Beam Quality and Lifetime

Introduction

Brilliance

Machine Stability

Apertures and Acceptance

Lifetime

Beam Instabilities

Introduction

User Requirements

Stable, **long lived** and **tuneable brilliant light**.

These are conflicting requirements.

High brilliance means small photon spot sizes and reduced costs and tolerances o optical elements.

Long lifetime means constant heat-load on optical elements giving stability and improve quality of experiments.

Lifetime is a key issue since high brilliance leads to lower lifetimes. Brilliance is ofte compromised for increased lifetime in VUV and soft X-ray machines. This is less of problem for high energy machines.

Third generation synchrotron radiation facilities are characterized by the use of insertio devices as their main source of photons.

These devices affect the dynamic aperture and impose small physical apertures, bot which affect the lifetime.

They also need stability of the electron beam to be fully exploited.

Introduction - Brilliance

Requires low emittance - Conflicts with long lifetime
- Increased Touschek effect & Intra-Beam Scattering

Low Emittance needs strong focusing quadrupoles
- Worsens the effects of machine misalignments (coupling, dispersion, COD's)
- Large chromatic effects and small dispersion which need strong sextupoles
  - Tune dependence on amplitude
  - Smaller momentum acceptance
  - Reduction in dynamic aperture

Increase Brilliance by using smaller insertion device gaps and longe devices
- Reduction in gas scattering lifetime
- Reduction in dynamic aperture and increased optics distortions
- Increase in resistive wall effect

Increase current
- Easily reach thresholds for instabilities
- Increased out-gassing
- Reduced lifetime (Touschek and Gas scattering)
- Frequent refills

Good closed orbit
- Needs good stability

Introduction - Lifetime

Long lifetime conflicts with Brilliance

Reduce the Touschek effect and Bremsstrahlung scattering
Large momentum acceptance => Adequate RF and off momentum dynamic aperture

Reduce Elastic scattering off residual gas
Good vacuum
Design vacuum chamber to reduce "out-gassing"

Have a large dynamic aperture
Careful construction of linear elements
Reduce the non-linear effects of ID's =>
- Reduce construction errors
- Increase transverse width of poles
- Appropriate lattice functions

Use many families of sextupoles

Eliminate ion/dust trapping
Good Vacuum, Careful design of ID vacuum chambers

Combat Multi-bunch Instabilities

Long lifetime also means increased component reliability

Introduction - Stability & Reproducibility

Mechanical Stability

Appropriate Choice of Site.
Uncouple storage ring from experimental area.
Place magnets on supports which do not amplify ground vibrations.

Thermal stability

Longer lifetime lessens heat load effects.
Temperature regulation of ring environment.
Temperature regulation of service area.

Magnetic Stability

Full energy injection.
Tight tolerances on power supplies, both short and long term.

Reduce closed orbit distortions when changing ID gaps

Good magnetic field performance of ID's

Eliminate beam instabilities

Careful design of vacuum chamber and RF cavities

Eliminate ion trapping

Good vacuum
or Use positrons (costly)

Use Feedback systems

Transverse Global and Local
Longitudinal

Brilliance and Flux

Brilliance

The brilliance is the phase space density of photon flux evaluated in the forward directio and at the centre of the source:

$$B = \left. \frac{d^4 F}{d\theta\, d\phi\, dx\, dy} \right|_0 \qquad F = \frac{dN}{dt}$$

Integration in either angle or space gives the angular and spatial flux densities:

$$\frac{d^2 F}{d\theta\, d\phi} = \int \frac{d^4 F}{d\theta\, d\phi\, dx\, dy} \cdot dx\, dy$$ Intensity/Brightness

$$\frac{d^2 F}{dx\, dy} = \int \frac{d^4 F}{d\theta\, d\phi\, dx\, dy}\, d\theta\, d\phi$$

If we are interested in a small energy range about a given photon energy, then dividin by $d\omega/\omega$ we obtain the **spectral brilliance** and **spectral flux**.

$$B = \frac{Number\ of\ \ photons}{[\sec]\,[mm^2]\,[mrad^2]\,[0.1\%\ bandwidth]} \qquad F = \frac{Number\ of\ \ photons}{[\sec]\,[0.1\%\ bandwidth]}$$

Brilliance

A systematic approach to calculate the brilliance is to compute the intensity of the electri field of a single electron and convolute it with the probability distribution function of the electrons:

$$B = \int B_{e^-} \cdot \eta \, dV$$

Brilliance of a single e⁻

Probability distribution function of e⁻

Consider the photons to be particles rather than waves with a Gaussian distribution in spatial and angular coordinates, then:

$$B = \frac{1}{d\omega/\omega} \frac{\boxed{F}}{\boxed{4\pi^2 \, \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}}$$

Flux in the forward direction

phase space volume of the photons

Σ are the spatial and angular standard deviations of the photons in the two planes.

Σ are the convolution of the electron beam distribution $\sigma_{xyx'y'}$ and that of the photo distribution from a single electron $\sigma_{rr'}$

$$\Sigma_{xy} = \left(\sigma_{x,y}^2 + \sigma_r^2\right)^{1/2} \qquad \Sigma_{x'y'} = \left(\sigma_{x',y'}^2 + \sigma_{r'}^2\right)^{1/2}$$

Brilliance

The brilliance is an invariant and can be considered as an emittance.
It obeys Liouvilles theorem and is conserved by linear transformations.
Optical elements in the beam line propagate the brilliance from one point to another:

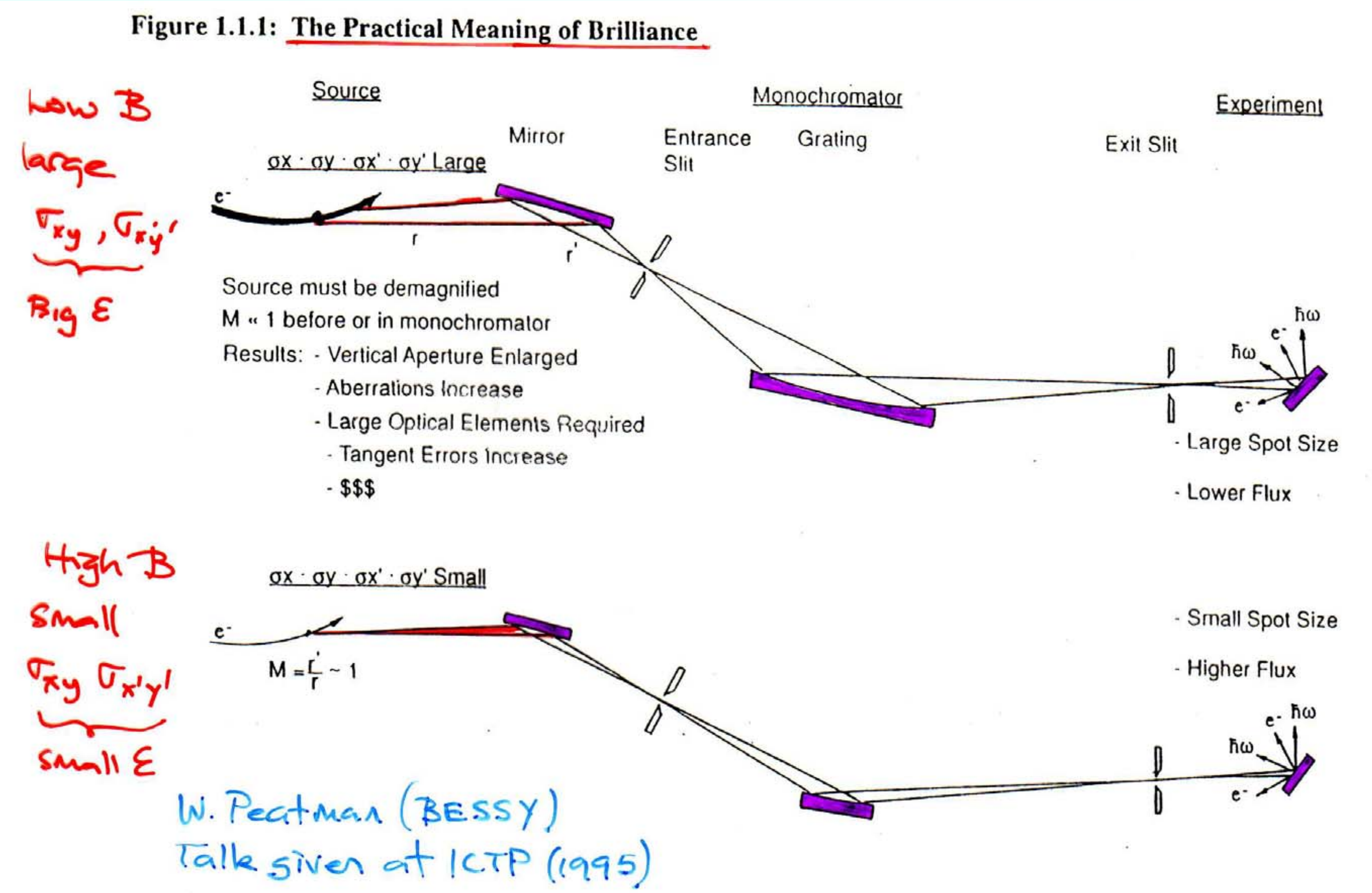
$$B_1 = \mathbf{M} B_0 \qquad \mathbf{M} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \; or \; \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$$

Emittance is area in phase space - the product of divergence and size

Objective: a small photon spot size on sample

Large ε -> Large photon beam divergence -> large optics (costs, aberrations, errors, etc..)

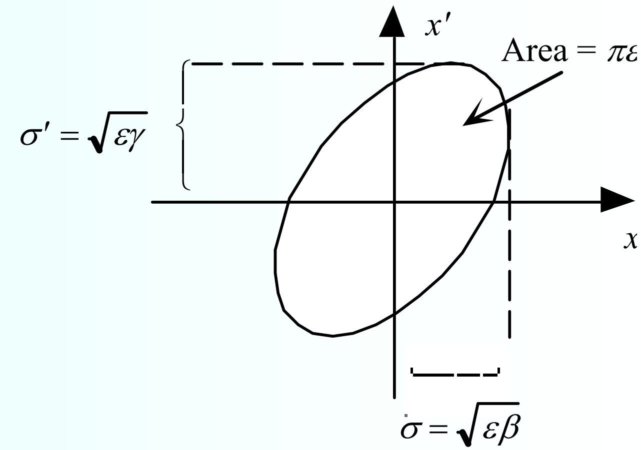
The practical meaning of Brilliance



Source Sizes - Electrons

The electron beam sizes and divergences are given by the beam emittance and the Courant-Synder parameters (properties of the lattice).

$$\sigma_x = \sqrt{\beta_x \varepsilon_x} \qquad \sigma_{x'} = \sqrt{\gamma_x \varepsilon_x} \qquad \gamma_x = \frac{1+\alpha^2}{\beta}$$



The natural electron beam emittance is determined by radiation damping, quantum emission and intra-beam scattering. Beam distribution is Gaussian in the six dimensions.

Storage rings are flat and dispersion exists in the horizontal plane.

$$\sigma_x = \sqrt{\beta_x \varepsilon_x + D^2 \left(\frac{\Delta p}{p}\right)^2} \qquad \sigma_{x'} = \sqrt{\gamma_x \varepsilon_x + D'^2 \left(\frac{\Delta p}{p}\right)^2}$$

i.e., beam size is a convolution,

$$\sigma_x^2 = \sigma_\beta^2 + \sigma_{\Delta p/p}^2$$

Source Sizes - Electrons

The vertical emittance for a lattice with no errors or coupling is ~10^{-4} nmrad.
A real lattice has errors that couples the horizontal and vertical emittances.

Errors: quadrupole roll, vertical closed orbit displacements in sextupoles.

Define an emittance ratio g: $g = \frac{\varepsilon_y}{\varepsilon_x}$ with $\varepsilon_0 = \varepsilon_x + \varepsilon_y$

$$\Rightarrow \varepsilon_y = \frac{g}{1+g}\varepsilon_0 \quad \text{and} \quad \varepsilon_x = \frac{1}{1+g}\varepsilon_0$$

ε_0 is the emittance in the absence of coupling.
g is typically 0.1 to 3% in 3rd generation light sources

Vertical beam size and divergence: $\sigma_y = \sqrt{g\varepsilon_x\beta_y}, \ \sigma_{y'} = \sqrt{g\varepsilon_x\gamma_y}$

Beamlines use the vertical plane as the dispersive plane - monochromators have better resolution. Important to conserve vertical emittance.

Source Sizes - Photons

The size and divergence of the photon beam from a single electron satisfies the condition:

$$\sigma_r \sigma_{r'} = \frac{\lambda}{4\pi}$$

Where λ is the radiation wavelength.
The product is the diffraction limited emittance.

For a **bending magnet** the vertical opening angle is:

$$\sigma_{r'} = \frac{560}{\gamma}\left(\frac{\lambda}{\lambda_c}\right)^{0.43} [\mathrm{mrad}]$$

For $0.2\lambda_c < \lambda < 100\lambda_c$

Since $\Sigma_y = \sqrt{\sigma_y^2 + \sigma_r^2}$,

If $\sigma_r > \sigma_y$ a there is no increase in brilliance from a reduction in electron beam emittance.

Source Sizes - Photons

Plane **undulator** emits radiation at harmonic (k) frequencies:

$$\omega_k = \frac{\omega_0\, 2\, k\, \gamma^2}{\left(1 + K^2/2 + \gamma^2\theta^2\right)}$$

$$\omega_0 = \frac{2\pi c}{\lambda_0}$$

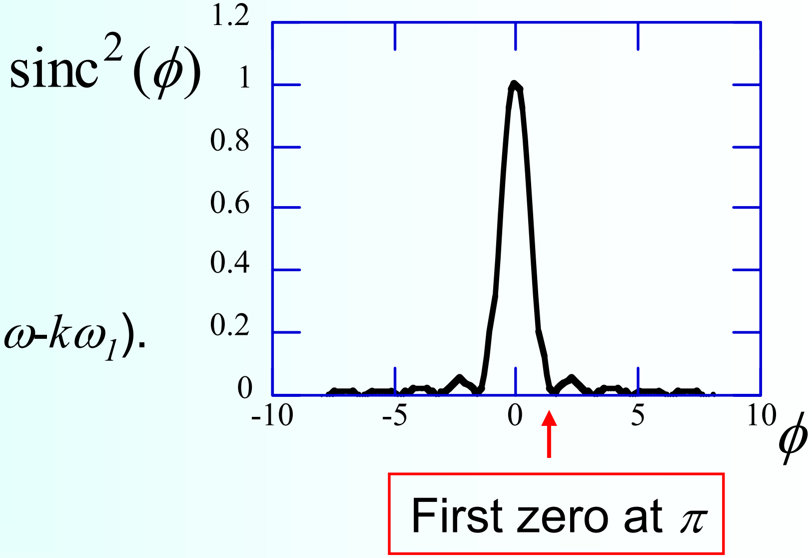
λ_0	length of undulator period
γ	relativistic factor E/m_0c^2
K	magnetic field strength parameter 0.934 B[T]λ_0[cm]
θ	observation angle with respect to the closed orbit

The intensity of the light at the end of the undulator is given by the interference of the beamlets from each deflection point.

The intensity has a sinc function dependence.

Source Sizes - Photons

$$I \propto \mathrm{sinc}^2\left(N\pi\frac{\Delta\omega}{\omega_1(\theta)}\right)$$



N is the number of periods
ω_1 is the frequency of the first harmonic, $\Delta\omega=(\omega-k\omega_1)$.
Writing,

$$\frac{\omega}{\omega_1(\theta)}=\frac{\omega}{\omega_1(0)}\left(1+\frac{\gamma^2\theta^2}{1+K^2/2}\right)$$

Near the location of the *k*'th harmonic, i.e., at $\omega/\omega_1(0)=k$, sinc² ~ Gaussian.

$$\mathrm{sinc}^2\left(\frac{N\pi\omega}{\omega_1(\theta)}\right)\approx \mathrm{sinc}^2\left(\frac{N\pi k\gamma^2\theta^2}{1+K^2/2}\right)\approx \exp\left(\frac{-\theta^2}{2\sigma_{r'}^2}\right)$$

Source Sizes - Photons

To determine the opening angle of the radiation, fit sinc^2 to the Gaussian to have the same integrated intensity.

$$\sigma_{r'} \sim \frac{1}{2\gamma}\sqrt{\frac{1+K^2/2}{kN}} = \sqrt{\frac{\lambda}{2L}}\Bigg|_{\substack{forward\ direction \\ \theta=0}}$$

Where $L=N\lambda_0$ is the undulator length and λ the radiation wavelength.
The opening angle is about $(kN)^{1/2}$ smaller than that from a bending magnet $\theta \sim \gamma^{-1}$.
The photon source size is.

$$\sigma_r \sigma_{r'} = \frac{\lambda}{4\pi} \quad \Rightarrow \quad \sigma_r = \frac{\sqrt{\lambda L}}{2\sqrt{2}\,\pi}$$

Taking the limit of $N \to \infty$

$$\mathrm{sinc}^2\left(\frac{N\pi\Delta\omega}{\omega_1(\theta)}\right) \to \frac{1}{N}\delta\left(\frac{\Delta\omega}{\omega_1(\theta)}\right) = \frac{1}{kN}\delta\left(\frac{\Delta\omega}{\omega-\Delta\omega}\right) \sim \frac{1}{kN}\delta\left(\frac{\Delta\omega}{\omega}\right)$$

Gives the natural line width for the k'th harmonic,

$$\left.\frac{\Delta\omega}{\omega}\right|_{\theta=0} \sim \frac{1}{kN}$$

Source Sizes - Photons

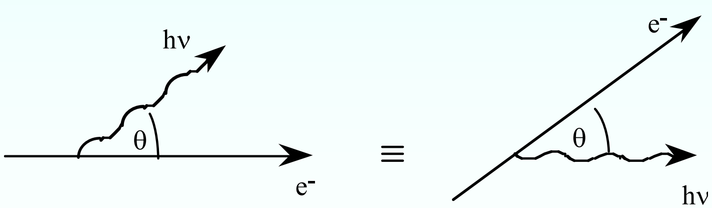
Dependence on viewing angle and beam energy

$$\left.\frac{\Delta\omega}{\omega}\right|_{\theta\sim 0} \sim \frac{\gamma^2\Delta\theta^2}{1+K^2/2} \qquad\qquad \left.\frac{\Delta\omega}{\omega}\right|_{\theta\sim 0} = 2\,\frac{\Delta\gamma}{\gamma}$$

Full bandwidth of k'th harmonic is convolution of these three effects

$$\left(\frac{\Delta\omega}{\omega}\right)_{\Delta\theta,\Delta\gamma} \sim \left[\left(\frac{1}{kN}\right)^2 + \left(\frac{\gamma^2\Delta\theta^2}{1+K^2/2}\right)^2 + 4\left(\frac{\Delta\gamma}{\gamma}\right)^2\right]^{1/2}$$

For fixed γ, to keep linewidth comparable to the natural width $\Delta\theta \sim \sigma_{r'}$
However, not possible to distinguish the source of photons in $\Delta\theta$,



$$\left(\frac{\Delta\omega}{\omega}\right)_{\Delta\sigma_{x,y},\Delta\gamma} \sim \left[\left(\frac{1}{kN}\right)^2 + \left(\gamma^2\left(\sigma_{x'}^2+\sigma_{y'}^2\right)\right)^2 + 4\left(\frac{\Delta\gamma}{\gamma}\right)^2\right]$$

Affected by closed orbit
Stability and coupling

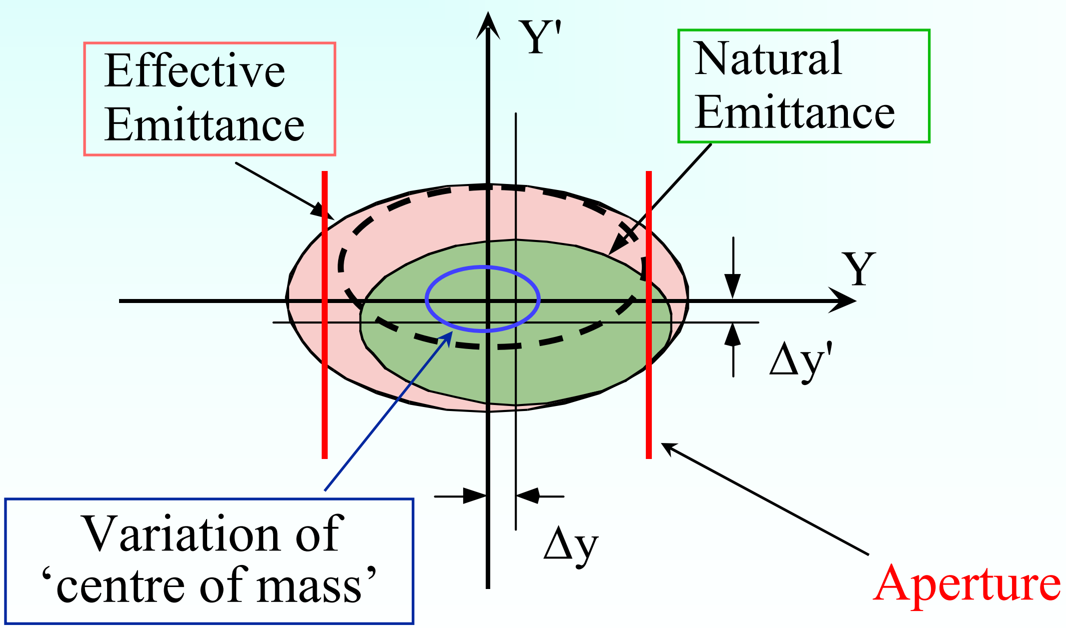
Affected by
multibunch
instabilities

Motion and Apertures

The source point is the centre of an insertion device.
The lattice functions usually have a waist at that point and usually have zero dispersion.
Then $\alpha=0$, $\gamma=1/\beta$ and

$$\varepsilon_{x,y} = \sigma_{x,y}\sigma_{x',y'}$$

Beam movement Δy, $\Delta y'$ produces an effective increased source emittance.
Behaviour of the disturbance at the source is described by an invariant ε_{cm}.



Motion and Apertures

A beamline is composed of masks, collimators, mirrors, slits, monochromators.
These define an aperture for the photon beam.
Motion with respect to the beamline aperture can result in a reduction of intensity and/or energy resolution.

Focused beam: on slits or pinhole matched to the beam size or smaller.
Consider a symmetric 2D Gaussian photon intensity distribution, 3σ ~ 99% of photons.

Fraction of beam in radius $r = 1 - \exp(-r^2/2\sigma^2)$

If aperture is ±3σ and beam is miss-steered by 10% σ, reduction in flux is 0.01%

If aperture is ±2σ and beam is miss-steered by 10% σ, reduction in flux is 0.1%

If beam size increases by 10% (~20% emittance), reduction in flux is 1.3% (circular aperture).

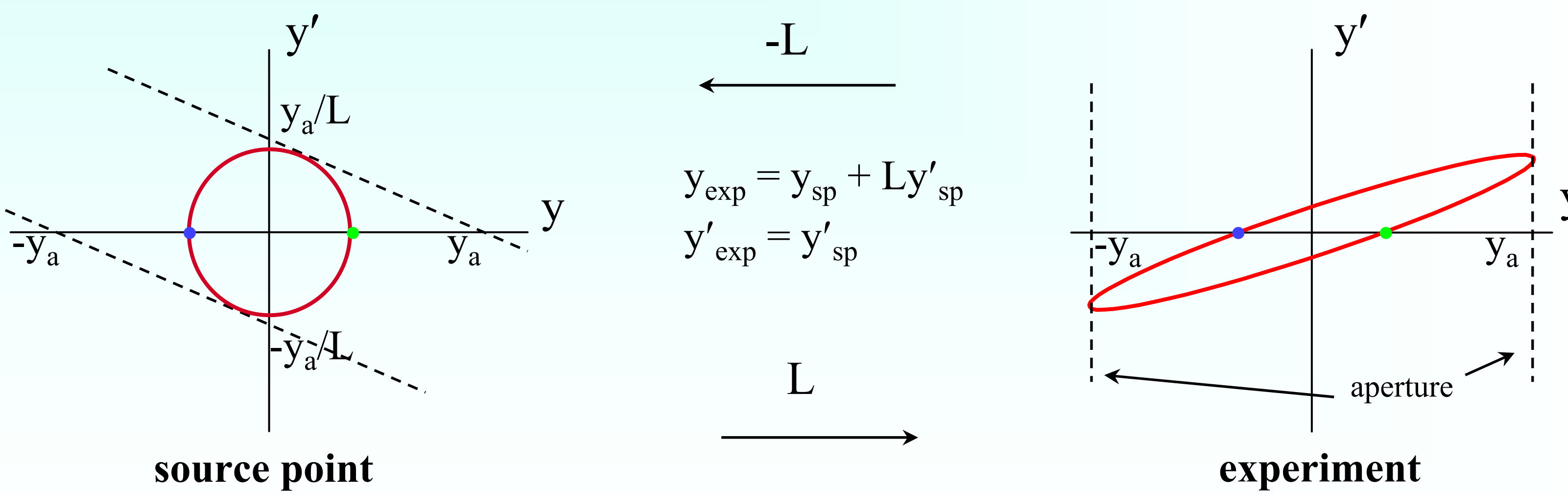
Motion and Apertures

For an **unfocused** beam the divergence dominates.
At a position L meters away from the source the beam size is,

$$\Sigma_y^2(L) = \Sigma_y^2(0) + L^2\Sigma_{y'}^2(0)$$

10% change in angle gives 10% change in beam size.

Changes in angle changes the energy of photons transmitted by a monochromator.



From B. Hettel, SSILS, Shanghai, 2001

Time Scales of Disturbance

- If the time scale of the disturbance is greater than the time to perform an experiment, the result is a simple miss-steering.

  This manifests as an energy calibration error and a loss of intensity.

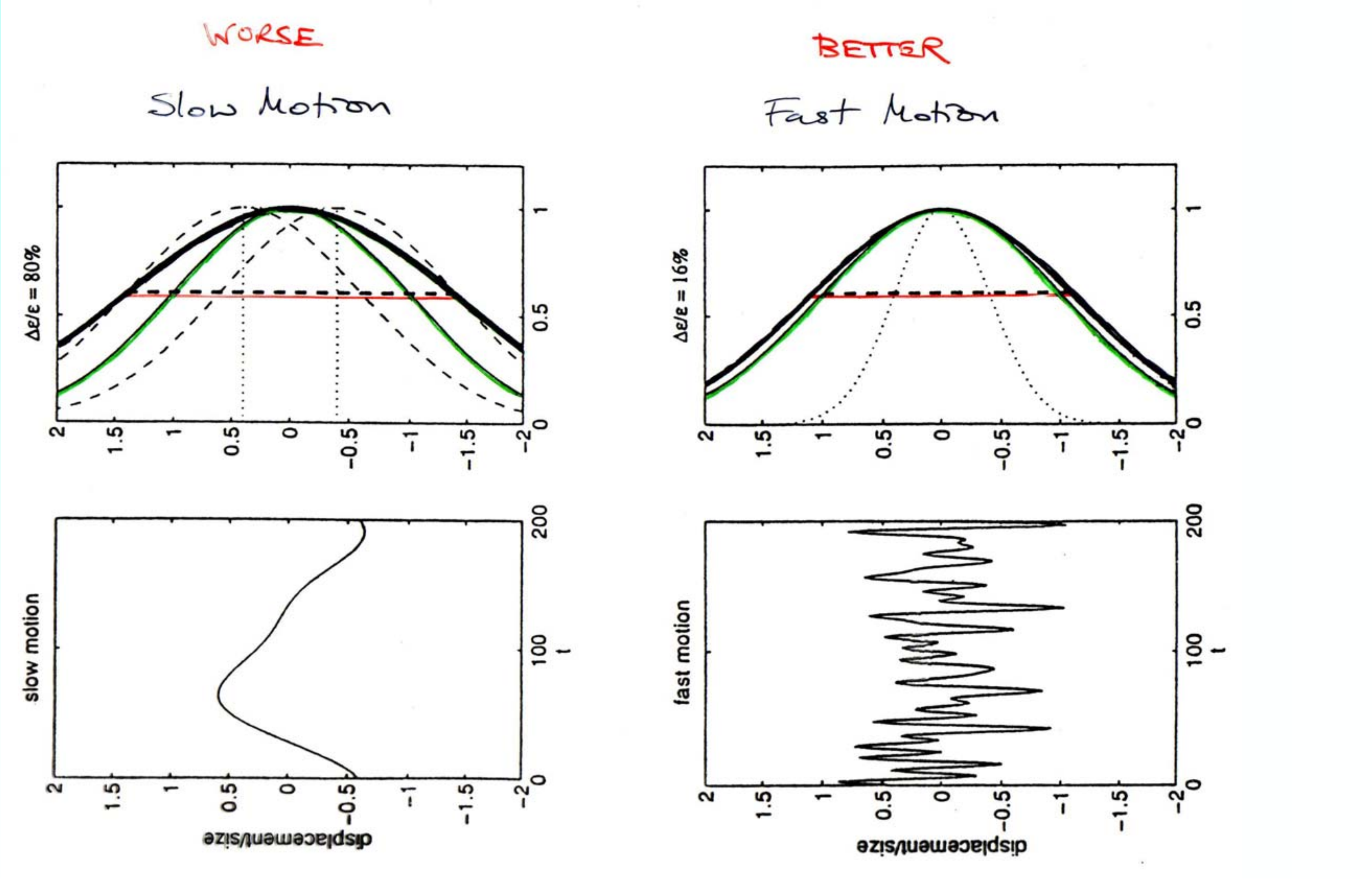
  The emittance increase is: $\frac{\Delta\varepsilon}{\varepsilon} = 2\sqrt{\frac{\varepsilon_{cm}}{\varepsilon_0}}$, $(\varepsilon_{cm} << \varepsilon_0)$

- If the time scale of the disturbance is much faster than the time to perform the experiment, the beam is blurred and there is an effective emittance increase.

  The emittance increase is: $\frac{\Delta\varepsilon}{\varepsilon} = \frac{\varepsilon_{cm}}{\varepsilon_0}$, $(\varepsilon_{cm} << \varepsilon_0)$

The effect is more severe for slow (> 1 sec) motion: a 20% $\Delta\varepsilon$ from Δ_y, $\Delta_{y'}$ ~ 10%
For fast (< 1 sec) motion a 20% $\Delta\varepsilon$ occurs for Δ_y, $\Delta_{y'}$ of ~ 45%

Time Scales of Disturbance



(L. Farvacque, CAS 98-04)

Electron Beam Emittance

To maximise the brilliance we need to reduce the electron beam emittance. However since

$$\Sigma_{xy} = \left(\sigma_{x,y}^2 + \sigma_r^2\right)^{1/2} \qquad \Sigma_{x'y'} = \left(\sigma_{x',y'}^2 + \sigma_{r'}^2\right)^{1/2}$$

If $\sigma_r > \sigma_{x,y}$ and $\sigma_{r'} > \sigma_{x',y'}$ the brilliance is dominated by diffraction effects. This occurs for long wavelengths.

If $\sigma_r < \sigma_{x,y}$ and $\sigma_{r'} < \sigma_{x',y'}$ the brilliance is dominated by the electron beam emittance. For most of the operating machines and those planned the brilliance is dominated by the electron beam.

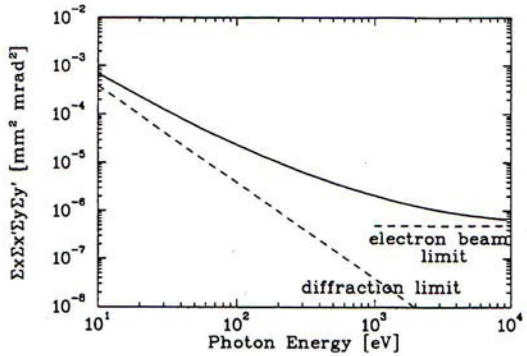


Fig. 13 Product of photon beam emittances in the case of ELETTRA

R.P.Walker, CAS 98-04, 129

For machines of comparable emittance the effect of finte emittance is greater for the higher energy machine since $\sigma_{y'}$ is independent of energy but $\sigma_{r'} \sim \gamma^{-1}$.

Electron Beam Emittance

Finite emittance and energy spread cause broadening of undulator lines and a reduction in flux at fixed frequency.

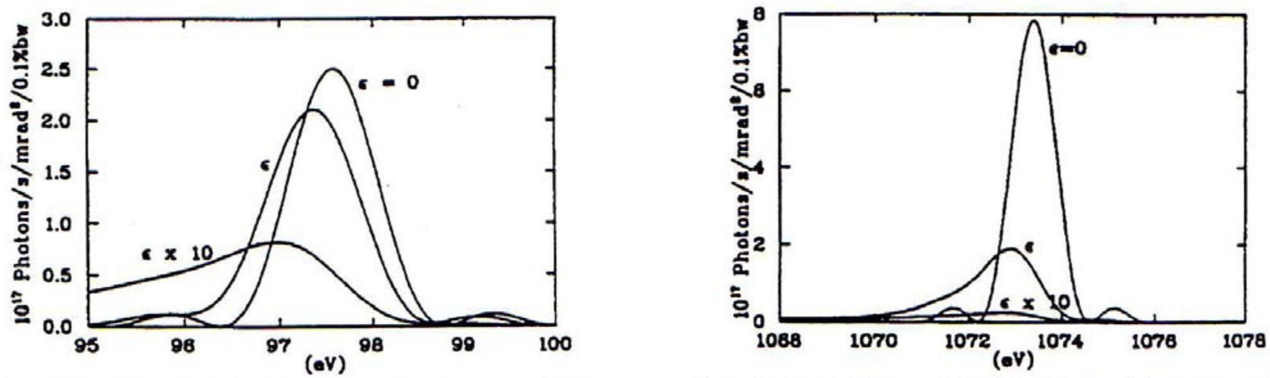


Fig. 17 Effect of electron beam emittance on the 1st (left) and 11th (right) harmonics for an undulator in ELETTRA; E = 2 GeV, λ_o = 56 mm, N = 81, K = 3.45

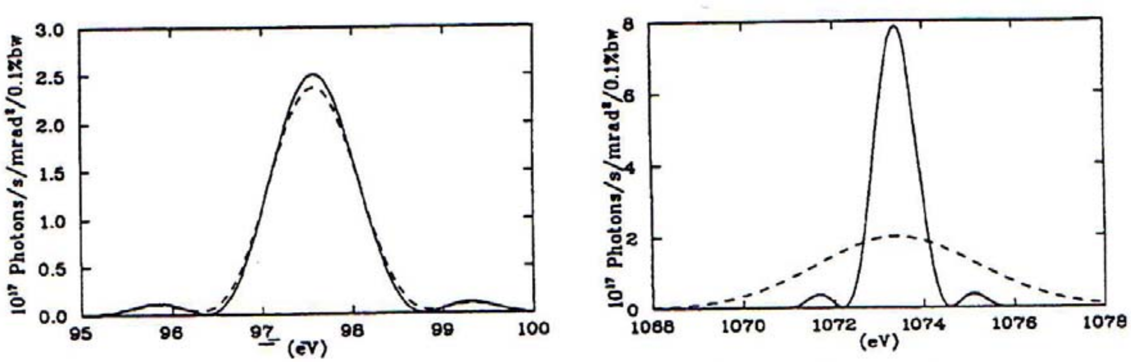


Fig. 18 Effect of electron beam energy spread on the 1st (left) and 11th (right) harmonics for an undulator in ELETTRA; parameters as Fig. 17

R.P.Walker, CAS 98-04, 129

Intensity

The photon beam intensity is proportional to the electron beam current.

Apart from electron beam stability, a loss of intensity at an aperture results from

- The beam lifetime

- Changes in beam size
  - coupling mis-alignments
  - spurious dispersion
  - resonances
    - driven by insertion devices
    - working point close to a coupling resonance

- Instabilities
  - multibunch, transverse and longitudinal
  - ions