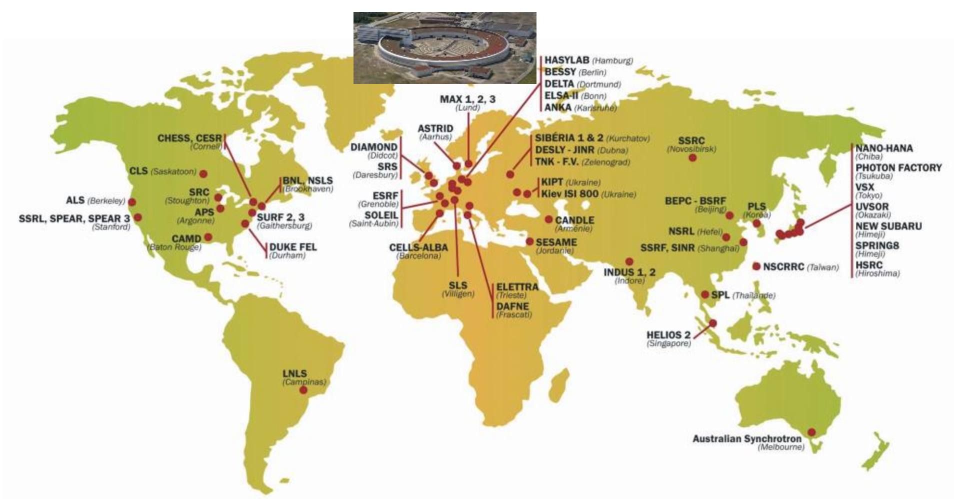
Light Sources
based on Storage Rings

Lenny Rivkin

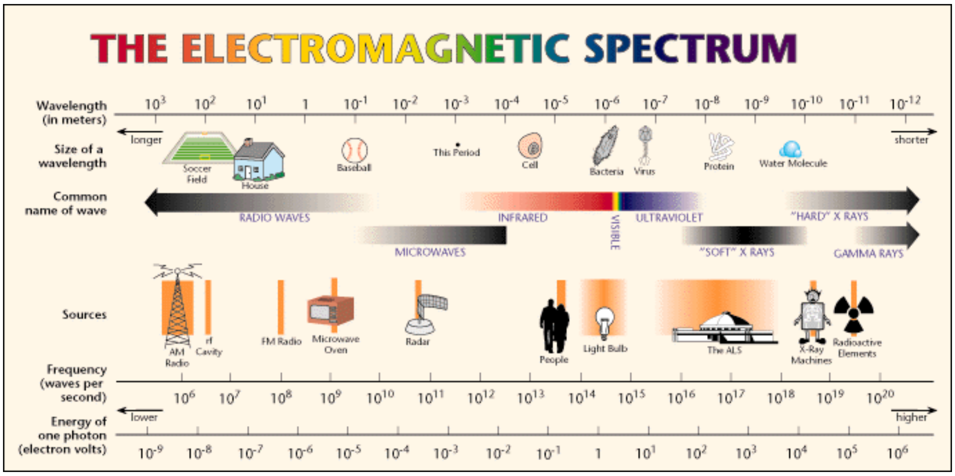
Paul Scherrer Institute (PSI)
and
Swiss Federal Institute of Technology Lausanne (EPFL)

Light sources: > 50 producing synchrotron light

60‘000 users world-wide



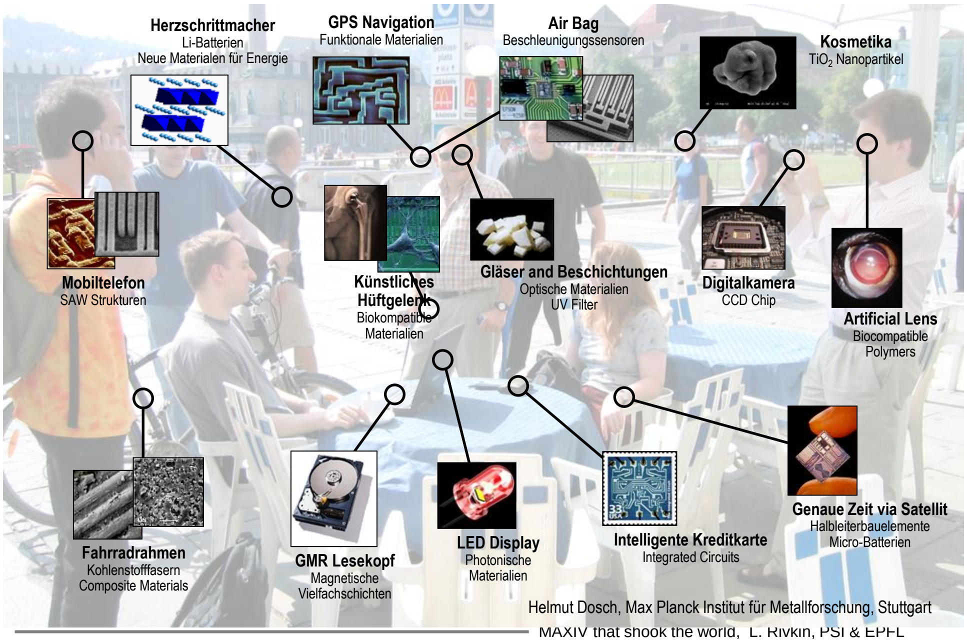
Electron Beam Dynamics, L. Rivkin, Introduction to Accelerator Physics, Budapest



Wavelength continuously tunable !

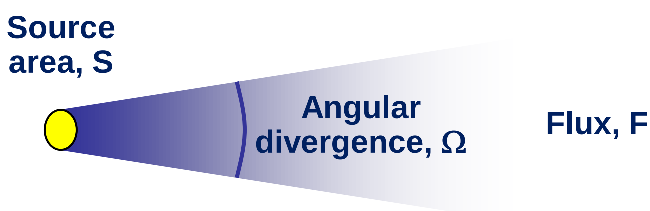
Materials – key to our technologies

Materials – key to our technologies

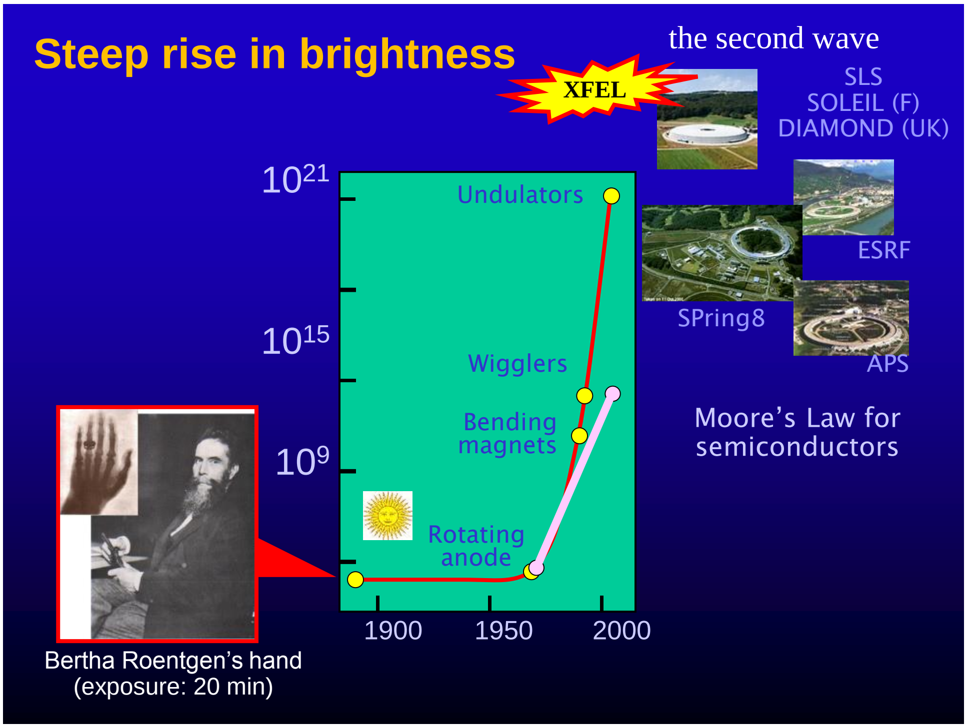


MAXIV that shook the world, L. Rivkin, PSI & EPFL

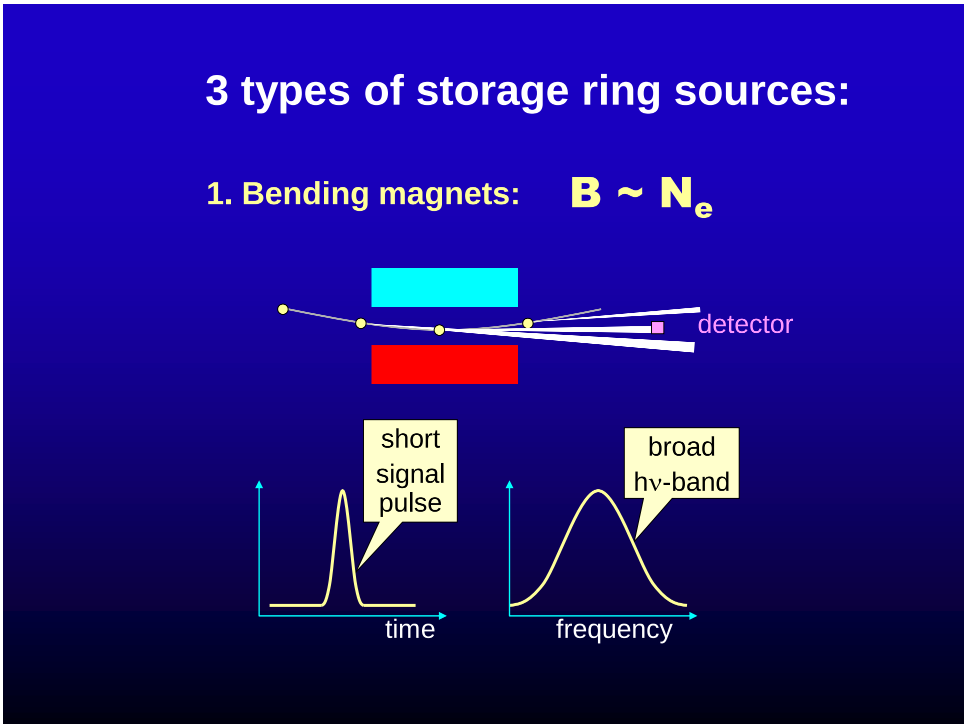
The "brightness" of a light source:



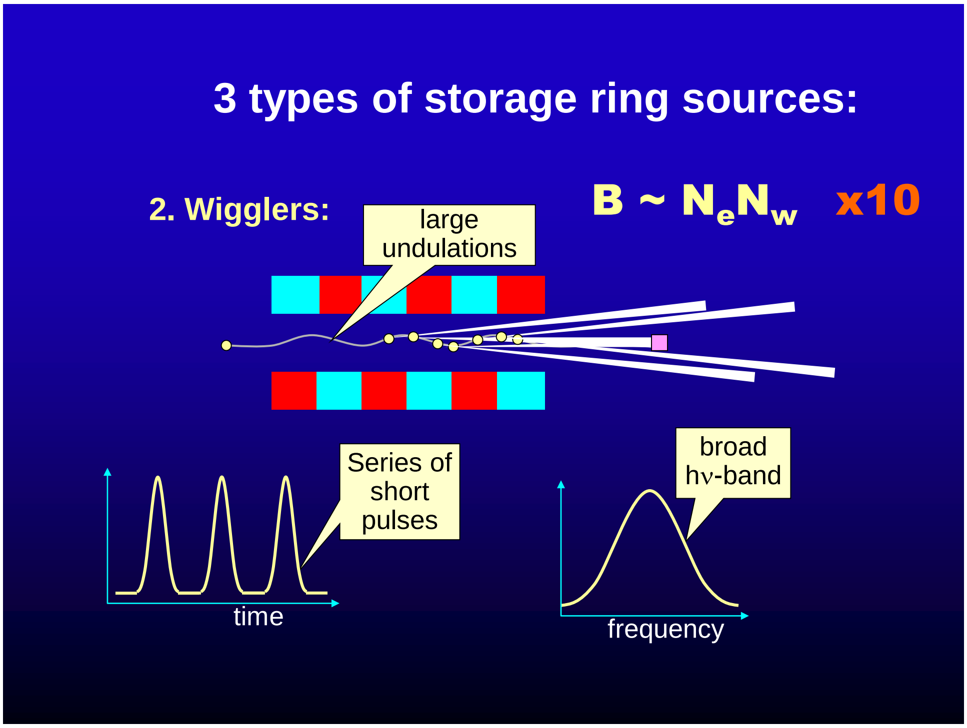
$$\text{Brightness} = \text{constant} \times \frac{F}{S \times \Omega}$$

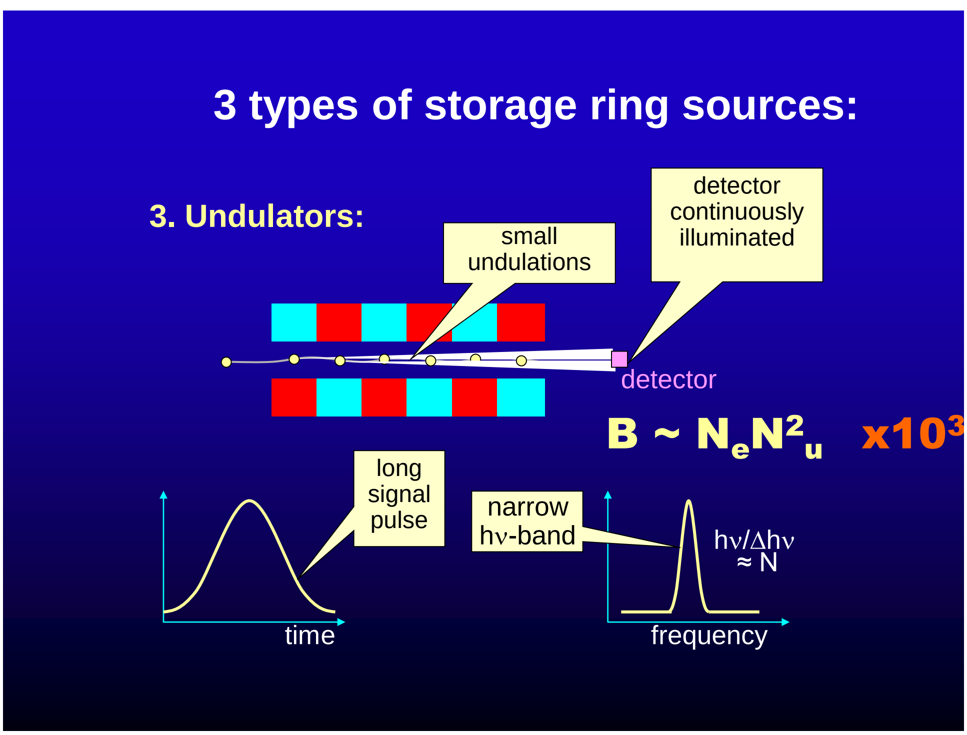


Steep rise in brightness
the second wave
XFEL
SLS
SOLEIL (F)
DIAMOND (UK)
ESRF
SPring8
APS
10^21
10^15
10^9
Undulators
Wigglers
Bending magnets
Rotating anode
1900
1950
2000
Moore's Law for semiconductors
Bertha Roentgen's hand
(exposure: 20 min)

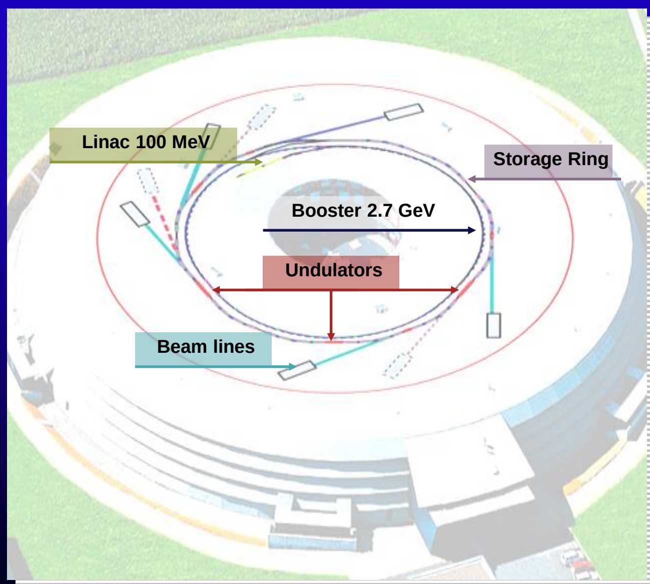


3 types of storage ring sources:
1. Bending magnets:
B ~ N_e
detector
short signal pulse
broad hν-band
time
frequency

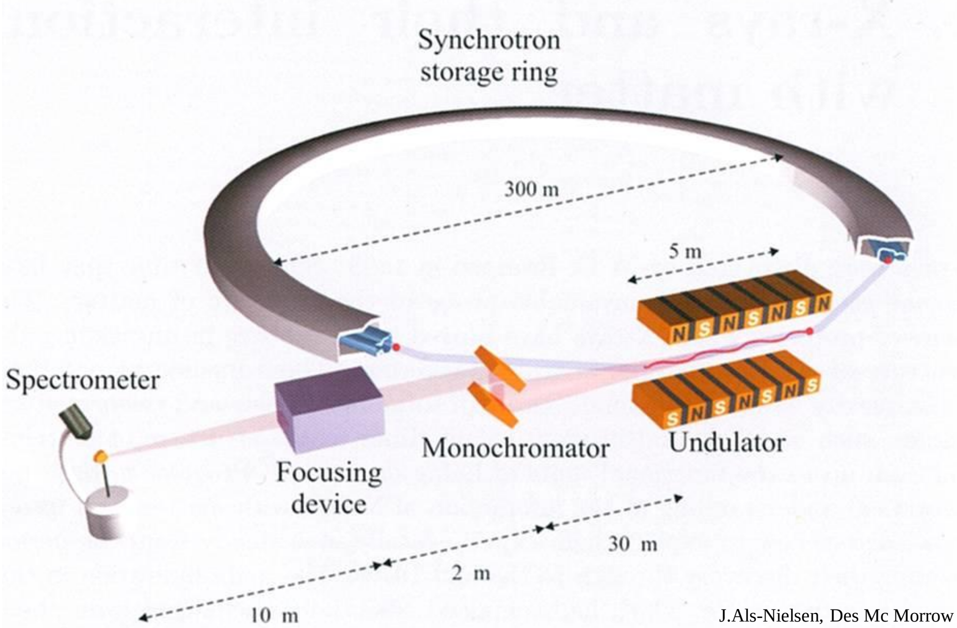

3 types of storage ring sources:
2. Wigglers:
large undulations
B ~ NeNw
x10
Series of short pulses
broad hν-band
time
frequency


3 types of storage ring sources:
3. Undulators:
small undulations
detector continuously illuminated
detector
B ~ NeN2u
x103
long signal pulse
narrow hν-band
hν/Δhν ≈ N
time
frequency

Anatomy of a light source



Undulator based beamline



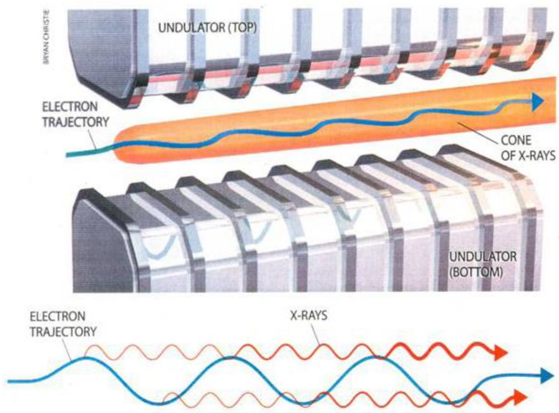
J.Als-Nielsen, Des Mc Morrow

Bright beams of particles: phase space density

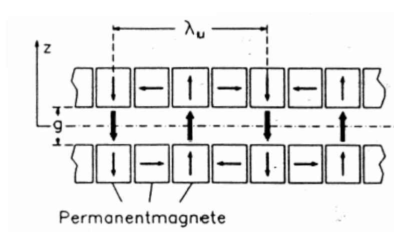
Incoherent, spontaneous emission of light:

Large phase space

Coherent, stimulated emission of light



Permanent magnet undulators

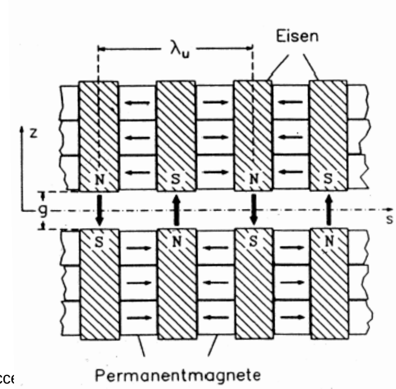


Permanent magnet materials: $SmCo_5$, NdFeB

e.g. a pencil made of such material corresponds to 15'000 A-turns!

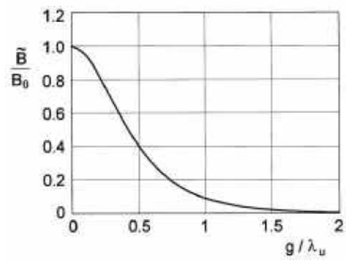
Hybrid undulator:

permanent magnets and iron



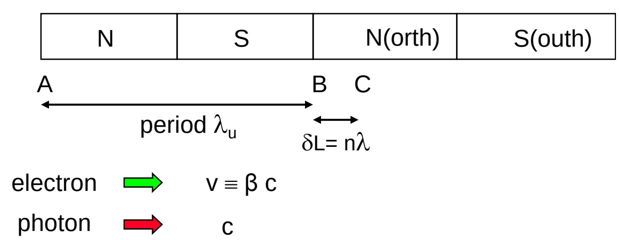
Field tuning with gap

$$B \approx 1.8 \cdot B_r \cdot e^{-\pi \cdot \frac{gap}{\lambda_u}}$$



Permanent magnet material	Remanent field [T]
$SmCo_5$	0.9 – 1.0
Sm_2Co_{17}	1.0 – 1.1
NdFeB	1.0 – 1.4

Selection of wavelength in an undulator II

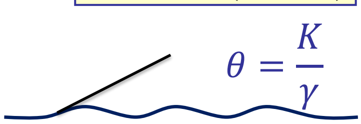


The path difference

$$\delta L \equiv n\lambda \approx (1-\beta)\lambda_u \,, \quad 1-\beta \approx \frac{1}{2\gamma^2}$$

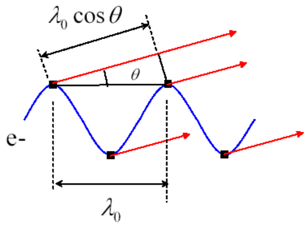
$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1+\frac{K^2}{2}\right)$$

detour through slalom

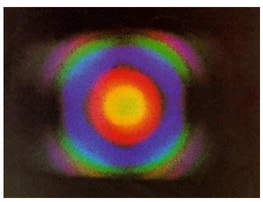


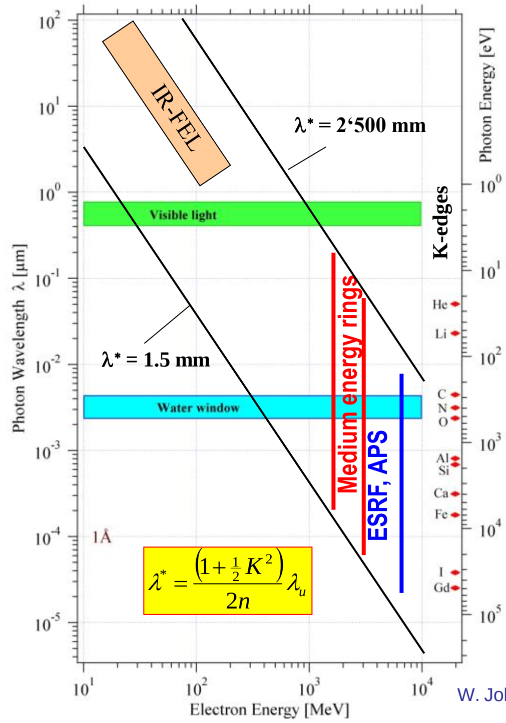
$$K = 0.0934 \cdot \lambda_u[mm] \cdot B[T]$$

Undulator radiation



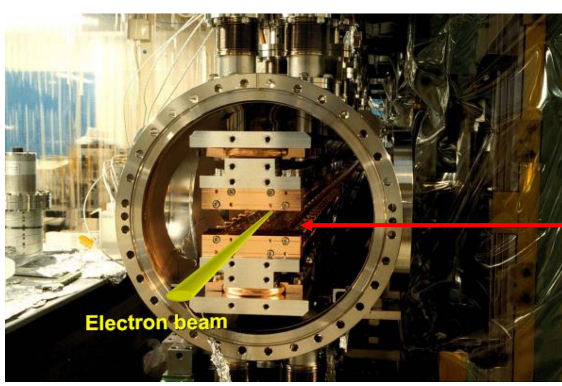
$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$





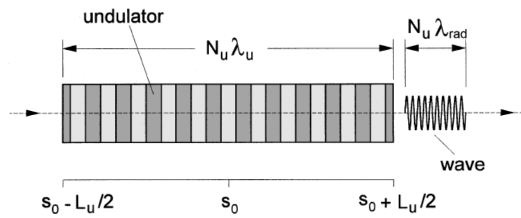
W. Joho

In-vacuum undulators / s.c. undulators



Gaps down to 3 mm

Undulator line width



Undulator of infinite length $N_u = \infty \quad \Rightarrow \quad \frac{\Delta\lambda}{\lambda} = 0$

Finite length undulator

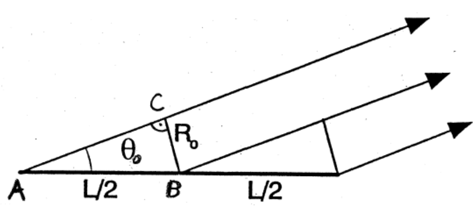
- radiation pulse has as many periods as the undulator
- the line width is $\frac{\Delta\lambda}{\lambda} \sim \frac{1}{N_u}$

Due to the electron energy spread $\frac{\Delta\lambda}{\lambda} = 2\frac{\sigma_E}{E}$

Radiation cone of an undulator

Undulator radiates from the whole length L into a narrow cone.

Propagation of the wave front BC is suppressed under an angle θ_0,



if the path length AC is just shorter by a half wavelength compared to AB (negative interference). This defines the central cone.

$$\Delta L = AB - AC = \frac{1}{2}L(1-\cos\theta_0) \approx \frac{1}{4}L\theta_0^2$$

Negative interference for $\Delta L = \frac{\lambda}{2}$

$$\theta_0 = \sqrt{\frac{2\lambda}{L}} \qquad R_0 = \sqrt{\frac{\lambda \cdot L}{2}} \qquad \varepsilon_0 = \theta_0 R_0 = \lambda$$

W. Joho

WHAT DO USERS EXPECT FROM A HIGH PERFORMANCE LIGHT SOURCE ?

- PROPER PHOTON ENERGY FOR THEIR EXPERIMENTS
- BRILLIANCE
- STABILITY

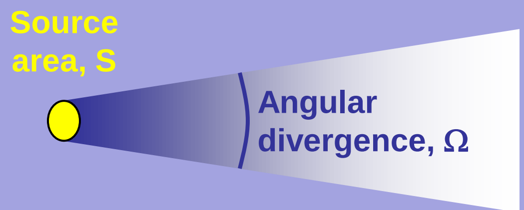
$$B = \frac{\Phi}{(2\pi)^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

FIGURE OF MERIT

$$\Sigma^2 = \sigma_e^2 + \sigma_\gamma^2 \qquad \Sigma_x \Sigma_{x'} \approx \sigma_x \sigma_x' \sim \varepsilon_x$$

Photon beam size (U): $\sigma_\gamma' = \sqrt{\frac{\lambda}{L}}$ $\quad \sigma_\gamma = \frac{\sqrt{\lambda L}}{4\pi}$

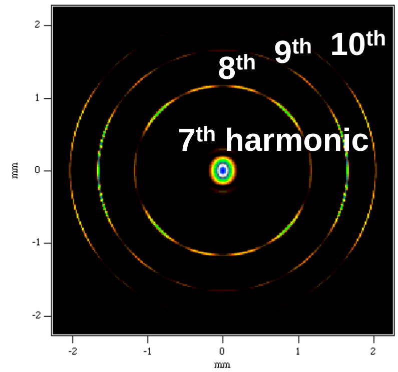
The electron beam "emittance":

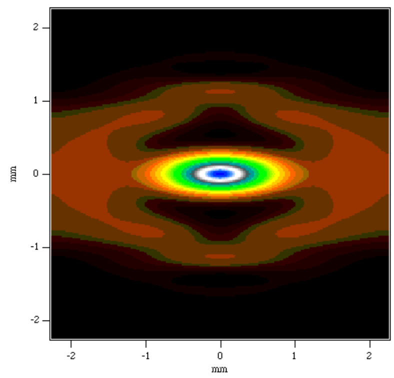


The brightness depends on the geometry of the source, i.e., on the electron beam emittance

Emittance = S x Ω

Undulator radiation from 6 GeV beam with zero emittance, energy spread (example ESRF)





Emittance 4 nm·rad, 1% coupling, finite energy spread

Electron beam phase space

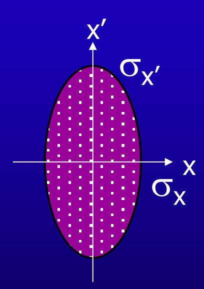
Area $= \pi \cdot \varepsilon$

Emittance

Units of ε $[m \cdot rad]$

Transverse electron beam distribution

- Gaussian
- "Typical" particle: 1 - σ ellipse (in a place where $\alpha = \beta' = 0$)



$$\sigma_x = \sqrt{\varepsilon\,\beta}$$
$$\sigma_{x'} = \sqrt{\varepsilon/\beta}$$

$$\varepsilon = \sigma_x \cdot \sigma_{x'}$$

$$\beta = \frac{\sigma_x}{\sigma_{x'}}$$

Radiation effects in electron storage rings

Average radiated power restored by RF

- Electron loses energy each turn to synchrotron radiation
- RF cavities accelerate electrons back to the nominal energy

Radiation damping

- Average rate of energy loss produces **DAMPING** of electron oscillations in all three degrees of freedom (if properly arranged!)

Quantum fluctuations

- Statistical fluctuations in energy loss (from quantized emission of radiation) produce **RANDOM EXCITATION** of these oscillations

Equilibrium distributions

- The balance between the damping and the excitation of the electron oscillations determines the equilibrium distribution of particles in the beam

Small emittance lattices

Equilibrium horizontal emittance

$$\varepsilon_{x0} \equiv \frac{\sigma^2_{x\beta}}{\beta} = \frac{C_q E^2}{J_x} \cdot \frac{\langle \mathcal{H} \rangle_{mag}}{\rho}$$

- one tries to optimize the $\mathcal{H}$ function in **bending magnets**

$$\mathcal{H} = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

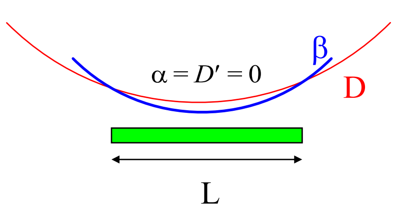
- the equilibrium emittance can be written as:

$$\varepsilon_{x0} = \frac{C_q E^2}{J_x} \cdot \theta^3 \cdot \mathbf{F_{latt}}$$

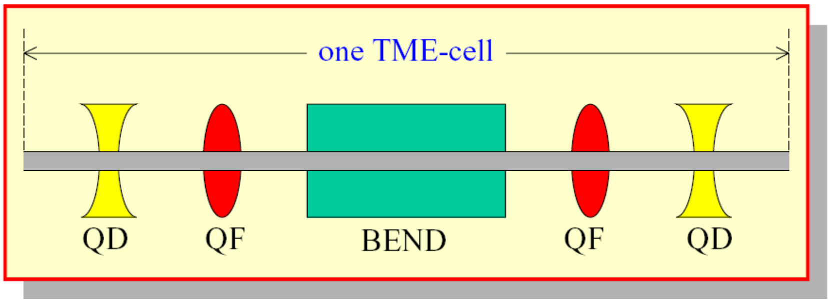
$$\mathrm{F_{min}} = \frac{1}{12\sqrt{15}}$$

there exists a minimum

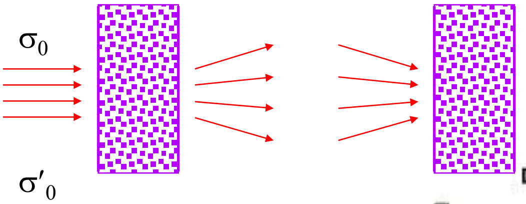
$$\beta^* = \frac{L}{2\sqrt{15}}, \quad D^* = \frac{L\theta}{24}$$



Theoretical minimum emittance

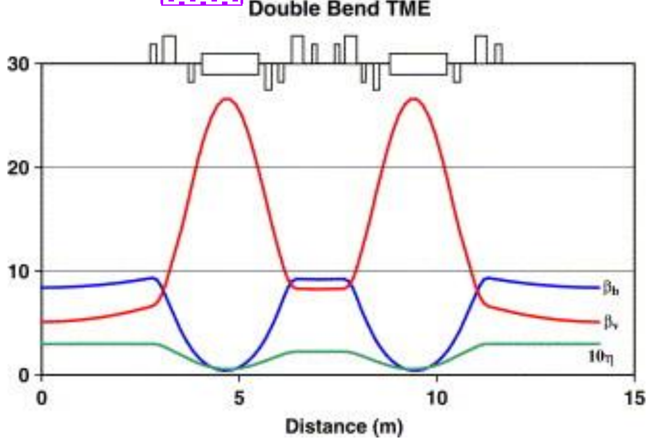


Minimum emittance lattices



$$\varepsilon_{x0} = \frac{C_q E^2}{J_x} \cdot \theta^3 \cdot F_{latt}$$

$$F_{min} = \frac{1}{12\sqrt{15}}$$

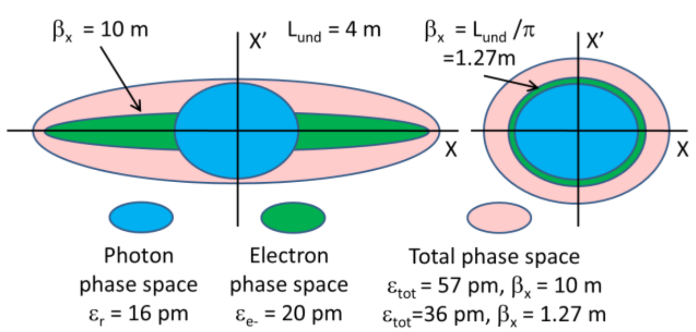


Tight focus in the middle of the bending magnets – need space!

Many bending magnets – need space!

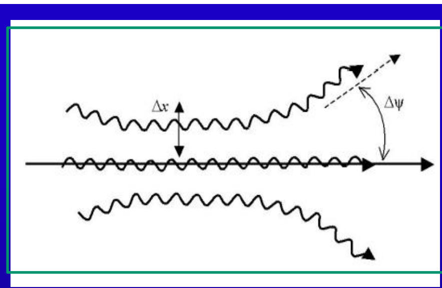
X-ray emittance from electron source:
a convolution of electron and photon phase space

$$\text{Brightness} = \frac{\Phi}{(2\pi)^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \qquad \Sigma^2 = \sigma_e^2 + \sigma_\gamma^2$$

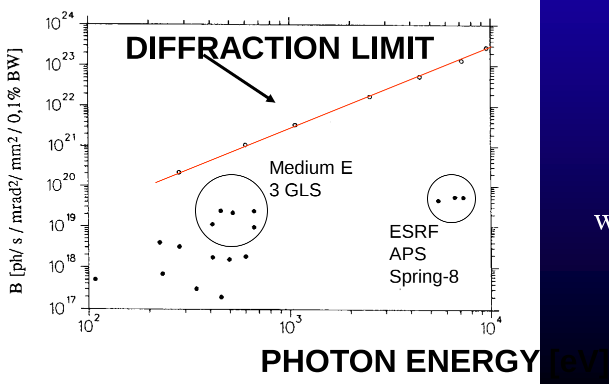


R. Hettel

HITTING THE DIFFRACTION LIMIT

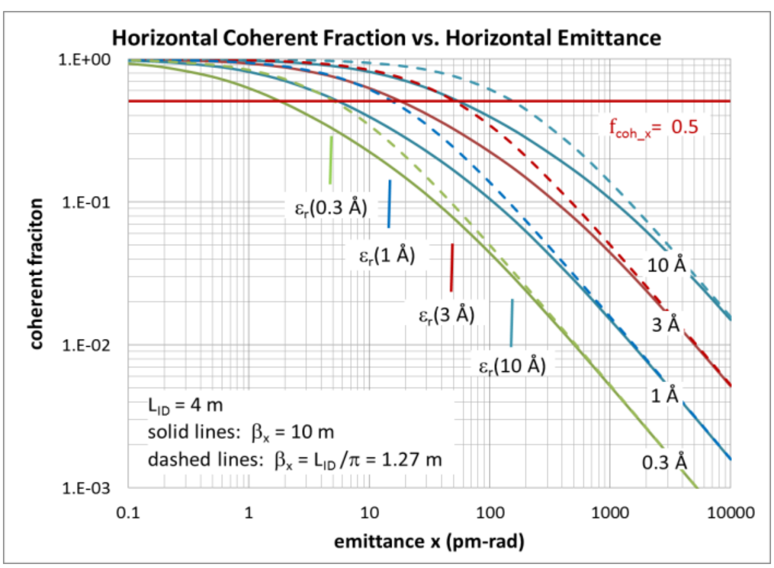


BRIGHTNESS:



Light of wavelength λ focused to spot size Δx will diffract with angle $\Delta\psi = \sim \lambda/\Delta x$

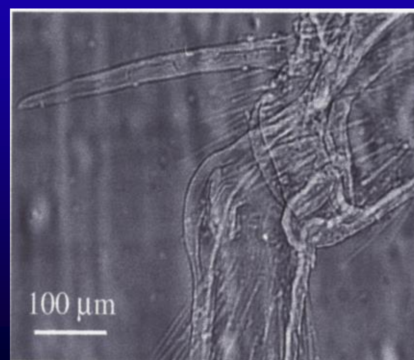
Coherence fraction



Transverse coherence

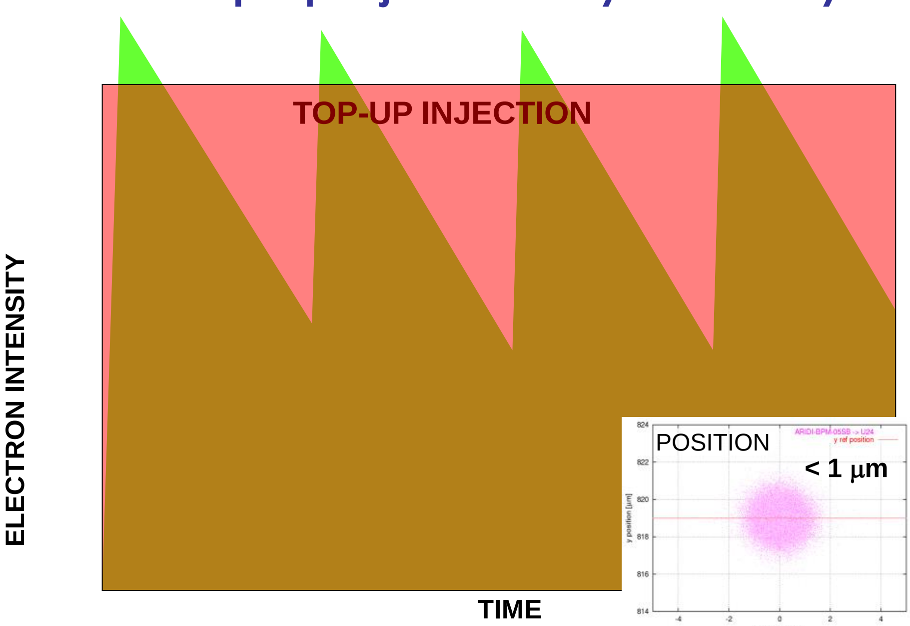
- High brightness gives coherence
- Wave optics methods for X-rays (all chapters in Born & Wolf)
- Holography

The knee of a spider



phase contrast imaging

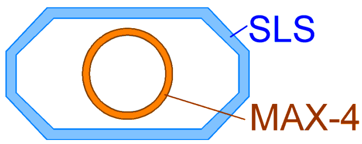
Top-up injection: key to stability

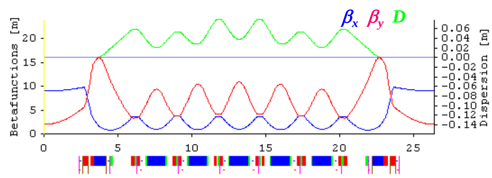


A revolution in storage ring technology

Pioneer work: MAX IV (Lund, Sweden)

Aperture reduction ⟷ **Multi-Bend Achromat (MBA)**





Technological achievement:
NEG coating of small vacuum chambers

⇨ Small magnet bore
⇨ High magnet gradient

⇨ short lattice cells
⇨ many lattice cells
⇨ low angle per bend

emittance $\varepsilon \propto (\text{energy})^2 \times (\text{bend angle})^3$

⇨ Emittance reduction from nm to 10...100 pm range

The MAX IV Laboratory in Lund, Sweden

The world is moving to ever brighter ring sources

2-bend achromat

BNL**: NSLS-II** (2014): 3 GeV, <1000pm x 8 pm, 500 mA (**New**)

7- bend achromat

Sweden: **MAX-4** (2016): 3 GeV, 230 pm x 8 pm, 500 mA (**New**)

5- bend achromat

Brazil**: SIRIUS** (2016/17): 3 GeV, 280 pm x 8 pm, 500 mA (**New**)

1st multi-bend achromat ring upgrade

France: **ESRF-II** (2020): 6 GeV, 160 pm x 3 pm, 200 mA (**New**)

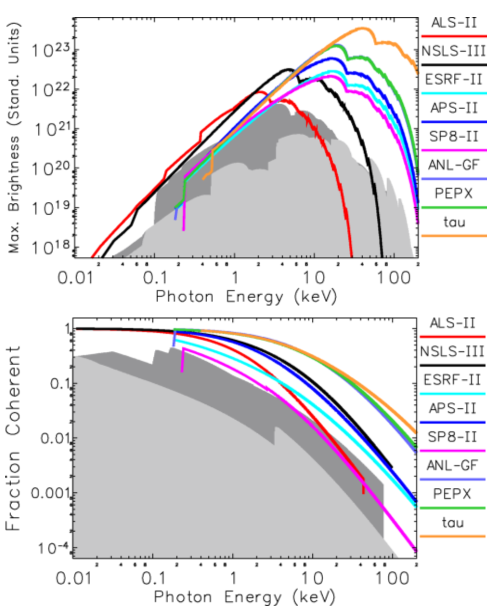
U.S. Proposals

APS-U: 6 GeV, 60 pm x 8 pm, 200 mA (**Upgrade Proposal**)

ALS-U: 2 GeV, 50 pm x 50 pm, 500 mA (**Upgrade proposal**)

***Other international upgrades:* Japan (Spring 8, 6 GeV), China (BAPS, 5 GeV), Germany (PETRA-IV, France (SOLEIL), Switzerland (SLS, 2.4 GeV), Italy (ELETTRA) and others are developing plans**

Brightness and coherence of 3rd and 4th gen rings



Legend:
- 0.2km/2GeV: ALS-II, 52 pm
- 0.8km/3GeV: NSLS-III, 30 pm
- 1.1km/6GeV: APS-II, 80 pm
- 2.2km/6GeV: PEP-X, 5 pm
- 6.2km/9GeV: tauUSR, 3 pm

For 6 GeV rings, a common set of IDs, including advanced SCUs, was assumed

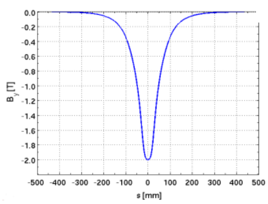
M. Borland

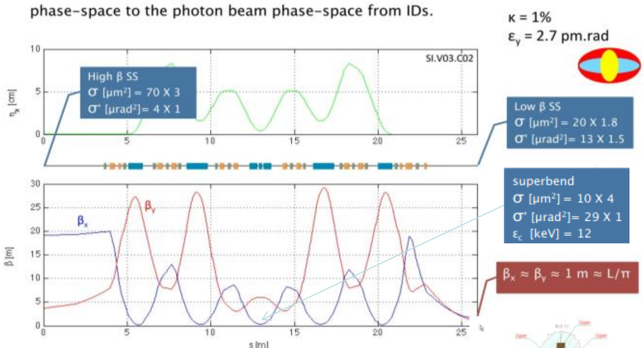
Sirius: 5 Bend Achromat

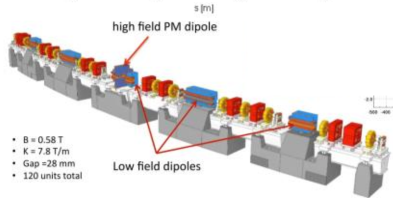
$\varepsilon_{x/y}$ = 190-270/3 pm.rad @ 3 GeV, 350 mA, C = 518 m

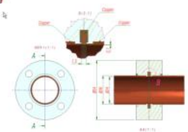
- New optics with lower β at the 6 m straight sections to match the electron beam phase-space to the photon beam phase-space from IDs.

- PM Superbend
- B = 2 T
- Gap = 28 mm
- Field flexibility = 6% (using lateral control gap)
- 20 units total





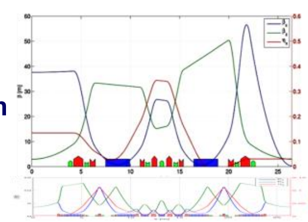




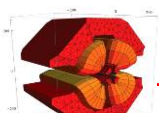
- gapless flanges
- NEG coating capability

ESRF-II – hybrid 7BA

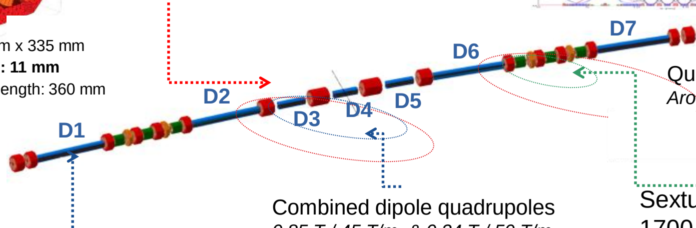
6 GeV, 844 m, 4 nm → 0.15 nm



High gradient quadrupoles
85 T/m



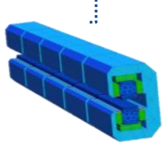
- Spec: 100 T/m x 335 mm
- **Bore radius: 11 mm**
- Mechanical length: 360 mm
- 1 kW



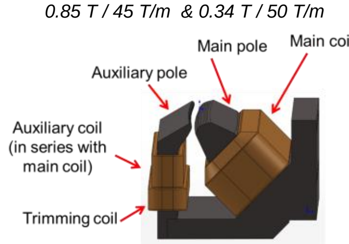
Quadrupole
Around 50 T/m

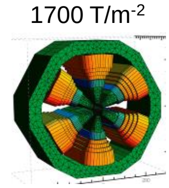
Combined dipole quadrupoles
0.85 T / 45 T/m & 0.34 T / 50 T/m

Sextupoles
1700 T/m^{-2}

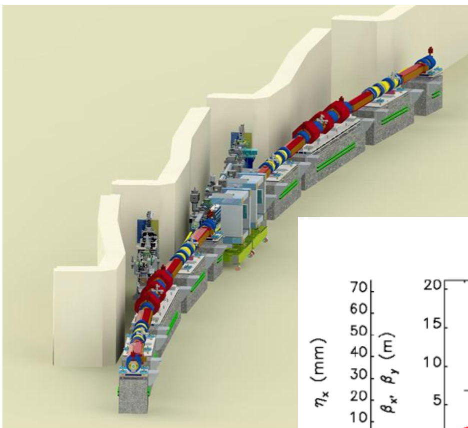


Permanent magnet dipoles
longitudinal gradient 0.16 – 0.6 T,
magnetic gap 22 mm
2 metre long, 5 modules
With a small tuning coil 1%

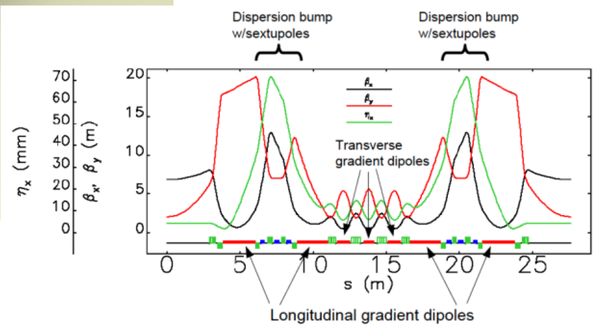




APS-U – hybrid 7BA



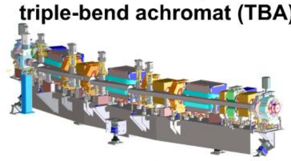
- $\varepsilon_{x/y}$ = 67/8 pm.rad @ 6 GeV, 200 mA
- C = 1.1 km
- 41-pm.rad option using reverse bend lattice

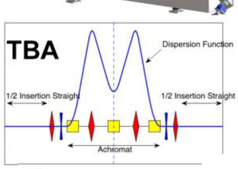


ALS-U – hybrid 9 Bend Achromat

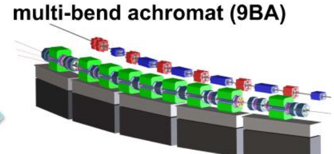
$\varepsilon_{x/y}$ = 50/50 pm.rad @ 2 GeV, 500 mA

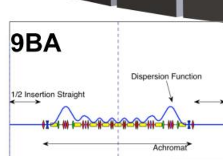
ALS today
triple-bend achromat (TBA)

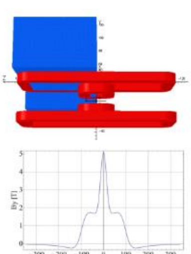




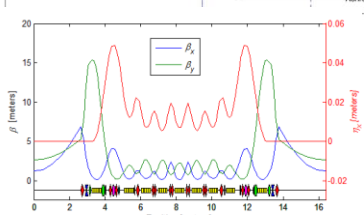
ALS-U
multi-bend achromat (9BA)







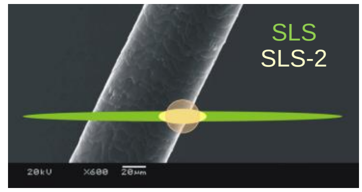
superbend option

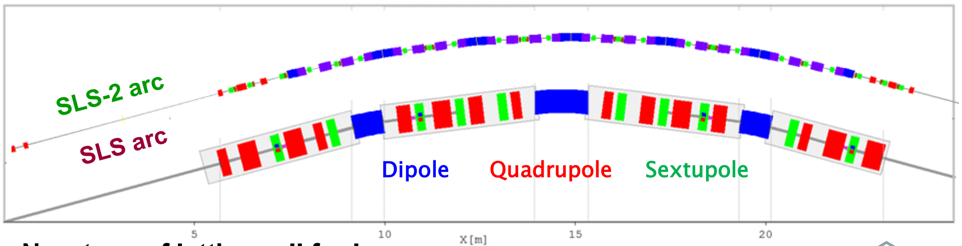


includes octupoles

SLS 2.0 upgrade plans

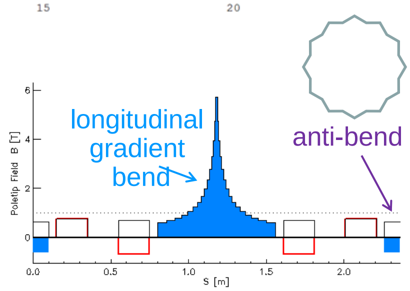
ε_x = 140 pm.rad @ 2.4 GeV



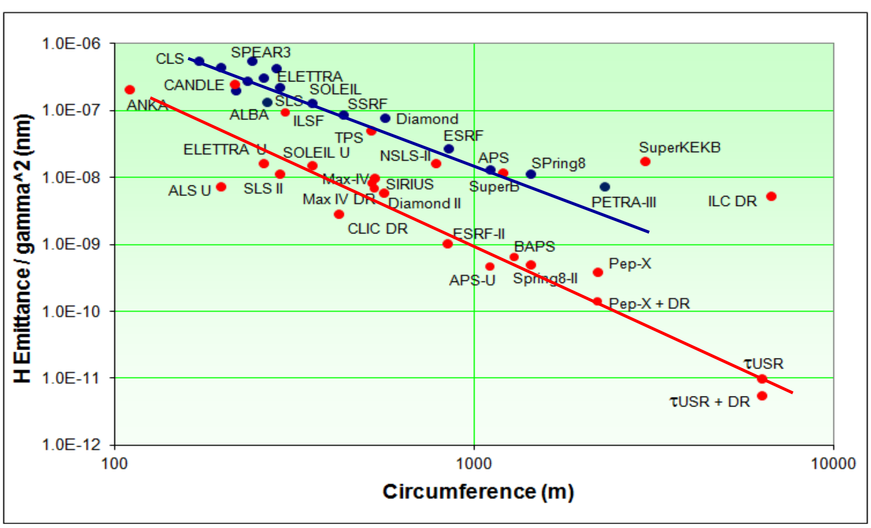


New type of lattice cell for low emittance

- bending magnets with longitudinal field variation (2 T peak)
- options for 5-6 T peak field superbends
- anti-bends for beam dynamics
  ⇒ star-shaped lattice



Diffraction limited rings: the new wave

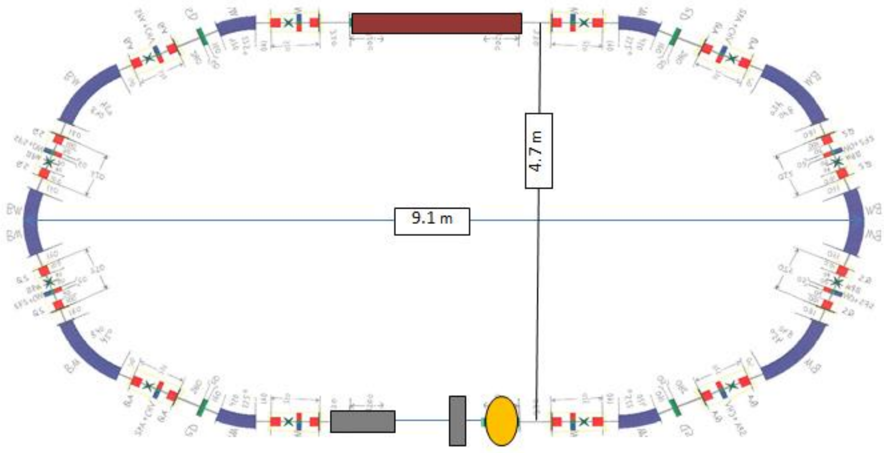


Storage rings in operation (•) and planned (•).
The old (—) and the new (—) generation.

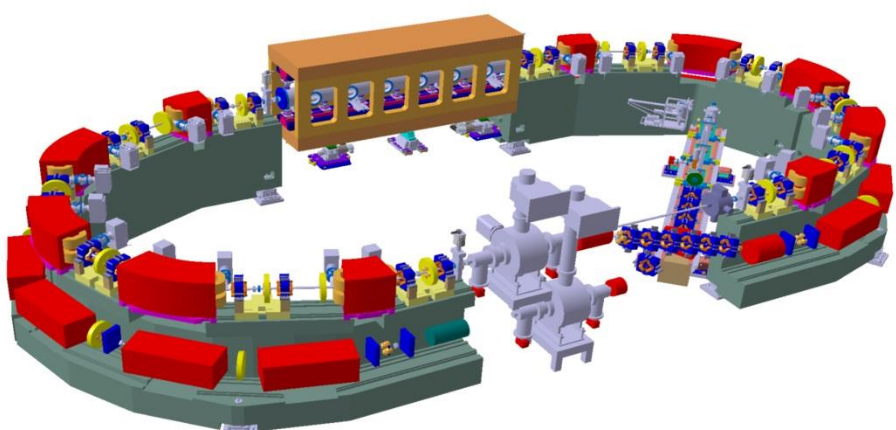
R. Bartolini

Compact light source COSAMI

Conventional, normal conducting magnetic structure

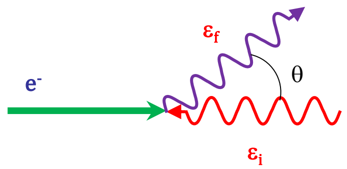


Injector and storage ring integration



When an electron collides with a photon…

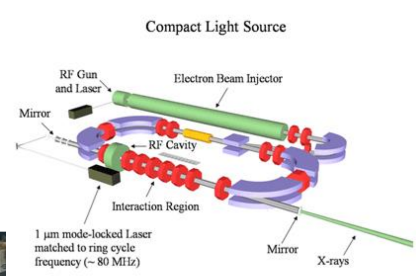
Also known as **Compton** or Thomson scattering



$$\varepsilon_f = \frac{4\gamma^2\varepsilon_i}{1+\gamma^2\theta^2}$$

- backscattered photon has the maximum energy
- at an angle of $1/\gamma$ the energy drops by a factor of 2
- undulator's periodic magnetic field could be viewed as a «photon», with useful parallels between the two cases

Compact light source based on Compton scattering



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