Accelerator physics, hardware, and operations at NSLS and NSLS-II.

Wednesday 24 Nov 2010 at 12:15 (00h55')

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II Mexican Workshop on Accelerator Physics

Principles of Synchrotron Radiation and Storage Ring Light Sources

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Office of Science
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
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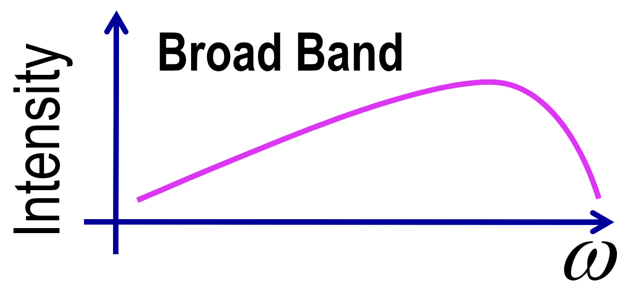
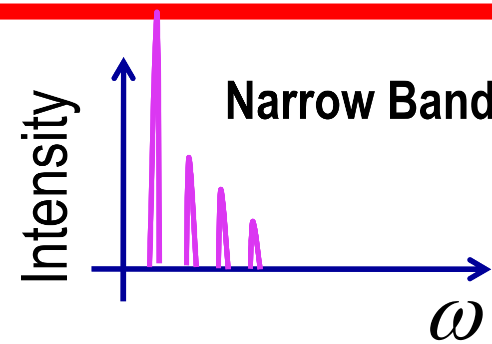
Outline

- **Synchrotron Radiation (SR) Primer**
  - SR definition & properties (brightness, flux, opening angle, polarization, BW, power)
  - Generation of SR
  - Bend magnets, Undulators and Wigglers
- **Principles of Synchrotrons**
  - How to build a synchrotron light source
  - Performance metrics
  - Properties of e-beam that affect performance
- **Few generations of synchrotron light sources (LS)**
- **Summary**
- **Not Covered (but important)**
  - Injection System, Vacuum, RF, power supplies, controls, etc.
  - Beamlines, Detectors, SR Uses and Techniques

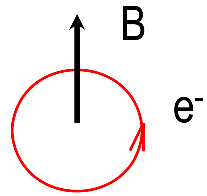
Thanks to
J.B. Murphy
G. Rakowsky
F. Sannibale

Charged Particle Radiation Processes

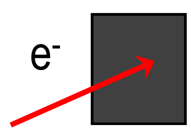




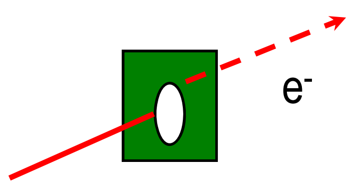
- Synchrotron



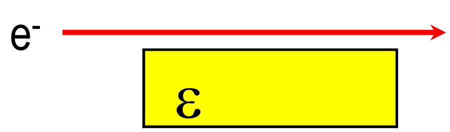
- Bremsstrahlung



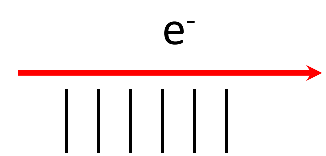
- Diffraction /Transition



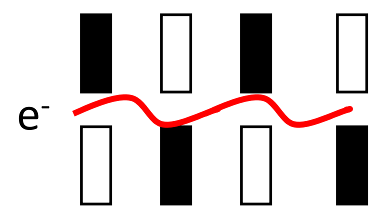
- Cerenkov



◆ Smith-Purcell



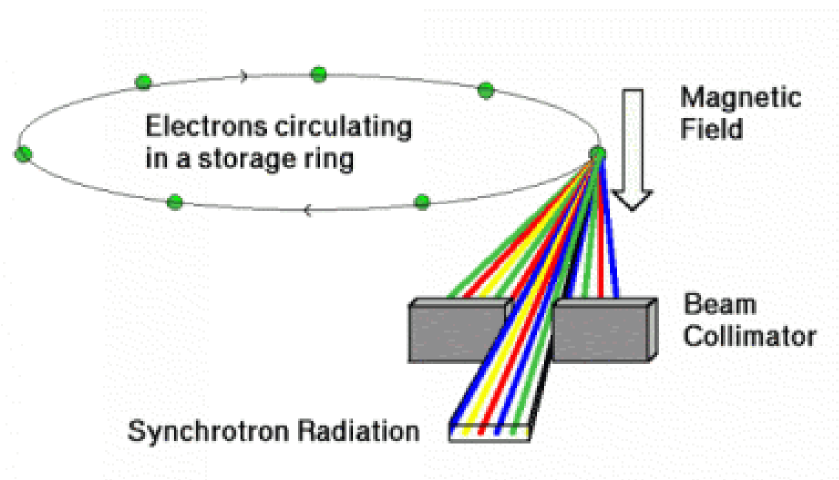
◆ Undulator



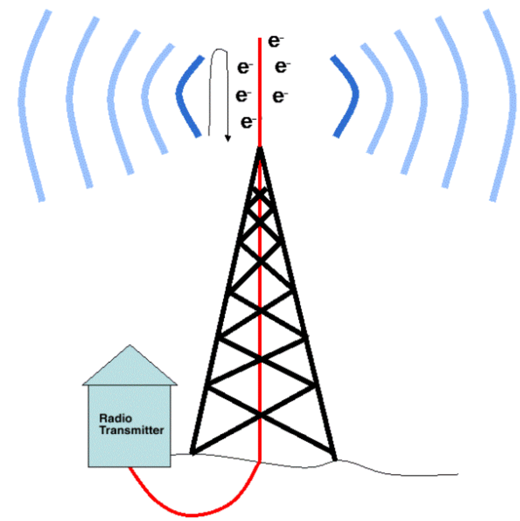
Periodicity in the “structure” yields a repetitive pulse train in the time domain, resulting in a spectral narrowing in the frequency domain!

Synchrotron Radiation

SR is EM radiation emitted when charged particles are radially accelerated (move on a curved path).



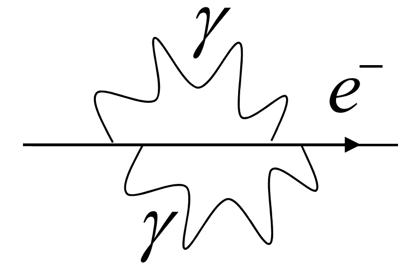
Electrons accelerating by running up and down in a radio antenna emit radio waves



Both cases are manifestation of the same physical phenomenon:
***Charged particles radiate when accelerated*.**

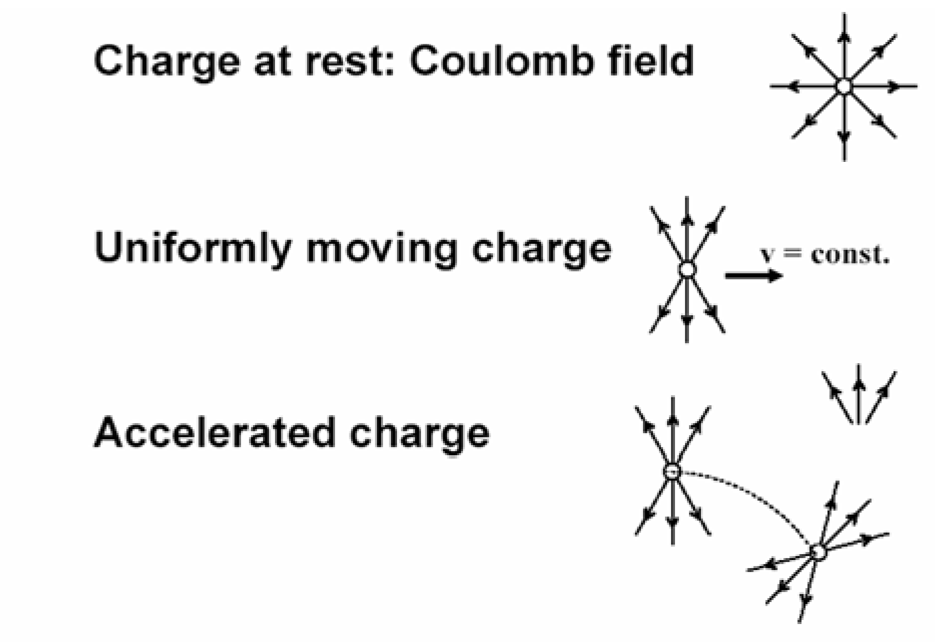
Why Do Particles Emit SR?

• A charge moving in free space is "surrounded" by a cloud of virtual photons that indissolubly travel with it.



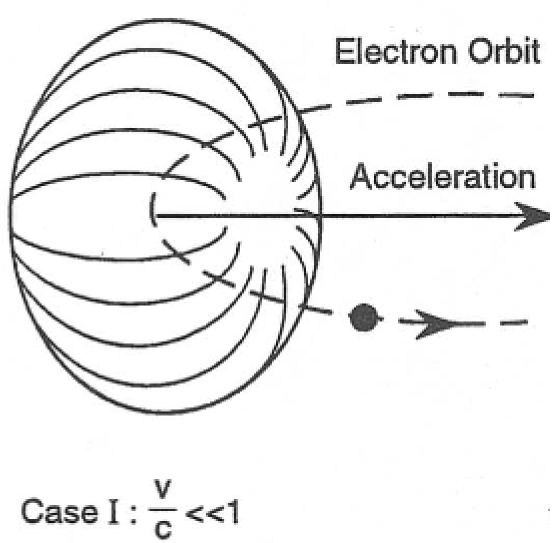
• When accelerated, the particle receives a "kick" separating it from the photons that become real and independently observable.

•Lighter particles are easier to accelerate so they radiate photons more efficiently => light sources use electrons

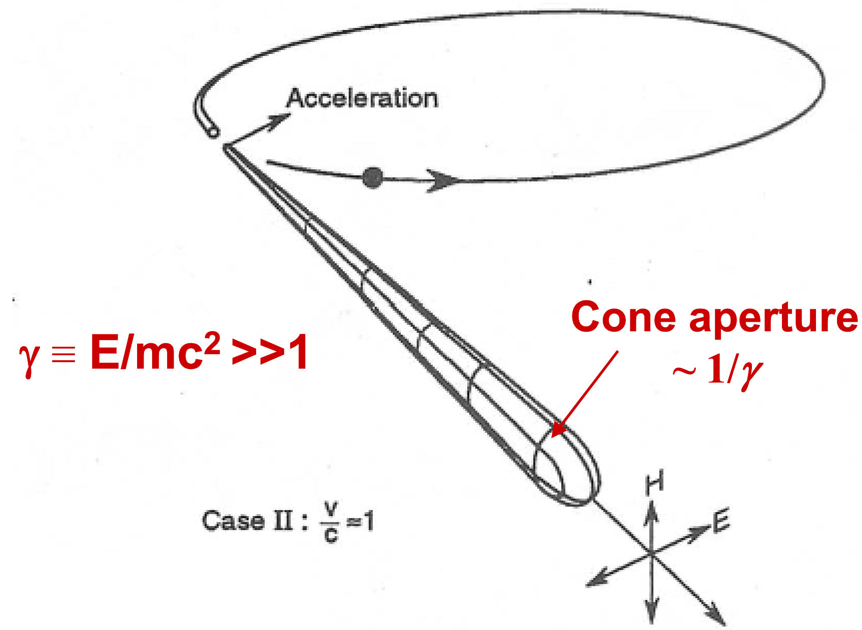


In a light source electrons follow curved trajectories in bend magnets and insertion devices. The transverse acceleration creates e^- - γ separation generating *synchrotron radiation*.

SR Angular Distribution



At low electron velocity (non-relativistic case) the radiation is emitted in a non-directional pattern



When the electron velocity approaches the velocity of light, the emission pattern is folded sharply forward.

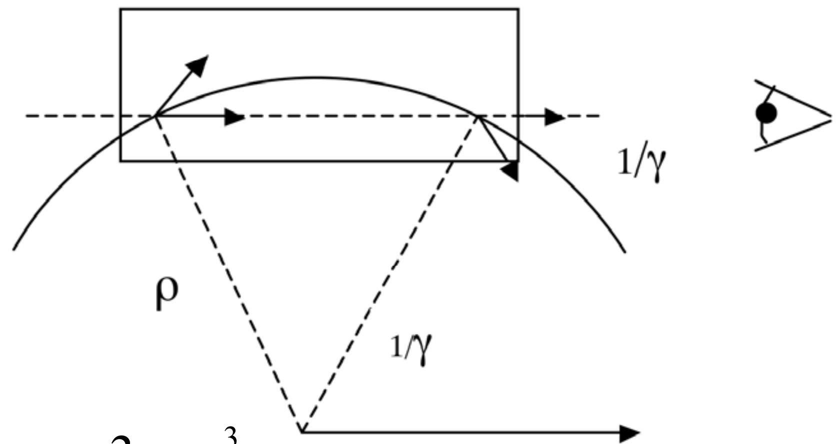
Radiation becomes more focused at higher energies.

SR Bandwidth

Due to the small opening angle the observer sees the electron first when it arrives on its trajectory at an angle of –1/γ with respect to the z-axis and last when this angle is +1/γ. The length of the electromagnetic pulse observed is just the difference in travel time between the electron and the photon going from the point at –1/γ to the point at +1/γ,

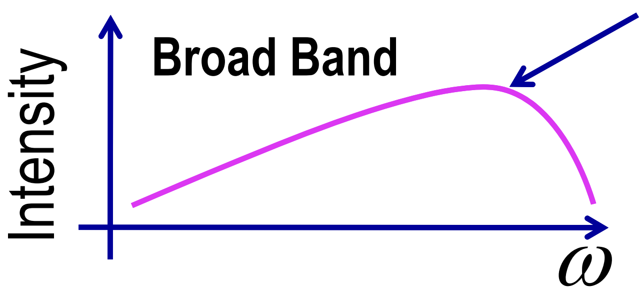
$$\Delta T = T_e - T_\gamma = \frac{2\rho}{\beta\gamma c} - \frac{2\rho\sin(1/\gamma)}{c}$$

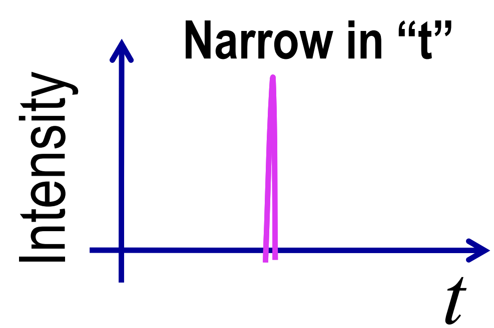
$$\approx \frac{2\rho}{\beta\gamma c}\left(1-\beta+\frac{\beta}{6\gamma^2}\right) \approx \frac{4\rho}{3c\gamma^3}.$$



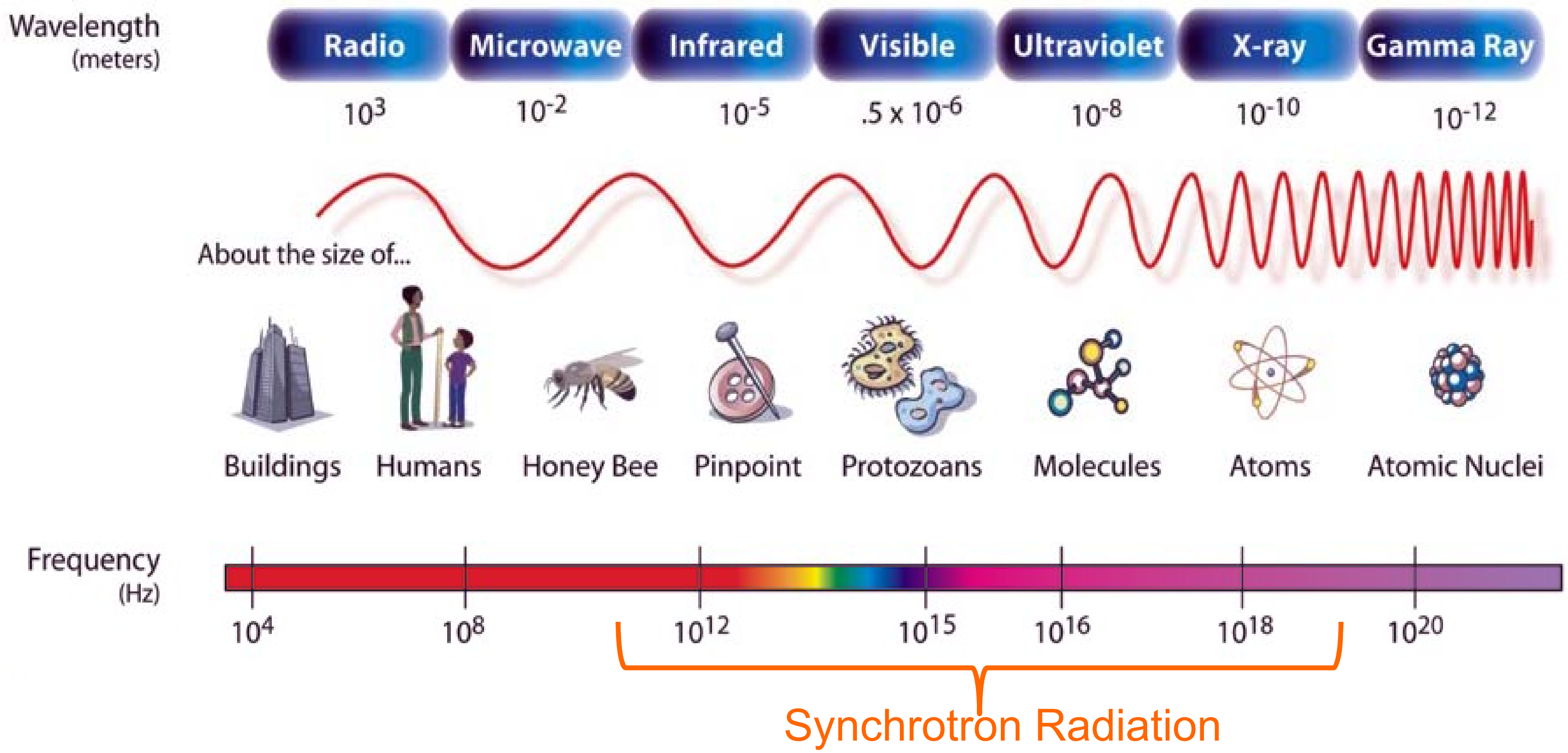
The characteristic frequency is then,

$$\omega_c \approx \frac{2\pi}{\Delta T} = \frac{3\pi c\gamma^3}{2\rho}.$$



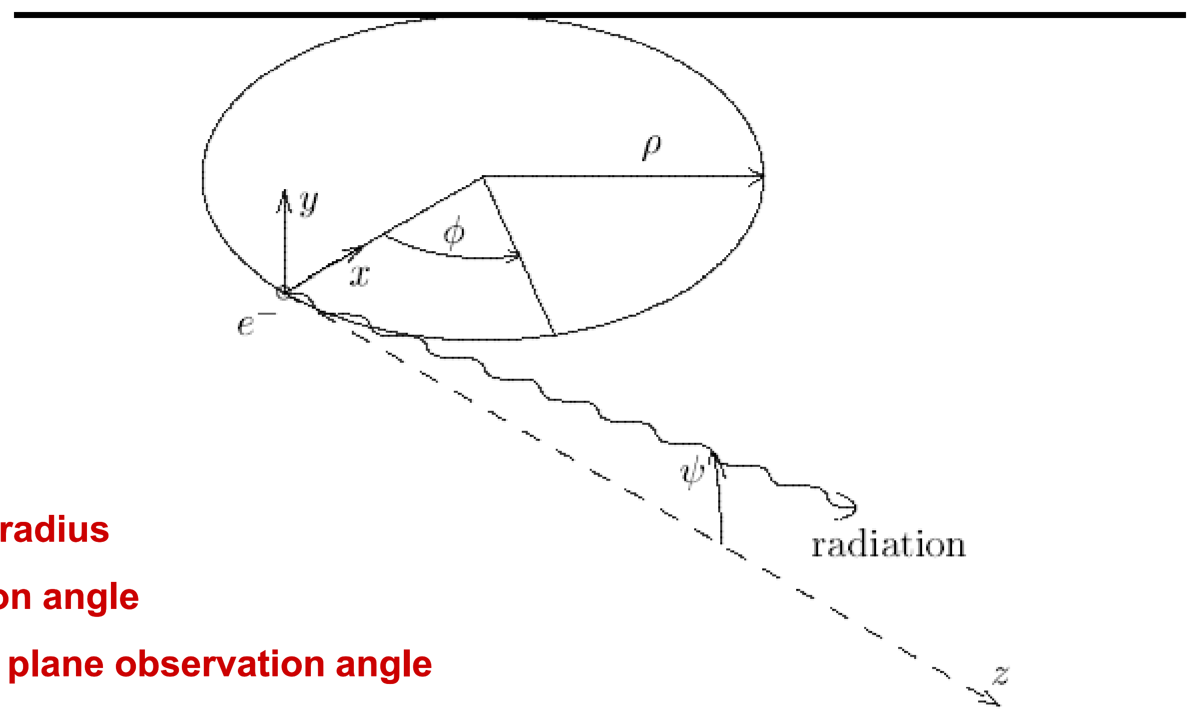


SR Spectrum



To "see" atoms, molecules & nanostructures you need light with wavelengths comparable to the size of those objects (UV, X-rays)

SR Geometry



ρ – orbit radius

φ – rotation angle

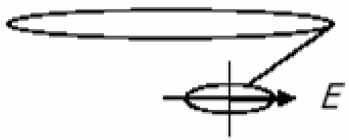
ψ - out of plane observation angle

Ω - solid angle , d Ω = dφ dψ

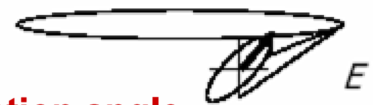
A. Hoffmann, CERN-98-04

SR Polarization & Angular Distribution

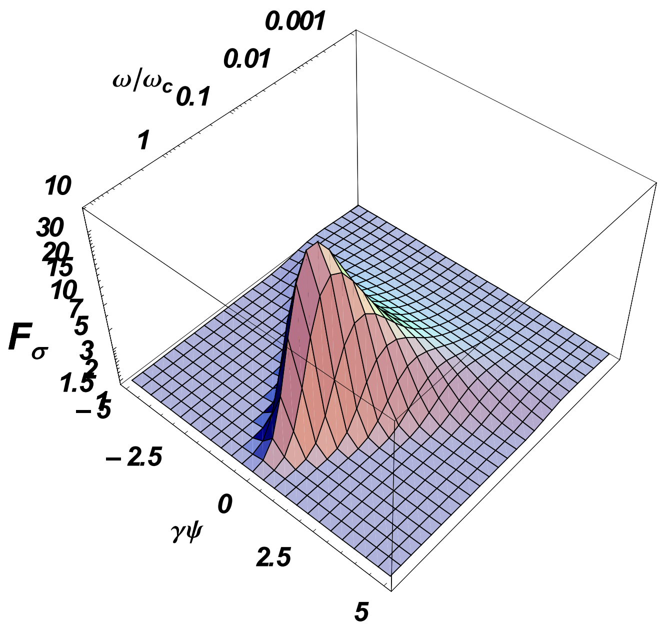
Synchrotron radiation observed in the plane of the particle orbit is horizontally polarized, i.e. the electric field vector is horizontal



Observed out of the horizontal plane, the radiation is elliptically polarized



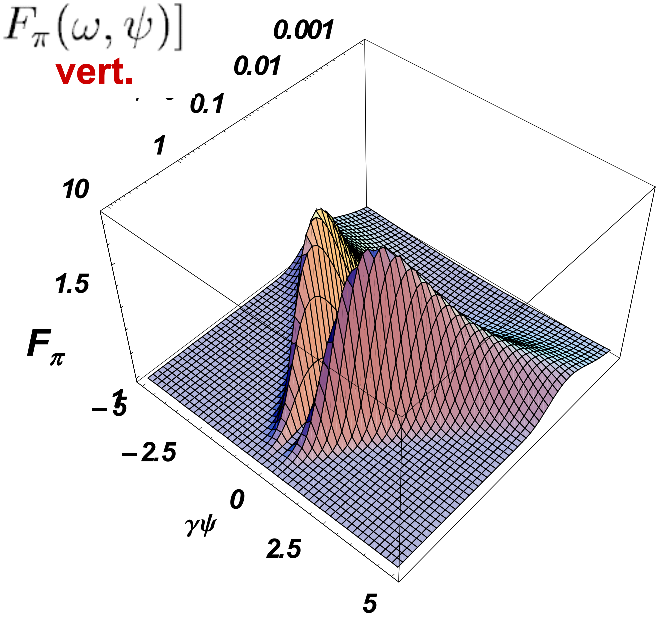
ψ - out of plane observation angle



$$\frac{P_0\gamma}{\omega_c}\left[F_\sigma(\omega,\psi)+F_\pi(\omega,\psi)\right]$$

hor. vert.

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



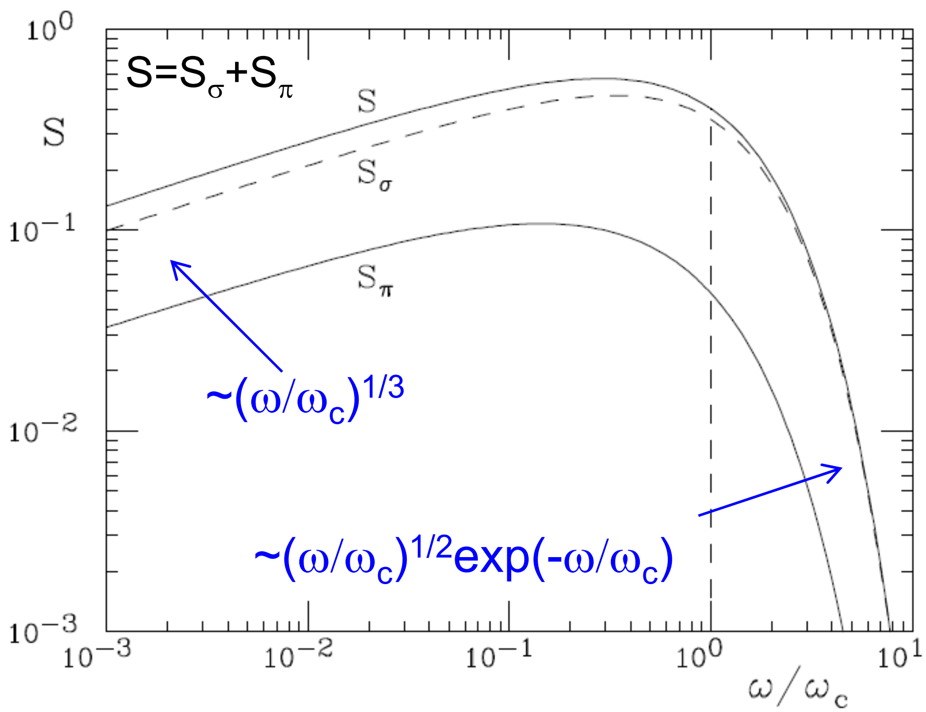
Most power in hor. polarization, distribution peaks at $\psi=0$, $\psi_{\sigma\_rms}(\omega_c)\approx 1/\gamma$

Less power in ver. polarization; double peaks around $\psi=0$, $\psi_{\pi\_rms}(\omega_c)\approx 1/\gamma$

Synchrotron Radiation Power

Spectral Power

$$\frac{dP}{d\omega} = \int \frac{d^2P}{d\omega d\Omega} d\Omega = \frac{P_0}{\omega_c} \left[S_\sigma \left(\frac{\omega}{\omega_c} \right) + S_\pi \left(\frac{\omega}{\omega_c} \right) \right]$$



Total Power & Loss/turn

$P_0 \sim \gamma^4/\rho^2 \sim \gamma^2 B^2 \sim E^2 B^2$

Rises fast with beam energy !

U_0(KeV)=88.5 E^4(GeV) /ρ(m)

Electron energy loss per turn

P_{total}(kW)=88.5 E^4(GeV) I(A)/ρ(m)

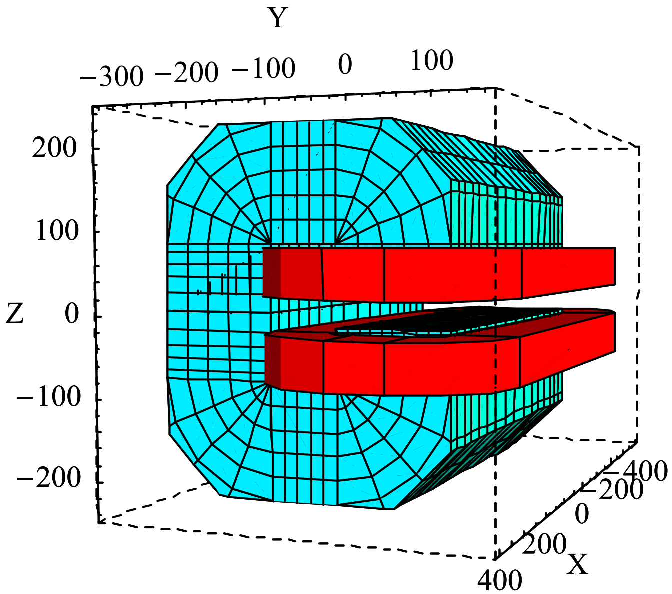
for beam current I

$$\int_0^1 S\left(\frac{\omega}{\omega_c}\right) d(\omega/\omega_c) = 0.50 \qquad \omega_c = \frac{3c\gamma^3}{2\rho}$$

Half the power is below ω_c, the other half is above
7/8 is horiz. polarization; 1/8 is vertical polarization.
SR power sharply falls down at $\omega >> \omega_c$

Bend (Dipole) Magnets

Typical Synchrotron Dipole Magnet

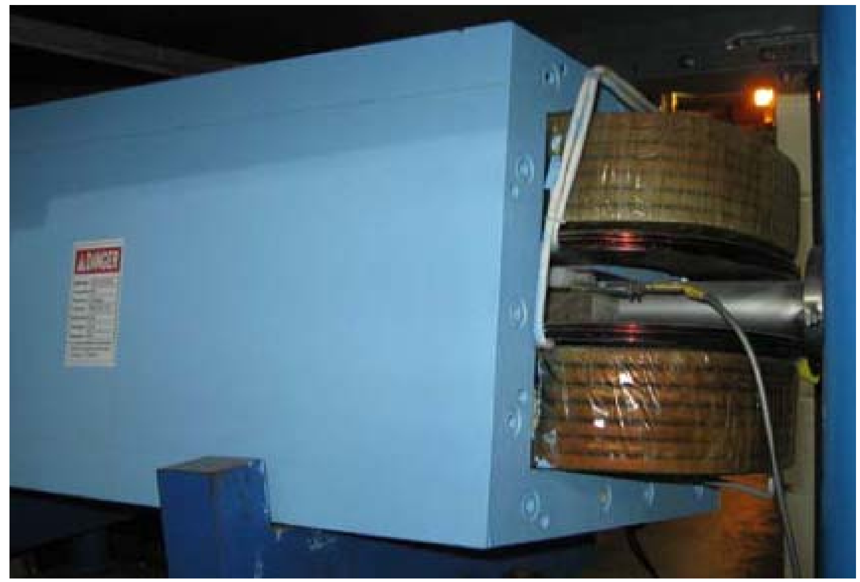


Field in gap $B = \mu_o NI / g$ (typ. 1.4 T)

Water-cooled copper coils

Low-carbon steel C-frame yoke

NSLS X-ray Ring Dipole



ρ= 6.875 m, L=2.7 m, gap=55 mm

At E=2.8 GeV:

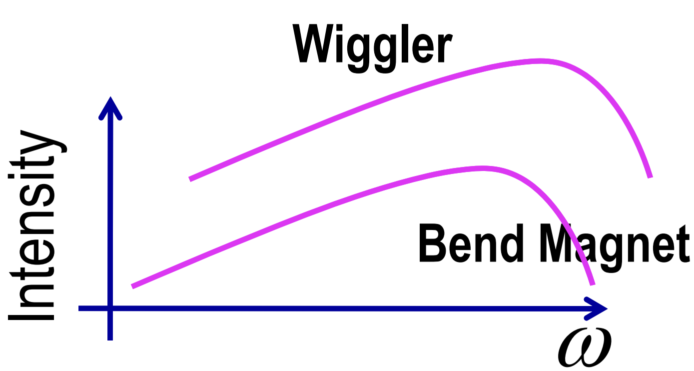
ε_c=7.1 keV, B=1.36 T, I=1.5 kA

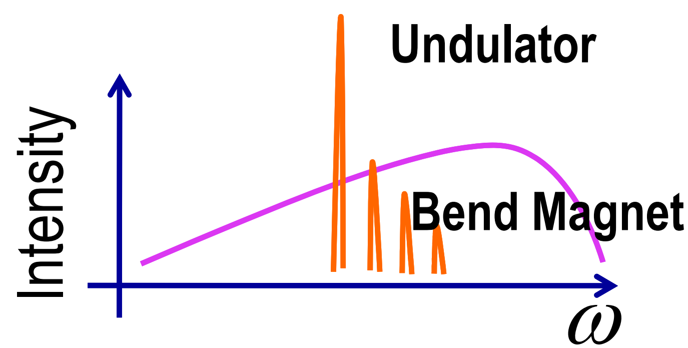
Motivation for Having Insertion Devices

- **Wigglers (K >> 1)**
  - Wavelength shifter to get harder photons,
  - ε_c = .665 B [T] E^2 [GeV]
  - Increased flux $\approx 2N_w$ (Arc source flux)
  - Typical parameters: λ_w = 10 cm & B = 5 T

- **Undulators (K ~ 1)**
  - Concentrate photons in frequency & position leading to higher brightness
  - Lower power consumption
  - Variable polarization (for some designs)
  - Typical parameters: λ_u = 6 cm & B = 0.2 T

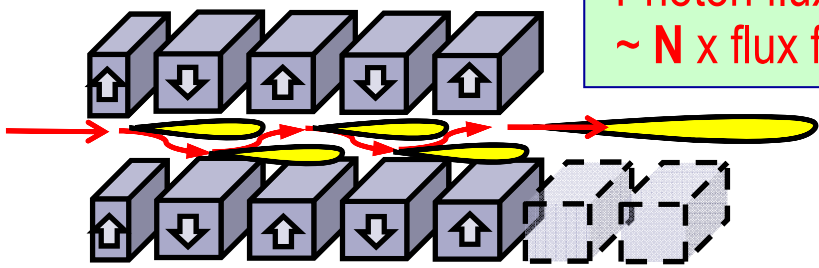
- High Intensity
- Tunable, Narrow Spectrum
- Natural Vertical Collimation
- High Degree of Polarization
- High Brightness





Wigglers & Undulators: Arrays of Dipoles of Alternating Polarity

Photon flux from N bends = ~ **N** x flux from single bend;



Peak field $B = B_{rem} \exp[-\pi(g/\lambda_u)]$

Deflection parameter K:

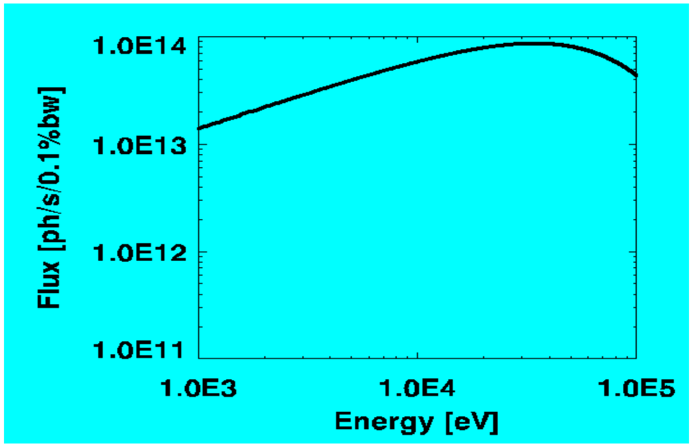
$$K = 0.0934\ \lambda_u[mm]\ B[T]$$

Resonant wavelengths:

$$\lambda_m = \frac{\lambda_u}{2m\gamma^2}\left(1 + \frac{K^2}{2}\right), \quad m = 1,3,5\ldots$$

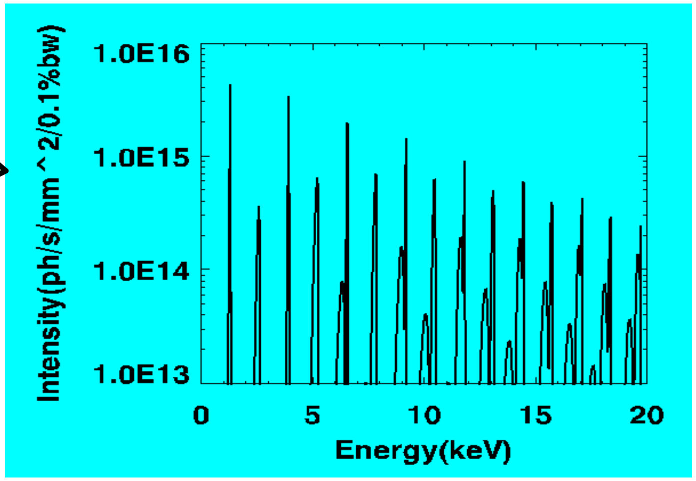
- In a ***Wiggler*** K >> 1;
- Radiation from poles adds ***incoherently***, producing a broad, dipole-like spectrum

Wiggler Spectrum



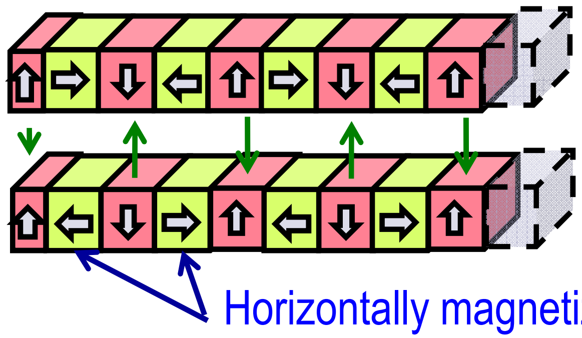
- In an ***Undulator*** K < 3;
- Radiation from poles adds ***coherently*** at resonant wavelengths, thus a sharply peaked spectrum.
- Spectral peaks are ***tunable*** by varying ***K*** (i.e., ***B***) by varying the *gap*

Undulator Spectrum



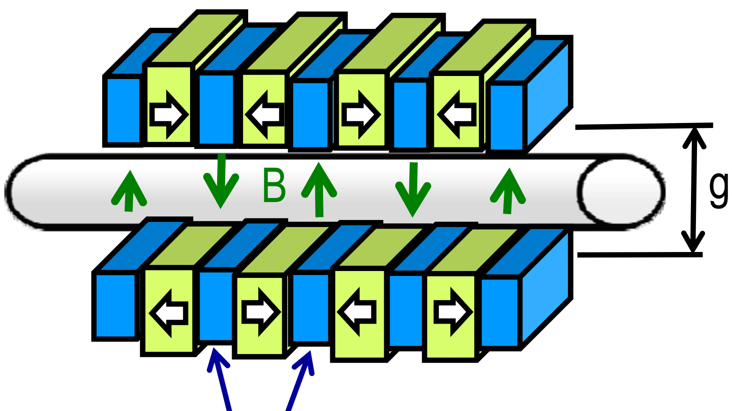
More on Wigglers & Undulators

Halbach Pure-PM Undulator



Horizontally magnetized blocks boost on-orbit field

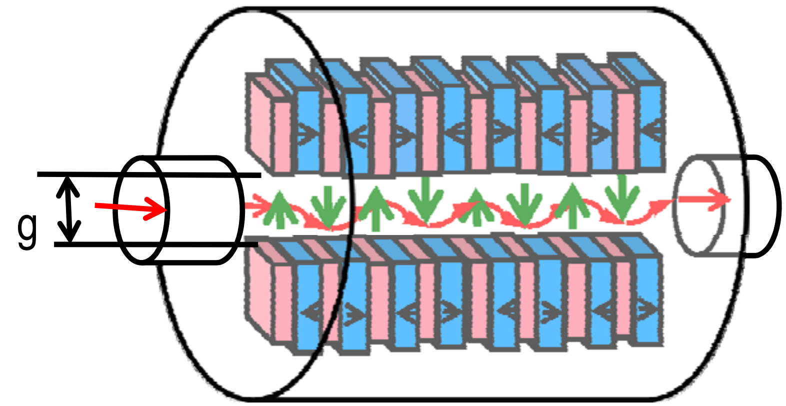
Halbach PM-hybrid Undulator



Iron poles concentrate flux from larger magnet blocks

In-Vacuum Undulator

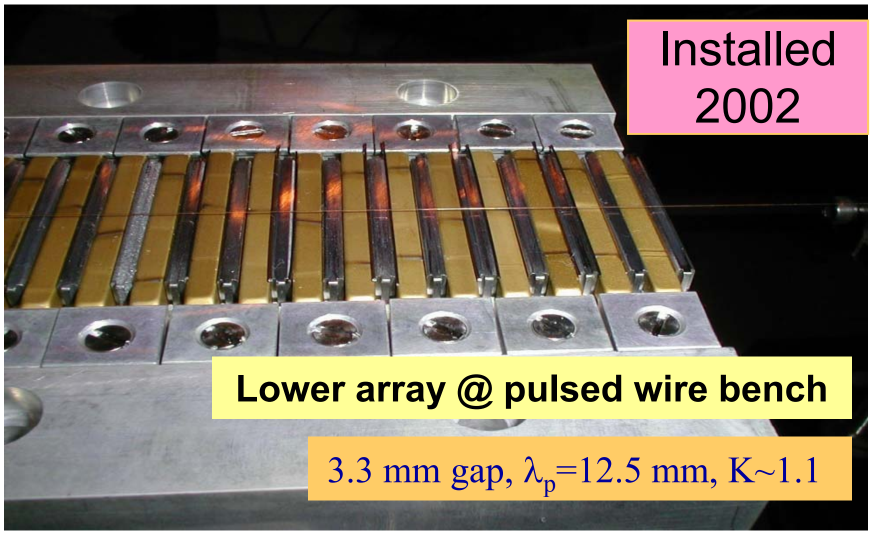
(For hard x-rays)



- Put magnet arrays *inside* vacuum chamber
- Minimum gap can be reduced to stay-clear required by electron and photon beams (a few mm)
- Reduce period → more periods → more photons!
- Shorter period → higher photon energies
- Must be UHV-compatible → Ni- or Ti-N-coated
- PM must withstand baking to >100°C without demagnetizing → Use Hybrid car motor grades of PM

Mini-Gap In-Vacuum Undulators

NSLS X13 MGU



NSLS X25 MGU

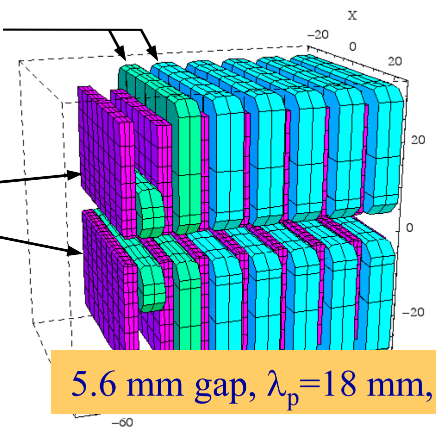
NdFeB Magnets:
new "hybrid car motor" grade

Vanadium Permendur Poles

Design:

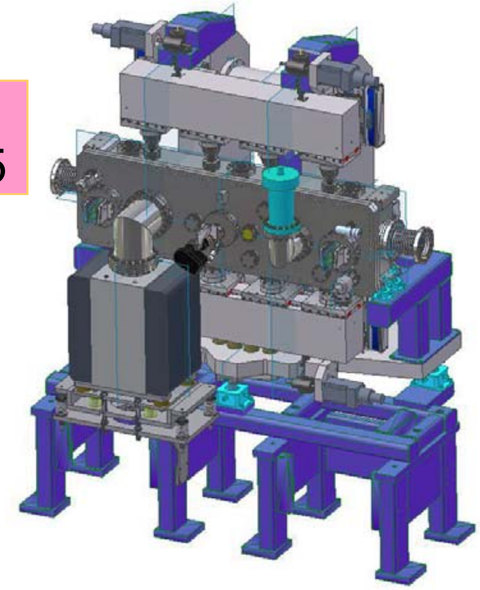
NSLS (magnetic)

ADC, Inc (mech.)



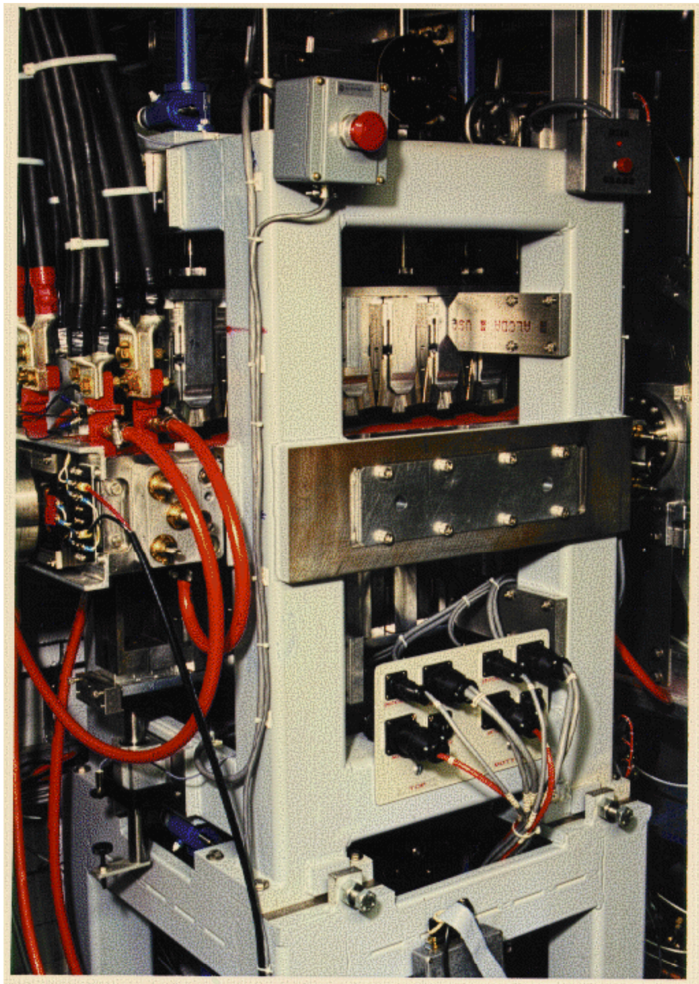
5.6 mm gap, λ_p=18 mm, K~1.5

Installed
Dec. 2005



- •MGUs are one of greatest successes at NSLS
- •Provide hard X-ray photons on the cheap
- •Paved the way for Intermediate Energy Light Sources
- •Will be heavily used at NSLS-II

Elliptically Polarizing Wiggler



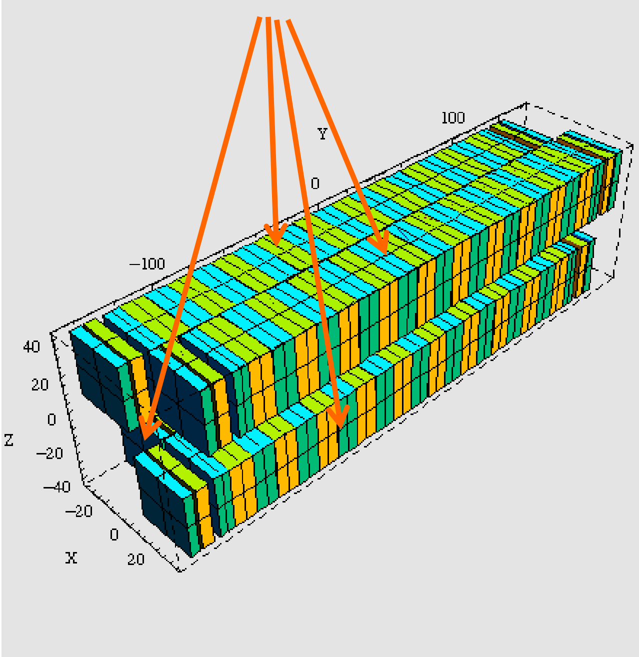
NSLS X13 EPW

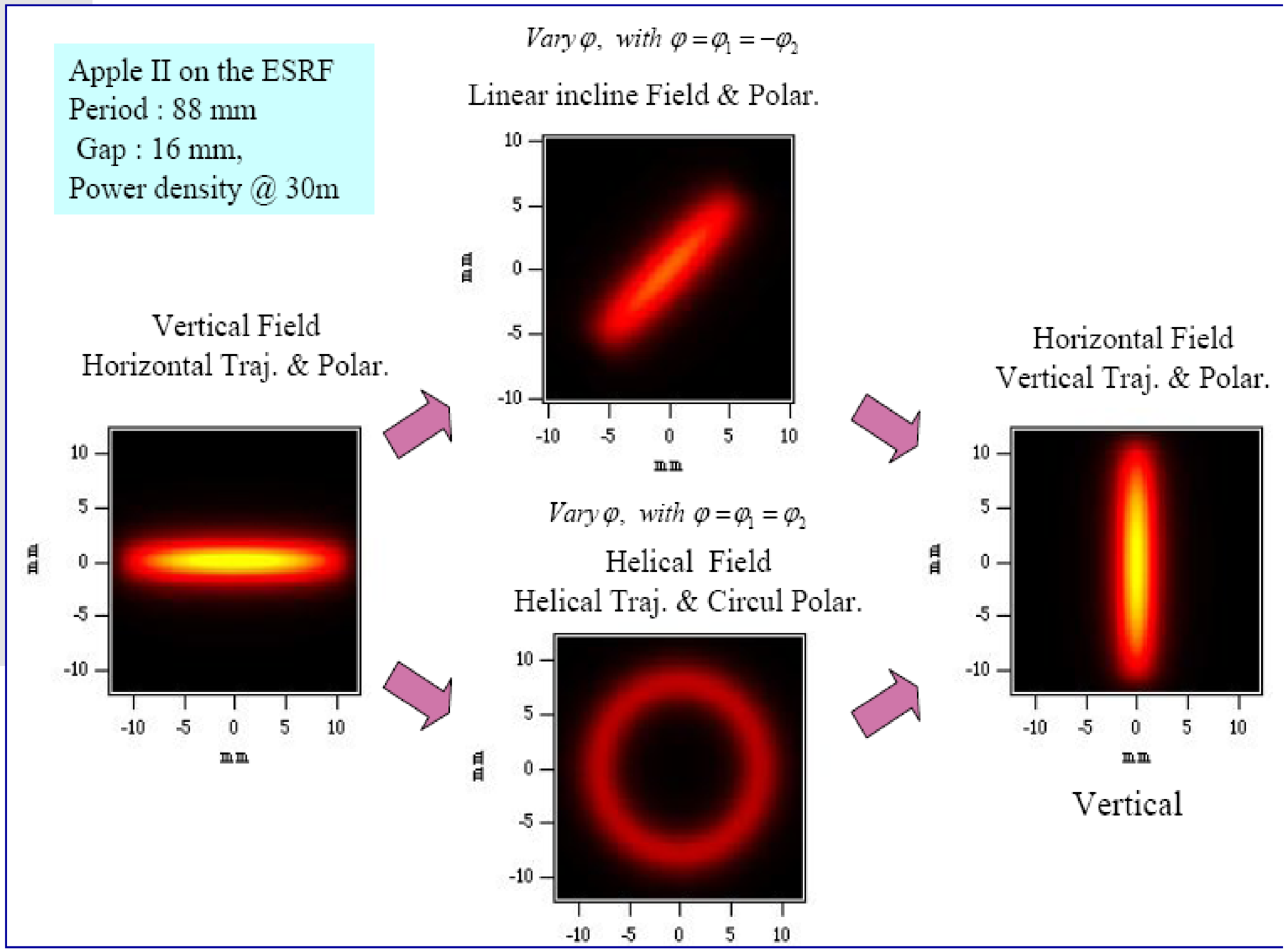
- Vertical field: PM hybrid
- Horizontal field: Electromagnet
- Hor. array offset by ¼ period
- Switching polarity of current switches helicity (RH & LH) at up to 100 Hz (typ. 22 Hz)

Varying horizontal field “moves” the beamline in-and-out of orbit plane => time-varying elliptical polarization

APPLE-II Variable Polarization Undulator

4 Movable PM Arrays

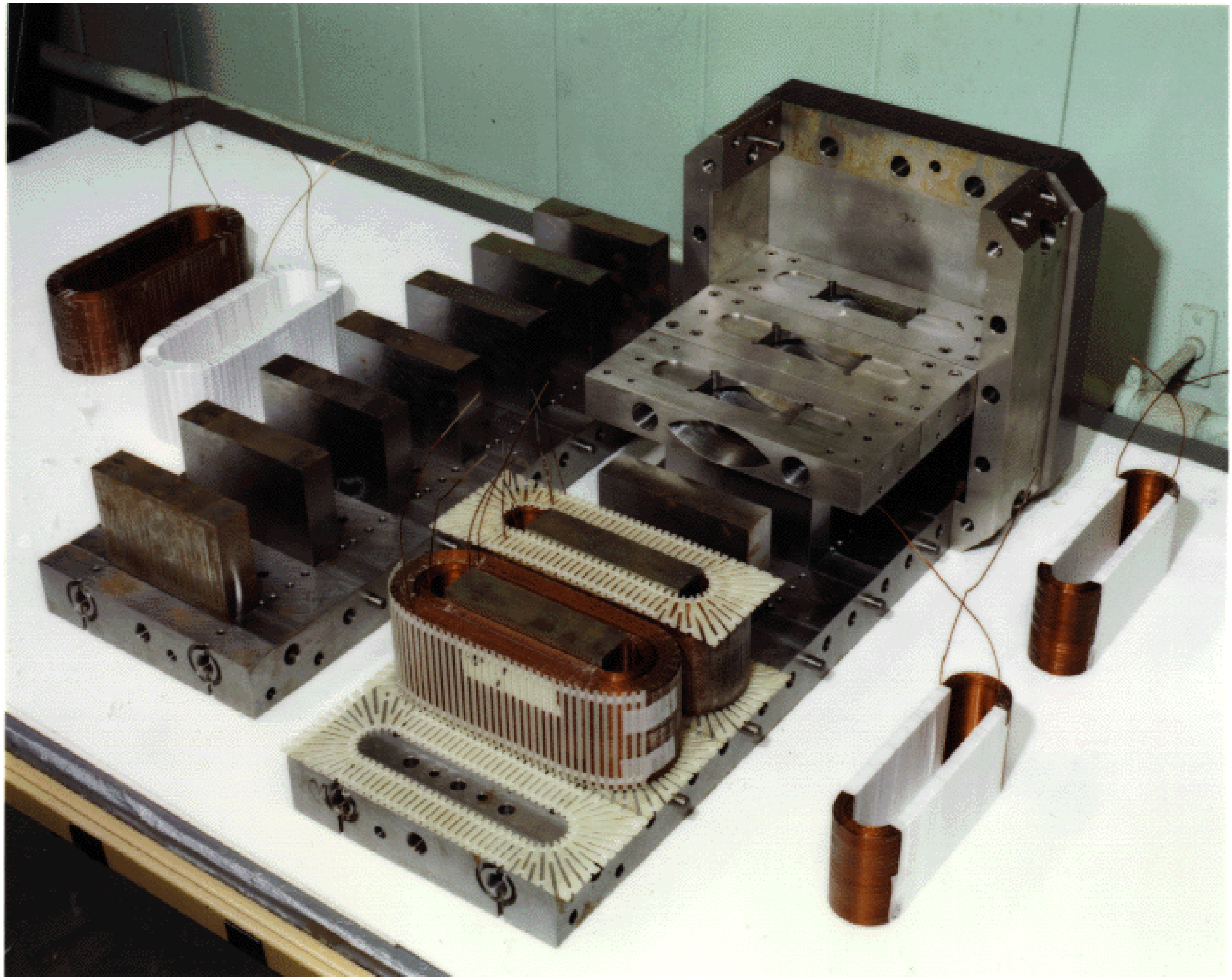




Planned for NSLS-II

Boris Podobedov, Nov. 22, 2010

Superconducting Wigglers



- B_o = 4.2 Tesla
- Period = 17.5 cm
- K = 68
- E_{crit} = 22 keV

NSLS X17 SCW

Provides the hardest (up to 100 keV) usable x-rays at NSLS

Building a Storage Ring Light Source 101

1) Take evacuated beam pipe

ADD:

2) Bends (dipoles) to form e-beam trajectory (& as SR sources)

3) Quadrupole magnets to focus e-beam transversely

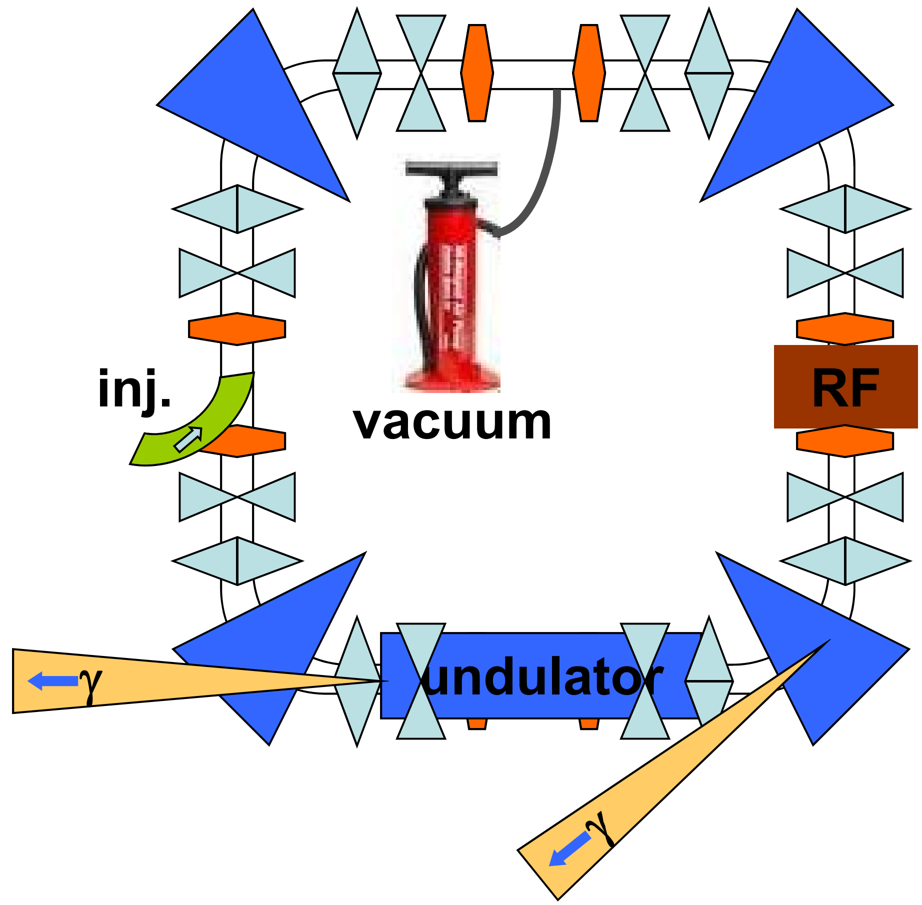
4) Sextupoles for achromatic focusing

5) RF to make up for energy loss; also provides longitudinal focusing (bunching)

6) Injection system

7) IDs into avail. straight sections

8) Beamlines to deliver photons to the Users



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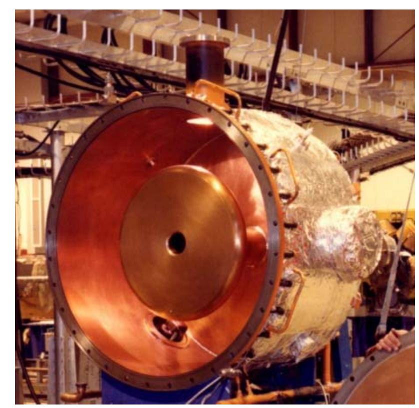
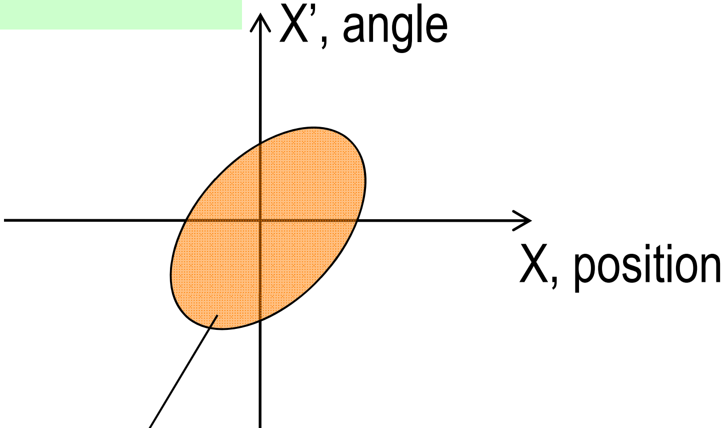
Essential Elements of a Light Source



Beam Brightness

Phase Space



Emittance , ε, is the area occupied in phase space

Brightness is the density in phase space = $\dfrac{\text{Number of “fish”/unit time}}{\text{Phase Space Area}} \propto \dfrac{I}{\varepsilon_x \varepsilon_y}$

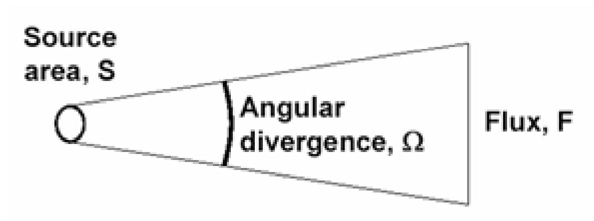
Average Brightness ~ photons/pulse x pulse rate
Peak Brightness ~ photons/pulse/pulse time

$$B_{peak} \approx B_{ave} / f \times \tau_{pulse}$$

Beam Brightness Continued

- **brightness is the key parameter of any particle source, incl. SR sources**
- **brightness is defined as 6-D phase space (x, p_x, y, p_y, t, E) density of particles**
- **The same definition applies to the photon case; taking into account that the Pauli exclusion principle does not apply to bosons => no limitation to achievable photon brightness exists from Quantum Mech.**

$$\textbf{Brightness} = \frac{\#\text{ of photons in given } \Delta\lambda/\lambda}{\text{sec, mrad } \theta\text{, mrad } \varphi\text{, mm}^2}$$

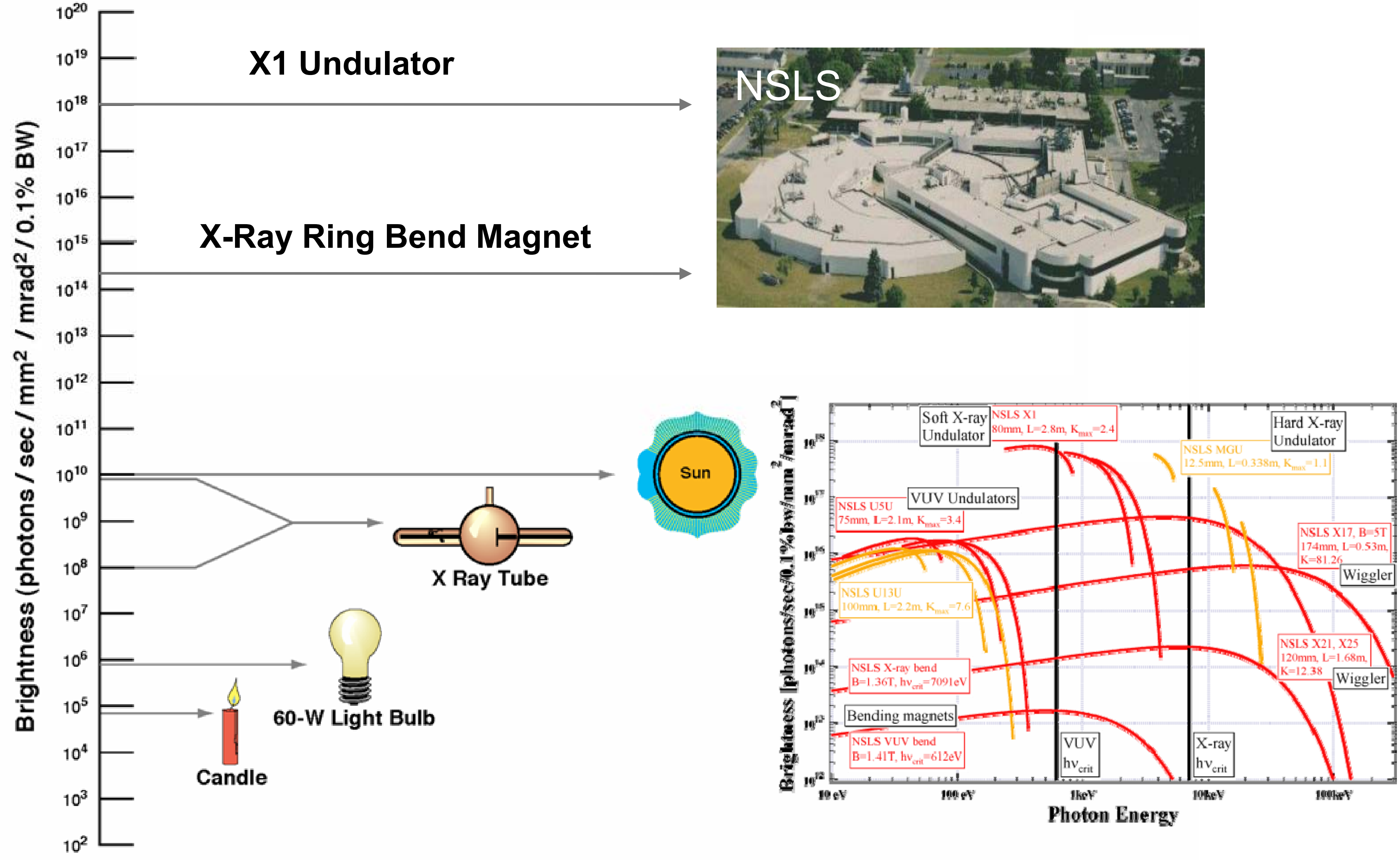


$$\textbf{Flux} = \frac{\#\text{ of photons in given } \Delta\lambda/\lambda}{\text{sec}}$$

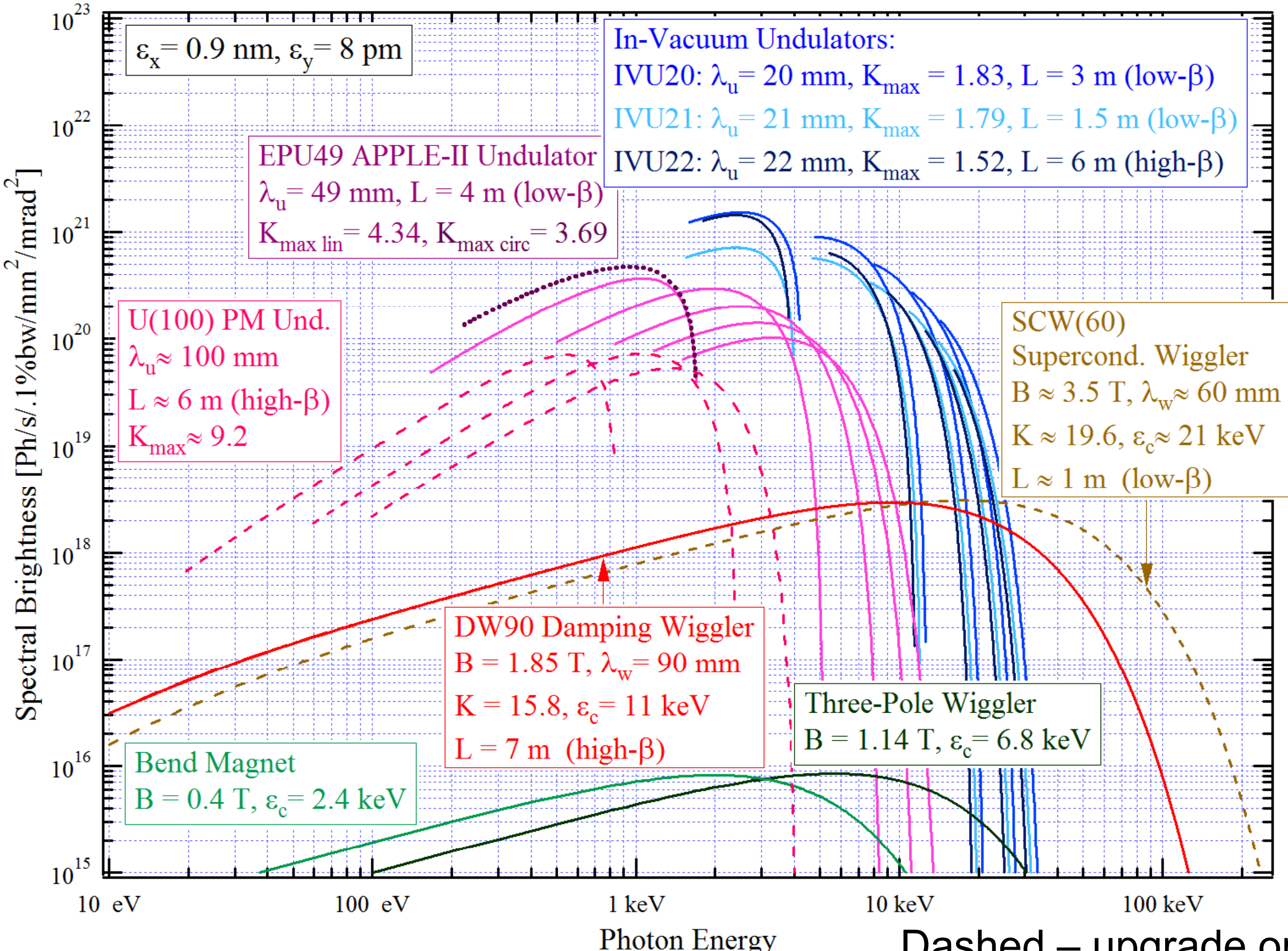
$$Flux = \frac{d\dot{N}}{d\lambda} = \int Brightness\, dS\, d\Omega$$

•**For a given flux, smaller emittance** (transverse phase space area) **sources have larger brightness**

How Bright Are We?



NSLS-II Brightness Curves



Dashed – upgrade options

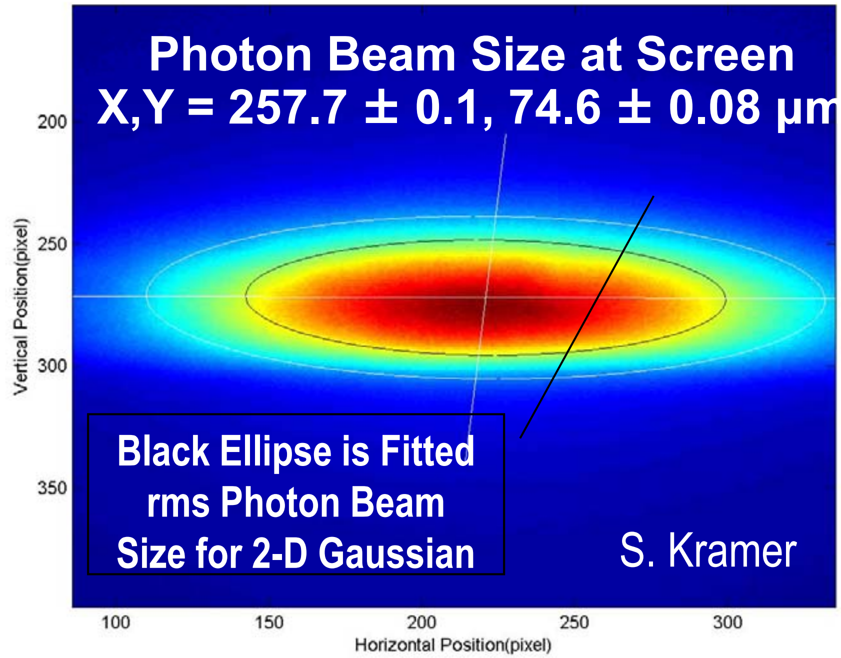
Boris Podobedov, Nov. 22, 2010

Equilibrium Beam Sizes in Storage Ring: Transverse Emittance

- For bright source photon beam emittances need to be small
- Photon beam emittance is due to convolution of e-beam emittance and "light emittance" $\lambda/4\pi$
- In storage ring LS typically 0.1 nm $<\varepsilon_x<$100 nm, $\varepsilon_y=\varepsilon_x$ /100
- Diffraction limited (x-rays) in vert. plane, but not in the horizontal
- => electron beam emittance is important until its $<\lambda/4\pi$
- Emittance is invariant, but beam sizes vary around the ring, i.e.

$$\sigma_y = (\beta_y (z)\varepsilon_y)^{1/2},$$

here β_y (z) is periodic β-function

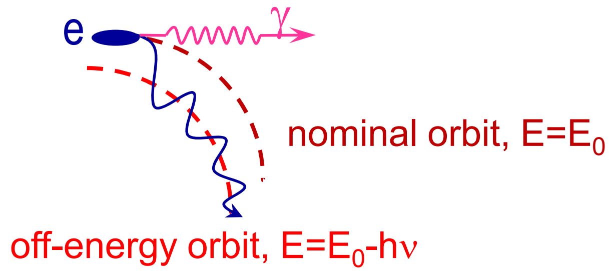


$\varepsilon_{x,y}$ = 68 ± 3 , 0.36 ± 0.05 nm

$\varepsilon_y / \varepsilon_x$ ~ 0.53 ± 0.08 %

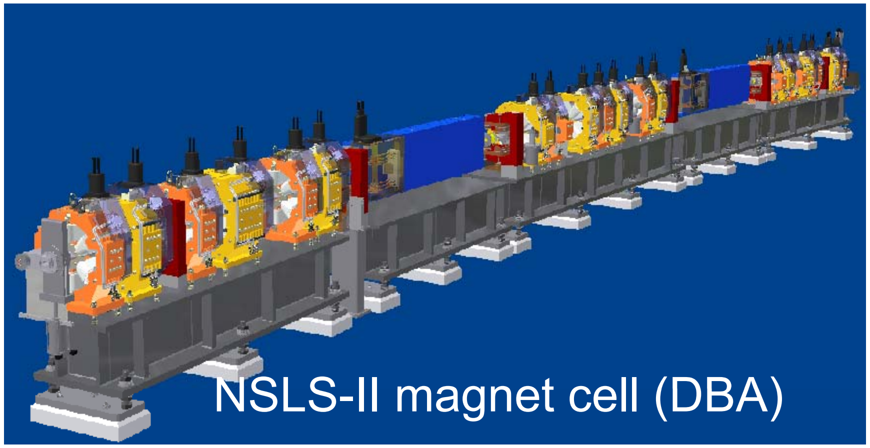
Transverse Emittance Cont'd

- Emittance in electron storage rings is due to balance of SR damping (makes it smaller) and quantum excitation (increases it), i.e. $\varepsilon_x = S_x \tau_x$



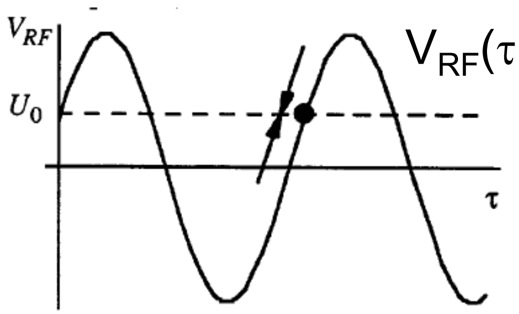
$$S_x \approx E^5 \oint B^3 \frac{\eta_x^2 + \left(\beta_x \eta_x' - \frac{\beta_x'}{2}\eta_x\right)^2}{\beta_x} ds, \quad \frac{1}{\tau_x} \approx J_x E^3 \oint B^2 \, ds$$

- When e emits a photon, it goes on a different energy orbit => increase in beam energy spread and beam size.
- Emittance generated by SR where there is dispersion η_x.
- Vertical emittance is usually due to coupling from the horizontal.
- Modern LS minimize the dispersion => many short magnet cells, N>>1, $\varepsilon_x \sim N^{-3}$



Longitudinal Beam Sizes in Storage Ring and Bunch Train Structure

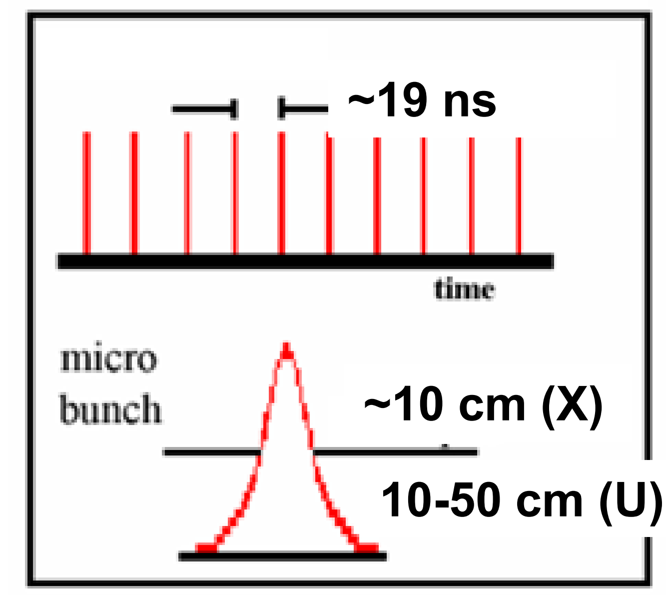
- RF cavity provides longitudinal E-field that makes up beam energy loss/turn due to SR:



$V_{RF}(\tau)\sim\cos(2\pi f_{RF}\tau)$

- Beam arrival and RF phase are synchronized => there are maximum $h=f_{RF}/f_{rev}$ bunches stored in the ring
- Each electron randomly loses discrete photons to SR, each exciting energy- time oscillations
- Balance of quantum excitation and SR radiation damping determines bunch length and energy spread

Time structure @ NSLS



f_{RF}=53 MHz = 1/(19 ns)
h=30 (X-ray)
h=9 (VUV)

Longitudinal Bunch shape is constant around the ring

Light Sources: Definition of Generation

- **1st Gen**: parasitic synchrotron radiation source from the dipoles of HEP ring (SPEAR, CESR, etc)
- **2nd Gen**: dedicated ring for synchrotron radiation, dipole rad & some undulators; medium brightness
- **3rd Gen**: dedicated ring optimized for undulator radiation; high brightness
- **4th Gen**: dedicated free electron lasers, IR to X-Ray

NSLS X-ray and VUV rings are (one of the first) 2nd generation LS
NSLS-II ring will be 3rd generation LS
Recently commissioned LCLS at SLAC is 4th generation X-ray LS

Synchrotron Light Source Quality Factors

ID Capacity $N_{ID} >> 1$	**Ave Flux** $\Phi \sim I\,E$	**Stability** $\frac{\Delta_{x,x',\ldots}}{\sigma_{x,x',\ldots}} < \Delta_{limit}$
Ave Brightness $B \propto \frac{I\,N_u}{\left(\varepsilon_x \oplus \bar{\lambda}/2\right)\left(\varepsilon_y \oplus \bar{\lambda}/2\right)}$	**Pulse length & rep. rate** σ_t=1-100 ps (0.1 ps @ low rep. rate)	**Cost** $\$ < \$_{limit}$

Try to break new ground on the first 5 without violating the last!

$\bar{\lambda}/2 \equiv \lambda/4\pi$ Diffraction limit

Boris Podobedov, Nov. 22, 2010

3^{rd} & 4^{th} Generation Sources Survey

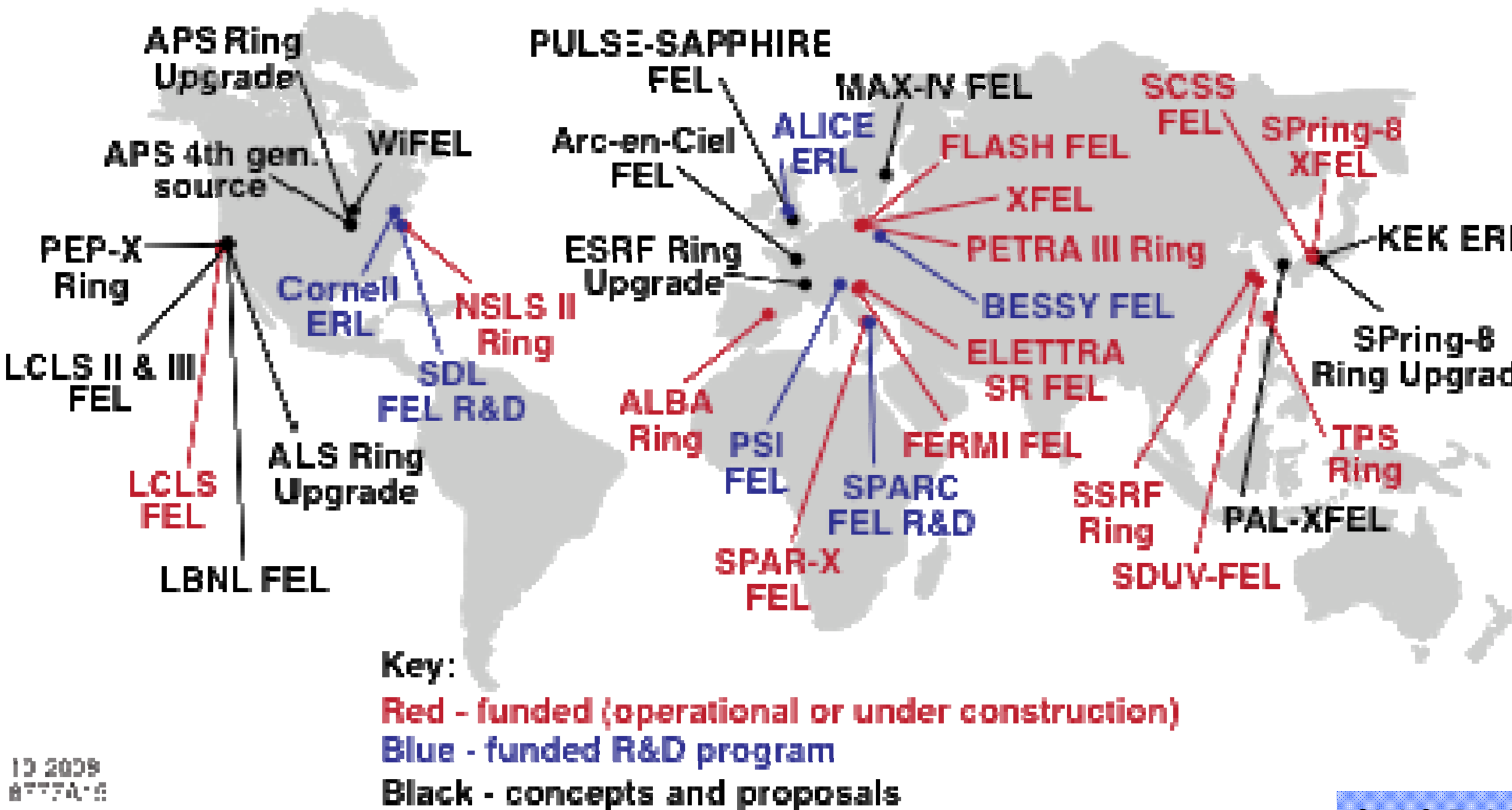
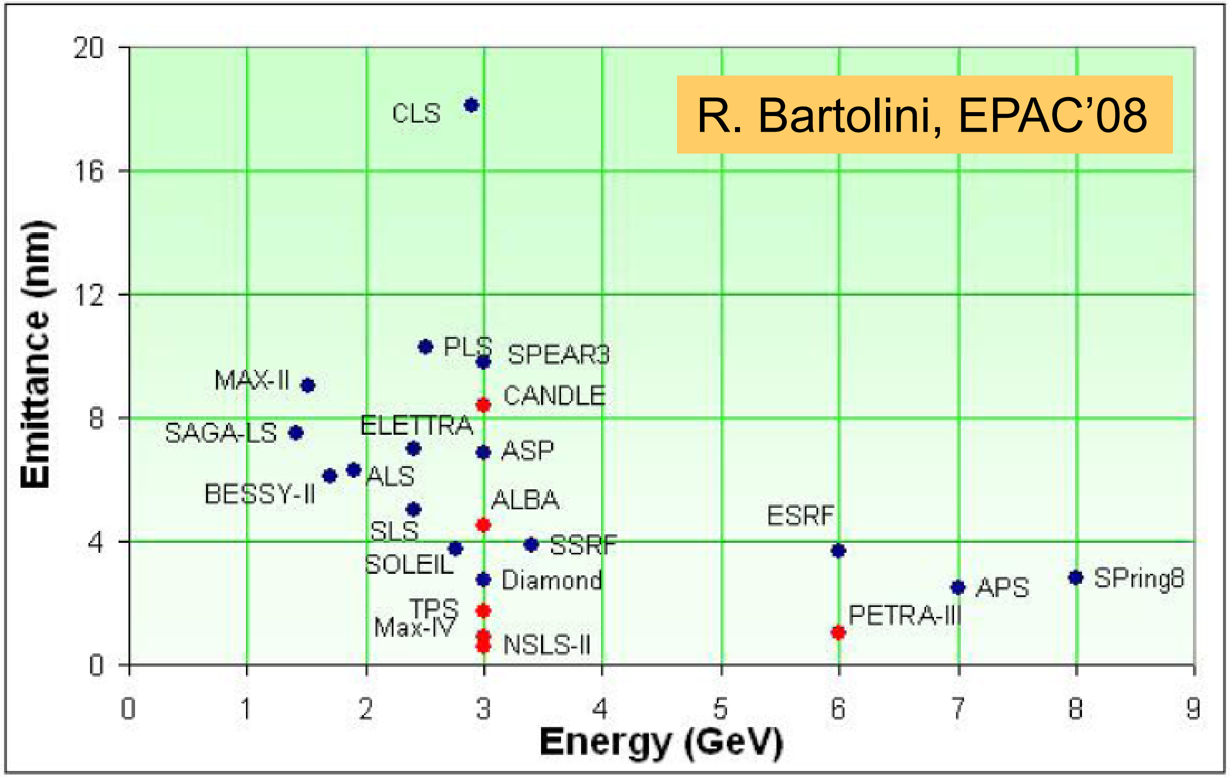


Figure 5 1. Proposed and funded x-ray light sources and R&D facilities around the world

SLAC-R-910
LBNL-1090E

Emittances of Modern Ring Light Sources



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

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

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

Photon beam brightness is determined (mostly) by electron beam emittance that defines the source size and divergence

Summary

- **SR generation and properties**: spectrum, BW, power, polarization, angular distribution, …
- **Brightness, emittance and diffraction limit**
- **Benefits of having IDs** (wigglers and undulators)
- **LS Performance Metrics**: brightness, flux, N_{ID}, …
- **Building blocks of a storage ring**: dipoles, quads, sextupoles, RF system, …
- **Emittances and beam sizes in a storage ring**: balance of SR damping and SR quantum excitation
- **SR lightsources worldwide**

References

For primers and further information, link to www.lightsources.org

Good reviews of synchrotron radiation and electron storage ring physics

- A. Hoffmann: in CAS - CERN Accelerator School : Synchrotron Radiation and Free Electron Lasers, Grenoble, France, 22 - 27 Apr 1996, pp.1-44, search for report CERN-98-04 at http://cdsweb.cern.ch/
- M. Sands: http://www.slac.stanford.edu/pubs/slacreports/slac-r-121.html

Review of present state-of-the art and future directions in LS world

- Scientific Needs for Future X-Ray Sources in the U.S.
  http://www.slac.stanford.edu/pubs/slacreports/slac-r-910.html