Photon and Electron Beam Stability Requirements for Storage Ring Light Sources

A Workshop Exercise for 4GSRs

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DLSR 2014

APS, ANL November 20, 2014

- SR beam parameters and stability criteria
- Photon-electron relationships
- Electron beam properties
- Stability time scales
- Basic stability requirements

SR Beam Parameters

Photon beam parameters of interest to experimenter include:

- position and pointing accuracy on small apertures and samples
- beam size

  both of these affect intensity constancy at the sample
- angle and divergence at optical components and sample

  contribute to resolution of energy, scattering angle, intensity
- energy and energy bandwidth

  contribute to energy resolution of experiment
- photon pulse time-of-arrival and bunch length

  for timing experiments
- polarization
- coherence
- lifetime
- …..

Beam stability characterized in 6-D phase space: (x, x', y, y', E, t)

Beam Stability Criteria

Beam stability requirements depend on:

- beam line optical configuration and apertures
- sample size
- measurement technique and instrumentation
- data acquisition time scale
- data averaging and processing methods

Stability is relative:

- flux constancy with respect to apertures within the 6-D acceptance phase space of the experiment

While stability requirements vary, generic requirements can be estimated from criteria common to many experiments

Beam Stability Criteria – cont.

Today, sources of photon beam instability can be divided into 2 categories:

- those associated with beam line optical components and experimental apparatus

the beam line staff's problem!

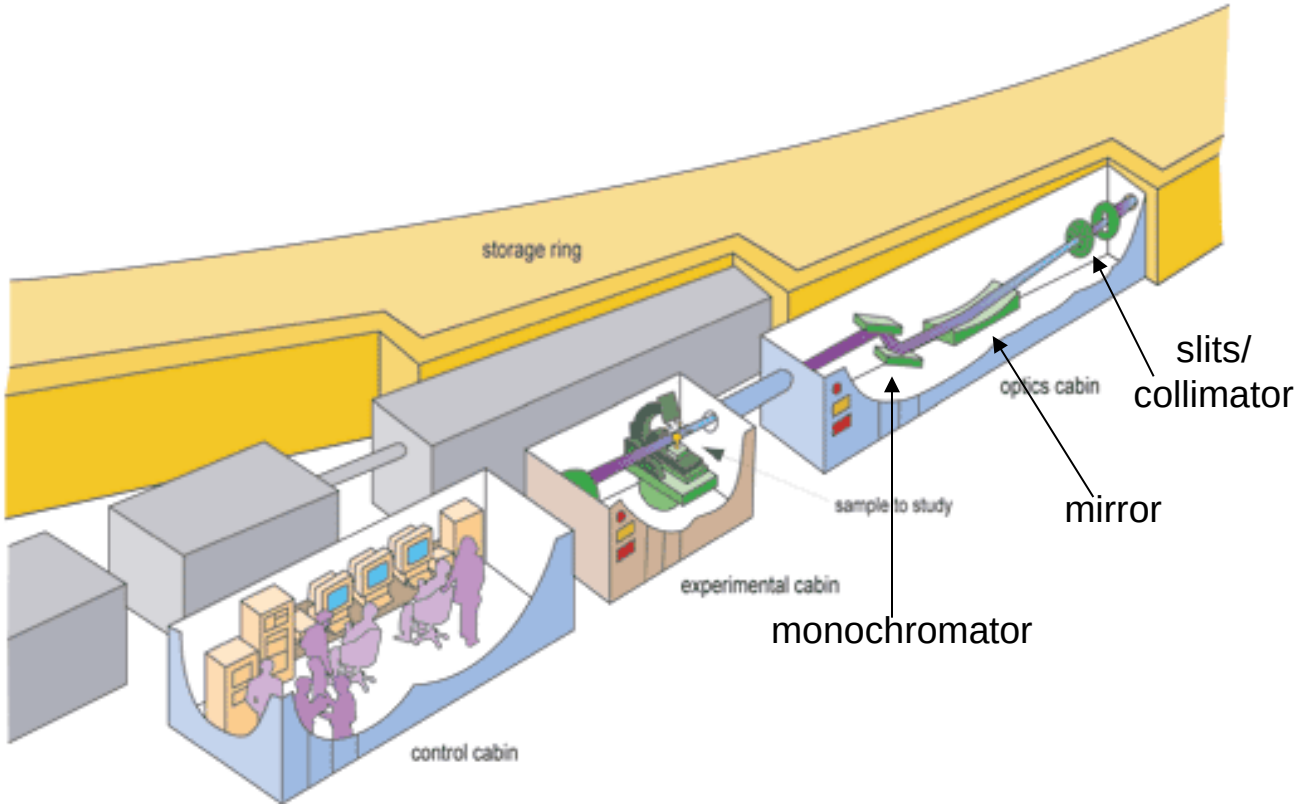
- those associated with the electron beam

the accelerator staff's problem!

In the future, for DLSRs, accelerator and beam line stability should be a joint challenge, perhaps requiring integrated stabilizing systems

meeting stability requirements will be everyone's problem!

SR Generic Beam Line



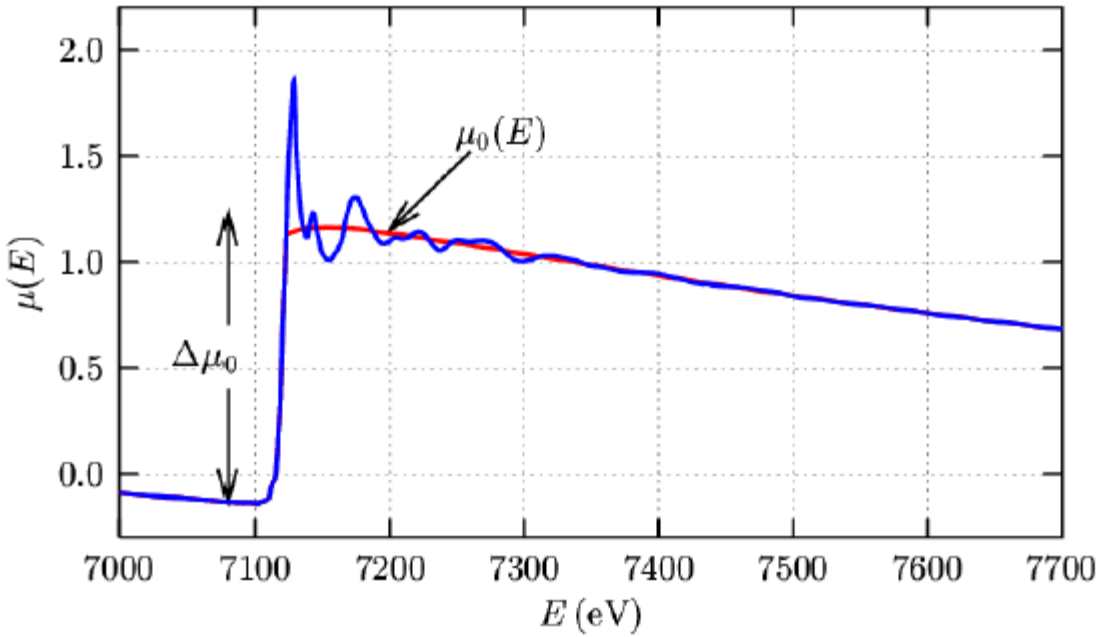
could be more apertures (slits, etc) than shown

XAFS Measurement

We're interested in the energy-dependent oscillations in $\mu(\mathrm{E})$, as these will tell us something about the neighboring atoms, so define the EXAFS as:

$$\chi(\mathrm{E}) = \frac{\mu(\mathrm{E}) - \mu_0(\mathrm{E})}{\Delta\mu_0(\mathrm{E}_0)}$$

We subtract off the smooth *"bare atom" background* $\mu_0(\mathrm{E})$, and divide by the *"edge step"* $\Delta\mu_0(\mathrm{E}_0)$ to give the oscillations normalized to 1 absorption event:



SR requirements:

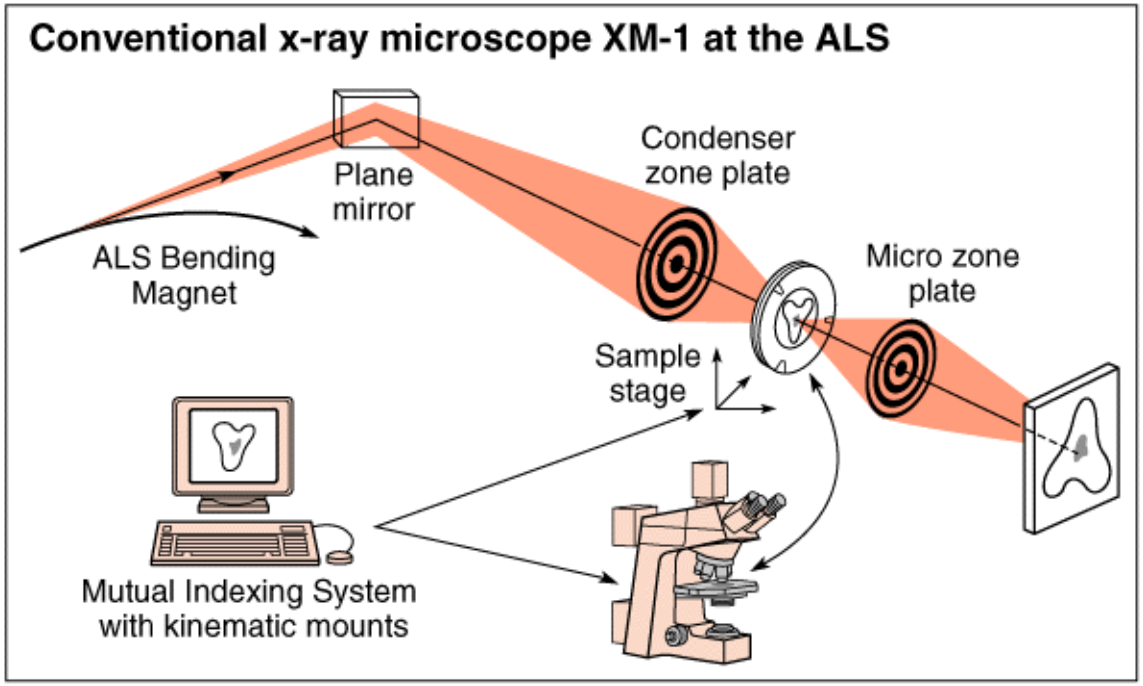
intensity stability: **10^{-3}**

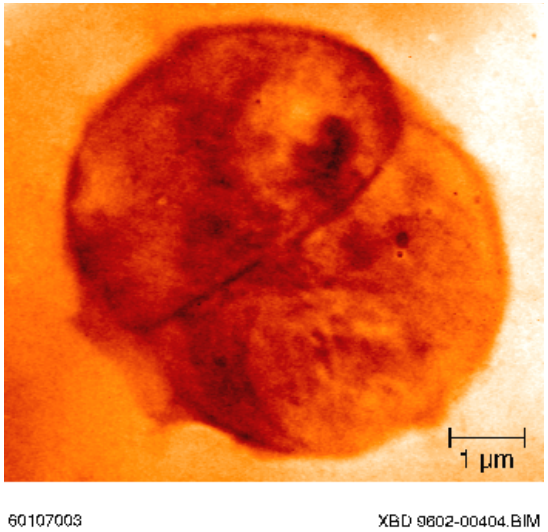
energy resolution: **10^{-4}**

from M. Newville, CARS, U. Chicago, 2002

X-ray Microscopy and Micro-diffraction

Focus spot size to micron level to examine single micron-sized structures





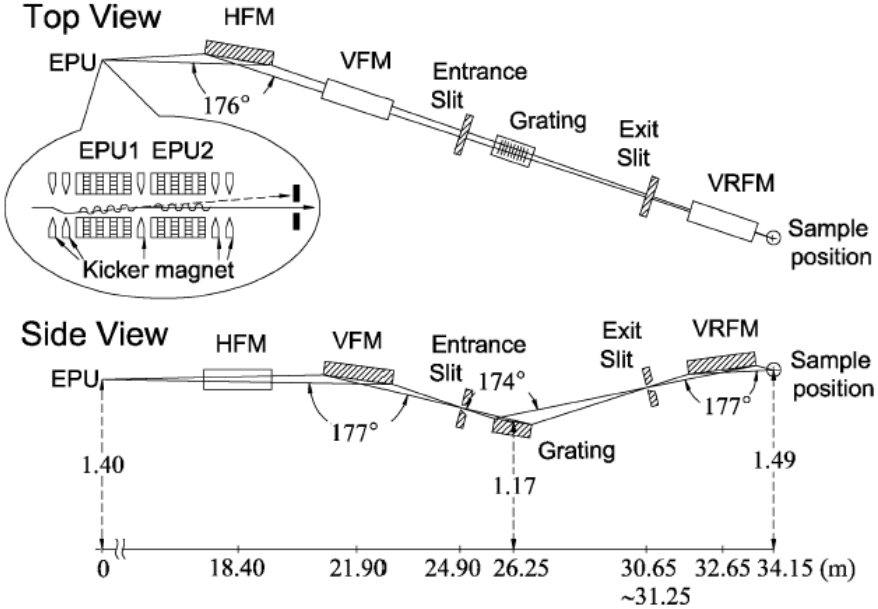
white or monochromatic light, 100-1000 eV

SR requirements:

intensity stability: **10^{-3}**

focused position stability: **<1 µm**

Circular Dichroism Beam Lines

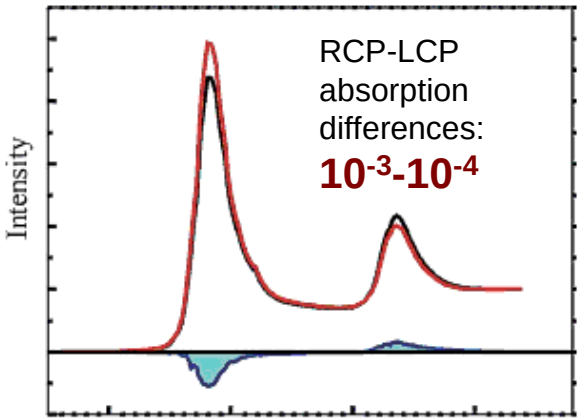


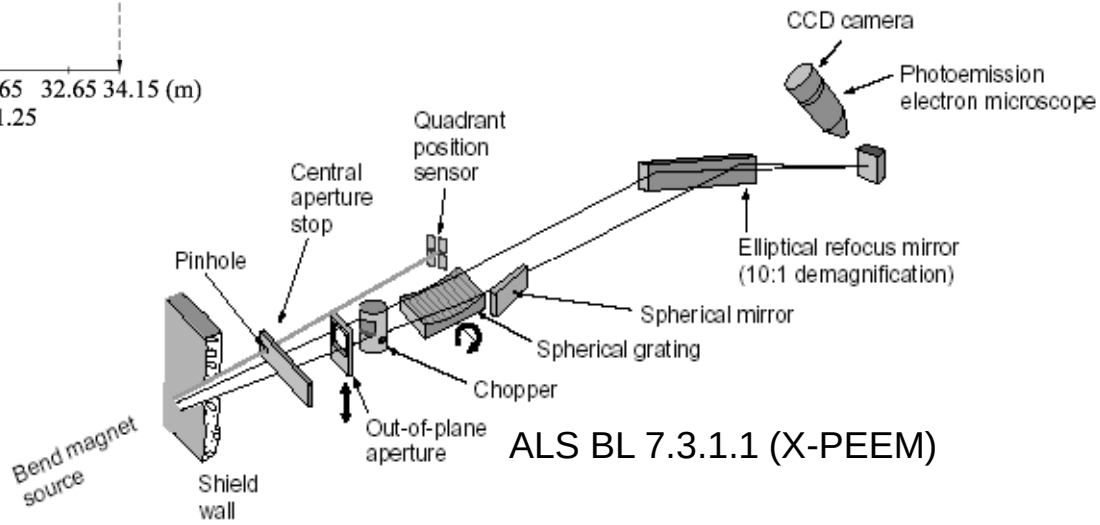
PLS EPU6

SR requirements:

intensity stability: <**10^{-4}**

focused position stability: **< 1 μm**

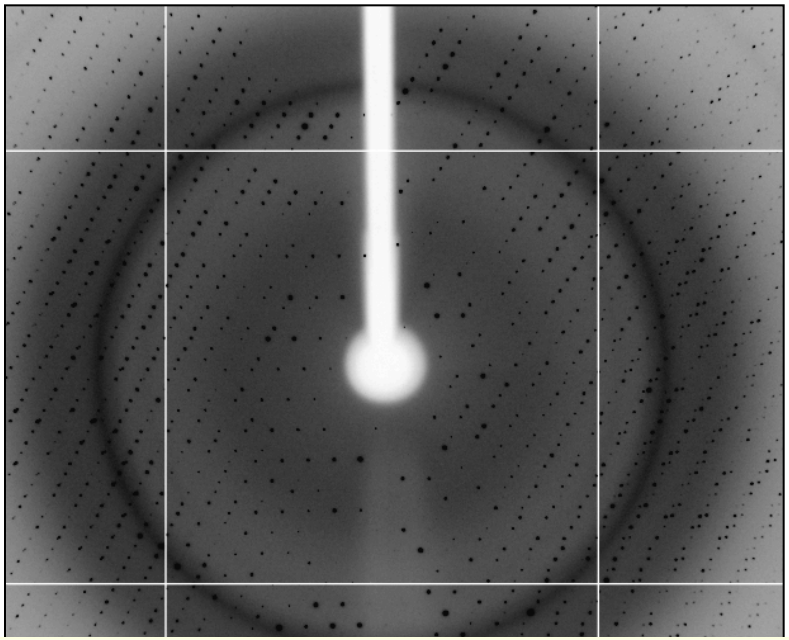




ALS BL 7.3.1.1 (X-PEEM)

Schematic layout of Branchline 7.3.1.1.

Macromolecular Crystal Diffraction Patterns



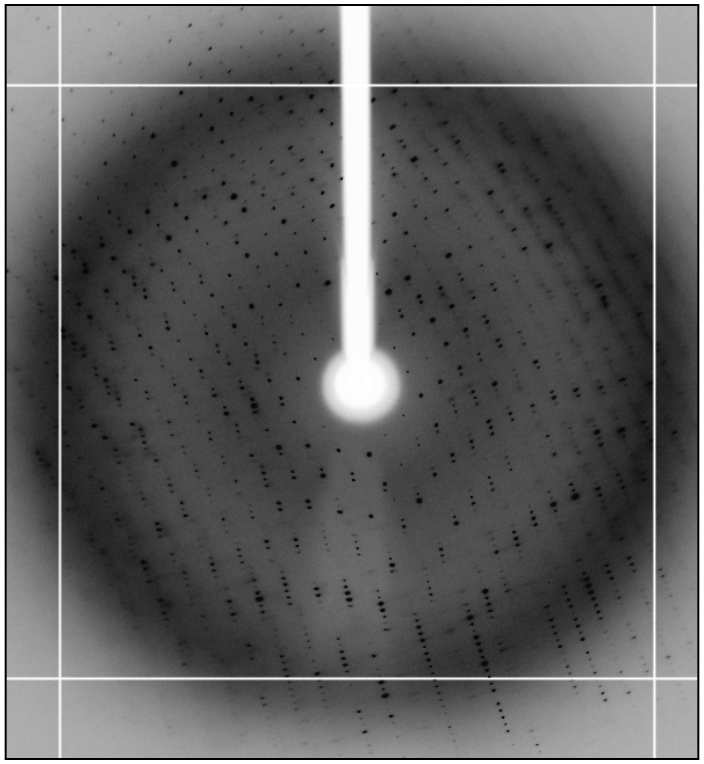
low mosaicity crystal

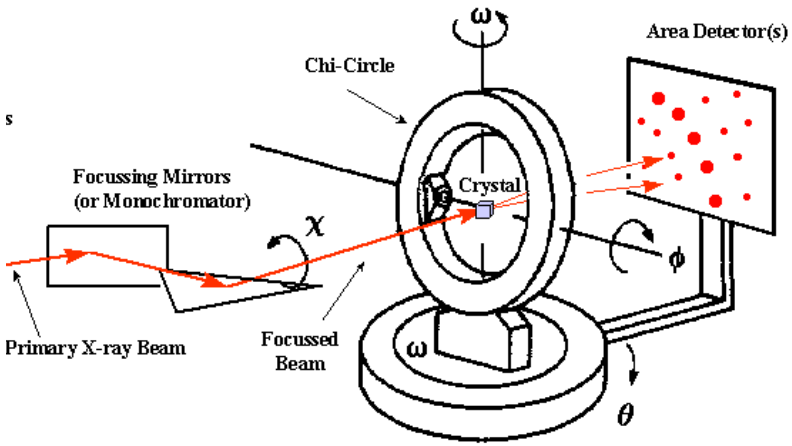
SR requirements:

intensity stability: 10^{-3}

energy resolution: 10^{-4}

high mosaicity crystal





4-Circle Goniometer (Eulerian or Kappa Geometry)

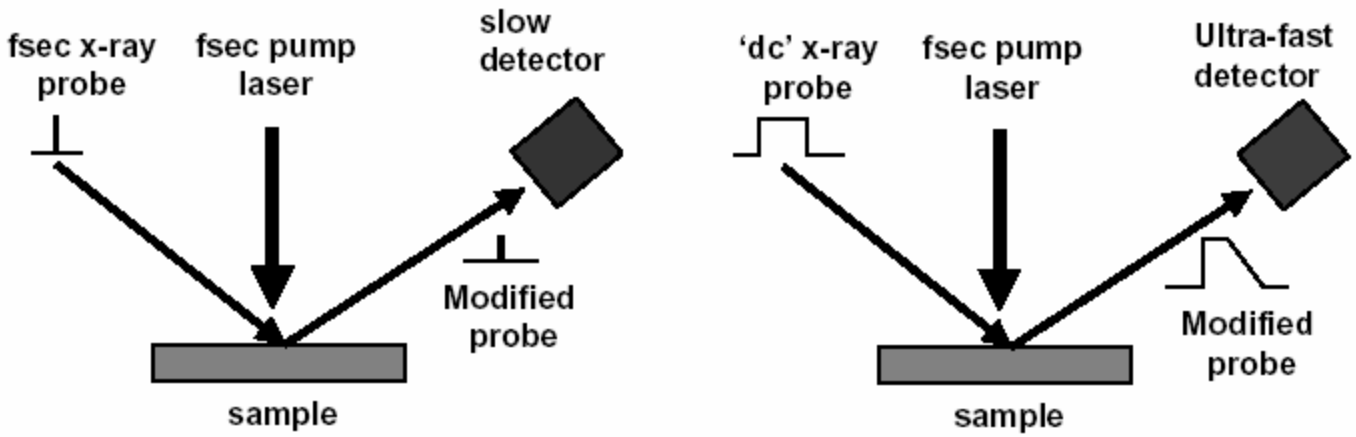
Femtosecond X-ray Spectroscopy and Diffraction

H. Padmore, ALS

Goal: measurement of structure on the fundamental time scale of a vibrational period ~100 fs

Research areas: ultrafast phase transitions, chemical reactions, biological processes

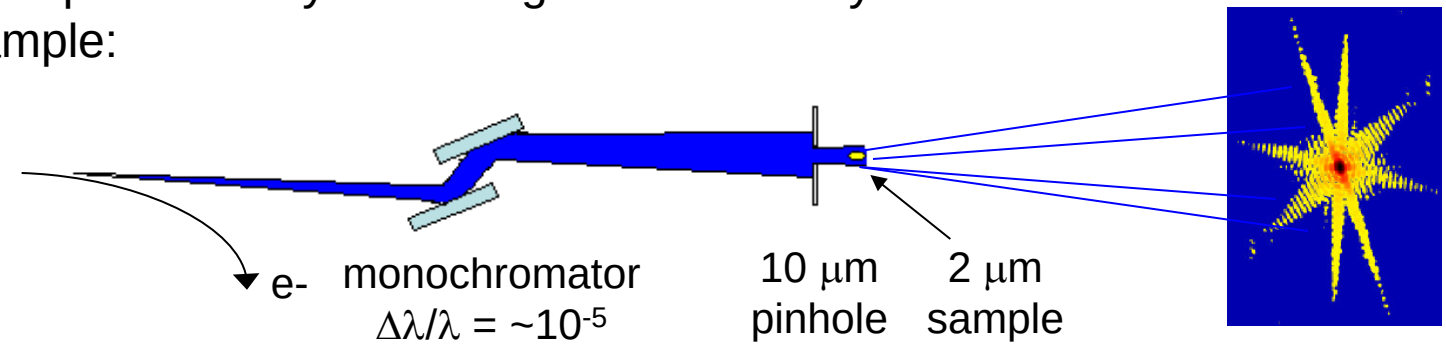
Probes: x-ray diffraction; ordered systems, structural phase transitions spectroscopy; disordered/complex materials, chemical reactions



Timing stability requirement: pump-probe timing synchronization **< ~50 fs**, or else be able to measure actual shot-shot synchronization to that level

Coherence Experiments

Speckle pattern produced by scattering of transversely coherent photons in sample:



Longitudinal coherence length > sample thickness to obtain coherent speckle pattern

Longitudinal coherence length increased using narrow bandwidth monochromator:

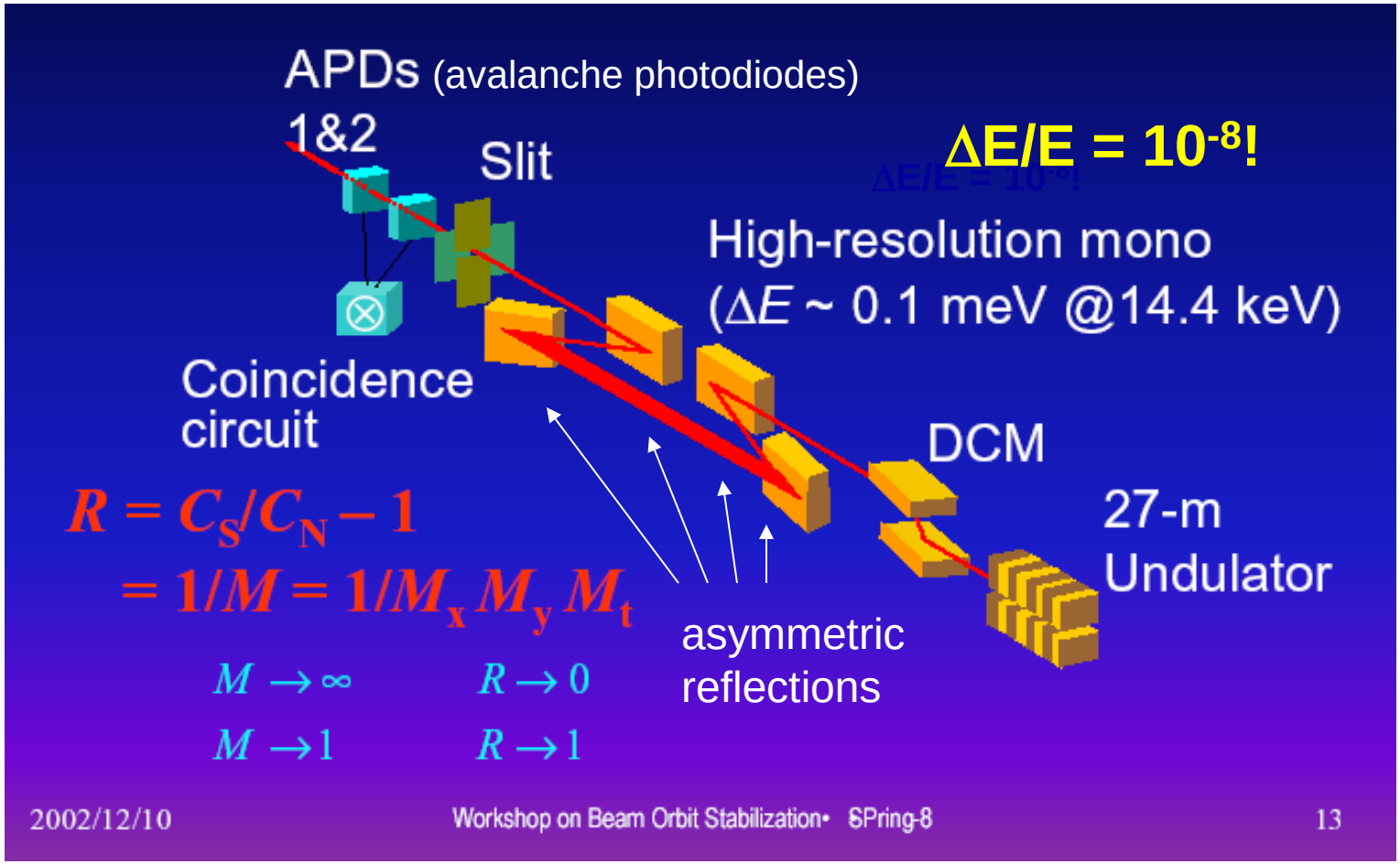
$$l_{coh} = \lambda_{ph}(\lambda/\Delta\lambda)_{mono} = \sim 20\ \mu m \text{ for } 2\ \text{Å photons}$$

SR requirements:

intensity stability at sample: **~10^{-3}**

X-ray Intensity Interferometry

T. Ishikawa



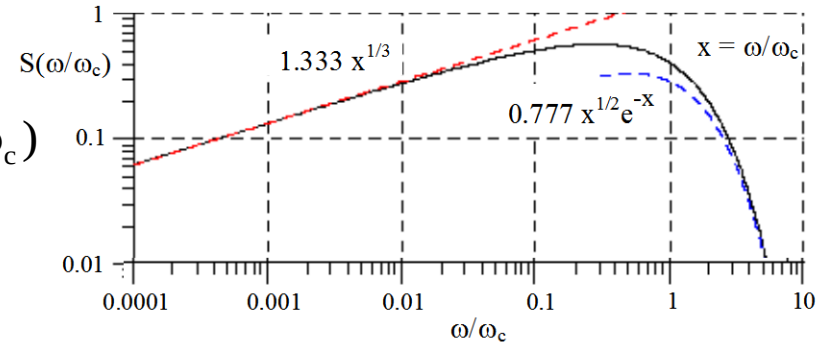
Hambury Brown-Twiss Interferometer at SPring-8

Photon-Electron Relationships – Photon Emission

K-J Kim

Dipole spectral flux density (per horizontal mrad, integrated over vertical angle):

$$\frac{dF_{dip}(\omega)}{d\theta} = 2.457\,x\,10^{16}\,\frac{\Delta\omega}{\omega}\,E_{e-}{}^{2}(GeV)\,I(A)\,S(\omega/\omega_c)$$



Wiggler spectral flux density:

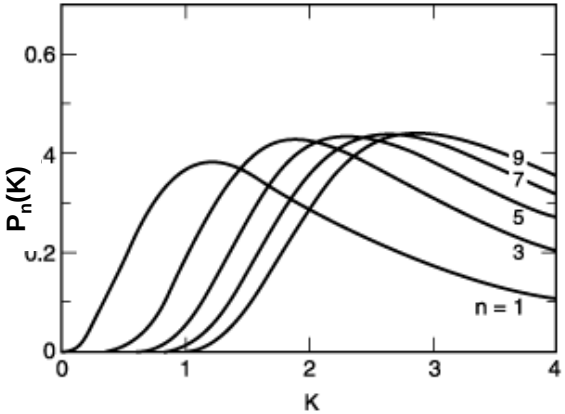
$$\frac{dF_{wigg}(\omega)}{d\theta} =\sim N_{wigg}\,\frac{dF_{dip}(\omega)}{d\theta}$$

$$N_{wigg} = \#\,\text{wiggler poles}$$

Undulator spectral flux density:

$$\left.\frac{d^2F_{und}(\omega_n)}{d\theta\,d\varphi}\right|_{\varphi,\theta=0} = 1.744\,x\,10^{14}\,\frac{\Delta\omega}{\omega}\,N_u{}^{2}E_{e-}{}^{2}(GeV)\,I(A)\,P_n(K)$$

N_u = # undulator periods



Photon-Electron Relationships – cont.

Photon beam divergence:

$\sigma'_{ph}(L) = \sigma'_{ph}(0) = [\sigma'_{e-}{}^2 + \sigma'_{\Psi}{}^2]^{1/2}$

$\sigma'_{e-} = [\varepsilon\gamma(s) + (\eta'\delta)^2]^{1/2}$

for dipoles and wigglers:

$$\sigma'_{\psi}(\lambda) \cong \begin{cases} \frac{1.07}{\gamma}\left(\frac{\lambda}{\lambda_c}\right)^{1/3} & \lambda >> \lambda_c \\ \frac{0.64}{\gamma} & \lambda = \lambda_c. \\ \frac{0.58}{\gamma}\left(\frac{\lambda}{\lambda_c}\right)^{1/2} & \lambda << \lambda_c \end{cases}$$

$$\lambda_c = \frac{2\pi c}{\omega_c} = \frac{hc}{E_c}$$

h = Planck's const.
= 4.14 x 10^{-18} keV-s

$$E_c(\text{keV}) = \frac{3\hbar c\gamma^3}{2\rho} = 0.665\,B(T)\,E^2(\text{GeV})$$

for planar undulators:

(on-axis, central cone)

$$\sigma'_{\Psi}(n) = \sqrt{\frac{\lambda_n}{L_u}} = \frac{1}{\gamma}\left[\frac{\lambda_u(1+K^2/2)}{2nL_u}\right]^{1/2} = \frac{1}{\gamma}\left[\frac{1+K^2/2}{2nN_u}\right]^{1/2}$$

n = harmonic # L_u = undulator length λ_u = undulator period N_u = # periods K = ~1

Photon-Electron Relationships – Photon Energy

Dipole critical energy:

$$E_{crit\,dip}(keV) = \frac{h}{2\pi}\,\omega_c = 0.665B(T)E_{e-}{}^2(GeV)$$

Wiggler critical energy:

$$E_{crit\,wigg}(\theta) = E_{crit\,dip}\left[1-\left(\frac{\theta\gamma}{K}\right)^2\right]^{1/2}$$

where θ is horizontal viewing angle,

$K = \delta/\gamma^{-1}$, ratio of wiggler deflection angle δ to beam opening angle

Undulator harmonics:

$$E_n(keV) = 0.95\frac{nE_{e-}{}^2(GeV)}{\lambda_u(cm)}\left(\frac{1}{1+K^2/2+(\gamma\theta)^2}\right)$$

$$\frac{\Delta E_n}{E_n} = \frac{1}{nN_u}$$

n = harmonic number λ_u = undulator period N_u = # periods θ = hor or vert view angle

for zero-emittance, zero-energy-spread electron beam

Undulator Radiation

Angular distribution of 1st harmonic:

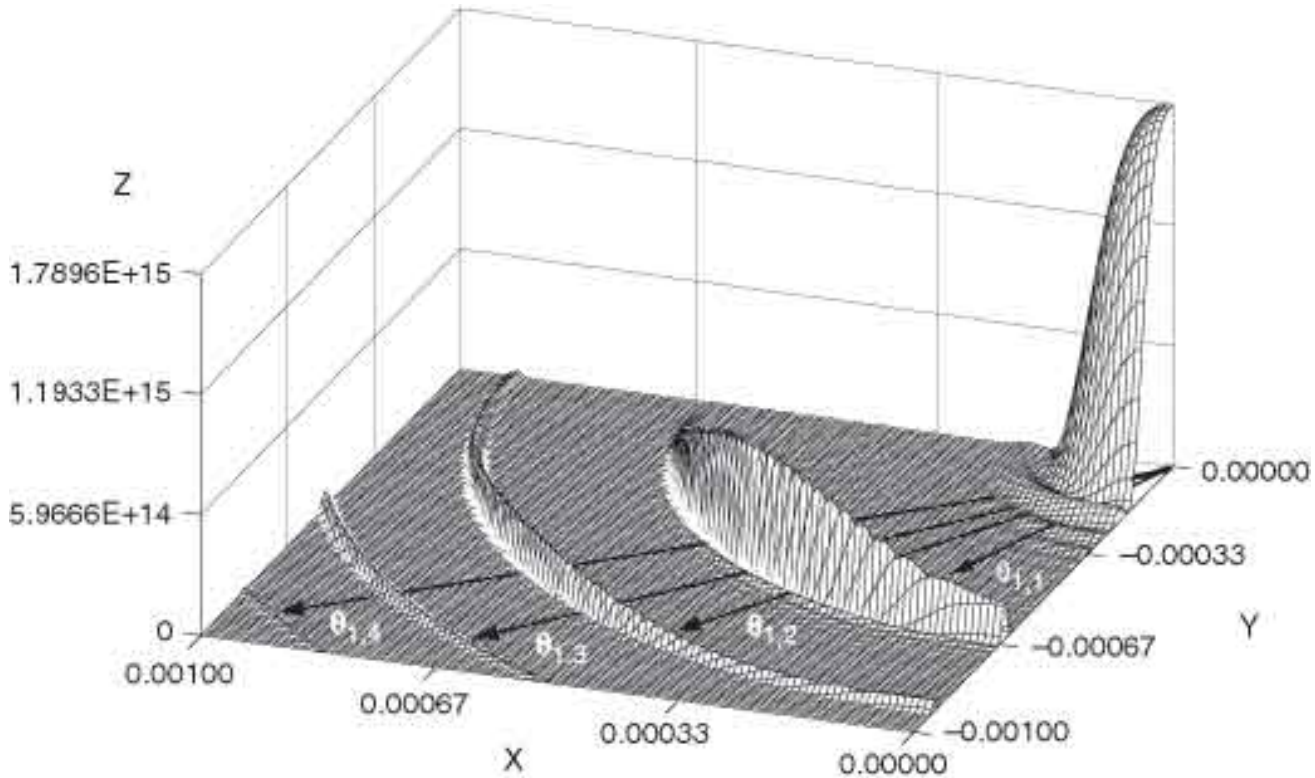


Fig. 2-5. *The angular distribution of fundamental (n = 1) undulator radiation for the limiting case of zero beam emittance. The x and y axes correspond to the observation angles θ and ψ (in radians), respectively, and the z axis is the intensity in photons·s^{-1}·A^{-1}·(0.1 mr)$^{-2}$·(1% bandwidth)$^{-1}$. The undulator parameters for this theoretical calculation were N = 14, K = 1.87, λ_u = 3.5 cm, and E = 1.3 GeV. (Figure courtesy of R. Tatchyn, Stanford University.)*

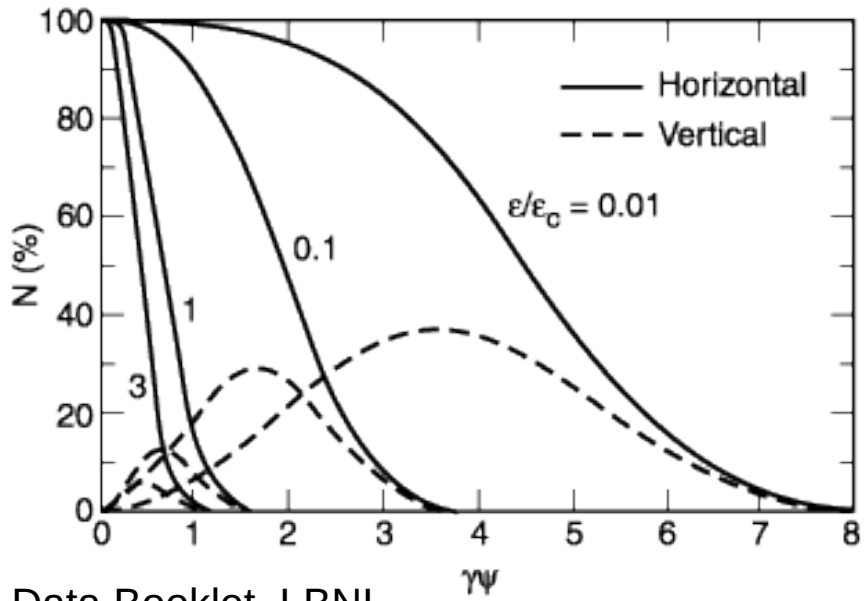
K-J Kim, from X-ray Data Booklet, LBNL

Photon-Electron Relationships - Polarization

- SR from dipole is linearly polarized in horizontal plane when viewed in this plane
- Polarization is elliptical when viewed out of horizontal plane

  rotation sense reverses as vertical angle changes from positive to negative

- Elliptical polarization can be decomposed into horizontal and vertical components:



K-J Kim, from X-ray Data Booklet, LBNL

Photon-Electron Relationships

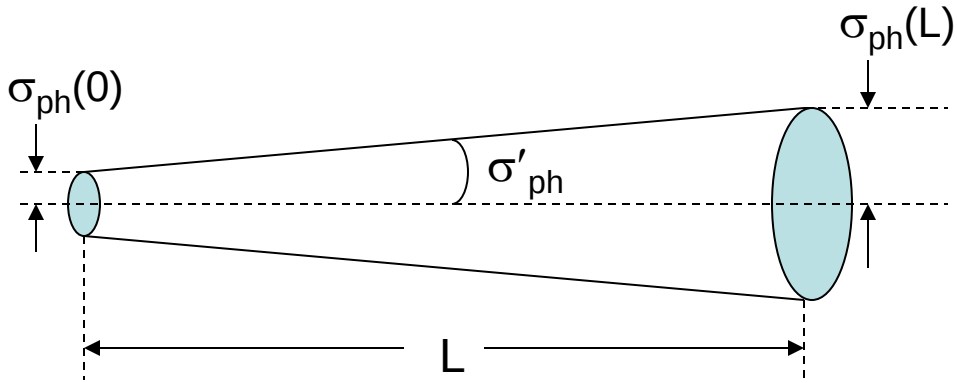
Photon beam size:

- unfocused, vertical plane:

  (assume depth of field = 0)

  $\sigma_{ph}(L) = [\sigma_{ph}(0)^2 + L^2\sigma_{ph}'^2]^{1/2}$

  $\sigma_{ph}(0) = [\sigma_{e-}^2 + \sigma_{diff}^2(\lambda)]^{1/2}$



i.e the convolution of electron beam size and diffraction-limited apparent size of a single electron (quadrature sum of 2 Gaussian distributions).

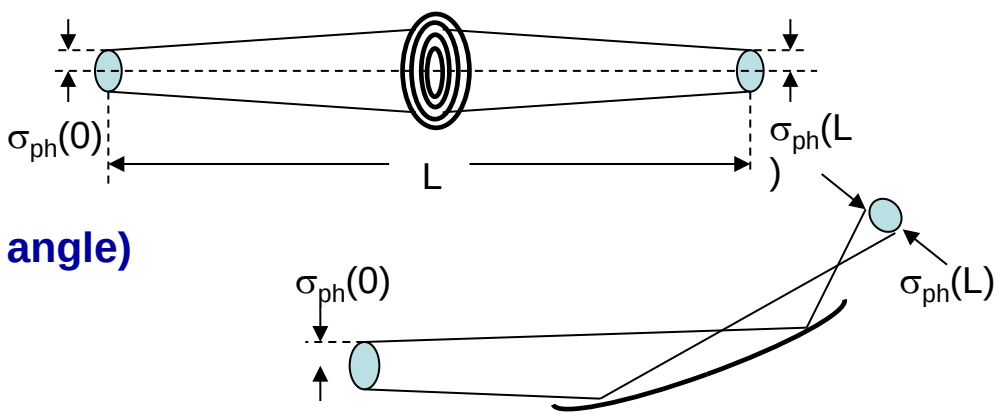
$$\sigma_{diff} = \frac{\lambda}{4\pi\sigma'_{\Psi}(\lambda)} \quad \left(\sigma_{diff} = \frac{\lambda}{2\pi\sigma'_{\Psi}(\lambda)}\right)$$

$\sigma_{e-} = [\varepsilon\beta(s) + (\eta(s)\delta)^2]^{1/2}$

- focused (1:m, m = magnification):

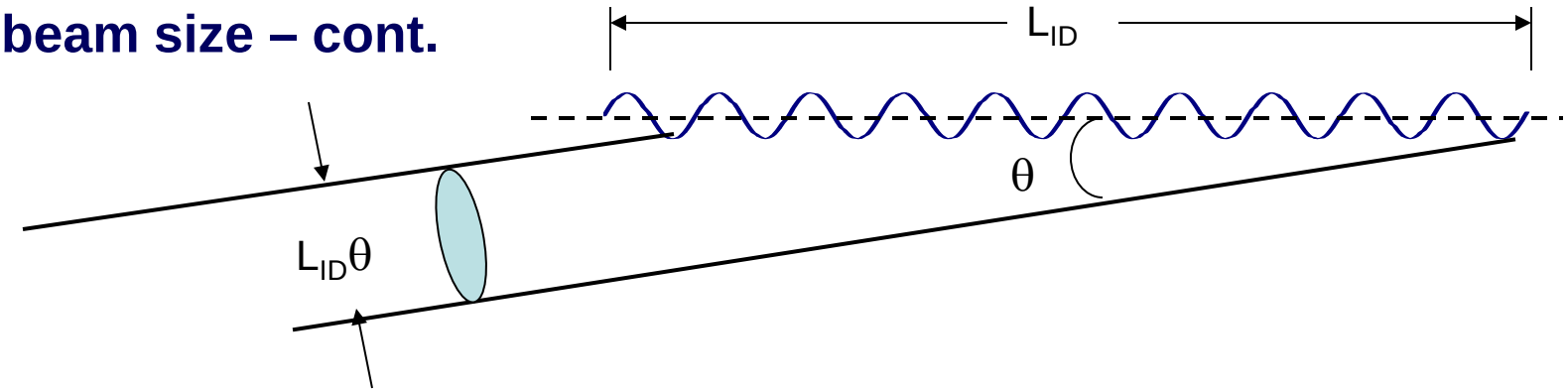
  $\sigma_{ph}(L) = m\sigma_{ph}(0)$ **(~insensitive to angle)**

  $\sigma'_{ph}(L) = -\sigma'_{ph}(0)/m$



Photon-Electron Relationships – cont.

Photon beam size – cont.



- Off-axis view of ID radiation adds to focused beam size due to extended source
- On-axis beam size has additional terms arising from wiggle amplitude and ID length:

$$\sigma_{Tx}^2 = \sigma_r^2 + \sigma_x^2 + a^2 + \tfrac{1}{12}\sigma_{x'}^2 L^2 + \tfrac{1}{36}\varphi^2 L^2 \qquad \sigma_{Tx'}^2 = \sigma_{r'}^2 + \sigma_{x'}^2$$

$$\sigma_{Ty}^2 = \sigma_r^2 + \sigma_y^2 + \tfrac{1}{12}\sigma_{y'}^2 L^2 + \tfrac{1}{36}\psi^2 L^2 \qquad \sigma_{Ty'}^2 = \sigma_{r'}^2 + \sigma_{y'}^2$$

from I.V.Bazarov

- DIpole source size is slightly increased from finite depth of field and orbit arc

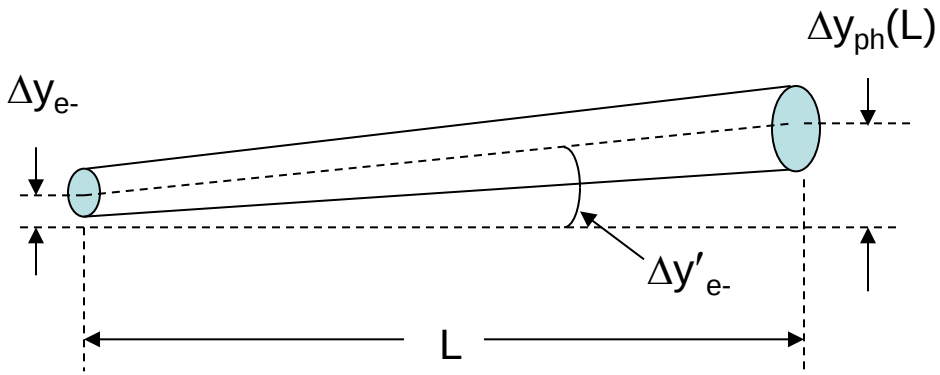
Photon-Electron Relationships – cont.

Beam line steering:

- pointing parameters (1st order) for **unfocused** photon centroid:

$$\Delta y_{ph}(L) = \Delta y_{e-} + L\Delta y'_{e-}$$

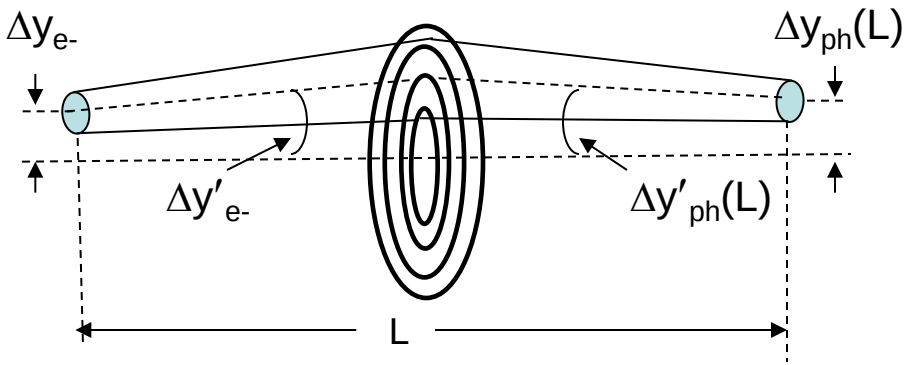
$$\Delta y'_{ph}(L) = \Delta y'_{e-}$$



- **focused** (1:m) photon centroid:

$$\Delta y_{ph}(L) = m\Delta y_{e-}$$

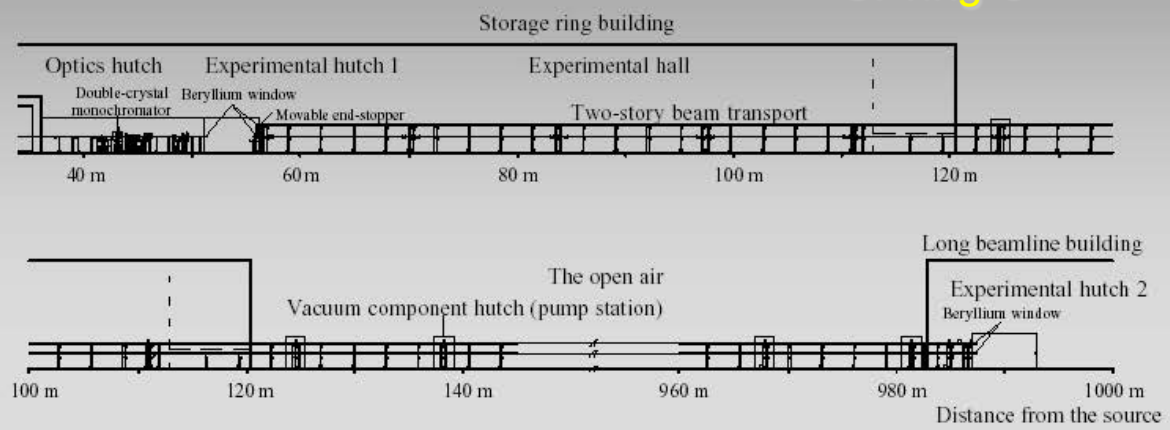
$$\Delta y'_{ph}(L) = -\Delta y'_{e-}/m$$



L is large in some cases…..

1000 m Beamline, BL29XU

SPring-8



Ishikawa *et al*, *Proc. SPIE* (2001)

Electron Beam Properties

Electron beam characterized by conjugate variable pairs in 6-D phase space:

x, x′ **y, y′** **E, t (or ϕ)**

-------- transverse ---------- **longitudinal**

For each conjugate pair, beam occupies phase space ellipse of constant area - or emittance (A = πε)

transverse:

$$\varepsilon = \gamma(s)x^2 + 2\alpha(s)xx' + \beta(s)x'^2 = \text{constant}$$

$$\varepsilon_y \cong k\varepsilon \quad (k = \text{coupling},\ k <\sim 0.1)$$

$$\left(\alpha = -\beta'/2 \qquad \gamma = \frac{1+\alpha^2}{\beta}\right)$$

e- beam size:

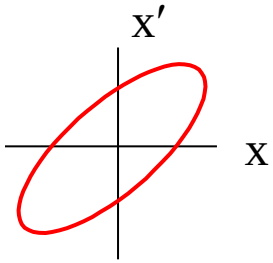
$$\sigma_x(s) = \sqrt{\varepsilon_x \beta_x(s) + \left(\eta(s)\delta E/E\right)^2} \qquad \sigma_y(s) = \sqrt{\varepsilon_y \beta_y(s)}$$

e- divergence:

$$\sigma_{x'}(s) = \sqrt{\varepsilon_x \gamma_x(s) + \left(\eta'(s)\delta E/E\right)^2} \qquad \sigma_{y'}(s) = \sqrt{\varepsilon_y \gamma_y(s)}$$

longitudinal:

$$\Delta\phi\ (\text{rad}) = \frac{h\alpha_c}{\nu_s}\frac{dE}{E} \quad \left(= \sim 30\frac{dE}{E}\ \text{for APS-U}\right)$$



Electron Beam Properties – cont.

Have coupling between phase space planes:

- H-V by skew quads, orbit in sextupoles, resonances, ID changes
- longitudinal-transverse (energy-orbit, $\Delta x = \eta \Delta E/E$)
- photon energy dependent on orbit through IDs
- photon polarization dependent on vertical orbit through dipole
- etc.

Experiment Sensitivity to Electron Beam Parameters

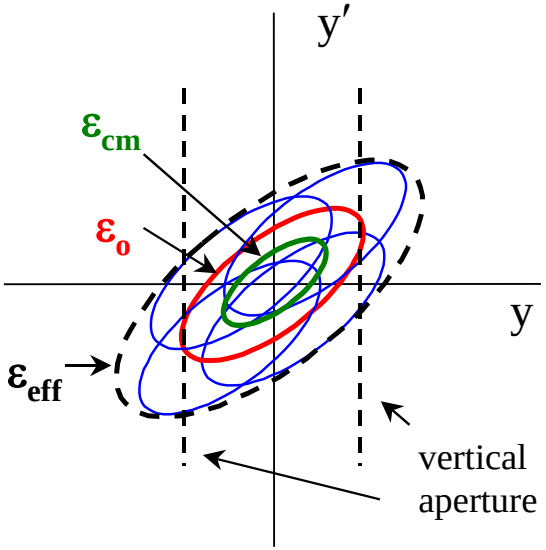
Response of experiment observable parameters to source point electron beam parameters: sensitivity matrix M(i,j)

$$[\Delta P_{exp}(i)] = \mathbf{[M(i,j)]}\ [\Delta P_{e-}(j)]$$

where

$$[\Delta P_{exp}(i)] = \begin{pmatrix} \Delta I_{ph} \\ \Delta E_{ph} \\ \Delta E_{ph}/E_{ph}\,(\mathrm{rms}) \\ \Delta\sigma_x \\ \Delta\sigma_y \\ \Delta\sigma'_x \\ \Delta\sigma'_y \\ \Delta\sigma_z \\ \Delta x \\ \Delta y \\ \Delta x' \\ \Delta y' \\ \Delta t_{bunch} \\ \text{polarization} \\ \text{coherence} \end{pmatrix} \qquad [\Delta P_{e-}(i)] = \begin{pmatrix} \Delta I_{e-} \\ \Delta E_{e-} \\ \Delta E_{e-}/E_{e-}\,(\mathrm{rms}) \\ \Delta\sigma_x \\ \Delta\sigma_y \\ \Delta\sigma_z \\ \Delta\sigma'_y \\ \Delta\sigma_z \\ \Delta\theta_{rot} \\ \Delta x \\ \Delta y \\ \Delta x' \\ \Delta y' \\ \Delta t_{\ bunch} \end{pmatrix}$$

Beam Position Instability and Emittance Growth from Orbit Motion



For disturbance time scale **<<** experiment integration time:

(effective "blow-up" of emittance ellipse)

$$\varepsilon = \varepsilon_o + \varepsilon_{cm} \qquad \Delta\varepsilon/\varepsilon = \varepsilon_{cm}/\varepsilon_o$$

For disturbance time scale **>** experiment integration time:

("coherent displacement" of nominal emittance ellipse)

$$\varepsilon\ (\text{envelope}) = \varepsilon_o + 2\sqrt{\varepsilon_o\,\varepsilon_{cm}} + \varepsilon_{cm} \qquad \Delta\varepsilon/\varepsilon \cong 2\sqrt{\varepsilon_{cm}/\varepsilon_o}$$

($\varepsilon_{cm} << \varepsilon_o$; L. Farvacque, ESRF)

Note: can apply similar analysis to other phase space dimensions

Beam Stability Time Scales

- **Disturbance time scale << experiment integration time:**

  Orbit disturbances blow up effective beam σ and σ', reduce intensity at experiment, but do not add noise

  For $\Delta\varepsilon/\varepsilon = \varepsilon_{cm}/\varepsilon_o < \sim 10\%$: **$\Delta y_{cm}$(rms) < ~0.3 σ_y** **$\Delta y'_{cm}$(rms) < ~0.3 $\sigma_{y'}$**

  Note: can have frequency aliasing if don't obey Nyquist….

- **Disturbance periods ≥ experiment integration time:**

  Orbit disturbances add noise to experiment

  For $\Delta\varepsilon/\varepsilon = \sim 2\sqrt{\varepsilon_{cm}/\varepsilon_o} < \sim 10\%$: **$\Delta y_{cm}$(rms) < 0.05 σ_y** **$\Delta y'_{cm}$(rms) < 0.05 $\sigma_{y'}$**

- **Disturbance periods >> experiment time (day(s) or more):**

  Realigning experiment apparatus is a possibility

- **Sudden beam jumps or spikes can be bad even if rms remains low**

  Peak amplitudes can be **> x5** rms level

Beam Stability Time Scales – cont.

Most demanding stability requirements:

- Orbit disturbance frequencies approximately bounded at high end by data sampling rate and a low end by data integration and scan times

  ⇒ **noise not filtered out**

Data acquisition time scales:

- Most experiments average for 100 ms or more
- Some experiments average over much shorter times (e.g. 100 kHz)

  ⇒ **sensitive to synchrotron oscillations (~10 kHz)**

- Acquisition rates are increasing, averaging times decreasing

  MHz for turn-turn measurements

  single-shot acquisition for pulsed sources (e.g. pump-probe)

Stability Tolerances

- Tolerance budget for electron beam parameters contributing to instability of a specific photon beam parameter can be derived from stability sensitivities, assuming random uncorrelated effects:

$$\sqrt{\sum_{i=1}^{n}\left(\frac{p_{tol}}{p_{sen}}\right)_i^2} < 1$$

p_{tol} = tolerance for parameter p, p_{sen} = sensitivity to parameter p

- e.g., to obtain <0.1% intensity stability, must reduce tolerances for orbit, beam size and energy stability below their sensitivity levels by ~$1/\sqrt{3}$ (0.57)

- Can increase tolerance for difficult parameters by reducing tolerance for easy parameters

Some Electron Orbit- and Size-Perturbing Mechanisms

Long term (weeks-years):

- ground settlement (mm)
- seasonal ground motion (< mm, sometimes more)

Medium term (minutes-days):

- diurnal temperature (1-100 μm)
- crane motion (1-100 μm)
- fill patterns (1-100 μm)
- coupling changes
- river, dam activity (1-100 μm)
- machine fills (heating, BPM intensity dependence)
- RF drift (microns)
- gravitational earth tides (ΔC = 10-30 μm)

Short term (milliseconds-seconds):

- ground vibration, traffic, trains, etc. (< microns, <50 Hz typ)

  ground motion amplified by girder + magnet resonances (x~20 if not damped) and by lattice (x ~5+)

  ⇒ **nm level ground motion can be amplified close to μm level**

- cooling water vibration (microns)
- booster operation (microns)
- power supplies (microns)
- rotating machinery (air conditioners, pumps) (microns)
- insertion device changes (1-100 μm)
- vac chamber vibration from BL shutters, etc. (microns)

High frequency (sub-millisecond):

- high frequency PWM and pulsed power sources (microns)
- synchrotron oscillations (1-100 μm)
- single- and multibunch instabilities (1-100 μm)

Intensity Stability

Want high level of flux (F) constancy through aperture or steering accuracy to hit small sample **(sample size on order of beam size σ)**

$\Delta F/F < 10^{-3}$ (typical)

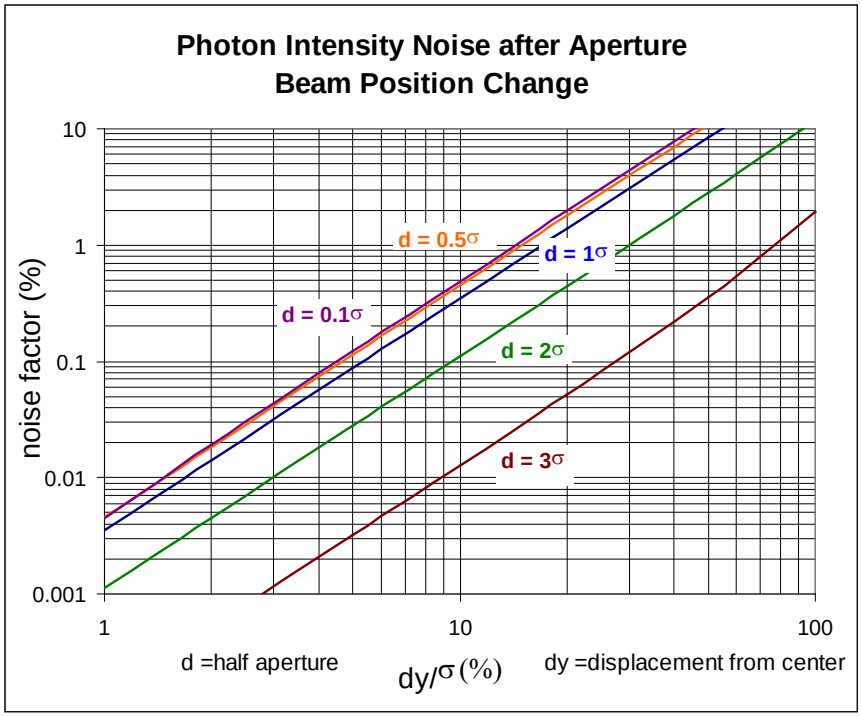
Note: some experiments require $< 10^{-4}$ flux constancy

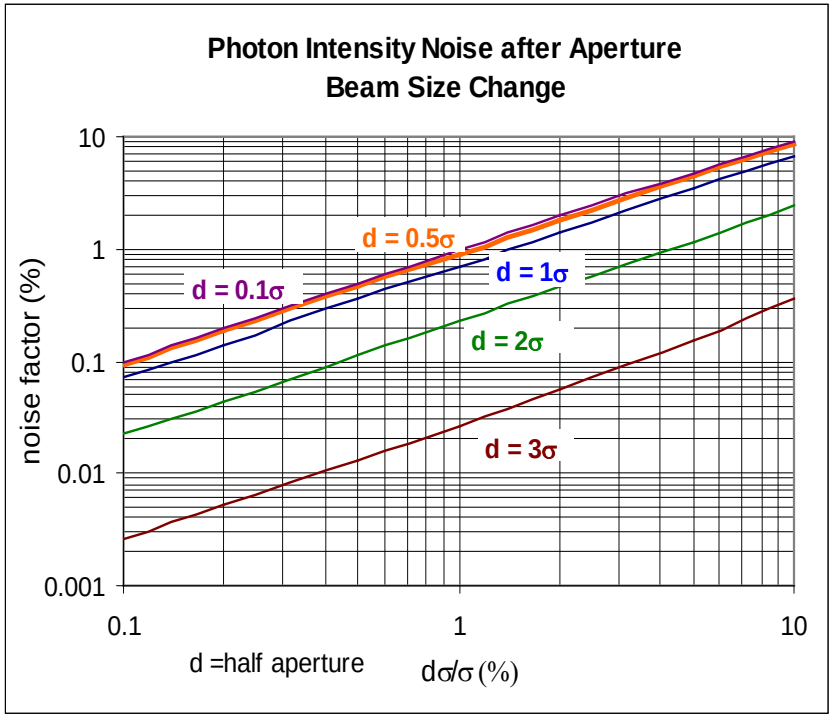
e.g. **photoemission electron spectroscopy combined with dichroism spectroscopy (subtractive processing of switched polarized beam signals)**

Flux variations caused by

- orbit instability
- beam size instability
- energy instability
- other

Intensity Stability after Apertures





Intensity variations for beam with Gaussian size σ due to position motion dy from the center and beam size change dσ for various sized apertures.

Noise factor (position) = $|F_0-F_{dy}|/F_0$ **~ dy^2**

For noise factor (intensity stability) <0.1%:

$dy < 5\% \sigma_y$ (<1.5% σ_y for 0.01% stability)

Noise factor (size) = $|F_{\sigma 0}-F_{\sigma 0+d\sigma}|/F_{\sigma 0}$ **~ $d\sigma$**

For noise factor <0.1%:

$d\sigma < 0.1\% \sigma_y$ (<0.01% σ_y for 0.01% stability)

Note: 4GSR beam size may be small enough to eliminate small apertures, relaxing beam position and size stability requirements.

Photon Energy Stability and Resolution

Photon energy resolution after monochromator: <10^{-4} – 10^{-5}

- Angle of incidence on monochromator
- Beam size on dispersive monochromator
- other…

$$\frac{\Delta E_{ph}}{E_{ph}} = \frac{\Delta\theta}{\theta_B} \Rightarrow \Delta y'_{cm} < \sim 1\text{-}10\ \mu\text{rad}$$

Undulator line energy and width

•Line wavelength = $\lambda_n = n\,\lambda_u(1+k^2/2)/2\gamma^2 \Rightarrow d\,\lambda_n/\lambda_n = -2\,\Delta E/E$

•Natural line width = $\delta\,\lambda_n/\lambda_n = 1/Nn$ (N = # periods, n = harmonic)

Undulator energy affected by:

- Synchrotron oscillations
- RF frequency stability and phase noise
- Orbit through ID
- other…

- for **<10%** line width increase (N = 100, n = 7)
  $\Rightarrow \Delta E/E\ (\text{rms}) < \sim 3 \times 10^{-4}$
- for **<10^{-4}** coherent energy shift (N = 100, n = 7)
  $\Rightarrow \Delta E/E\ (\text{coherent}) < \sim 7 \times 10^{-5}$

Note: for 10^{-5} resolution

$\Rightarrow \Delta E/E\ (\text{coherent}) < \sim 7 \times 10^{-6}$

($\Rightarrow$ $\Delta\phi < 0.01^{o}$ for SPEAR 3)

Timing and Bunch Length Stability

Bunch time-of-arrival stability (Δt_{bunch}):

Δt_{bunch} < ~0.1 of critical time scale in experiment **(pump-probe sync, etc.)**

- or -

Δt_{bunch} < ~0.1 bunch length

whichever is larger

(bunch length = ~10-100 ps for rings, 10-100 fs for linac FELs and ERLs)

Time-of-arrival variations caused by energy oscillations:

$$\Delta t_{bunch} = \frac{\Delta\phi\ (\mathrm{rad})}{\omega_{rf}} = \frac{\alpha_c}{\Omega_s}\frac{\Delta E}{E}(\mathrm{coher}) \quad \Rightarrow$$

$\Delta E/E$ (coherent) < 2 x 10^{-5} for SPEAR3

< 2 x 10^{-3} for APS-U

Bunch length variations associated with changes in energy spread cause beam size variation:

$\Delta E/E$ (rms) < 10^{-3} $\Rightarrow$ $\Delta\sigma_{bunch}$ < 5% σ_{bunch}

Source Stability Relationships

Can derive basic some basic relationships experimental observables and beam properties based simple (1st-order) dependencies (-- = 2nd order):

parameters	e- orbit	e- size/ rotation	e- energy/ energy spread (& RF stability)	ID field (esp EPUs)
intensity (pointing, beam size, emission)	x	x	x	x
energy and energy resolution	x	x (dispersive monos)	x	x
timing, bunch length	-- (pseudo 1-bunch?)	x	x	--
polarization	x (dipole, EPU)	--	--	x
coherent fraction	--	x	x ID high harmonics	--

Not included: accelerator lattice stability, lifetime stability, other

User observable - electron observable sensitivity matrix

M. Green, Aladdin

Requirement	User Observables	Photon Beam Observables								
		x	y	x′	y′	θ_z (coupling)	σ_x	σ_y	$\delta z, \delta t$	$\delta\epsilon$
	Throughput									
	Energy									
	Shift									
	Spread									
	Image									
	x									
	y									
	σ_x									
	σ_y									
	Timing									
	Polarization									

Beam Stability Requirements - Summary

(subject to change after DLSR '14 Workshop)

Parameter	Present	Future trend
intensity stability	< 0.1%	< 0.01%
steering accuracy	< 5-10% σ_{e-}, σ'_{ph}	< 2% σ_{e-}, σ'_{ph}
beam size stability	< few % σ_{ph}	< 0.1% σ_{ph}
energy resolution	10^{-4}	10^{-5}
timing stability	< 10% bunch length	< 10% bunch length
min data avg time	order 1 ms	order 0.1 ms (ring) single shot (FEL)
emittance	~5-20 nm-rad	~0.05-0.2 nm-rad
e- beam size (vert)	~30-300 μm	~3-30 μm
ph beam divergence	~10-200 μrad	~0.5-10 μrad
e- bunch length	~10-100 ps	1-100 fs (FEL)
e- position stability (vert)	~1-5 μm	~0.1-1 μm
e- angle stability	~1-10 μrad	~0.05- 0.5 μrad
e- bunch length stability	~1-10 ps	~10-100 fs (FEL)
e- energy stability	< 10^{-4} ($\Delta\phi < 0.1^{o}$)	< 5 x 10^{-5}

Conclusion

Storage ring stability requirements are stringent:

- intensity stability < 0.1%
- pointing accuracy < 5% beam dimensions
- photon energy resolution < 10^{-4}
- timing stability < 10% bunch length

Requirements are becoming more difficult to meet for 4GSRs:

x 5-10 more stringent stability

- faster data acquisition time-scales
- fast-switched polarization, ID changes
- short bunch and other special operating modes

Stability that can be reached by mechanical design alone is limited:

- feedback is ultimately needed for accelerator and beam line components (integrated)
- demands for passive stability can be relaxed, possibly resulting in a lot of cost savings in facility construction

1 μm