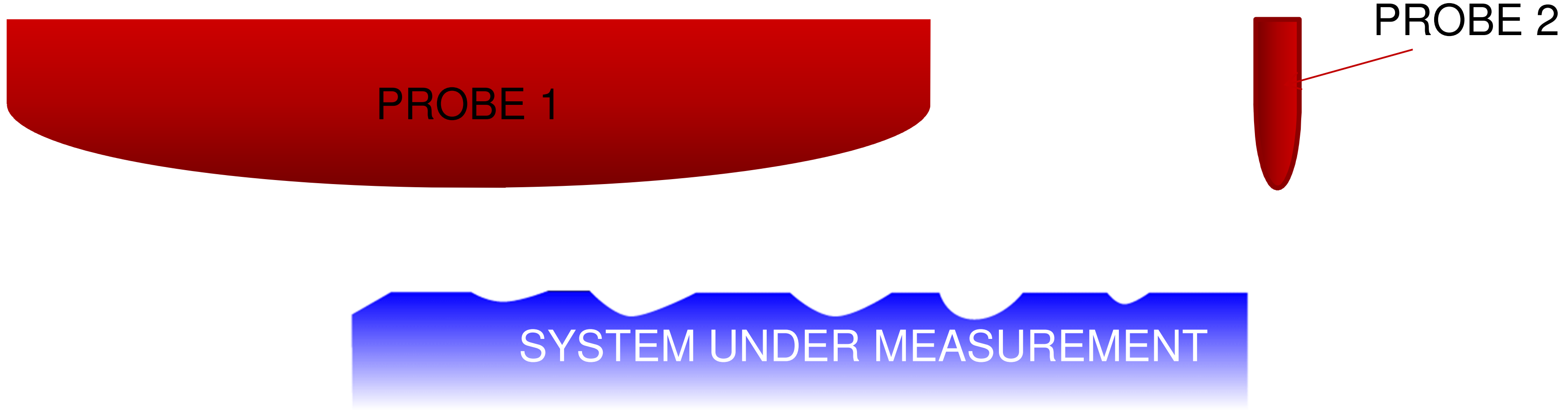
Ring-Based Synchrotron Light Sources
(Optimizing Brightness in Storage Rings)

Fernando Sannibale
Lawrence Berkeley National Laboratory

Outline

- **The need of an efficient, high resolution probe to investigate nature**
- **Using photons (synchrotron radiation) as such a probe**
- **Synchrotron radiation brightness and other properties.**
- **Accelerator-based light sources.**
- **Optimizing photon brightness in storage rings based light sources**
  - **The concept of diffraction limited source**
  - **Diffraction limited light source (or ultimate) storage ring (USR) optimization, properties and challenges.**

Probing Nature: Spatial Resolution

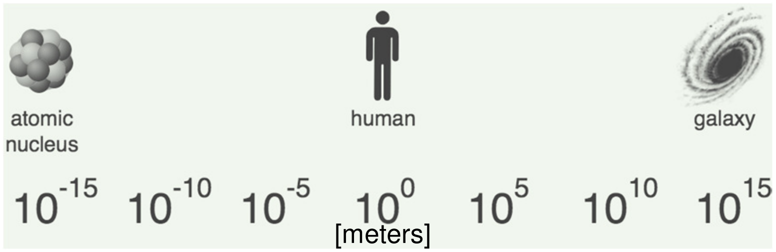


Question: which of the probes is appropriate for measuring the surface roughness of the system?

Important concept: "the probe must be smaller or at least comparable in size with the object to be measured".

The size of the probe defines the "spatial resolution" of the measurement

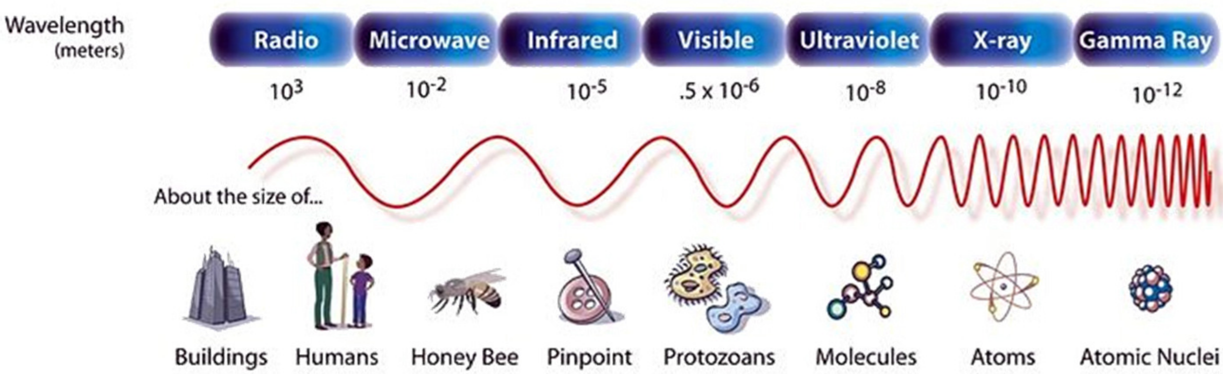
Size Scale in Nature



http://scaleofuniverse.com/

What kind of probe can allow us measuring over such a broad range?

Photons, a.k.a. electromagnetic waves!



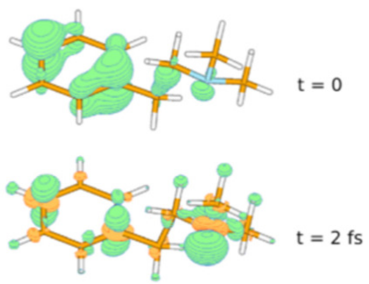
When photons are used as the probe, the spatial resolution is defined by the photons' wavelength λ

We can investigate bacteria using photons in the visible (optical microscopes), but we need X-rays for measuring atoms, and gamma rays for nuclei!

Probing Nature: Temporal Resolution

Similarly to the case of spatial resolution, if you want to measure fast phenomena you have to probe them with a high time resolution probe.

Example. The blinking of an eye can be as fast as 100 ms. If you want to capture it in multiple frames (make a movie), you can use a flash to send a train of pulses of light each with duration shorter than the blinking itself.



Electron motion in atoms and electron exchange in chemical reaction happens at the attosecond time scale (~ 100 as = 10^{-16} s)

Molecules vibration periods are in the femtosecond time scale (1 fs = 10^{-15} s). Phase transitions from solid to liquid, to gas, …

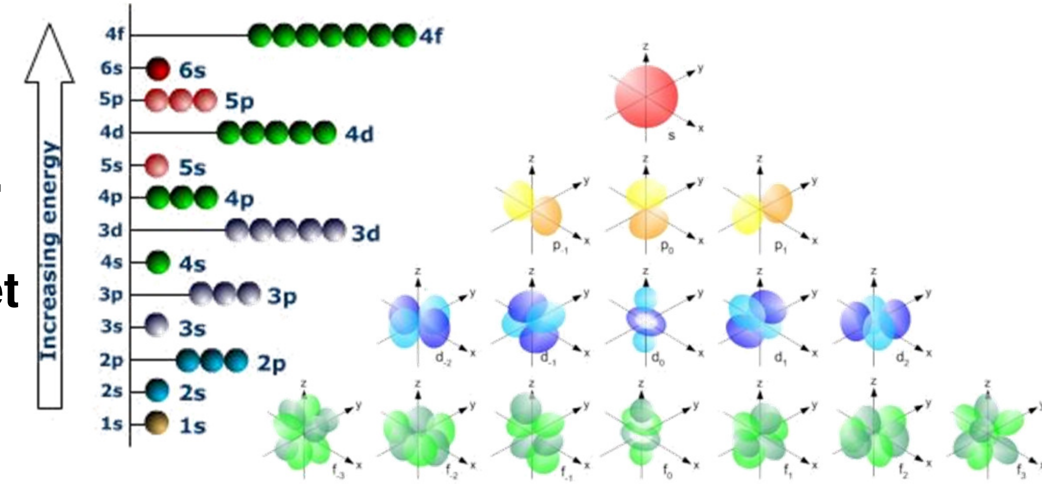
Magnetic domains can flip orientation in the picosecond time scale (1 ps = 10^{-12} s). Computer magnetic data storage devices (hard disks)

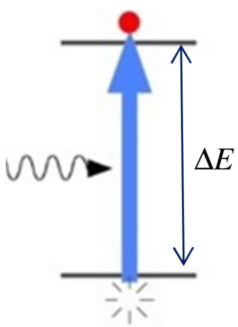
Protein folding happens in > 100 μs (10^{-4} s).

Short pulses of photons can offer time resolutions at these levels!

Probing Nature: Energy Resolution

Electrons in atoms are located in orbitals with different energy levels. Each element in the periodic table has its own unique and distinctive set of energy levels.





Photons with the appropriate energy ΔE can be absorbed by the atom (setting it in an excited state where one electron is now in a higher energy level).
For example, sending on a particular atom pulses of photons all with the same energy ΔE, and observing for what values of ΔE the photons are absorbed, it is possible to measure the energy levels of an atom.

**This is an example where single-energy (or almost single-energy) photon pulses are necessary to perform the experiment.
Many other experiments requires similar characteristics.**

The Ideal Probe

In the previous slides, it was shown as **mono-energetic (or quasi mono-energetic) short pulses of photons with the appropriate wavelength represent a close-to-ideal probe with high spatial, temporal, and energy resolution!**

Additionally, if we want to perform measurements within an acceptable time we need **a large number of particles or photons** in each bunch or pulse.

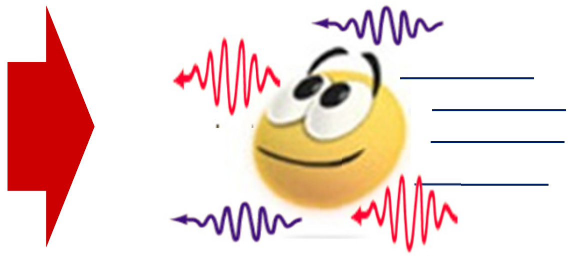
Qualitatively, this implies that the path that an experimental physicist/engineer has to follow if he wants to build a great probe is clearly defined:
He has to find the way to generate short pulses with a lot of photons with the appropriate wavelength (momentum)!

High quality photon pulses can be generated by lasers.
But at the present time the shortest wavelength achievable by lasers with an acceptable number of photons/pulse is limited to ~ a few tens of nm.

At the present time only accelerators-based light sources can generate pulses with a large number of shorter wavelengths (down to ~ 0.01 nm) photons

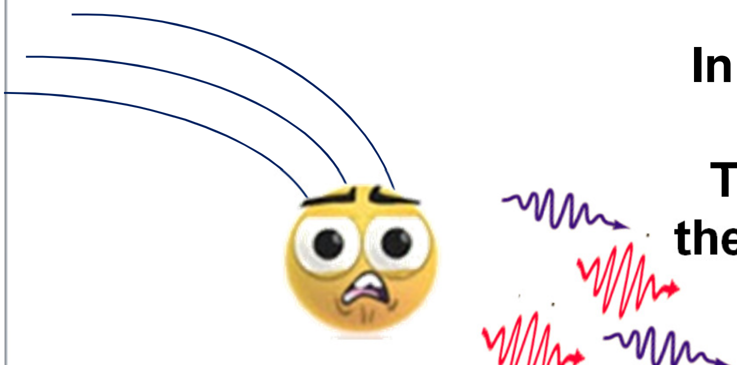
Accelerators as a Source of Photons

- **According to quantum field theory, a particle moving in free space is "surrounded" by a cloud of virtual photons that appear and disappear and indissolubly travel with it.**



- **Such photons live for extremely short periods and are so closely tight to the particle that cannot be detected (from there the name of virtual photons).**

- **Nevertheless, if the particle undergoes a strong transverse acceleration, it can detach itself from its virtual photons, that now become real and can be detected (and used!).**



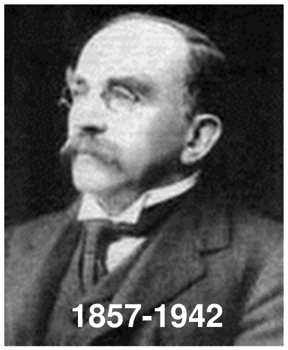
In accelerators, (charged) particles can be forced on curved trajectories by magnetic fields.
The consequent transverse acceleration allows for the separation of the virtual photons and *synchrotron radiation* is generated.

- **The higher the particle energy and the sharper the curved trajectory, the shorter is the wavelength that the photons can have, and the larger is the number of photons generated. Lighter particles radiate more photons than heavier ones (electrons are much much better with respect to protons for example).**

The Classical Picture

• **The description of synchrotron radiation presented in the previous viewgraph made use of quantum field theory.**

• **Historically, the whole theory was developed well before quantum mechanics was even conceived:**



- in 1897 Joseph Larmor derived the expression for the instantaneous total power radiated by an accelerated charged particle.

$$P = \frac{q^2}{6\pi\varepsilon_0 c^3} a^2$$

Larmor Power

1898 Liénard:

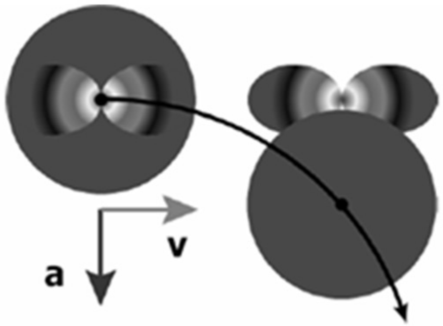
ELECTRIC AND MAGNETIC FIELDS PRODUCED BY A POINT CHARGE MOVING ON AN ARBITRARY PATH

(by means of retarded potentials)

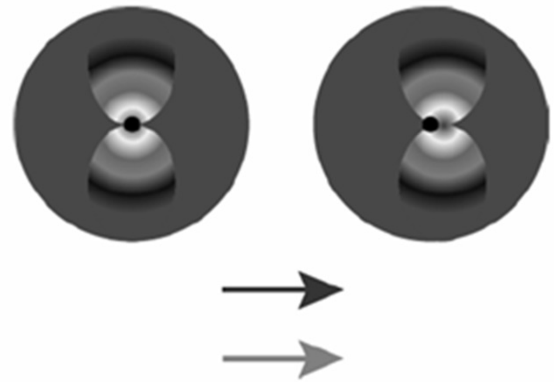

L'Éclairage Électrique
REVUE HEBDOMADAIRE D'ÉLECTRICITÉ
DIRECTION SCIENTIFIQUE
CHAMP ÉLECTRIQUE ET MAGNÉTIQUE

- and in 1898 Alfred Lienard (before the relativity theory!) extended Larmor's result to the case of a relativistic particle undergoing centripetal acceleration in a circular trajectory

Longitudinal vs. Transverse Acceleration



Radiation field quickly separates itself from the Coulomb field



Radiation field cannot separate itself from the Coulomb field

$$P_\perp = \frac{q^2}{6\pi\varepsilon_0 m_0^2 c^3}\gamma^2\left(\frac{d\mathbf{p}_\perp}{dt}\right)^2$$

$$P_\parallel = \frac{q^2}{6\pi\varepsilon_0 m_0^2 c^3}\left(\frac{d\mathbf{p}_\parallel}{dt}\right)^2$$

negligible!

$$P_\perp = \frac{c}{6\pi\varepsilon_0} q^2 \frac{(\beta\gamma)^4}{\rho^2} \qquad \rho = curvature\ \ radius$$

- **Radiated power for transverse acceleration increases dramatically with energy. This sets a practical limit for the maximum energy obtainable with a storage ring, but makes the construction of synchrotron light sources extremely appealing!**

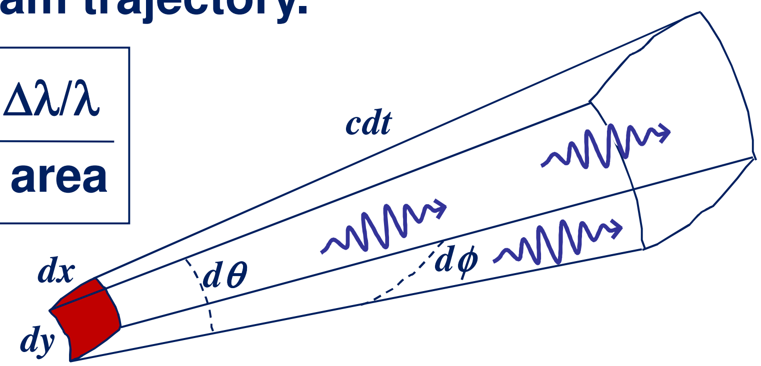
The Brightness of a Light Source

• The **photon brightness** (sometimes referred as *spectral brightness* or *brilliance*) is the ultimate parameter to characterize the performance of a light source.

• The longitudinal phase space is typically represented by using the conjugate variables time and energy (ct and λ in practical cases).
Because photon energy is an important parameter for users, brightness is usually measured within a bandwidth, and the time component is integrated and represented as average value.

• In the transverse plane the momentum component is replaced by the divergence angle with respect to the beam trajectory.

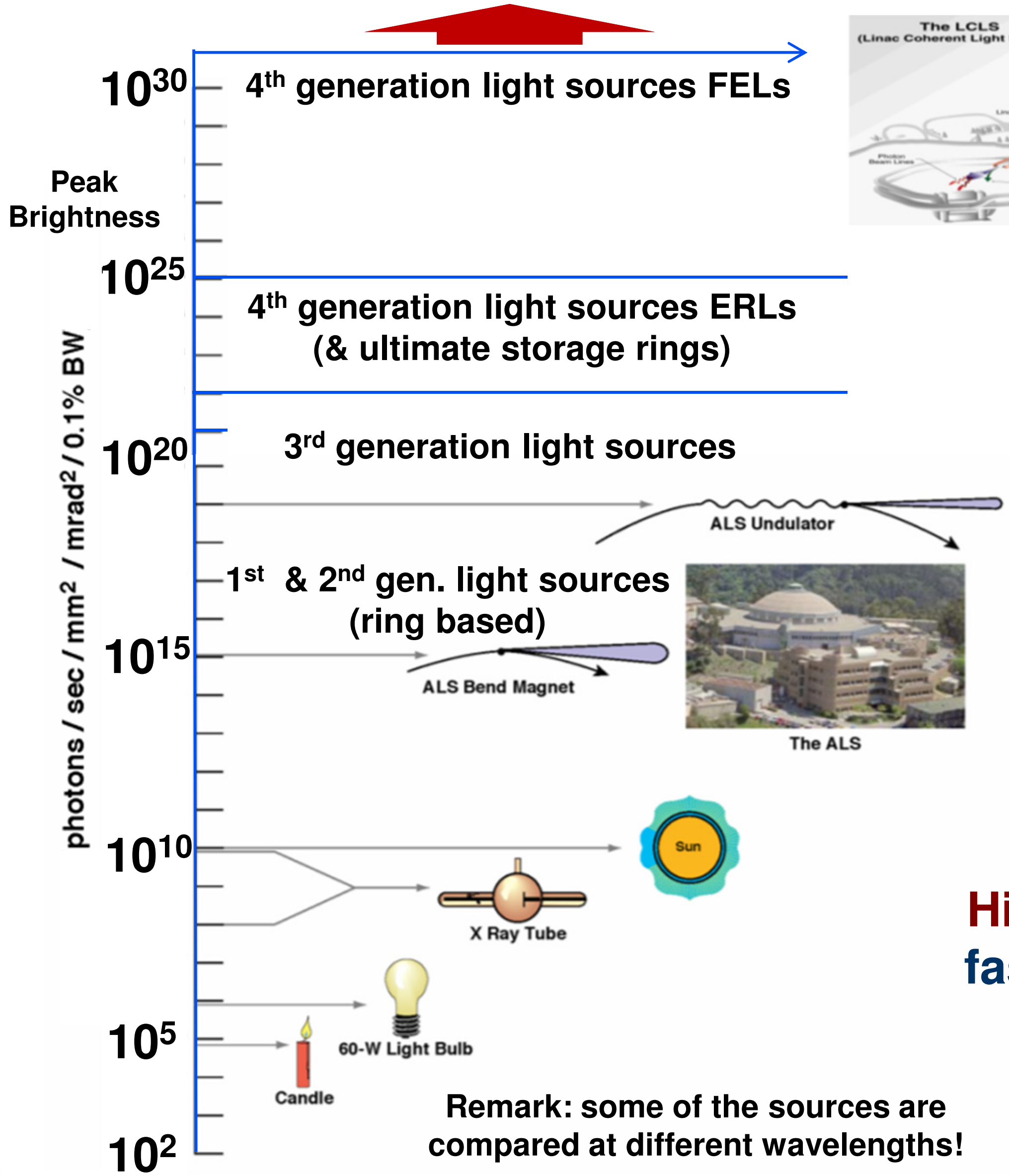
Brightness unit = $\dfrac{\text{number of photons in a given } \Delta\lambda/\lambda}{\text{unit time, unit solid angle, unit area}}$



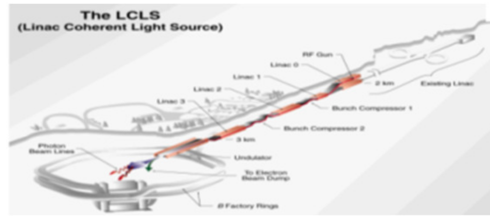
Flux unit = $\dfrac{\text{\# of photons in a given } \Delta\lambda/\lambda}{\text{unit time}}$

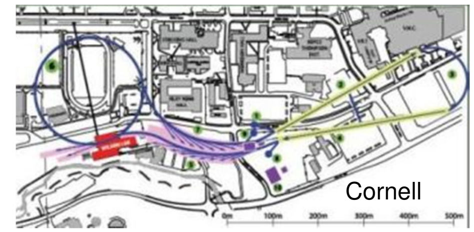
• From the above definitions, one can see that for a given flux, sources with a smaller emittance will have a larger brightness.

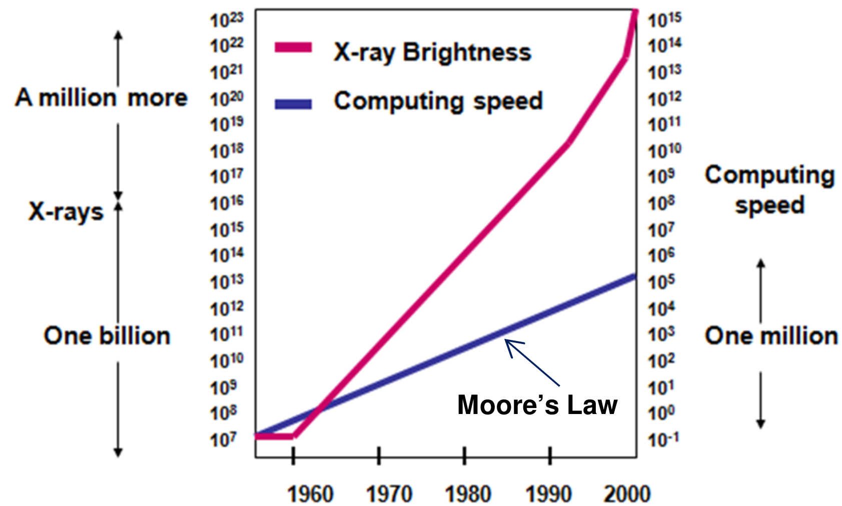
How Bright is a Synchrotron Light Source?



Remark: some of the sources are compared at different wavelengths!



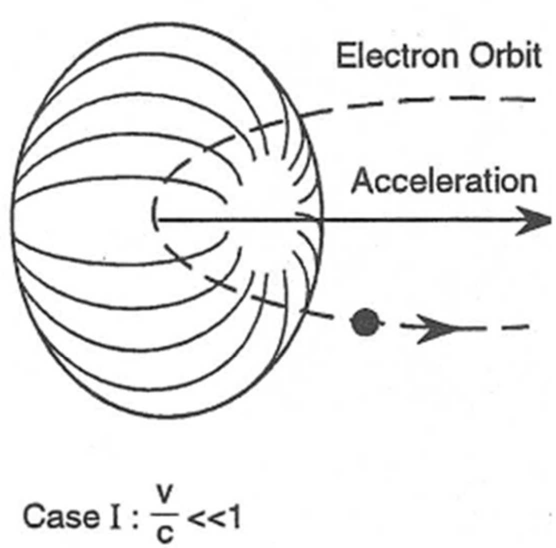




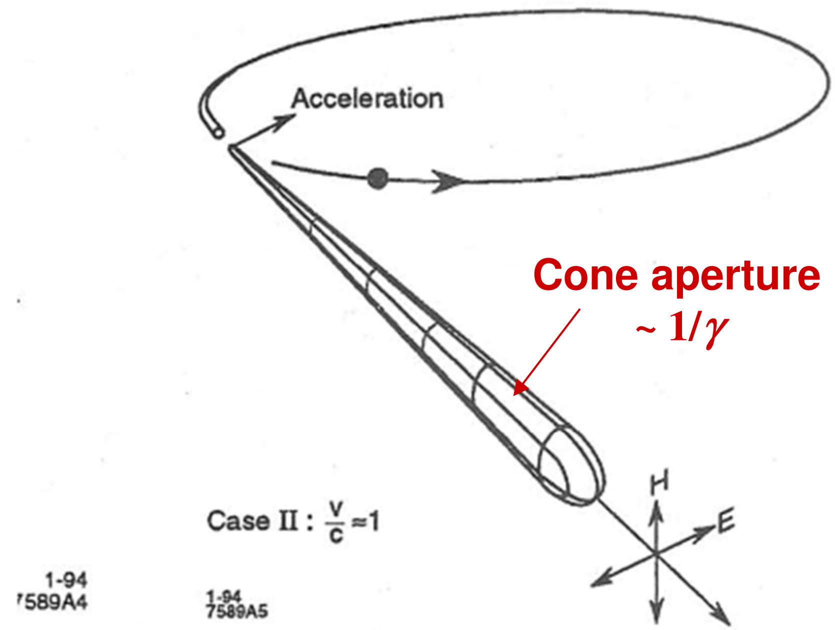
High brightness is strongly desirable: faster experiments, higher coherence, improved spatial, time and energy resolutions in experiments, …

Synchrotron Radiation Angular Distribution

- **Radiation becomes more focused at higher energies.**



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.

Bandwidth of Synchrotron Radiation

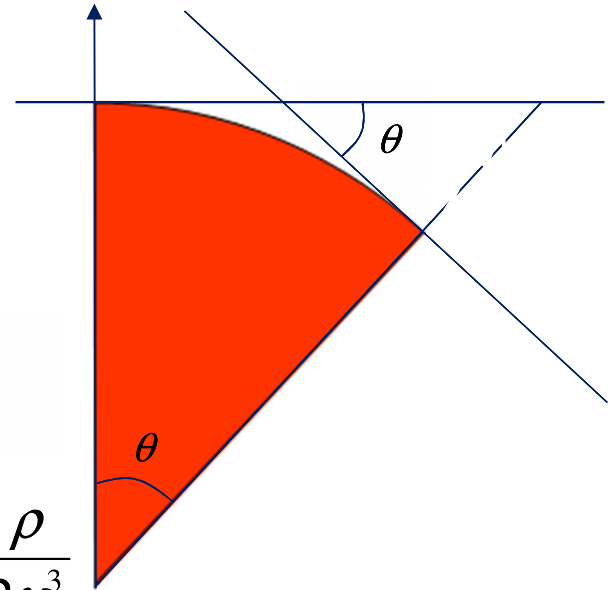
Due to extreme collimation of light

$$\theta \approx \frac{1}{\gamma}$$

- observer sees only a small portion of electron trajectory **(a few mm)**

$$l = \theta\rho \approx \frac{\rho}{\gamma}$$

- Pulse length: difference in times it takes an electron and a photon to cover this distance



$$\Delta t \approx \frac{l}{\beta c} - \frac{l}{c} = \frac{l}{\beta c}(1-\beta) = \frac{l}{\beta c}\frac{(1-\beta^2)}{1+\beta} \approx \frac{l}{\beta c}\frac{1}{2\gamma^2} \approx \frac{1}{\beta c}\frac{\rho}{2\gamma^3}$$

$$\Delta\omega = \frac{1}{\Delta t} \quad \longleftrightarrow \quad \Delta\omega \approx \beta c \frac{2\gamma^3}{\rho}$$

- **Example for an electron ring with 1.9 GeV and with a bending radius of 5 m:**

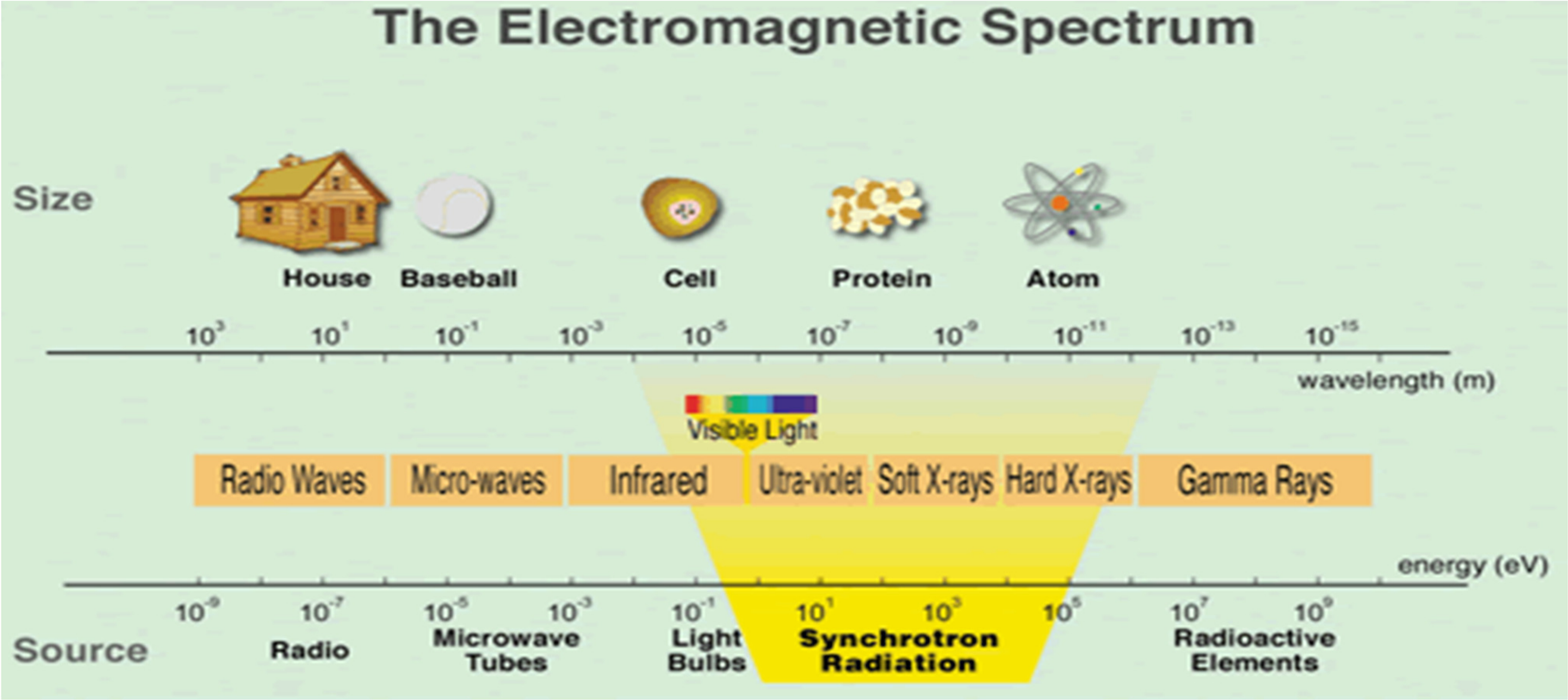
$$l \cong 1.34\ mm \Rightarrow \Delta t \cong 1.62\times 10^{-19}\ s \Rightarrow \Delta\omega \cong 6.17\times 10^{18}\ s^{-1}$$

$$f_{MAX} \approx \frac{\Delta\omega}{2\pi} \cong 9.82\times 10^{17}\ Hz \quad \Leftrightarrow \quad \lambda_{MIN} = \frac{c}{f_{MAX}} \cong 0.31\ nm$$

Very broad band!

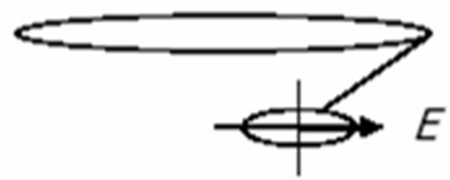
Accelerator-Based Light Sources

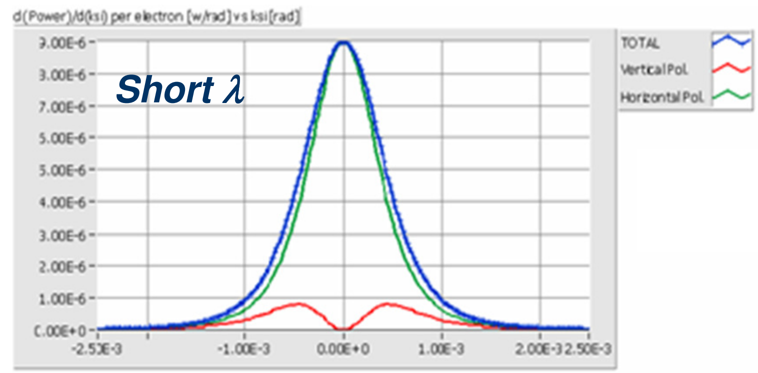
- As it was discussed earlier, by forcing in accelerators light charged particles (electrons) on a curved trajectory, we can efficiently generate synchrotron radiation, i.e. a large number of photons to perform experiments with exceptionally high spatial, temporal and energy resolution.



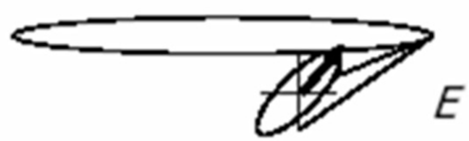
Polarization

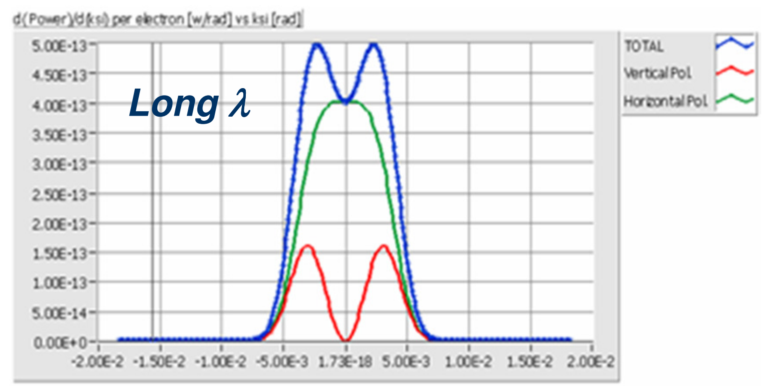
Synchrotron radiation observed in the plane of the particle orbit is horizontally polarized, i.e. the electric field vector is horizontal





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



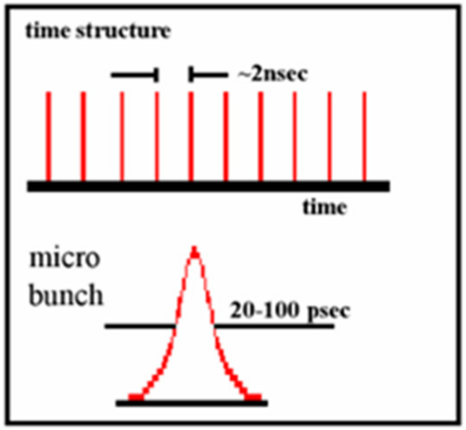


This characteristic of synchrotron radiation is heavily exploited in those experiments where the polarization of the light is important.

What Properties Make Synchrotron Radiation so Useful?

Recapitulating the main properties of synchrotron radiation:

- **High brightness and flux**
- **Wide energy spectrum**
- **Highly polarized and short pulses**



SR offers many characteristics of visible lasers but into the x-ray regime!

- **Partial coherence**
- **High Stability**

Science Opportunities

Medicine

Biology

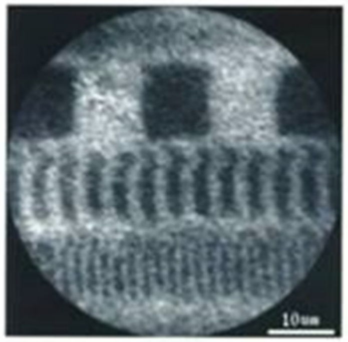
Chemistry

Material Science

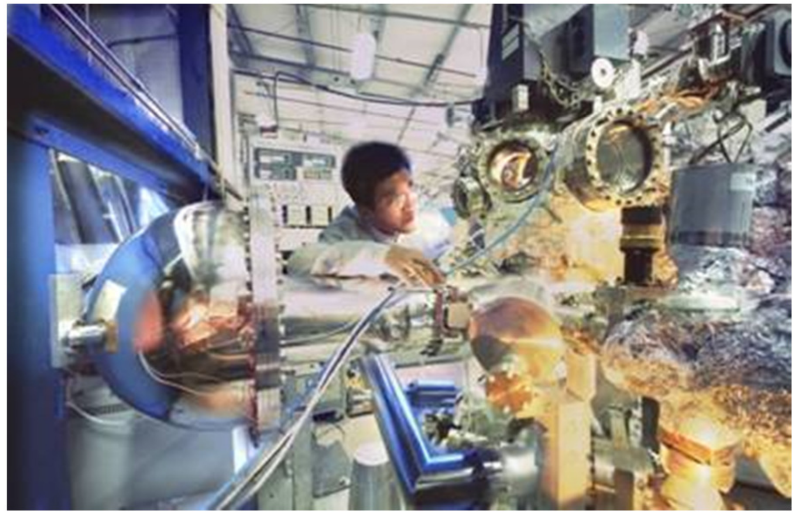
Environmental Science

and much more…

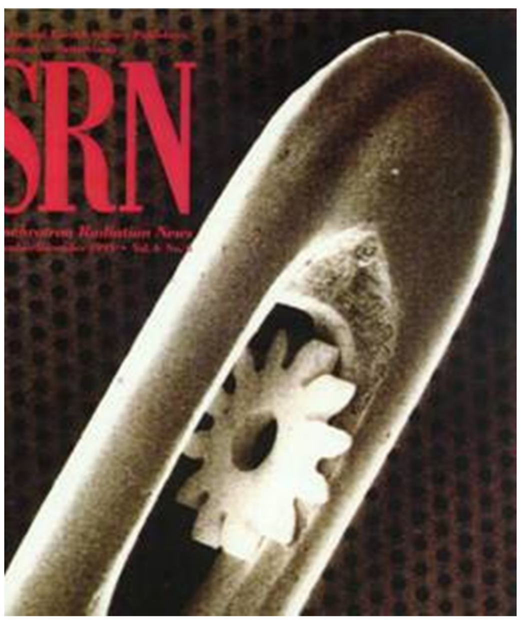
Materials Science



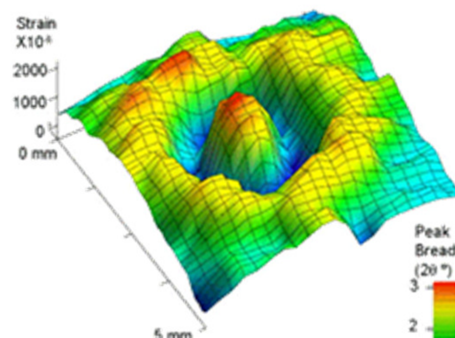
Visualizing magnetic bits on a computer hard drive

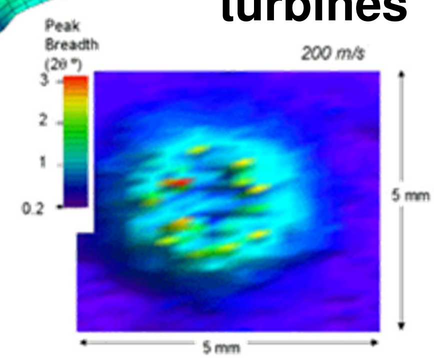


Using SR to learn how high temperature superconductors work



Using SR to make miniature mechanical and electromechanical devices

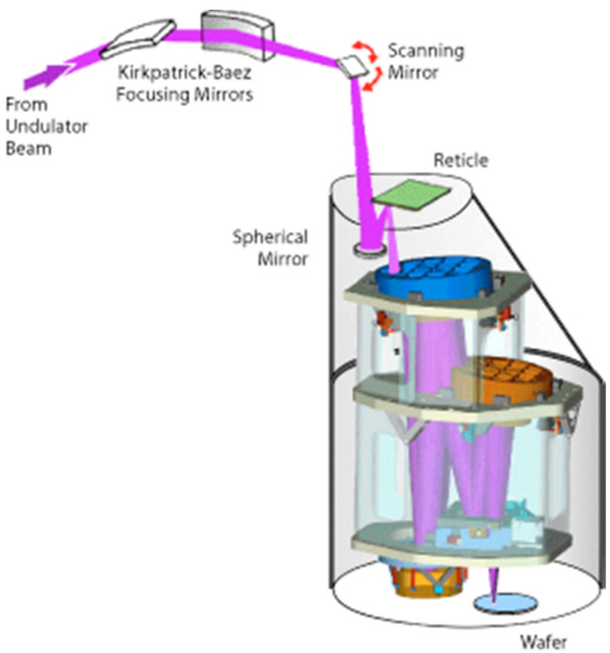


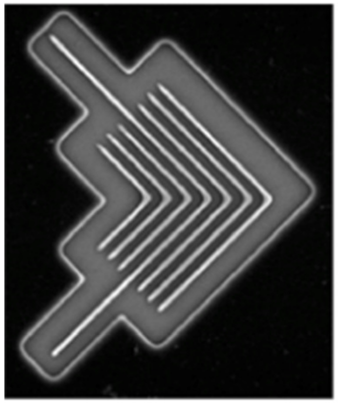


Understanding how debris causes damage to aircraft turbines

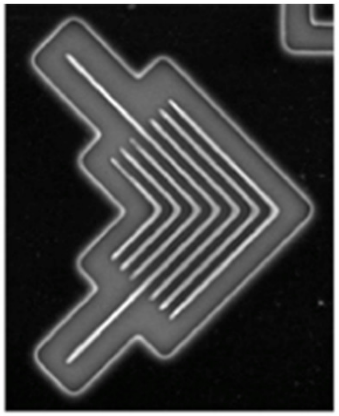
Next Generation of Semiconductors

EUV Lithography

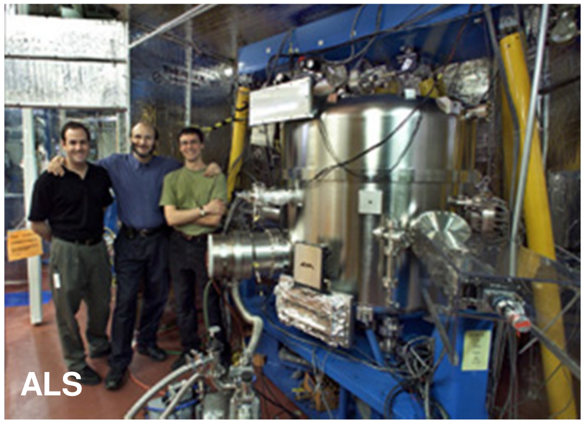




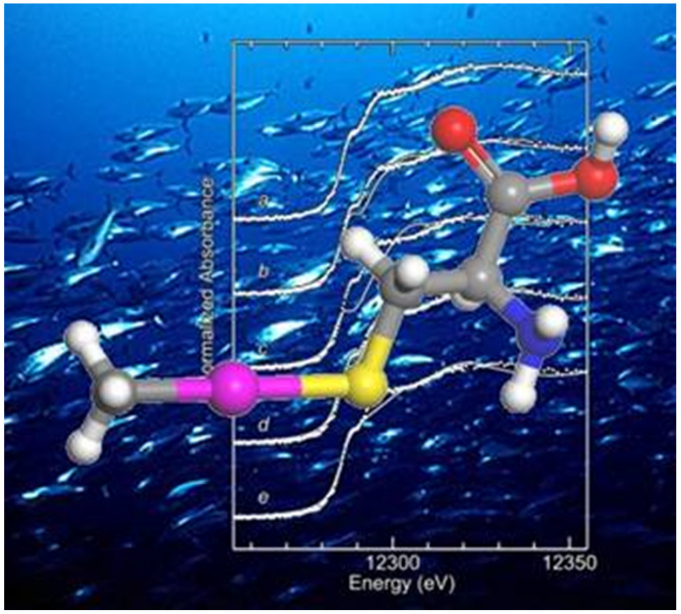
45 nm 3:1



39 nm 3:1

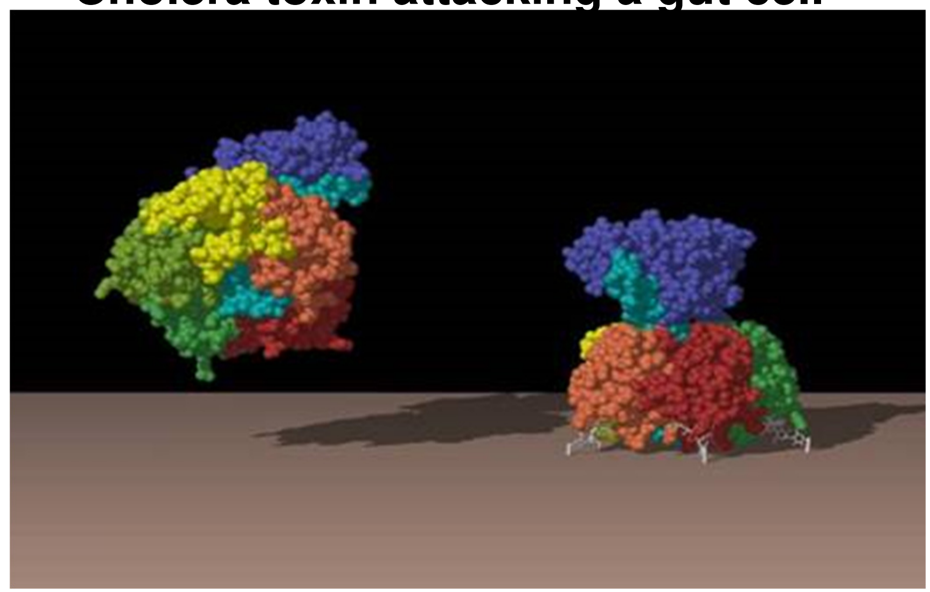


Chemistry and Biology

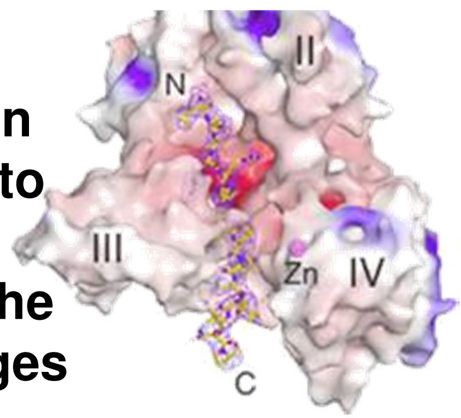


Measuring very low levels of mercury in fish and determining its chemical form.

Cholera toxin attacking a gut cell

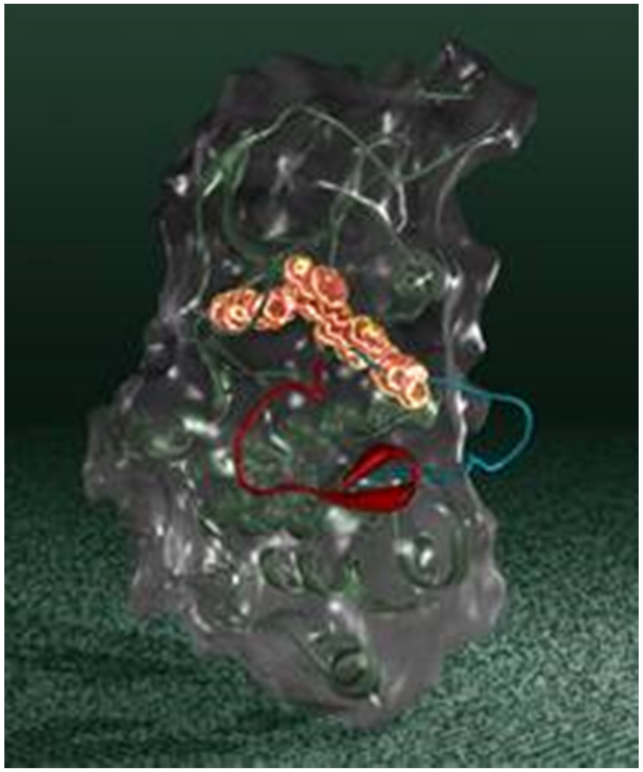


Studying Anthrax Toxin components to develop treatment in the advanced stages of infection.



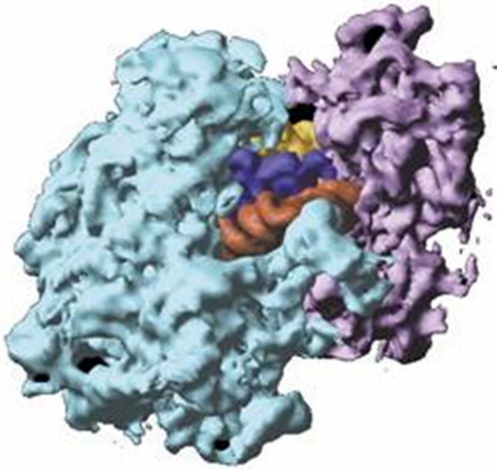
Protein Crystallography

Drug Design
GLEEVEC



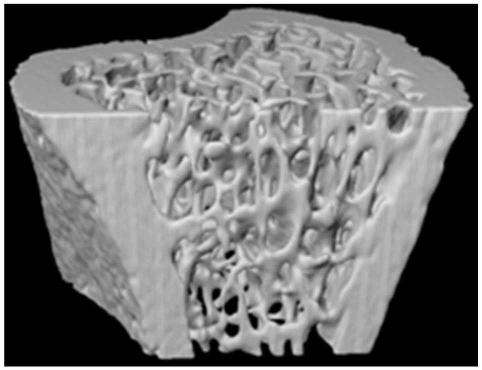
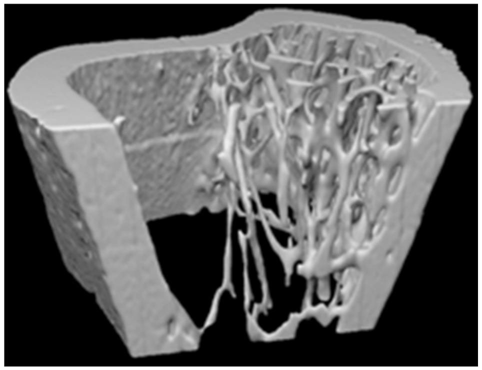
Leukemia

Understanding how protein's are made



Ribosomes make the stuff of life. They are the protein factories in every living creature, and they churn out all proteins ranging from bacterial toxins to human digestive enzymes

Biomedicine

before estrogen loss *after estrogen loss*

Studies of osteoporosis at SSRL

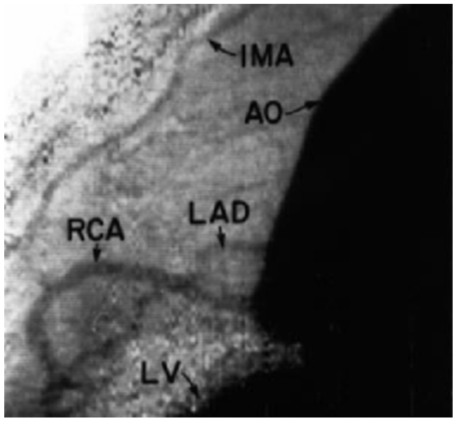
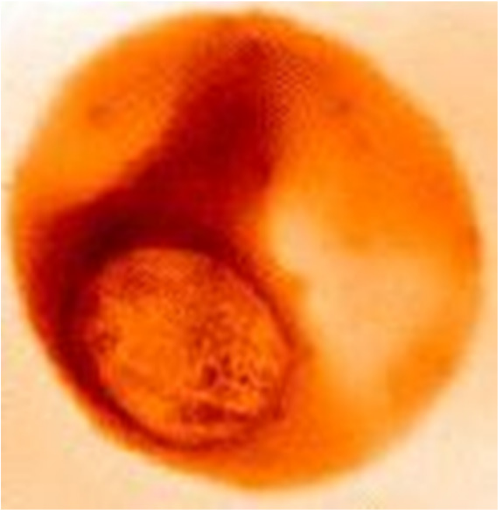


Image of a human coronary artery taken with synchrotron radiation at SSRL

These studies make use of the penetrating power of X-rays, rather than their short wavelength

This is an image taken with the x-ray microscope of a malaria-infected blood cell. Researchers at Berkeley Lab use pictures like this to analyze what makes the malaria-infected blood cells stick to the blood vessels.



Art & Archaeology

Sulfuric acid causing the decay of the *Vasa*, the Swedish warship which sank in Stockholm harbor in 1628

Virgin, Child, and Saint John **A renaissance panel painting by Jacopo Sellaio or Filippino Lippi being restored at the Cantor Art Center**

Examples of Existing Ring Based Light Sources

SLS (2002) 2.4 GeV

ε_x= 3.9 nm, ε_y=72 pm, I=300 mA

ALS (1993) 1.9 GeV

ε_x= 2.0/2.5 nm, ε_y=30 pm, I=500 mA

LNLS (1997) 1.37 GeV

ε_x= 100 nm, ε_y ~ 1nm, I=250 mA

Soleil (2006) 2.75 GeV

ε_x= 3.7/5.6 nm, ε_y=37 pm, I=400(500) mA

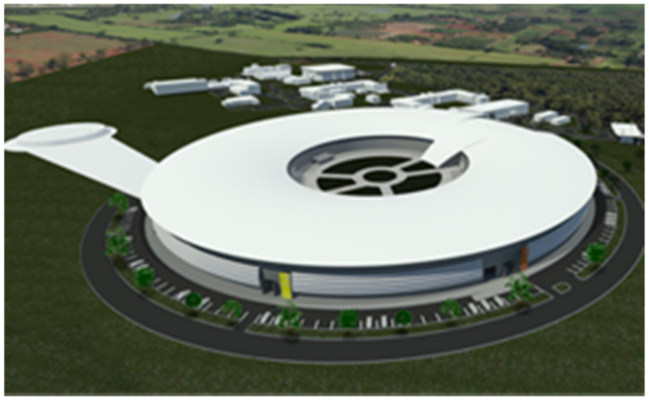
APS (1995) 7 GeV

ε_x= 2.5/3 nm, ε_y=30 pm, I=100 mA

Diamond (2007) 3 GeV

ε_x= 3.0 nm, ε_y= 30 pm, I=300(500) mA

Examples of Future and Proposed Storage Ring Light Sources

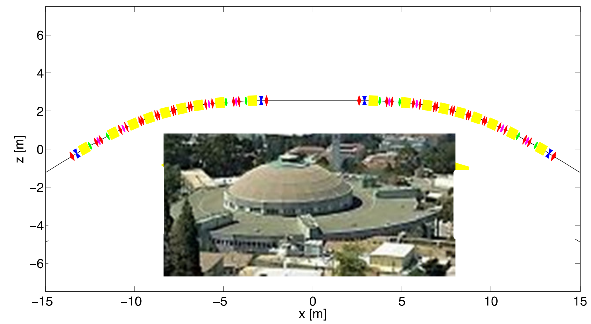


SIRIUS (2017) 3 GeV

ε_x= 0.28 nm, ε_y=2.8 pm, I=500 mA

MAX-4 (2016) 3 GeV

ε_x= 0.2-0.3 nm, ε_y= 8 pm, I=500 mA



ALS-U (20XX) 2 GeV

ε_x= 0.05 nm, ε_y= 50 pm, I=500 mA

PEP-X (20XX ?) 4.5 GeV

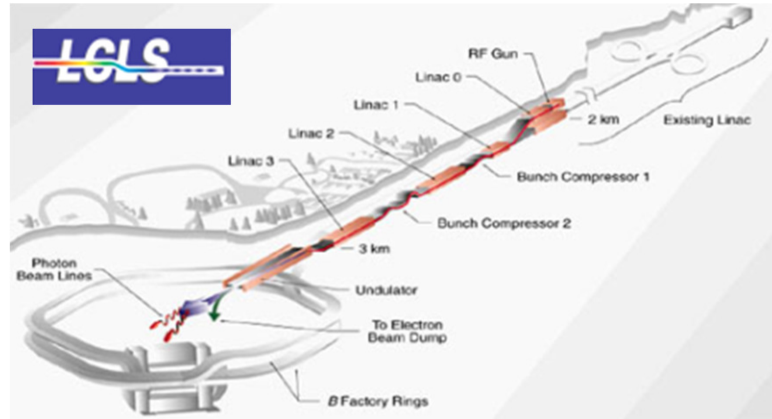
ε_x= 0.14 nm, ε_y = 8 pm, I=1500 mA

NSLS-II (2013) 3 GeV

ε_x= 1.1 (0.6) nm, ε_y= 8 pm, I=300(500) mA

APS-U, …

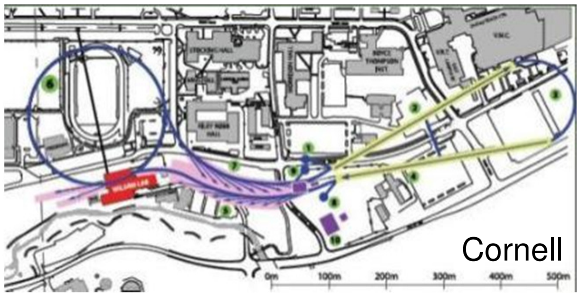
Existing X-ray FELs



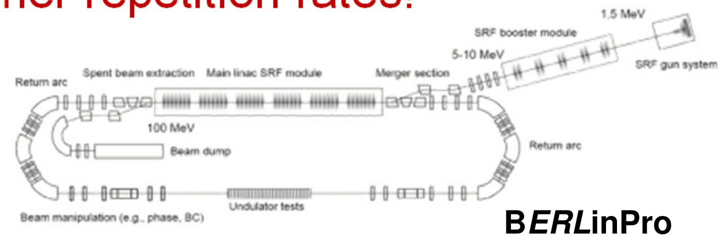
Their spectacular results represent a revolutionary opportunity for science!

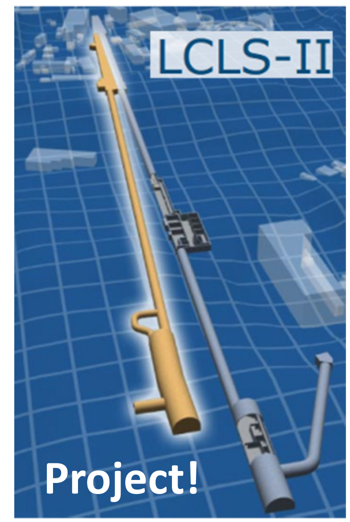
Proposed Future Linac-Based X-Ray Light Sources

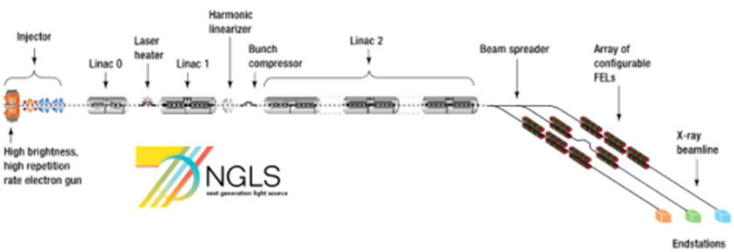
All operating 4th generation light sources are low repetition rate (< 120 Hz)
But science is driving towards much higher repetition rates!



Proposed X-ray ERLs require the same beam quality at GHz repetition rates.

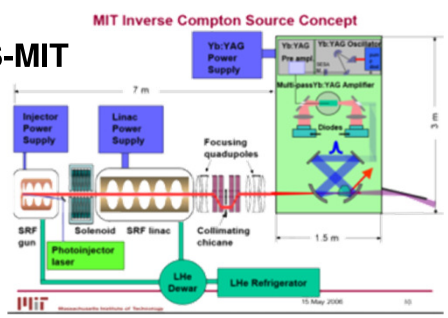


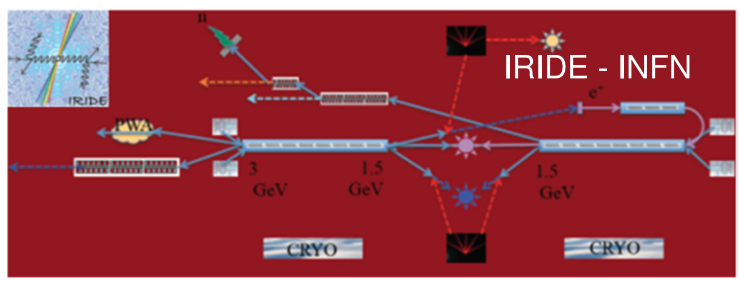




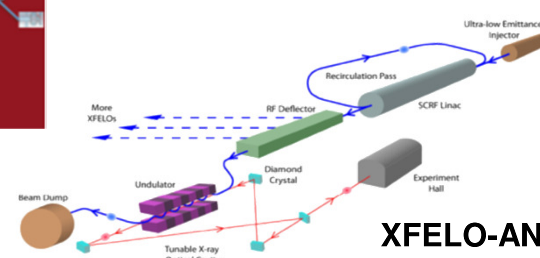
And proposed high repetition rate X-ray FELs, FEL oscillators and inverse Compton sources all require the similar beam quality at MHz repetition rates.

ICS-MIT

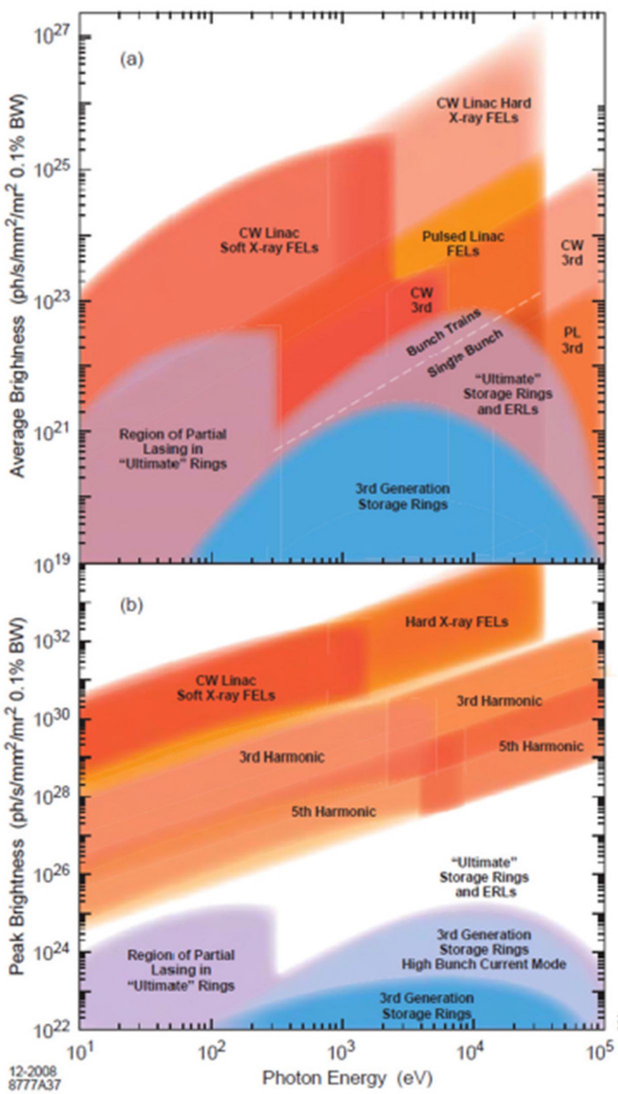


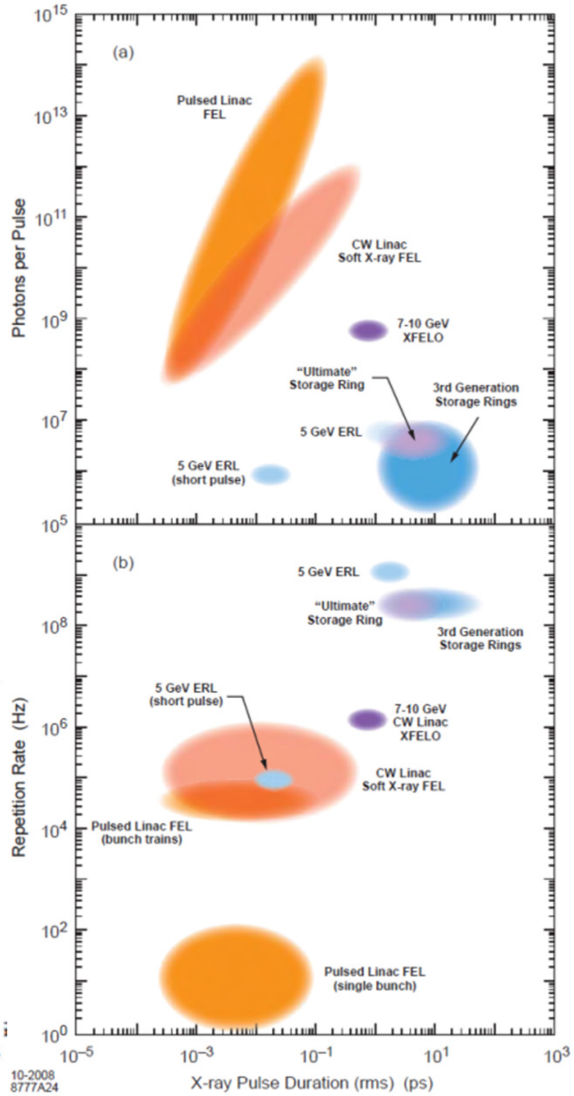


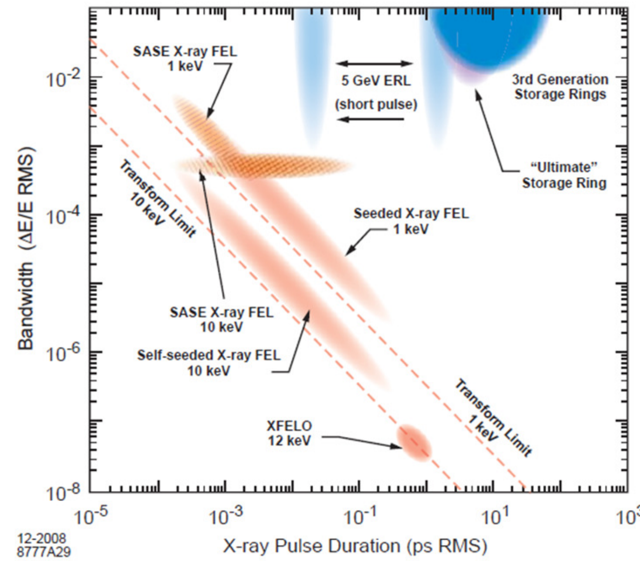
High repetition rate wakefield accelerators, UED, UEM, …



Rings are Complementary to FELs







Specific properties of interest for USRs and any X-ray light source include:

- spectral brightness and flux (average and peak)
- coherent fraction and coherent flux
- beam size, divergence and pulse length
- pulse repetition rate and pulse train structure
- energy spectrum and energy spread
- spatial, temporal and spectral stability
- photon polarization

Storage rings typically are more stable (smaller parameter fluctuations)

How to Optimize a Synchrotron Light Source

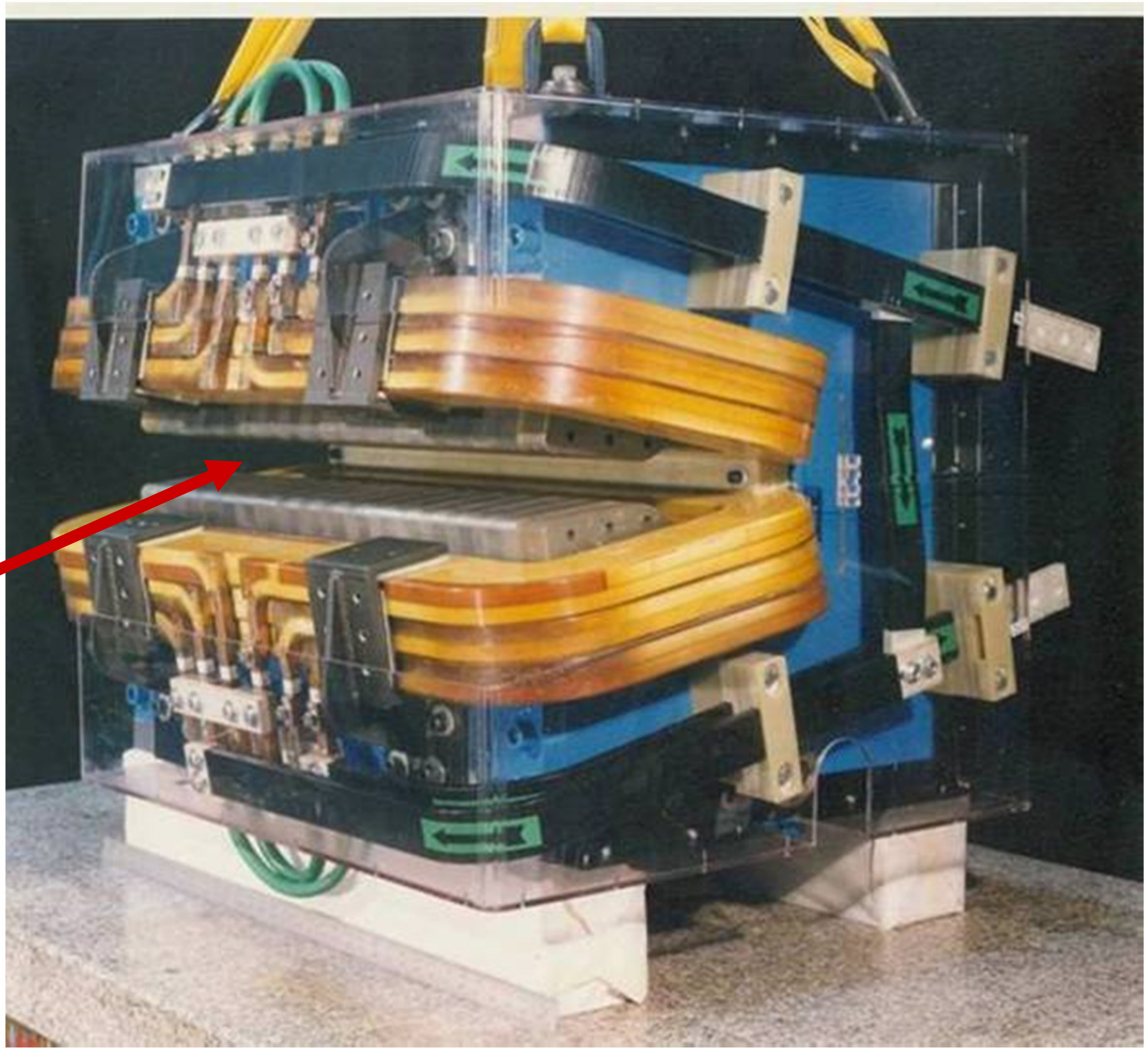
- **The ultimate performance parameter of a synchrotron light source is the brightness.**

- **The battle for the brightness maximization is fought in two fronts:**
  - **<u>In the accelerator</u>. Optimizing the design to get small emittances.**
  - **In the accelerator elements where the synchrotron radiation is actually generated: <u>dipole magnets and insertion devices</u>.**

- **Light sources are usually classified for increasing brightness as:**
  - ***1st generation*: "parasitic"synchrotron radiation sources from dipoles in colliders.**
  - ***2nd generation*: dedicated storage rings with sources from dipoles.**
  - ***3rd generation*: dedicated storage rings with insertion devices**
  - ***4th generation*: free electron lasers, ...**

Bend Magnet

Normal-Conductive
~ 1.5 T Max



"C" shaped for allowing to the radiation to leave the magnet

Bend Magnet Synchrotron Radiation Spectrum

Spectrum:

$$\frac{dP}{d\omega} = \frac{P_{tot}}{\omega_c} S\left(\frac{\omega}{\omega_c}\right)$$

$$P_{tot} = \frac{2}{3} \hbar c^2 \alpha \frac{\gamma^4}{\rho^2}$$

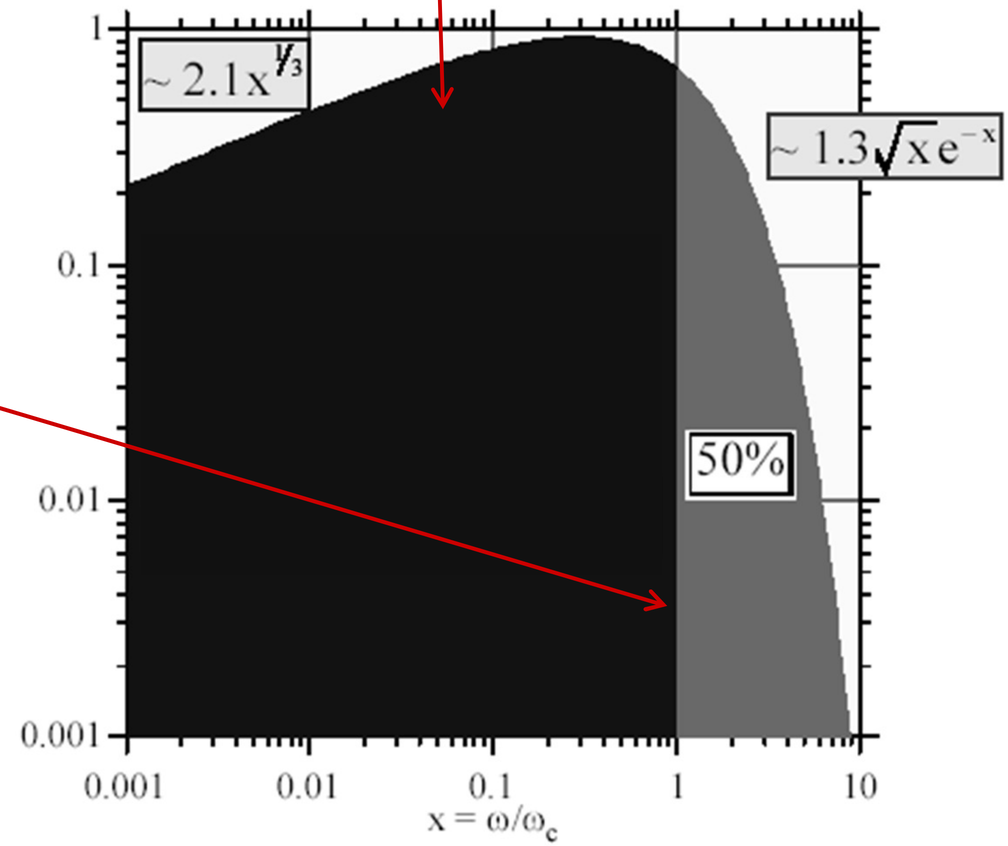
Universal function

$$S(x) = \frac{9\sqrt{3}}{8\pi} x \int_x^{\infty} K_{5/3}(x')dx' \qquad \int_0^{\infty} S(x')dx' = 1$$

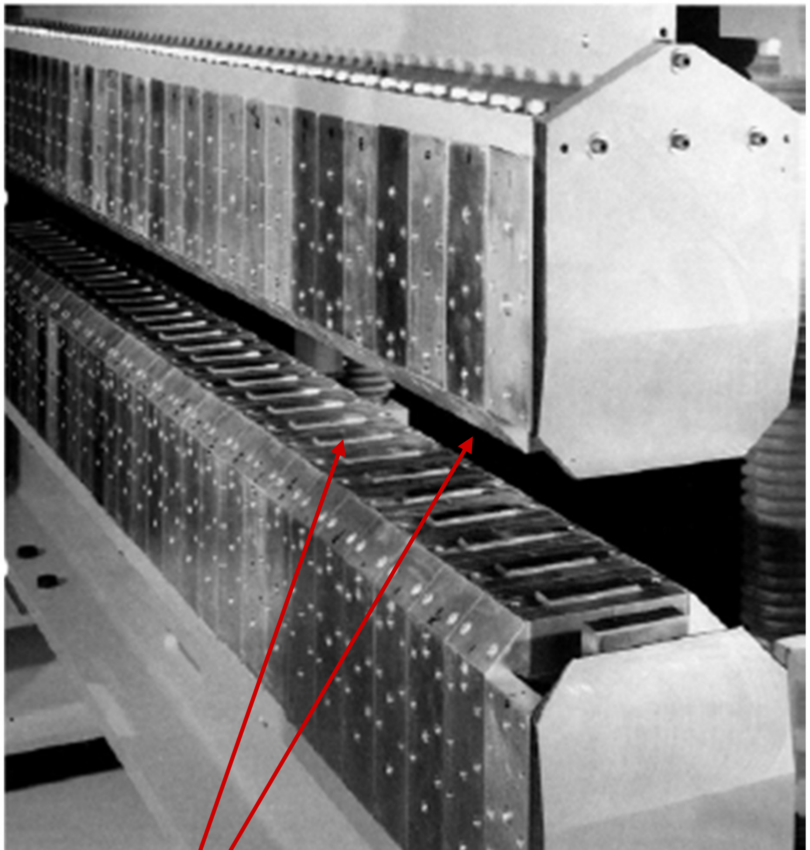
$$\omega_c = \frac{3}{2}\frac{c\gamma^3}{\rho}$$

Critical frequency

$$\varepsilon_c[eV] = 665\ E^2[GeV]\ B[T]$$

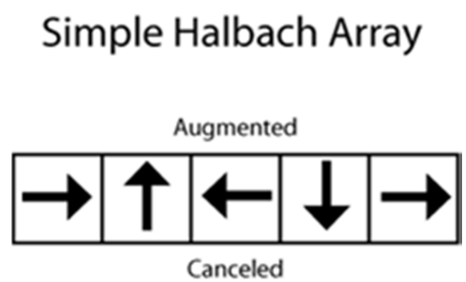


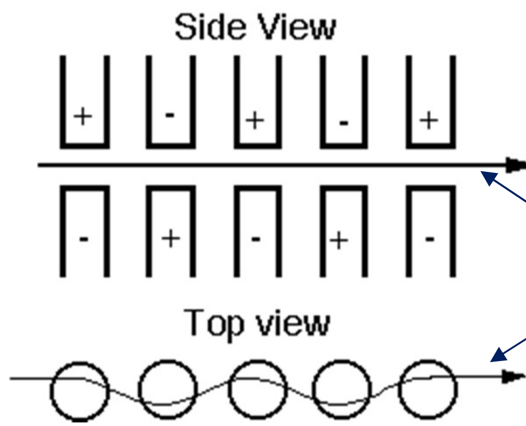
Planar Undulators



Permanent Magnets

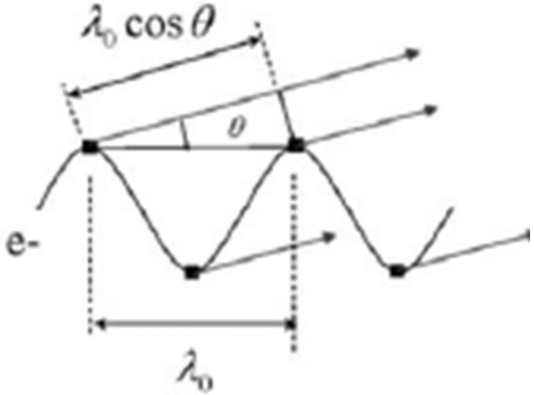
Invented by Klaus Halbach at LBNL



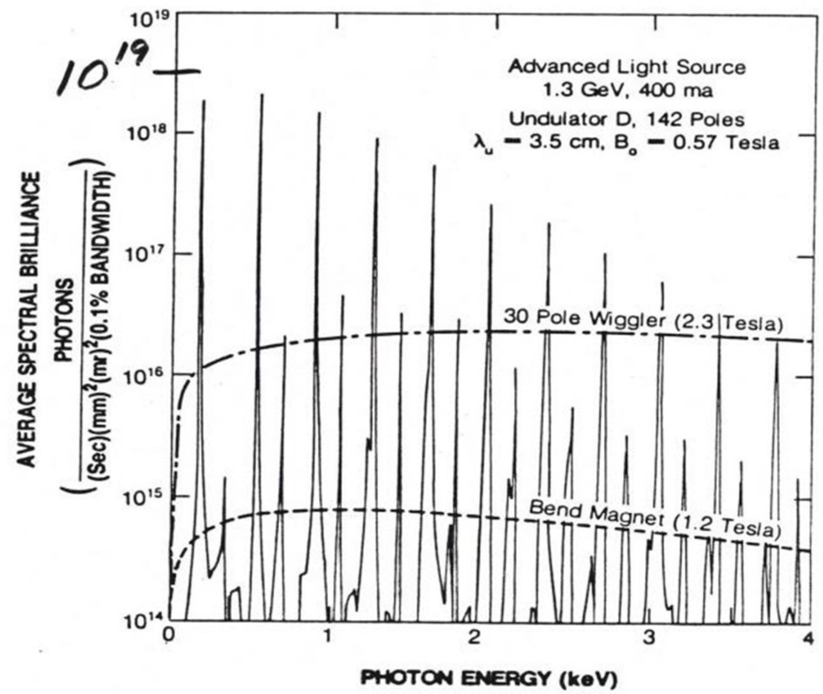


Particle trajectory

Undulator Radiation



$$\lambda = c\left(\frac{\lambda_0}{v_s} - \frac{\lambda_0}{c}\cos\theta\right) \cong \lambda_0\left(1 - \frac{v_s}{c} + \frac{\theta^2}{2}\right) \cong \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$



Photons emitted by different poles interfere transforming the continuous dipole-like spectrum into a discrete spectrum

The condition for <u>constructive interference</u> requires that, while traveling along one period of the undulator, the electrons slip by one radiation wavelength with respect to the (faster) photon.

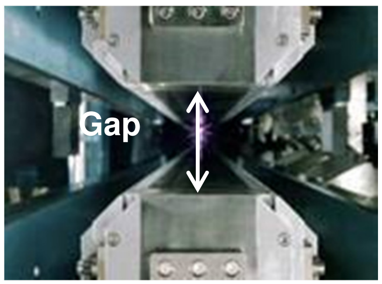
From Undulator Radiation to Wiggler Radiation

The spectrum of the undulator radiation: $$\lambda_1 = \frac{\lambda_U}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \quad 1^{st}\ harmonic$$

depends strongly on the strength parameter K: $$K = \gamma\varphi \quad where\ \ \varphi \approx \frac{\lambda_U}{2\rho} \quad is\ the\ bending\ angle\ in\ each\ pole$$

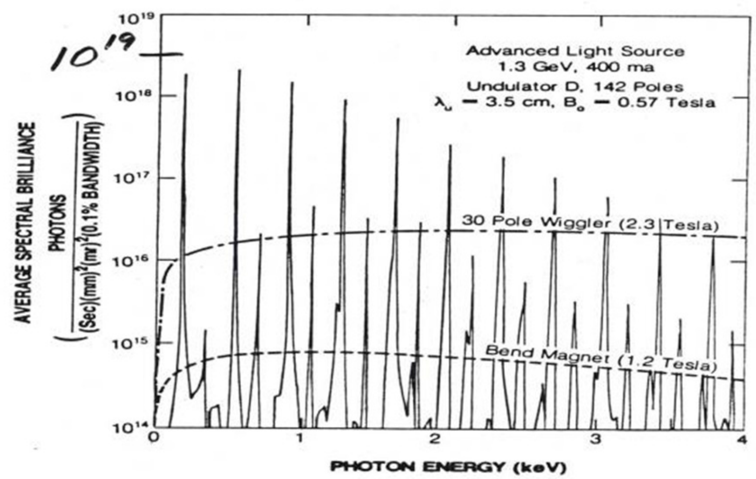
Remembering that: $$\rho = \frac{\gamma\beta m_0 c}{eB}$$

One can see that K is proportional to the field B: $$K \approx \frac{e}{2m_0c}\lambda_U\frac{B}{\beta}$$



In a permanent magnet undulator, B and consequently K can be modified by changing the gap height. The larger the gap the lower the field.

When B is increased, both K and the "wiggling" inside the undulator increase as well. With the larger wiggling, the overlap between the radiated field ($1/\gamma$ cone) decreases and the interference is reduced. For $K >> 1$ no interference is present and the undulator presents the continuum spectrum typical of the wiggler.

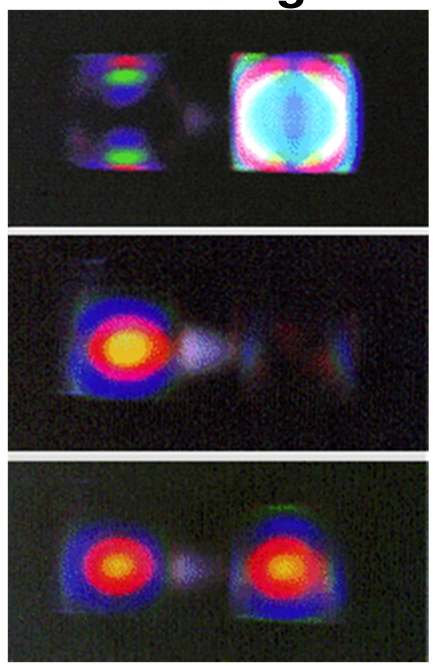


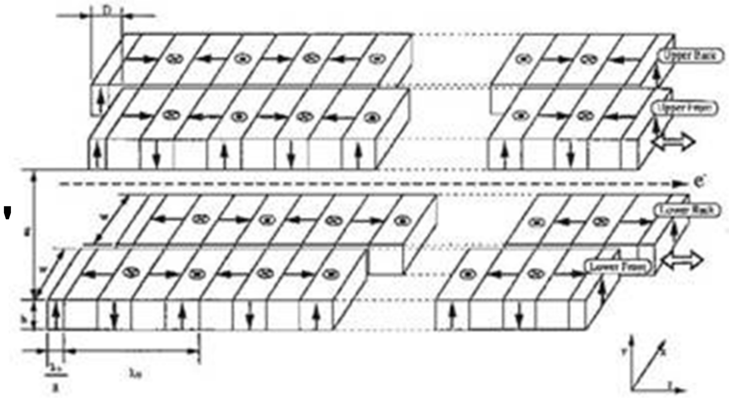
Elliptically Polarizing Undulators

ALS EPU50 (1998)

Pure permanent magnet technology, Elliptically polarizing capability.

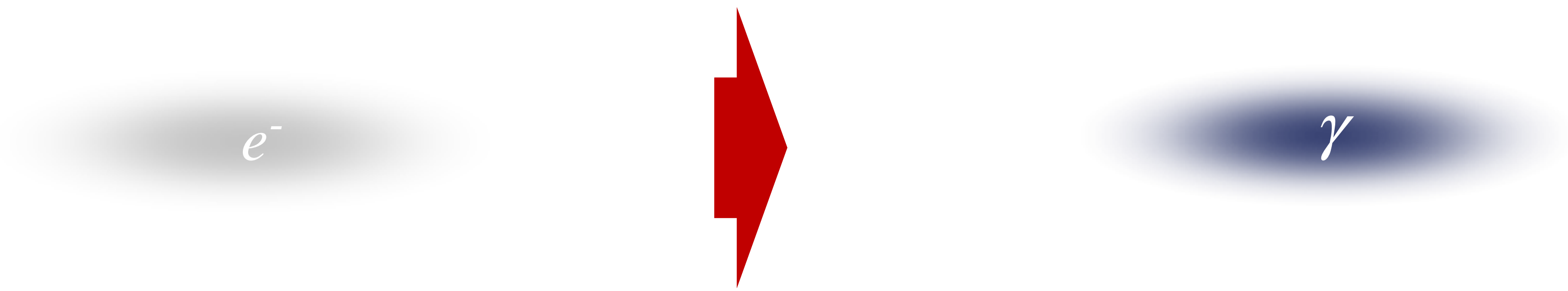
The arrays of permanent magnets can be mechanically shifted modifying the plane of the "wiggling" and thus the polarization of the radiated light.





Such a device allows for the complete control of the polarization from linear in to elliptical.

Maximizing Photon Brightness in Accelerator-based Light Sources



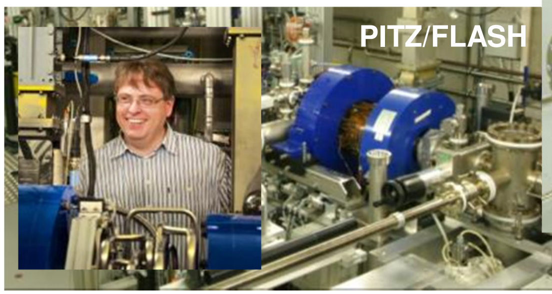
In all types of accelerator based light sources, to increase the photon brightness it is necessary to increase the electron beam brightness.

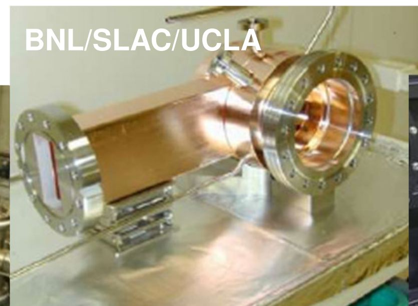
Techniques to increase electron brightness can be very different depending on the type of accelerator used.

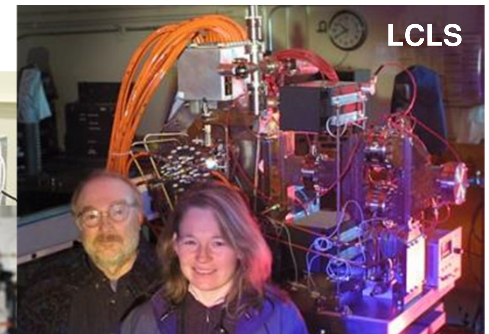
Electron Brightness in Linear Accelerators

- **In linear accelerators the ultimate brightness of the beam is defined at the electron injector and at the electron gun in particular.**
- **This has led to the development of a number of successful high-brightness electrons guns.**

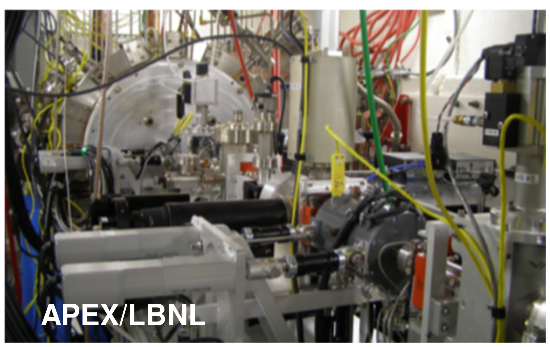
For example:



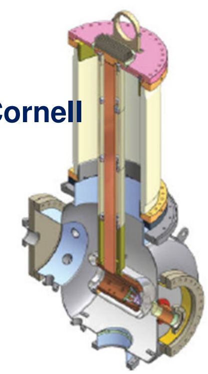


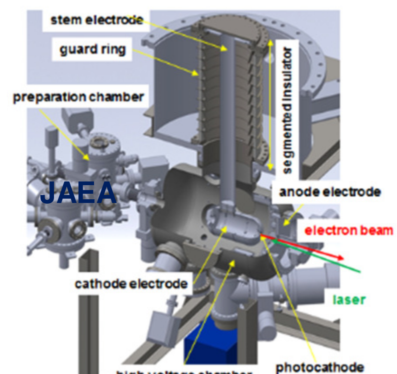


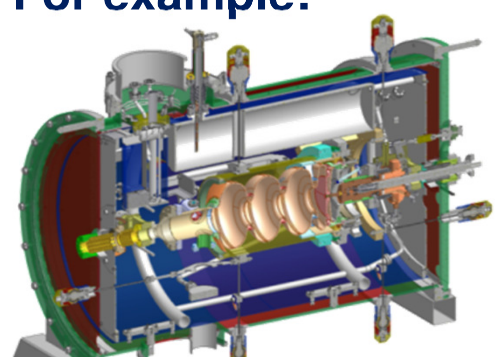
- **Such sources operate at a maximum repetition rates of ~ hundred Hz.**
- **New high repetition sources are being developed. For example:**



Cornell







Rossendorf

Electron Brightness in Storage Rings

$$B_{ph} \propto \frac{\dot{N}_{ph}(\lambda)}{\Sigma_x \Sigma'_x \Sigma_y \Sigma'_y}$$

$$\Sigma_{x,y} = \sqrt{\sigma_{x,y}^2 + \sigma_{ph}^2} \qquad \sigma_{x,y} = \sqrt{\varepsilon_{x,y}\beta_{x,y} + D_{x,y}^2 \left(\sigma_p / p_0\right)^2} \qquad \sigma_{ph} \approx \frac{1}{2\pi}\sqrt{\frac{\lambda L_u}{2}}$$

$$\Sigma'_{x,y} = \sqrt{\sigma'^2_{x,y} + \sigma'^2_{ph}} \qquad \sigma'_{x,y} = \sqrt{\varepsilon_{x,y} / \beta_{x,y}} \qquad \sigma'_{ph} \approx \sqrt{\frac{\lambda}{2L_u}}$$

Once λ is fixed (by the science goals) the "single photon emittance" ($\lambda/4\pi$) is also fixed.

When the electron beam size and divergence are smaller than the single photon diffraction size and divergence the light source is diffraction limited.

The most effective configuration for a diffraction limited source has e^- beam size and divergence equal or slightly smaller than their photon counterparts. Further decreasing of the electron quantities will marginally help!

To maximize brightness in a diffraction limited ("ultimate") storage ring:

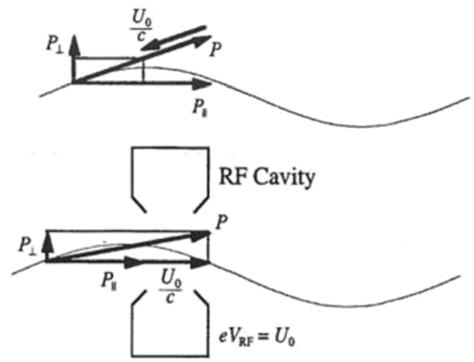
- **Maximize current**
- **Match electron to the (very small for x -rays!) single photon emittance**
- **Match electron beam size and divergence by tuning the optical functions (β, η) at the source point and the undulator length L_u.**

Equilibrium emittance in Storage Rings

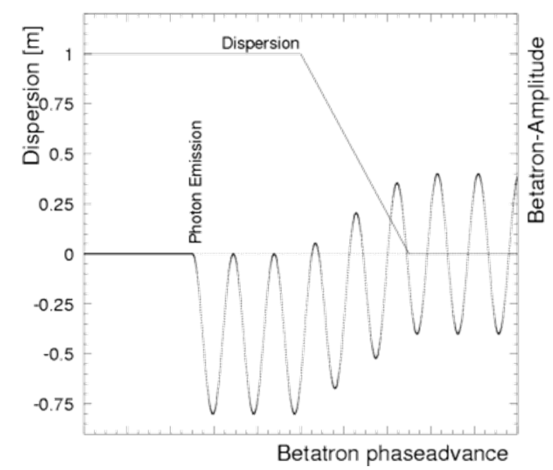
Energy damping:
Larger energy particles lose more energy

$$P_{SR} \propto \frac{\gamma^4}{\rho^2}$$

Transverse damping:
Energy loss is in the direction of motion while the restoration in the s direction



Quantum excitation:
Particles that radiate a photon (changing their energy) in a region of dispersion undergo transverse oscillations



The balance between damping and excitation gives the equilibrium emittances.

Minimizing Emittance in Storage Rings

More quantitatively, in a storage ring the (geometric) emittance is given by:

$$\varepsilon_x = C_q \frac{\gamma^2}{J_x}\frac{I_{5x}}{I_2}$$

$$I_{5x} = \oint \frac{H_x}{\rho^3} ds = \oint \frac{\beta_x \eta_x'^2 + 2\alpha_x \eta_x \eta_x' + \gamma_x \eta_x^2}{\rho^3} ds$$

$$I_2 = \oint \frac{1}{\rho^2} ds$$

with the integrals taken along the reference particle orbit.

γ = beam energy in rest mass units
ρ = dipole magnet bending radius
β_x, α_x, γ_x = Horizontal Twiss pameters (electron beam optical functions)
η, η' = Horizontal dispersion and its derivative with respect to s
J_x = Horizontal partition number < ~ 2
C_q = 3.8319 10^{-13} m

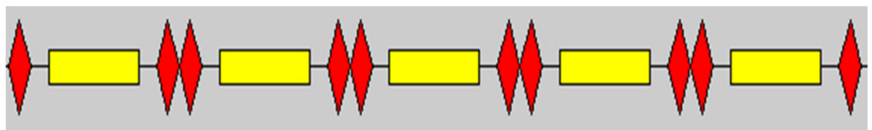
Matching the single photon diffraction emittance in the x-ray range requires very small electron beam emittances.

How to minimize the emittance?

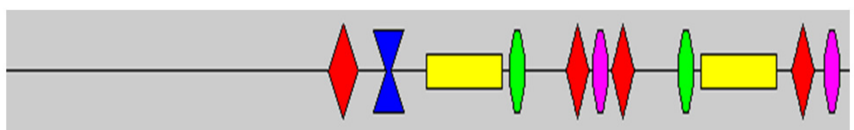
- γ **is not a free "knob". High** γ **required for extending SR spectra in the x-ray.**
- **Increase** ρ **(larger rings)**
- **Minimize** H_x **by reducing dispersion and beta function inside bend magnets (wigglers/undulators).**
  - **Achieved by refocusing beam 'inside' bending magnets**
  - **Requires splitting of bending magnets to insert focusing elements.**

Low Emittance Lattices

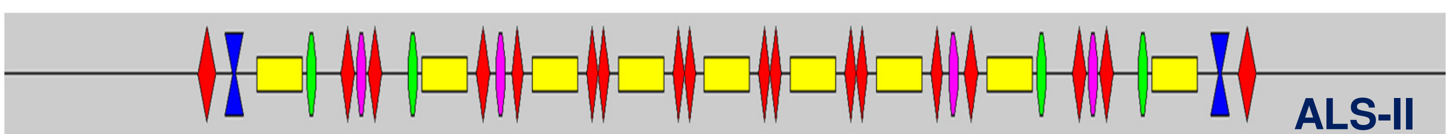
- Ultimate (diffraction limited) storage rings have a number of **superperiods** each with a large number of short bending magnets alternated by focusing elements (quadrupoles). Dipoles can have gradient for horizontal focusing.
  Center dipoles cells are designed to have very small dispersion.



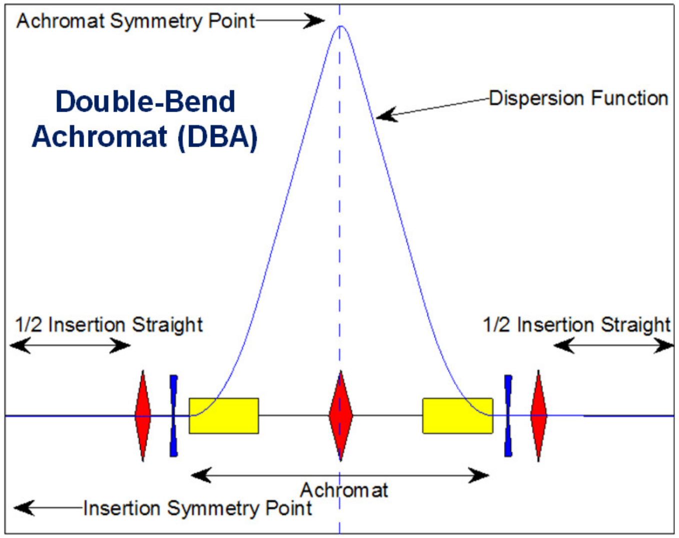
- Matching cells (one at each side of the central cell):
  - To match zero dispersion in the straight sections and low beta values for matching the electron-photon phase spaces.
  - Creates high dispersion within the cell for chromatic and harmonic correction.

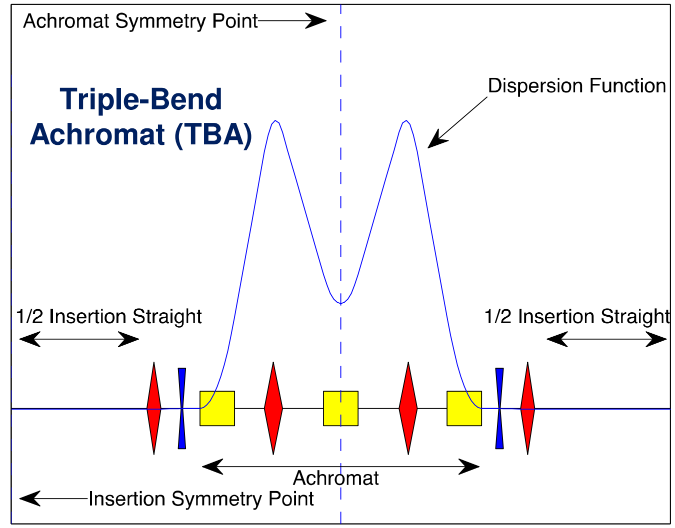


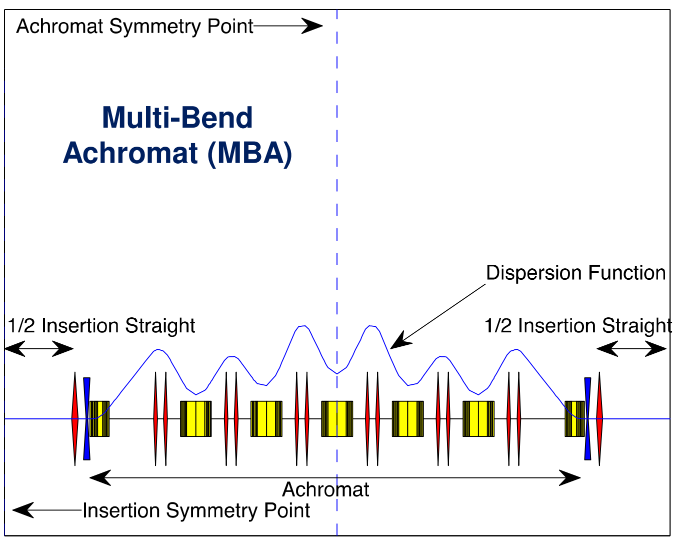
- Complete lattice cell (superperiod). Insertion devices (undulators, wigglers) located in the straight sections.



Common Lattice Options







- **Early 3rd generation SR sources all used double/triple bend achromats* (some with gradient dipoles)**
- **Later optimization included detuning from achromatic condition (optimizing effective emittance).**
- **New designs (including USRs) employ MBA**
- **Damping wigglers can help (emittance, damping time, IBS) but trade energy spread.**

***Achromats: lattices with zero dispersion in straight sections.**

Photon & Electron Emittance Matching

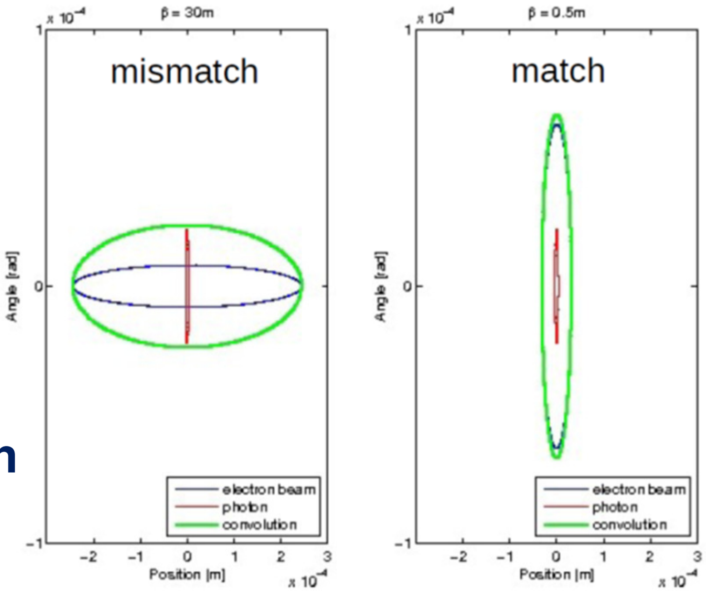
Goal:

$$\sigma_{x,y} \approx \sigma_{ph}$$
$$\sigma'_{x,y} \approx \sigma'_{ph}$$

$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\beta_{x,y} + D^2_{x,y}\left(\sigma_p / p_0\right)^2}$$
$$\sigma'_{x,y} = \sqrt{\varepsilon_{x,y} / \beta_{x,y}}$$

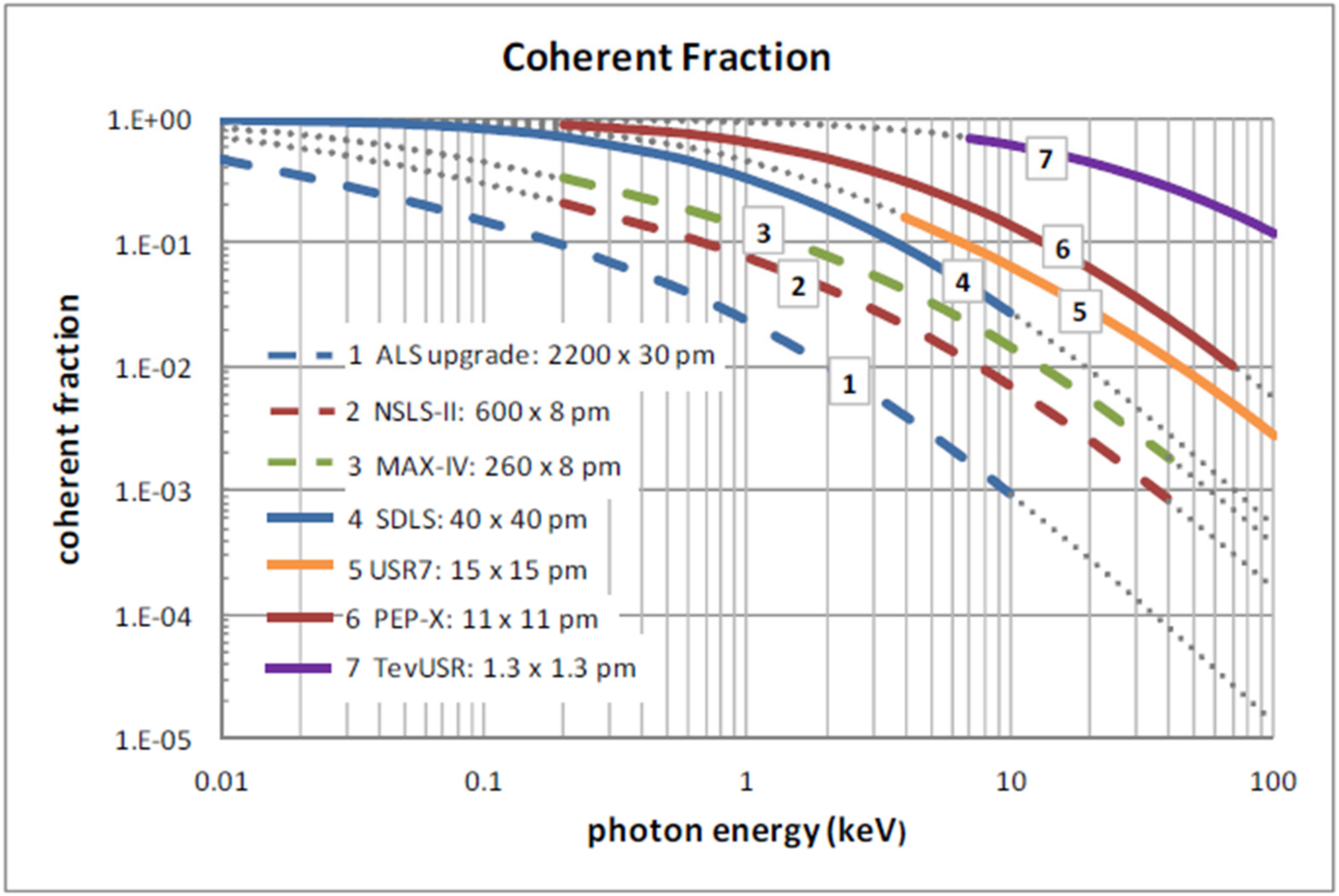
$$\sigma_{ph} \approx \frac{1}{2\pi}\sqrt{\frac{\lambda L_u}{2}}$$
$$\sigma'_{ph} \approx \sqrt{\frac{\lambda}{2L_u}}$$

- **Emittance of the beam is only one factor.**
- **Lattice functions are important**
  - **resulting photon emittance can be much larger and therefore brightness smaller if electron beam ellipse and diffraction ellipse are not matched**
- **Photon wavelength λ and insertion device length L_u are relevant as well.**



Question: **does the case in the figure represent a diffraction limited situation?**

Diffraction limited = High Transverse Coherence



Acknowledgements

Part of this lecture was prepared using material from Herman Winick, David Robin and Christopher Steier.

L12 Homework

- **Calculate the critical energy in eV for the ALS superbends knowing that the electron beam energy is 1.9 GeV, the field is 5 T and the total deflection angle for the magnet is 10 deg. Remember that the photon energy is given by hf (with h the Planck constant, 6.626068×10^{-34} m^2 kg / s, and f the photon frequency)**

- **Always for the ALS case, calculate the critical energy for the normal bends knowing that the bending radius is 4.957 m and the total deflection angle for the magnet is 10 deg.**

- **Using the universal spectrum for the bending magnet radiation, calculate for both the above cases, the maximum radiated power in 0.1% bandwidth when 400 mA electrons are stored (the ring length is 197 m). Indicate at which photon energy is the maximum located.**

- **How to minimize the emittance in a linac based light source, and in ring based light source?**

- **Describe the conditions when a light source is “diffraction limited”**

Backup Slides

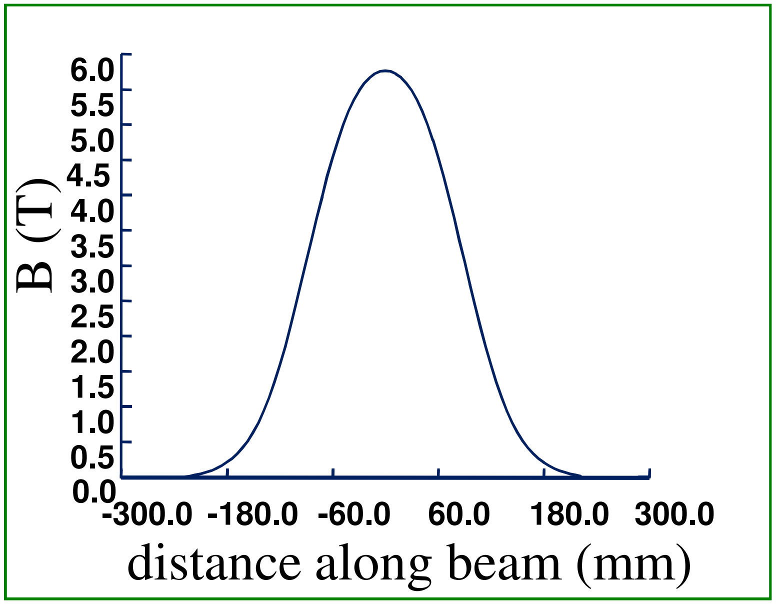
Dipoles for Hard X-rays

At the Advanced Light Source three of the existing thirty six 1.3 T dipoles were replaced by three 5 T superconducting dipoles ("superbends") for extending the spectrum to higher frequencies (>10 keK photons).

Superbend with cryostat

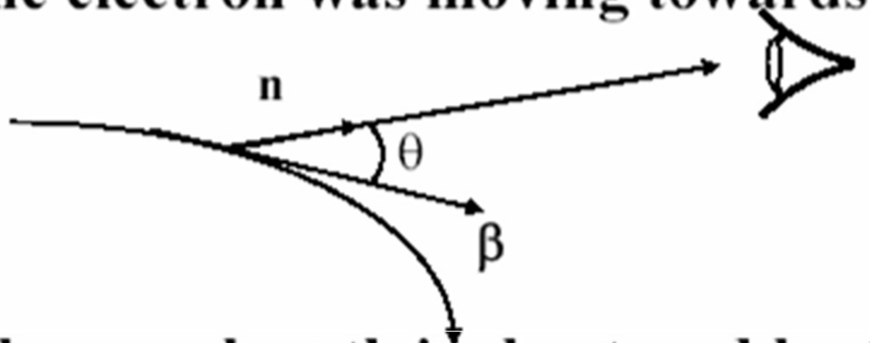
Superbend without cryostat

Superbend magnetic field



Time Compression and Frequency Shift

Electron with velocity β emits a wave with period T_{emit} while the observer sees a different period T_{obs} because the electron was moving towards the observer



$$T_{obs} = (1 - \mathbf{n} \cdot \boldsymbol{\beta}) T_{emit}$$

The wavelength is shortened by the same factor

(Doppler effect)

$$\lambda_{obs} = (1 - \beta \cos\theta)\, \lambda_{emit}$$

in ultra-relativistic case, looking along a tangent to the trajectory

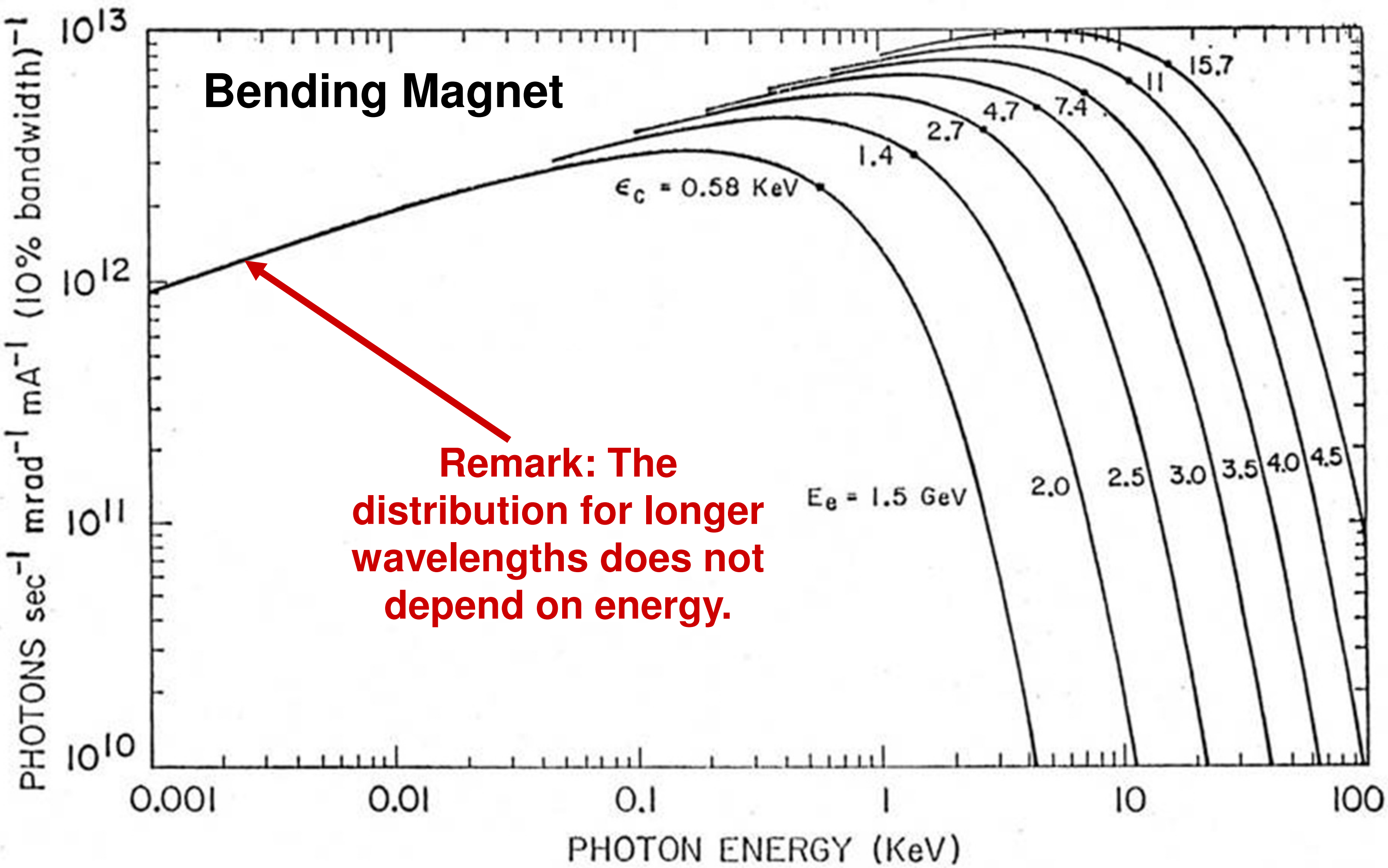
$$\lambda_{obs} = \frac{1}{2\gamma^2} \lambda_{emit}$$

since

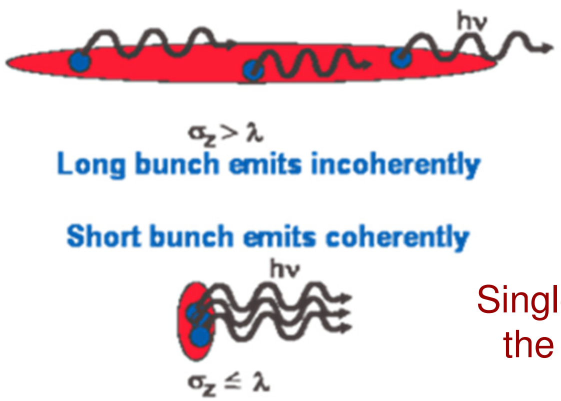
$$1 - \beta = \frac{1 - \beta^2}{1 + \beta} \cong \frac{1}{2\gamma^2}$$

Strong wavelength shortening for relativistic beams!

Spectrum Energy Dependency



Longitudinal Coherent and Incoherent Regime



The power spectrum of the radiation from a bunch with N particles is given by:

$$\frac{dP}{d\omega} = \frac{dp}{d\omega}\left\{ \underbrace{N\left[1 - g(\omega)\right]}_{P_{SR} \propto N \text{ incoherent}} + \underbrace{N^2 g(\omega)}_{P_{CSR} \propto N^2 \text{ coherent}} \right\}$$

Single particle power spectrum for the particular radiating process (dipole, undulator, …)

$P_{SR} \propto N$ *incoherent*

$P_{CSR} \propto N^2$ *coherent*

The CSR factor $g(\omega)$ determines the high frequency cutoff for CSR, the shorter the bunch the higher the frequency of coherent emission.

$$g(\omega) = \left| \int_{-\infty}^{\infty} dz\, S(z)\, e^{i\omega \cos(\theta) z/c} \right|^2$$

$$0 \leq g(\omega) \leq 1$$

$$\theta \equiv \begin{matrix} \textit{observation} \\ \textit{angle} \end{matrix}$$

Normalized Bunch Longitudinal Distribution

FELs, THz CSR ring sources, …: $g(\omega) >> 1/N$

3rd gen. light sources, USRs, ERLs: $g(\omega) << 1/N$

In such sources the gain in brightness is at best linear with N.

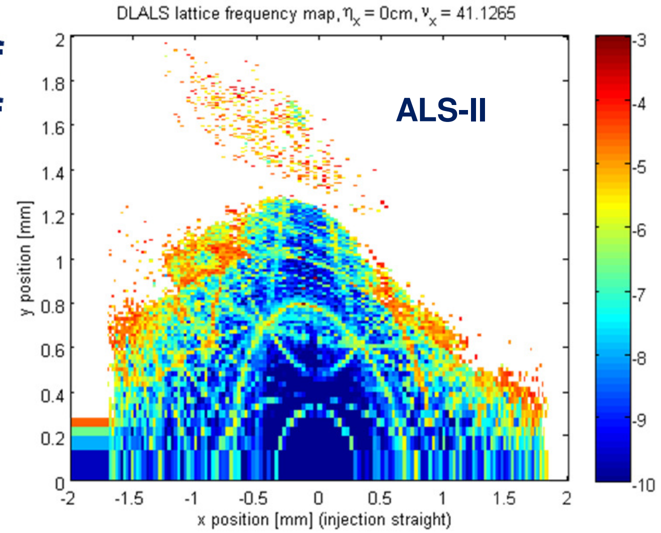
Nonlinear Dynamics

- **Beam dynamics in a real storage ring is not linear.**

The presence of sextupole magnets (their nonlinear focusing is used for chromatic aberration corrections), jointly with magnets and RF field imperfections and beam induced fields (wakefields), make the dynamics in storage rings quite nonlinear.

- **Particles far from to the reference orbit (center of the magnets) experience nonlinear "kicks" that if strong enough can cause them to be lost.**

- **Simulations including nonlinear effects are used to define the dynamic aperture of the ring. Particles outside the dynamic aperture are lost.**



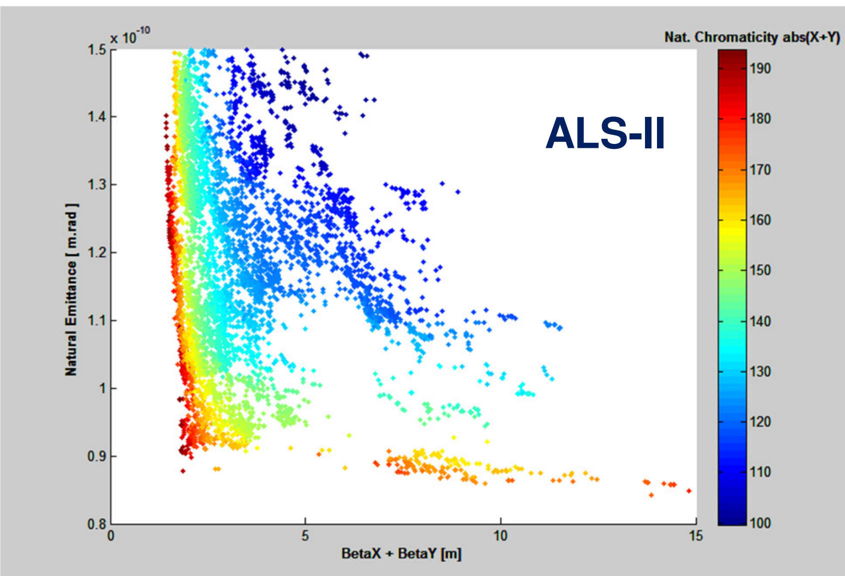
- **In general, the lower the emittance, the lower the dynamic aperture!**

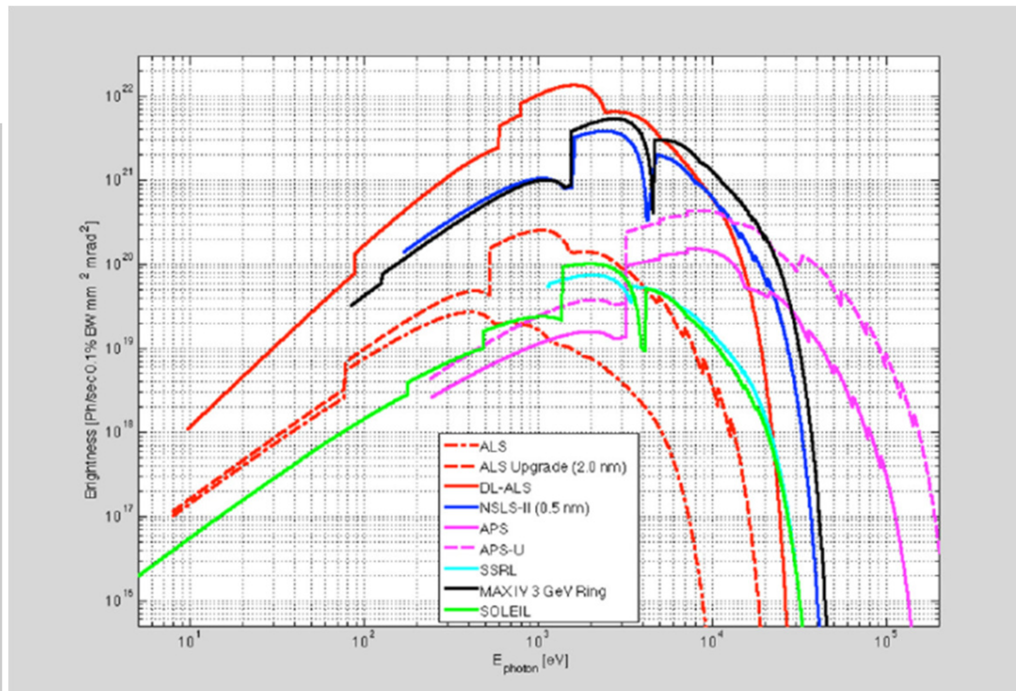
- **In diffraction limited (ultimate) rings the dynamic aperture is in general sufficient to ensure acceptable beam lifetimes.**

- **Conventional off-axis injection can be an issue in the case of very small emittance rings …**

Finding the Optimal Solution(s)

Multiple objectives to optimize in a multi-dimensional parameter space.
An ideal application for multi-objective genetic algorithms (MOGA)

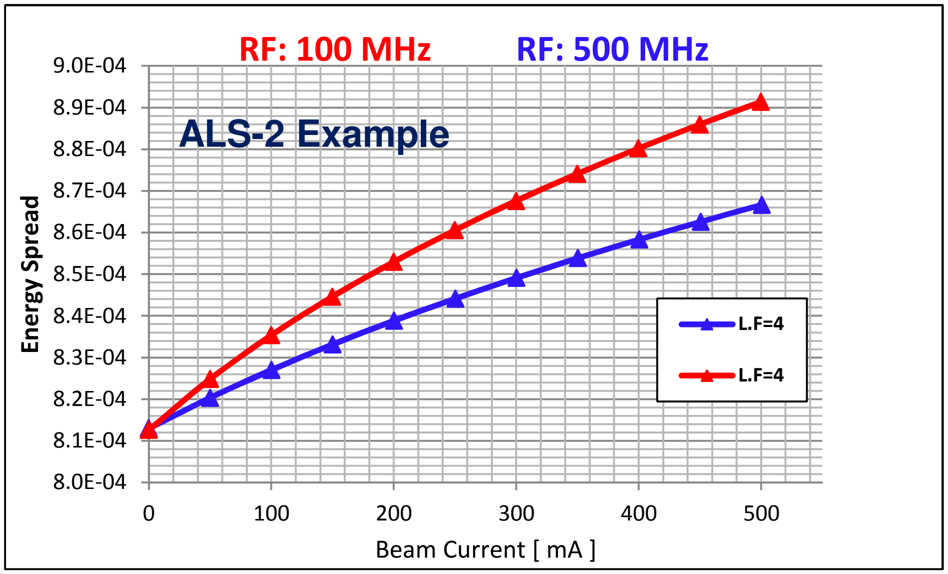


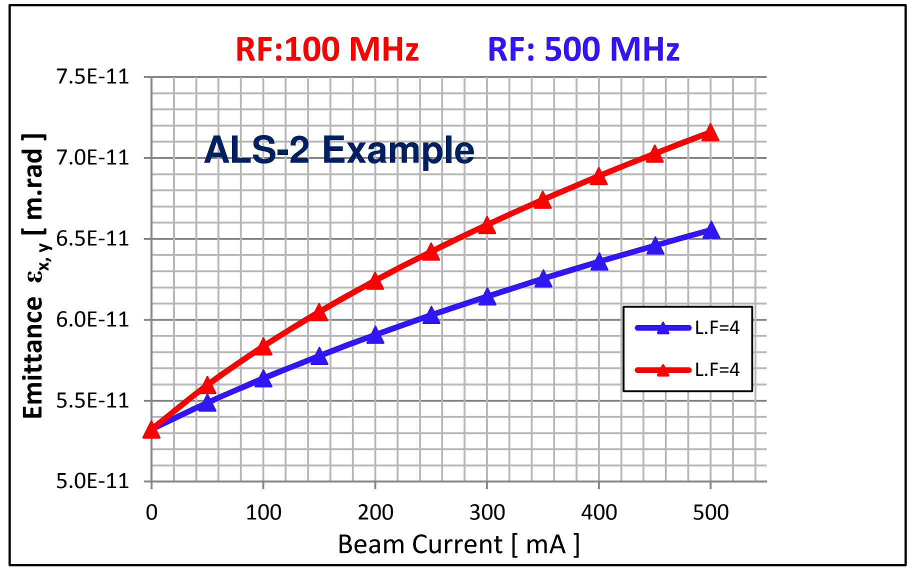


Current Limitations: Intra Beam Scattering (IBS)

IBS = multiple Coulomb scattering among the electrons

Generates emittance increase in all planes.





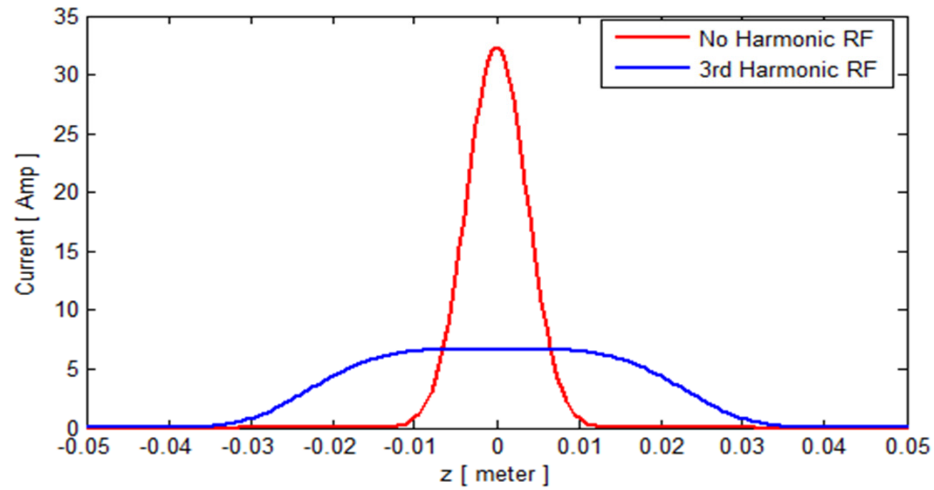
- **Effects reduced by reducing particle beam density**
- **Transverse plane (emittance) cannot be touched. Question: why?**
- **Bunch lengthening essential to keep IBS in check**
- **Lengthening factors appear realistic with third harmonic RF**

Current Limitations: Single Bunch Instabilities

The momentum compaction factor α_C measures the ring longitudinal dispersion.

$$\frac{\Delta C}{C_{ref}} = \alpha_C \frac{\Delta p}{p_{ref}} \qquad \alpha_C = \oint \frac{D_x}{\rho} ds$$

$C_{ref} \equiv$ *Length of reference closed orbit*

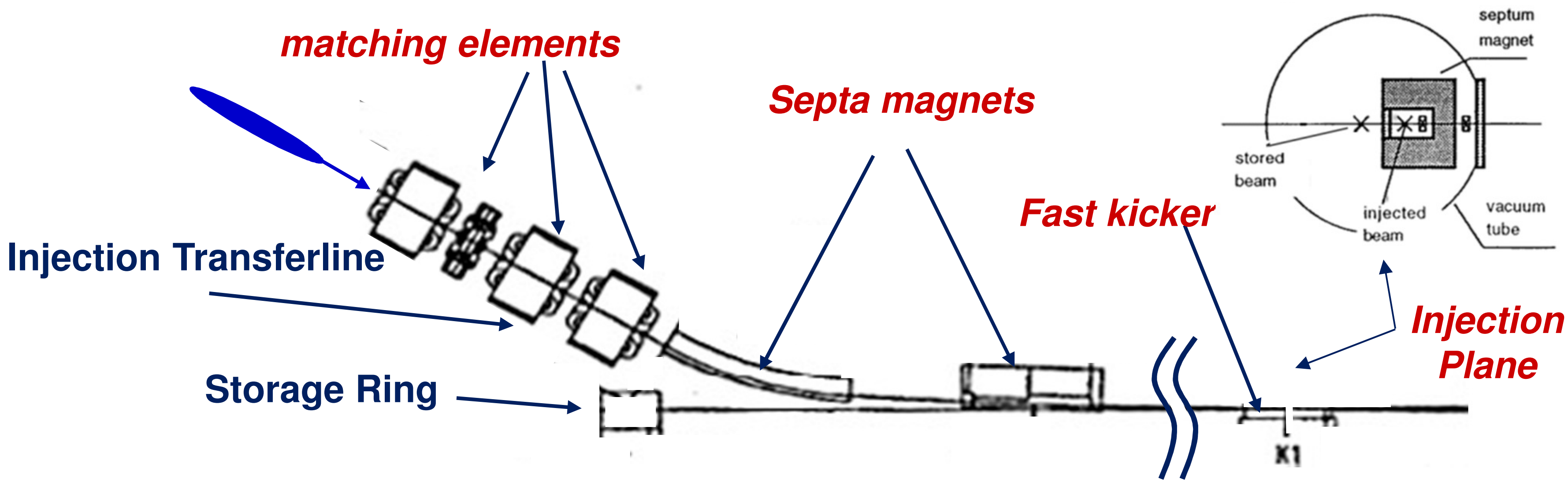


In general, low momentum compaction factors α_C come with small emittances.

Low momentum compaction factors lower single bunch instability thresholds (by shortening the bunch and hence increasing the peak current).

Again, bunch lengthening (high-harmonic cavity) helps significantly.

Conventional Off-Axis Injection Scheme



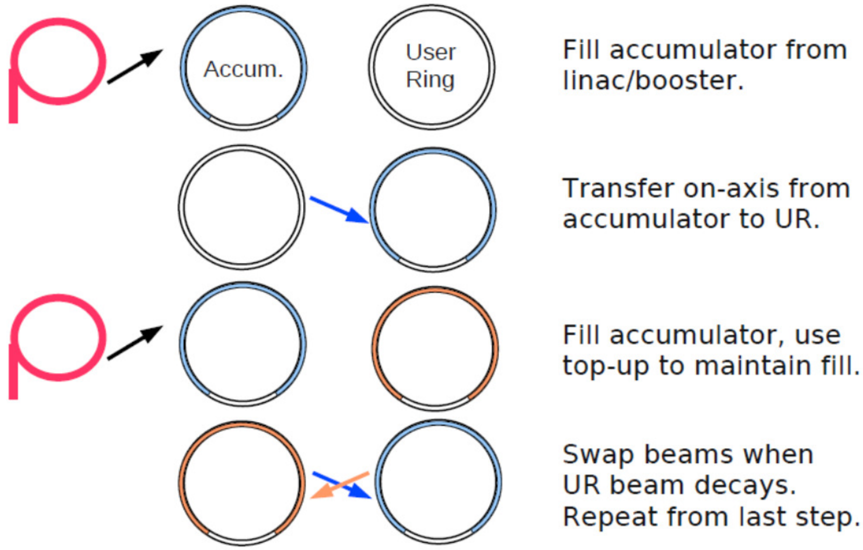
- ***Septum Magnet*: Special magnet with a "thin" wall that allows to place the magnet close to the stored beam orbit.**
- ***Fast Kicker*: It is the pulsed element that gives the final kick that puts the injected beam on the storage ring orbit. Another fast kicker, upstream the injection section is required to stack the beam.**
- **At the injection plane, the injected beam is relatively far from the reference orbit (stored beam).**

In other words, off-axis injection requires large (~cm) dynamic apertures.
(Question: why?)

Swap Out- Injection

Once the lattice is pushed to achieve ultrasmall emittances, the dynamic aperture usually shrinks, potentially making beam accumulation (off-axis injection) impossible.

A scheme first proposed by Borland and Emery and later studied elsewhere promises to potentially overcome this obstacle. In this scheme, the whole beam in the storage ring is replaced at once by on-axis injection (using either an accumulator ring or a full energy linac with a long bunch train).

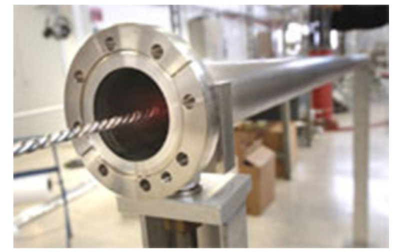


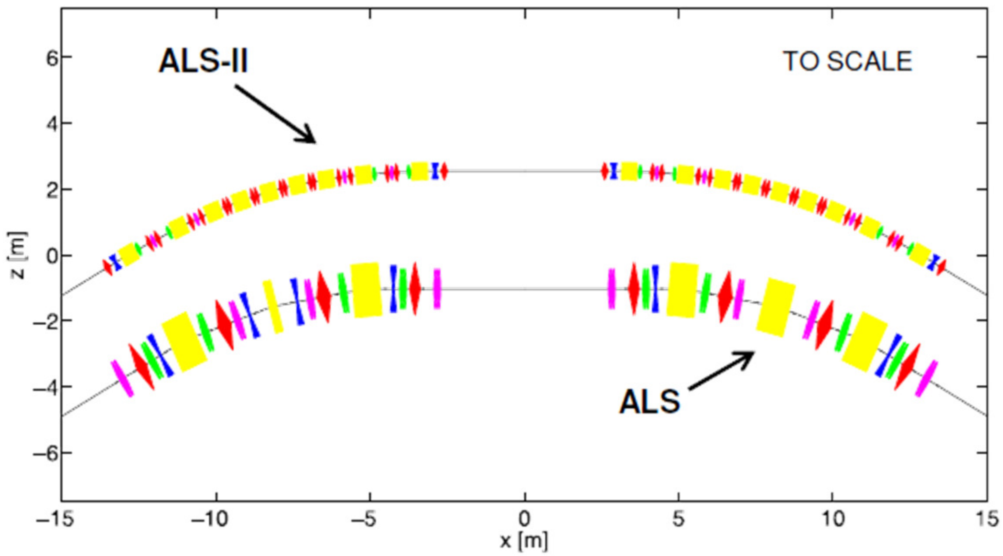
[1] M. Borland, "Can APS Compete with the Next Generation?", APS Strategic Retreat, May 2002.
[2] M. Borland, L. Emery,"Possible Long-term Improvements to the APS," Proc. PAC 2003, 256-258 (2003).

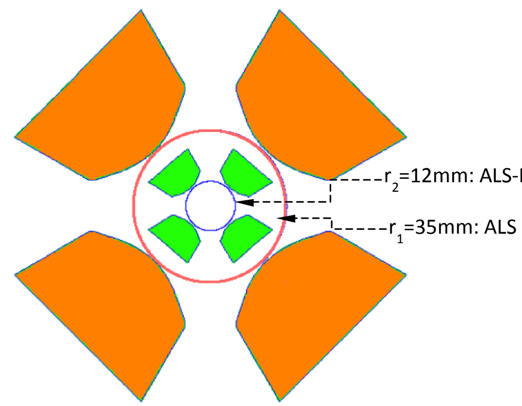
The Vacuum Issue

The MBA lattices have a large number of magnets closely packed.
No room for placing interleaved vacuum pumps!

The successful development of NEG (non-evaporable getter) pumping thin films that can be used for coating the internal wall of the vacuum chamber solved the problem.







- **That allowed for smaller vacuum chambers and for smaller magnet gaps.**
  - **Nowadays field quality with smaller magnet apertures achievable.**