Beam Size Measurements with Synchrotron Radiation – An Overview

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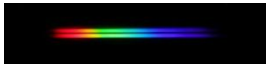
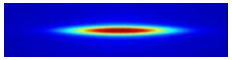
US Particle Accelerator School
January 14-18, 2008

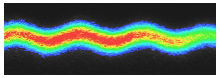
- Motivation

- Electron beam properties

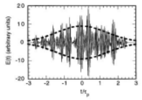
- SR beam properties

-Standard imaging – visible spectrum  λ=550nm

- X-ray pinhole camera 

- Fast imaging – gated ICCD and streak cameras 

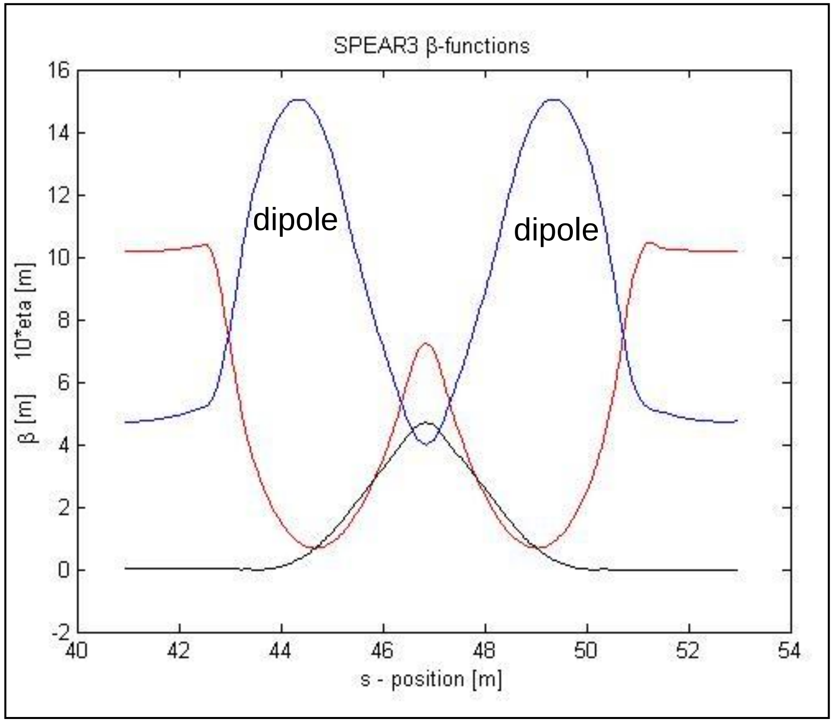
-Interferometer & vertical polarization

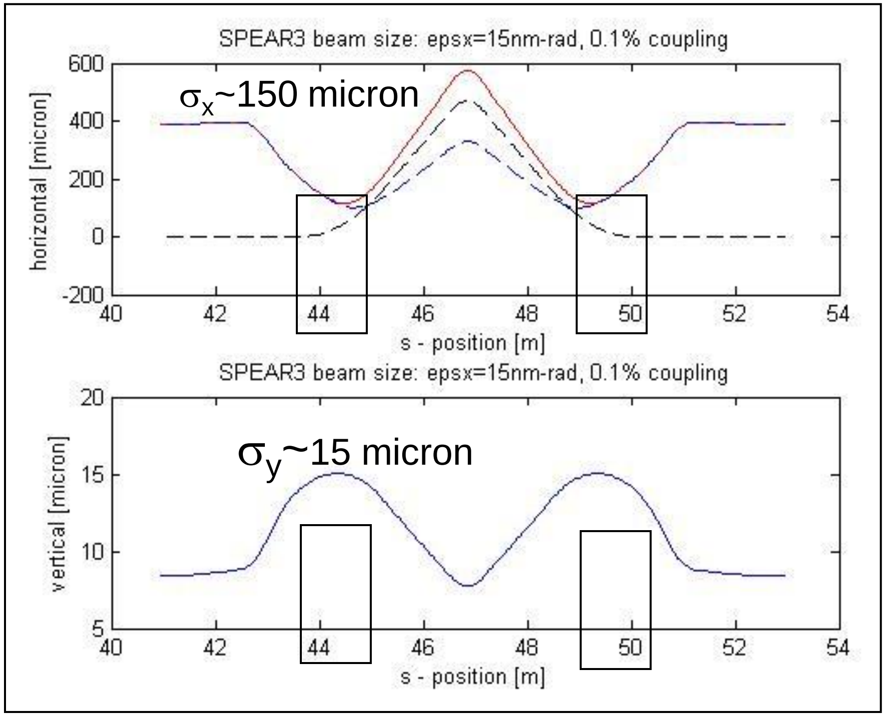
-Fluctuation measurements 

Motivations for beam size measurements

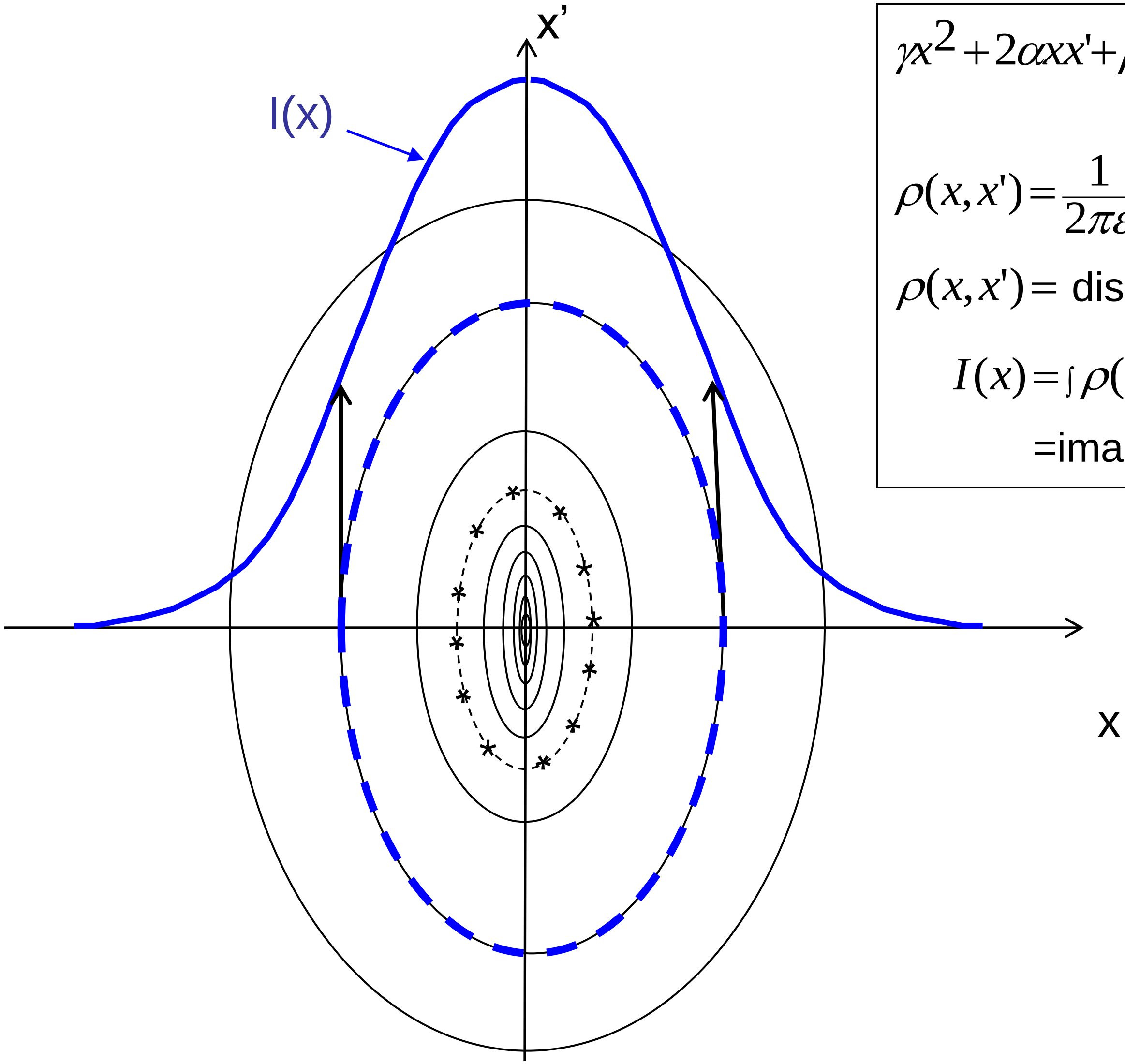
- ‘eye’ into the accelerator
- faithful photon image reproduces electron beam (x,y,z)
- optics verification, coupling, brightness
- impedance and instabilities
- other techniques less accurate (e.g. scraper, RMA)

Electron beam properties: β-functions and beam size





Electron beam properties: Phase Space



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

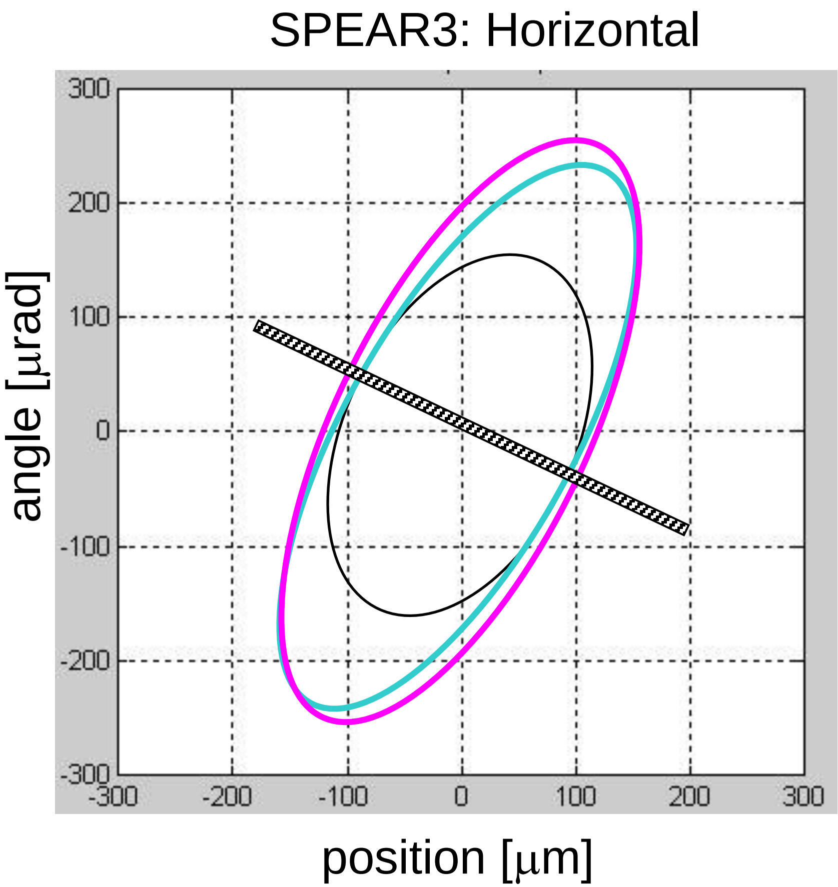
$$\rho(x,x') = \frac{1}{2\pi\varepsilon} e^{-(\gamma x^2 + 2\alpha x x' + \beta x'^2)/2\varepsilon}$$

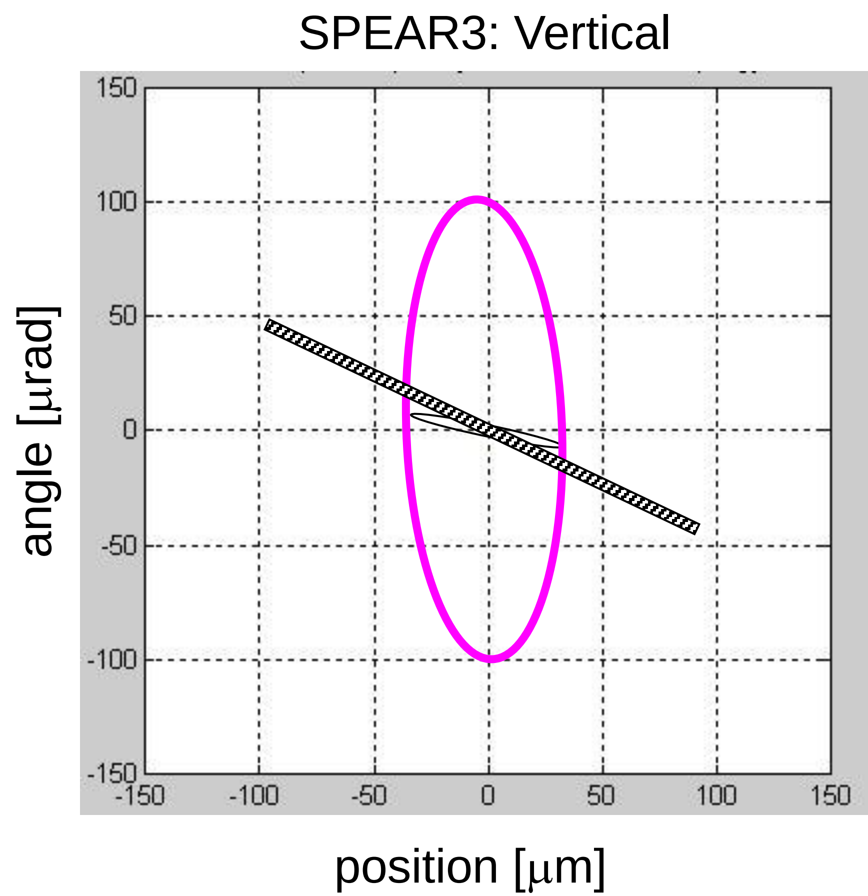
$\rho(x,x') =$ distribution in phase space

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

=image projected on screen

Photon beam properties: Phase Space





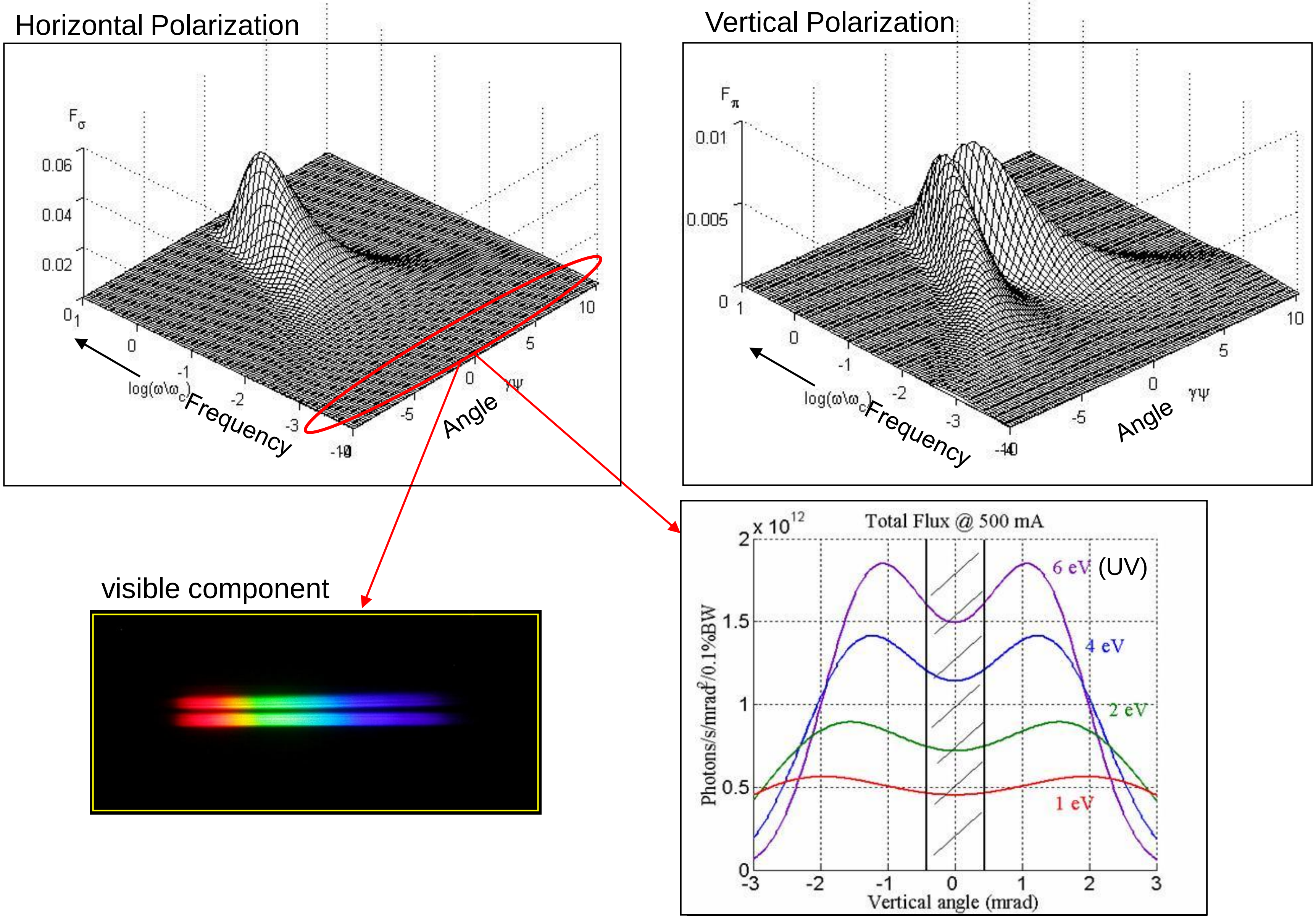
$$\sigma_x^2 = \varepsilon_x \beta_x + (\eta_x \delta)^2$$

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

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

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

Photon beam properties: Angular spectral power density

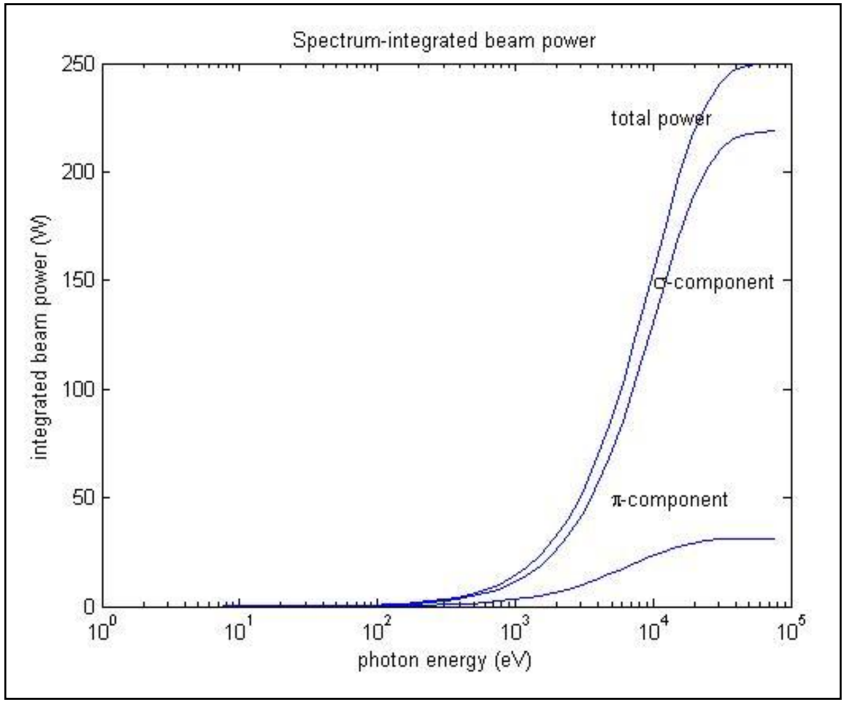


Photon beam properties: Beam power

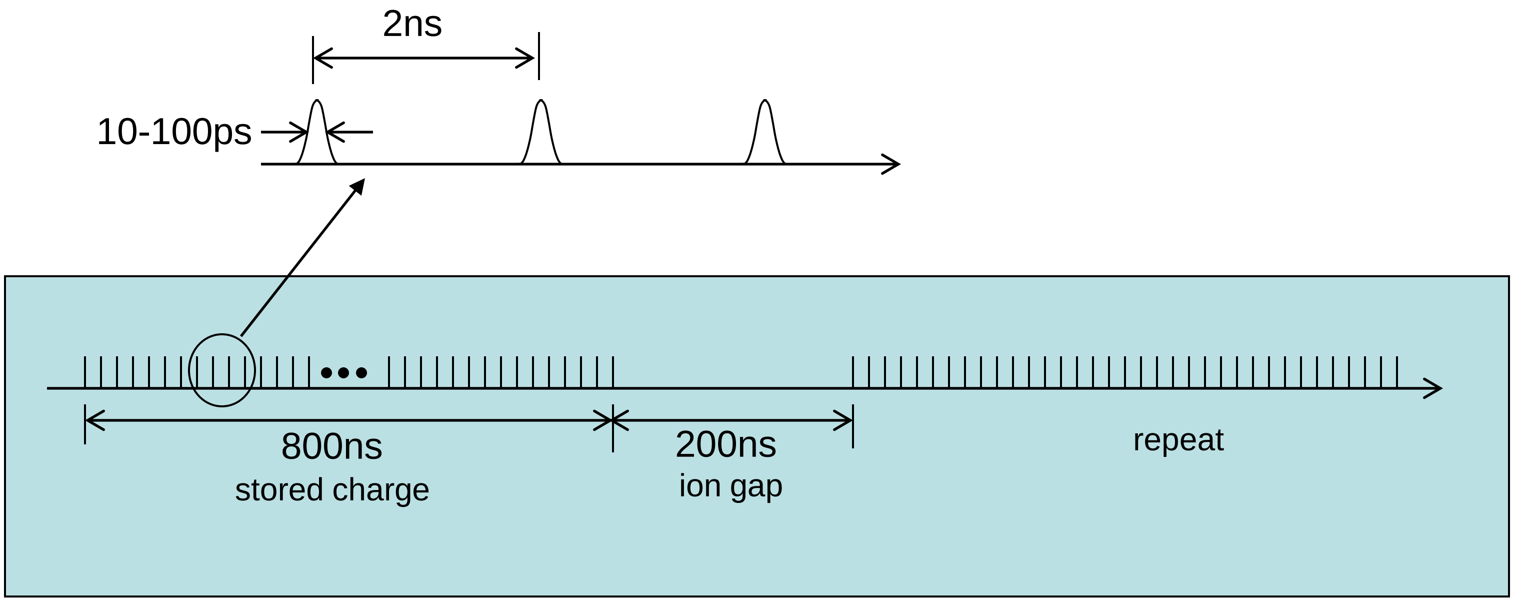
Example:
3 GeV and 200 ma current
P_{SR}~200kW (total)

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

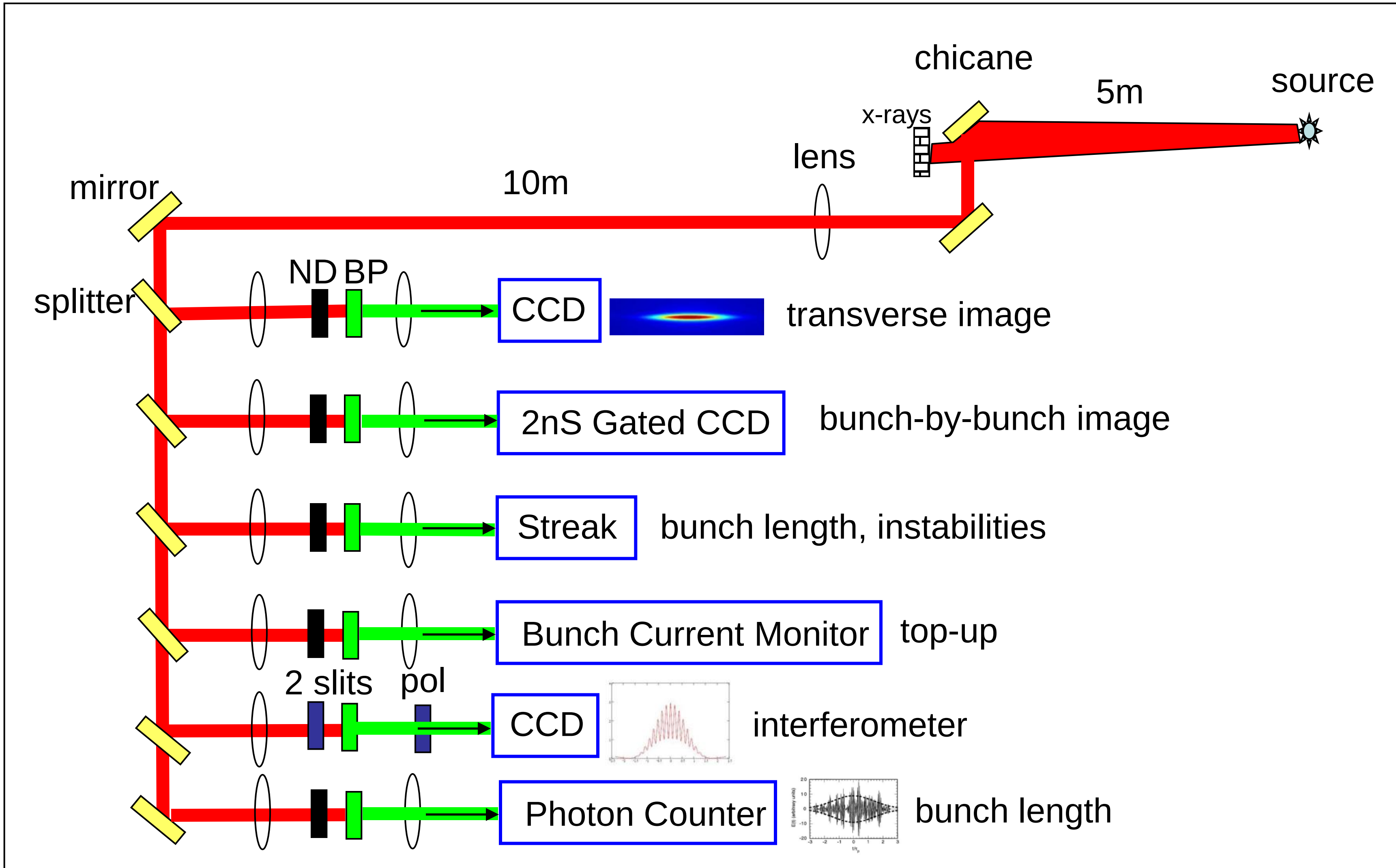
pinhole camera (15keV)
25μm aperture at 5 m (5 μrad)
P_{SR}~100μW before filter



Photon beam timing pattern - storage rings



Visible beam line components

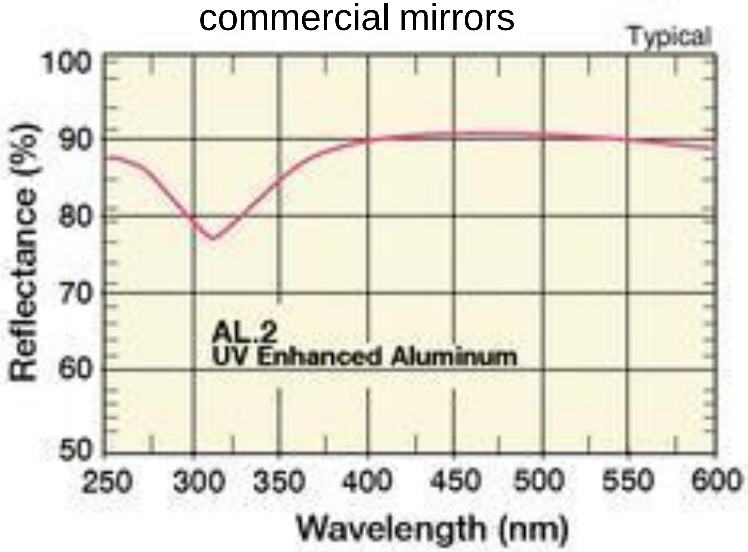


Visible beam line components (cont'd)

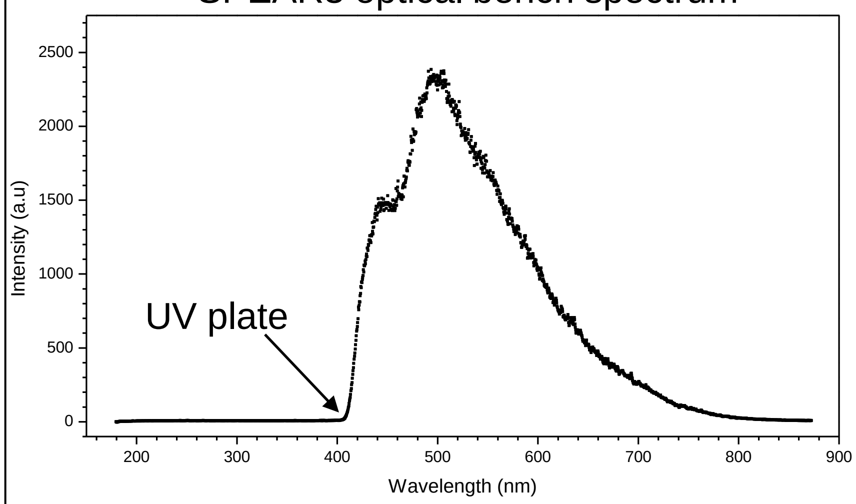
Beam line optics
Windows - quartz can pass down to about 220nm
Mirrors – flat or focusing, UV enhanced
Lenses – focusing, defocusing, doublets, achromats >350nm
Filters –highpass and bandwidth to about 10n FWHM
Slits and diaphrams – 1ms mechanical shutters, 10ps Pockel cells

About 90% transmission per element

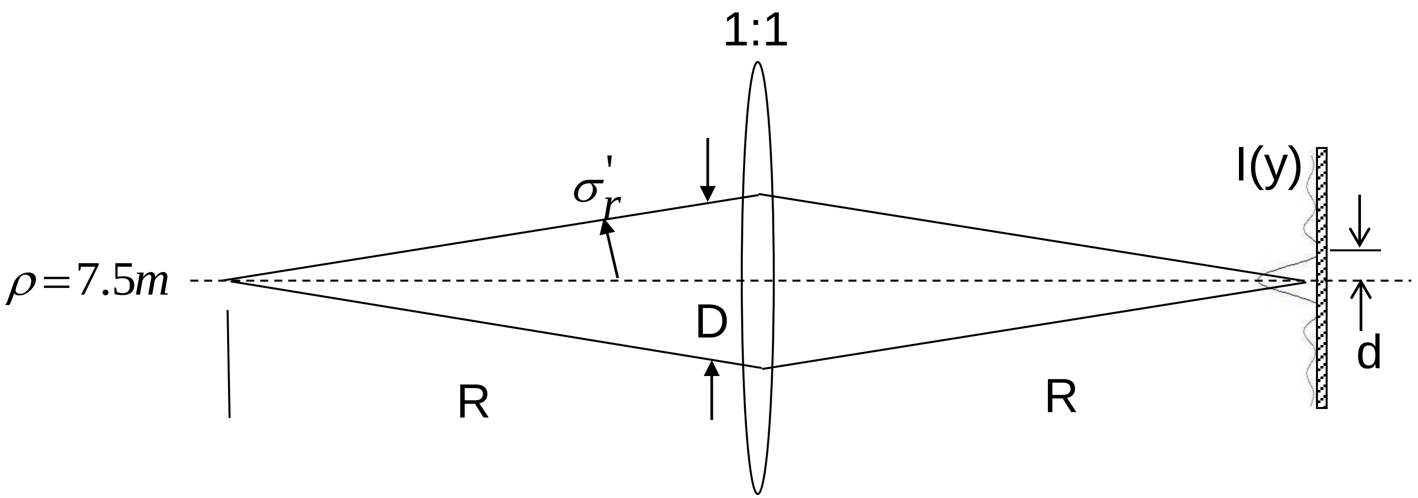
commercial mirrors



SPEAR3 optical bench spectrum



Diffraction Limited Resolution



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

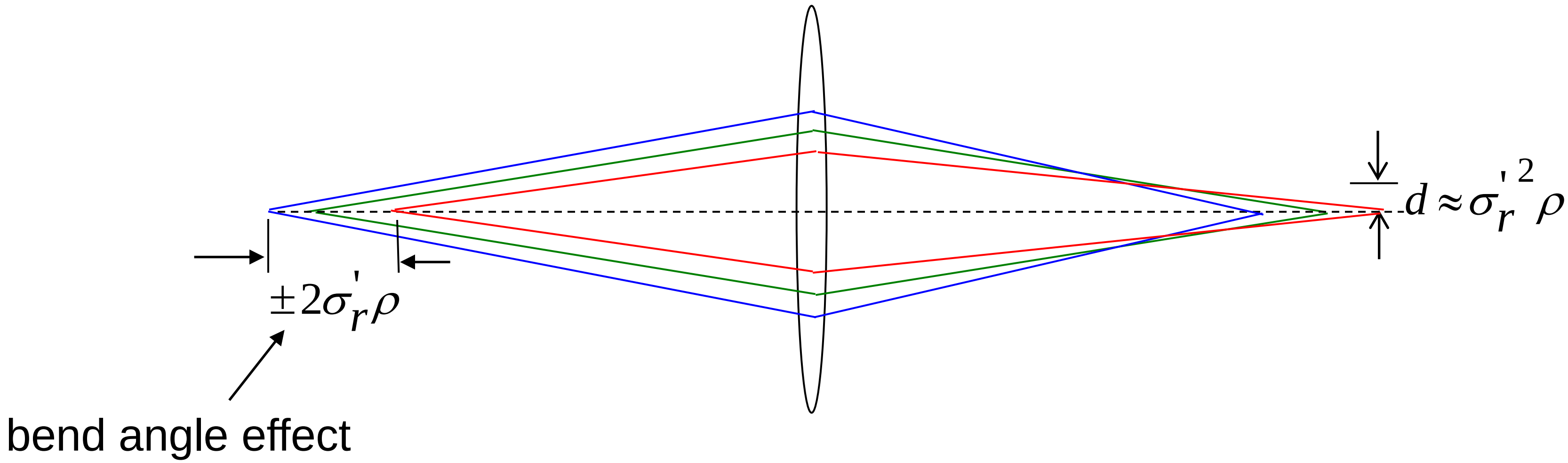
$\sigma'_r = 0.41 \cdot (\lambda / \rho)^{1/3}$ visible

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

$d \approx 40\mu m$ at λ=550nm

more diffraction later...

Depth of Field



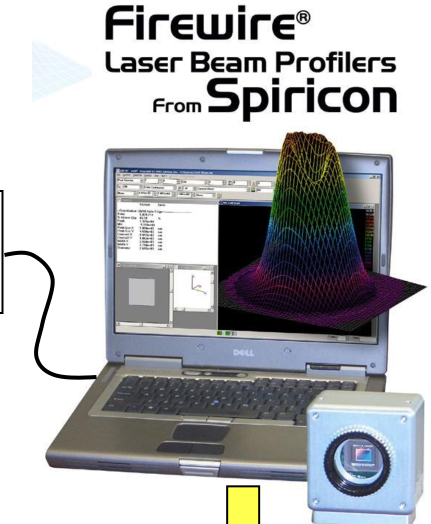
$$d \approx \sigma_r'^2 \rho$$

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

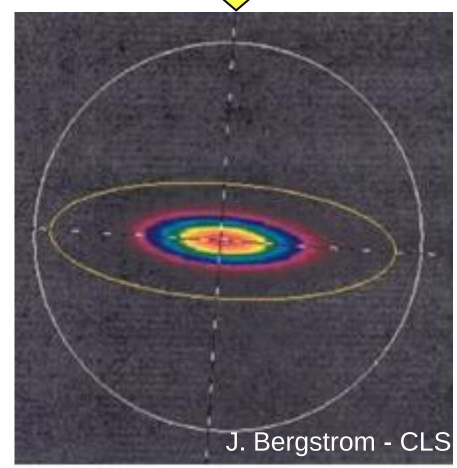
(source length related to opening angle)

Cameras I: CCD's and Video

Frame Grabber

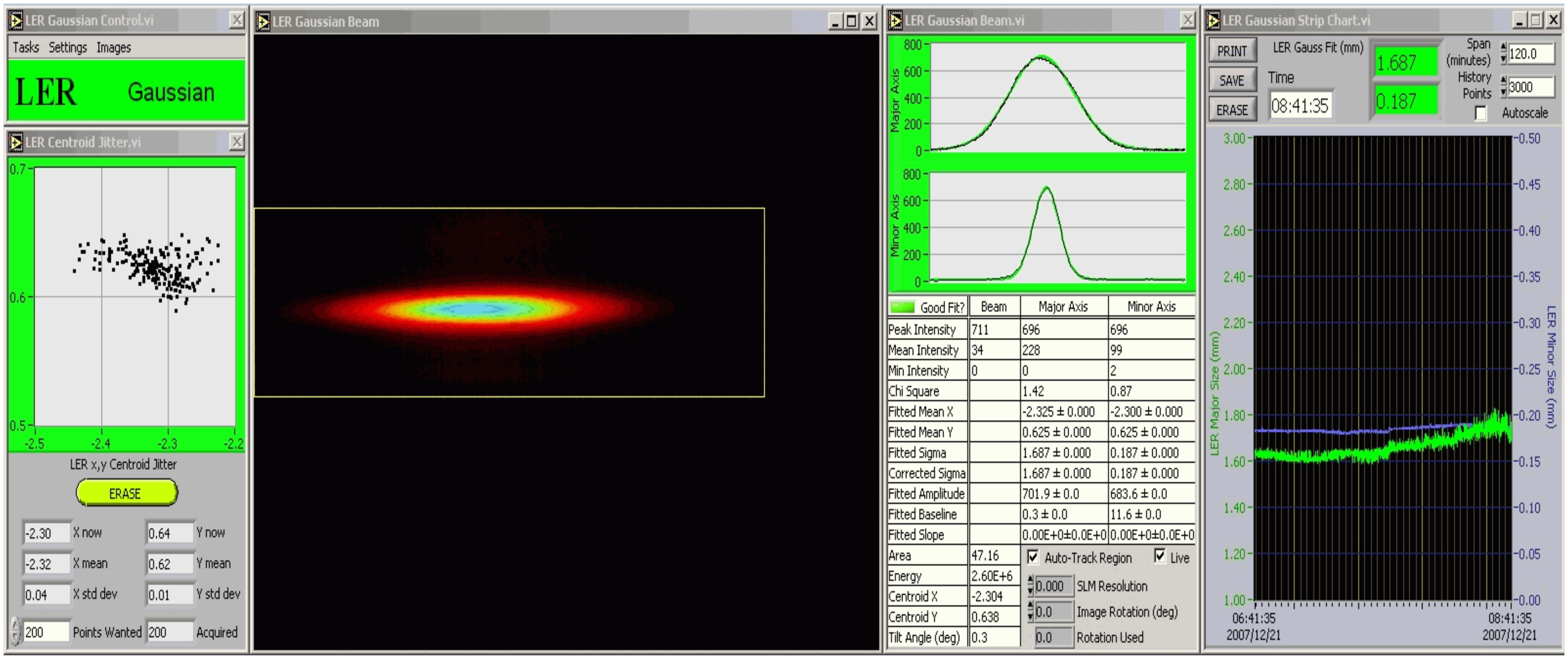


EPICS, MATLAB

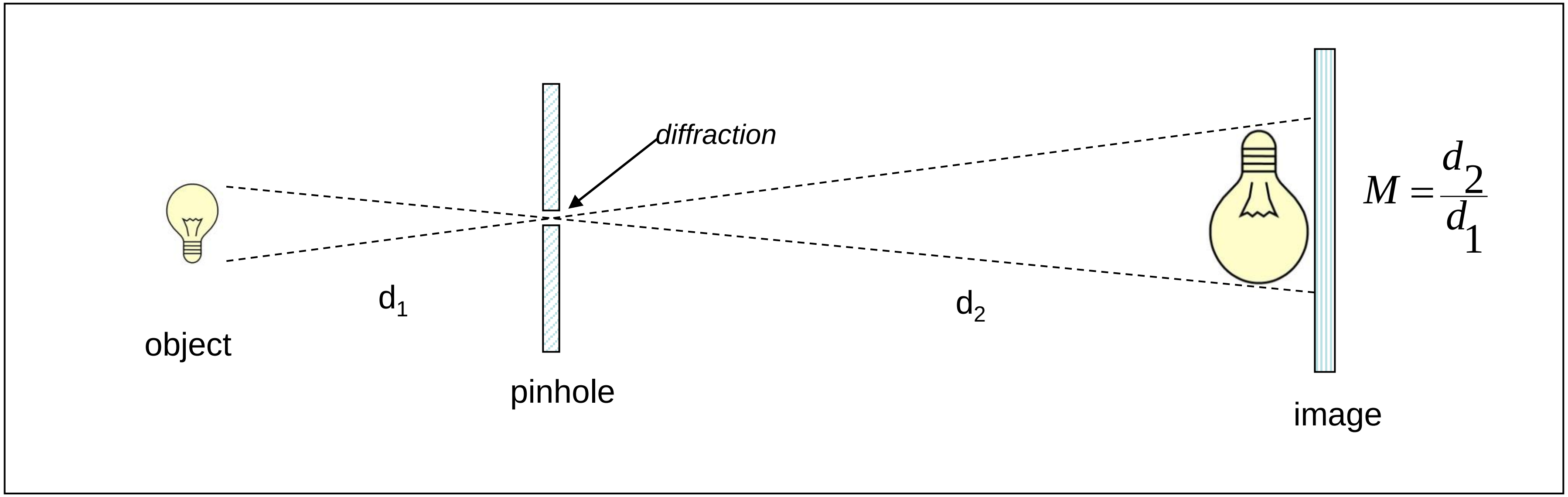


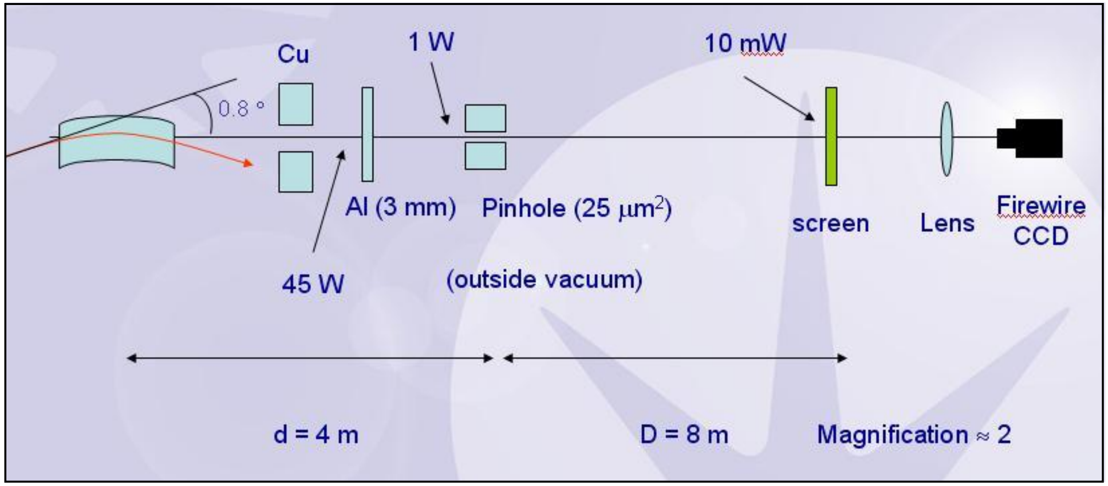
Beamspot at XSR

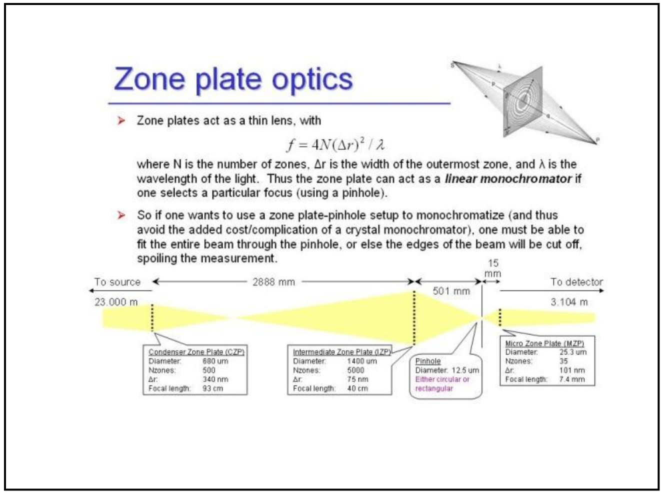
PEP-II: visible light monitor software (LabView)



X-ray pinhole cameras – Reduce diffraction with small λ

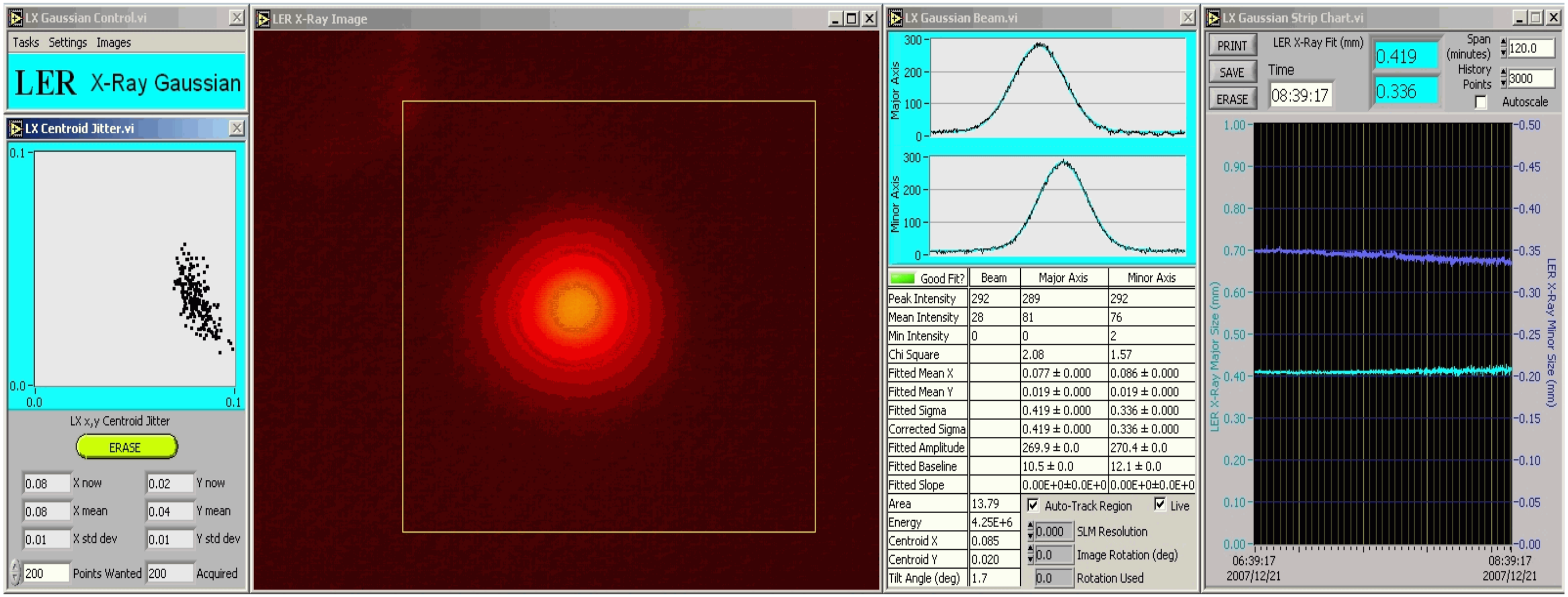






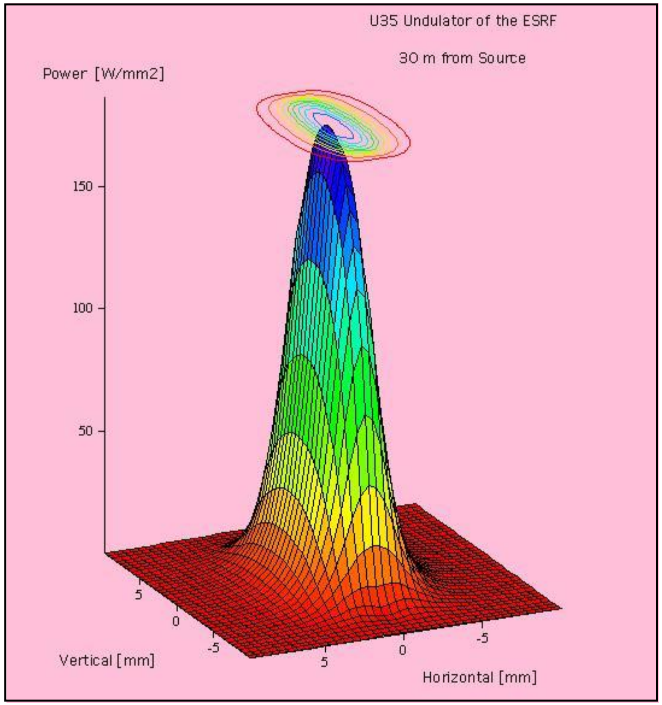
W. Peatman and K. Holldack, 'Diagnostic Front End for BESSY-II'
J. Synch. Rad. 5, 639, (1998)

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

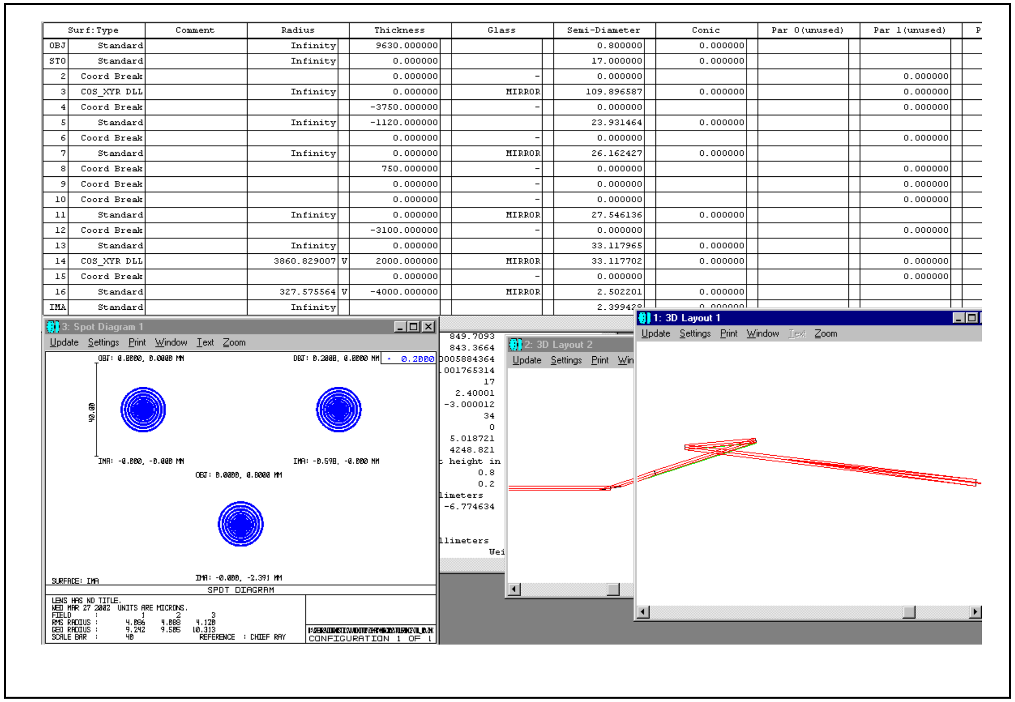


Photon beam propagation programs

SRW
(synchrotron radiation workshop)



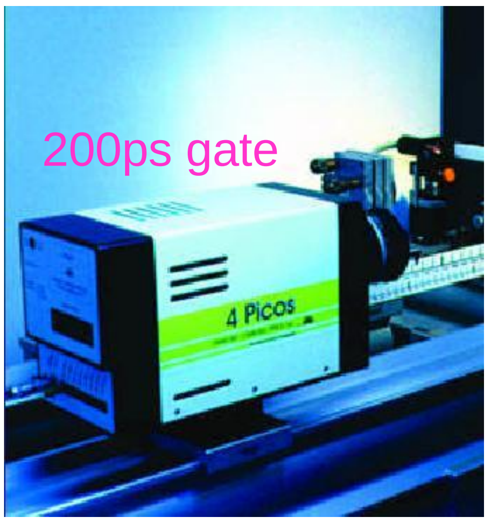
Zemax
(commercial product)



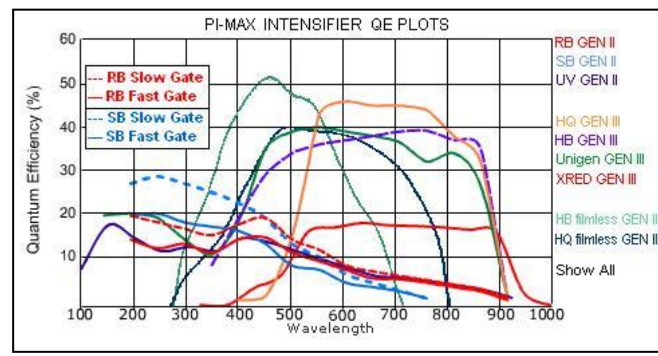
Surf	Type	Comment	Radius		Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Par 1(unused)
OBJ	Standard		Infinity		9630.000000		0.800000	0.000000		
STO	Standard		Infinity		0.000000		17.000000	0.000000		
2	Coord Break				0.000000	-	0.000000			0.000000
3	COS_XYR DLL		Infinity		0.000000	MIRROR	109.896587	0.000000		0.000000
4	Coord Break				-3750.000000	-	0.000000			0.000000
5	Standard		Infinity		-1120.000000		23.931464	0.000000		
6	Coord Break				0.000000	-	0.000000			0.000000
7	Standard		Infinity		0.000000	MIRROR	26.162427	0.000000		
8	Coord Break				750.000000	-	0.000000			0.000000
9	Coord Break				0.000000	-	0.000000			0.000000
10	Coord Break				0.000000	-	0.000000			0.000000
11	Standard		Infinity		0.000000	MIRROR	27.546136	0.000000		
12	Coord Break				-3100.000000	-	0.000000			0.000000
13	Standard		Infinity		0.000000		33.117965	0.000000		
14	COS_XYR DLL		3860.829007	V	2000.000000	MIRROR	33.117702	0.000000		0.000000
15	Coord Break				0.000000	-	0.000000			0.000000
16	Standard		327.575564	V	-4000.000000	MIRROR	2.502201	0.000000		
IMA	Standard		Infinity				2.399428	0.000000		

Cameras II: Gated ICCD's

Stanford 4 Picos



Roper/PiMax



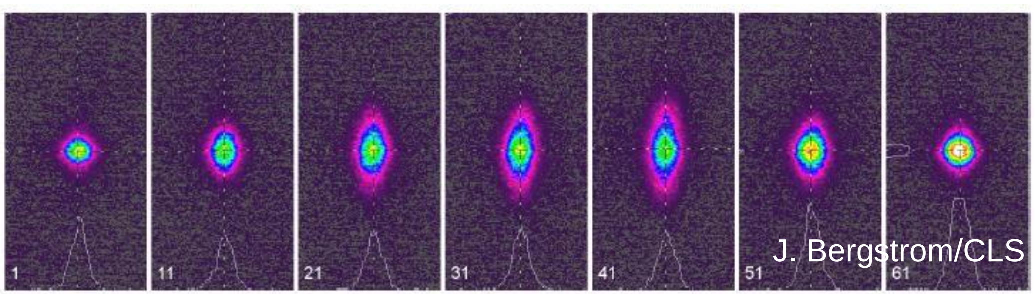
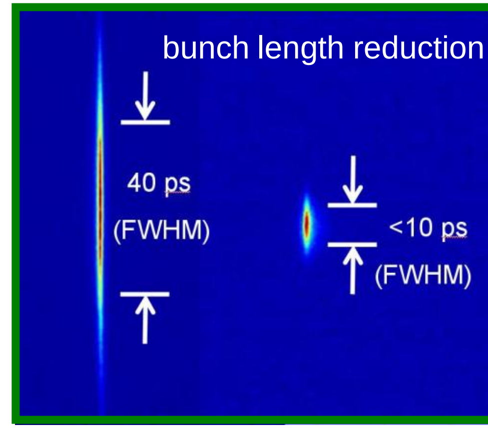


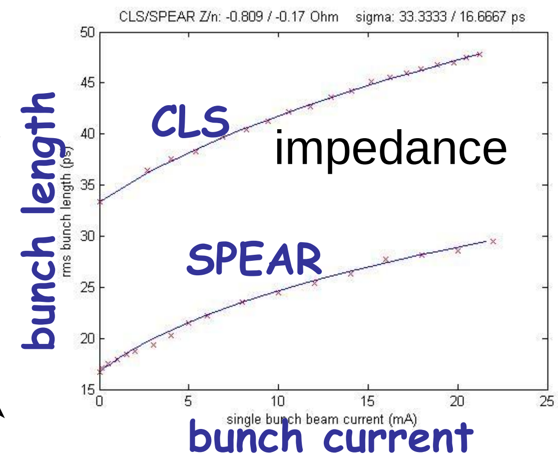
Fig. 8: Walking along a bunch train with the ICCD camera. This sequence shows every

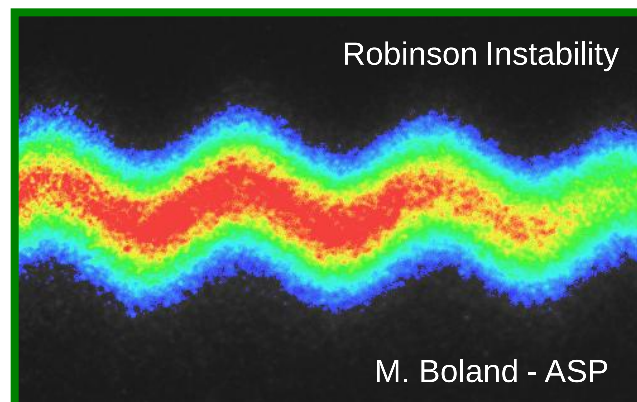
Cameras III - Streak tubes

Hamamatsu C5680
Optronis (ASP)

visible beam

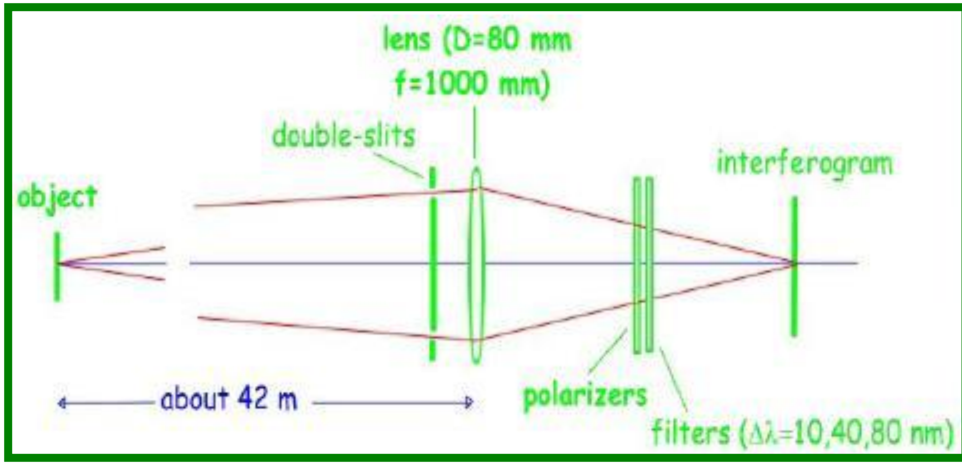


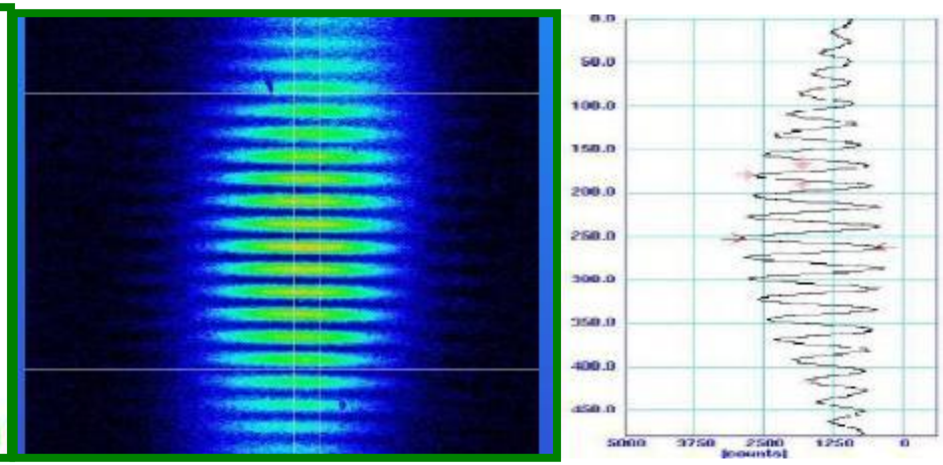




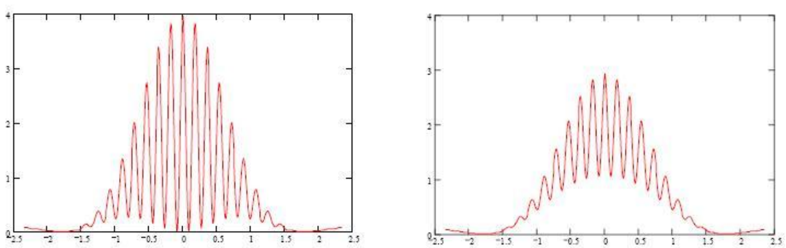
speed: up to 2 pixel/ps
chromaticity: BP filter needed
-bunch length
-impedance and instabilities

Small beam size – Interferometer technique





H. Mitsuhashi - Photon Factory



Point source

30-nm FWHM blue filter

Gaussian source

160-μm rms width

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:

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

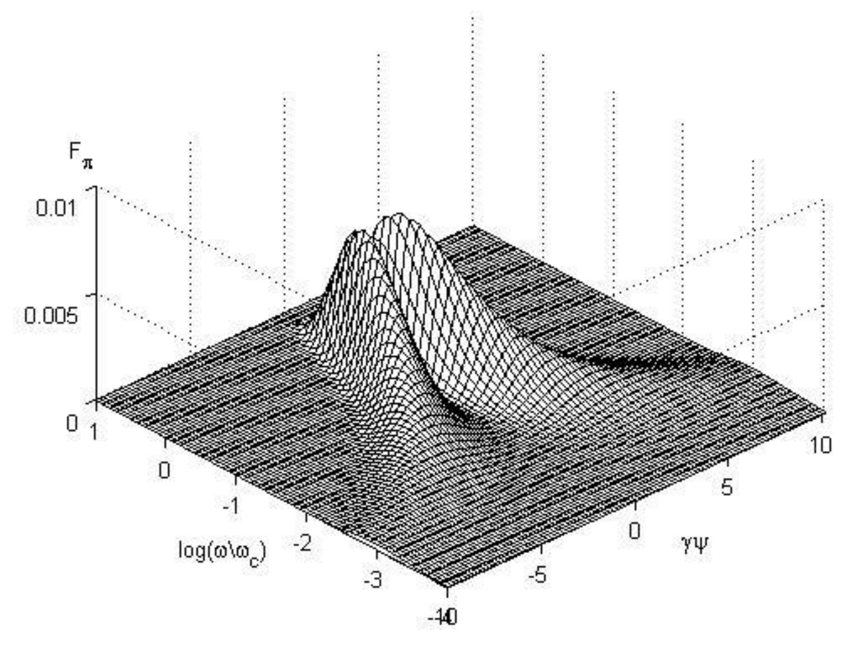
The ray leaving the slit at an angle θ hits the CCD at height y:

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

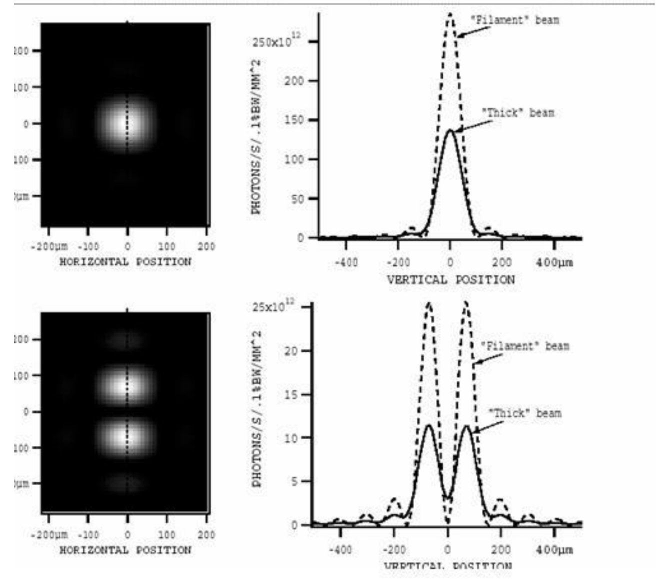
A. Fisher - SLAC

Small beam size – Vertical polarization technique

Vertical angular spectral density



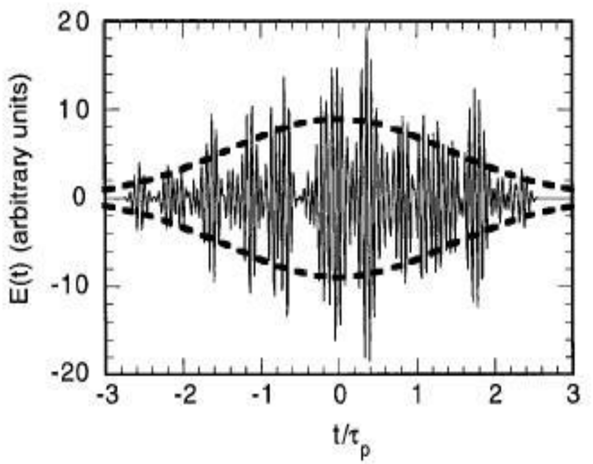
Measurements at MaxLab



A. Andersson MaxLab/SLS

Bunch Length Measurement – Statistical Fluctuations

Intra-pulse fluctuation of the electric field



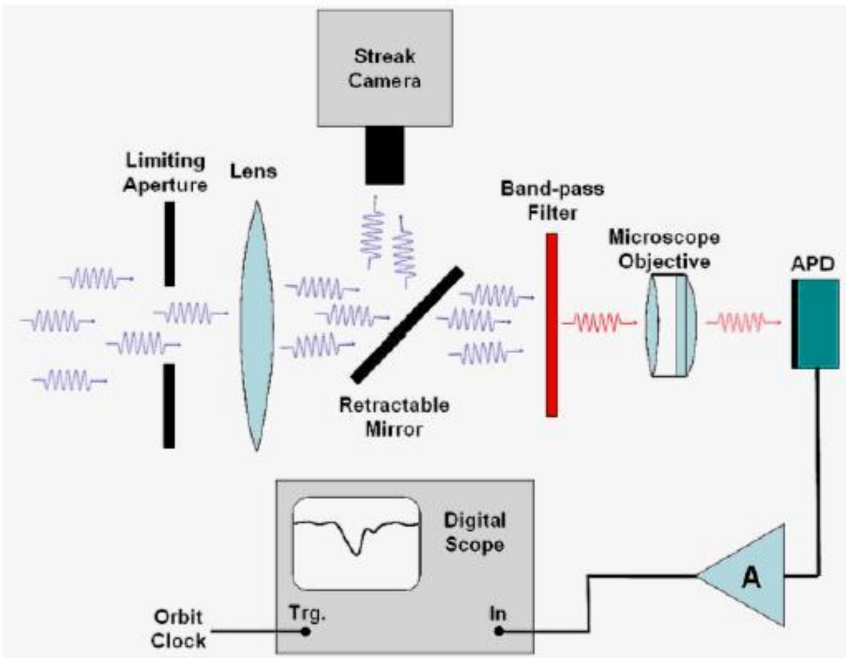
$$\delta^2 = \frac{\sigma_W^2}{\langle W \rangle^2} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} dt dt' \frac{|K(t-t')|^2}{|K(0)|^2} I(t) I(t')$$

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

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 $\sqrt{I(t)}$.

G. Stupajkov/SLAC

Fluctuation measurements at the ALS (F. Sannibale)



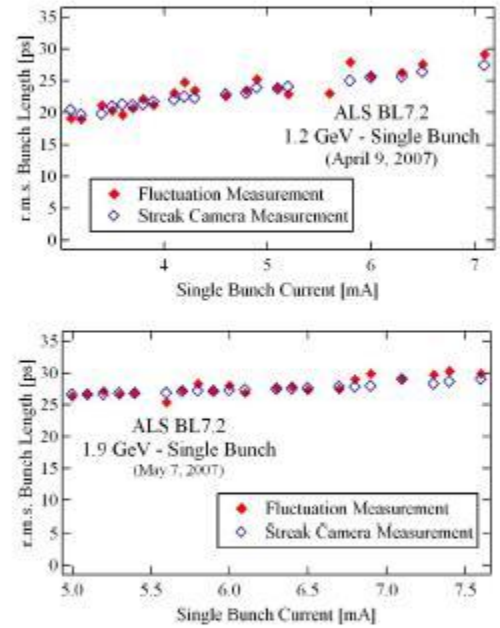


Figure 3: Examples of fluctuation and streak-camera bunch length measurements at the ALS for different beam parameters.

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
- Flucutation 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