Components of a Synchrotron

- **The electron storage ring (accelerator physics)**
- **The experimental beamlines (users)**
  - Front-end
  - Optics
  - End-stations

Ideally, the design of an experiment starts at designing the storage ring

Emittance: ε

The brightness of the light depends on how ***tightly the electron beam is squeezed.***

spatial deviation of the electron from the ideal orbit is σ_x , in the plane of the orbit with **angular spread** σ_x'.

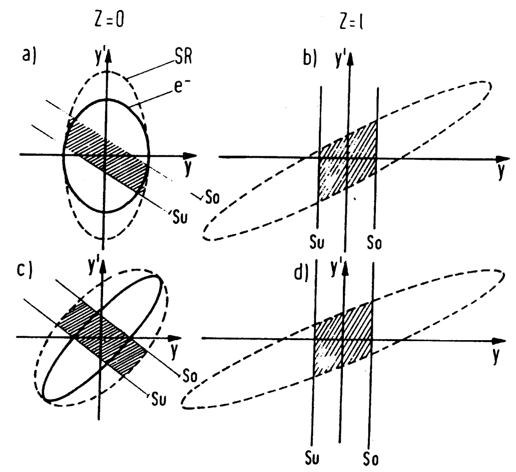
σ_y , vertical to the plane of the orbit, with σ_y'.

Emittance ε (nm-rad) is expressed as

$$\varepsilon_x = \sigma_x \sigma_x{'}$$
$$\varepsilon_y = \sigma_y \sigma_y{'}$$

Emittance is conserved (Liouville theorem)

Typical emittance of 3rd generation ring:10 - 1 nm-rad



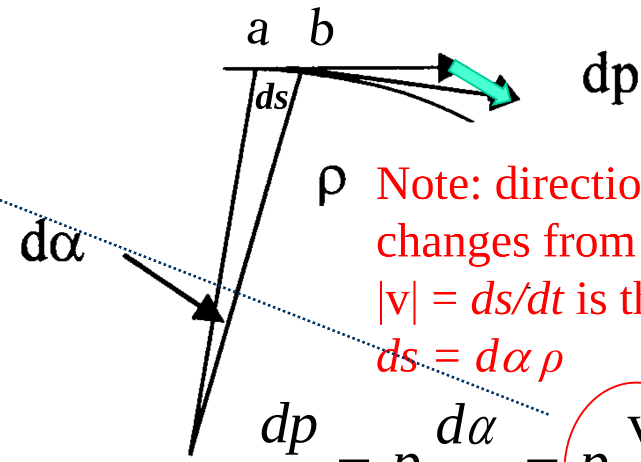
Phase space ellipsoids

Energy loss to synchrotron radiation

$$P = \frac{2}{3}\frac{e^2\gamma^2}{m_o^2 c^3}\left|\frac{dp}{dt}\right|^2$$

v ~c, pc = E
$\gamma = E/m_0c^2$

$$P = \frac{2}{3}\frac{e^2 c}{(m_o c^2)^4}\frac{E^4}{\rho^2}$$



Note: direction of p changes from a to b but |v| = *ds/dt* is the same
$ds = d\alpha\,\rho$

$$\frac{dp}{dt} = p\frac{d\alpha}{dt} = p\frac{v}{\rho}$$

$$\Delta E = \oint_{orbit} P\,dt = P\frac{2\pi\rho}{c} \longrightarrow \Delta E[keV] = 88.5\frac{E^4[GeV^4]}{\rho[m]}$$

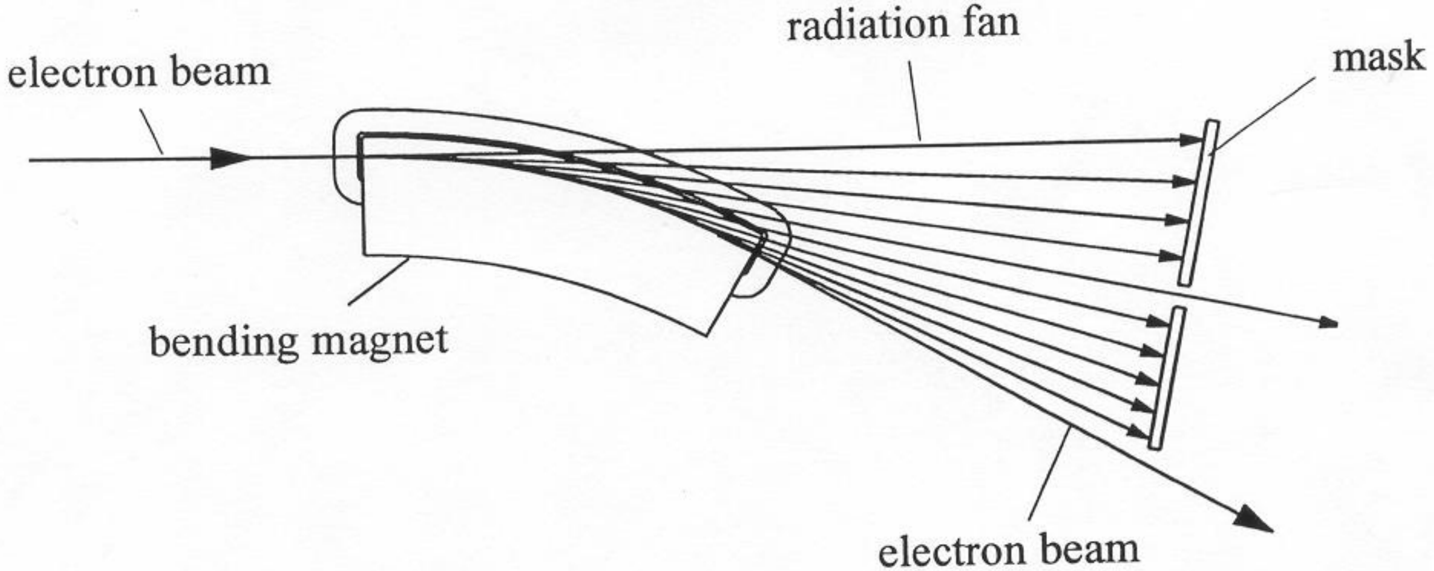
Energy loss per turn per electron → synchrotron radiation !

For a 3.5 GeV ring with a radius of 12.2 m, the energy loss per turn is ~10^6 eV => Most storage rings built to-day are ~ GeV rings

How is synchrotron radiation generated ?

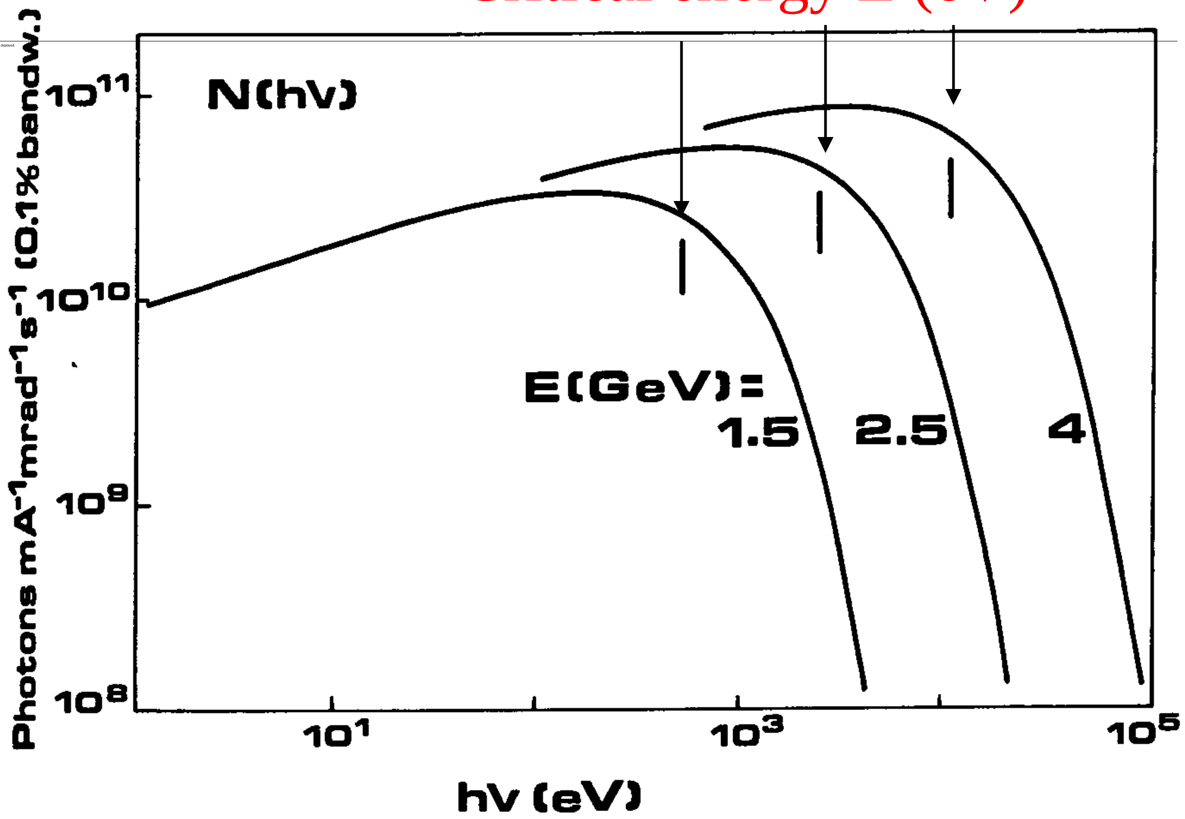
- There are three ways
  - ***To bend*** the electron with a **bending magnet (dipole radiation)**
  - ***To wiggle*** the electron with a periodic magnetic field called **insertion device**
    - high field with a big bent: **wigglers**
    - medium field with many small bents: **undulator**

Synchrotron radiation from BM



BM (dipole) spectrum and critical energy

Critical energy E (eV)



half of the radiated power is into photons with energy above E_c, and half of the power is below

$$E(eV) = 12398.5/\lambda(\overset{o}{A}) \quad \lambda_c = \frac{12386.5}{800(eV)}(\overset{o}{A}) = 15.5\,\overset{o}{A}$$

critical wavelength

critical energy

Wigglers and undulators

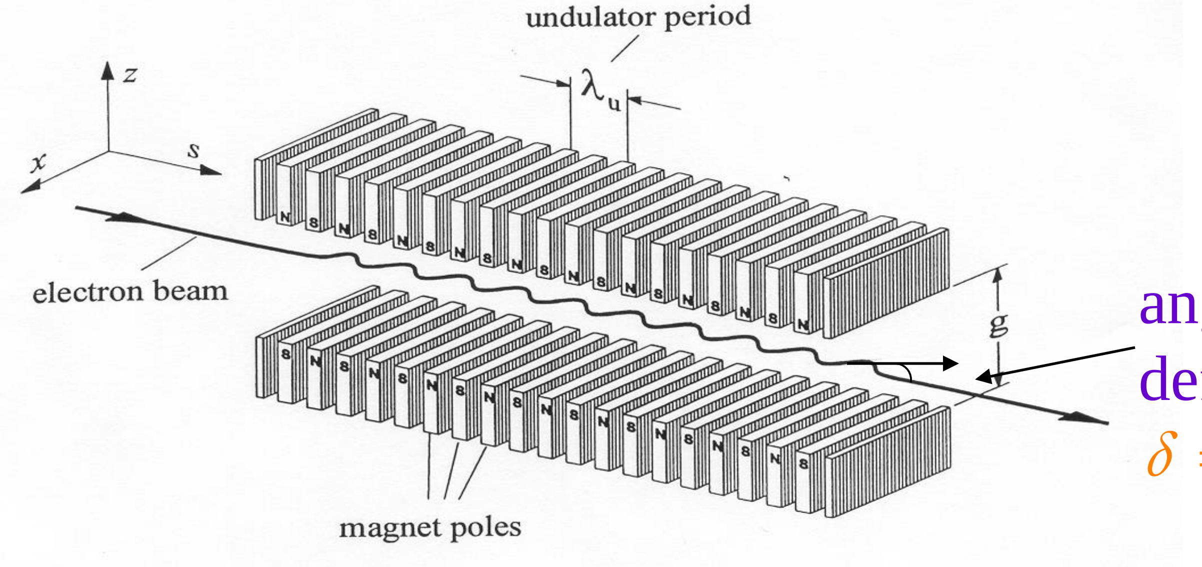
Alternating magnetic structures

short period, large bend: wiggler

long period, small bend: undulator

strength parameter → $K = 0.934\lambda_u\,[\mathrm{cm}]\,B_o[\mathrm{T}]$

peak magnetic field



angle of deflection

$\delta = K / \gamma$

Undulator equation

$$\lambda_1(\Theta) = \frac{\lambda_u}{2\gamma^2}\left[1 + \frac{K^2}{2} + \gamma^2\Theta^2\right]$$

Θ: angle of observation

K >>1: large field, sizable bend, negligible interference => wiggler
K<1: short period, modest bend, interference => undulator

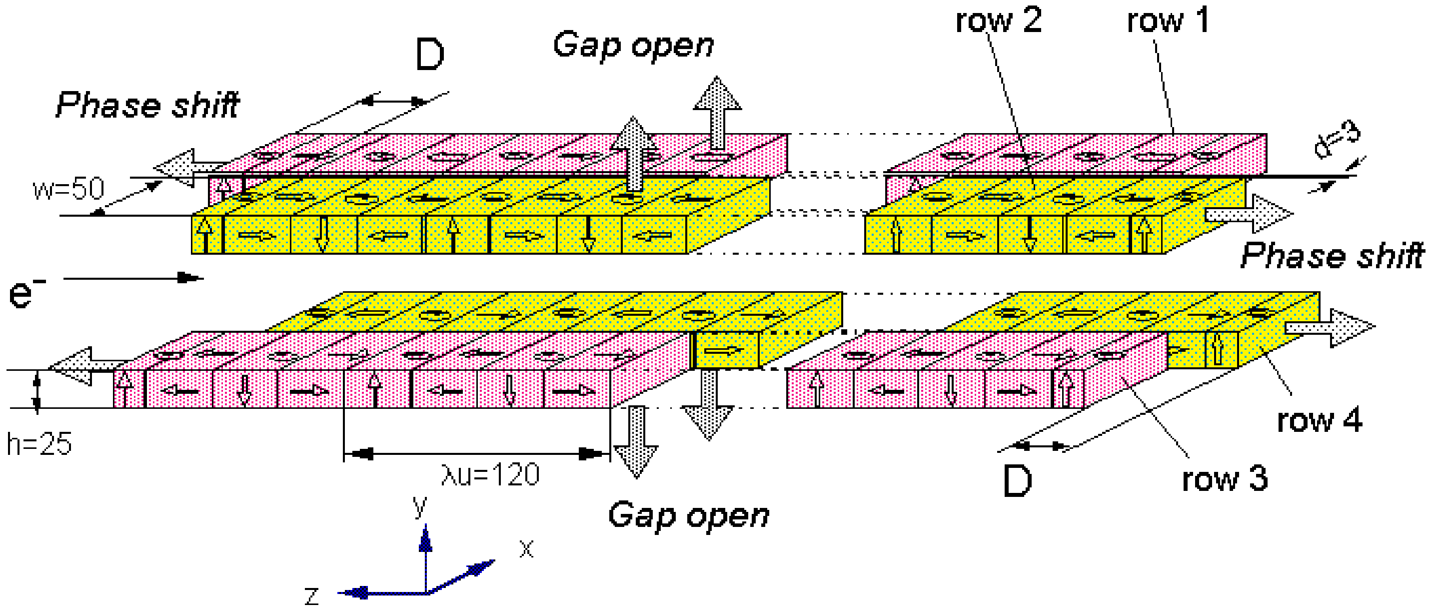
Fundamental energy/wavelength on axis

$$\varepsilon_1[keV] = \frac{0.950 E^2[GeV]}{(1+K^2/2)\lambda_u[cm]}$$

$$\lambda_1\left[\overset{o}{A}\right] = \frac{13.06\ \lambda_u[cm](1+K^2/2)}{E^2[GeV]}$$

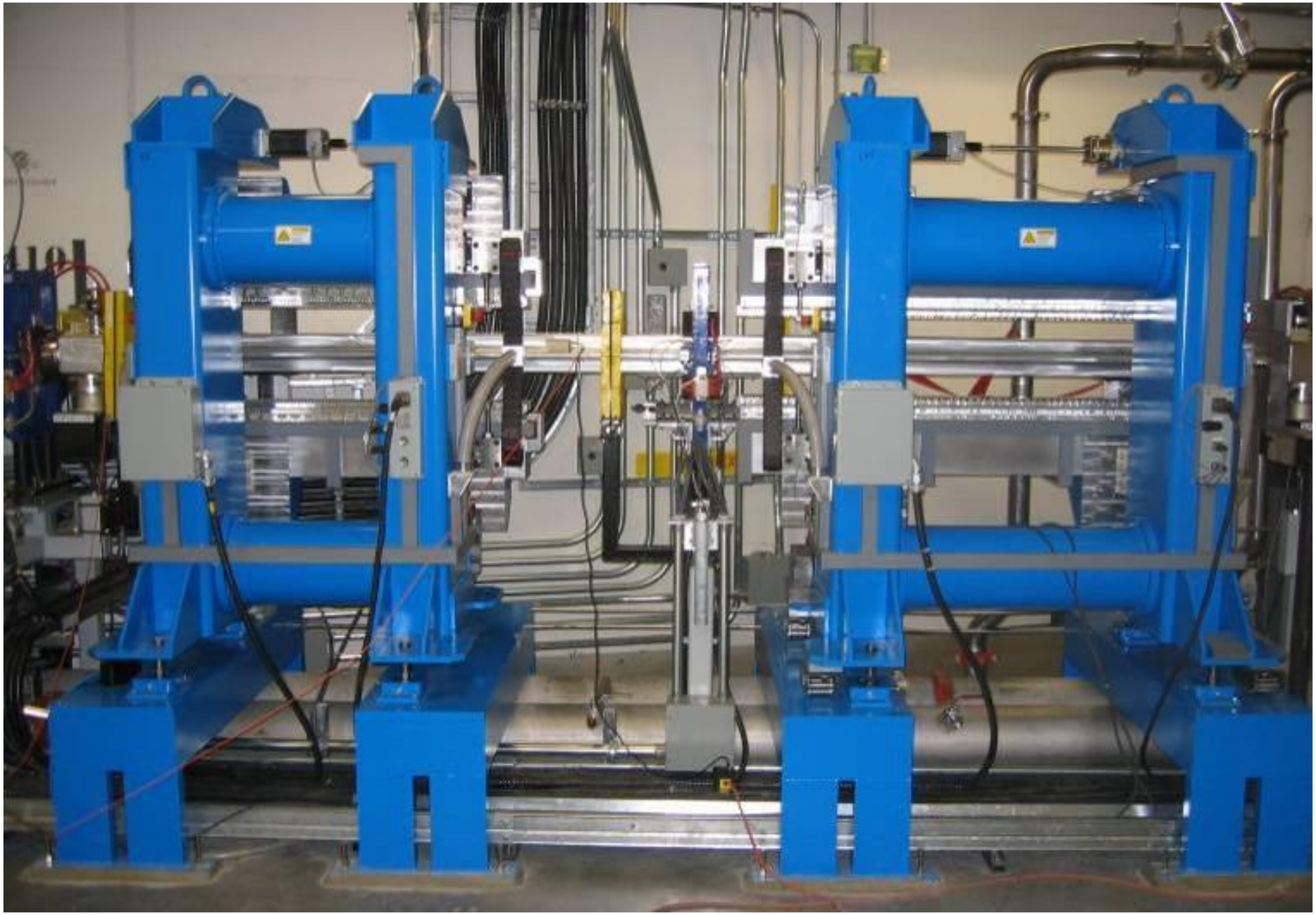
Modern Insertion Devices (APPLEII)

- Energy tunable by adjusting the gap
- In vacuum small gap undulator
- Polarization tunable by tuning the magnetic structures: EPU



The magnetic structure of the APPLE II consists of two pairs of arrays of permanent magnets.

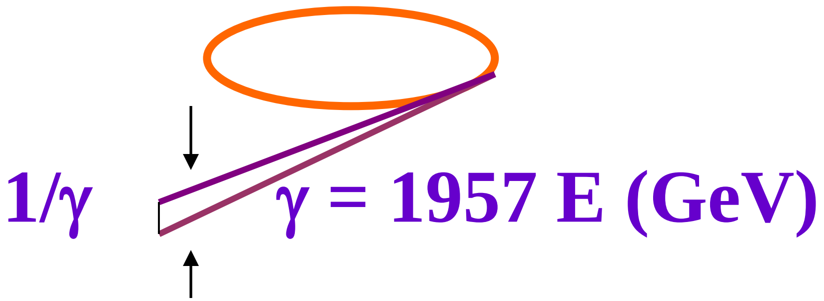
Chicane Insertion Device at CLS



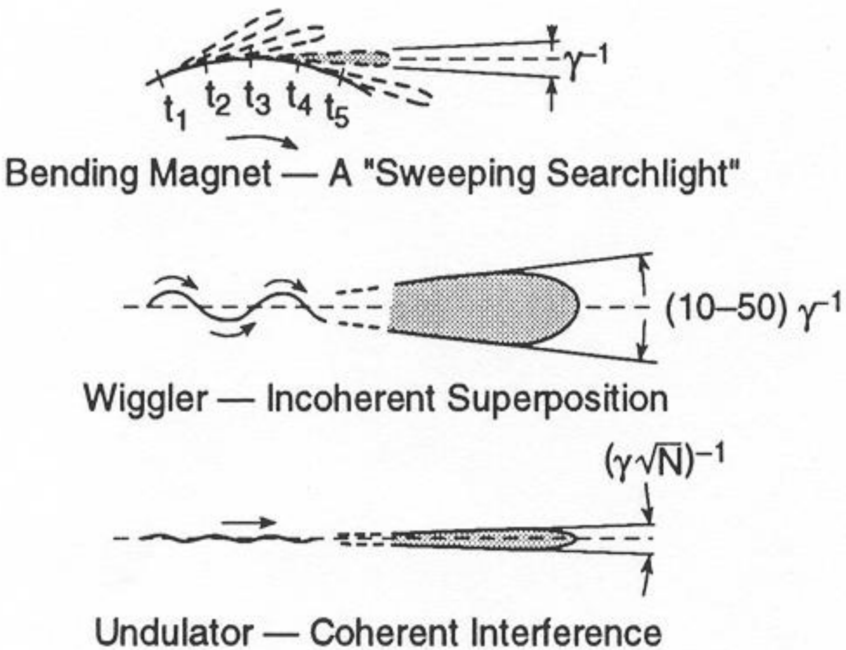
SGM **PGM**

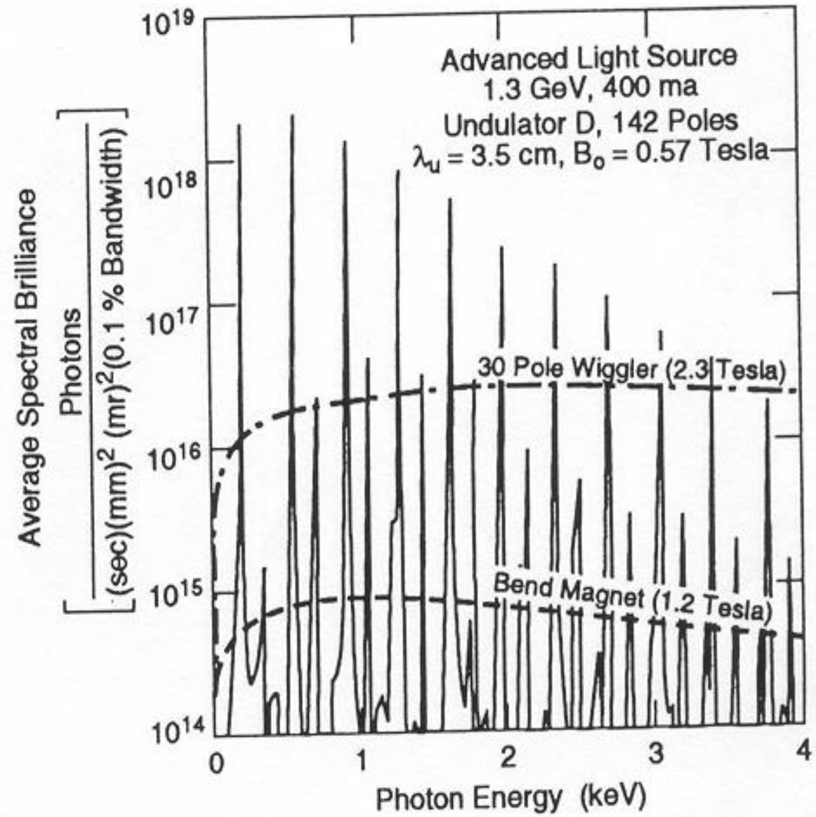
Characteristics of synchrotron radiation

- **Spatially distribution**: highly collimated half angle $\psi = 1/\gamma$, $\gamma = 1975$ E (GeV).
  - bending magnet: $1/\gamma$
  - undulator: $1/(\gamma\sqrt{N})$
  - wiggler: $\gg 1/\gamma$



- **Spectral distribution**: continuous at BM and wiggler sources, spike like peaks in undulator source due to interference effects



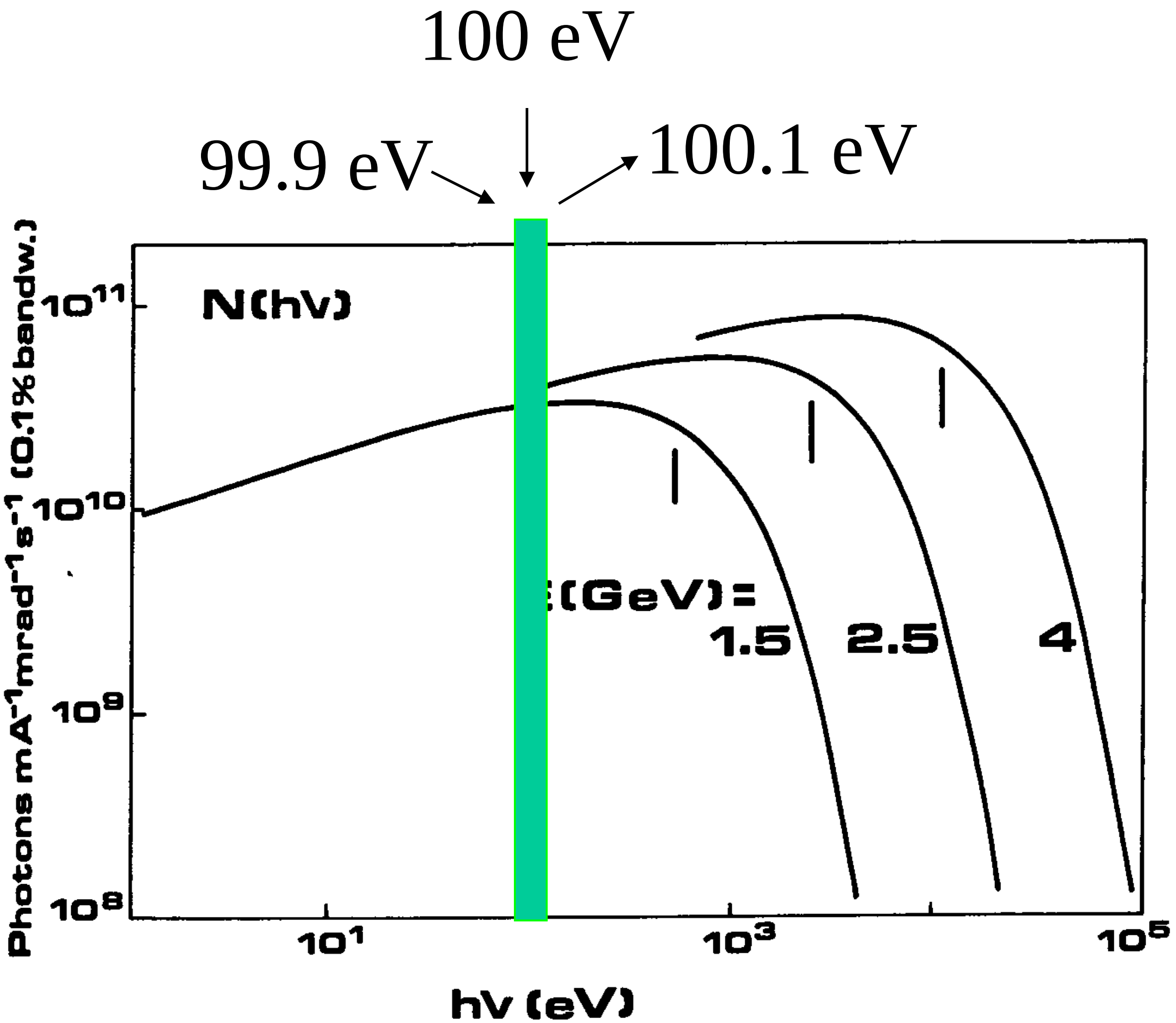


Spatial distribution **Spectral distribution**

Why is synchrotron radiation special For materials analysis ?

- Tunability (IR to hard x-rays)
- Brightness (highly collimated)
- Polarization (linear, circular, tunable)
- Time structure (short pulse)
- Partial coherence (laser-like beam from ID)

0.1% band path



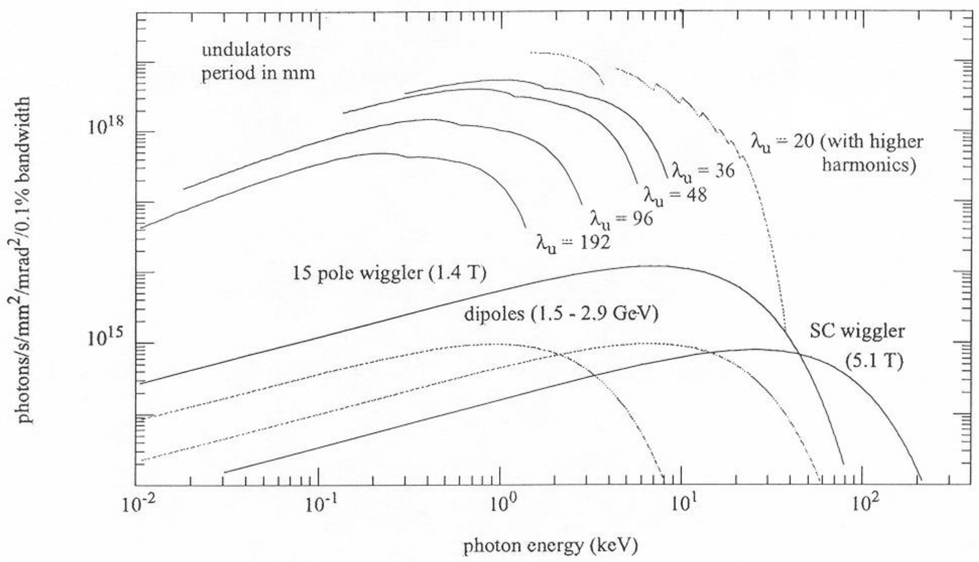
100 eV
99.9 eV
100.1 eV
N(hv)
Photons mA⁻¹mrad⁻¹s⁻¹ (0.1% bandw.)
10^{11}
10^{10}
10^{9}
10^{8}
E(GeV)=
1.5
2.5
4
10^{1}
10^{3}
10^{5}
hv (eV)

Brightness and flux

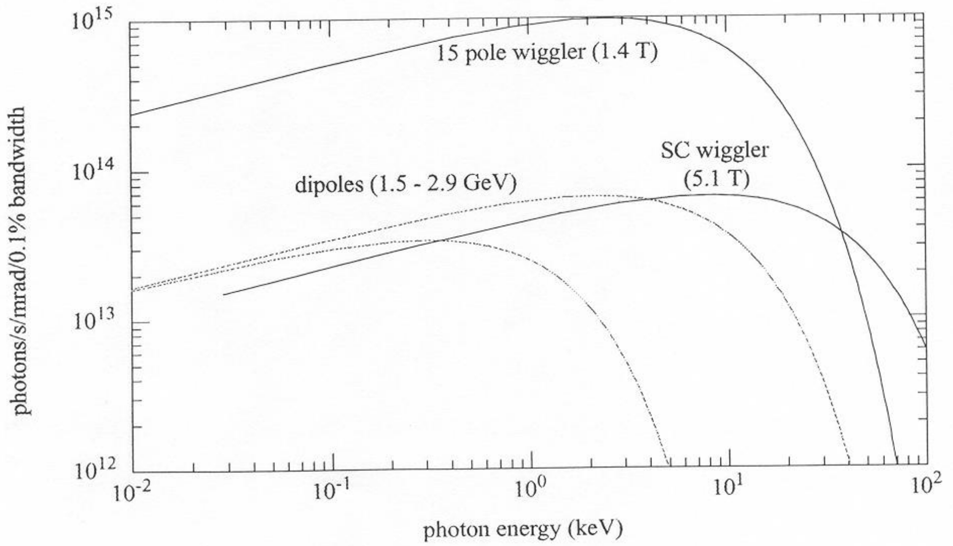
- **Brightness**: photons per 0.1% bandwidth sec^{-1} mm^{-2} $mrad^{-2}$ mA^{-1}
- Number of photons per bandwidth, per unit time per **unit source area**, per unit **solid angle** (***inherent to ring design: emittance***)
- **Flux**: photons per 0.1% bandwidth $sec^{-1} mA^{-1}$ Number of photons per bandwidth per unit time (scaled to ring current and orbit of arc, ***can be improved by beamline optics***)

Brightness and Flux revisited

Brightness:
No. of photons per sec per mm^2 (source size) per mrad^2 (source divergence) per mA, within a 01.% band width



Flux:
No. of photons per sec per mrad angle of arc within a 01.% band width



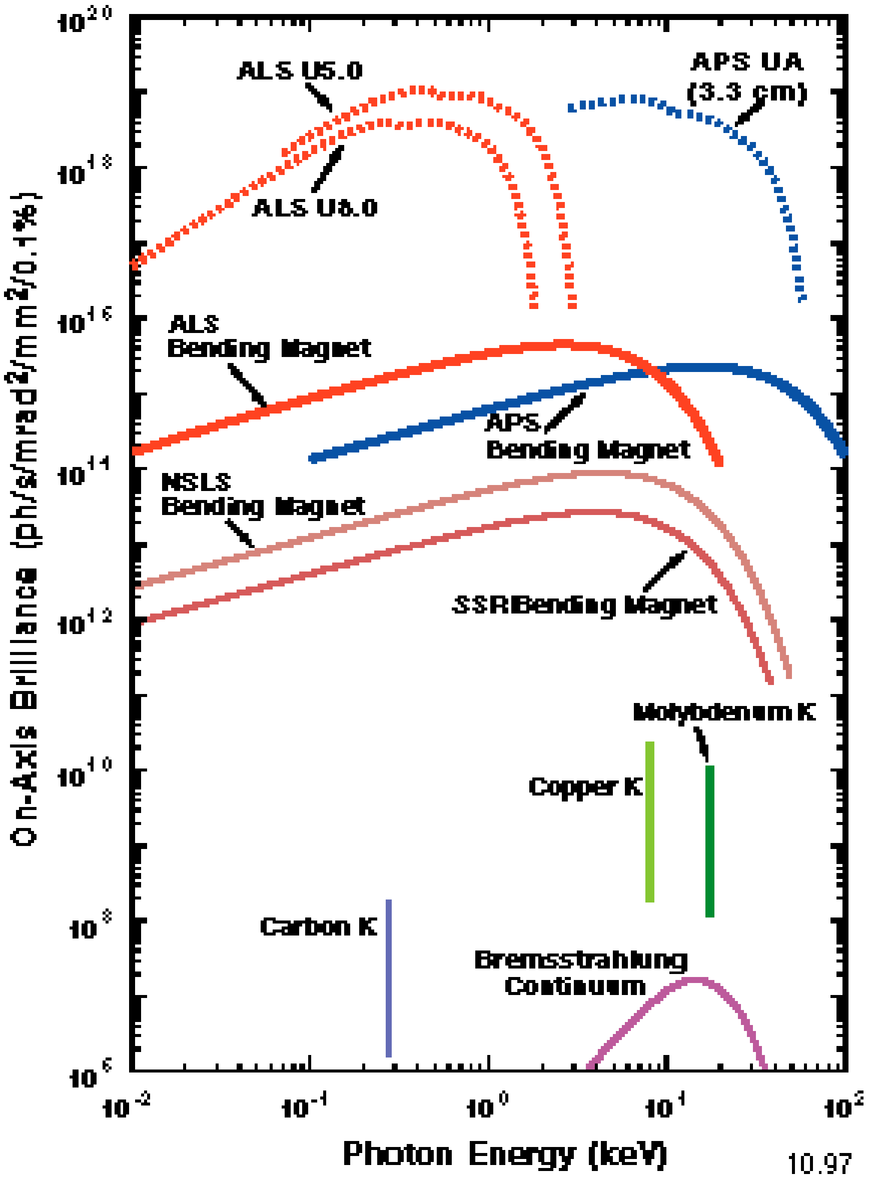
Spectral Distribution of a BM source

BM radiation has a wide energy distribution characterized by of λ_c

$$\lambda_c(\overset{o}{A}) = \frac{18.6}{E^2 B} = \frac{5.6\rho}{E^3} = \frac{4\pi\rho}{3\gamma^3}$$

$$note: \quad \gamma = 1957 E(GeV)$$

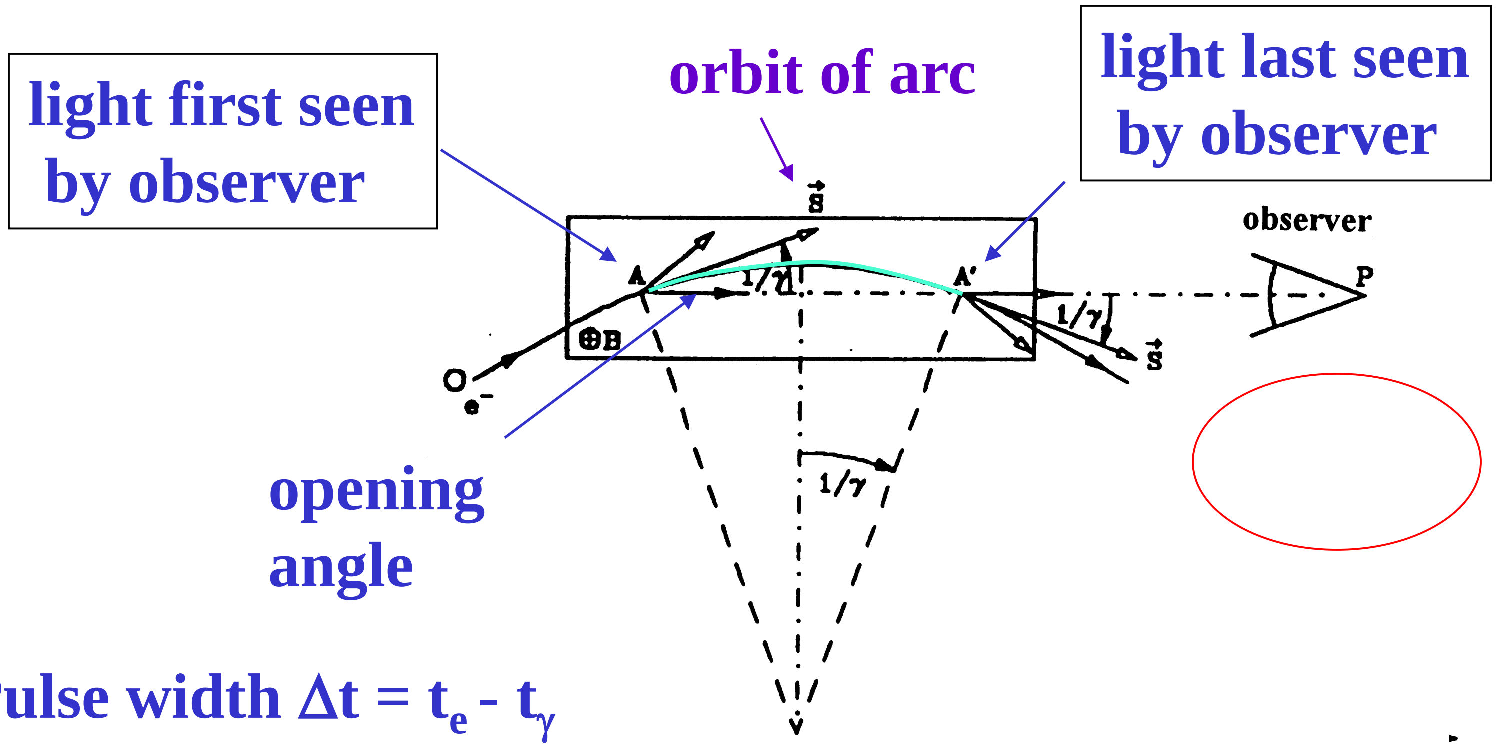
Example: SRC (WI)
E= 0.8 GeV,
ρ = 2.0833 m,
λ_c = 22.7Å
E_c =12398.5/22.7 = 546 eV



Exercise: Comment on the similarity between Bremstrhlung and SR

Why is there a wide spread in photon energy?

Qualitative understanding: Uncertainty Principle



Pulse width $\Delta t = t_e - t_\gamma$

photon travels faster than electron

$$\Delta t = t_e - t_\gamma = \frac{2\rho}{\beta\gamma c} - \frac{2\rho \sin(1/\gamma)}{c} \approx \frac{4\rho}{3c\gamma^3}$$

Exercise: Show this; hint: $\gamma >> 1$; $\sin x = x - x^2/3! + \ldots$

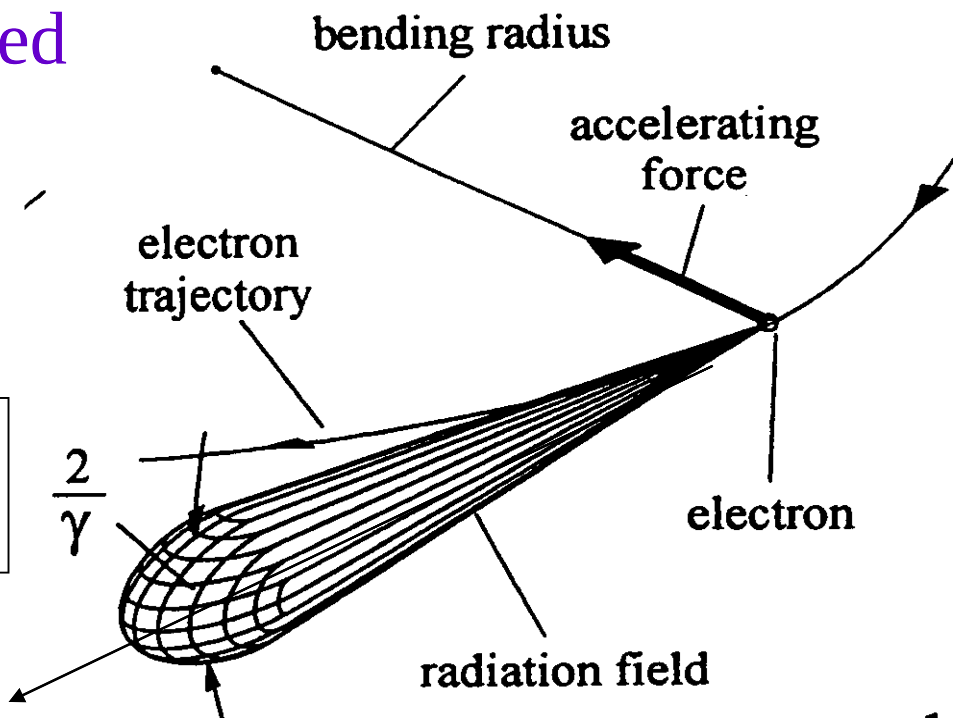
$\Delta E \cdot \Delta t \geq \hbar/2$

$\Delta E_{SR} \geq \hbar/2\Delta t \geq 3\hbar c\gamma^2/2\rho$

typically ~ keV

The opening angle: angular distribution

Opening angle, ψ, is defined as the half angle of the SR above and below the orbit plane.



$\psi \sim (1/\gamma)\ 0.57\ (\lambda/\lambda_C)^{0.43}$ (radian)

$\psi \sim (1/\gamma)$

We recall that **γ = 1957 E(GeV),** hence high energy electrons will produce a more **collimated** photon beam.
Also the shorter the wavelength the more collimated the light.
e.g.: X-ray is more collimated than IR

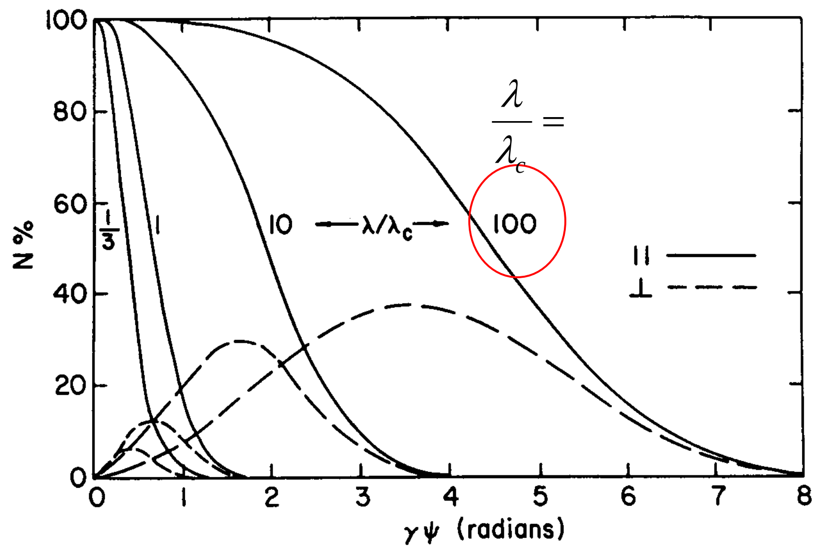
Polarization

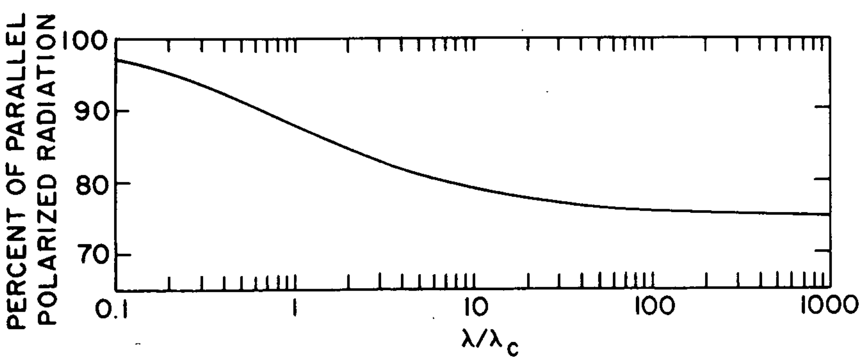
Degree of polarization

$p = (I_{\parallel} - I_{\perp})/(I_{\parallel} + I_{\perp})$

$\psi \sim \mathbf{(1/\gamma)}\ 0.57\ (\lambda/\lambda_C)^{0.43}$ (radian)

$\psi\gamma \sim \mathbf{0.57\ (\lambda/\lambda_C)^{0.43}}$





Polarization increases at shorter wavelength

The radio-frequency cavity

Where is a cavity located in a storage ring?

At a straight section

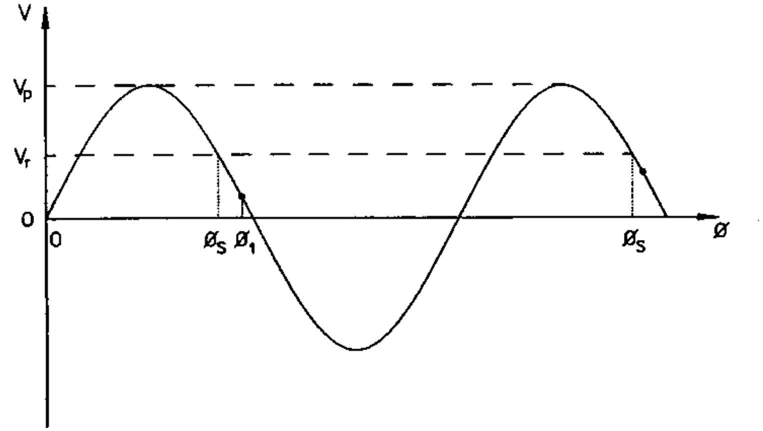
What does it do?

To replenish the energy loss by electrons as synchrotron radiation

How does it work ?

To provide a time varying electric field (voltage) that gives the electron a boost when it passes the accelerating gap (resonant cavity)

The bunching effect of the r.f. cavity



Cavity voltage varies sinusoidally with a phase angle ϕ. Since $(\phi/2\pi) \cdot$ frequency = time, the ϕ axis is equivalent to time

ϕ_s (stable phase angle): the electron receives the correct amount of energy it lost to synchrotron radiation

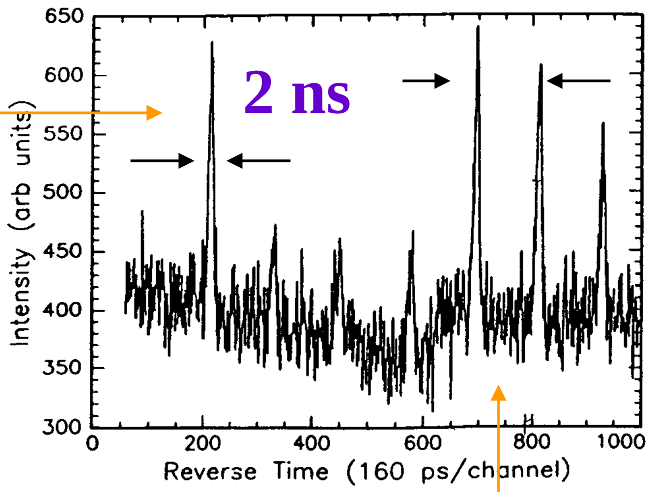
If an electron passes through the gap late (ϕ_1), it will not receive sufficient energy and moves into an orbit of smaller radius and will take less time to arrive back at the gap. Thus electrons are said to be bunched by the r.f. cavity.

The potential well within which they are stable is called the **bucket**.

Time Structure

NSLS UV

r.f. cavity bunches the electrons. Bunch length determines the pulse width



Number of bunches determines the repetition rate

ALS, 1.9 GeV

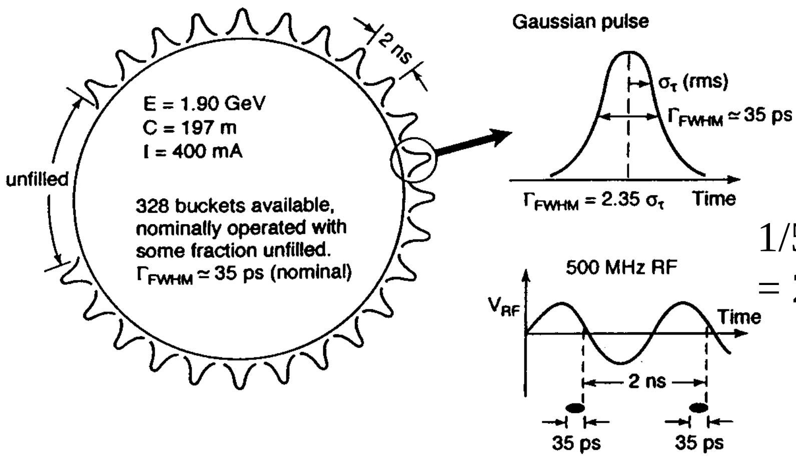
328 buckets, bunch: 35 ps

circumference = 197 m

197/328 = 0.6 m

Separating the bunches

$0.6 m/3 x 10^{8} ms^{-1} = 2 ns$



1/500MHz = 2 ns

Relevant storage ring parameters (CLS)

Parameters	Main hardware	Relevance to users
Energy (e.g. 2.9GeV)	B field and radius $\lambda_c(\overset{o}{A}) = \frac{18.6}{E^2 B} = \frac{5.6\rho}{E^3}$	practical photon energy (λ_c)
Current (500 mA)	r.f. cavity: time varying voltage	photon flux
Emittance (16 nm-mrad)	magnetic lattice	Brightness (microbeam)
Circumference (8 straight sections)	r.f. cavity (500 MHz), ID	time structure (dynamics), microbeam

The magnetic system (lattices)

The system of magnetic optics that guides and focuses an electron beam is called the **lattice**. The choice of the lattice is the most critical decision for it determines

Emittance (electrons) – brightness (photon beam)

Beam lifetime and stability

No. of insertion devices

Cost

Magnetic Lattice

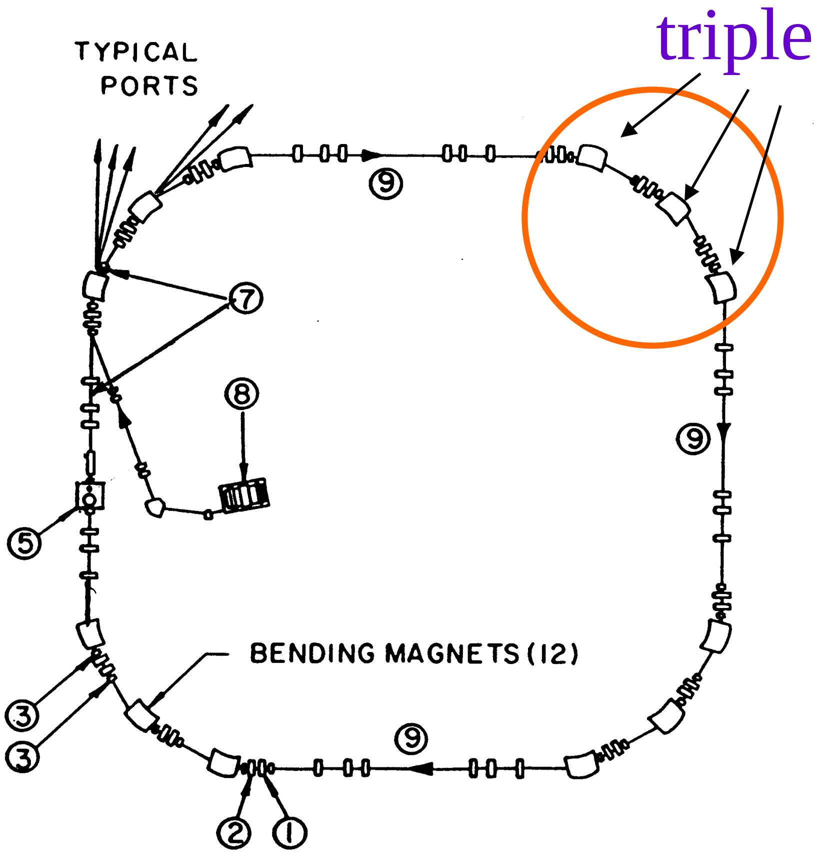
Lattice Characteristics

The cell: building block arrangement of bending magnet and focusing magnets

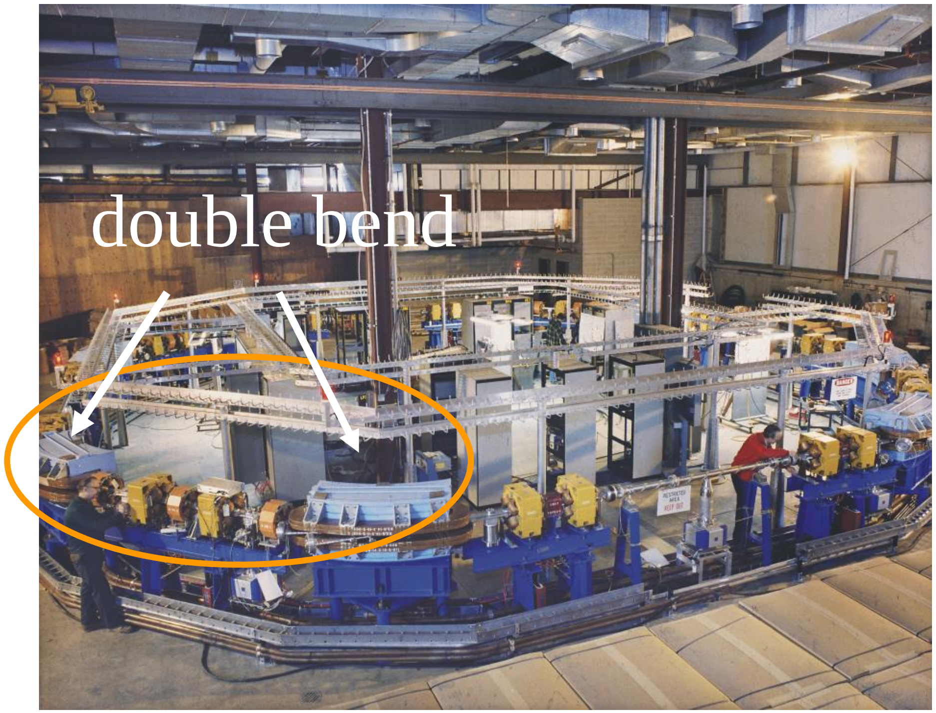
a. Double bend Achromat
b. Triple bend Achromat

New: Multiple bend achromat

The Aladdin Ring (Stoughton Wisconsin): Home of the Canadian Synchrotron Radiation Facility



1 Focussing Quadrupole
2 Defocusing Quadrupole
3 Sextupole Correction
5 Accelerating Cavity
7 Injection Kicker Magnets
8 100 MeV Microtron
9 Straight Sections (available for Undulators and Wigglers)



UV Ring NSLS, Brookhaven national Lab

The journey of the electron in the storage ring

Electron gun → **Linac** → **Booster**

↓ **injection**

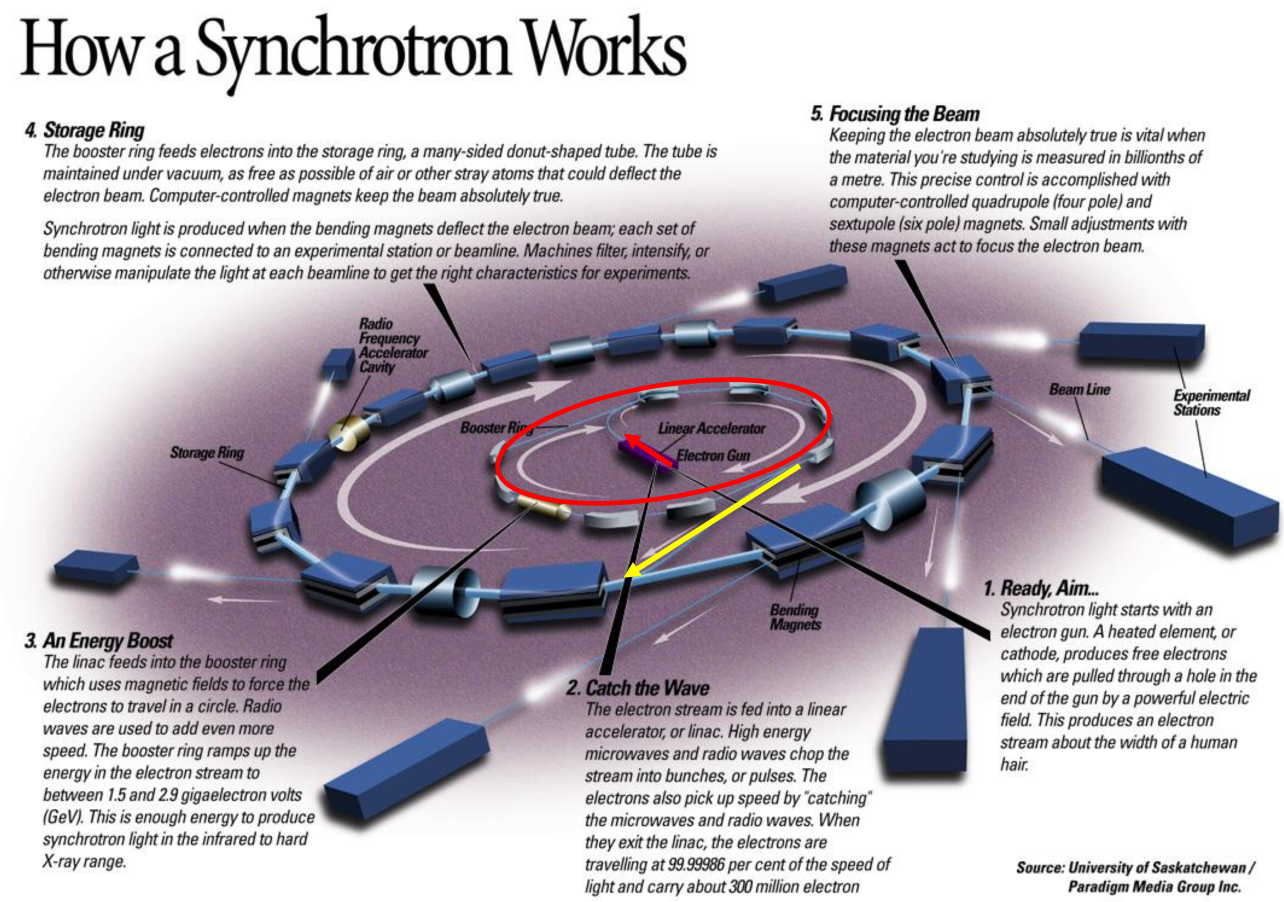
Storage ring

↓

BM and ID → **SR**

↑

R.f cavity replenishes the energy lost to SR



Beamlines and experimental stations

Beamline optics solution:
general considerations

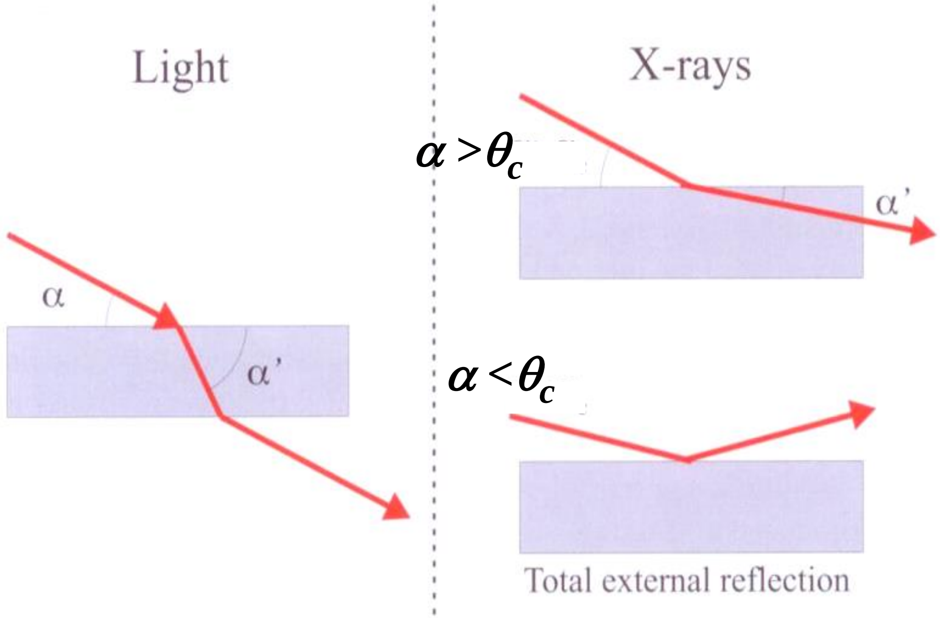
1. Energy region (monochromator)
2. Photon intensity vs. resolution
   (slits and mirrors)
3. Spatial resolution (emittance, focusing)
4. Polarization (undulator)
5. Coherence (undulator)

Optical elements

a. **Aperture/slits** (resolution and flux trade-off)
b. **Mirrors**
   (collimation, focus, higher order rejection)
a. **Monochromators** (monochromatic light)
   IR- gratings, FTIR (interferometer)
   UV,VUV (3- 100 eV) – gratings
   VUV- soft x-ray gratings (100 eV -5000 eV) and crystals with large 2d values, e.g. InSb(111)
   Hard x-rays – crystals (Si(111), Si (220) etc.)

X-ray Mirrors

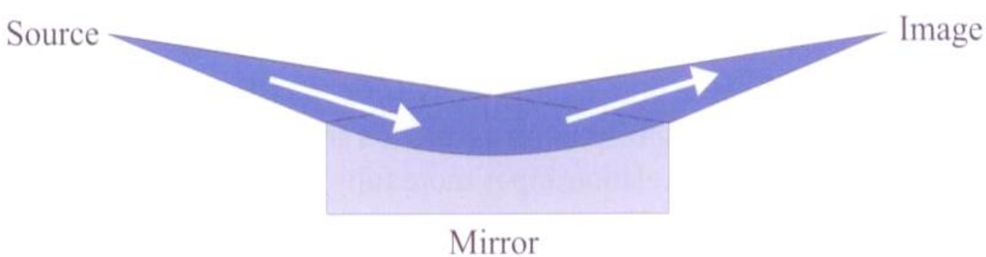
(a) Refraction and reflection of light and X-rays



The index of refraction for X-rays is slightly less than 1

θ_c: critical angle where total reflection occurs

(b) Focusing X-ray mirror



Plane mirror: collimation;
Curved mirror (spherical, elliptical, etc.): focusing

Mirror and X-ray reflectivity

Let θ_c be the angle at which total reflection occurs, then

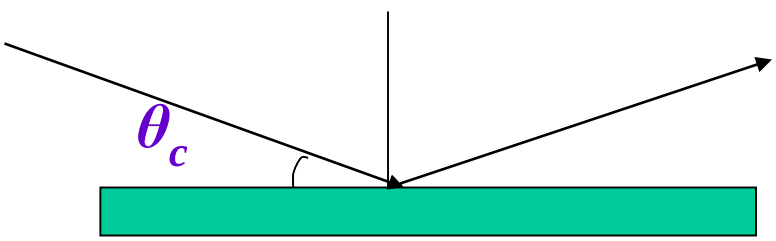
$$\sin\theta_c = \lambda(N r_0 \pi)^{1/2}$$

N: # of electrons per cm^3

n = 1 – δ + iβ

atomic #, density, atomic mass

at glancing angle $\theta_c \sim \sqrt{\delta} \sim (2.74\text{x}10^{-6} Z\rho A)^{1/2}\lambda$

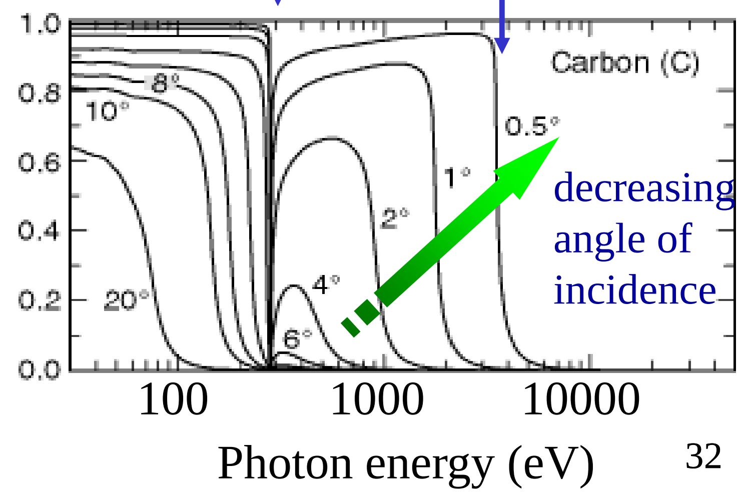


X-ray mirror

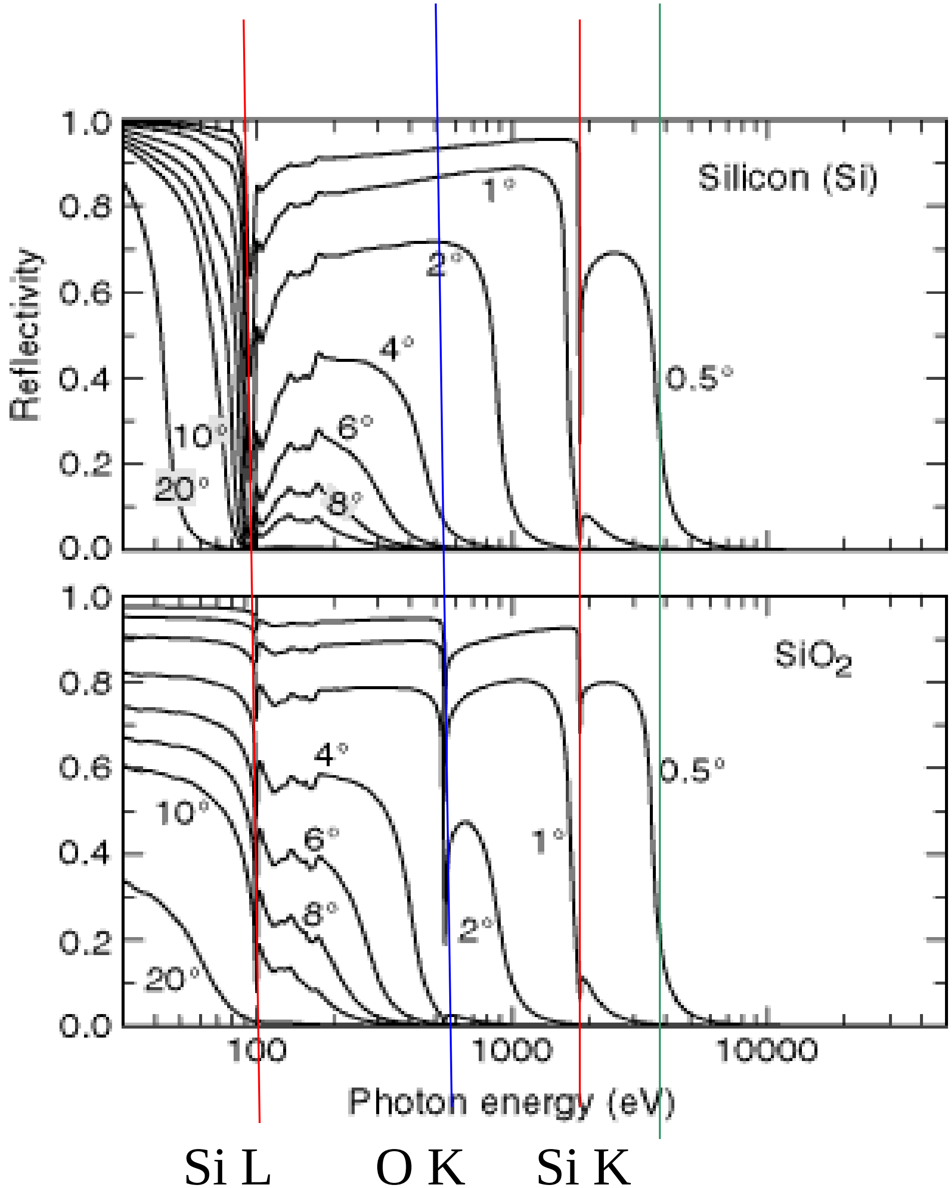
1 rad = 57.3 º, 1º = 17.45 mrad

C K-edge @ 290eV

high energy photon cutoff



Reflectivity as a function of incident energy and angle



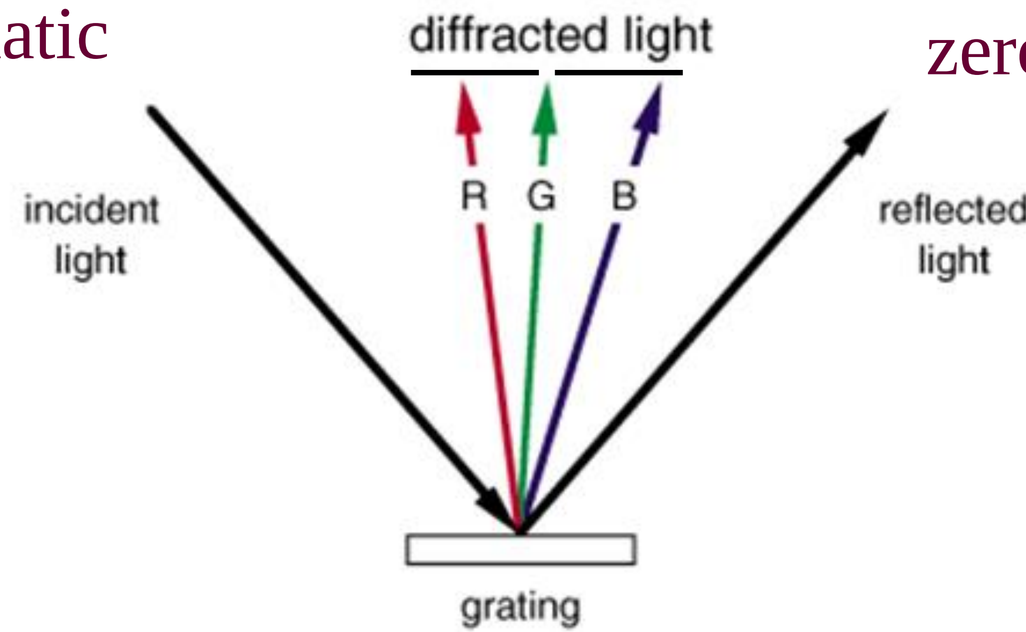
The **energy cutoff** at 0.5 º **angle of incidence** is ~ 4 keV; this property can be used to filter out high energy photons (higher order)

What is a grating and a grating monochromator?

Monochromatic light can be selected with a moving aperture or by rotating the grating

polychromatic

zero order



Grating: arrays of lines with well defined separation and profile

Grating equation

Consider a plane grating, the grating equation is

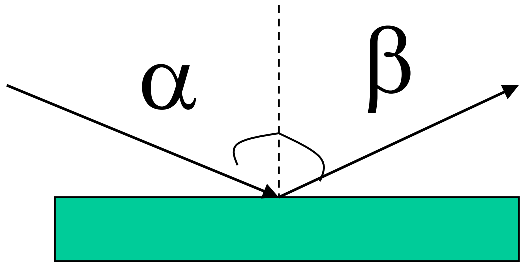
$$n\lambda = d(\sin\alpha + \sin\beta)$$

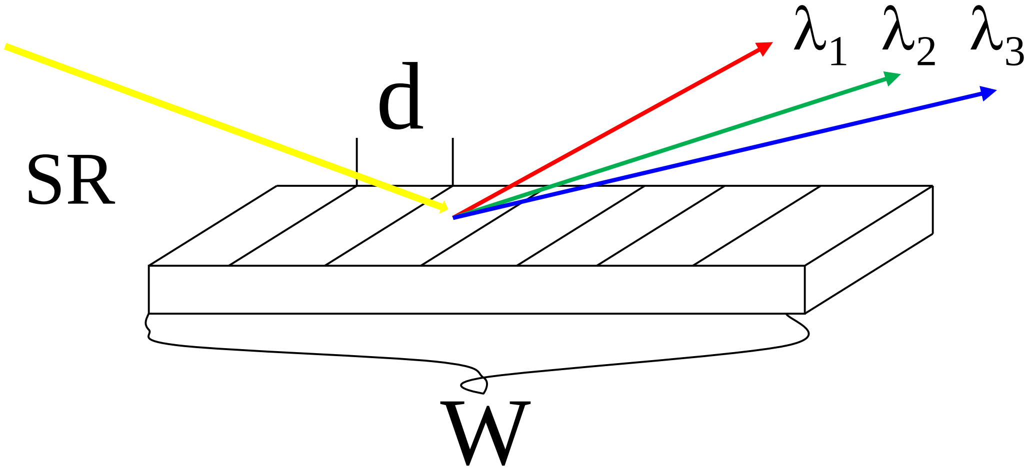
n: order of the diffraction; d: distance between the grating lines; d = W/N where W is the ruled width and N the no. of lines.

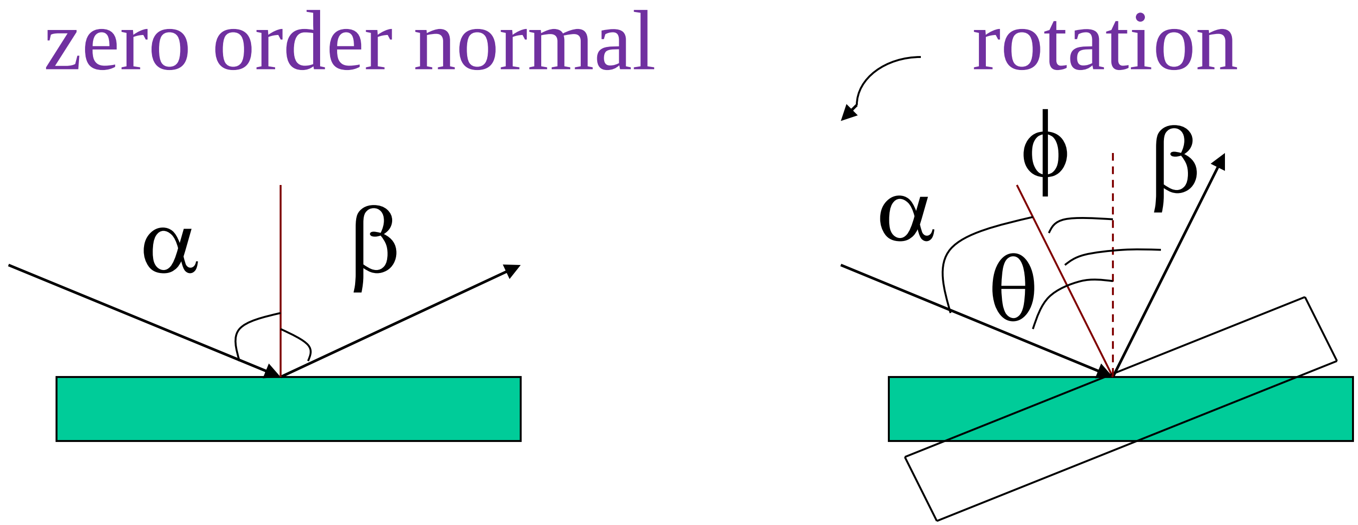
A 800 line grating means 800 lines per mm

α: angle of incidence   β: angle of diffraction

zero order position, α = -β







Φ: angle of rotation of grating away from the zero order position

θ: angle between zero order normal and incident beam

$\alpha = \theta - \phi$, $\beta = -\theta + \phi$; $n\lambda = 2d \cos\theta \sin\phi$

The resolution: $E/\Delta E = \lambda/\Delta\lambda \propto N_l n$

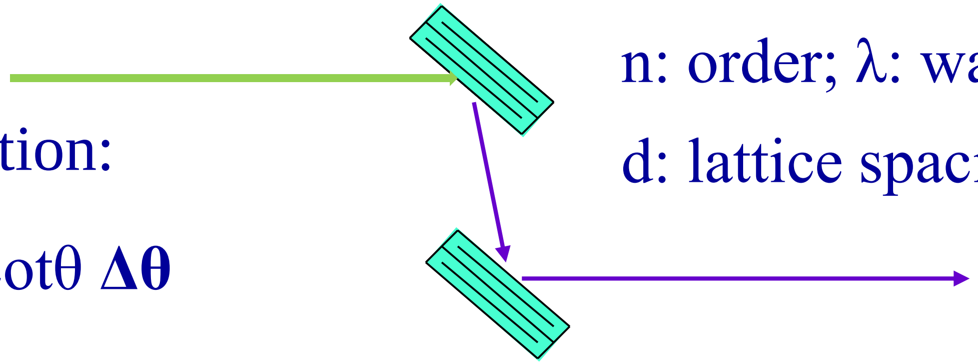
It can be seen high resolution can be obtained with high line density (N_l) grating or the use higher order (n) radiation. E.g.: A 1800 line grating has better resolution than a 1200 line grating

Double Crystal Monochromator (DCM)

Bragg's law $n\lambda = 2d \sin\theta$

n: order; λ: wavelength;

d: lattice spacing; θ: Bragg angle



The resolution:

$\Delta\lambda/\lambda = \cot\theta \, \boldsymbol{\Delta\theta}$

Δθ depends on the inherent width of the crystal (Darwin curve/ **rocking curve**) and the vertical angular spread of the SR

$$\Delta\theta = \sqrt{\Delta\theta^2_{SR} + \Delta\theta^2_{C}}$$

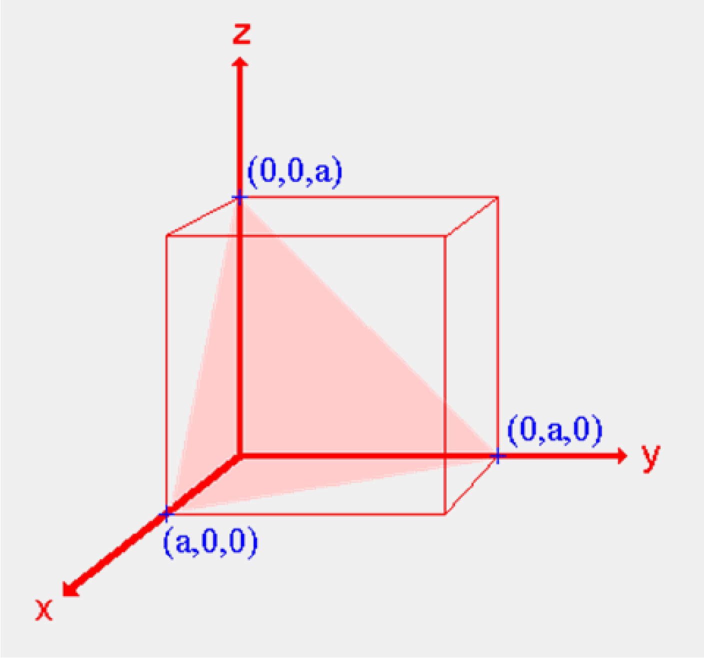
$\Delta\theta_{SR} = \psi$
$\sim (1/\gamma)\, 0.57\, (\lambda/\lambda_C)^{0.43}$ **(rad)**

For most crystals $\Delta\theta_C > \Delta\theta_{SR}$. Crystals used for DCM

Crystal	Bragg Reflection	2d(Å)
Si	(111)	6.271
InSb	(111)	7.481

Crystal planes and Miller indices

Miller indexes (h,k,l) are used to define parallel planes in a crystal from which the inter-planar spacing ***d*** can be obtained

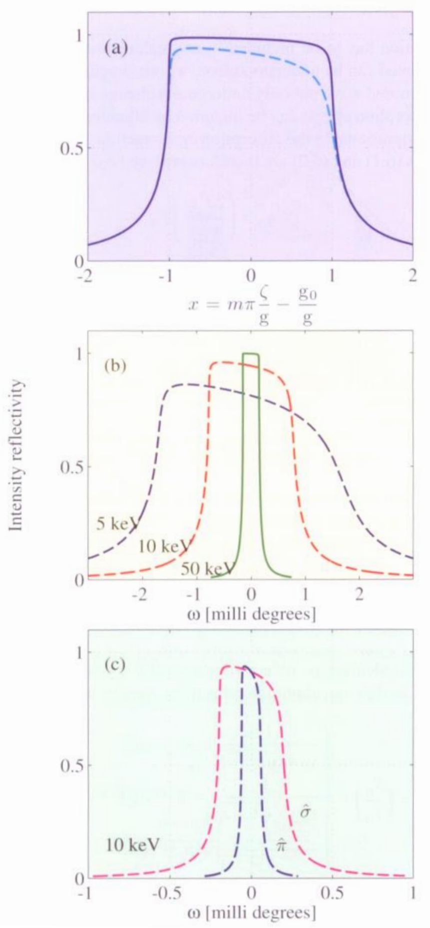


For a cubic crystal, the Miller indices (111) refers to the set of planes that is parallel to the plane that intercepts the three axes at x = a, y = a and z = a

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

Exercise: work out the lattice spacing for Si(111) shown above

What is a Darwin (rocking) curve ?



(a) Darwin curve of Si(111), reflectivity is 100% for *x* between -1 and 1,

(b) Darwin curve of Si(111) as a function of rotation angle @ 3 energies

(c) Darwin curve of Si(333) with different polarization

$$W = \zeta \tan\theta$$

	$\Delta\theta_C = w = \zeta \tan\theta$ (mrad)		
hv = 8050 eV	(111) $\tan\theta$ = 0.2534	(220) $\tan\theta$ = 0.4379	(400)
Si a = 5.4309 Å	ζ =139.8 x10^{-3} mrad	ζ =61.1.8 x10^{-3}	ζ =26.3 x10^{-3}
Ge a = 5.6578 Å	ζ =347.2 x10^{-3}	ζ =160.8 x10^{-3}	ζ =68.8 x10^{-3}