M.Bertolo
Sincrotrone Trieste

Introduction to beamline design

This instruction material is based on the

Lecture notes by
W.B.Peatman, BESSY, Berlin - Germany
for the School on the Use of Synchrotron Radiation in Science and Technology
30 October - 1 December 1995, ICTP, Trieste – Italy

and on the book

W.B.Peatman, "Gratings, mirrors and slits: beamline design for soft X-ray synchrotron radiation sources", Gordon and Breach Science Publishers, Amsterdam, 1997

with kind permission from the author

review of the sources of synchrotron radiation

the brilliance

geometrical characteristics of the radiation from the different sources:
- bending magnet
- wiggler
- undulator

gratings

Fermat's principle

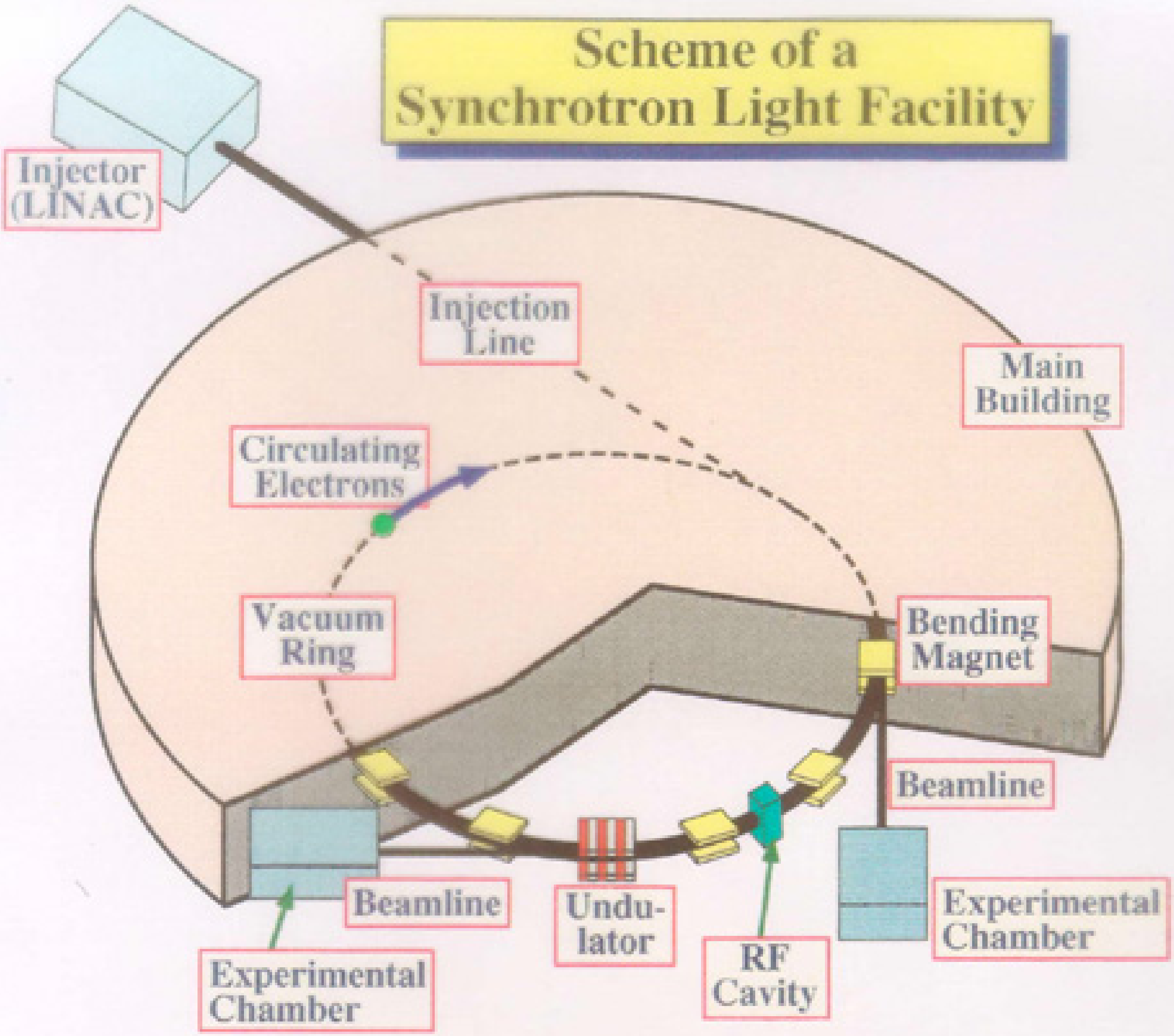
mirrors

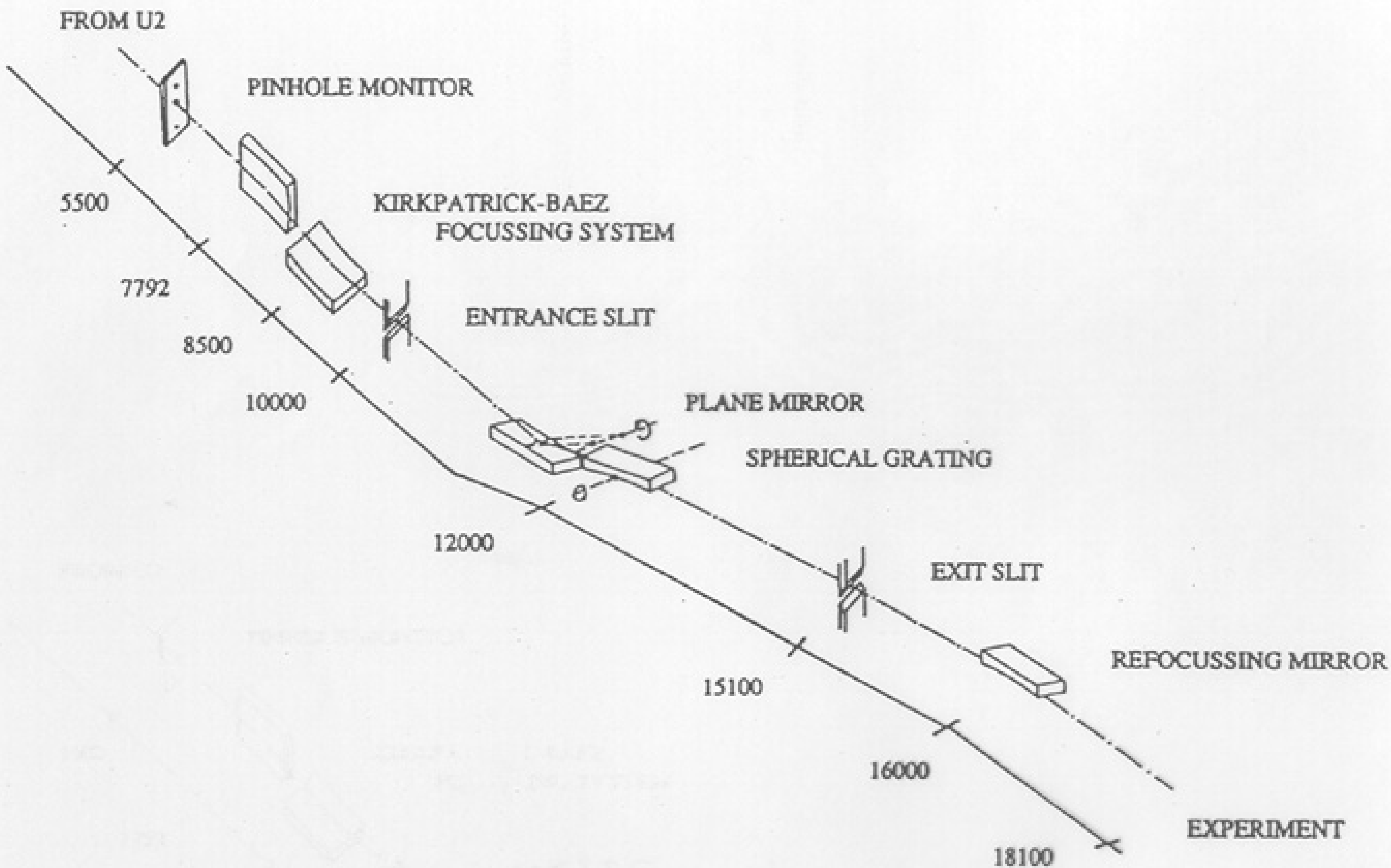
figure accuracy/ heat load on the optical elements

an example of focusing system

guidelines in designing a beamline

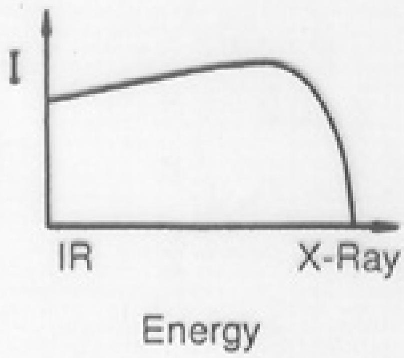
three examples of monochromator/beamlines


Scheme of a
Synchrotron Light Facility
Injector
(LINAC)
Injection
Line
Main
Building
Circulating
Electrons
Vacuum
Ring
Bending
Magnet
Beamline
Beamline
Undu-
lator
Experimental
Chamber
Experimental
Chamber
RF
Cavity


FROM U2
PINHOLE MONITOR
KIRKPATRICK-BAEZ
FOCUSSING SYSTEM
ENTRANCE SLIT
PLANE MIRROR
SPHERICAL GRATING
EXIT SLIT
REFOCUSSING MIRROR
EXPERIMENT
5500
7792
8500
10000
12000
15100
16000
18100

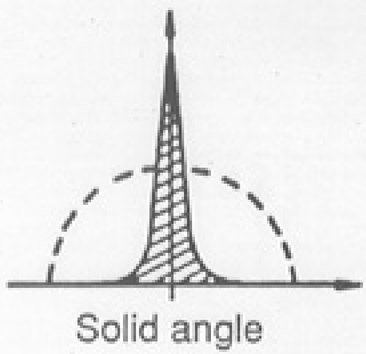
Important Characteristics of Synchrotron Radiation

1)



Continuous
spectrum

2)

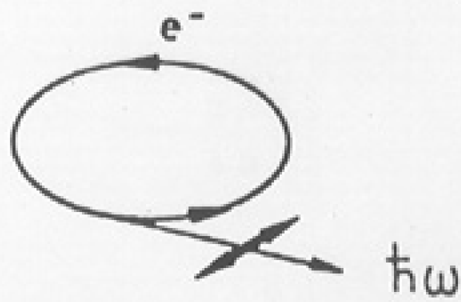


Emission in small
solid angle

3)

Pulsed time structure

4)



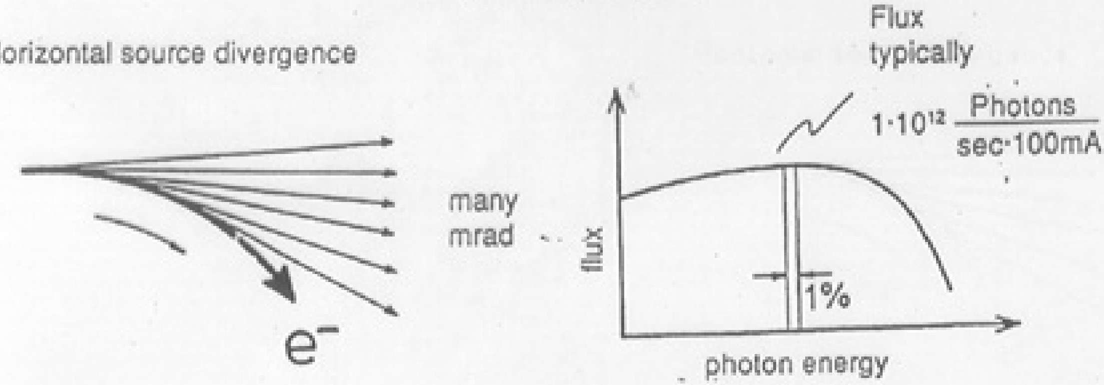
High degree of
polarisation

5) Properties can be calculated/predicted

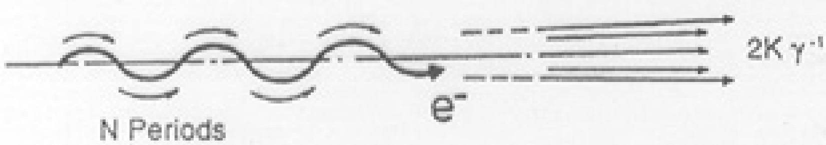
Synchrotron Radiation Sources

Dipole Magnet

Horizontal source divergence



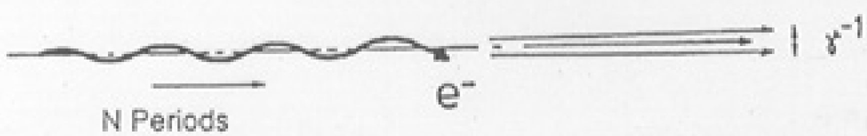
Wiggler



SR-collimated

Intensity N times that of a dipole source with the same number of mrad

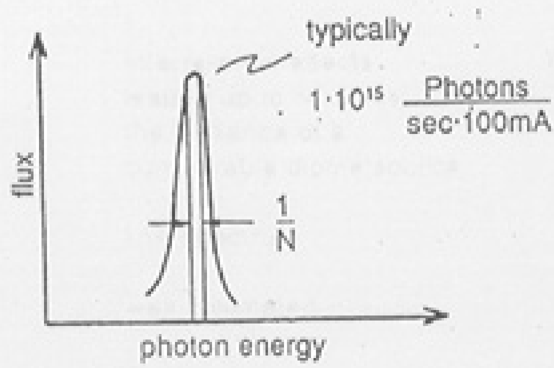
Undulator



Interference effects lead to up to N^2 times the brilliance of a comparable dipole source

line spectrum

well collimated



Flux = photons/sec

Brilliance (or Brightness) = $\dfrac{\text{Flux}}{\text{I}} \dfrac{1}{s_x s_y s'_x s'_y \,\text{BW}}$

I = electron current in the storage ring

$\sigma_x\sigma_y$ = the area from which the SR is emitted

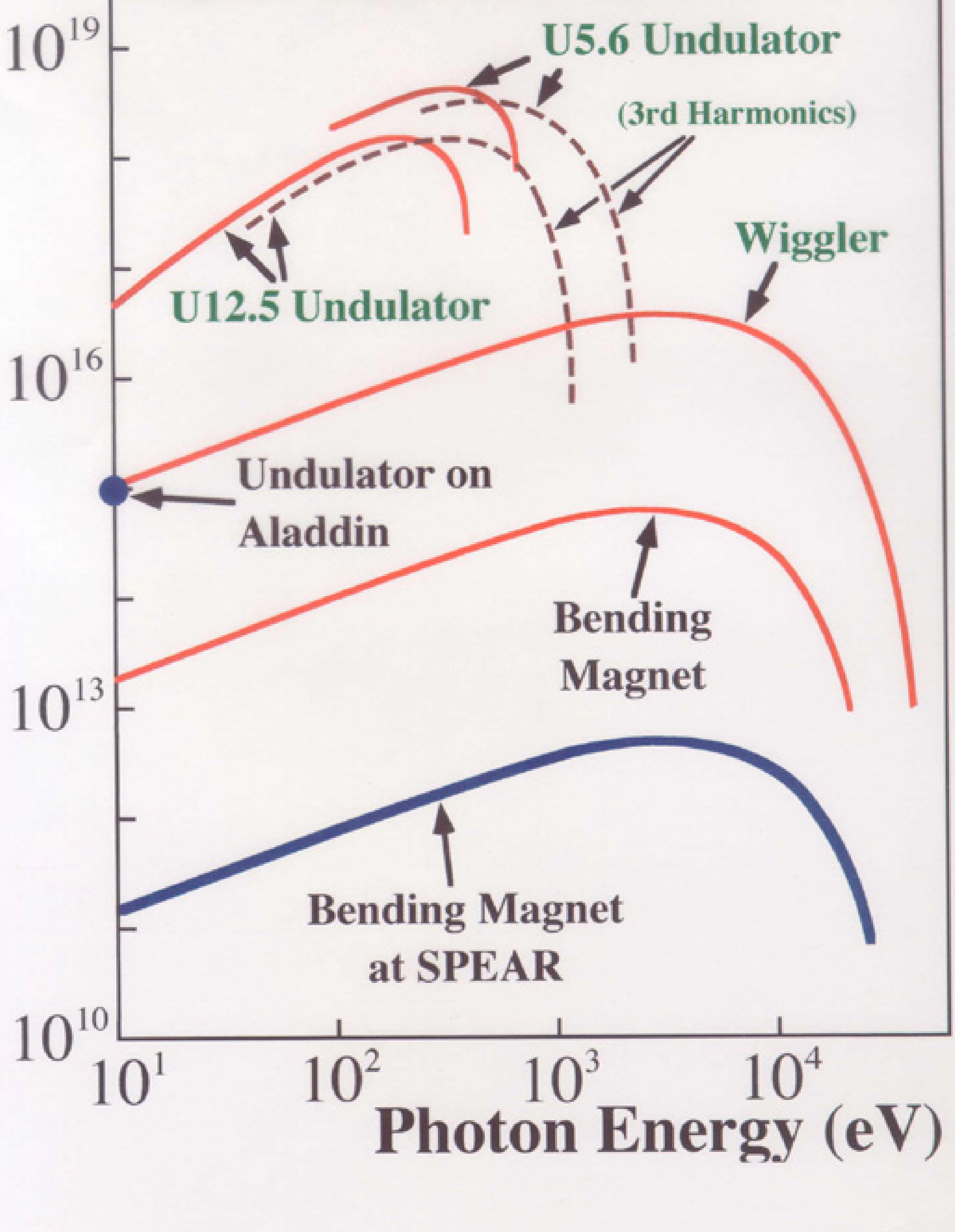
$\sigma'_x\sigma'_y$ = the solid angle into which the SR is emitted

BW = photon energy bandwidth

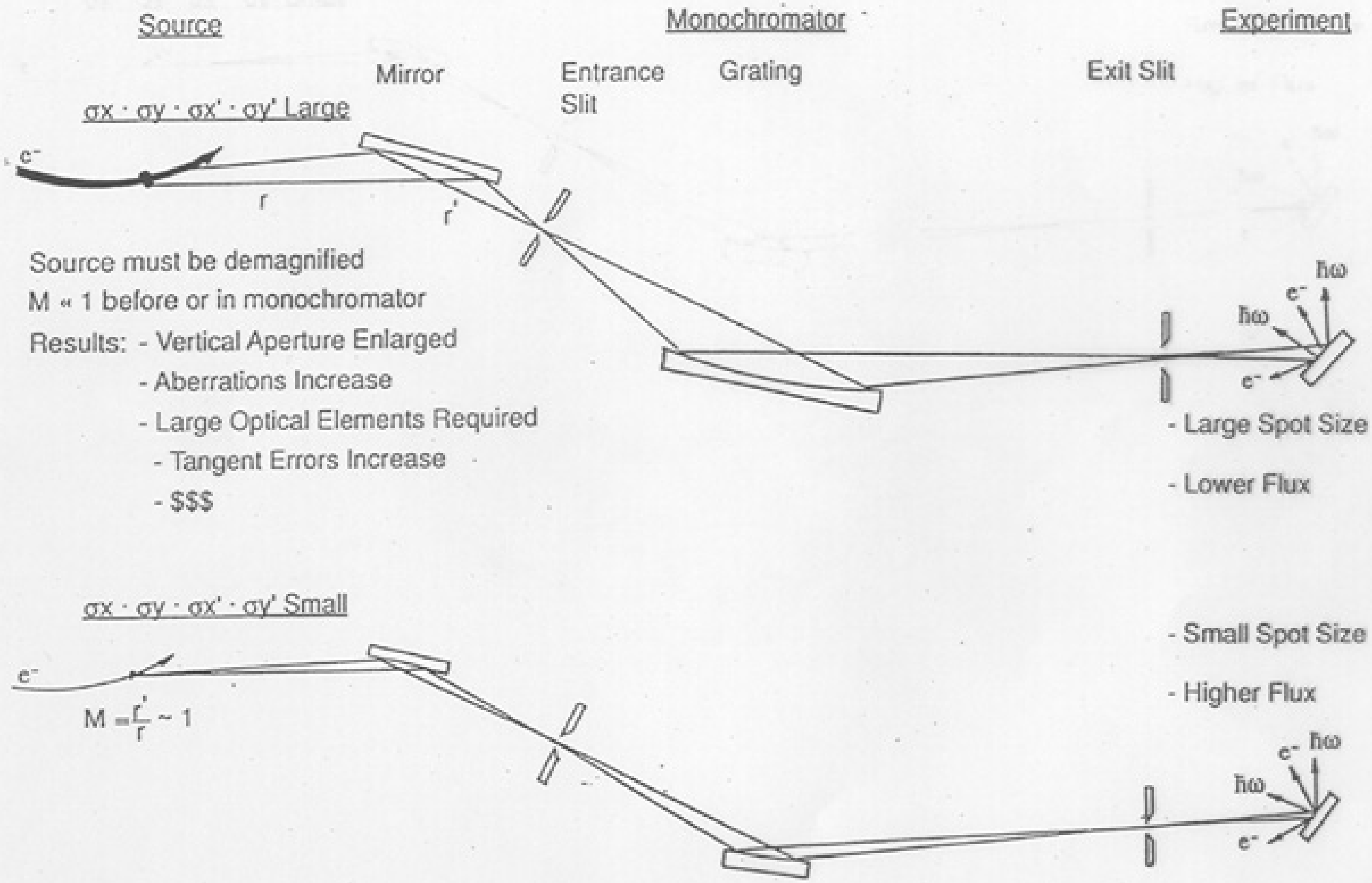
units = photons/sec mm^2 $mrad^2$ 0.1%BW
for given ring current I (typically 100 mA)

ELETTRA's Brightness Curves,

in Photons per second, per mrad2, per mm2, and for 0.1% bandwidth



The Practical Meaning of Brilliance



The electron beam

emittance = $\varepsilon = \sigma_e \sigma'_e$ = constant

$\varepsilon_y = C\, \varepsilon_x$

C = coupling factor (constant), typically 1-10 %

case of ELETTRA at 2 GeV

horizontal emittance ε_x = 7.0 nm·rad

coupling factor = 1%

beam dimensions in the straight sections (horizontal/vertical) in µm	241/15
beam divergence in the straight sections (horizontal/vertical) in µrad	29/6

The radiation emission process

effective size σ_r
opening angle σ'_r

Total

$$\sigma_t = \sqrt{\sigma_e^2 + \sigma_r^2}$$

$$\sigma'_t = \sqrt{\sigma'^2_e + \sigma'^2_r}$$

Dipole magnet

effective size

$\sigma_t = \sigma_e$

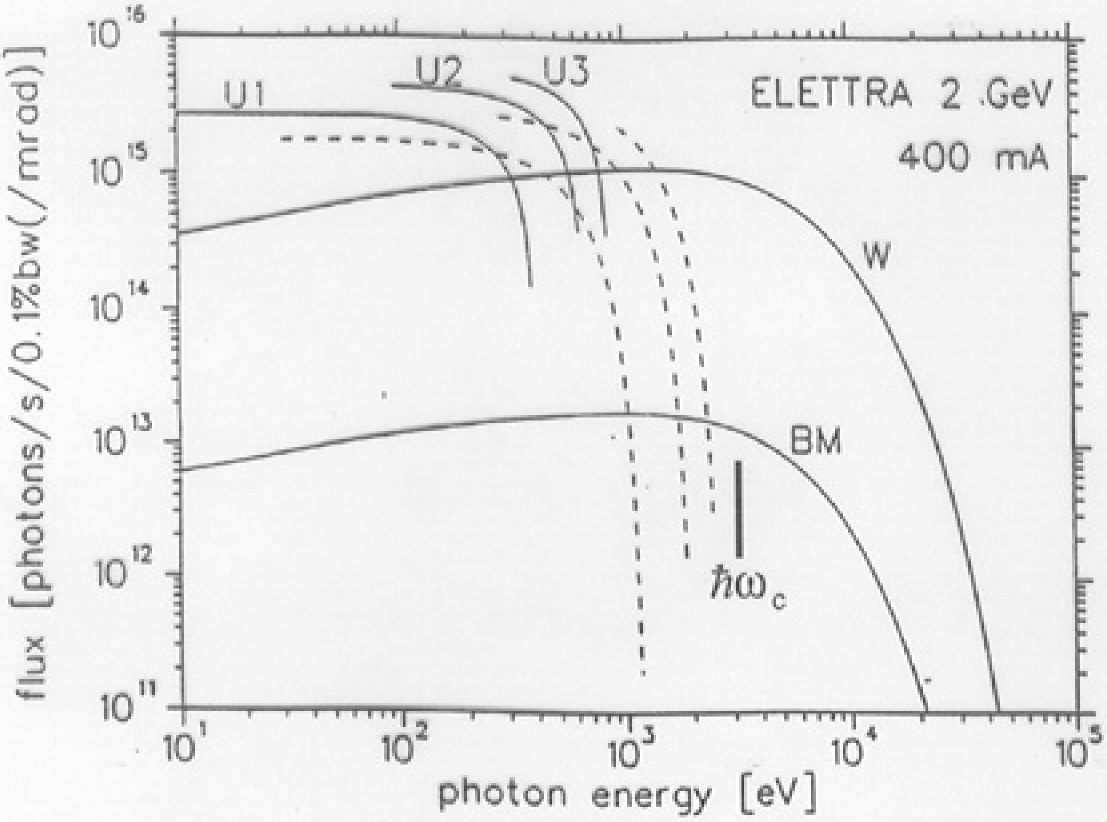
vertical opening angle

$$\sigma'_{rv}\,(\mathrm{rad}) = 0.57 \left(\frac{\lambda}{\lambda_c}\right)^{0.43} \frac{1}{\gamma} \qquad \text{for } 0.2 < \frac{\lambda}{\lambda_c} < 100$$

λ_c = critical wavelength
$\hbar\omega_c$ = critical energy
$\gamma = \dfrac{1}{\sqrt{1-\beta^2}}$ = relativistic factor

$\gamma = 1957\ E$
$\hbar\omega_c = 2218\ \dfrac{E^3}{\rho} = 667\ B\ E^2$

E = energy of the electrons in GeV
ρ = radius of curvature of the electrons in the dipole magnets in meters
B = magnetic field amplitude in Tesla
$\hbar\omega_c$ = critical energy in eV



Spectral flux of radiation sources in the storage ring at 2 GeV.

case of ELETTRA

$E = 2$ GeV
$\rho = 5.5$ m
$\hbar\omega_c \approx 3.2$ KeV

$\gamma = 3914$

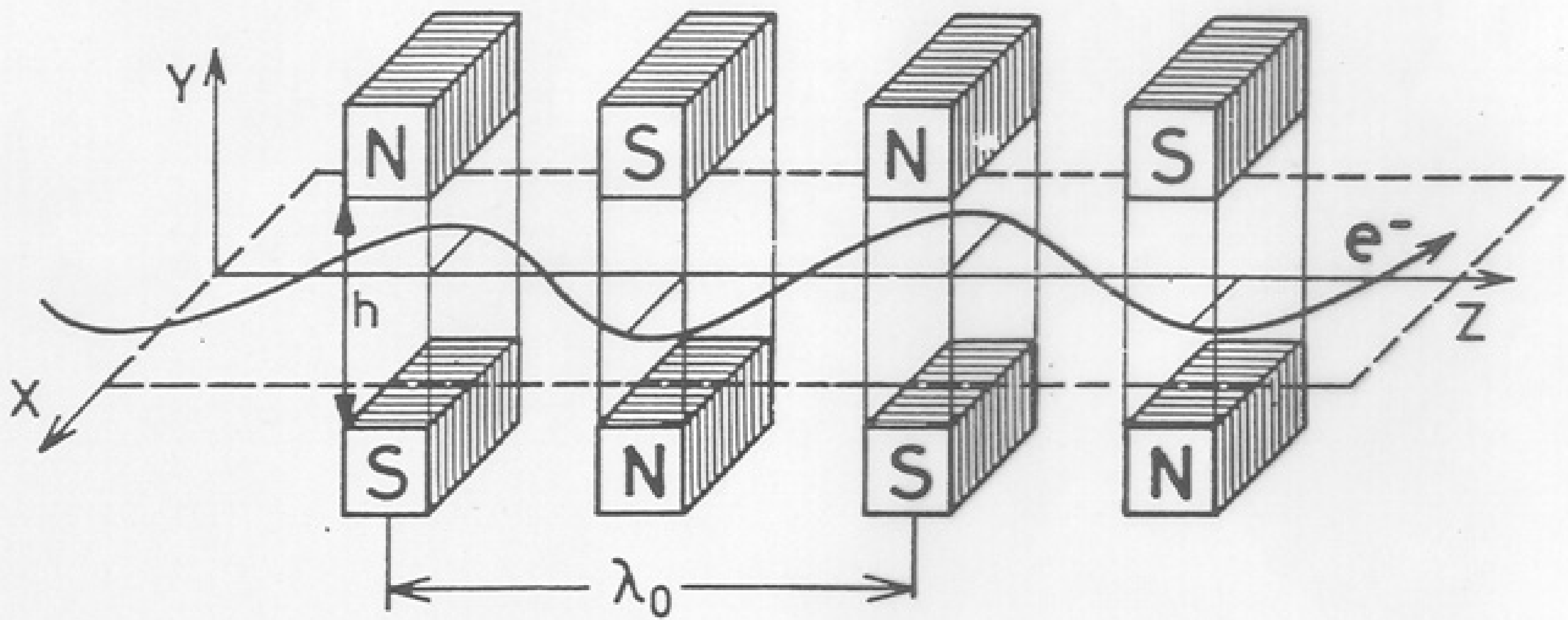
$$\sigma'_{rv}\,(\text{rad}) = 0.57\left(\frac{\lambda}{\lambda_c}\right)^{0.43} \cdot 255\ \mu\text{rad}$$

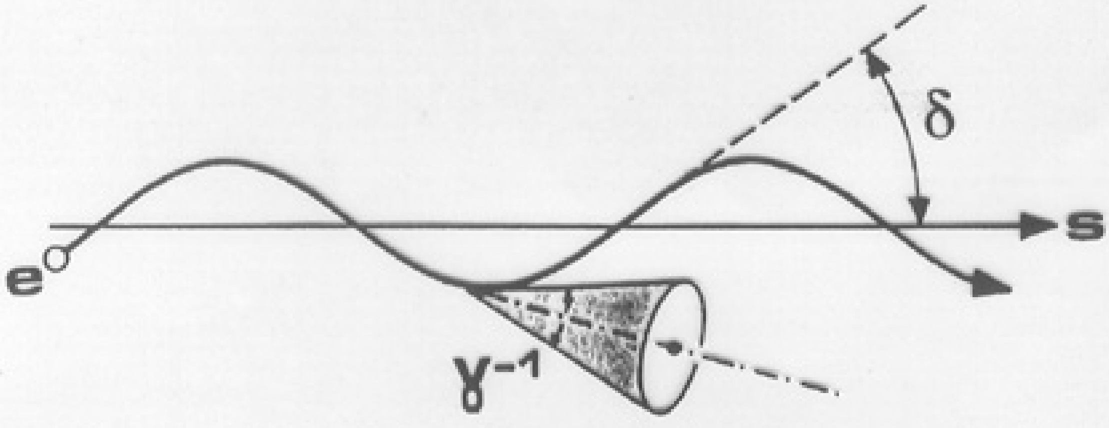
horizontal opening angle

defined by the geometry of the front end

at ELETTRA: 6 or 7 mrad

Layout of a Wiggler, Undulator





magnetic field strength parameter K

$$K = \frac{e\lambda_o B_o}{2\pi mc} = 0.934\ \lambda_o B_o$$

λ_o = length of the undulator period in cm
B_o = magnetic field amplitude in Tesla

$$K = \delta\gamma$$

at $K = 1$ is $\delta = \gamma^{-1}$

Wiggler

$K >> 1$

vertical opening angle

$\sigma'_{rv} = \sigma'_{rv}$ (dipole)

horizontal opening angle

$\sigma'_{rh} = \delta/2 = K/2\gamma$

vertical source size

$$\sigma_{rv} = \left(\frac{\sigma'^2_{ev}}{3} + \frac{\Delta\theta^2_v}{9}\right)^{1/2} \frac{L}{2}$$

horizontal source size

$$\sigma_{rh} = \left[\left(\frac{K}{\gamma}\frac{\lambda_o}{2\pi}\right)^2 + \left(\frac{\sigma'^2_{eh}}{3} + \frac{\Delta\theta^2_h}{9}\right)\left(\frac{L}{2}\right)^2\right]^{1/2}$$

where $\Delta\theta$ is the half opening angle of the optical system

Wiggler W14.0 of ELETTRA at 2 GeV

$L = 4.5$ m
$\lambda_o = 140$ mm
$B = 1.5$ T, $K = 19.6$
$2\Delta\theta = 1.5$ mrad H $\times$ 0.28 mrad V

$$x_o = \frac{K}{\gamma}\frac{\lambda_o}{2\pi} = 112\ \mu\text{m}$$

separation between the two "eyes"of the wiggler

$\hbar\omega_c = 4.0$ KeV

$$\sigma'_{rv}\,(\text{rad}) = 0.57\left(\frac{\lambda}{\lambda_c}\right)^{0.43}\frac{1}{\gamma} = 108\ \mu\text{rad (at } \hbar\omega = 8\text{ KeV)}$$

$\sigma'_{rh} = 2500$ μrad

$\sigma_{rv} = 105$ μm

$\sigma_{rh} = 575$ μm

Undulator

$0 < K \leq 2\text{-}3$

$$\lambda = \frac{\lambda_o}{2\gamma^2 k}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

$$\frac{\Delta\lambda}{\lambda} = \frac{1}{kN} \text{ or } \frac{\Delta\lambda}{\lambda} = \frac{1}{2kN}$$

k = number of the harmonic
N = number of periods of undulator
$N\lambda_o = L$ = total length of undulator

σ'_r = width of the central radiation cone

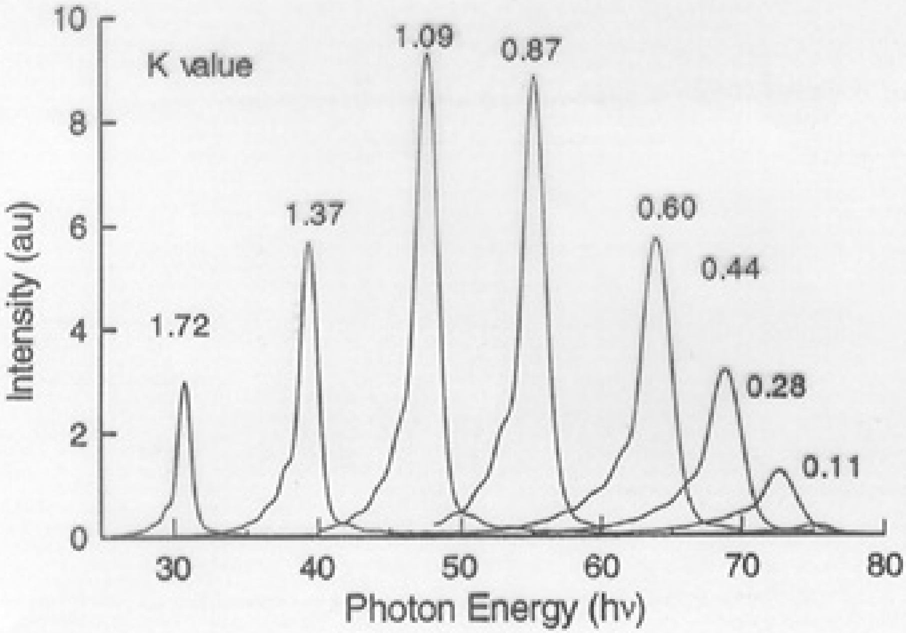
$$\frac{\Delta\lambda}{\lambda} = \frac{1}{kN} \qquad \sigma'_r = \frac{\sqrt{1 + \frac{K^2}{2}}}{\gamma}\frac{1}{\sqrt{kN}}$$

$$\frac{\Delta\lambda}{\lambda} = \frac{1}{2kN} \qquad \sigma'_r = \sqrt{\frac{\lambda}{L}}$$

Typical Undulator Spectra

Typical undulator spectra: λ_o = 70 mm, N = 35 and E_{el} = 800 MeV. The envelope of the spectra is determined mainly by the transmission of the monochromator used to record them [2.7].

a. Spectra of the first harmonic for different values of K. The acceptance of the monochromator was 0.13 mrad.



b. The first three harmonics for K = 1.09. The acceptance of the monochromator was 0.13 mrad.