Generating X-rays: the machines

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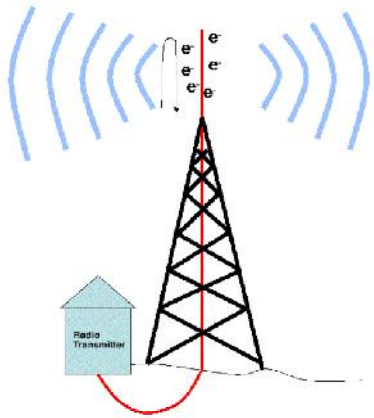
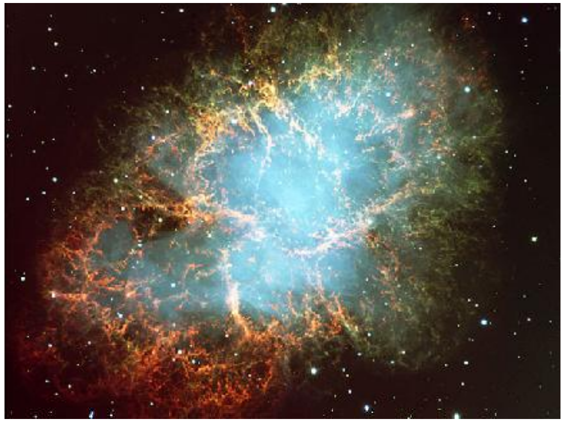
modern developments in FELs

Synchrotron radiation

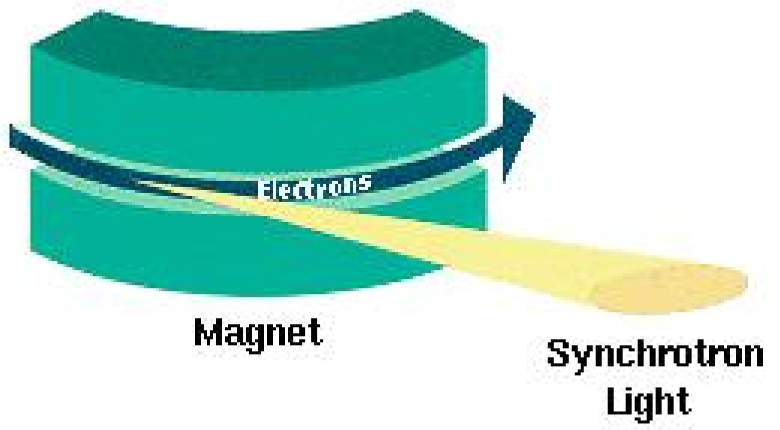
Electromagnetic radiation is emitted by charged particles when accelerated

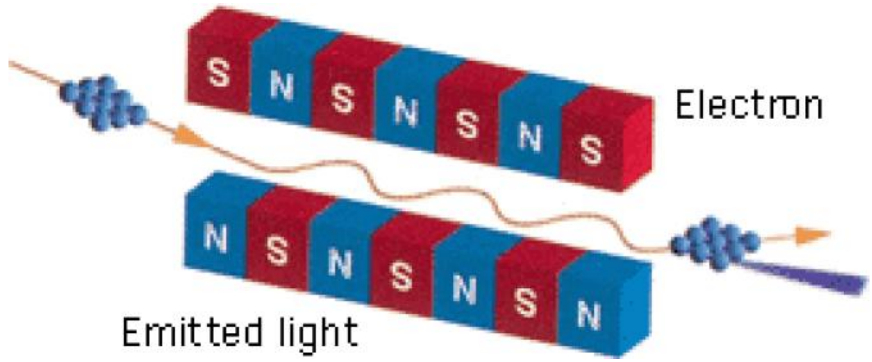




The electromagnetic radiation emitted when the charged particles are accelerated radially (v ⊥ a) is called synchrotron radiation

It is produced in the synchrotron radiation sources using bending magnets undulators and wigglers



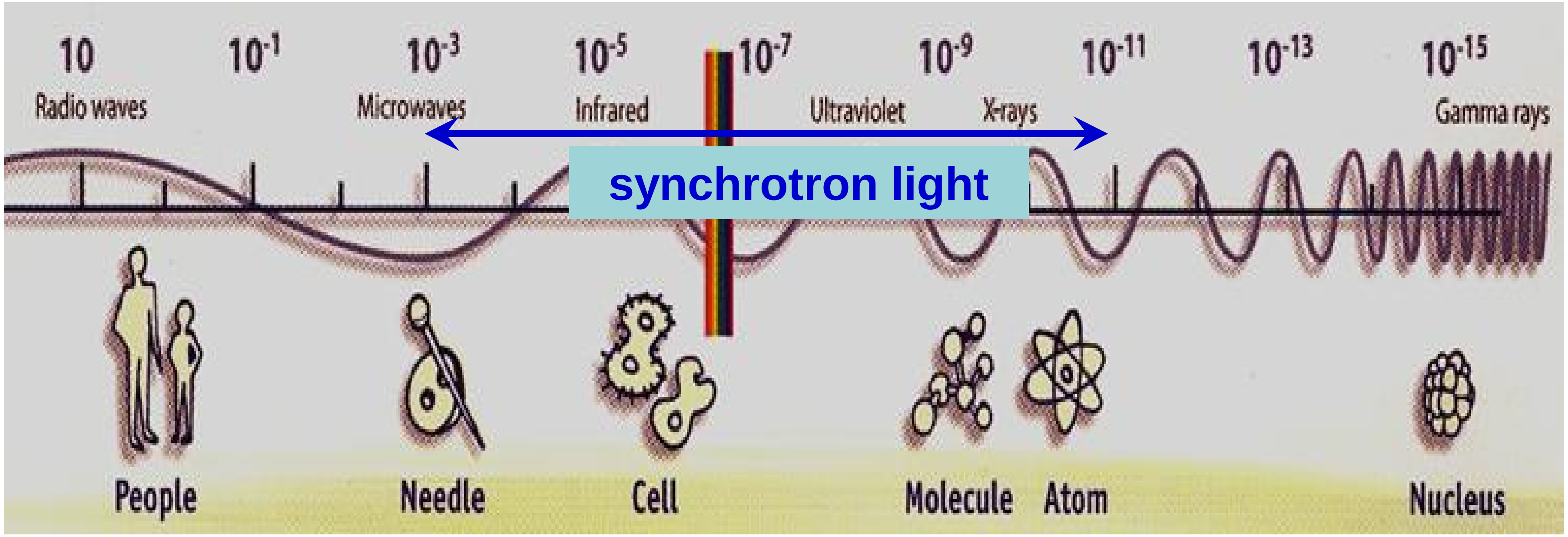


Synchrotron radiation sources properties (I)

Broad Spectrum **which covers from microwaves to hard X-rays:**

the user can select the wavelength required for experiment;

either with a monochromator
or adjusting the emission wavelength of insertion devices



Synchrotron radiation sources properties (II)

High Flux: high intensity photon beam, allows rapid experiments or use of weakly scattering crystals;

Flux = Photons / (s õ BW)

High Brilliance (Spectral Brightness): highly collimated photon beam generated by a small divergence and small size source

Brilliance = Photons / (s õ mm^2 õ $mrad^2$ õ BW)

Partial coherence in SRs

Full T coherence in FELs

Polarisation: both linear and circular (with IDs)

Pulsed Time Structure: pulsed length down to

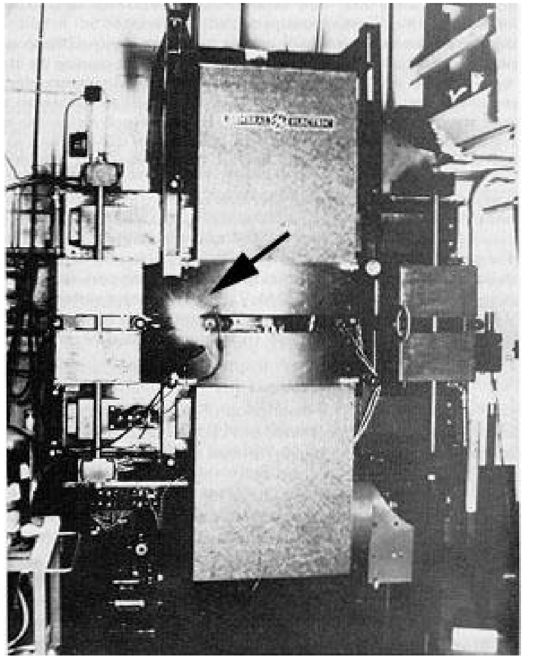
10s ps in SRs

10s fs in FELs

High Stability: submicron source stability in SR

… and **it can be computed!**

Evolution of synchrotron radiation sources (I)



- **First observation**:

  1947, General Electric, 70 MeV synchrotron

- **First user experiments**:

  1956, Cornell, 320 MeV synchrotron

- **1st generation light sources**: machine built for High Energy Physics or other purposes used parasitically for synchrotron radiation

- **2nd generation light sources**: purpose built synchrotron light sources, SRS at Daresbury was the first dedicated machine (1981 – 2008)

- **3rd generation light sources**: optimised for high brilliance with low emittance and Insertion Devices; ESRF, Diamond, …

Evolution of synchrotron radiation sources (II)

• **4th generation light sources**: photoinjectors LINAC based Free Electron Laser sources;

FLASH (DESY) 2007

LCLS (SLAC) 2009

SACLA (Japan) 2011

Elettra (Italy) 2012

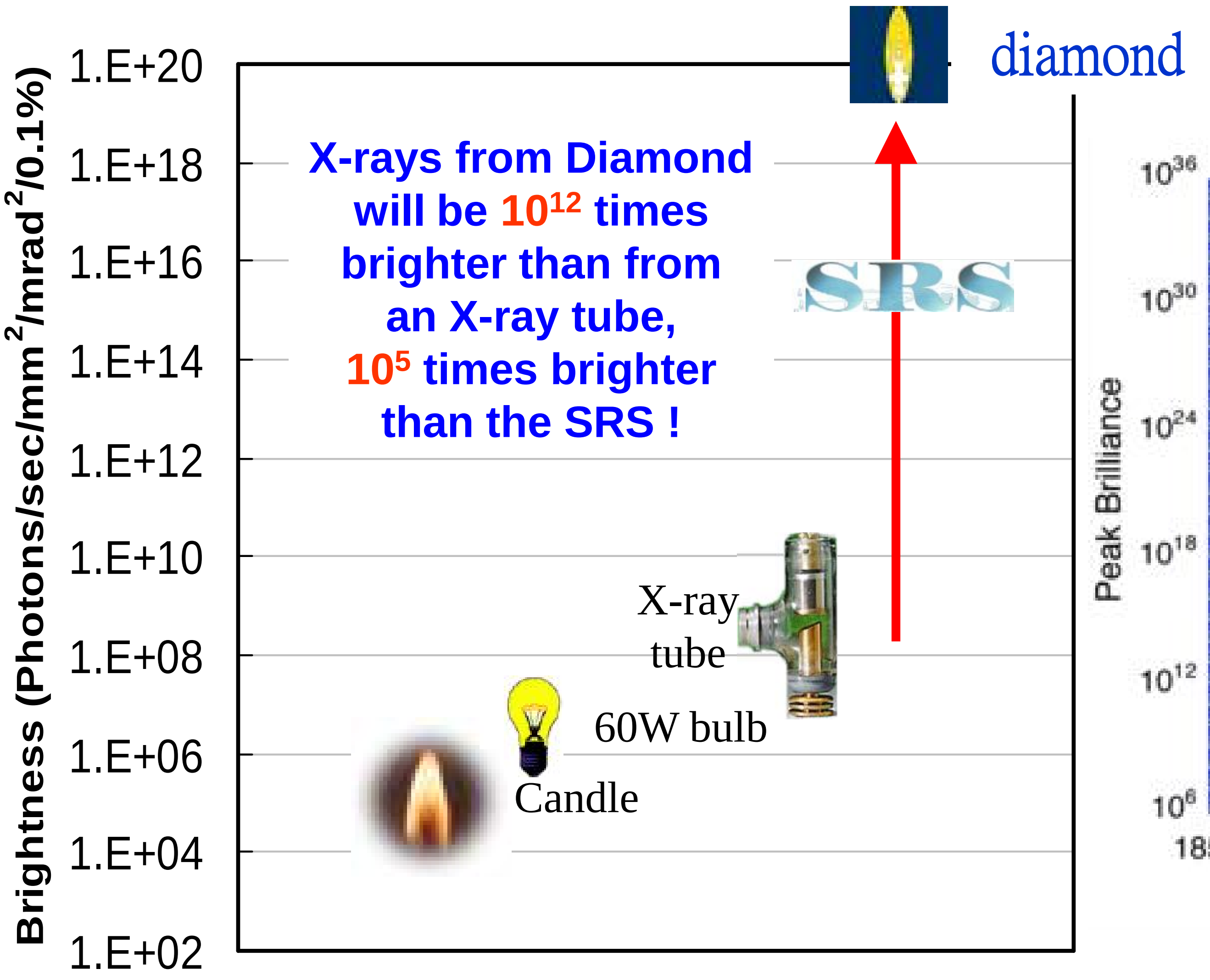
under construction European-XFEL – Swiss FEL – Pohang FEL

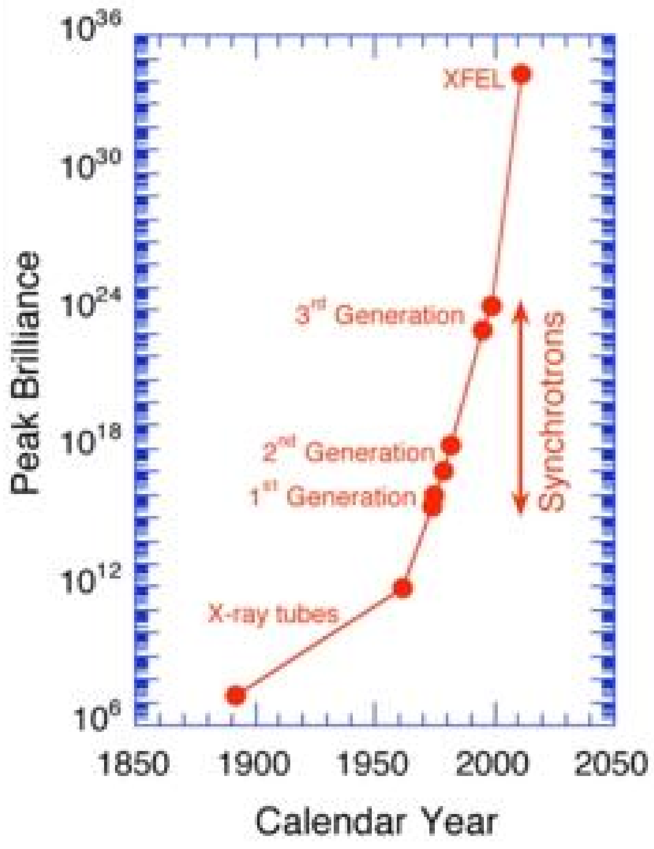
and in the near(?) future

• **4th generation light sources storage ring based**: diffraction limited storage rings

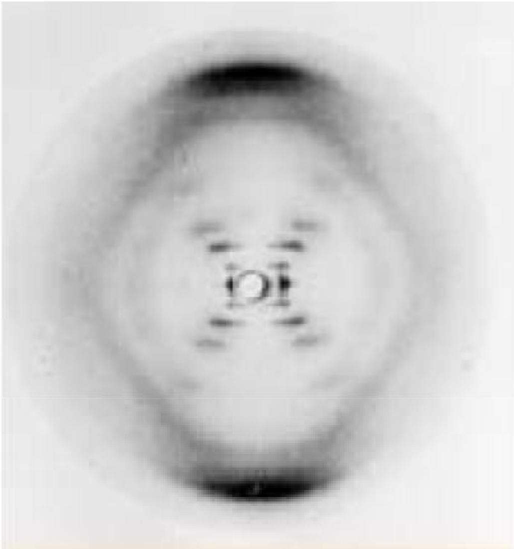
• …and even a **5th generation** with more compact and advanced accelerator technologies e.g. based on laser plasma wakefield accelerators

Peak Brilliance





Life science examples: DNA and myoglobin



Photograph 51
Franklin-Gosling

DNA (form B)

1952

Franklin and Gosling used a X-ray tube:

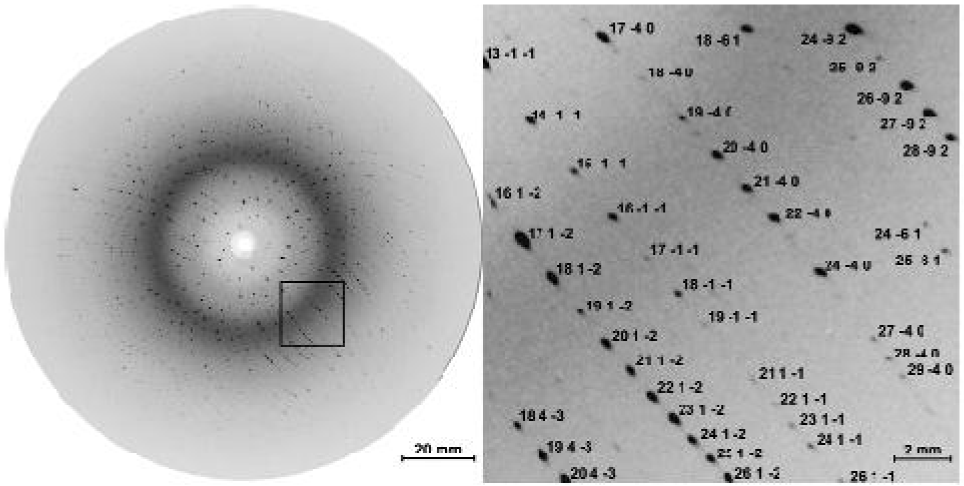
Brilliance was 10^8 (ph/sec/mm^2/mrad^2/0.1BW)

Exposure times of 1 day were typical (10^5 sec)

e.g. Diamond provides a brilliance of 10^{20}

100 ns exposure would be sufficient

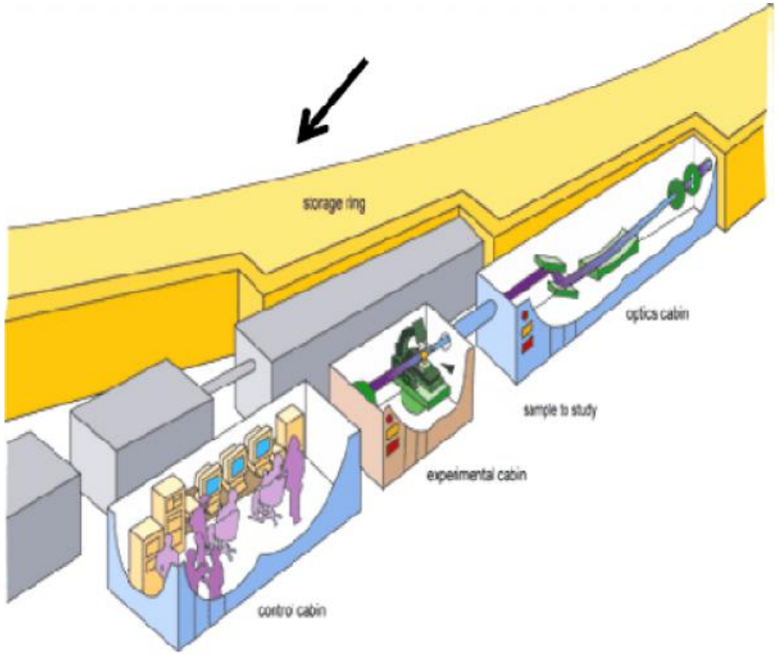
Nowadays pump probe experiment in life science are performed using 100 ps pulses from storage ring light sources: e.g. ESRF myoglobin in action

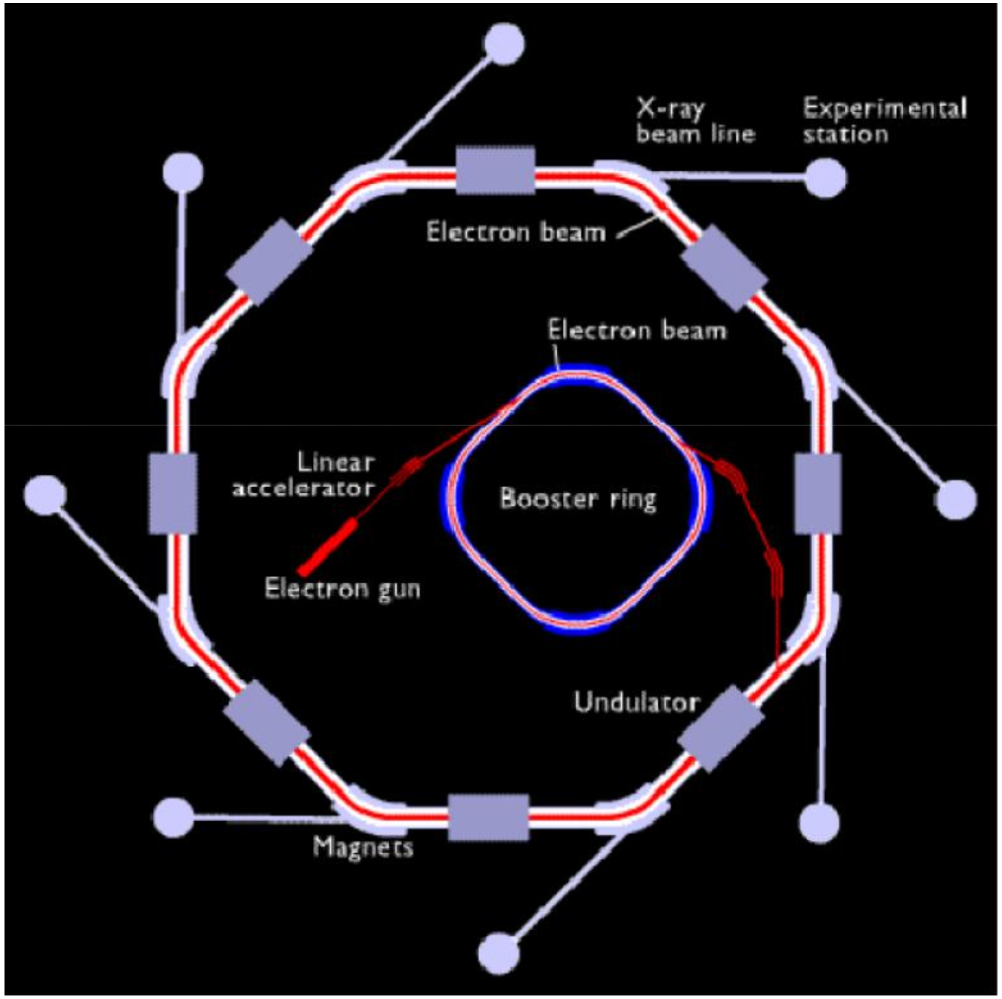


Layout of a synchrotron radiation source

Electrons are generated and accelerated in a <u>linac</u>, further accelerated to the required energy in a <u>booster</u> and injected and stored in the <u>storage ring</u>

The circulating electrons emit an intense beam of synchrotron radiation which is sent down the beamline





3rd generation storage ring light sources

1992	**ESRF**, France (EU)	6 GeV
	ALS, US	1.5-1.9 GeV
1993	**TLS,** Taiwan	1.5 GeV
1994	**ELETTRA**, Italy	2.4 GeV
	PLS, Korea	2 GeV
	MAX II, Sweden	1.5 GeV
1996	**APS**, US	7 GeV
	LNLS, Brazil	1.35 GeV
1997	**Spring-8**, Japan	8 GeV
1998	**BESSY II**, Germany	1.9 GeV
2000	**ANKA**, Germany	2.5 GeV
	SLS, Switzerland	2.4 GeV
2004	**SPEAR3**, US	3 GeV
	CLS, Canada	2.9 GeV
2006:	**SOLEIL**, France	2.8 GeV
	DIAMOND, UK	3 GeV
	ASP, Australia3 GeV	
	MAX III, Sweden	700 MeV
	Indus-II, India	2.5 GeV
2008	**SSRF**, China	3.4 GeV
2009	**PETRA-III**, Germany	6 GeV
2011	**ALBA**, Spain	3 GeV

3rd generation storage ring light sources

in commissioning or under construction

2014	**NSLS-II**, US	3 GeV
2015	**SOLARIS**, Poland	1.5 GeV
2016	**MAX-IV**, Sweden	1.5-3 GeV

planned

> 2016	**SESAME**, Jordan	2.5 GeV
	TPS, Taiwan	3 GeV
	CANDLE, Armenia	3 GeV

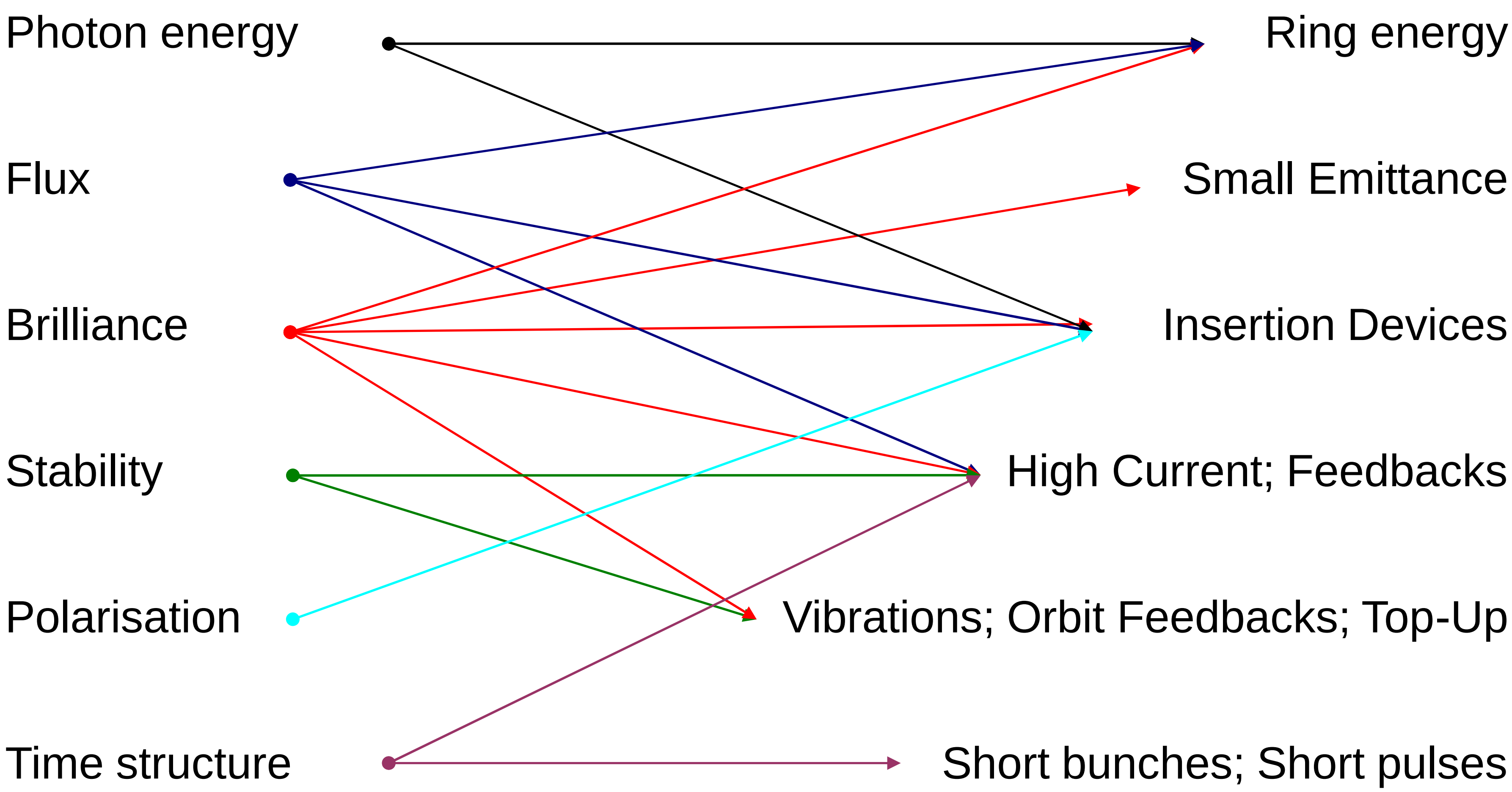
major upgrades

2019	**ESRF-II**, France	6 GeV
> 2020	**Spring8-II**, Japan	6 GeV
	APSU, US	6 GeV

Many existing facilities are studying upgrades – Diamond, SLS, ALS, Soleil, …

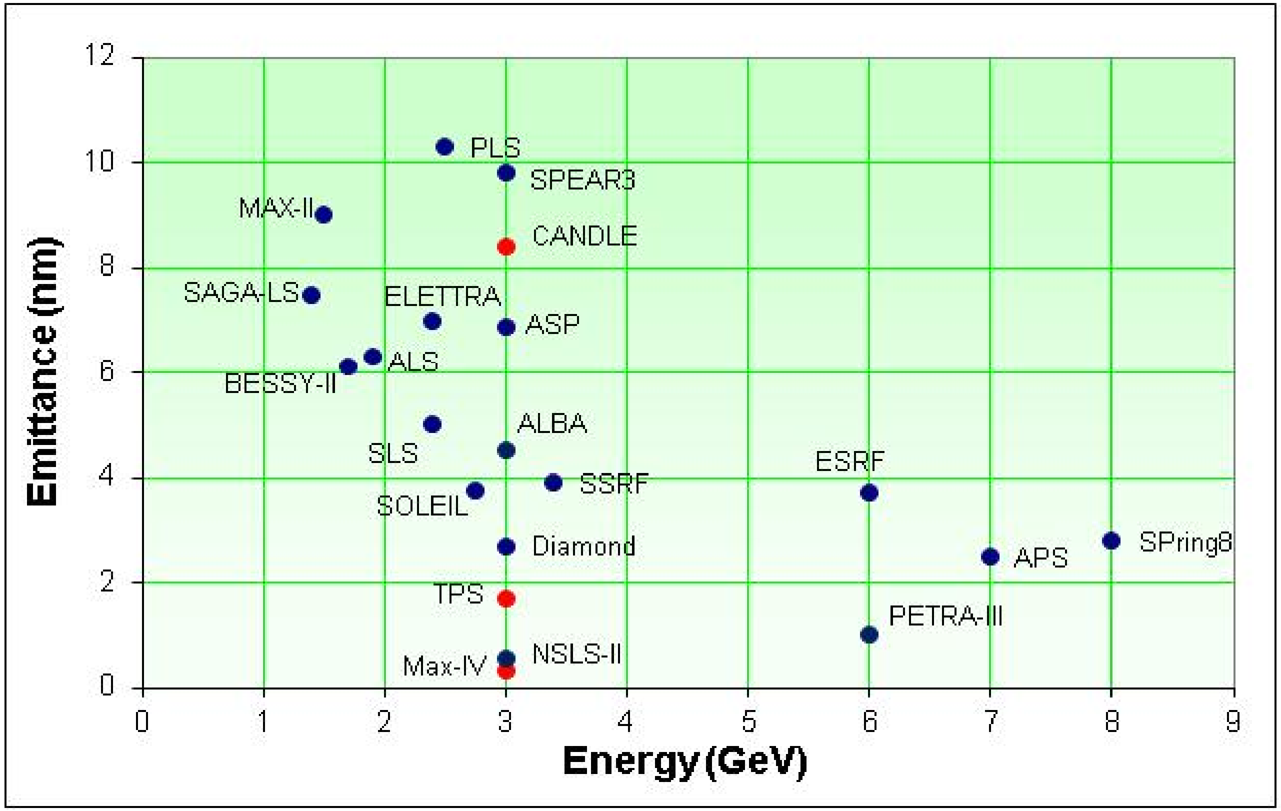
Diamond aerial views

Accelerator physics and technology challenges



Brilliance and low emittance

The brilliance of the photon beam is determined (mostly) by the electron beam emittance that defines the source size and divergence



- operating
- under construction

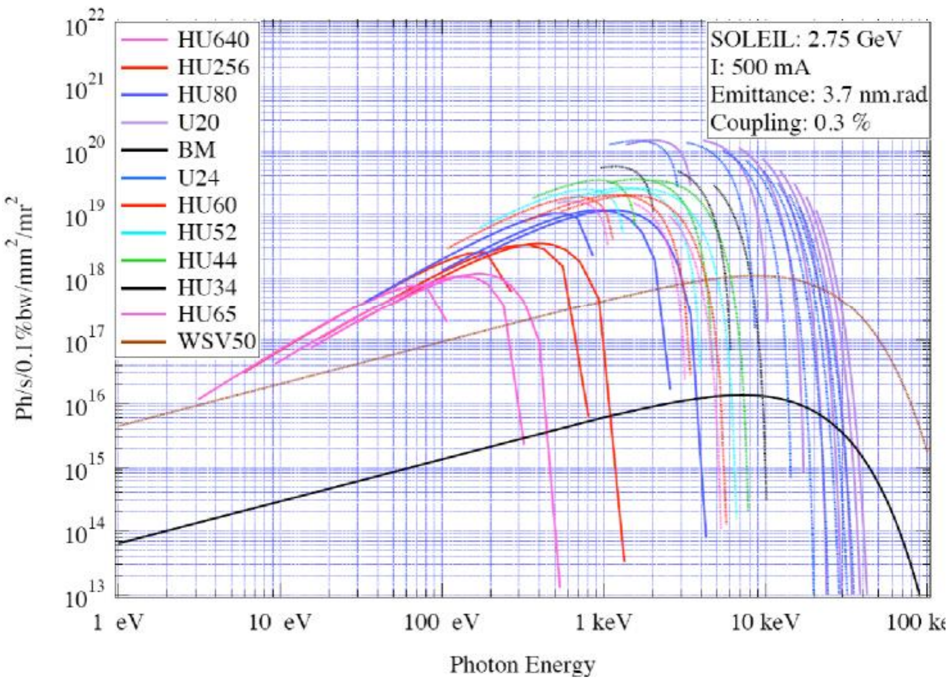
$$\text{brilliance} = \frac{\text{flux}}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

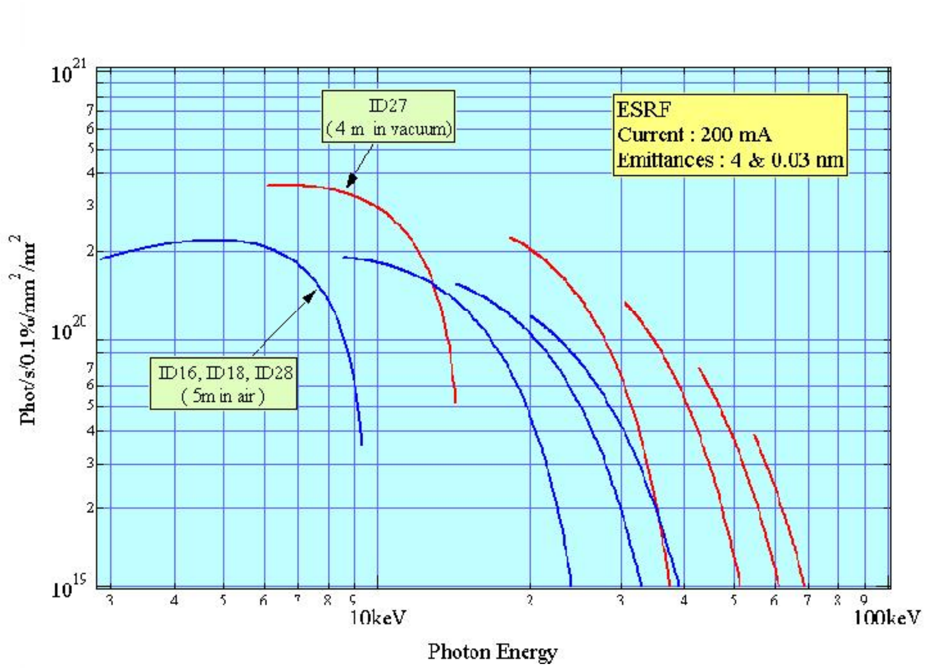
$$\Sigma_x = \sqrt{\sigma_{x,e}^2 + \sigma_{ph,e}^2} \qquad \sigma_x = \sqrt{\varepsilon_x \;{}_x + (D_x \sigma_\varepsilon)^2}$$

$$\Sigma_{x'} = \sqrt{\sigma_{x',e}^2 + \sigma'^2_{ph,e}} \qquad \sigma_{x'} = \sqrt{\varepsilon_x \;{}_x + (D'_x \sigma_\varepsilon)^2}$$

Brilliance with IDs

Thanks to the progress with IDs technology storage ring light sources can cover a photon range from few tens of eV to tens 10 keV or more with high brilliance





Medium energy storage rings with In-vacuum undulators operated at low gaps (e.g. 5-7 mm) can reach 10 keV with a brilliance of 10^{20} ph/s/0.1%BW/mm^2/mrad^2

Main components of a storage ring

Dipole magnets to bend the electrons

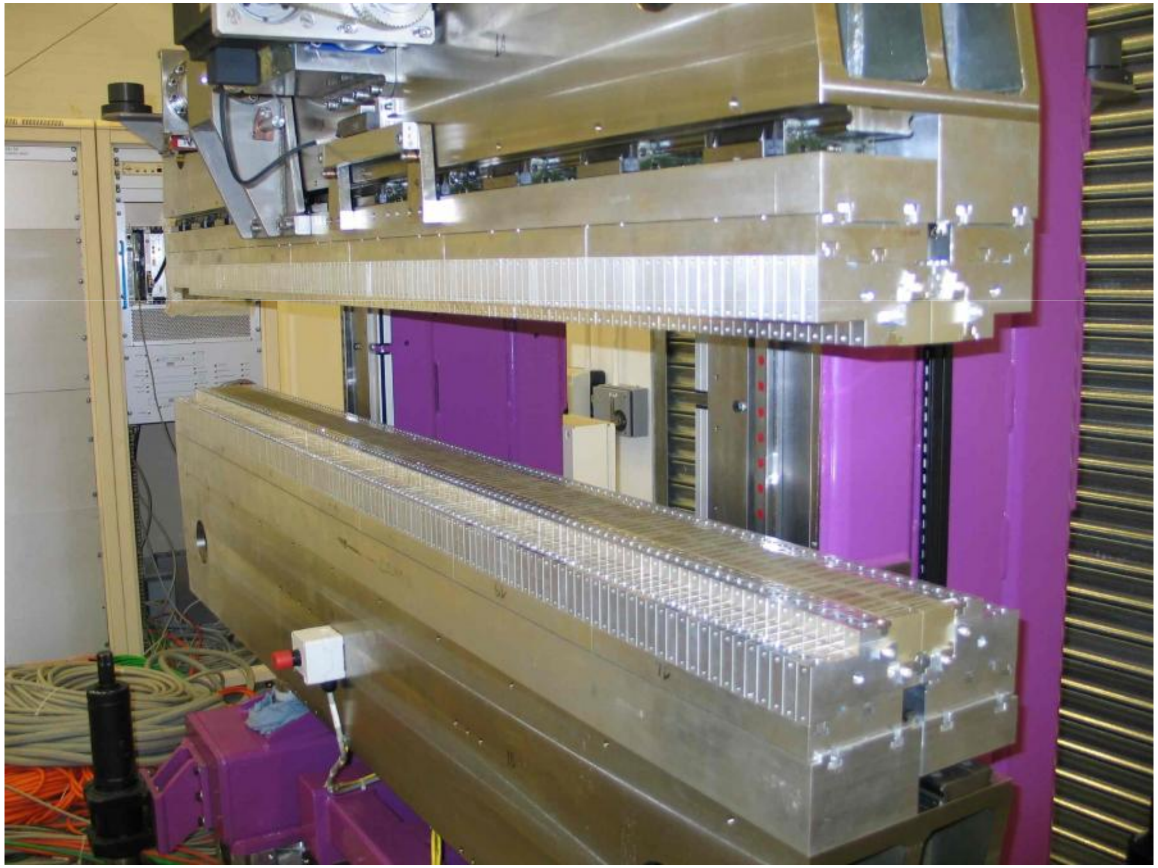
Quadrupole magnets to focus the electrons

Sextupole magnets to focus off-energy electrons (mainly)

RF cavities to replace energy losses due to the emission of synchrotron radiation

Main components of a storage ring

Insertion devices (undulators) to generate high brilliance radiation



Insertion devices (wiggler) to reach high photon energies

Generating the X-rays

Calculation of synchrotron radiation

radiation from bending magnets

radiation from undulators and wigglers

types of undulator and wigglers

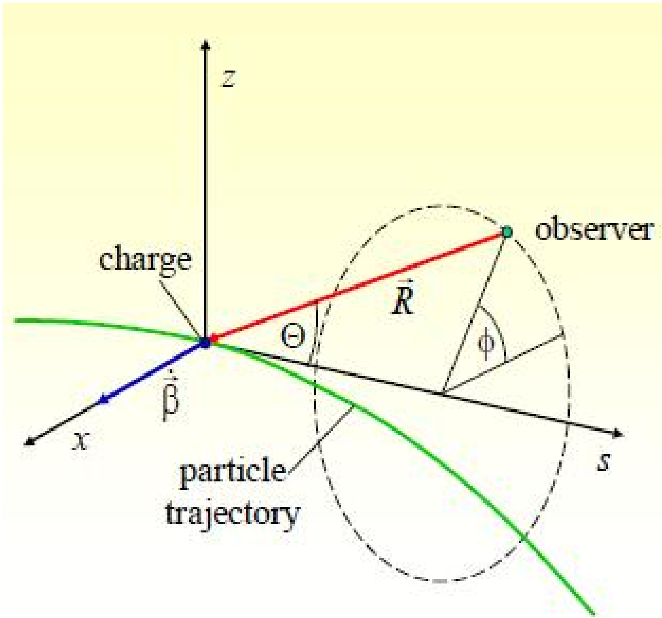
Calculation of synchrotron radiation

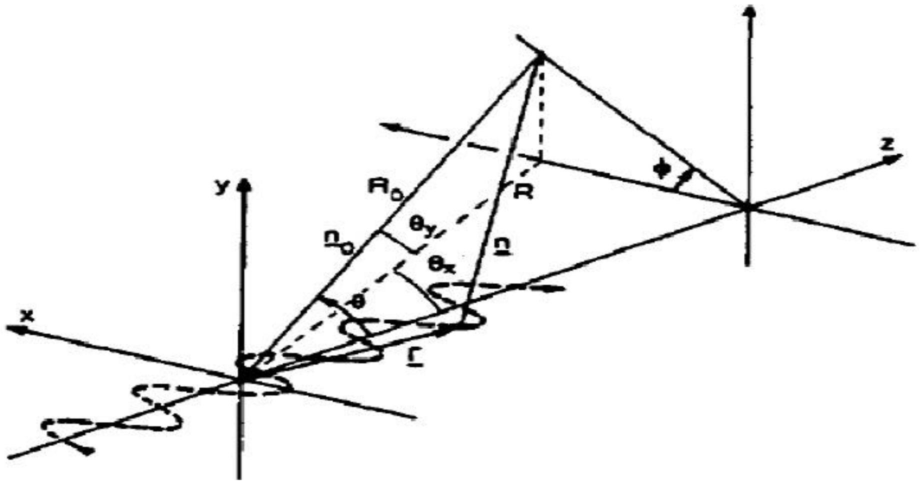
The angular and frequency distribution of the energy emitted by a charged particle in a magnetic field is computed from **[Jackson, Chapter 14]**

Maxwell's equations ì Lienard-Wiechert potentials ì radiation integral

$$\frac{d^3W}{d\Omega\, d\mu} = \frac{e^2 \mu^2}{4®£_0\, 4®^2 c} \left| \int_{-\infty}^{\infty} \hat{n} \times (\hat{n} \times \bar{\ }) e^{i\mu(t - \hat{n}\cdot\bar{r}/c)} dt \right|^2$$

once the trajectory of the charged particle is known

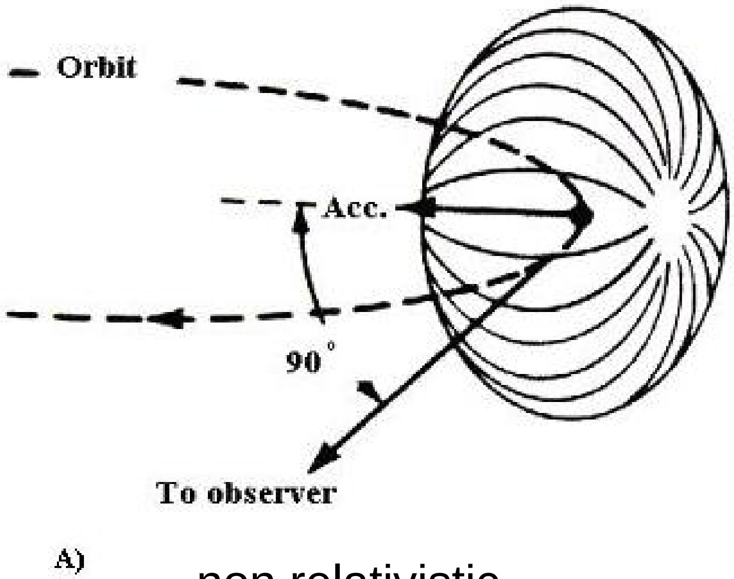




Radiation from a bending magnet (I)

In a bending magnet ¯ ⊥ ˙ the *angular distribution of the radiated power*

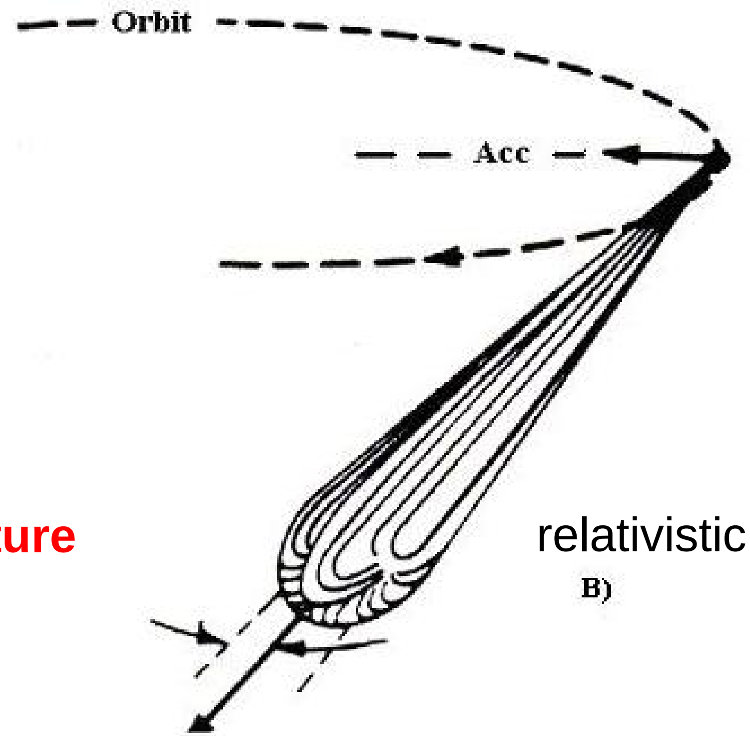
$$\frac{d^2P}{d\Omega} = \frac{e^2\left|\dot{\beta}\right|^2}{(4\pi)^2\,\varepsilon_0 c}\,\frac{1}{(1-\beta\cos\theta)^3}\left[1-\frac{\sin^2\theta\cos^2\phi}{\gamma^2(1-\beta\cos\theta)^2}\right]$$



non relativistic

cone aperture

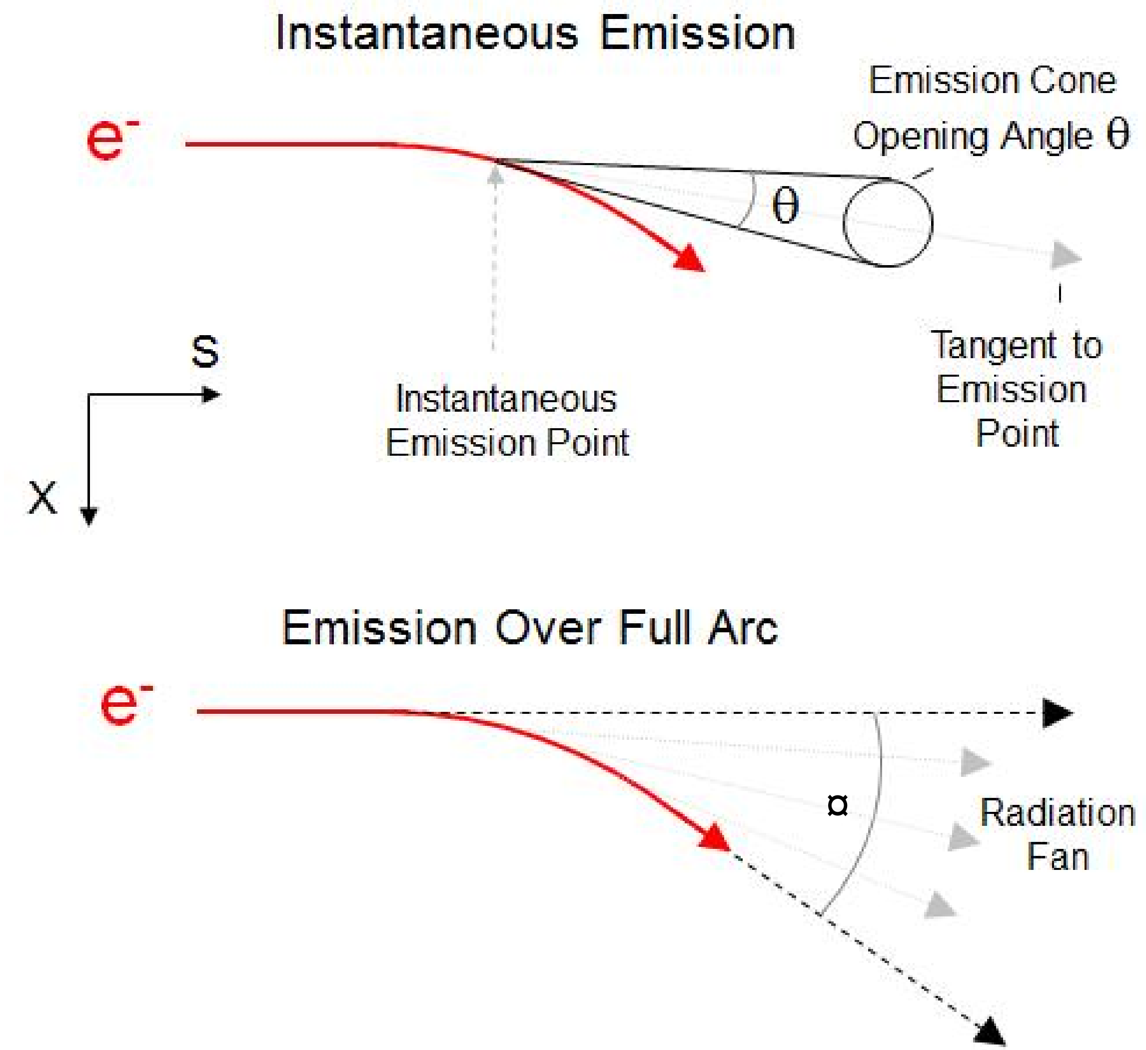
¼ 1/¥



relativistic

When the electron velocity approaches the speed of light, the emission pattern is sharply collimated forward

Radiation from a bending magnet (II)



Assuming that the total power is radiated in one turn (in a uniform distribution) in the angle ¤

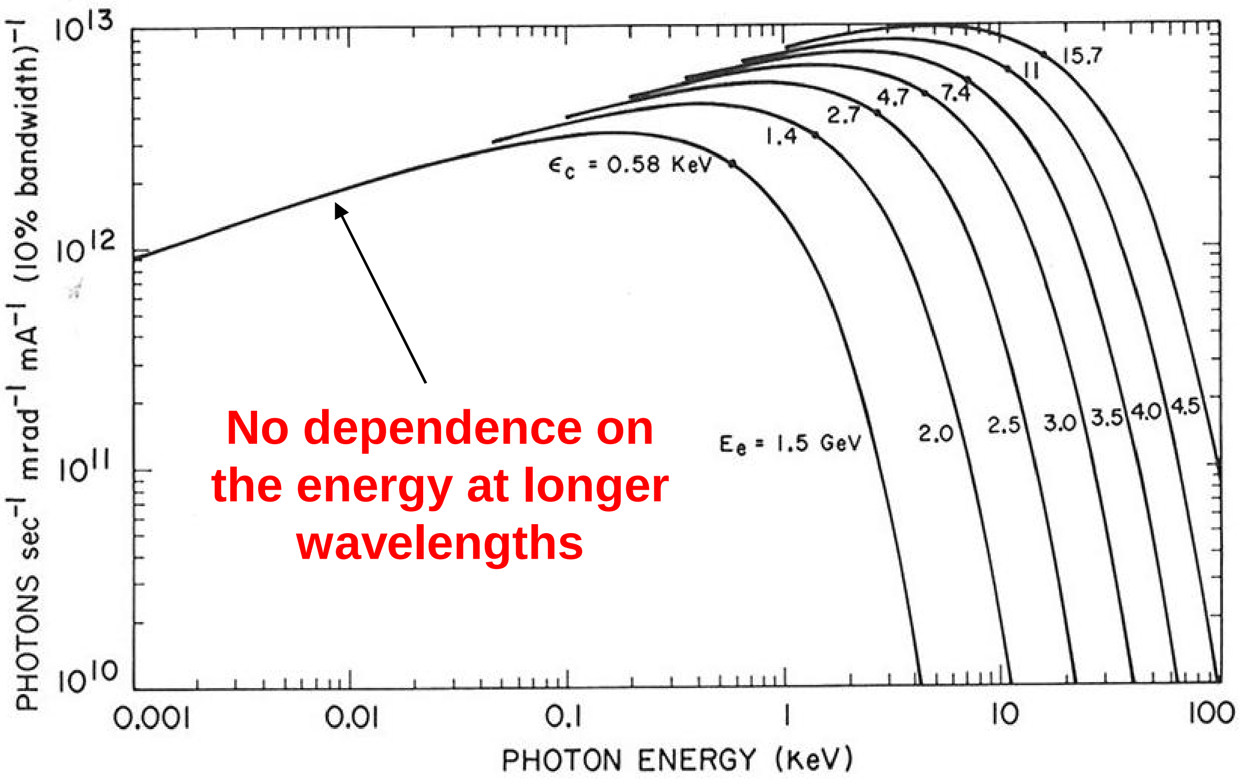
The angular distribution of the power emitted in ¤ (integrated in the vertical aperture) is

$$\frac{dP}{d\phi} = \frac{P}{2\pi} = \frac{e^2 \left|\dot{\vec{v}}\right|^2}{12\pi^2 \varepsilon_0 c^3} \gamma^4$$

Do not mix up ¤ and ¯…

Synchrotron radiation emission from a bending magnet

Dependence of the frequency distribution of the energy radiated via synchrotron emission on the electron beam energy



Critical frequency

$$\omega_c = \frac{3}{2}\frac{c}{\rho}\gamma^3$$

Critical angle

$$\theta_c = \frac{1}{\gamma}\left(\frac{\omega_c}{\omega}\right)^{1/3}$$

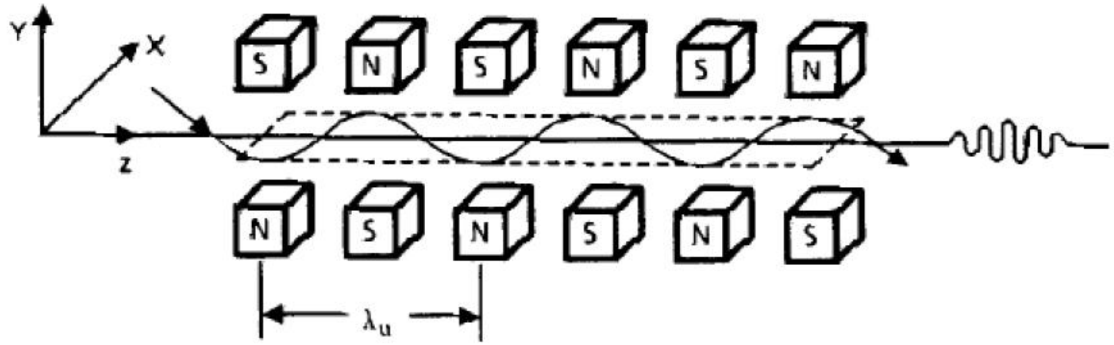
Critical energy

$$\varepsilon_c = \hbar\omega_c = \frac{3}{2}\frac{\hbar c}{\rho}\gamma^3$$

The critical frequency splits the total radiated power in two equal parts

Undulators and wigglers

Periodic array of magnetic poles providing a sinusoidal magnetic field on axis:



$$B = (0, \quad B_0 \sin(k_u z), \quad 0,)$$

Solution of equation of motions:

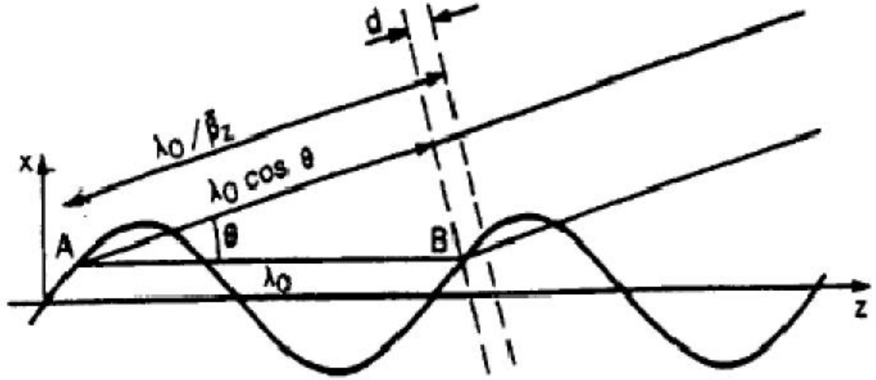
$$K = \frac{eB_0 \lambda_u}{2\pi mc}$$

Undulator parameter

$$\bar{r}(t) = -\frac{\lambda_u K}{2\pi\gamma} \sin \omega_u t \cdot \hat{x} + \left(\bar{\beta}_z ct + \frac{\lambda_u K^2}{16\pi\gamma^2} \cos(2\omega_u t) \right) \cdot \hat{z}$$

$$\bar{\beta}_z = 1 - \frac{1}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Constructive interference of radiation emitted at different poles



$$d = \frac{\lambda_u}{\bar{\beta}} - \lambda_u \cos\theta = n\lambda$$

$$\lambda_n = \frac{\lambda_u}{2\gamma^2 n}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

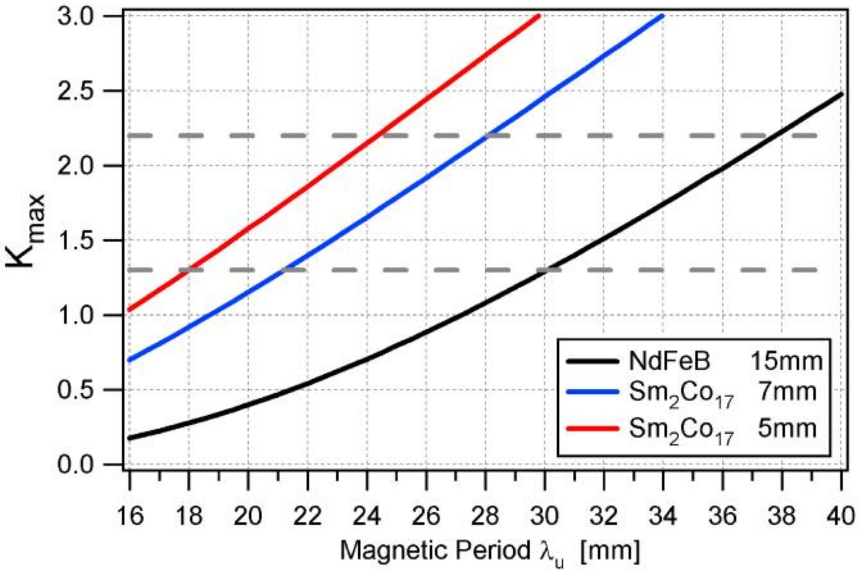
The undulator parameter K

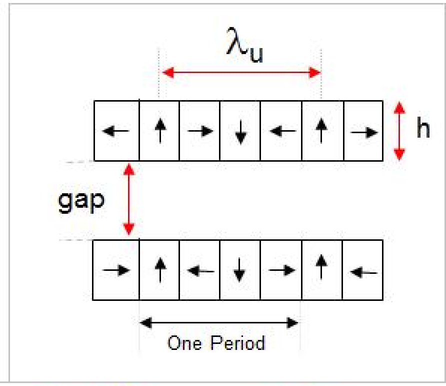
$$K = \frac{eB_0 \lambda_u}{2\pi mc}$$ Undulator parameter

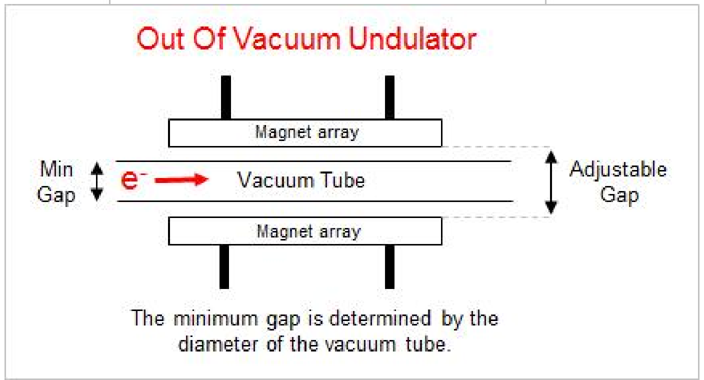
B_0 is the peak magnetic field on axis

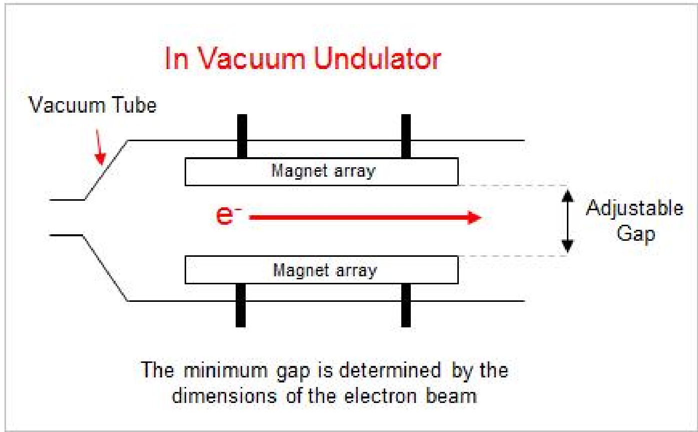
$$K = 0.168\ B_r \lambda_u\ e^{-\frac{\pi\,gap}{\lambda_u}}$$

lengths in [mm], B_r in [Tesla]
(K expression assumes $h > \lambda_u/2$)

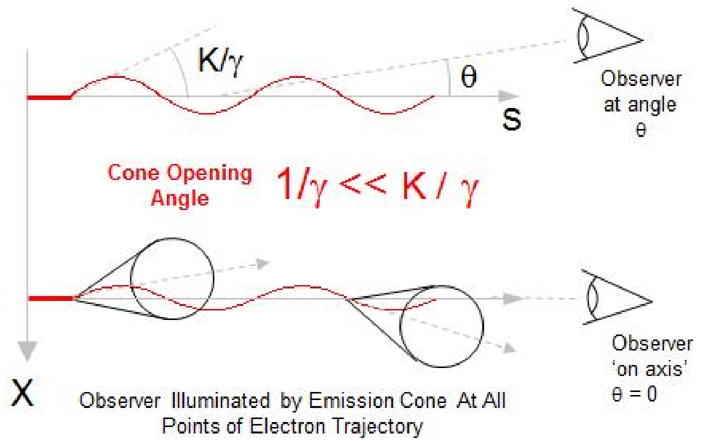






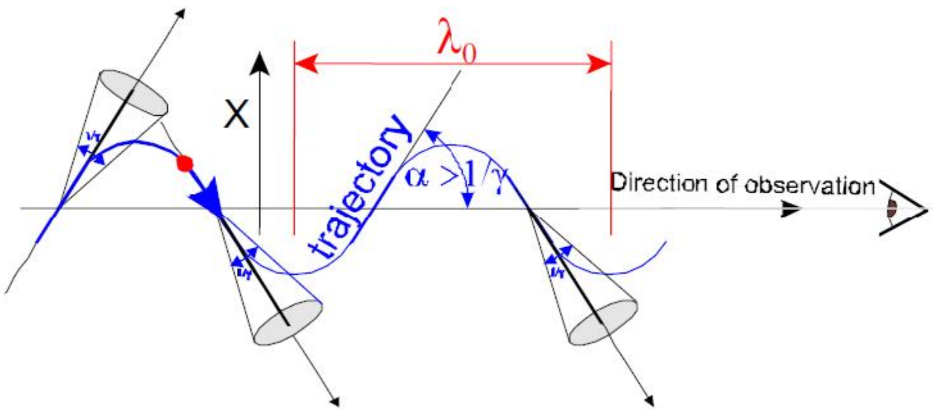


Emission from an undulator (I)



Case 1: K << 1

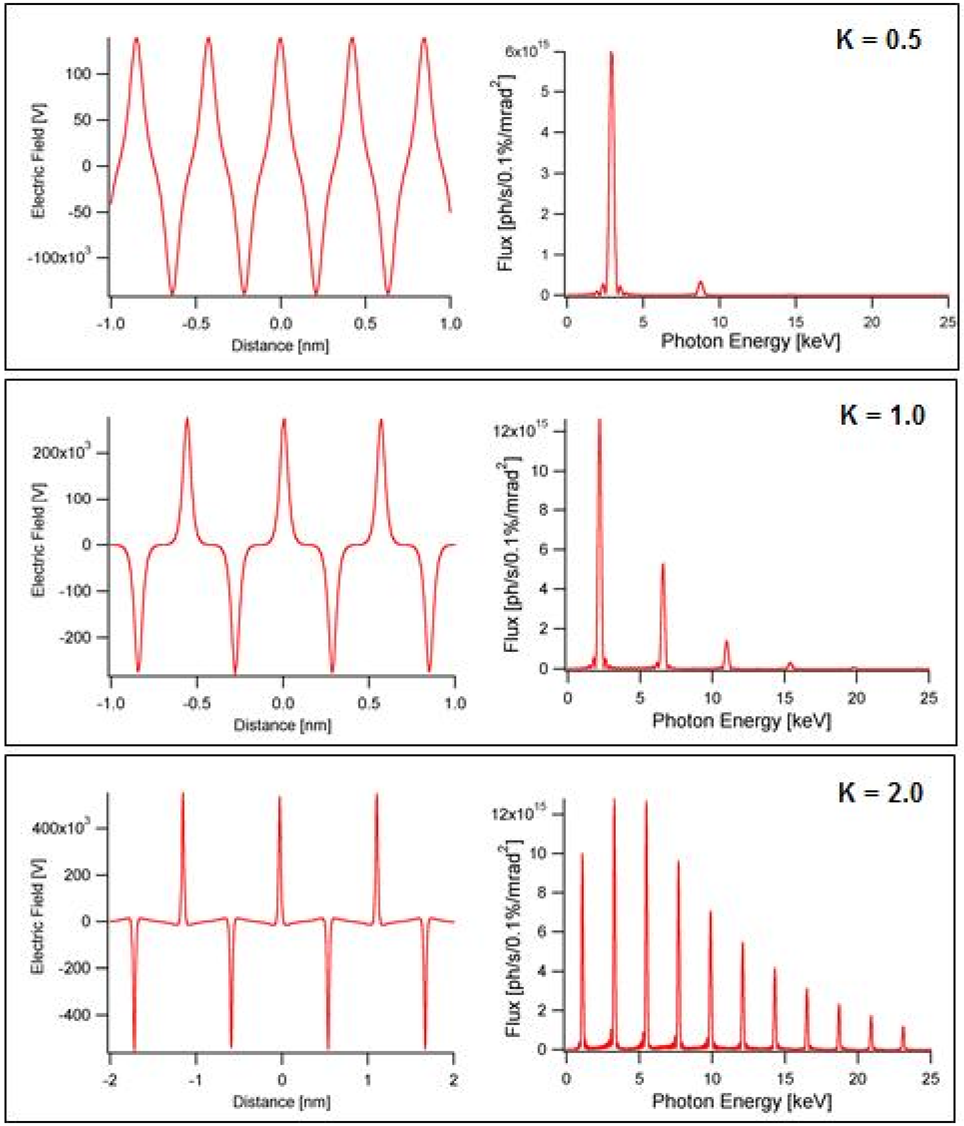
The max angular deflection is much less than the cone opening angle. The observes sees the radiation form the whole undulator length



Case 2: K ~ 1 or K >> 1

The max angular deflection is larger than the cone opening angle. The observer misses part of the radiation as the radiation fan sweeps right/left

Emission from an undulator (II)



Case 1: K << 1

The max angular deflection is much less than the cone opening angle. The observes sees the radiation form the whole undulator length

Case 2: K ~ 1 or K >> 1

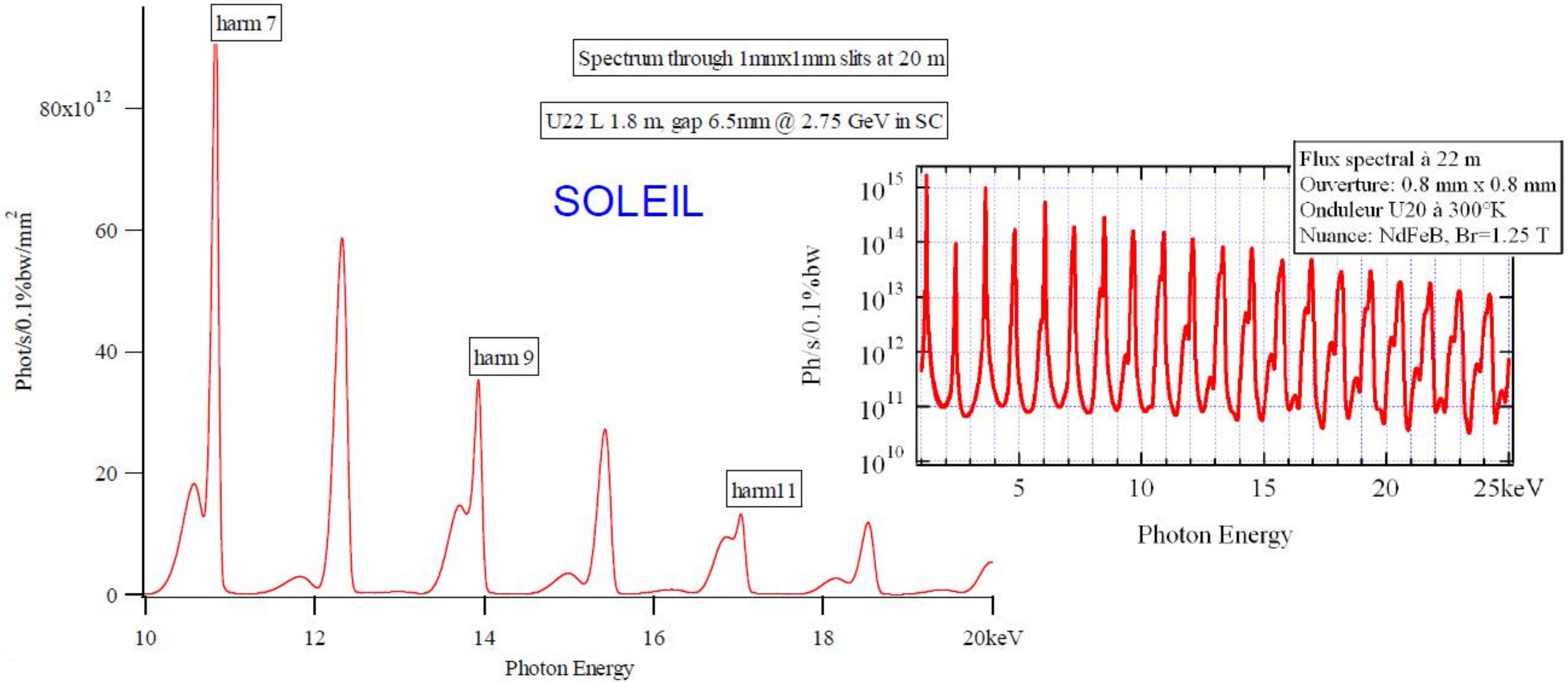
The max angular deflection is larger than the cone opening angle. The observer misses part of the radiation as the radiation fan sweeps right/left

Spectrum of undulator radiation

Interferences along the N periods =>

Discrete lines spectrum with :

- Line width scaling as $(\Delta\lambda/\lambda)_{\text{harm n}} \sim 1/nN$
- Peak value scaling as N^2



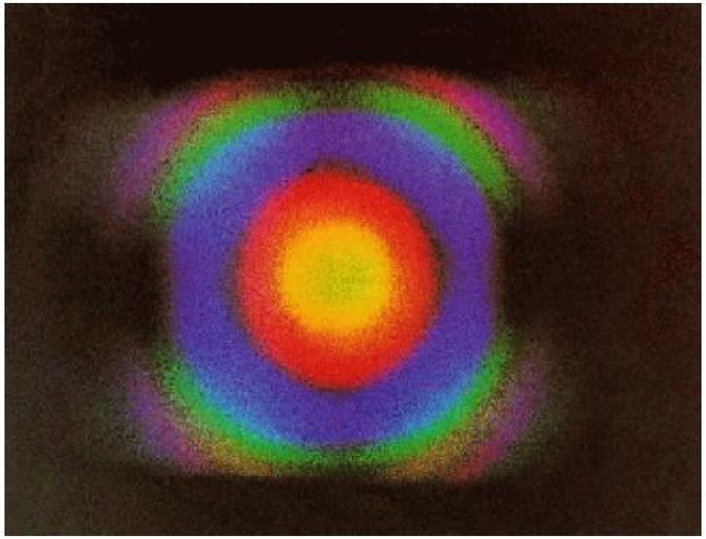
Courtesy J.M Filhol

Angular dependence of undulator radiation

Wave length emitted on harmonic n

$$\lambda_n = \lambda_u (1 + K^2/2 + \gamma^2\theta^2) / (2n\,\gamma^2)$$

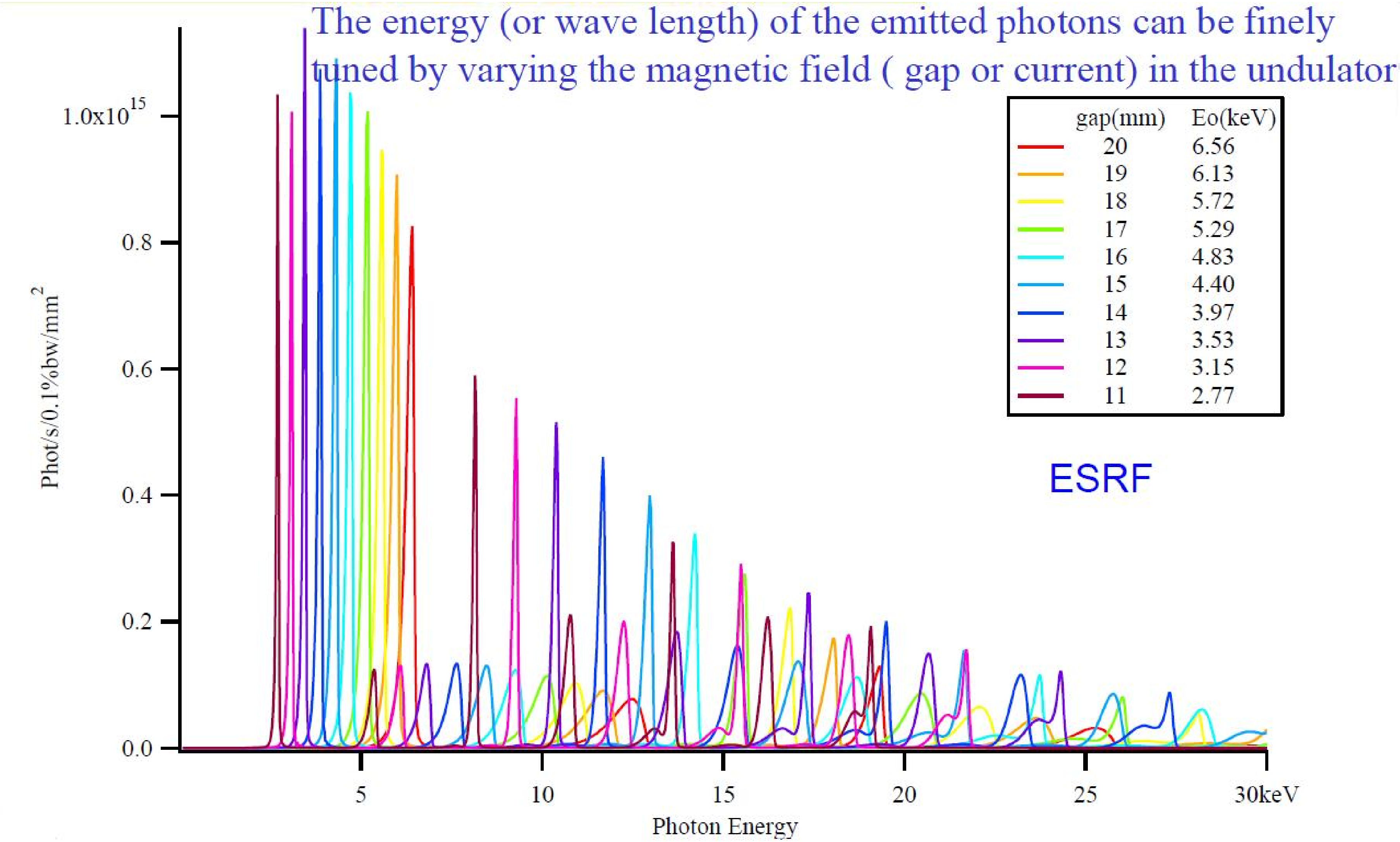
λ_u is the undulator magnetic period
θ is the angle of observation



⇒**Photon energy depends on the observation angle**
⇒**Great sensitivity to spread in θ or γ**

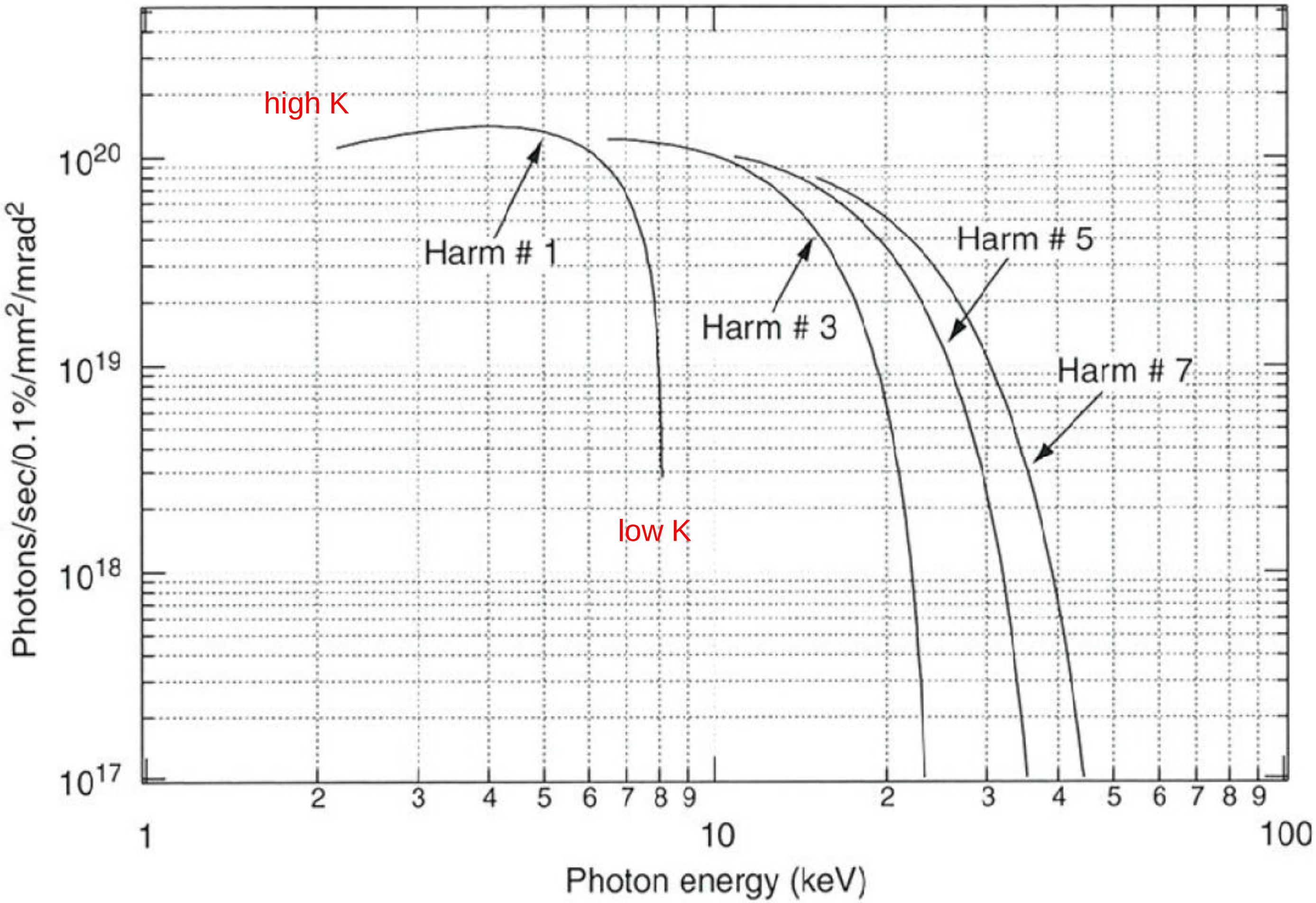
Courtesy J.M Filhol

Tunability of undulator radiation



Courtesy J.M Filhol

Undulator tuning curve (with K)



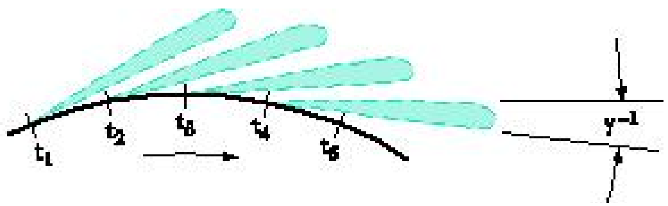
$$K = \frac{eB_0 \lambda_u}{2\pi mc}$$

Undulator parameter

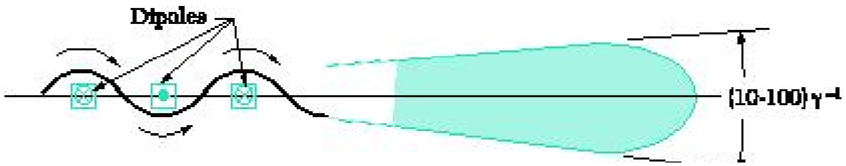
K decreases by opening the gap of the undulator (reducing B)

Brightness of a 5 m undulator 42 mm period with maximum K = 2.42 (ESRF)
Varying K one varies the wavelength emitted at various harmonics (not all wavelengths of this graph are emitted at a single time)

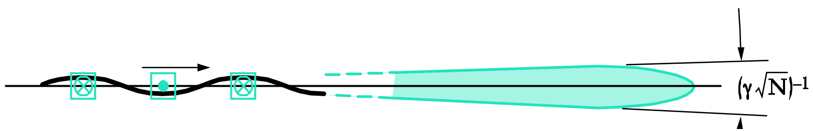
Comparison of angular distribution of radiated power



bending magnet - a “sweeping searchlight”



wiggler - incoherent superposition K > 1
Max. angle of trajectory > 1/γ



undulator - coherent interference K < 1
Max. angle of trajectory < 1/γ

Continuous spectrum characterized by ε_c = critical energy

ε_c(keV) = 0.665 B(T)E^2(GeV)

eg: for B = 1.4T E = 3GeV ε_c = 8.4 keV

(bending magnet fields are usually lower ~ 1 – 1.5T)

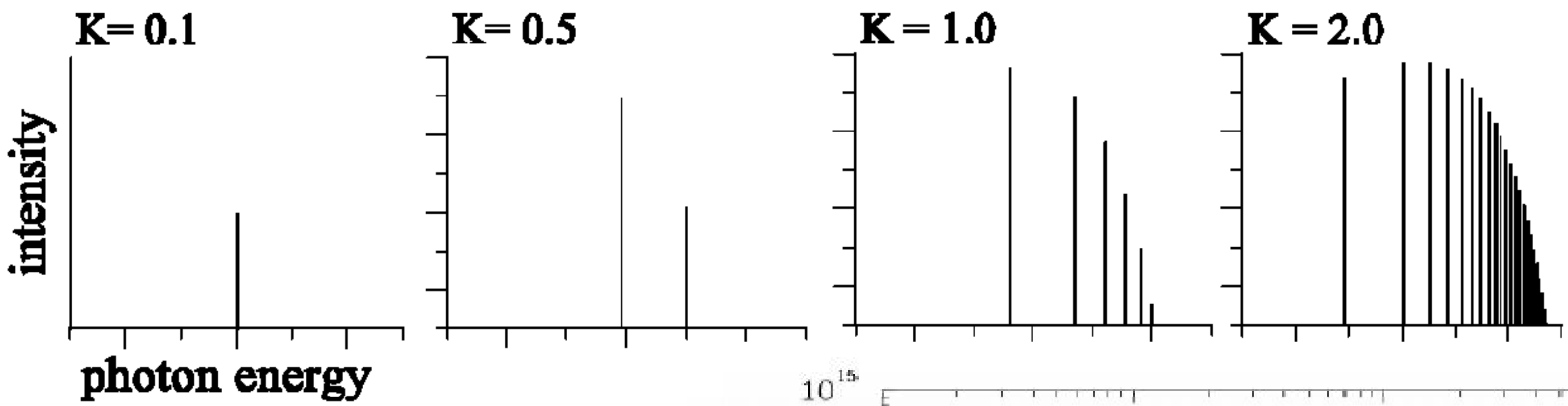
Quasi-monochromatic spectrum with peaks at lower energy than a wiggler

$$a_n = \frac{a_u}{2n¥^2}\left(1+\frac{K^2}{2}\right) \approx \frac{a_u}{n¥^2}$$

$$£_n(eV) = 9.496\frac{nE[GeV]^2}{a_u[m]\left(1+\frac{K^2}{2}\right)}$$

Undulators and wigglers (large K)

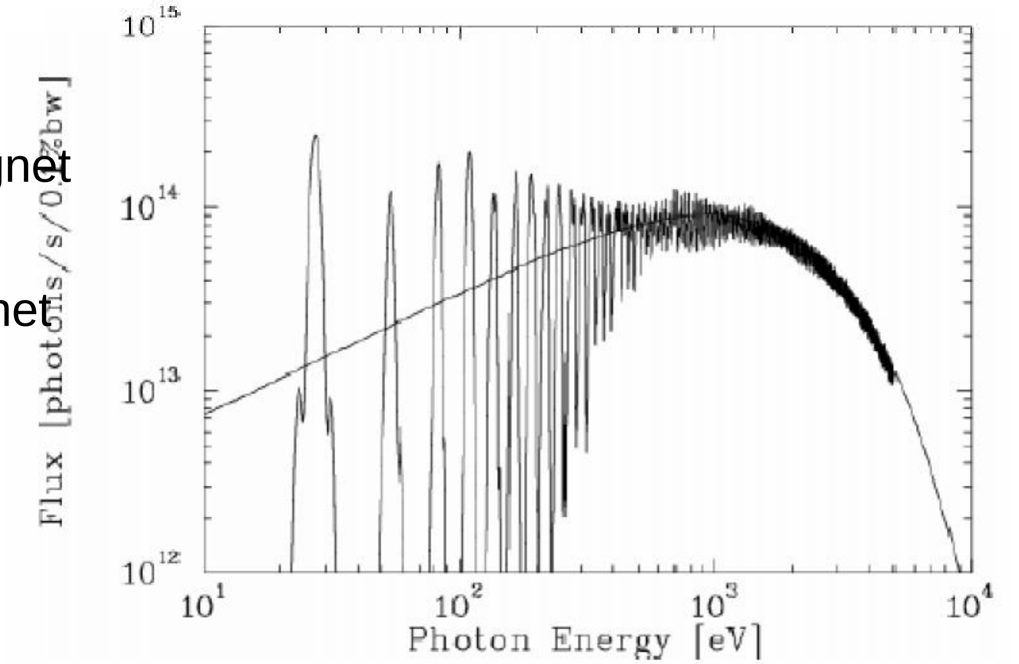
Radiated intensity emitted vs K



For large K the wiggler spectrum becomes similar to the bending magnet spectrum, $2N_u$ times larger.

Fixed B_0, to reach the bending magnet critical wavelength we need:

K	1	2	10	20
n	1	5	383	3015



Type of undulators and wigglers

Electromagnetic undulators: the field is generated by current carrying coils; they may have iron poles;

Permanent magnet undulators: the field is generated by permanent magnets Samarium Cobalt (SmCo; 1T) and Neodymium Iron Boron (NdFeB; 1.4T); they may have iron poles (hybrid undulators);

APPLE-II: permanent magnets arrays which can slide allowing the polarisation of the magnetic field to be changed from linear to circular

In-vacuum: permanent magnets arrays which are located in-vacuum and whose gap can be closed to very small values (< 5 mm gap!)

Superconducting wigglers: the field is generated by superconducting coils and can reach very high peak fields (several T, 3.5 T at Diamond)

Electromagnetic undulators

HU64 at SOLEIL:

variable polarisation electromagnetic undulator

Period 64 mm

14 periods

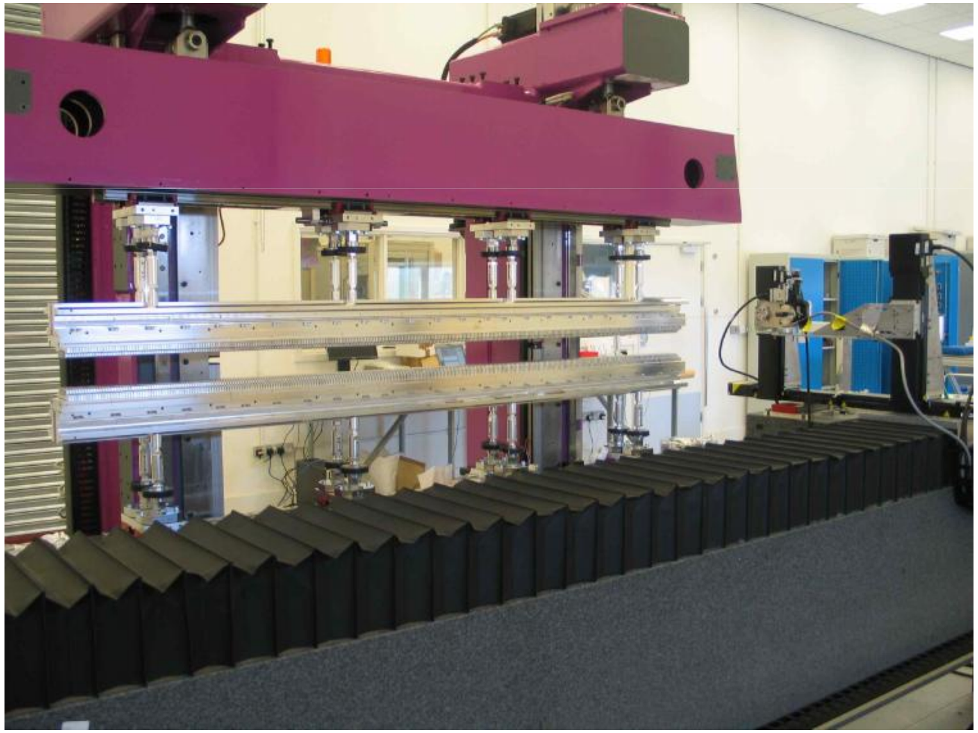
Min gap 19 mm

Photon energy < 40 eV (1 keV with EM undulators)

In-vacuum undulators

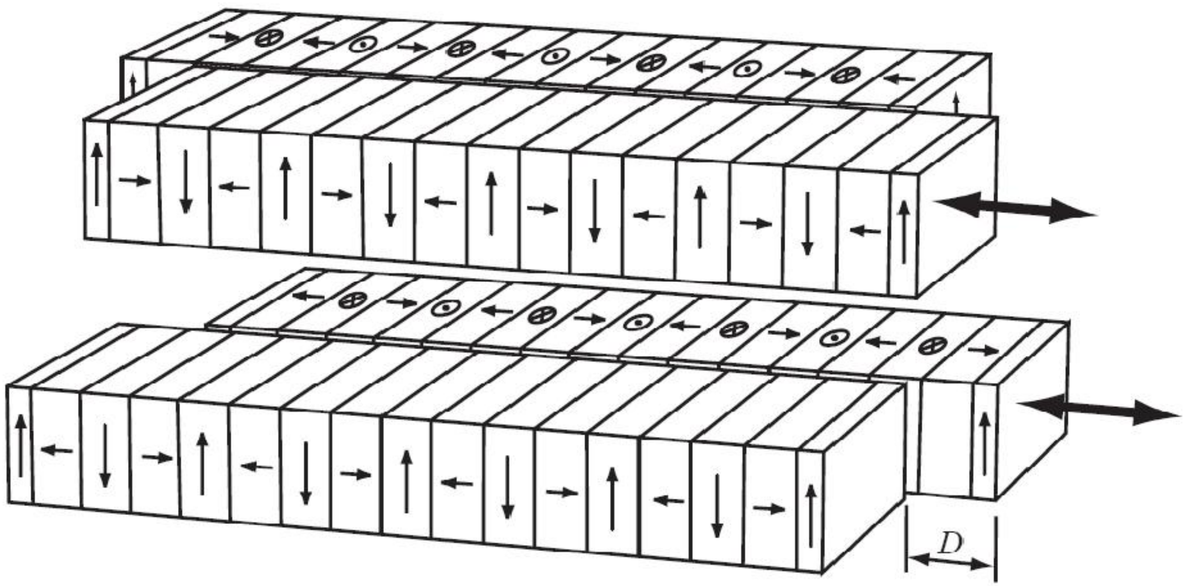
U27 at Diamond

27 mm, 73 periods 7 mm gap, B = 0.79 T; K = 2



Apple-II type undulators

Advanced Planar Polarisation Light Emitter



Four independent arrays of permanent magnets

Diagonally opposite arrays move longitudinal, all arrays move vertically

Sliding the arrays of magnetic pole it is possible to control the polarisation of the radiation emitted

Superconducting Wigglers

Superconducting wigglers are used when a high magnetic field is required

3 - 10 T

They need a cryogenic system to keep the coil superconductive

Nb_3Sn and NbTi wires

SCMPW60 at Diamond

3.5 T coils cooled at 4 K

24 period of 64 mm

gap 10 mm

Undulator K = 21

Summary of radiation characteristics of undulators or wiggler

Undulators have weaker field or shorter periods (K< 1)

Produce narrow band radiation and harmonics $\Delta\omega/\omega \sim 1/nN_u$

Intensity is proportional to N_u^2

Wigglers have higher magnetic field (K >1)

Produce a broadband radiation

Intensity is proportional to N_u

Basics of beam optics

Optics function

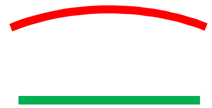
matrix formalism (ray tracing)

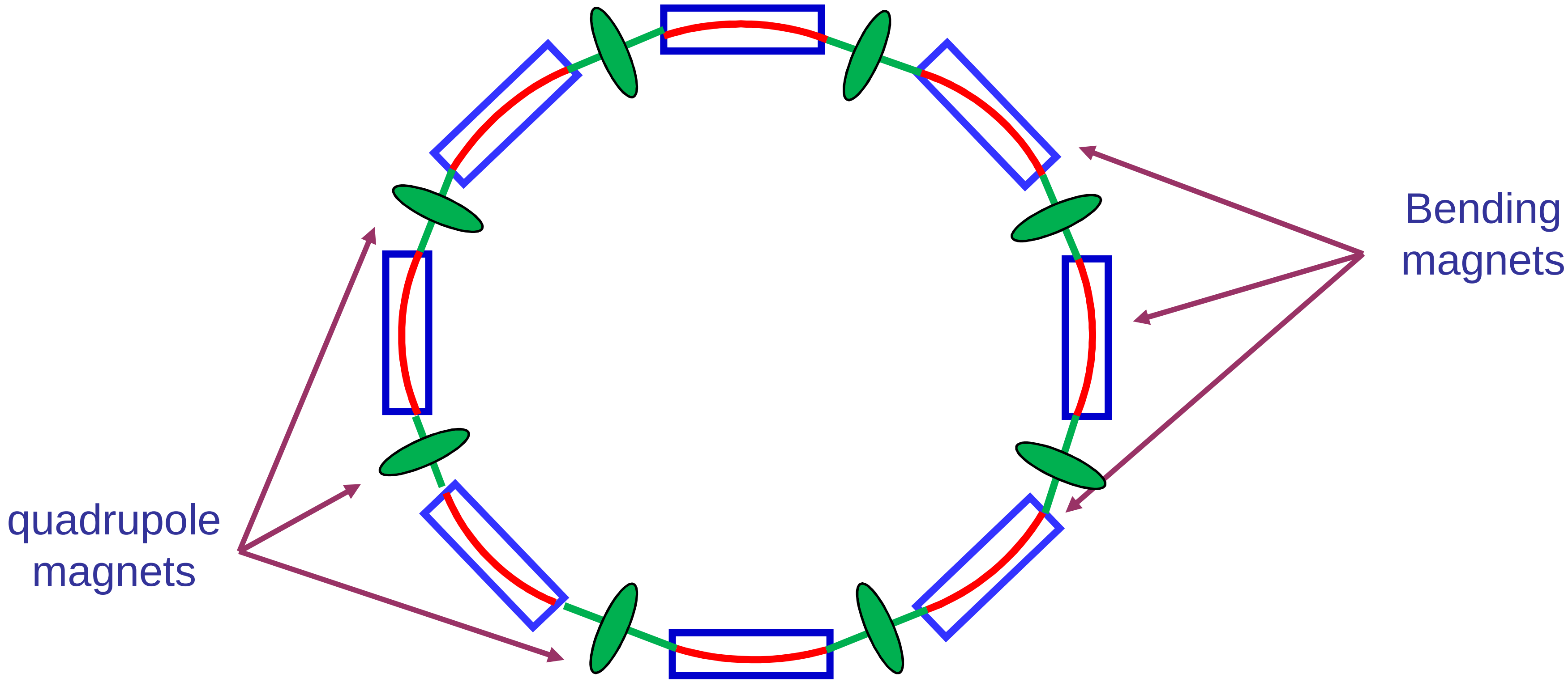
Emittance in electron storage rings

Building the ring…

We chose the nominal energy of the particle and closing the loop with

1) arcs of circumference (dipole fields)
2) straight sections (with quads)

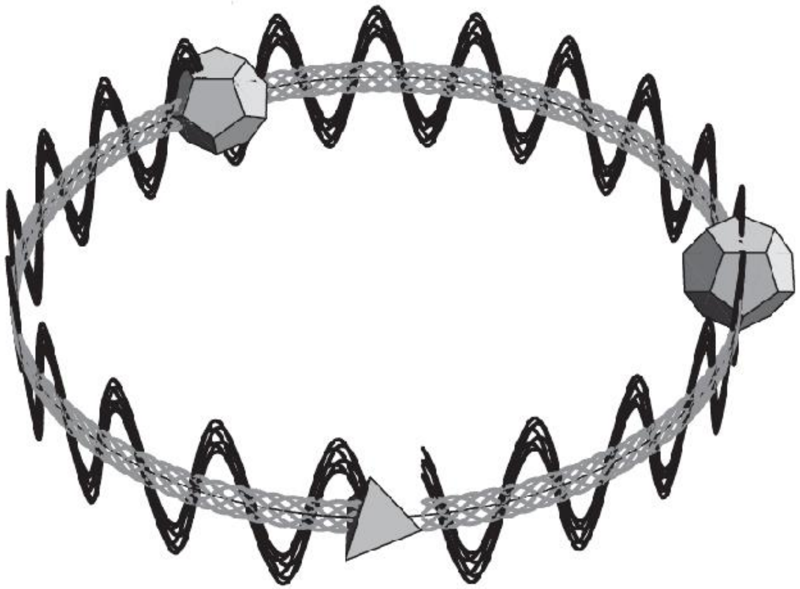




Dipoles and quadrupoles are necessary to guarantee the stable motion of the particles in the ring

What happens to particles that are close to the reference orbit?

Particles with slight offsets and angles with respect to the reference orbit will perform oscillations around it



Starting from the relativistic equation with the Lorentz force (and lots of math)

$$\frac{d^2y}{ds^2} + K_y(s)y = 0$$

$$K_x(s) = \frac{1}{\rho^2(s)} - \frac{1}{B\rho}\frac{\partial B_z(s)}{\partial x}$$

$$K_z(s) = \frac{1}{B\rho}\frac{\partial B_z(s)}{\partial x}$$

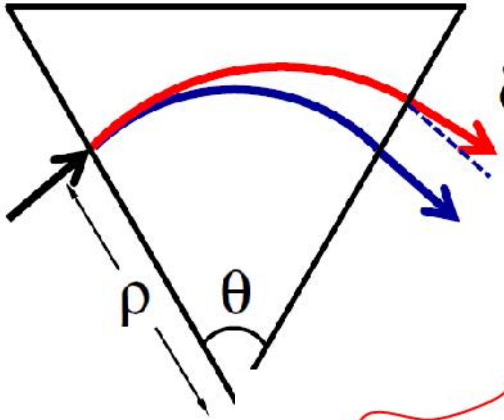
weak focussing of a dipole

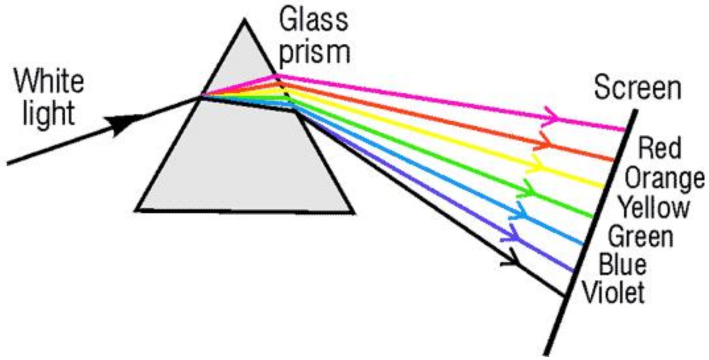
quadrupole focussing

K. Steffen in CERN Accelerator School – 85-19 (1985)

What happens to particles that do not have the correct energy?

Dispersive orbits
in a dipole

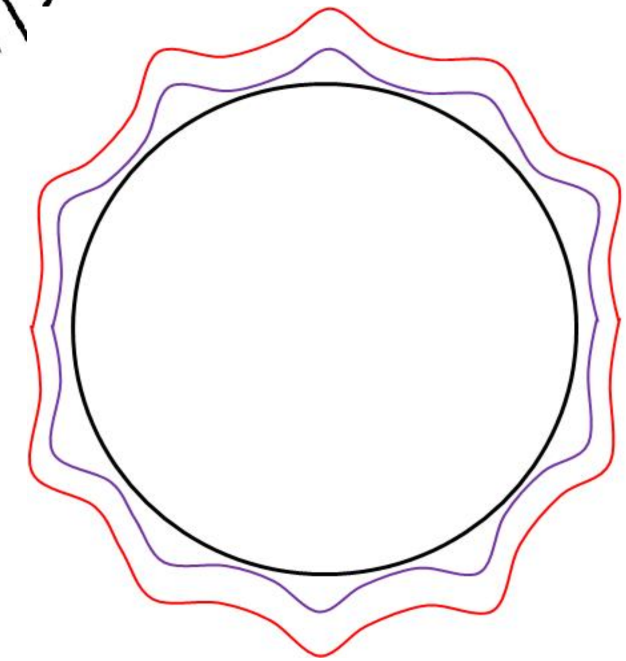




Dispersive orbits in a ring
(off energy closed orbit)

$X = D * \delta E/E$

D is called dispersion function



on-energy
$\delta E/E = 0$

off energy
$\delta E/E > \delta E/E > 0$

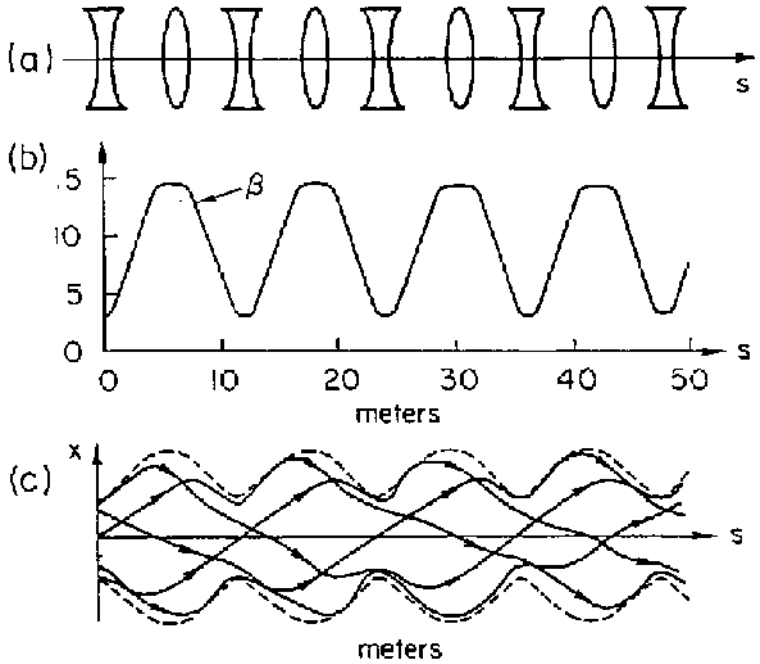
Particles with different energies also “oscillate” around the reference orbit. We can find a different closed orbit for each energy (off energy orbit)

Solution of Hill's equations: pseudo-harmonic oscillations

The solutions of $\frac{d^2y}{ds^2} + K_y(s)y = 0$ can be found in the form

$$y(s) = \sqrt{\varepsilon_y \beta_y(s)}\cos[\varphi_y(s) + \varphi] \qquad \varphi_y(s) = \int_{s_0}^{s} \frac{ds'}{\beta_y(s')}$$

which are *pseudo-harmonic oscillations* with s-dependent amplitude and phase



The beta functions (in x and z) are proportional to the square of the envelope of the oscillations

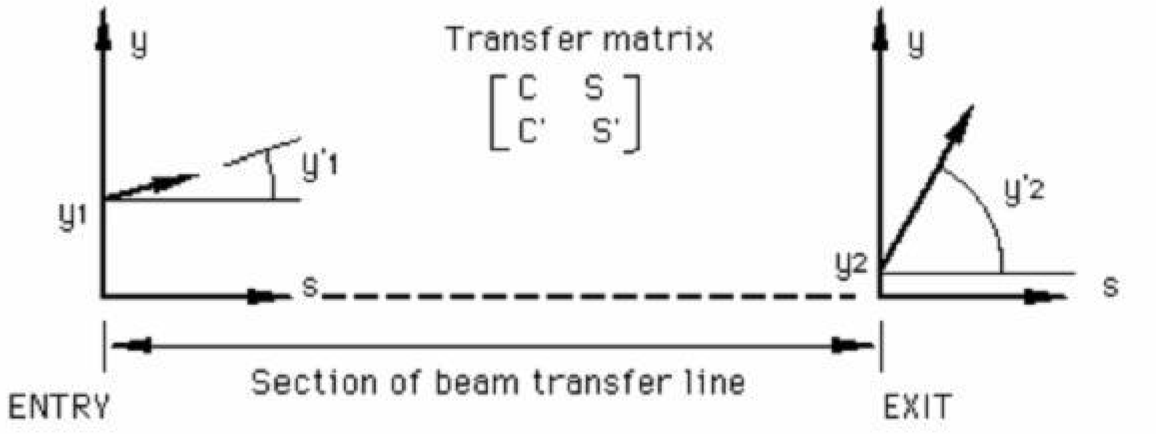
The functions φ (in x and z) describe the phase of the oscillations

Principal trajectories and matrix formalism

As a consequence of the linearity of Hill's equations, we can describe the evolution of the trajectories in a transfer line or in a circular ring by means of linear transformations

$$\begin{pmatrix} y(s) \\ y'(s) \end{pmatrix} = \begin{pmatrix} C(s) & S(s) \\ C'(s) & S'(s) \end{pmatrix} \begin{pmatrix} y(s_0) \\ y'(s_0) \end{pmatrix}$$

C(s) and S(s) depend only on the magnetic lattice not on the particular initial conditions

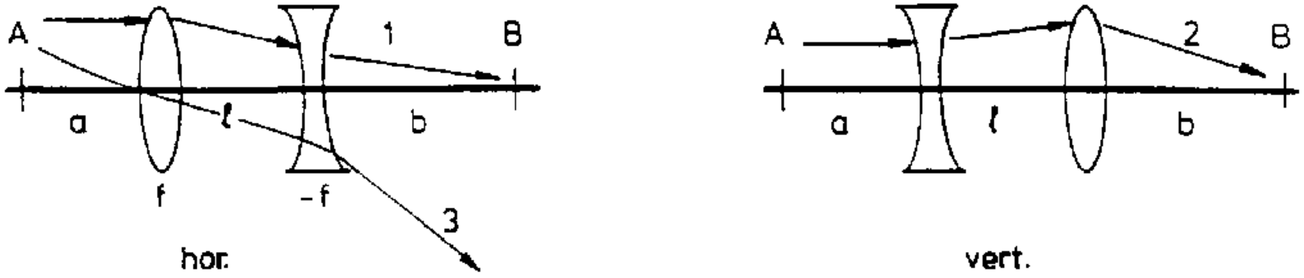


$$M_{1\to 2} = \begin{pmatrix} C(s) & S(s) \\ C'(s) & S'(s) \end{pmatrix}$$

This allows the possibility of using the matrix formalism to describe the evolution of the coordinates of a charged particles in a magnetic lattice

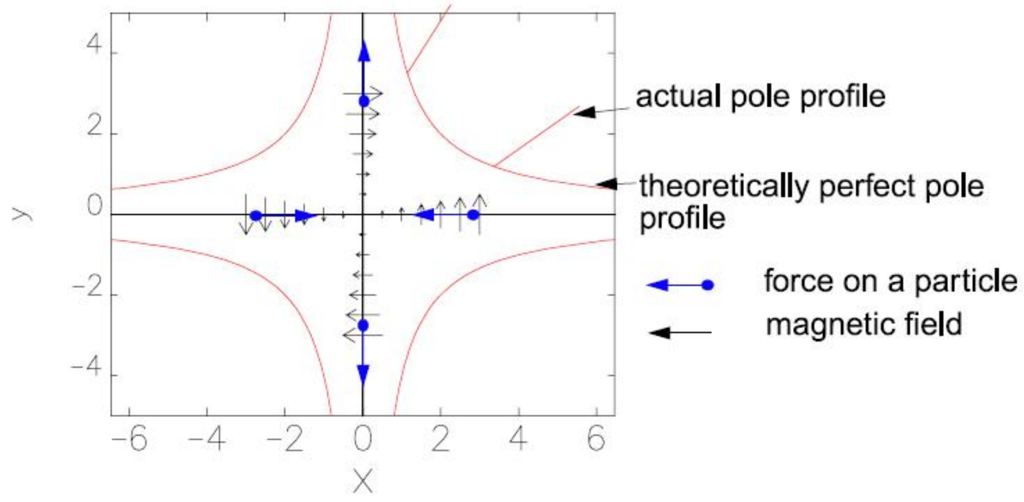
Matrix formalism and analogy with geometric optics

Particle trajectories can be described with a matrix formalism analogous to that describing the propagation of rays in an optical system.



The magnetic quadrupoles play the role of focussing and defocussing lenses, however notice that, unlike an optical lens, a magnetic quadrupole is focussing in one plane and defocussing in the other plane.

Magnetic field of a quadrupole and Lorentz force

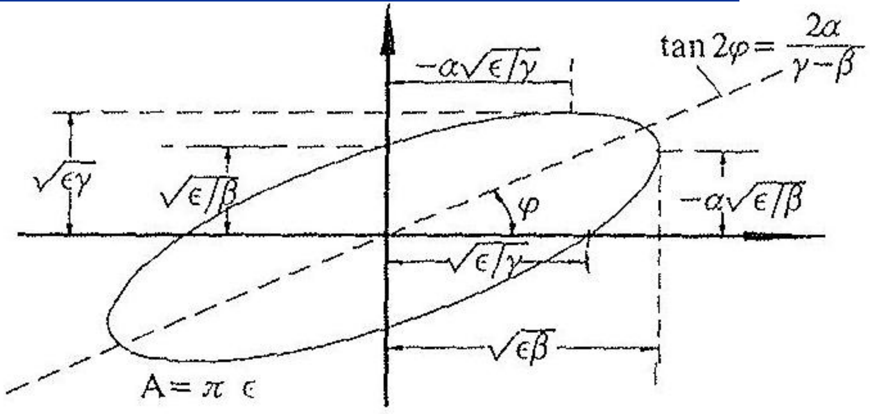


Betatron motion in phase space

The solution of the Hill's equations

$$\frac{d^2y}{ds^2} + K_y(s)y = 0$$

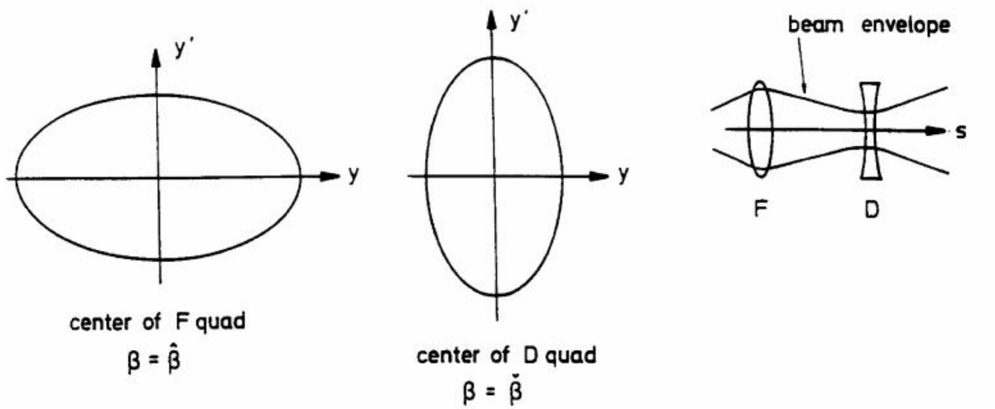
describe an ellipse in phase space (y, y')



area of the ellipse in phase space (y, y') is $A(s) = (\quad y'^2 + 2\sim yy' + ¥^2 y^2)/®$

It can be proven that this is invariant of motion (**Courant-Snyder invariant**)

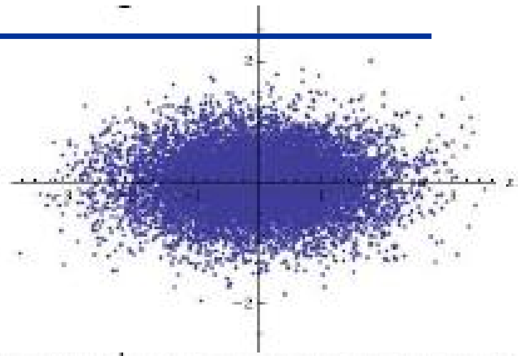
Whatever the magnetic lattice, *at each different sections s, the ellipse of the trajectories may change orientation shape and size but the area is an invariant.*



This is true for the motion of a single particle !

Real beams – distribution function in phase space

A beam is a collection of many charged particles

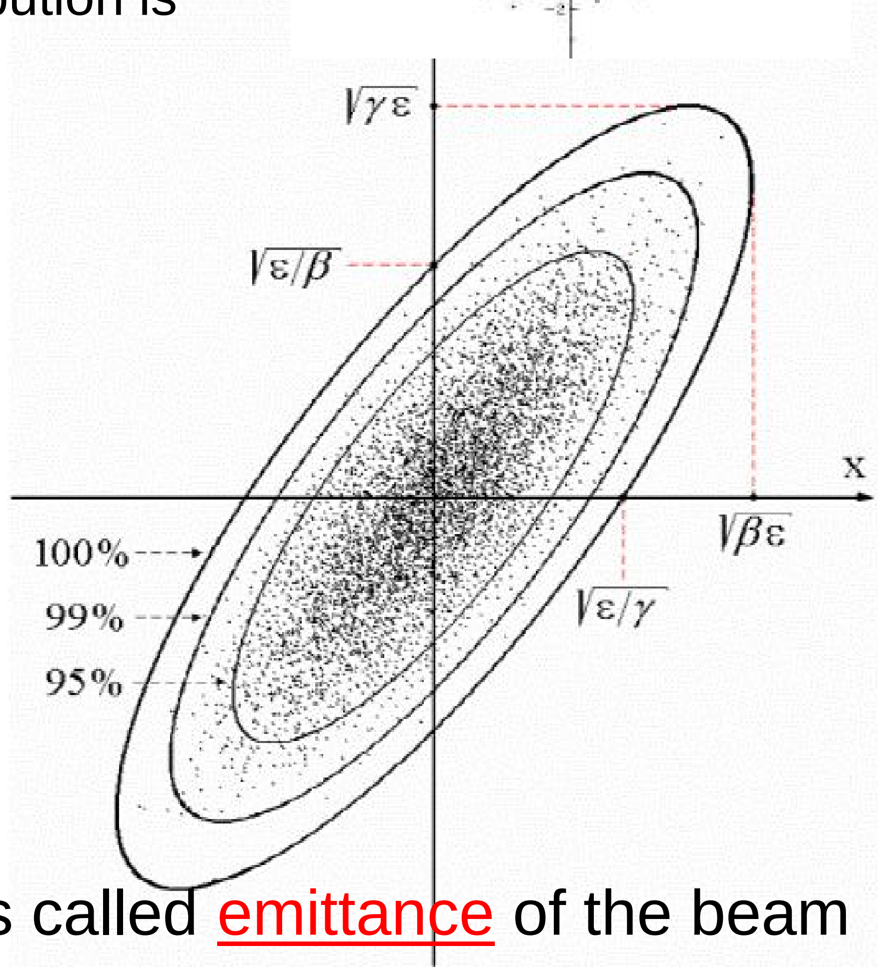


For electrons the equilibrium beam distribution is a Gaussian distribution

Usually the three planes are independent hence in each plane

$$\text{°}(x, x') = \frac{1}{2\text{®}\sqrt{\det R_{xx'}}} e^{-\frac{x'^2 + 2\text{\textasciitilde}xx' + \text{¥}x^2}{2\text{£}}}$$

The isodensity curves are ellipses



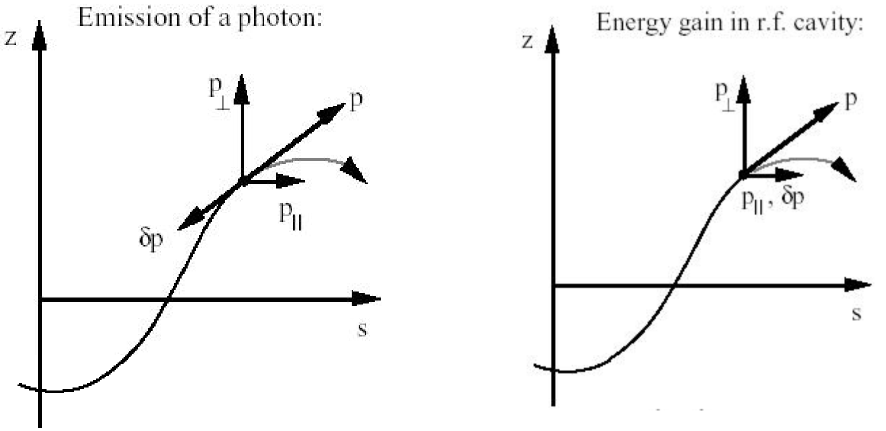
The motion of the whole beam is described by the evolution of the representative ellipse

ε is called emittance of the beam

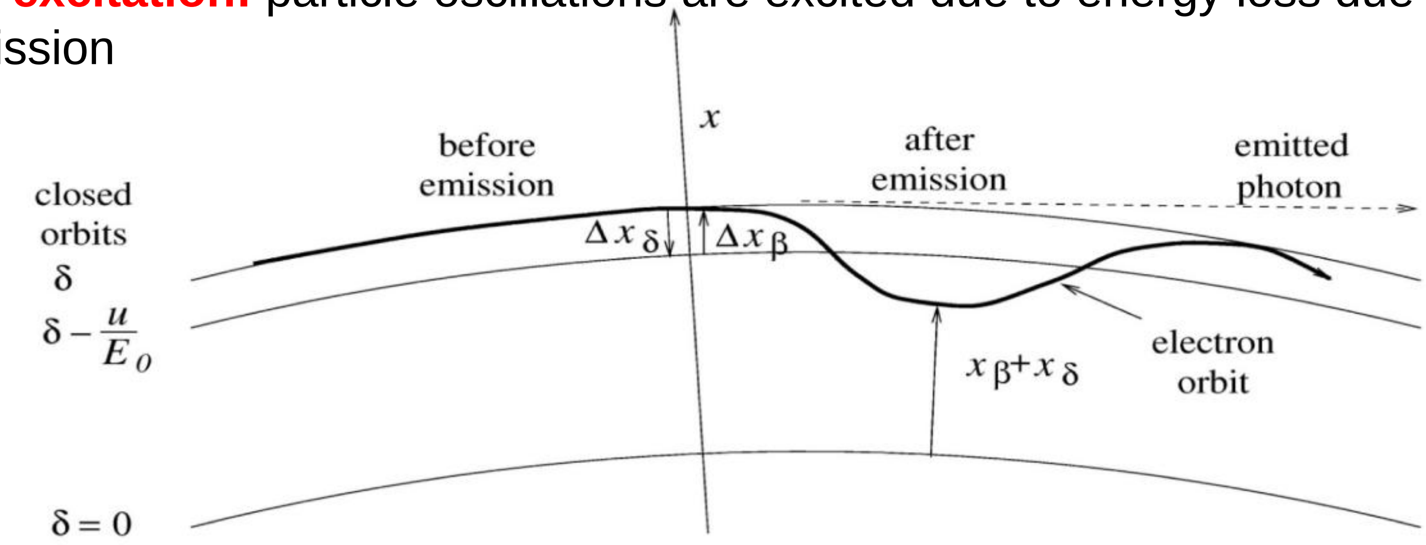
Emittance in electron storage rings

The emittance of the electron beam in a storage rings is the result of the equilibrium between two competing effects related to the emission of synchrotron radiation

• **radiation damping:** particle oscillations are damped due to energy loss due to photon emission and energy gain in RF



• **radiation excitation:** particle oscillations are excited due to energy loss due to photon emission



Low Emittance lattices

At equilibrium [**M. Sands SLAC-pub 121 (1970)**]

$$\varepsilon_x = C_q \frac{\gamma^2}{J_x \rho} < H >_{dipole} \qquad H(s) = ¥D^2 + 2{\sim}DD' + \;\; D'^2 \qquad C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc} = 3.84 \cdot 10^{-13} m$$

Minimise the emittance by reducing β and D and be close to a waist in the dipole

Lattice design has to provide low emittance and adequate space in straight sections to accommodate long Insertion Devices

Zero dispersion in the straight section was used especially in early machines

avoid increasing the beam size due to energy spread
hide energy fluctuation to the users
allow straight section with zero dispersion to place RF and injection
decouple chromatic and harmonic sextupoles

DBA and TBA lattices provide low emittance with large ratio between

$$\frac{\text{Length of straight sections}}{\text{Circumference}}$$

Low emittance lattices

Low emittance and adequate space in straight sections to accommodate long Insertion Devices are obtained in

Double Bend Achromat (DBA)

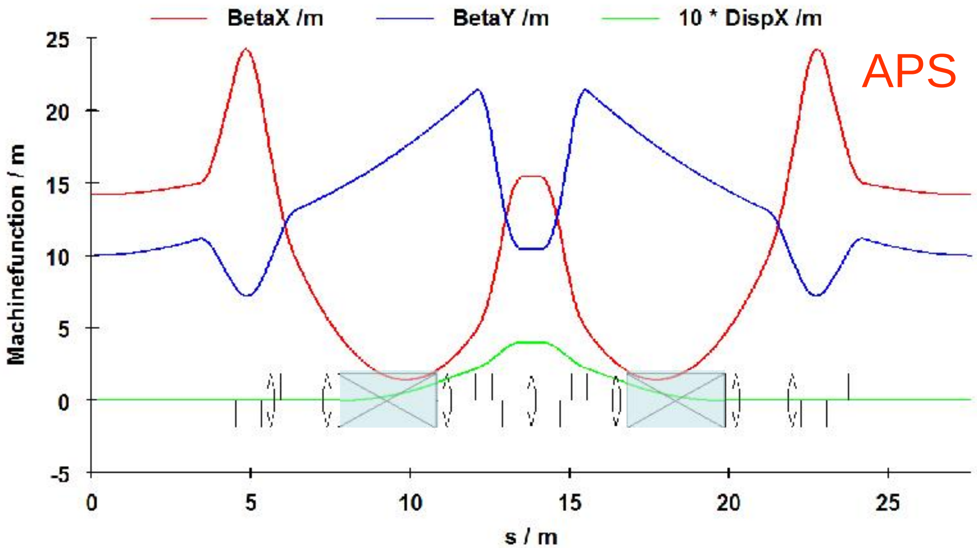
Triple Bend Achromat (TBA)

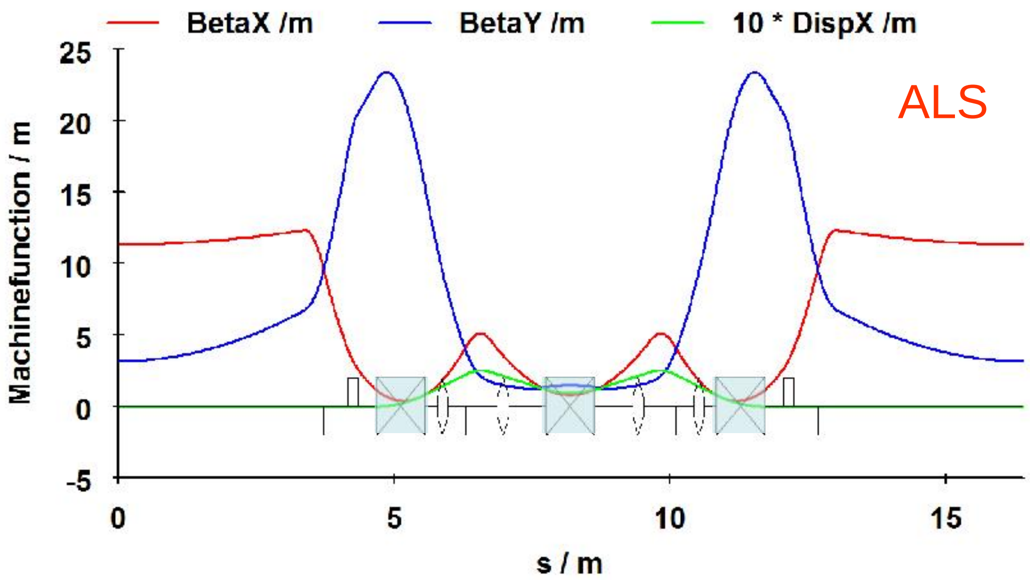
DBA used at:
ESRF,
ELETTRA,
APS,
SPring8,
Bessy-II,
Diamond,
SOLEIL,
SPEAR3
...

TBA used at
ALS,
SLS,
PLS,
TLS
…

$$\epsilon_x = F \frac{C_q \gamma^2 \theta_b^3}{J_x} \propto \frac{1}{N_b^3}$$

$$F_{MEDBA} = \frac{1}{4\sqrt{15}} \qquad F_{MEDBA-disp} = \frac{1}{12\sqrt{15}}$$





Breaking the achromatic condition

Leaking dispersion in straight sections reduces the emittance

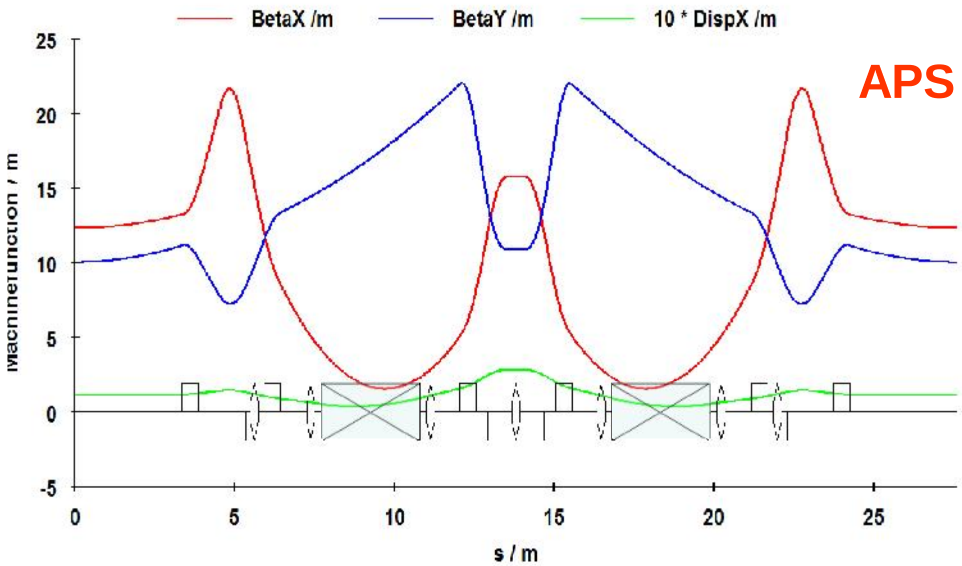
ESRF	7 nm → 3.8 nm
APS	7.5 nm → 2.5 nm
SPring8	4.8 nm → 3.0 nm
SPEAR3	18.0 nm → 9.8 nm
ALS (SB)	10.5 nm → 6.7 nm

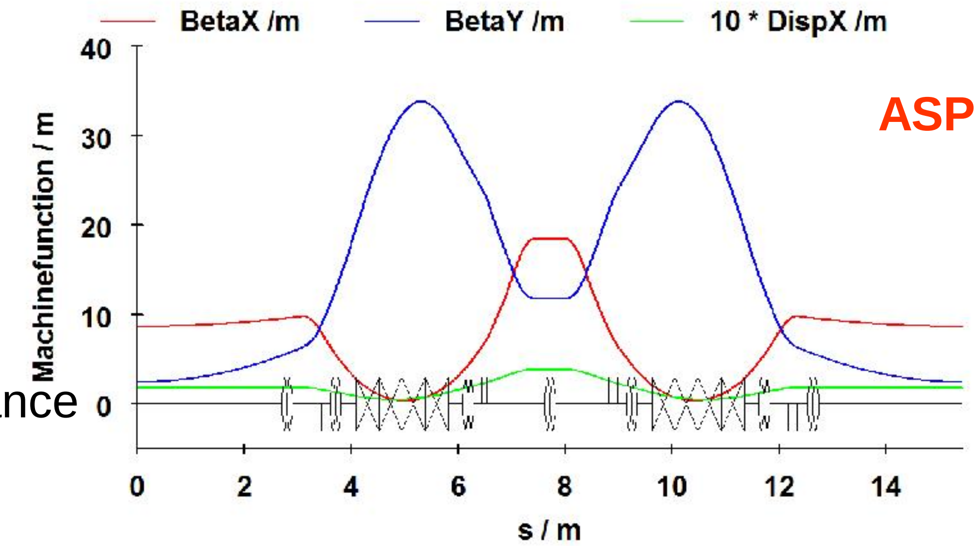
$$F_{MEDBA} = \frac{1}{4\sqrt{15}} \qquad F_{MEDBA-disp} = \frac{1}{12\sqrt{15}}$$

The emittance is reduced but the dispersion in the straight section increases the beam size

$$\sigma_x = \sqrt{\varepsilon_x \beta_x + (\sigma_E D_x)^2}$$

Need to make sure the effective emittance and ID effects are not made worse





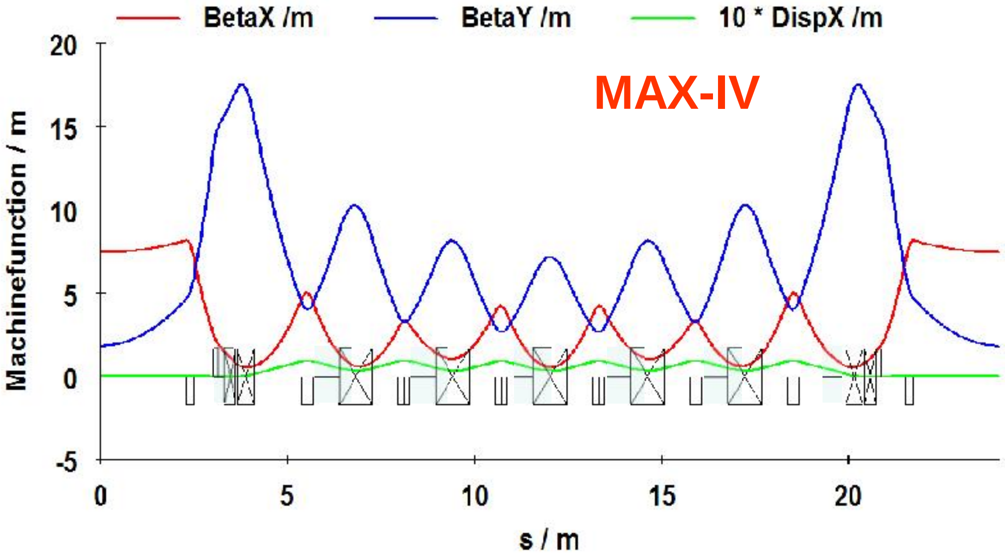
Low emittance lattices

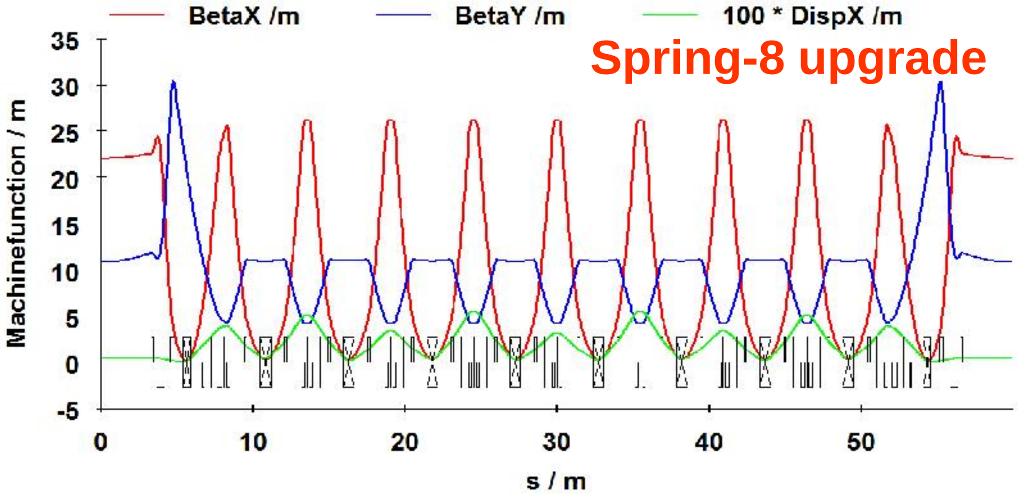
New designs envisaged to achieve sub-nm emittance involve

Damping Wigglers
Petra-III: 1 nm
NSLS-II: 0.5 nm

MBA
MAX-IV (7-BA): 0.3 nm
Spring-8 (10-BA): 83 pm (2006)

10-BA had a DA –6.5 mm +9 mm
reverted to a QBA (160 pm)
now 6BA with 70 pm



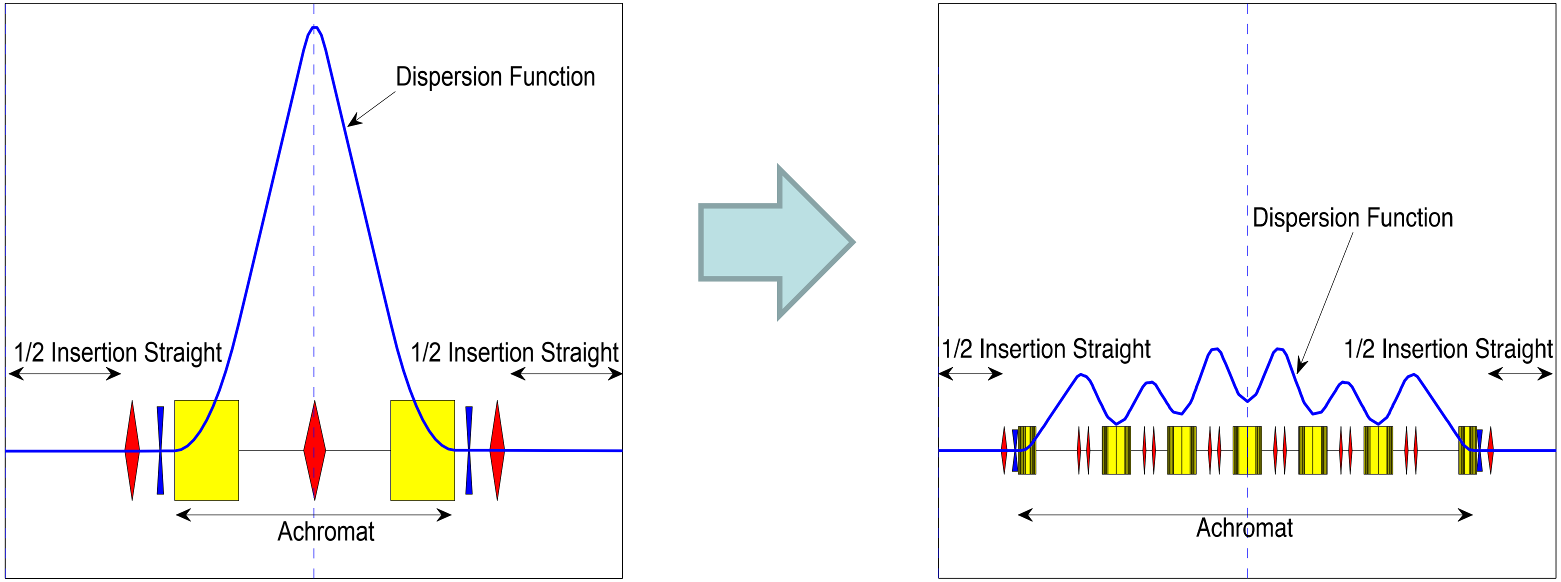


Multiple bend achromats

$$\text{£}_x = \frac{\text{¥}^2}{J_x \,°} < H >_{dipole}$$

DBA

7BA

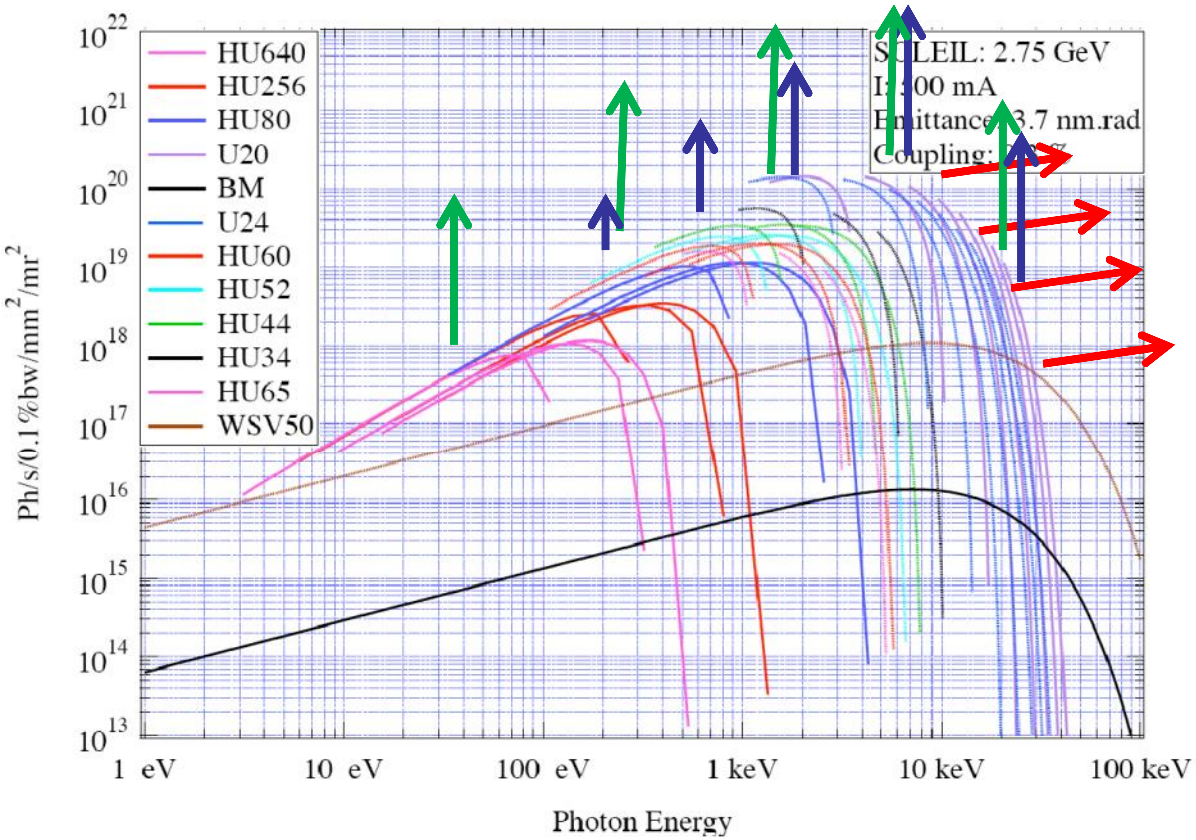


Simplified explanation

– Emittance is driven by randomness of photon emission in presence of dispersive (energy-dependent) orbits – electron recoils randomly

– Breaking up dipoles and putting focusing (quadrupoles) between the parts allows reducing the amplitude of dispersive orbits – smaller electron recoils

Brilliance with IDs (medium energy light sources)



Brilliance dependence

with current

with energy

with emittance

Medium energy storage rings with **in-vacuum undulators** operated at low gaps (e.g. 5-7 mm) can reach 10 keV with a brilliance of 10^{20} ph/s/0.1%BW/mm^2/mrad^2

Modern trends in third generation light sources

- ✓ IDs development (CPMU, Superconducting undulators)
- ✓ Stability improvements – long term top-up and over 1-1kHz
- ✓ Higher current and collective effects
- ✓ Short pulses with dedicated optics (low alpha lattices)
- ✓ Tailored straight sections – broken symmetry
- ✓ **Lower emittance for diffraction limited rings**

Brilliance and transverse coherence

Brilliance (spectral brightness): photon density in 6D phase space

$$\text{brilliance} = \frac{\text{flux}}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} = \frac{N_{\text{photons}}}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'} (\Delta\tau \Delta\omega / \omega)}$$

Σ's are the convolution of electron and photon beam size and divergence

$$\Sigma_x = \sqrt{\pm^2_{x,e} + \pm^2_{ph}} \qquad \Sigma_{x'} = \sqrt{\pm^2_{x',e} + \pm'^2_{ph}}$$

At the diffraction limit $\varepsilon_{e^-} \leq \varepsilon_{ph} = \frac{\lambda}{2\pi}$

$$\Sigma_x = \sqrt{\sigma^2_{x,e} + \sigma^2_{ph}} \rightarrow \sigma_{ph}$$

$$\Sigma_{x'} = \sqrt{\sigma^2_{x',e} + \sigma'^2_{ph}} \rightarrow \sigma'_{ph}$$

the brilliance is dominated by the photon source size and divergence

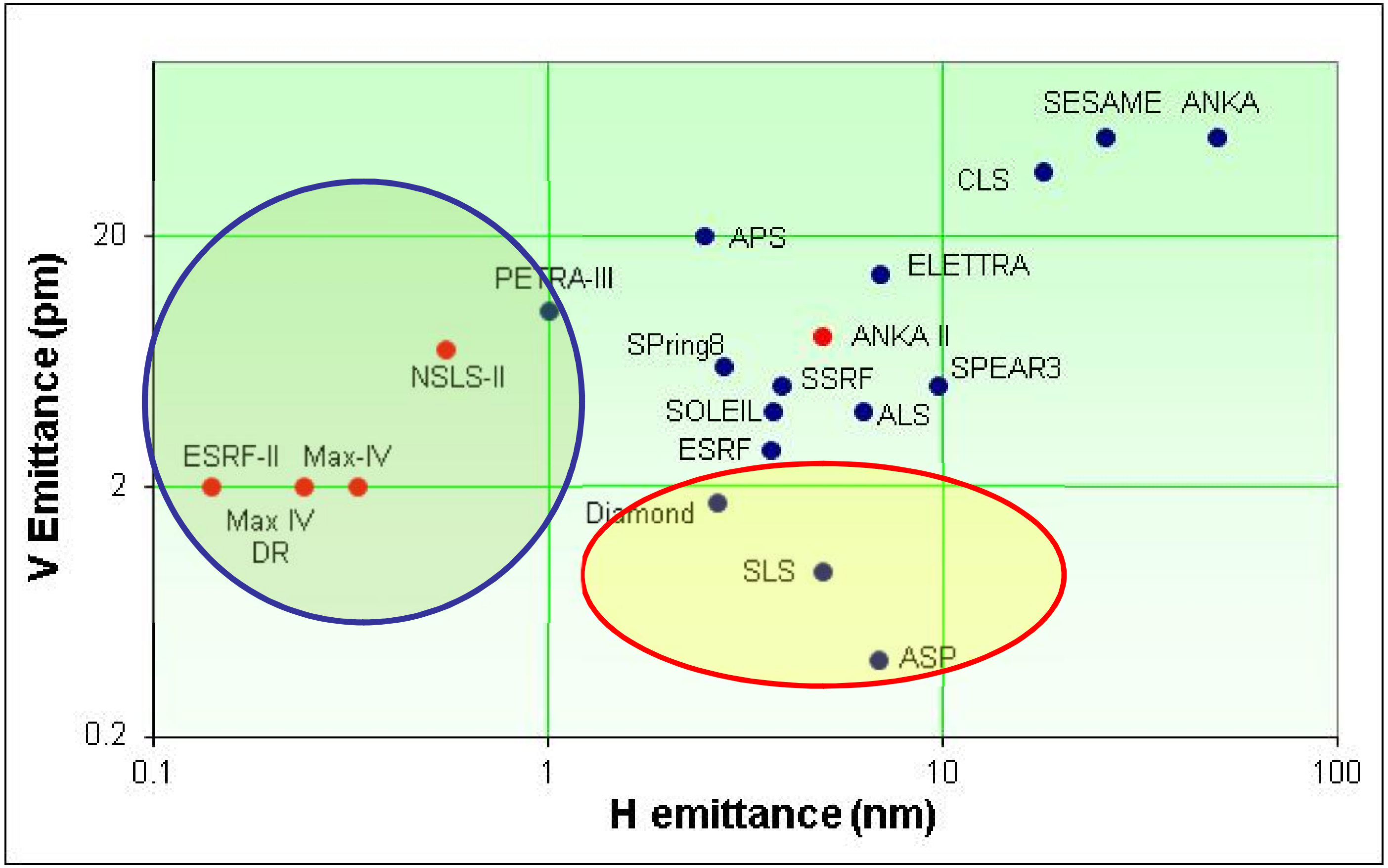
Reducing Σs also improve the **transverse coherence fraction** of synchrotron radiation

$$F = \frac{\lambda^2 / 4\pi^2}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

Emittance of third generation light sources

The emittance in the vertical plane however has been reduced to the pm range in several light sources.

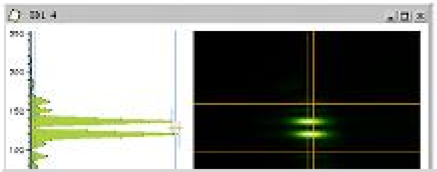
This radiation is diffraction limited in the vertical plane up to the hard X-rays



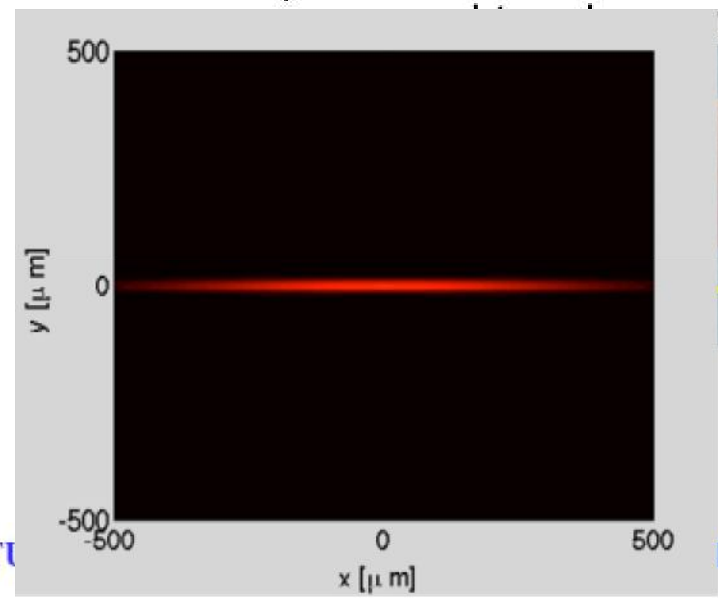
- operating
- under construction

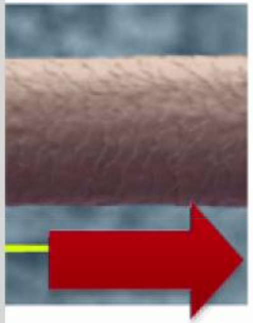
Records for smallest vertical emittance (2011-2014)

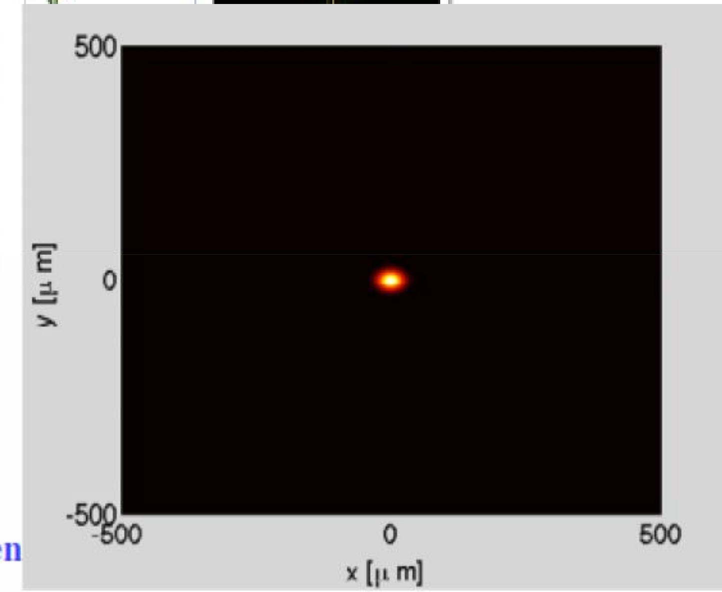
- Beam size $3.6 \pm 0.6\ \mu m$
- Emittance $0.9 \pm 0.4\ pm$
- SLS beam cross section (in short undulator straight, 2σ) … hair:



SLS







TU … IPAC2014, Dresden

kin

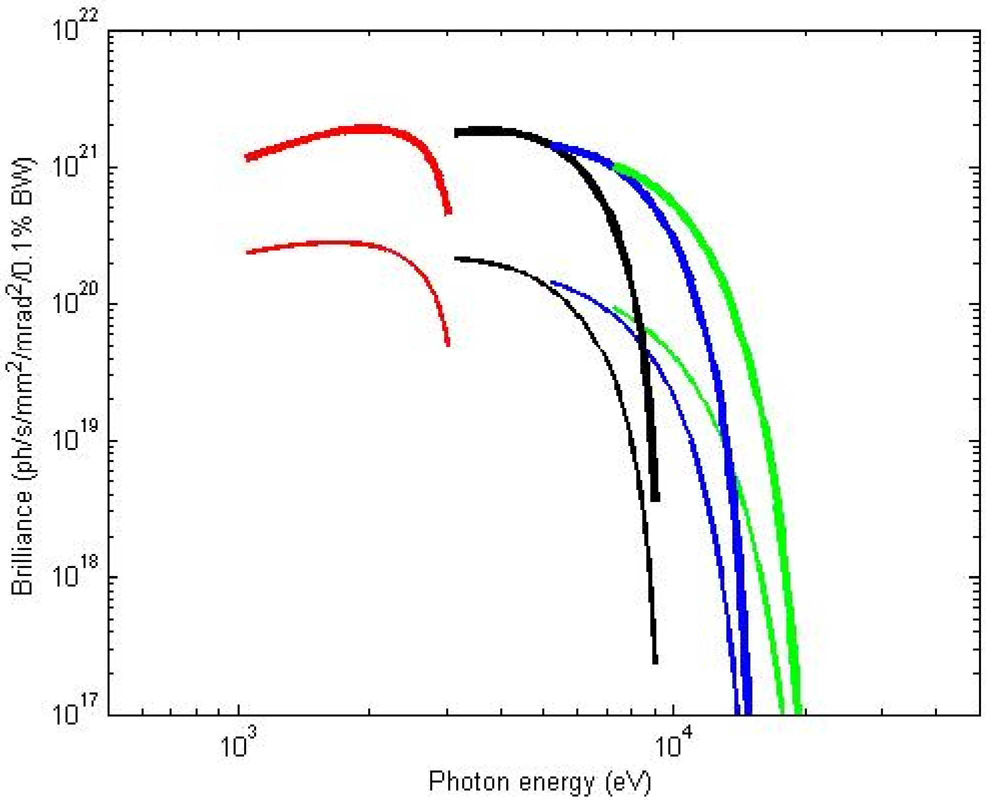
VERTICAL EMITTANCE AT THE QUANTUM LIMIT

0.35 pm

R. Dowd, Y-R. E. Tan, Australian Synchrotron, Clayton, Australia
K. P. Wootton, University of Melbourne, Parkville, Australia

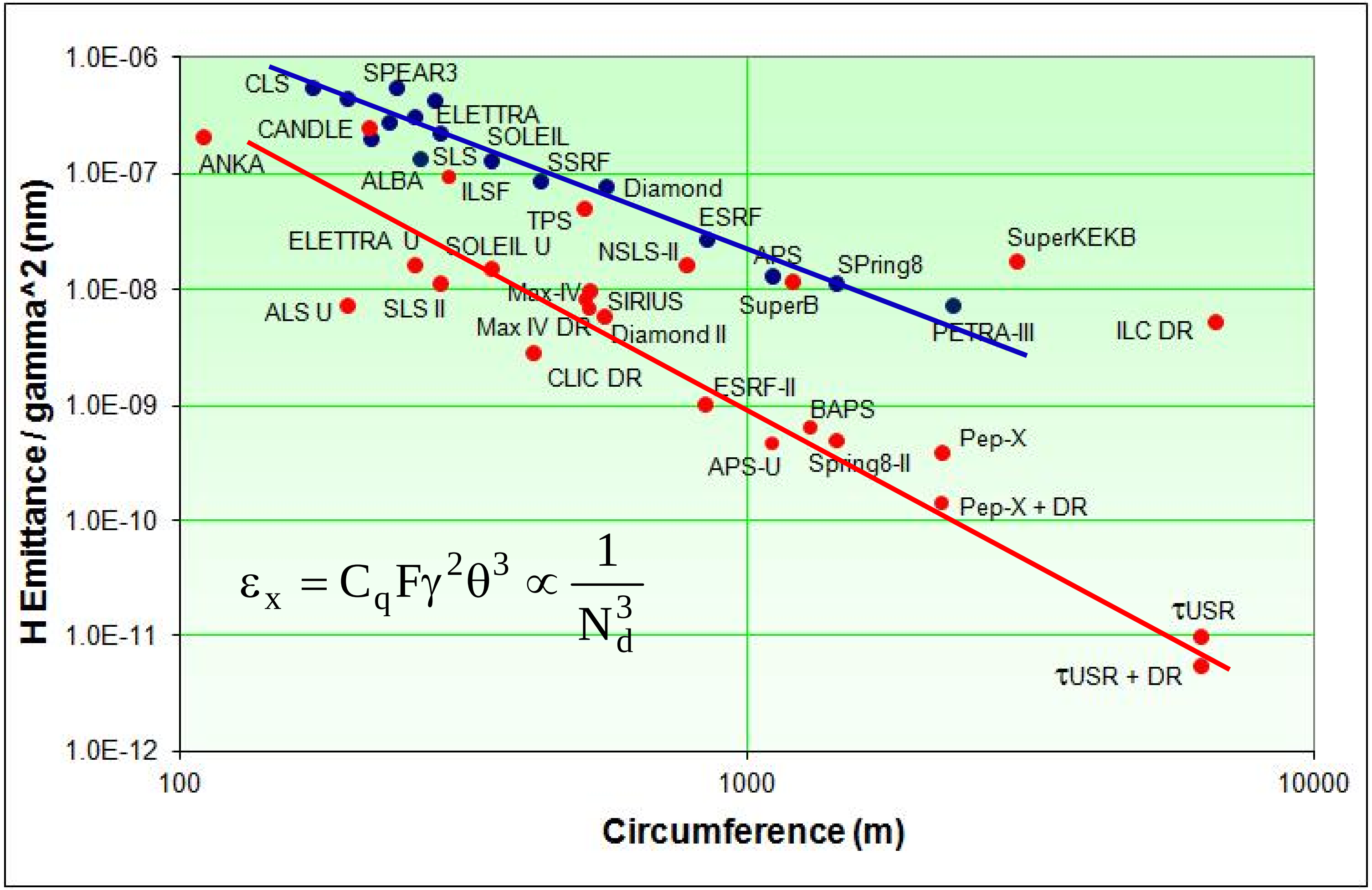
upgrade with Diamond-II
from 2.7 nm to 200 pm (300mA and 1%K)

Brilliance plot using U27 – 72 periods 2 m long with Kmax = 2.02



Tuning curves computed with Spectra 8.0

Survey of low emittance lattice rings



New storage rings will increase the average brightness and the transverse coherence

… however **peak brightness and pulses length** cannot compete with FELs

FEL basic concepts

In a storage ring the phase relationship between the radiation emitted by each electron is random and the spatial and temporal coherence of the radiation is limited.

The electrons emit radiation in an undulator **incoherently**

In a FEL the electrons interact with the radiation they emit in the undulator.

Under certain conditions this process can generate a **microbunching** of the beam.

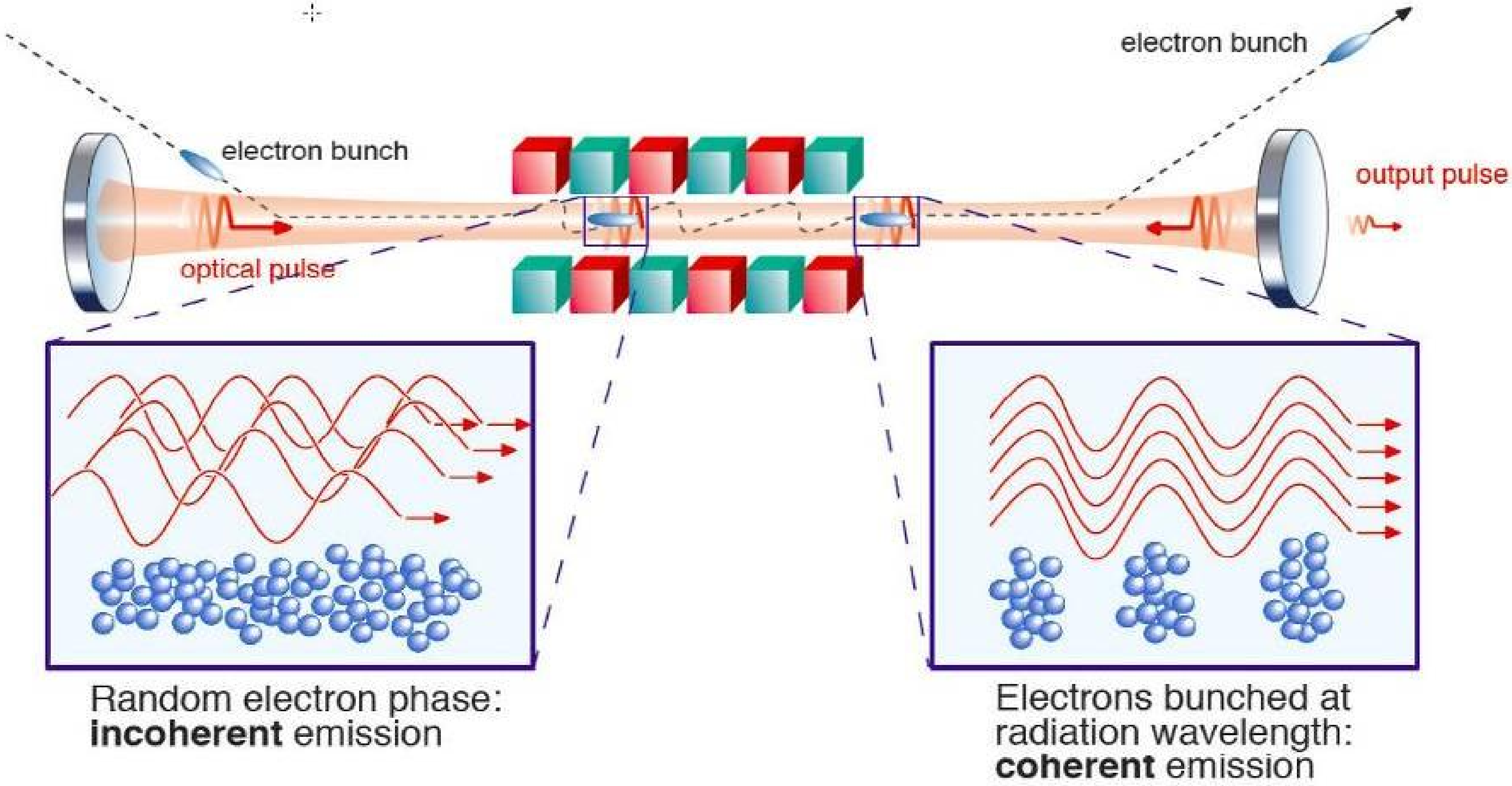
Microbunching happens mostly at the undulator resonant wavelength.

The electrons will now emit in phase with each other, **coherently**

The radiation power (and brilliance) will scale as N_e^2 not as N_e

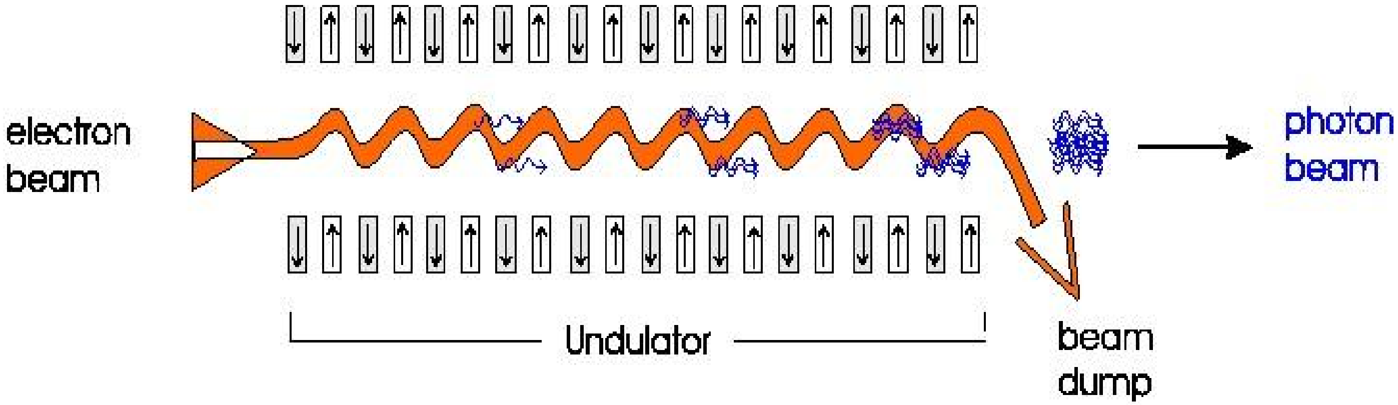
FEL oscillators

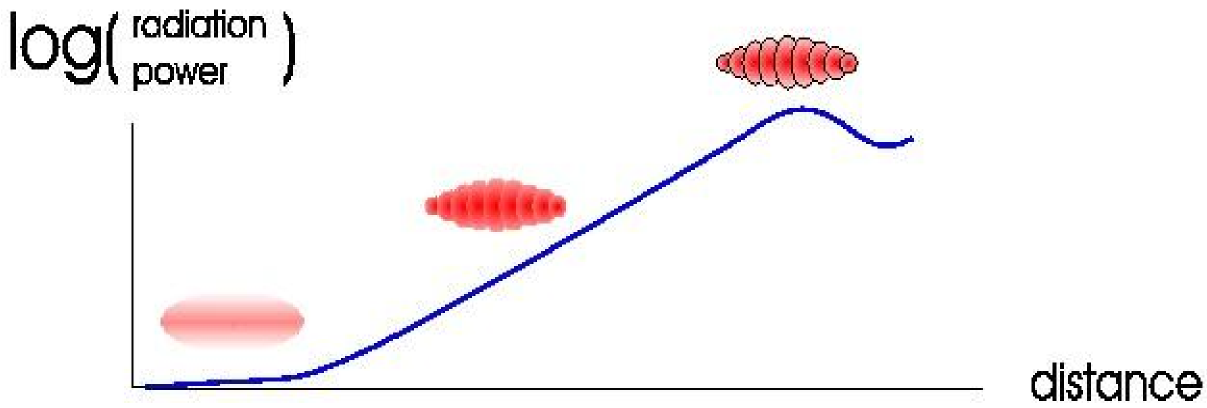
The FEL are of two types oscillators and amplifiers. In oscillators the radiation is stored in a cavity. The growth of radiation occurs over many bounces (low gain)



FEL amplifiers

The FEL are of two types oscillators and amplifiers. In amplifiers the radiation grows within a single pass in the undulator



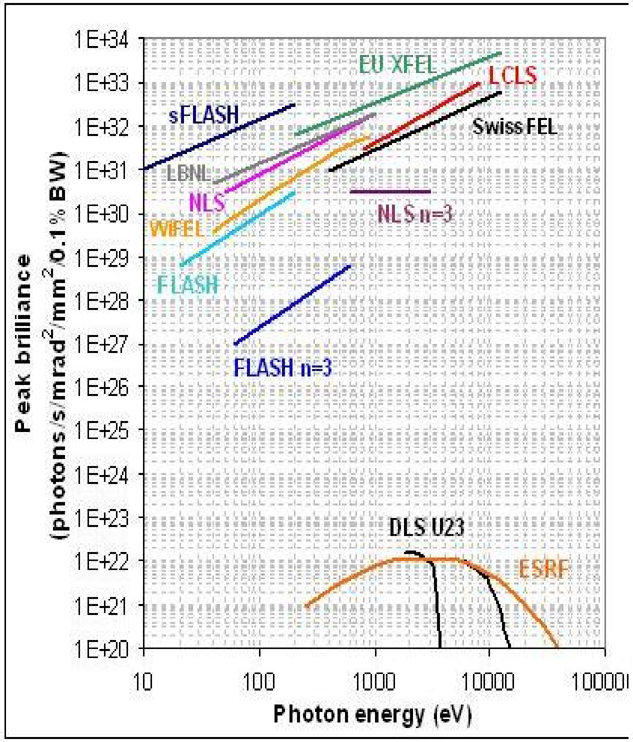


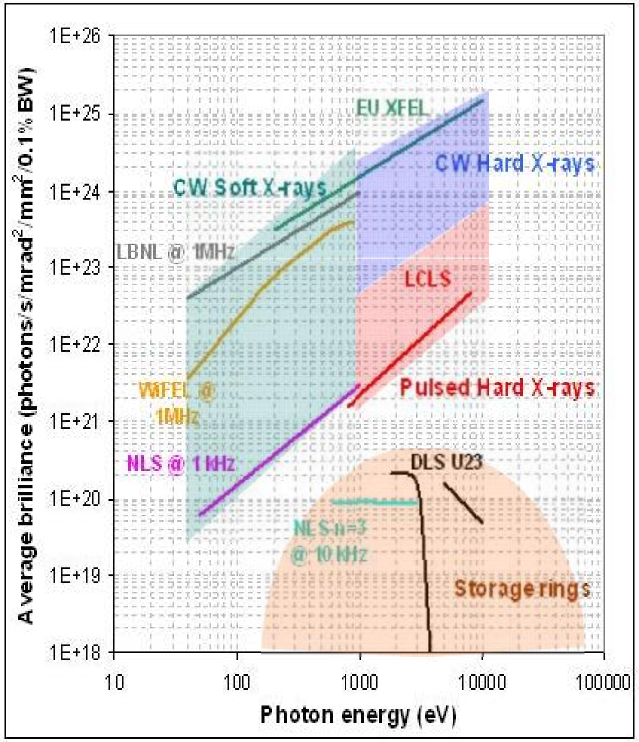
This mode of operation is called **SASE** (Self Amplified Spontaneous Emission)

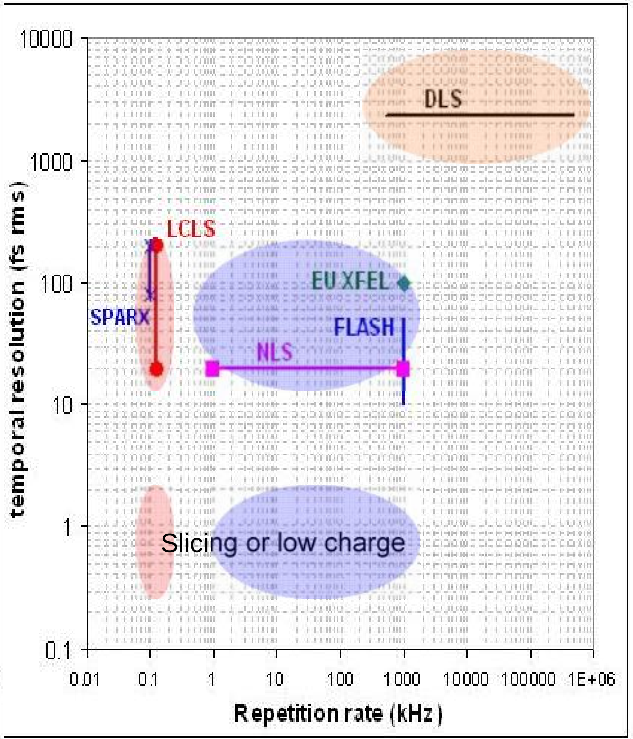
FEL radiation properties

FELs provide peak brilliance 8 order of magnitudes larger than storage ring light sources

Average brilliance is 2-4 order of magnitude larger and radiation pulse lengths are of the order of 100s fs or less







Many projects target Soft X-rays (<u>here 40 – 1 nm</u>) . Soft X-rays FELs require 1-3 GeV Linacs. Hard X-rays project will also provide Soft X-rays beamlines (Swiss FEL – LCLS)

Users' requirements - 4th generation light sources

Higher peak brightness

Transverse coherence — SASE

Multi-keV photons and tunability

Ultra short pulses (<100 fs down to sub-fs)

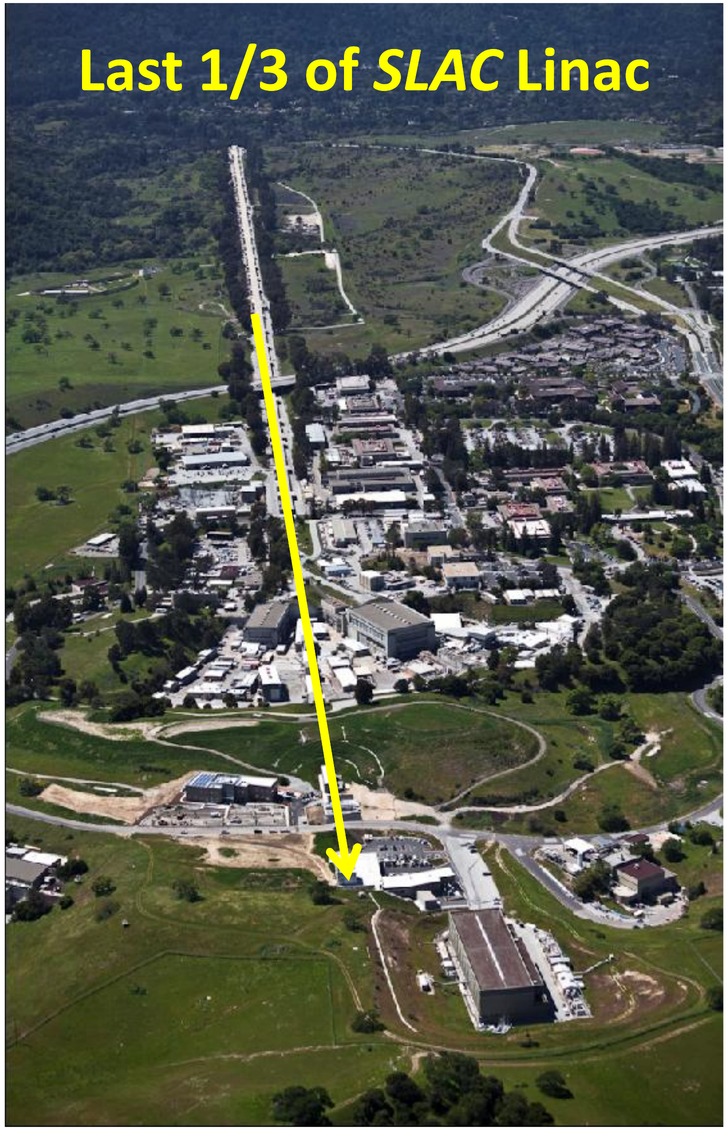
Temporal coherence — direct seeding - seeding + HG

High repetition rates / Time structure (equispaced pulses) — SC/NC RF

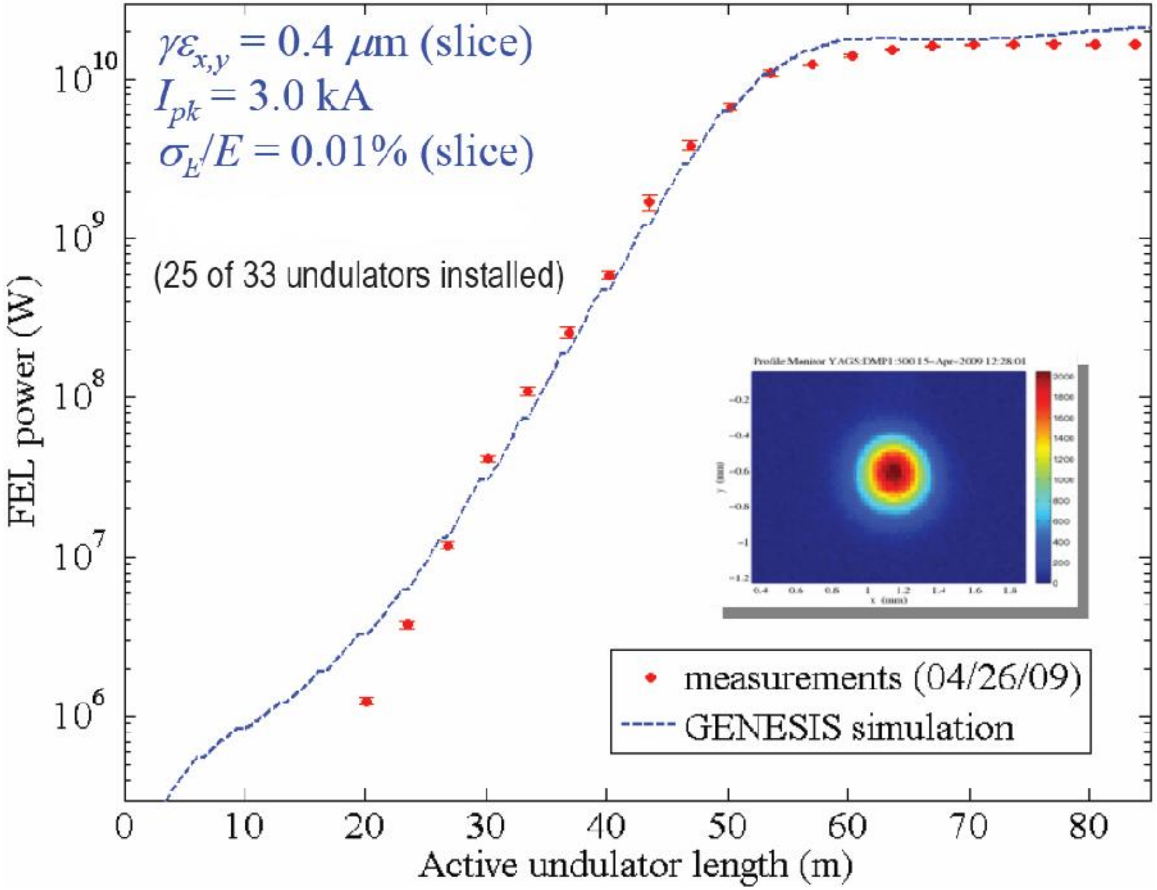
Polarisation control — IDs technology or novel schemes

Synchronisation to external lasers VUV and THz

LCLS lasing at 1.5 Å (April 2009)



Electron energy	= 3.3 - 15 GeV
Photon energy	= 0.5 - 10 keV
Repetition rate	= 120 Hz
Machine length	≈ 2 km



X-rays FELs

LCLS	**0.15 nm**	**14 GeV**	**S-band**	**120 Hz**	**SASE/ss**
SACLA	**0.1 nm**	**8 GeV**	**C-band**	**60 Hz**	**SASE**
XFEL	0.1 nm	17.5 GeV	SC L-band	CW (10 Hz)	SASE/ss
Swiss-FEL	0.1 nm	5.8 GeV	C-band	120 Hz	SASE
Pohang	0.06 nm	10 Gev	S-C-band	60 Hz	SASE

FLASH	**47-6.5 nm**	**1 GeV**	**SC L-band**	**1MHz (5Hz)**	**SASE/sFLASH**
FERMI	**40-4 nm**	**1.2 GeV**	**S-band**	**50 Hz**	**seeded HGHG**
SPARX	40-3 nm	1.5 GeV	S-C-band	100 Hz	SASE/seeded
Wisconsin	1 nm	2.2 GeV	SC/CW L-band	1 MHz	seeded HHG
LBNL	100-1 nm	2.5 GeV	SC/CW L-band	1 MHz	seeded
MAX-LAB	5-1 nm	3.0 GeV	S-band	>100 Hz	SASE/seeded
Shanghai	10 nm	0.8-1.3 GeV	S-band	10 Hz	seeded HGHG
NLS	20-1 nm	2.2 GeV	SC/CW L-band	1-1000 kHz	seeded HHG

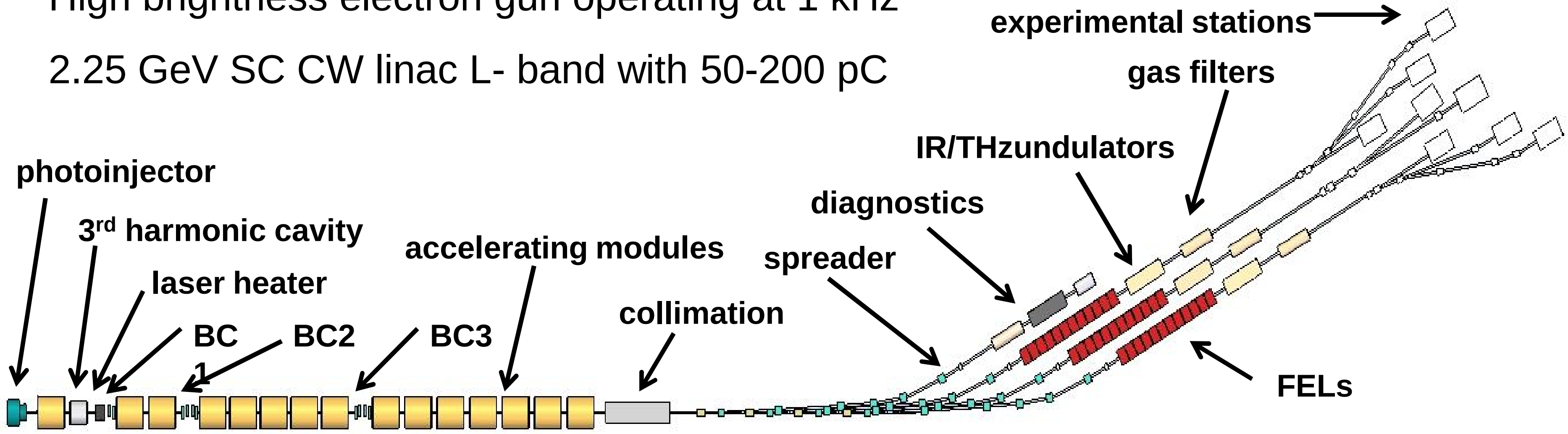
Swiss-FEL	10 nm	2.1 GeV	C-band	120 Hz	SASE/seeded
LCLS-II	4 nm	4 GeV	S-band	120 Hz	seeded

FEL amplifiers main components

An example taken from the UK New Light Source project (defunct)

High brightness electron gun operating at 1 kHz

2.25 GeV SC CW linac L- band with 50-200 pC



3 FELS covering the photon energy range 50 eV – 1 keV (50-300; 250-800; 430-1000)

- GW power level in 20 fs pulses
- laser HHG seeded for temporal coherence
- cascade harmonic FEL
- synchronised to conventional lasers and IR/THz sources for pump probe experiments

Accelerator Physics challenges for FELS

Soft X-ray FELs are driven by high brightness electron beam

1 – 3 GeV $\varepsilon_n \leq 1\ \mu m$ ~ 1 kA $\sigma_\gamma / \gamma \leq 10^{-4}$

This requires:

a low emittance gun (norm. emittance cannot be improved in the linac)

acceleration and compression through the linac keeping the low emittance

The operation of a seeded FEL poses additional requirements

Assuming a 20 fs FWHM seed laser pulse, we need an electron bunch with *constant slice parameters* over 20 fs plus the relative time jitter between the electron bunch and the laser seed pulse.

- e^- pulse shape control: constant slice parameters on a length of **100 fs – or longer**
- no residual energy chirp (or very limited)
- low sensitivity to jitter

The slice parameters to control are not only slice current, emittance, energy spread but also slice offset and angle and Twiss parameters

Design and Optimisation of LINACs driving FELs

- Tracking studies to optimise the beam quality at the beginning of the undulators:

  peak current, slice emittance, slice energy spread

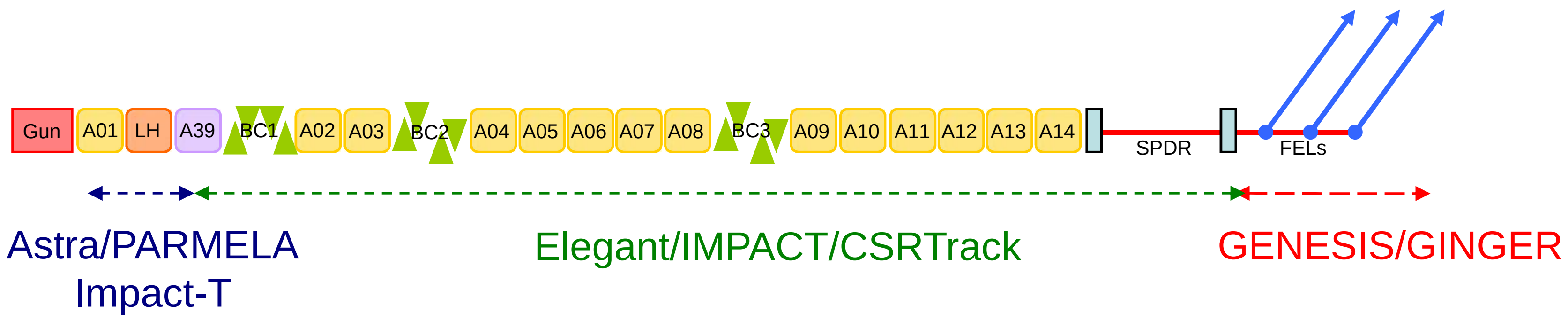
- linac simulations include

  CSR, longitudinal space charge, wake-fields in RF cavities

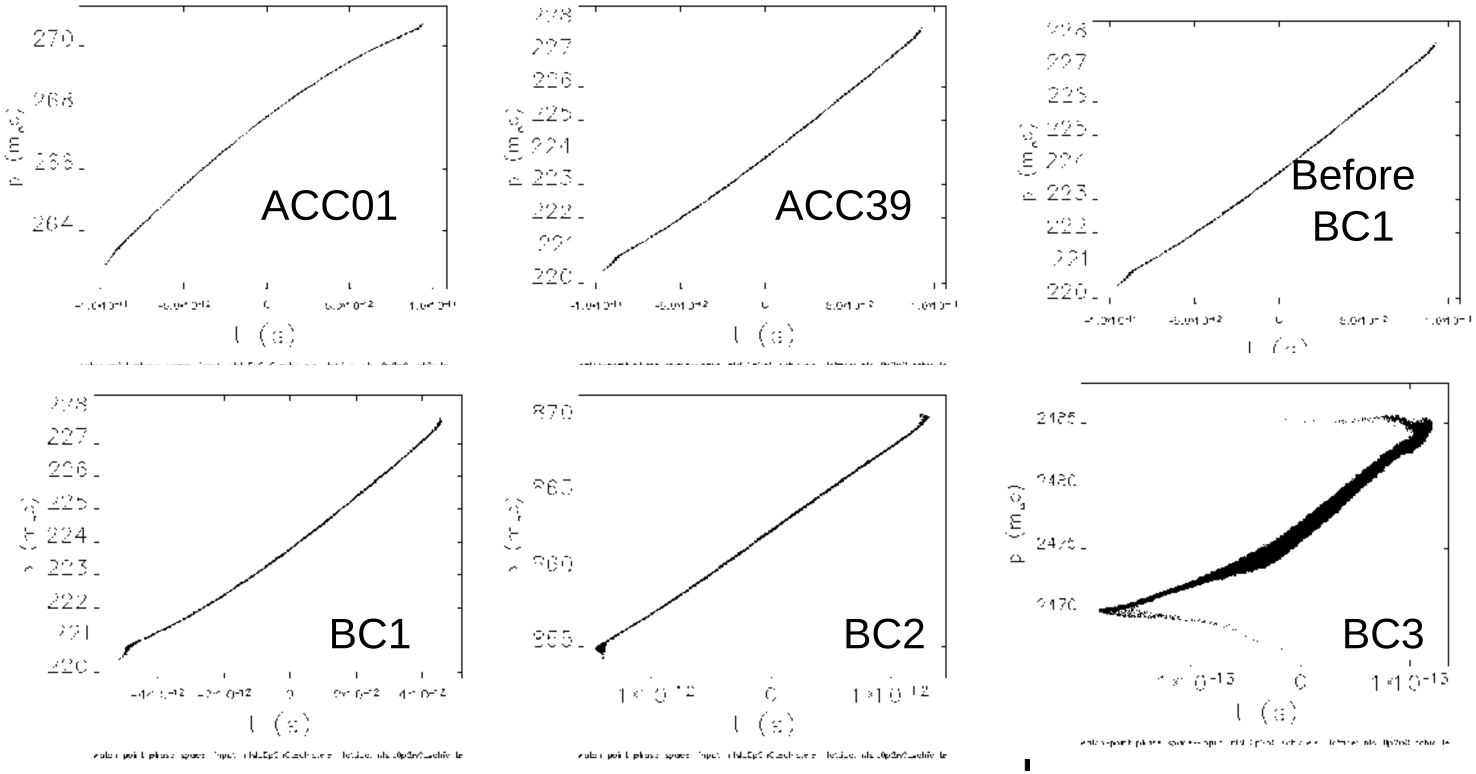
- Parameters used in the optimisation

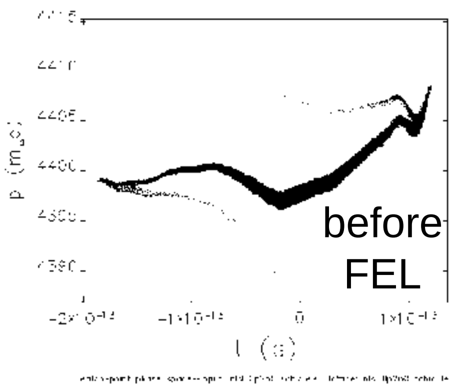
  Accelerating section and 3HC amplitude and phase,
  Bunch compressors strengths (R_{56})

- **Optimisation validated with full start-to-end simulations: Gun to FEL**



Beam evolution along the linac: 2M particle tracking



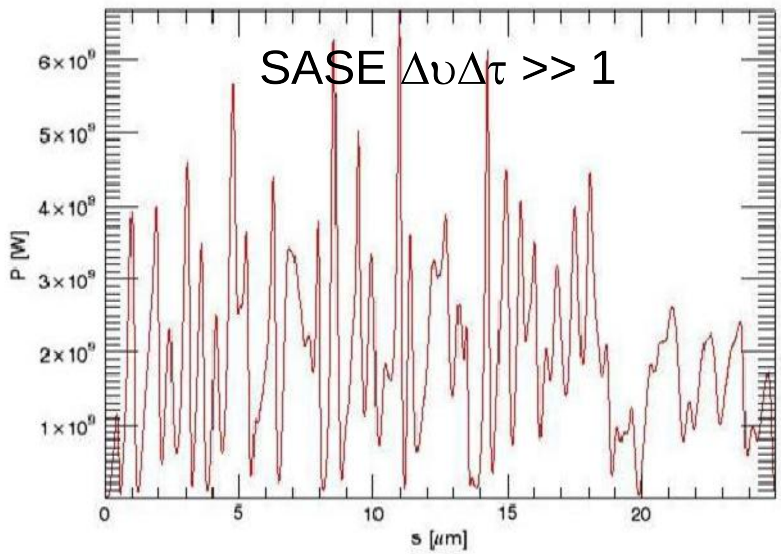


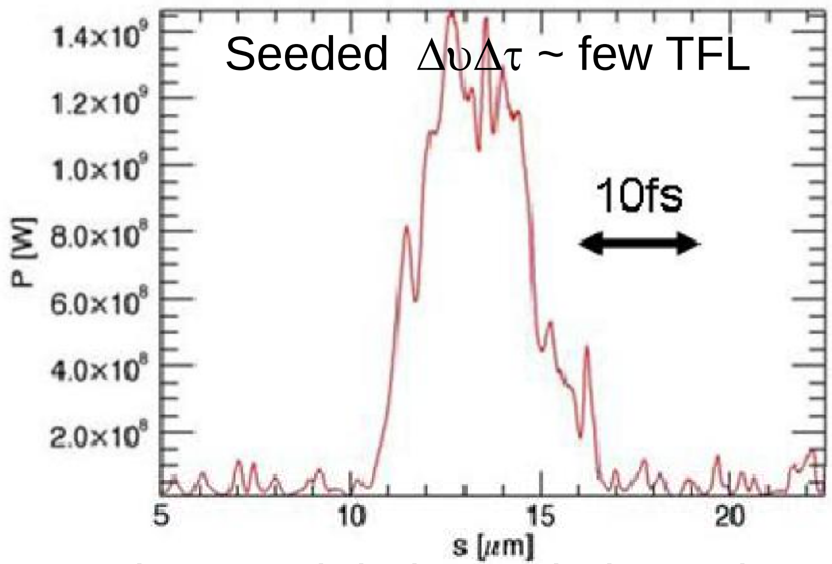
Pulse length compressed in 3BCs

18 ps FW at start 250 fs FW at end

Maintain a uniform 6D distribution over ~100 fs

SASE vs seeded FELs





SASE has a very spiky output: each cooperation length behaves independently: no phase relation among spikes

pulse length ~100 fs, bandwith is $\rho \approx 0.1\%$, the coherence length is $\approx \lambda/\rho$

Seeding improves

longitudinal coherence

shorter saturation length

stability (shot to shot power, spectrum, ...)

control of pulse length

allows synchronisation to external lasers

pulse length and the coherence length are given by the seed laser pulse lengh

FEL physics challenges: seed sources (I)

Seed source must be

powerful enough to dominate the shot noise power coherent (Tra & Lon)

high rep rate short pulses

tuneable stable (time jitter, pointing stability, etc)

Power seed requirements:

$P > 100\ P_{shot}$ for direct seeding

$P > 100 * n^2 * P_{shot}$ for HGHG

$$P_{shot} = \frac{1}{2}\rho^2\gamma\omega mc^2$$

P_{shot} increases with decreasing wavelength. Losses during seed transport and matching have to be taken onto account.

Seed source are not available down to 1 keV. Frequency up-conversion has the be done with the FEL itself

HGHG schemes (L.H. Yu, Science, (2000))
multistage HGHG
EEHG (ECHO-7 ok, proven at larger harmonic jumps – but soft X-rays)

FEL physics challenges: seed sources (II)

Conventional laser Ti:Sa and harmonics are used down to 260 nm (FERMI@Elettra)

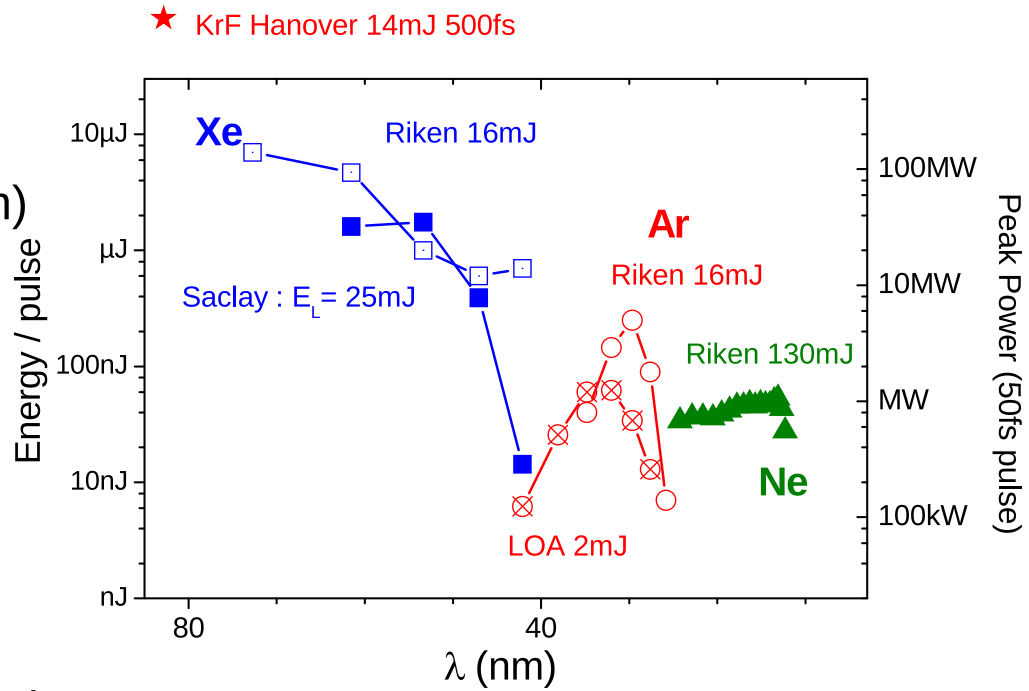
HHG sources used at

SCSS (160 nm), SPARC (400-114 nm)

proposed at

sFLASH, NLS, LBNL, WiFEL, …

HHG sources extend down to 10 nm (124 eV)



Courtesy J. Tisch

Tunability achieved by harmonic selection

Repetition rate:

30mJ/40fs @ 1kHz available **now**

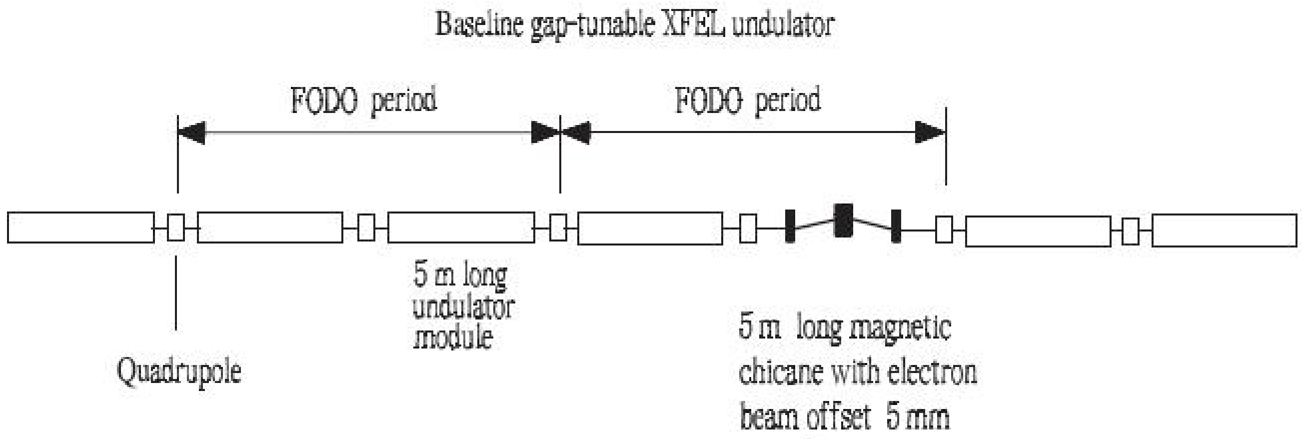
20mJ/40 fs @ 10kHz available **in approx 3-4 years**

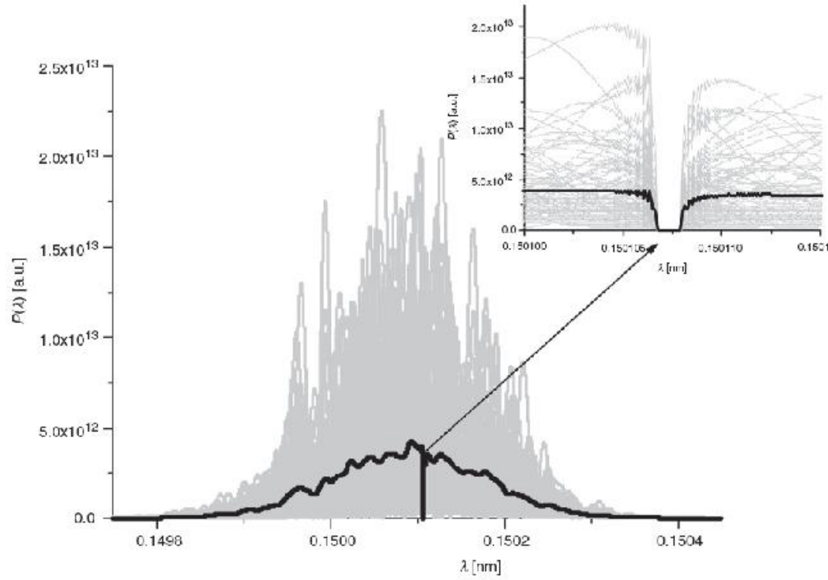
For NLS 400 kW at the undulator – 1.2 MW at the seed source (100 eV)

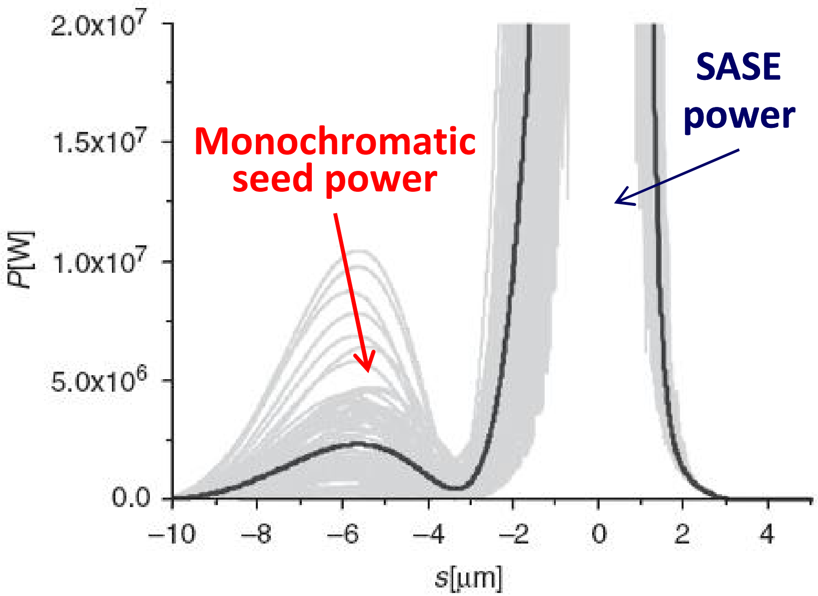
Direct self-seeding:

Geloni et al., Jour. Mod. Opt . 58, pg 1391, (2011)

Filtering the SASE output with a monochromator in transmission, creates a hole in the spectrum and a monochromatic tails in the SASE pulse







Direct self-seeding:

Geloni et al., Jour. Mod. Opt . 58, pg 1391, (2011)

Use the SASE in the first undulator to seed the bunch in the second undulator

• electrons are delayed to overlap with the (monochromatic) tail of the SASE pulse

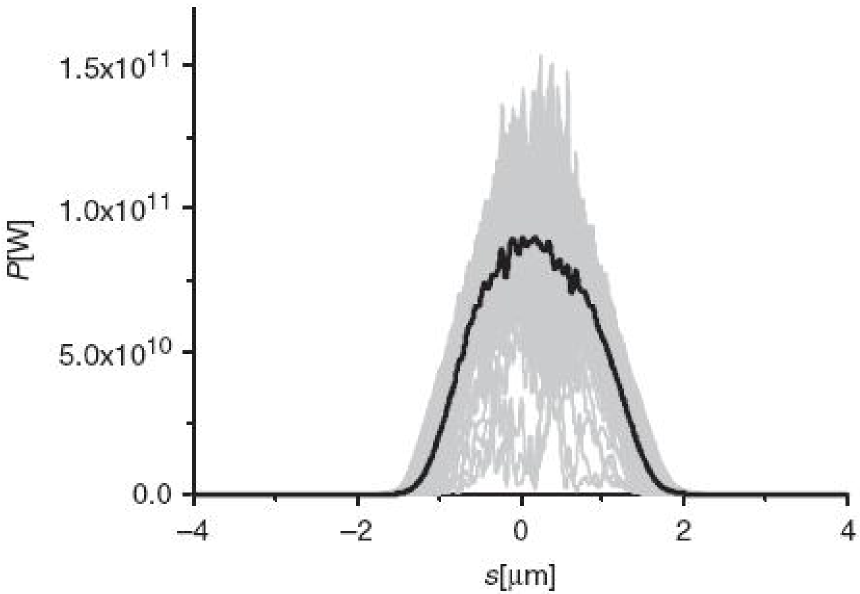
• SASE in the first undulator is in the linear regime: the beam quality is not spoiled

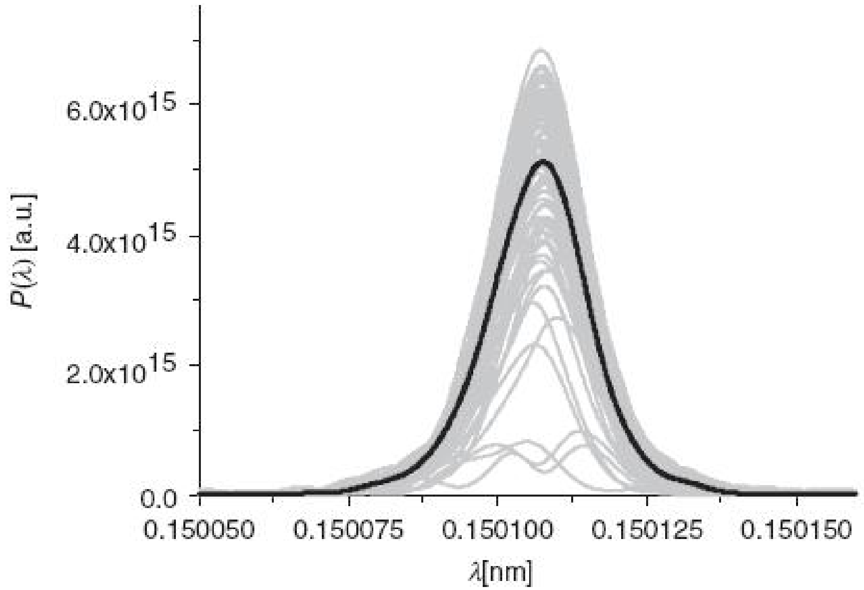
• the power in the tails (seed power) exceeds the shot noise

• direct seeding in the second undulator up to saturation

near Fourier-limited puses with 15 GW are predicted for LCLS

(100 GW with tapering and stability 10%)





Modern trends in FELs

Modern trends include

improvement of temporal coherence

extending self seeding

harmonic generation schemes (HGHG – cascaded HGHG, ...)

attosecond X-ray pulses (aggressive compression of the electron bunch)

elecotron bunch manipulation (slicing, ECHO, ...)

two colours generation

TW laser pules with tapering

Summary and bibliography

Third generation (storage rings) provide stable high brightness sources, serve many beamlines, approaching full transverse coherence with diffraction limited rings

Many laboratories are actively considering upgrade to new ultra low emittance light sources

FELs have higher peak brightness, short pulses, full transverse coherence but can serve a few beamlines at a time (and are very expensive)

Compact more economic design should be devised to make these machine affordable by national labs.

Bibliography

J.D. Jackson, Classical Electrodynamics

K. Steffen, CERN CAS 85-19 (1985)

M. Sands, the physics of electron storage rings, SLAC pub (1971)