Motivation

Electron beam properties

SR beam properties

Standard imaging – visible spectrum \( \lambda = 550 \text{nm} \)

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: $\beta$-functions and beam size

**SPEAR3 $\beta$-functions**

- Dipole

**SPEAR3 beam size: $\epsilon_x=15\text{mm-rad}, 0.1\%$ coupling**

- $\sigma_x \sim 150$ micron

**SPEAR3 beam size: $\epsilon_x=15\text{mm-rad}, 0.1\%$ coupling**

- $\sigma_y \sim 15$ micron
\[ y^2 + 2\alpha xx' + \beta x'^2 = \text{invariant oscillation amplitude} \]

\[ \rho(x, x') = \frac{1}{2\pi\varepsilon} e^{-(y^2 + 2\alpha xx' + \beta x'^2)/2\varepsilon} \]

\[ \rho(x, x') = \text{distribution in phase space} \]

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

= image projected on screen
Photon beam properties: Phase Space

SPEAR3: Horizontal

\[ \sigma_x^2 = \varepsilon_x \beta_x + (\eta_x \delta)^2 \]
\[ \sigma_{x}'^2 = \varepsilon_x \gamma_x + (\eta_x' \delta)^2 + \sigma_r^2 \]

SPEAR3: Vertical

\[ \sigma_y^2 = \varepsilon_y \beta_y + (\eta_y \delta)^2 \]
\[ \sigma_{y}'^2 = \varepsilon_y \gamma_y + (\eta_y' \delta)^2 + \sigma_r^2 \]
Photon beam properties: Angular spectral power density

Horizontal Polarization

Vertical Polarization

visible component

Total Flux @ 500 mA
Example:
3 GeV and 200 ma current
$P_{SR} \sim 200\text{ kW (total)}$

visible beam line (1.5eV)
25mm aperture at 5 m (5 mrad)
$P_{SR} \sim 150\text{ W}$

lucky to get 100$\mu$W visible
(Class I laser pointer)

pinhole camera (15keV)
25$\mu$m aperture at 5 m (5 $\mu$rad)
$P_{SR} \sim 100\mu\text{W before filter}$
Photon beam timing pattern - storage rings

800ns stored charge
200ns ion gap
repeat

10-100ps
2ns
Visible beam line components

- Source
- Chicane
- Lens
- X-rays
- 5m
- CCD Streak
- 2nS gated CCD
- Bunch Current Monitor
- 2 slits pol
- CCD interferometer
- Photon Counter
- Mirror
- Splitter
- ND BP
- 10m
- Transverse image
- Bunch-by-bunch image
- Bunch length, instabilities
- Top-up
- Bunch length
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 diaphragms – 1ms mechanical shutters, 10ps Pockel cells

About 90% transmission per element
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

\[ d \approx 40 \mu m \quad \text{at } \lambda = 550 \text{nm} \]

more diffraction later...
Depth of Field

\[ d \approx \sigma_r \rho \]

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

~same result as diffraction

(source length related to opening angle)
Cameras I: CCD's and Video

EPICS, MATLAB

Beamspot at XSR
PEP-II: visible light monitor software (LabView)
X-ray pinhole cameras - Reduce diffraction with small $\lambda$

\[ M = \frac{d_2}{d_1} \]

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**Zone plate optics**

Zone plates act as a thin lens, with

\[ f = \frac{4N(\Delta r)^2}{\lambda} \]

where \(N\) is the number of zones, \(\Delta r\) is the width of the outermost zone, and \(\lambda\) 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).

So if one wants to use a zone plate-pinhole setup to monochromatize (and thus avoid the added complication of a crystal monochromator), one must be able to fit the entire beam through the pinhole, or else the edges of the beam will be cut off, spoiling the measurement.

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W. Peatman and K. Holldack, 'Diagnostic Front End for BESSY-II'
PEP-II: x-ray pinhole camera software (LabView)
Photon beam propagation programs

SRW
(synchrotron radiation workshop)

Zemax
(commercial product)
Fig. 8: Walking along a bunch train with the ICCD camera. This sequence shows every
Cameras III - Streak tubes

Hamamatsu C5680
Optronis (ASP)

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

visible beam

Robinson Instability

M. Boland - ASP
Small beam size - Interferometer technique

Fringe Formulas

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

$$I_{\pm}(\theta) = \left( \frac{\cos \left( \frac{ka}{2} \left( \frac{\theta \mp d/2}{d/2} \right) \right)}{\cos \left( \frac{ka}{2} \left( \frac{\theta \mp d/2}{d/2} \right) \right)} \right)^2$$

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

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

The ray leaving the slit at an angle $\theta$ hits the CCD at height $y$:

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

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

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 $\sqrt{I(t)}$.

\[ \delta^2 = \frac{\sigma_\pi^2}{\langle I \rangle^2} = \int \left| \frac{\mathbf{K(t-t')}}{\mathbf{K(0)}} \right|^2 I(t)I(t') \]

\[ \delta^2 = \frac{1}{\sqrt{1 + 4\sigma_\pi^2 \sigma_\omega^2}} \]

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\textsuperscript{-} beam
- Need to unfold $\gamma_r$, DOF, diffraction, PSF, etc. from image
- Visible has advantage of commercial optics and cameras but suffers from large $\gamma_r$ 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