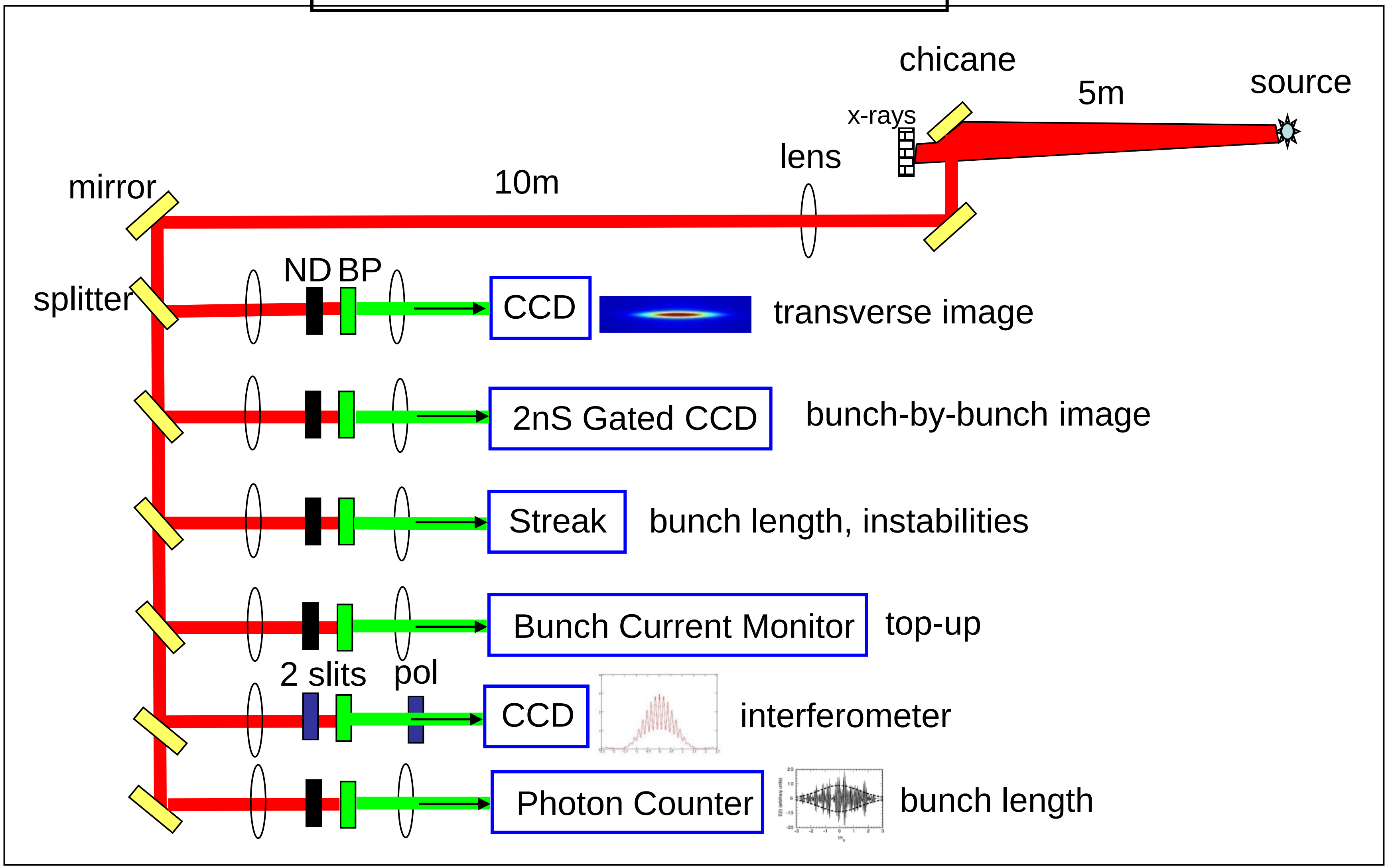


Hofmann: chapter 5

Photon beam timing pattern - storage rings



Visible beam line components

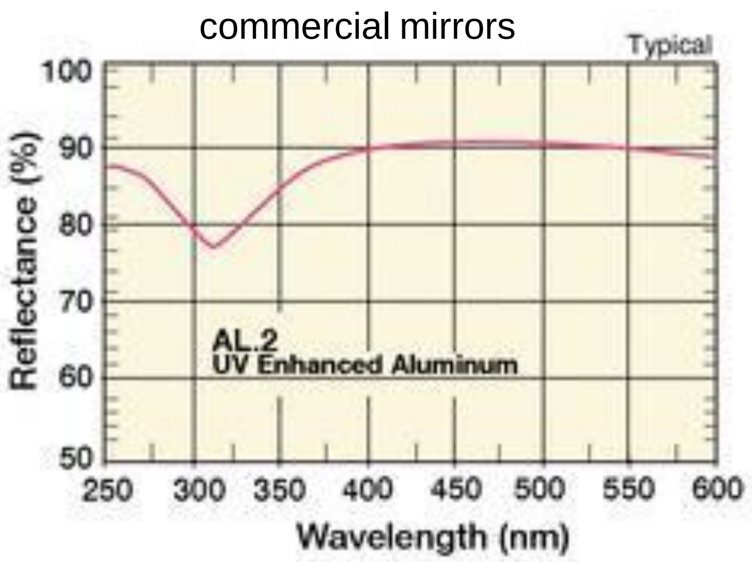


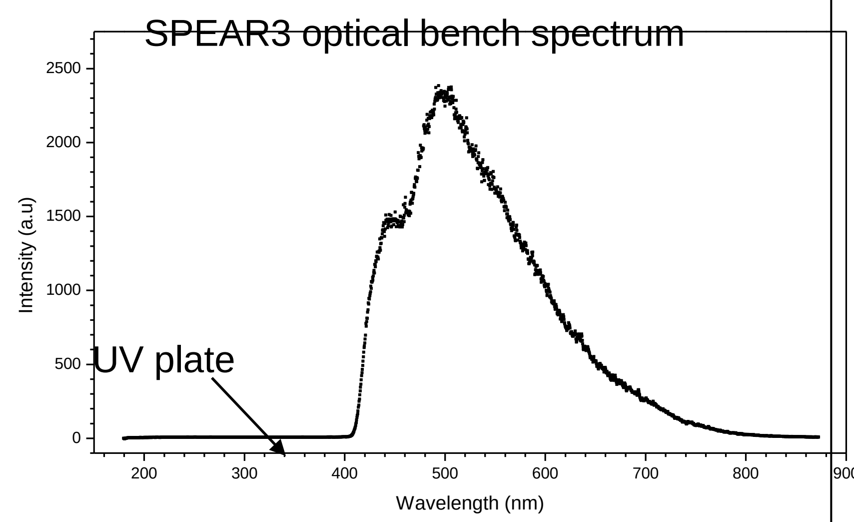
Visible beam line components (cont'd)

Beam line optics

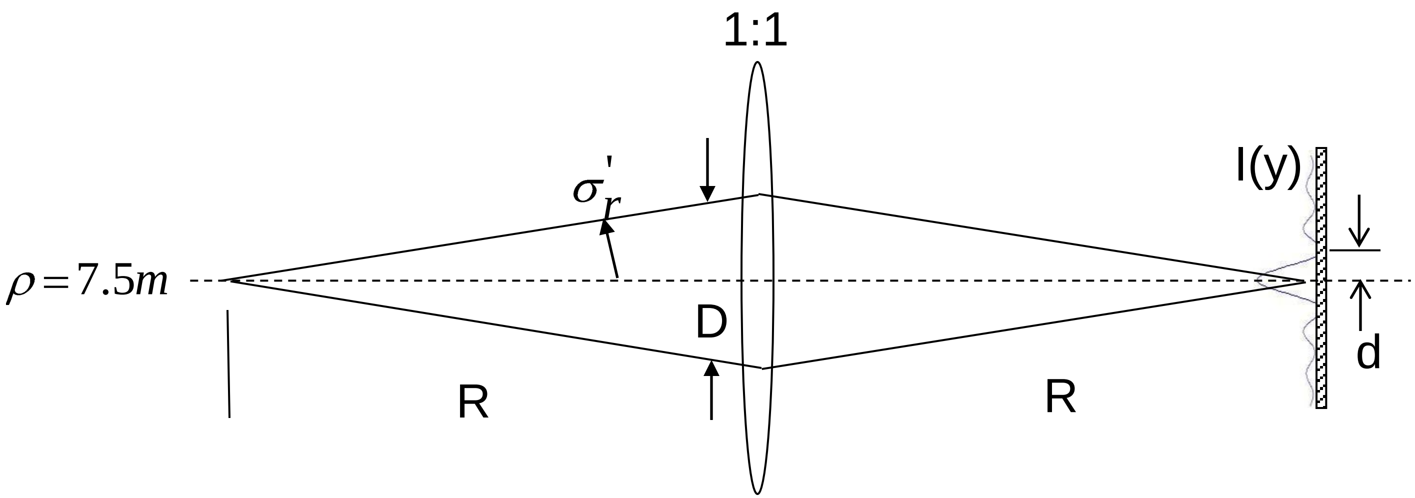
Windows - quartz can pass down to about 220nm
Mirrors – flat or focusing, UV enhanced
Lenses – focusing, defocusing, doublets, achromats >350nm
Filters –highpass and bandwidth to about 10n FWHM
Slits and diaphrams – 1ms mechanical shutters, 10ps Pockel cells

About 90% transmission per element





Diffraction Limited Resolution



For lens aperture: $d \approx \frac{\lambda R}{2D}$ where for SR $D = 2\sigma_r' R$

$\sigma_r' = 0.41 \cdot (\lambda / \rho)^{1/3}$ visible

$$d \approx \frac{1}{3} \cdot \left(\lambda^2 \rho\right)^{1/3}$$

$d \approx 40\mu m$ at λ=550nm

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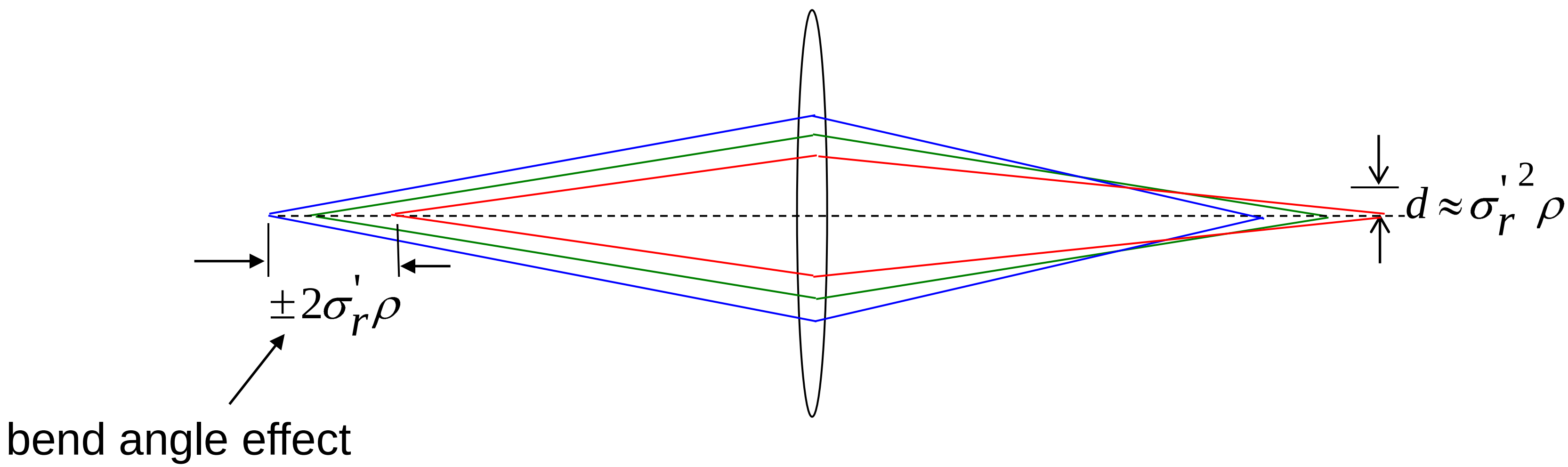
more diffraction later...

Depth of Field



$$d \approx \sigma_r'^2 \rho$$

$$d \approx \frac{1}{3} \cdot \left(\lambda^2 \rho\right)^{1/3}$$ ~same result as diffraction

(source length related to opening angle)

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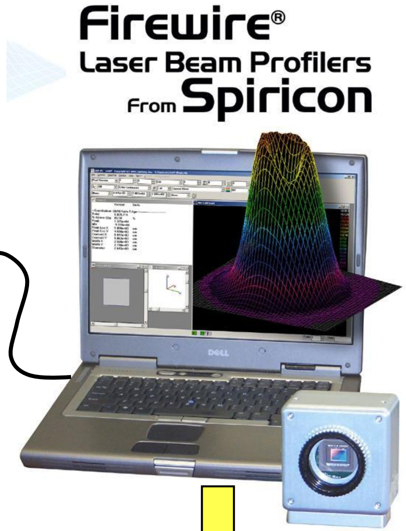
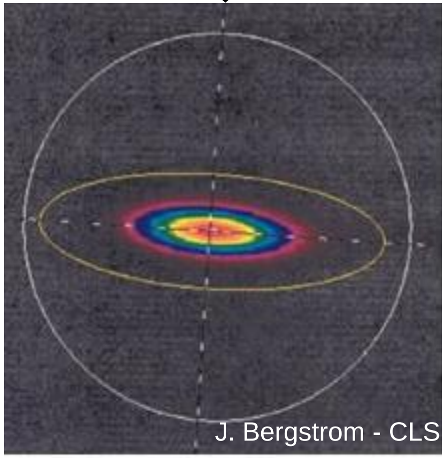
Cameras Part-I: CCD's and Video

Frame Grabber

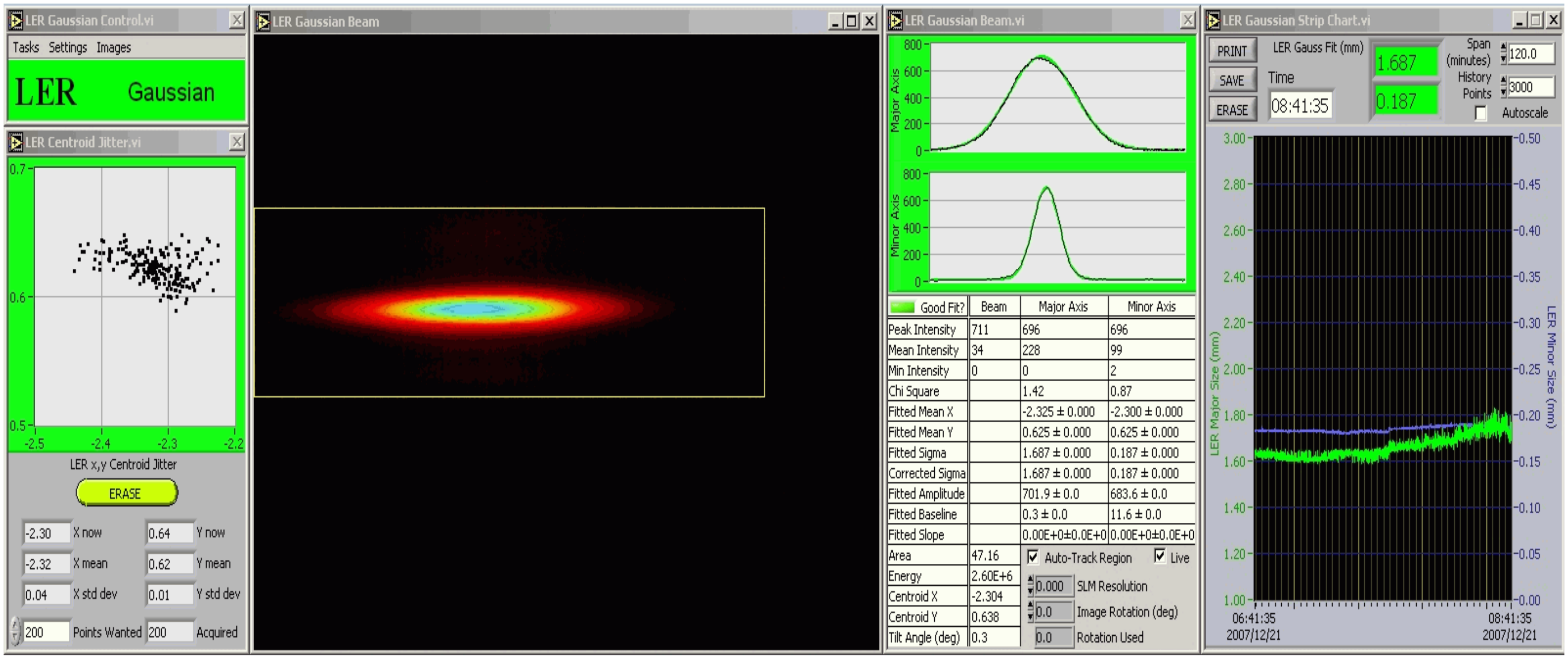


EPICS, MATLAB

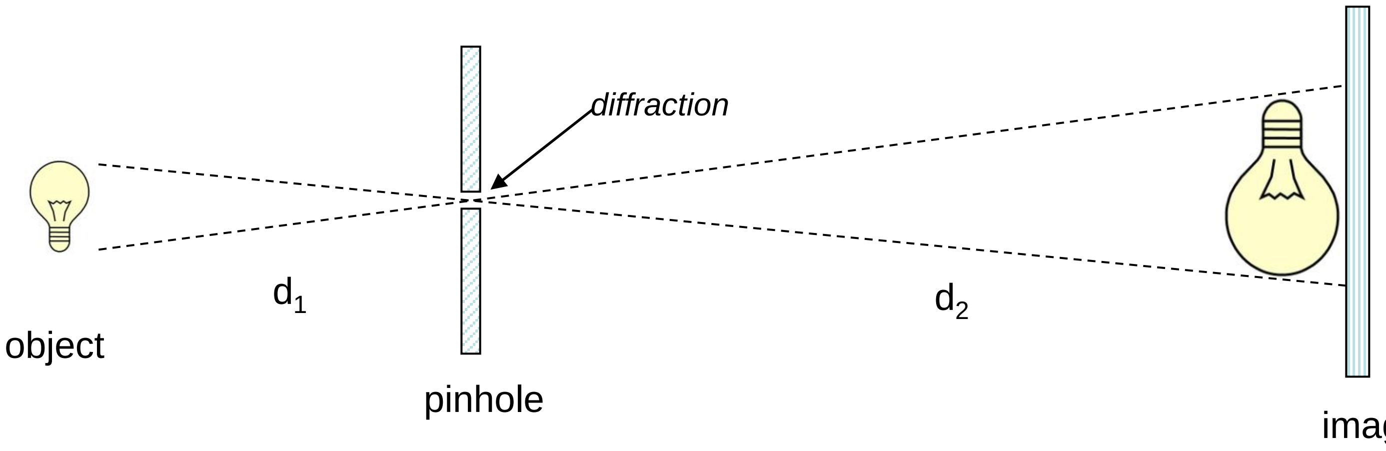


Beamspot at XSR

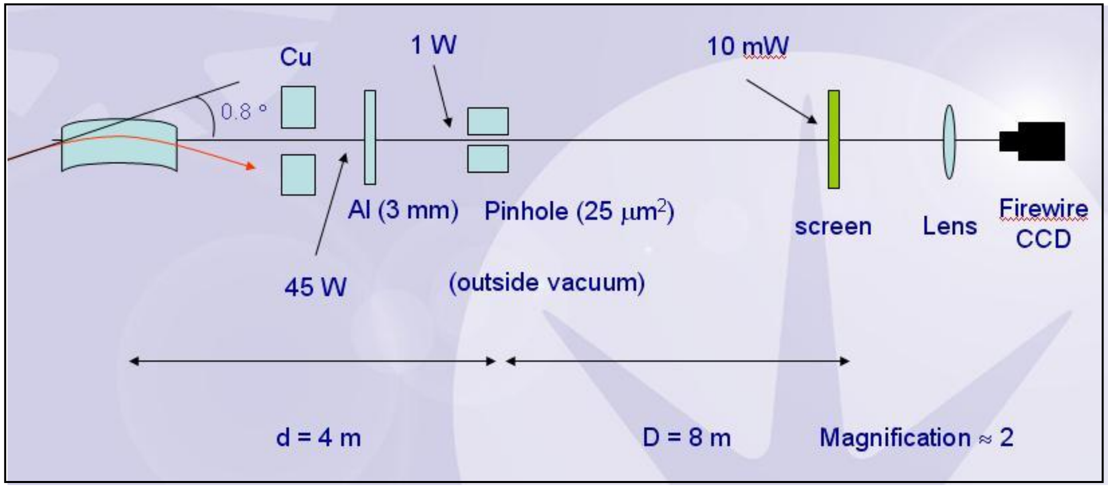
PEP-II: visible light monitor software (LabView)



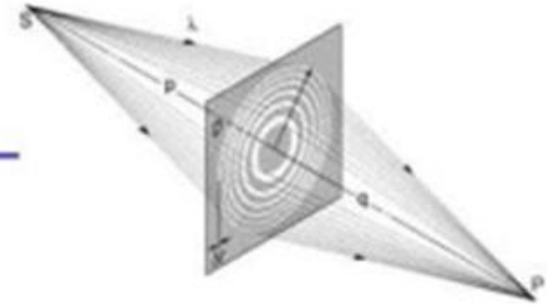
X-ray pinhole cameras – Reduce diffraction with small λ



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



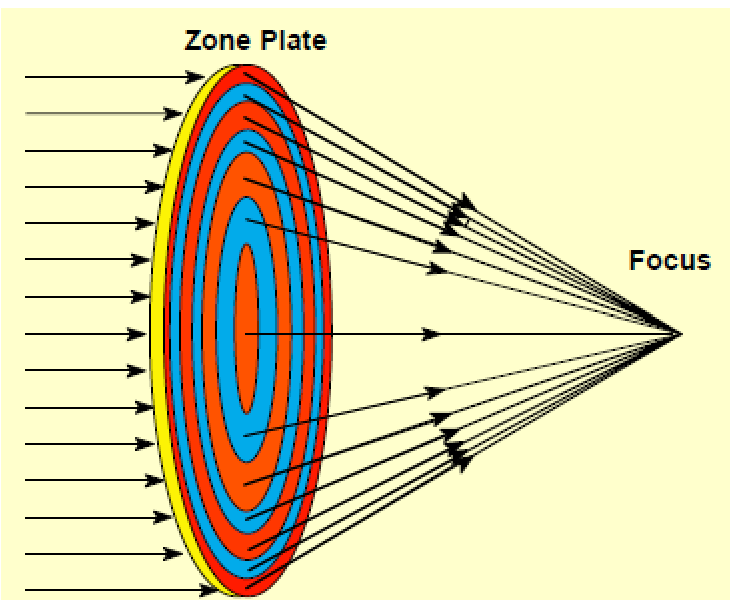
Zone plate optics



- Zone plates act as a thin lens, with

$$f = 4N(\Delta r)^2 / \lambda$$

where N is the number of zones, Δr is the width of the outermost zone, and λ is the wavelength of the light. Thus the zone plate can act as a ***linear monochromator*** if one selects a particular focus (using a pinhole).

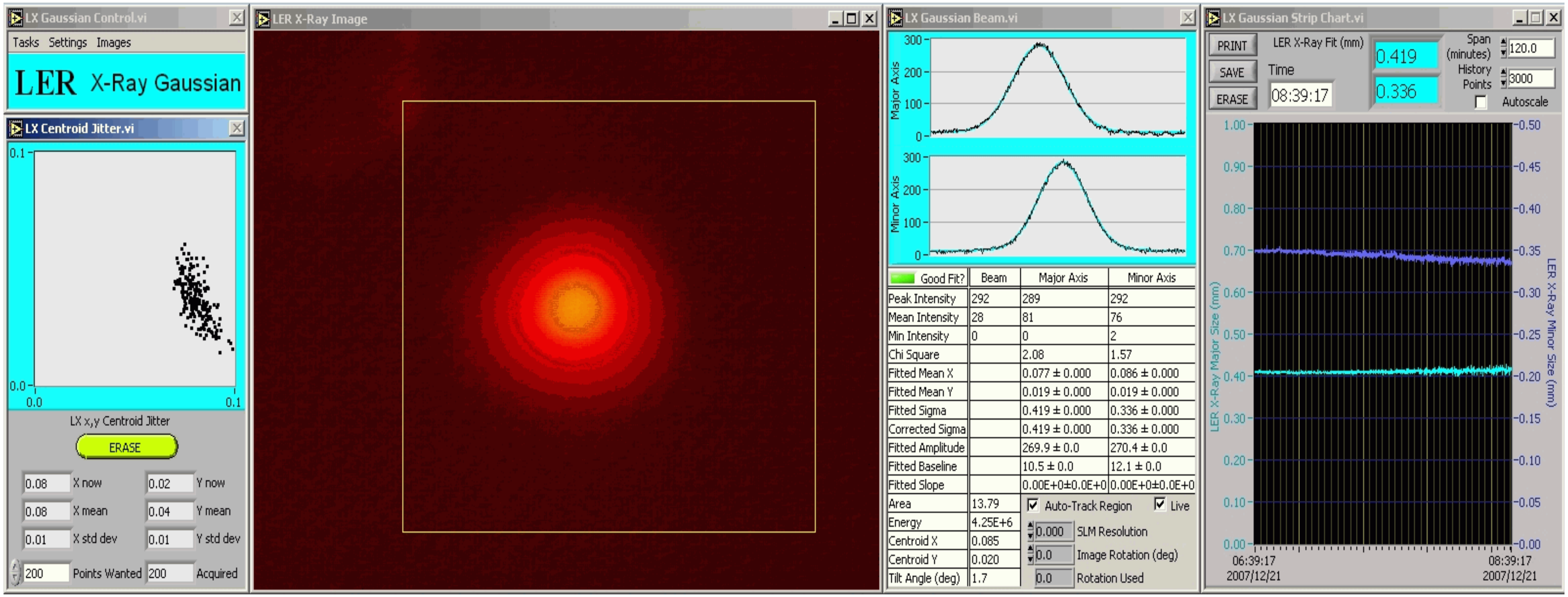


n^{th} zone radius:

$$r_n = \sqrt{nf\lambda + \frac{n^2\lambda^2}{4}} \approx \sqrt{nf\lambda}$$

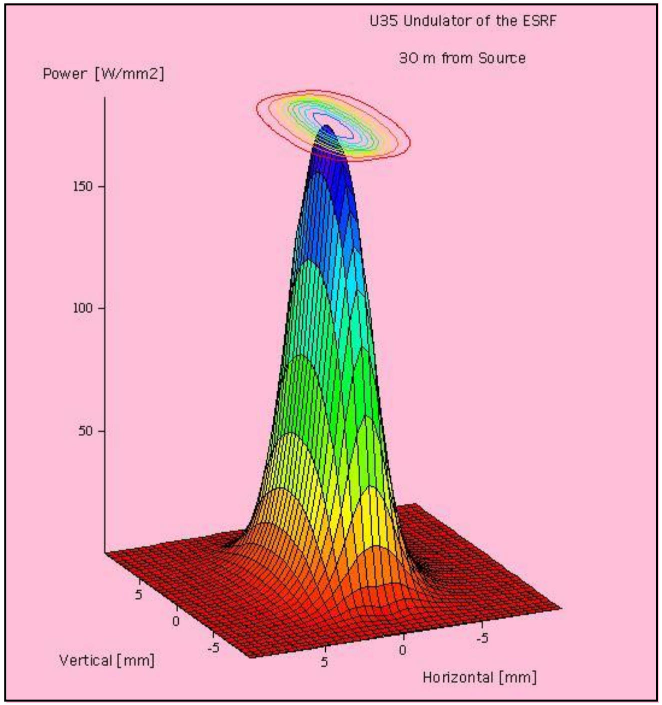
λ – photon wavelength
f – focal length for the wavelength

PEP-II: x-ray pinhole camera software (LabView)

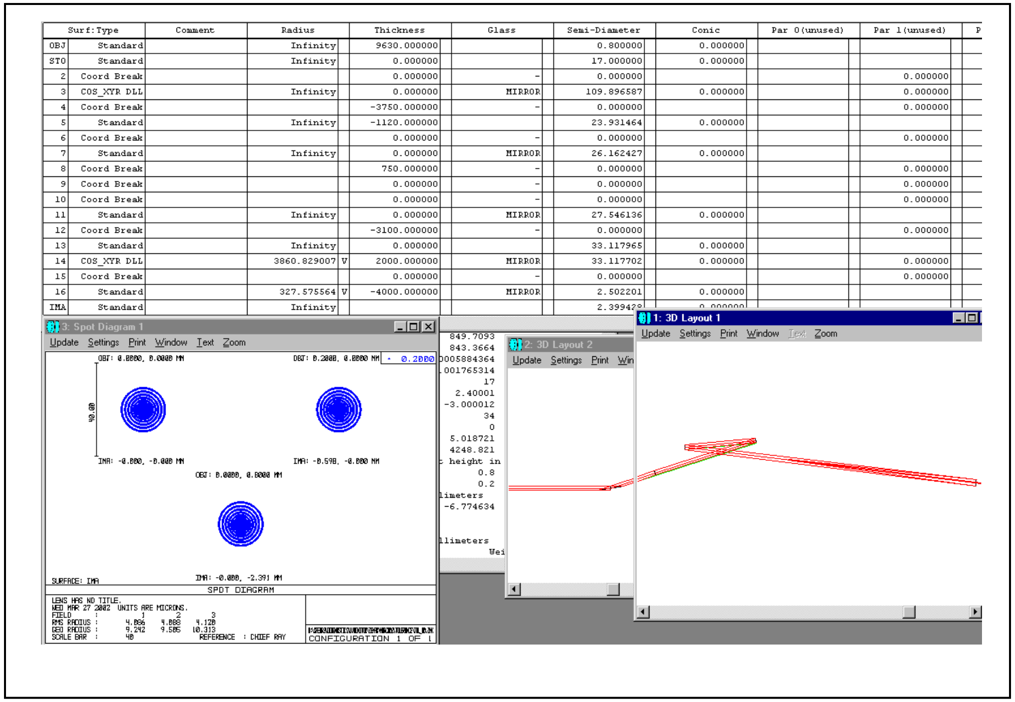


Photon beam propagation programs

SRW
(synchrotron radiation workshop)

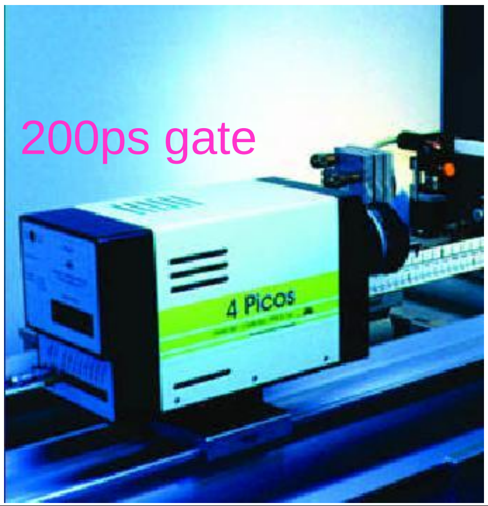


Zemax
(commercial product)

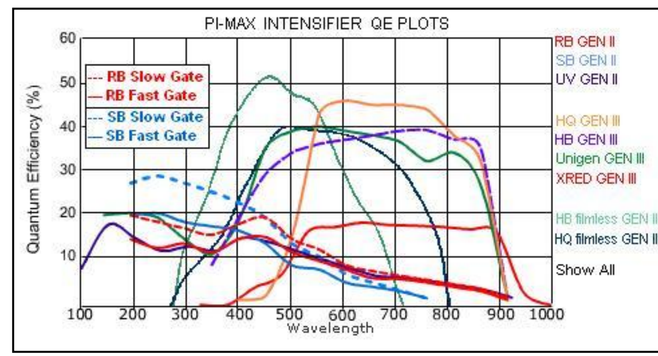


Cameras Part-II: Gated ICCD's

Stanford 4 Picos



Roper/PiMax



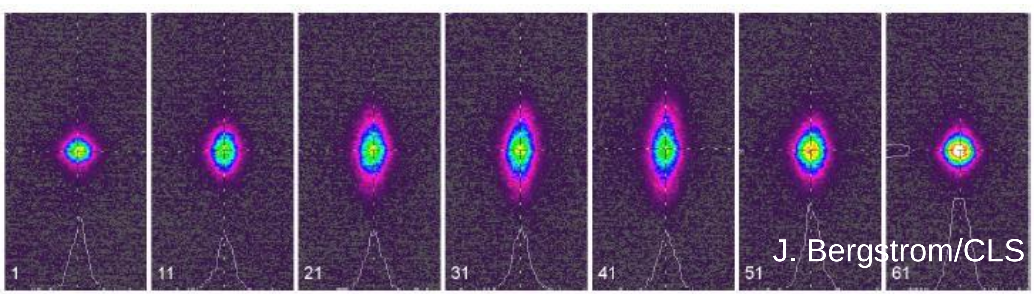
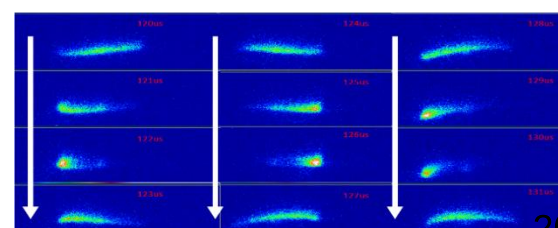
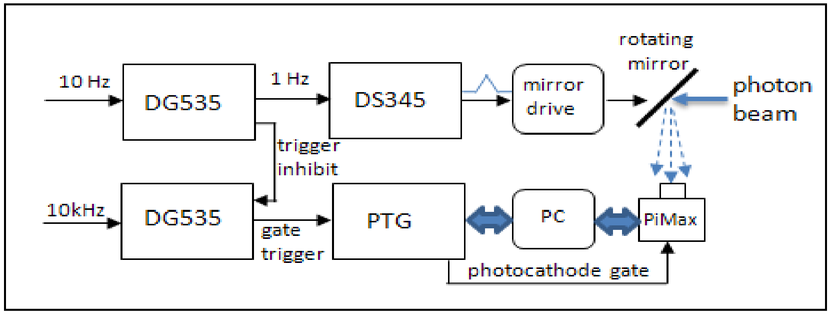


Fig. 8: Walking along a bunch train with the ICCD camera. This sequence shows every

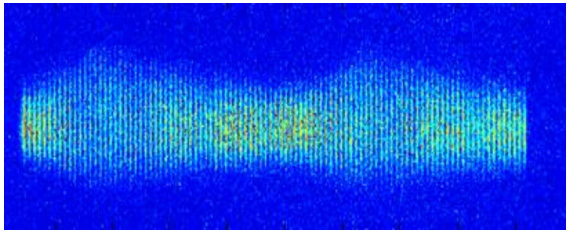


Injected beam in SPEAR3

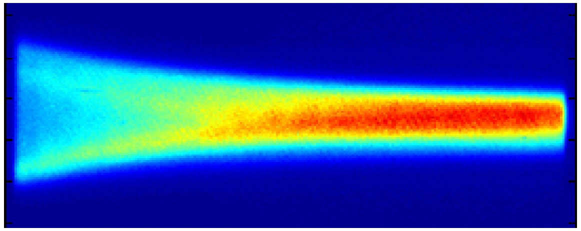
The Roper/PiMax Camera Experiment



Rotating Mirror and Timing System



Fast image sweep across photocathode



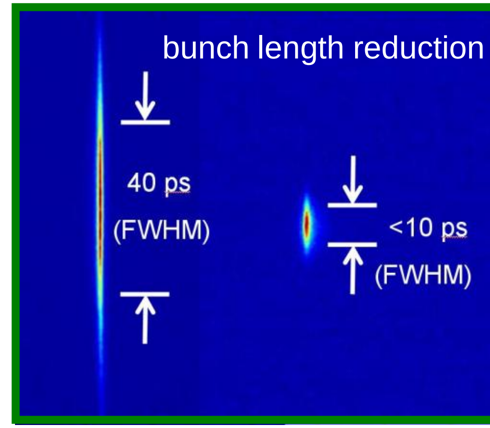
Slow image sweep across photocathode

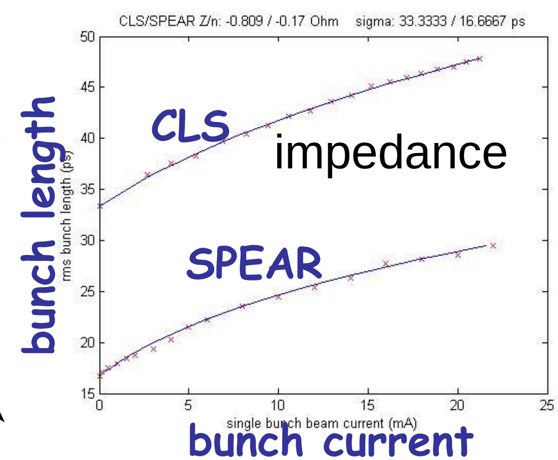
Cameras III - Streak tubes

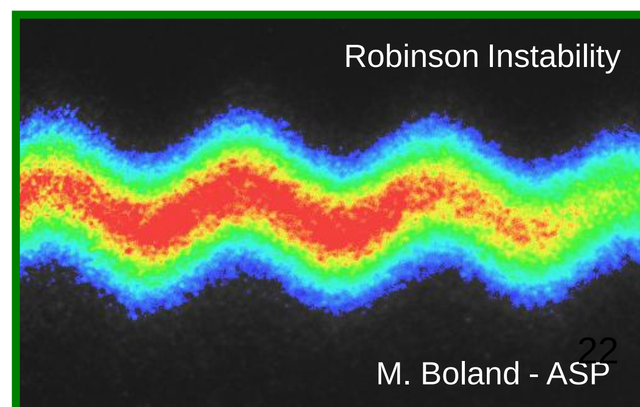
Hamamatsu C5680
Optronis (ASP)

visible beam

speed: up to 2 pixel/ps
chromaticity: BP filter needed
-bunch length
-impedance and instabilities

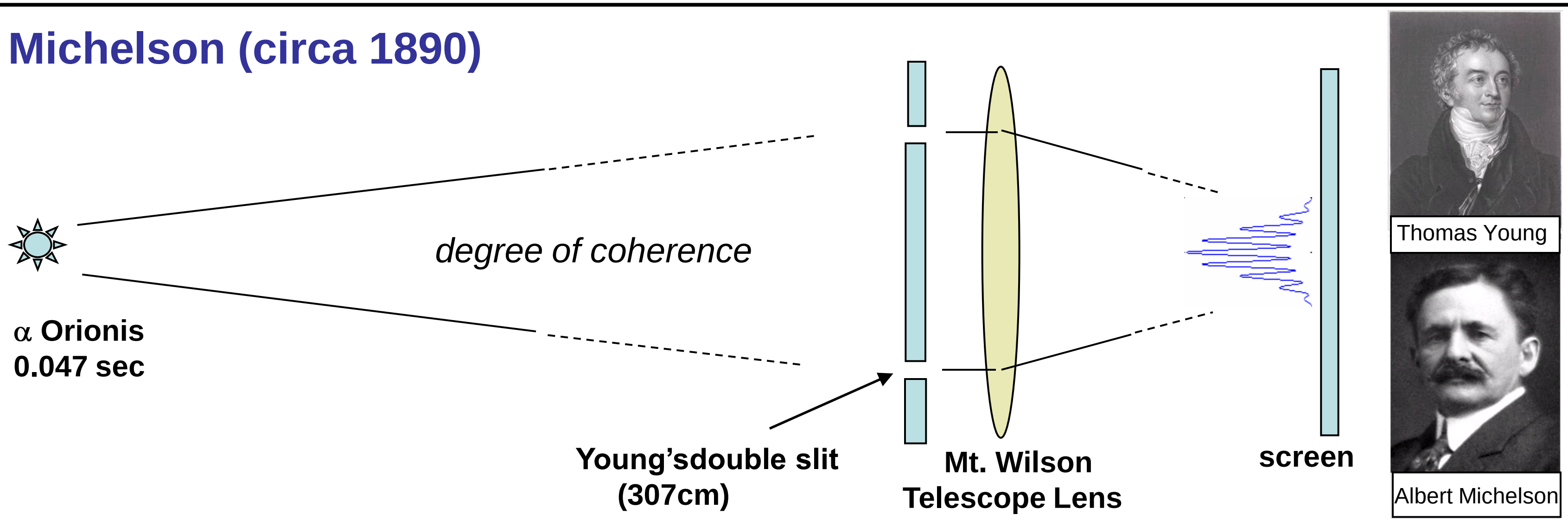




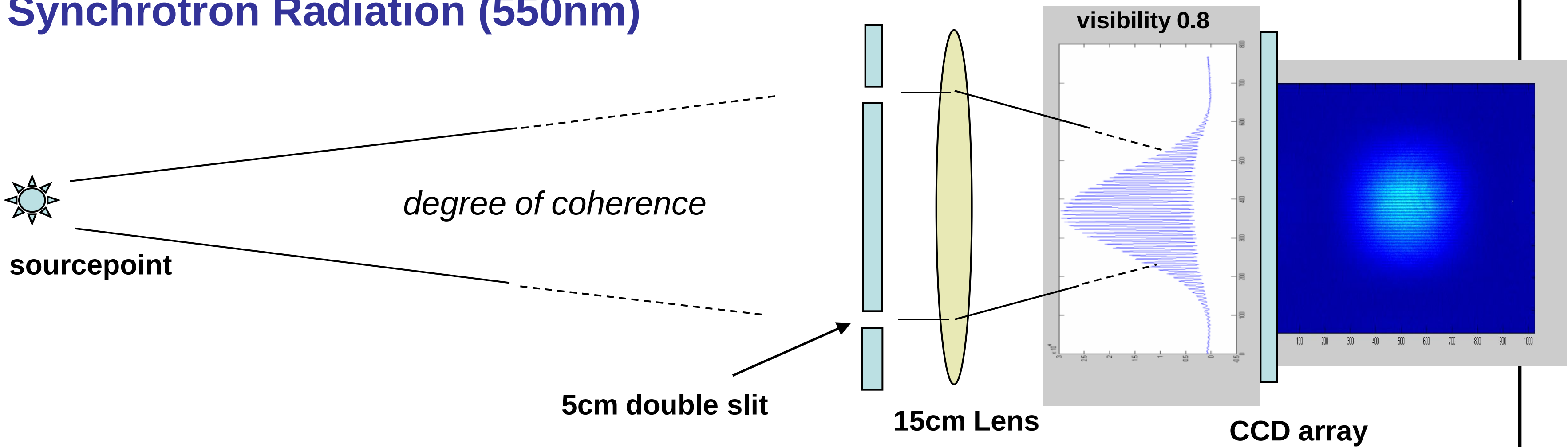


The Stellar Interferometer

Michelson (circa 1890)

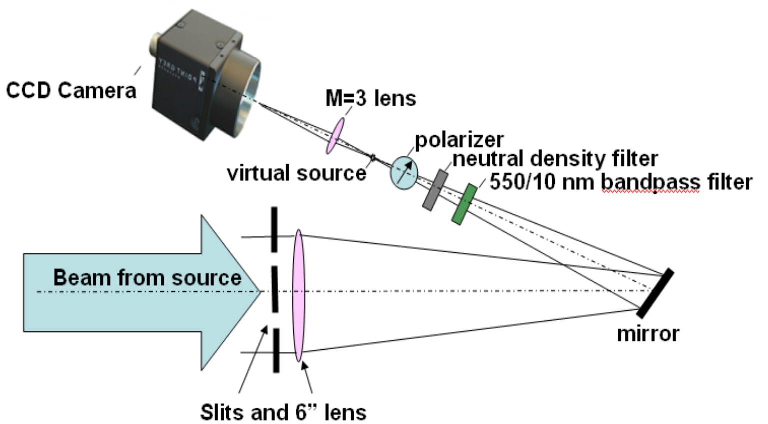


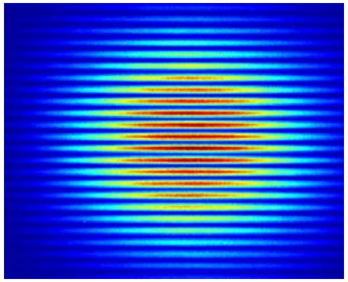
Synchrotron Radiation (550nm)

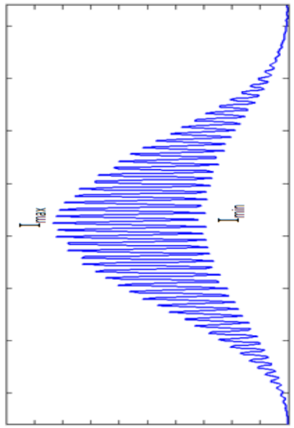


H. Mitsuhashi - Photon Factory

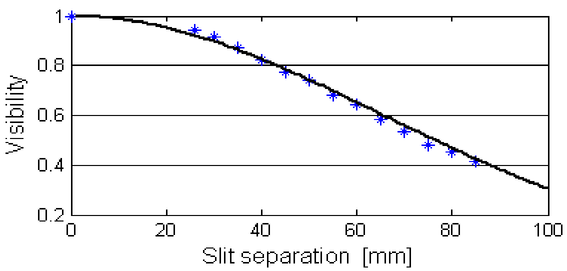
The Stellar Interferometer (cont'd)







Contrast/visibility



$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

$$I(y) = \frac{1}{\sqrt{2\pi\sigma_y}} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \longleftrightarrow V(d) = \exp\left(-\frac{d^2}{2\sigma_d^2}\right)$$

VanCittert/Zernike

Fringe Formulas

The slits have width a and center-to-center spacing d. The pattern from a single slit is:

$$I_\pm(\theta) = \left(\frac{\sin\left[\frac{ka}{2}\left(\theta \mp \frac{d}{2s_0}\right)\right]}{\frac{ka}{2}\left(\theta \mp \frac{d}{2s_0}\right)}\right)^2$$

The interference from both slits at height y on the CCD, integrated over the optical bandpass filter, shows decreasing modulation with beam size:

$$I(y) = \int_{-\infty}^{\infty} \left[I_+ + I_- + 2\sqrt{I_+ I_-} \exp\left(-\frac{(kd\sigma_y)^2}{2s_0^2}\right) \cos\left(\frac{kdy}{f + \Delta z}\right) \right] g(\lambda)\, d\lambda$$

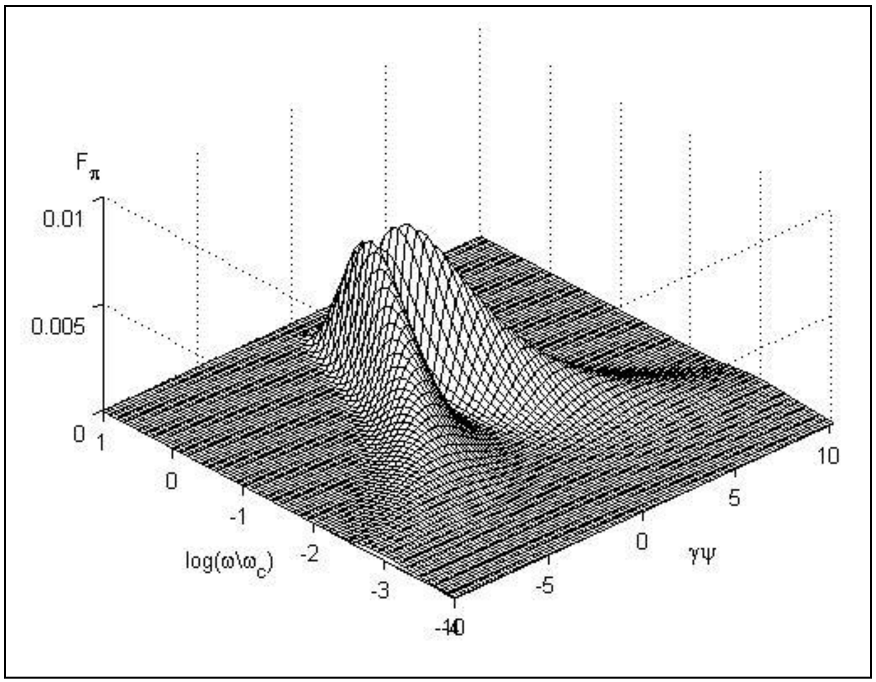
The ray leaving the slit at an angle θ hits the CCD at height y:

$$\theta_\pm(y) = \frac{y \pm \frac{d\Delta z}{2f}}{f + \Delta z\left(1 - \frac{\Delta s}{f}\right)}$$

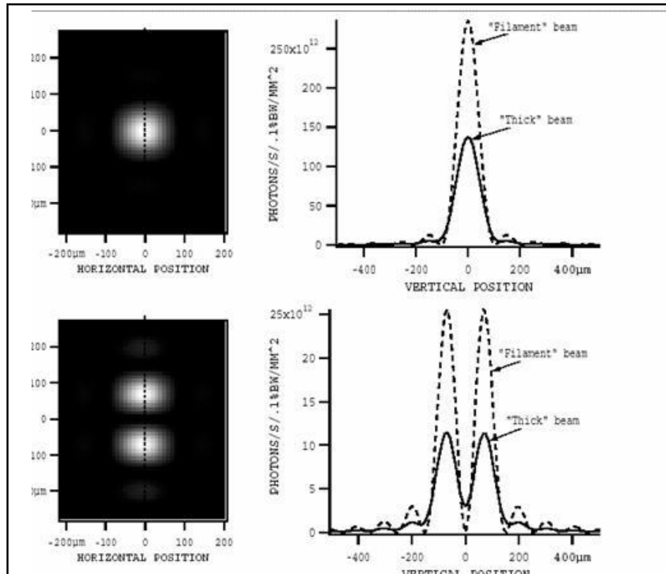
A. Fisher - SLAC

Small beam size – Vertical polarization technique

Vertical angular spectral density



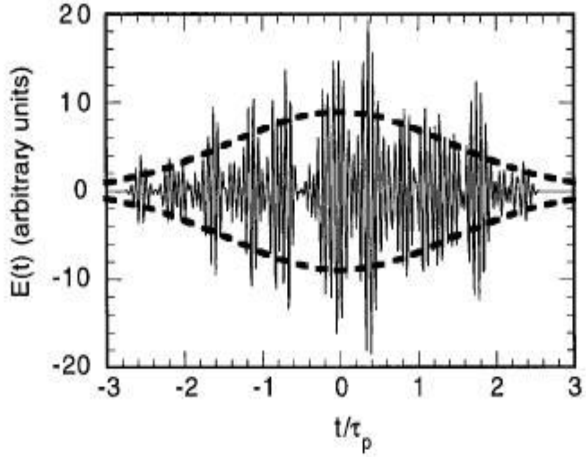
Measurements at MaxLab



A. Andersson MaxLab/SLS

Bunch Length Measurement – Statistical Fluctuations

Intra-pulse fluctuation of the electric field
Statistics of pulse-to-pulse variations



$$\delta^2 = \frac{\sigma_W^2}{\langle W \rangle^2} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} dt dt' \frac{|K(t-t')|^2}{|K(0)|^2} I(t) I(t')$$

$$\delta^2 = 1/\sqrt{1 + 4\sigma_\tau^2 \sigma_\omega^2}$$

$$\frac{Signal}{Noise} \sim \frac{1}{\sqrt{M}}$$

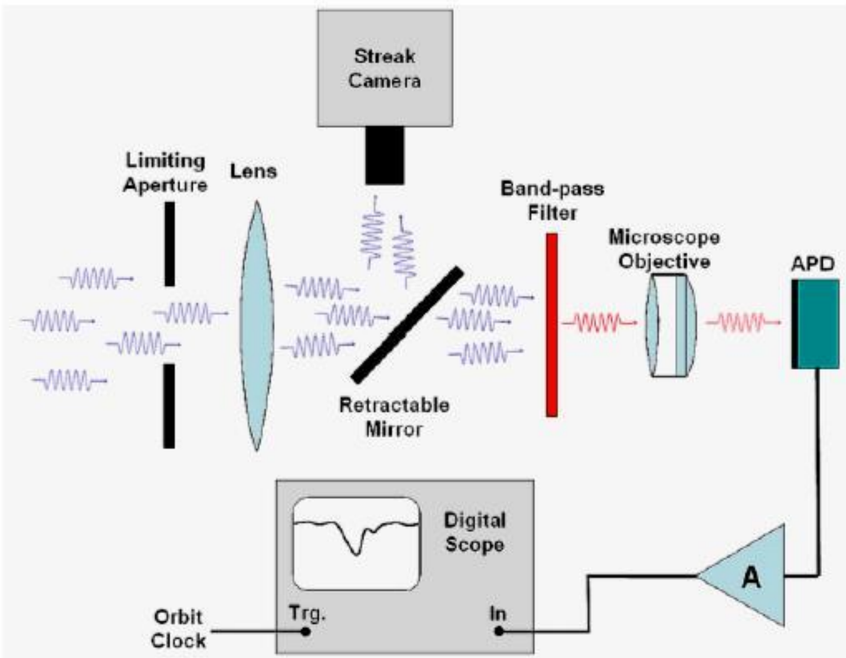
$$\frac{< N >}{\sigma} \sim \left(\frac{\tau_{coh}}{\tau_{pulse}}\right)^{1/2}$$

Fig. 1. Electric field of a pulse of incoherent radiation as a function of time. The ratio $\Delta\omega/\omega_0 = 0.1$, and the parameter $N = 10$. The dashed lines show $\sqrt{I(t)}$.

Hofmann: chapter 15

G. Stupajkov/SLAC

Fluctuation measurement



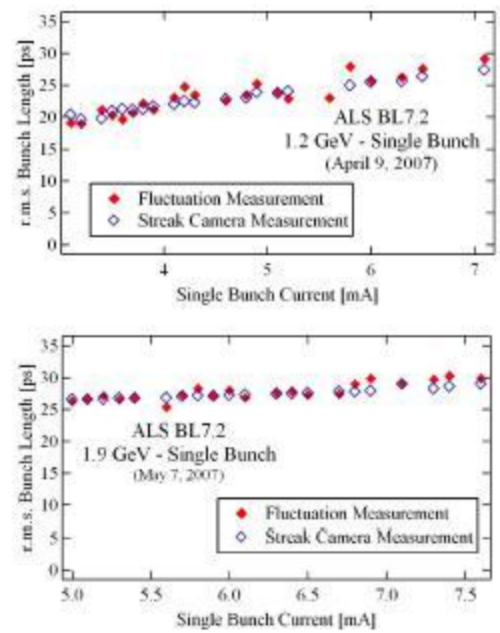


Figure 3: Examples of fluctuation and streak-camera bunch length measurements at the ALS for different beam parameters.

F. Sannibale/LBL

Summary of beam size measurements

- Photon emission provides valuable diagnostic of e^- beam
- Need to unfold γ_r, DOF, diffraction, PSF, etc. from image
- Visible has advantage of commercial optics and cameras
  but suffers from large γ_r and diffraction
- Broad array of cameras, fast shutters, streak frames
- X-ray pinhole has advantage of less diffraction
  but generally less versatile
- Interferometers and central-null technique improve resolution
- Fluctuation measurements cheaper than streak, provide insight
- other techniques:
  - screens, OTR, wires and lasers in transmission lines
  - scraper in storage ring (quantum lifetime)
  - response matrix analysis