"The Machine"
(a.k.a. Ring-based Synchrotron Light Sources)

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ALS Accelerator Physics

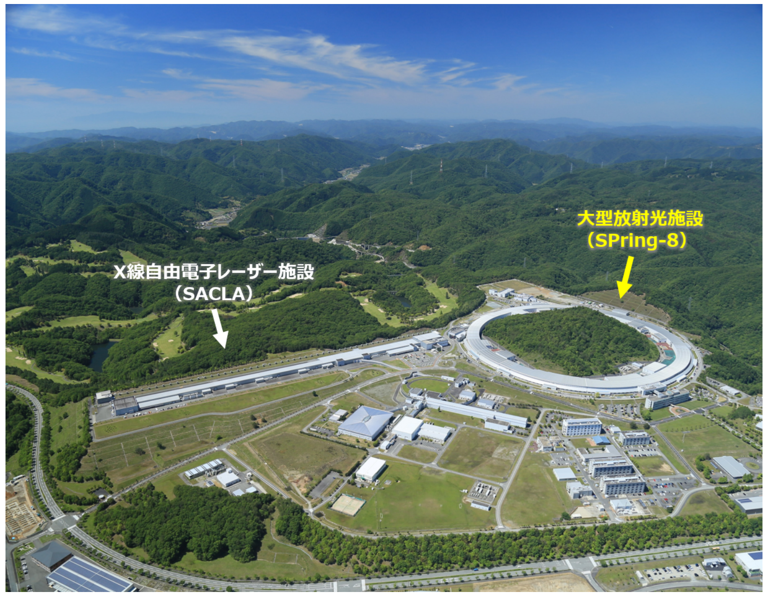
Light Sources 101 Tutorial
ALS User Meeting, Lawrence Berkeley National Laboratory, Aug 27, 2020

BERKELEY LAB
U.S. DEPARTMENT OF ENERGY | Office of Science
ALS ADVANCED LIGHT SOURCE

Outline

- The mission of a synchrotron light source designer
- The photon as an (almost) ideal investigation tool
- Electrons as sources of high quality photons
- Properties of synchrotron radiation
- Building the accelerator — ring-based synchrotron light sources
- Optimizing the accelerator for use as a synchrotron light source

Synchrotron Light Source Designer's Mission



SPring-8 (Hyogo, Japan)


MAX IV (Lund, Sweden)

“Design the best probe to characterize natural processes and derive laws of nature.”

ESRF (Grenoble, France)

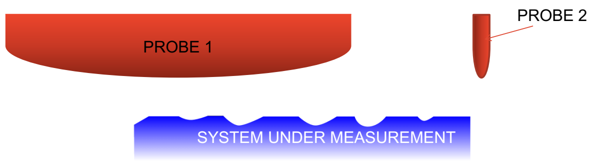

SSRF (Shanghai, China)


In the Broadest Sense

Chemistry
Biology
Physics
Medicine
Material Science
Environmental Science
and much more…

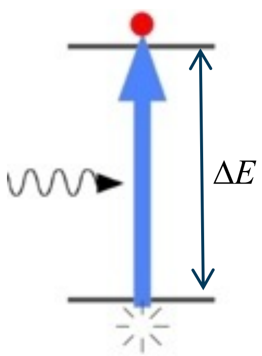
Probing Nature: Resolution Requirements

- Size of the probe defines the **spatial resolution** of the measurement ➔ probe must be smaller or at least comparable in size to the object to be measured ➔ ***photons*** allow covering broad range

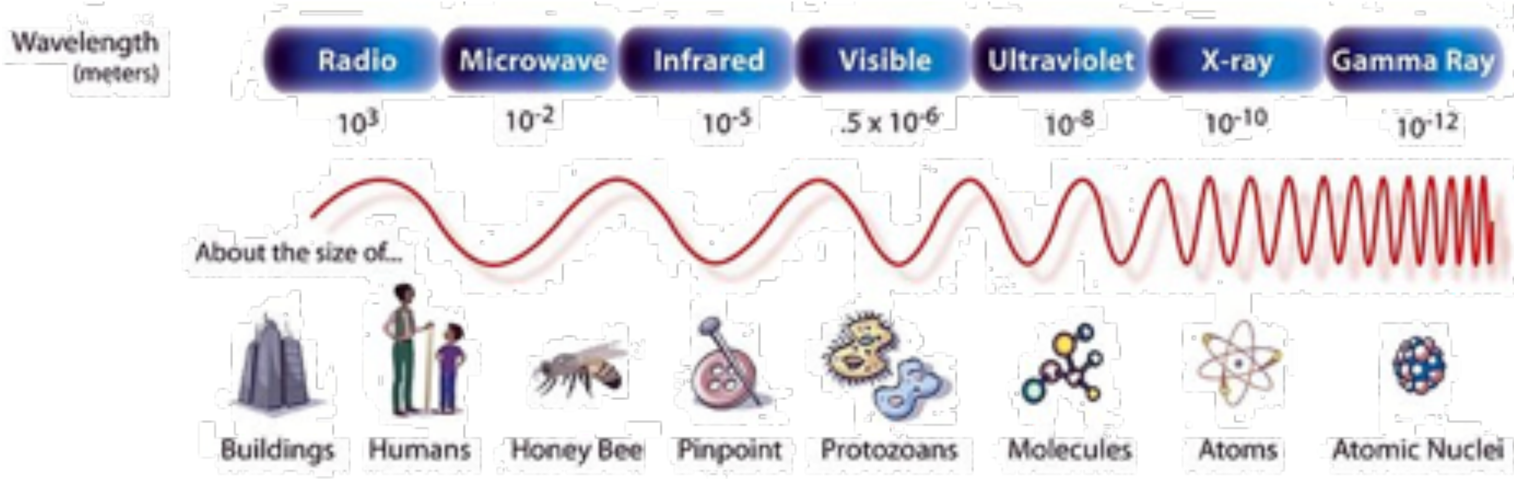


- Similarly, if you want to measure fast phenomena you have to probe them with a high **temporal resolution** ➔ short ***photon pulses*** are such a probe

- Photons with appropriate ΔE can be absorbed by atoms ➔ want to select specific probe energy with high accuracy ➔ **energy resolution**



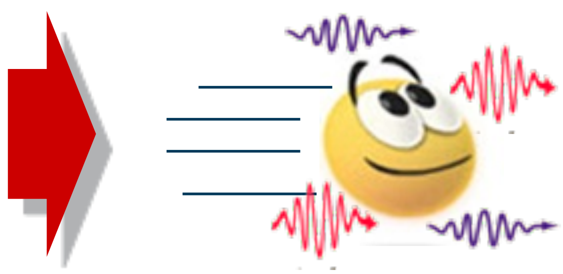
➡ Experimental physicist/engineer who wants to build a great probe: has to find the way to generate short pulses with lots of photons at many wave-lengths distributed over a tightly controlled bandwidth!



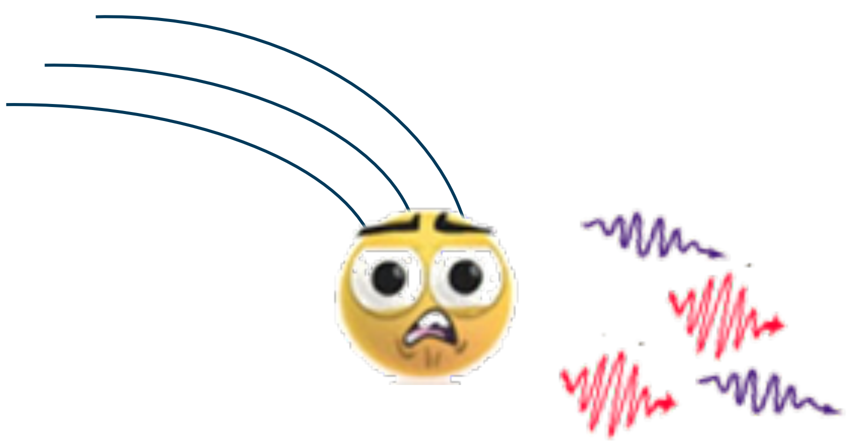
- Lasers do that to a certain extent, but if you need many photons per pulse or wavelengths all the way down to hard x-rays ➔ ***synchrotron light sources***

Accelerated Electrons as Sources of Photons

- According to **quantum field theory**, a particle moving in free space is “surrounded” by a cloud of additional **virtual particles** including **photons** that form and dissolve, and indissolubly travel with it



- Such photons live for extremely short periods of time and are bound so tightly to the particle that they cannot be detected (hence the attribute “virtual”)



- However, if a particle undergoes strong **transverse acceleration**, it can detach itself from its virtual photons which then become real and can be detected (and used!)

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

Accelerated Electrons as Sources of Photons (cont.)

- So how does this transverse acceleration generate synchrotron radiation (SR)?
  ➔ **Alfred Liénard, 1898**: high-velocity particle undergoing centripetal acceleration along a circular trajectory at radiates:

$$P_\perp = \frac{q^2 c}{6\pi\varepsilon_0 (mc^2)^2} \gamma^2 \left(\frac{d\vec{p_\perp}}{dt}\right)^2 \qquad \gamma = \frac{E_{\mathrm{tot}}}{mc^2}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \qquad \beta = \frac{v}{c}$$

- For a particle accelerator this results in the following SR power:

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

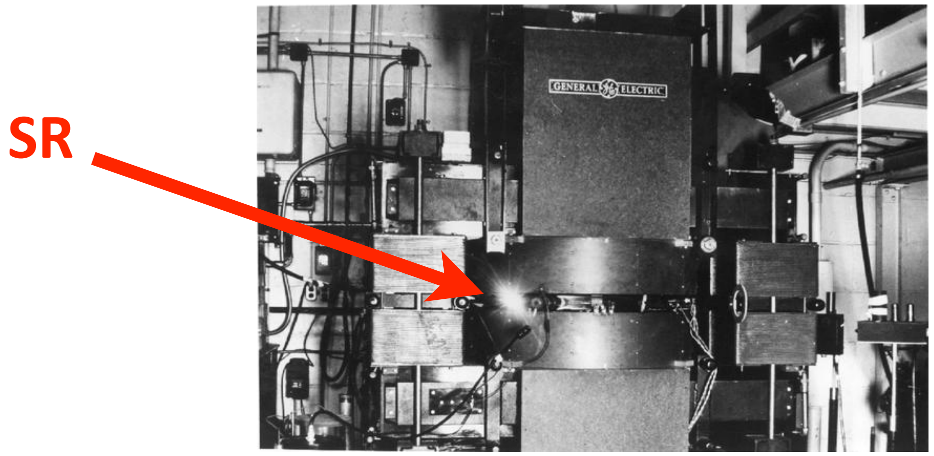
ALS electrons at 1.89 GeV
➔ γ = 3700
➔ *v* = 0.99999999635 × *c*

- Radiated power increases *dramatically* with energy *γ* ➔ sets practical limit for maximum energy obtainable with a synchrotron

- The higher the particle energy *γ* and the sharper the curved trajectory *ρ*, the shorter the wavelength photons can have, and the larger the number of photons generated ➔ lighter particles radiate more photons than heavier ones

➡ **Need to build compact high-energy electron accelerators for generation of SR**

The Troubled Origins of Synchrotron Radiation



- First observation of synchrotron radiation (SR) from an accelerator in **1947**: from 70 MeV electron beam at the General Electric **Synchrotron** (hence the name) in Schenectady, NY

- Electron accelerators were initially developed to probe **elementary (subnuclear) particles** to study the fundamental nature of matter, space, time, and energy

- In such accelerators, SR had been considered a **waste product** limiting achievable performance in circular electron accelerators

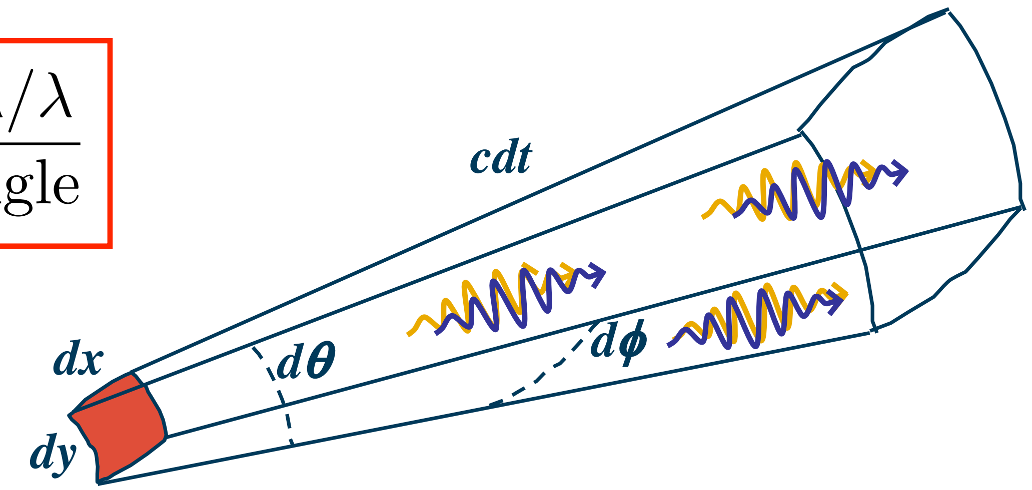
- However, other researchers soon realized that **SR was the brightest source of infrared, ultraviolet, and x-rays**, and that it could be most useful for studying matter on the scale of atoms & molecules

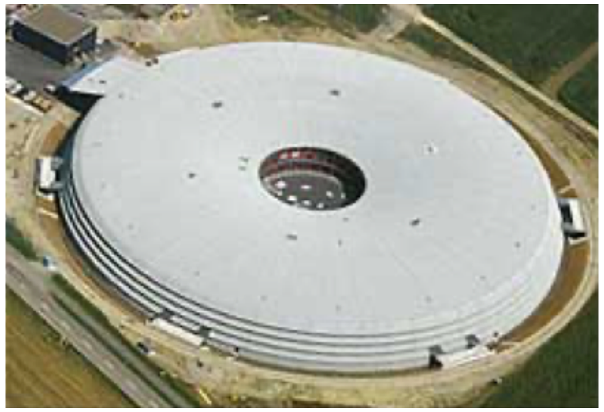
Brightness of a Light Source

- **Photon brightness** (sometimes referred to as *spectral brightness* or *brilliance*) is the ultimate parameter to characterize performance of a light source

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

$$\boxed{\text{Flux unit} = \frac{\text{number of photons in a given } \Delta\lambda/\lambda}{\text{unit time}}}$$

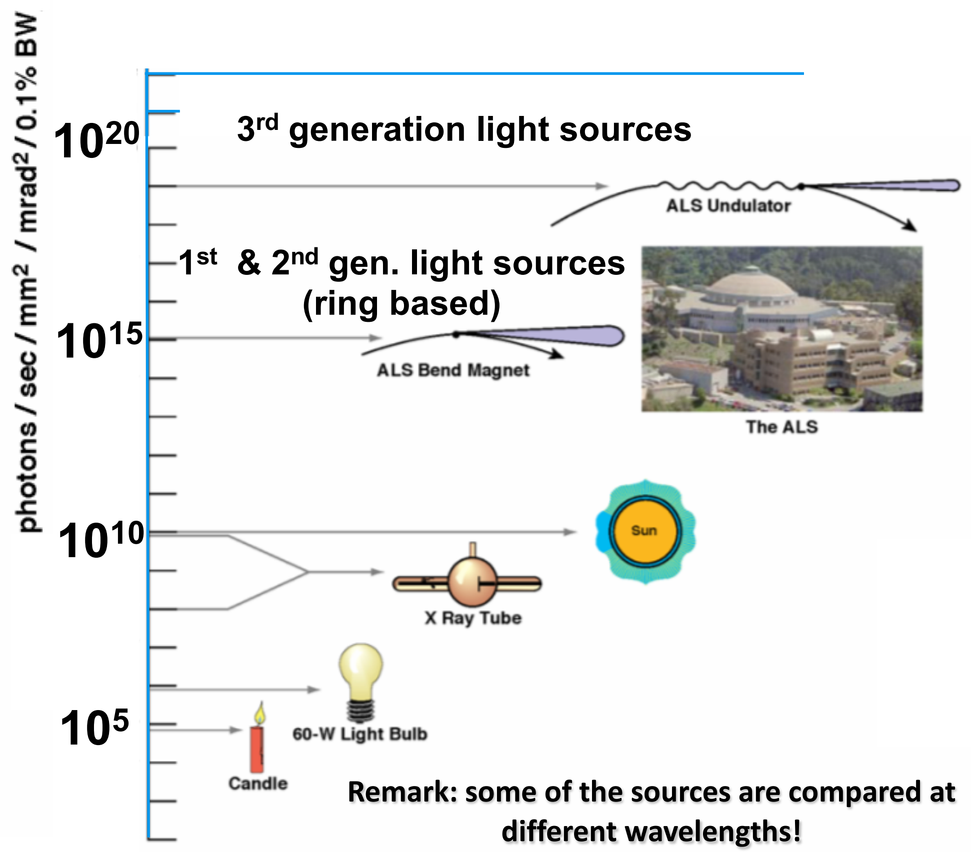


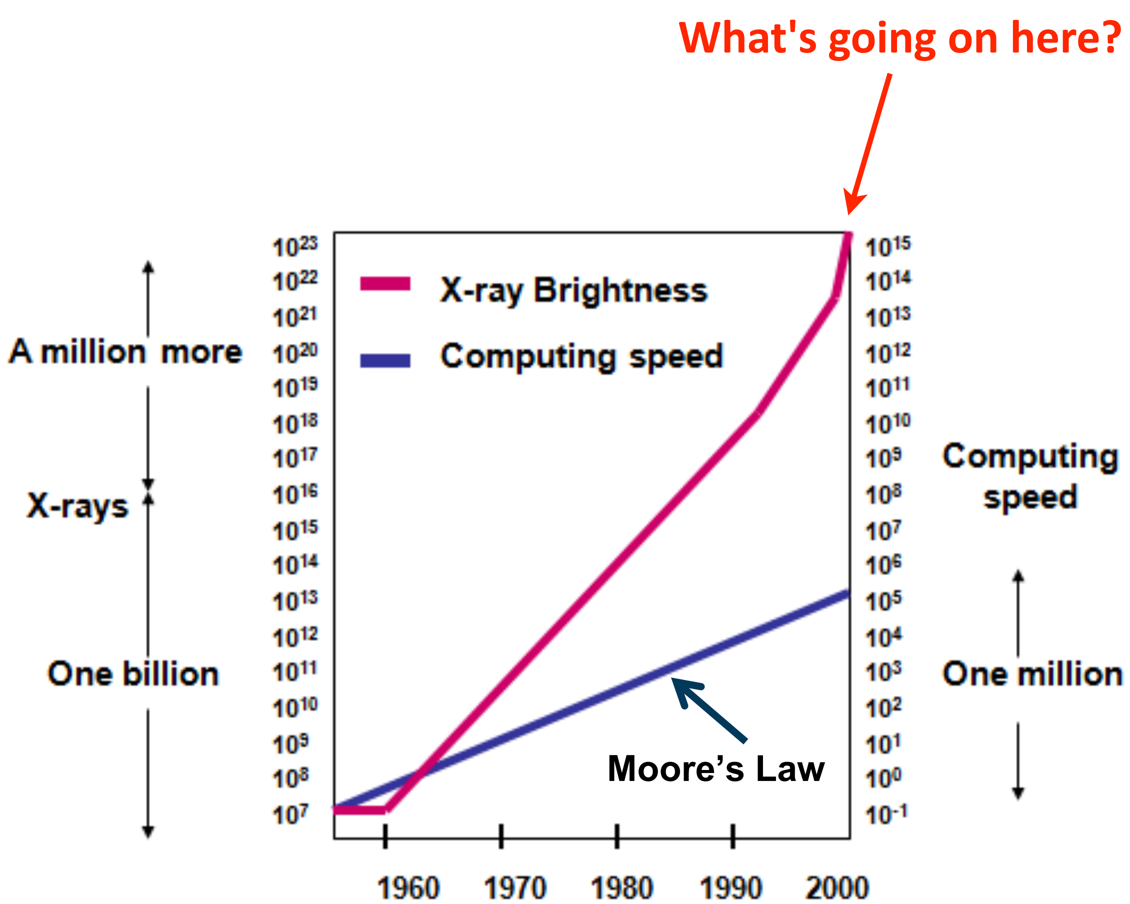


SLS (Villigen, Switzerland)

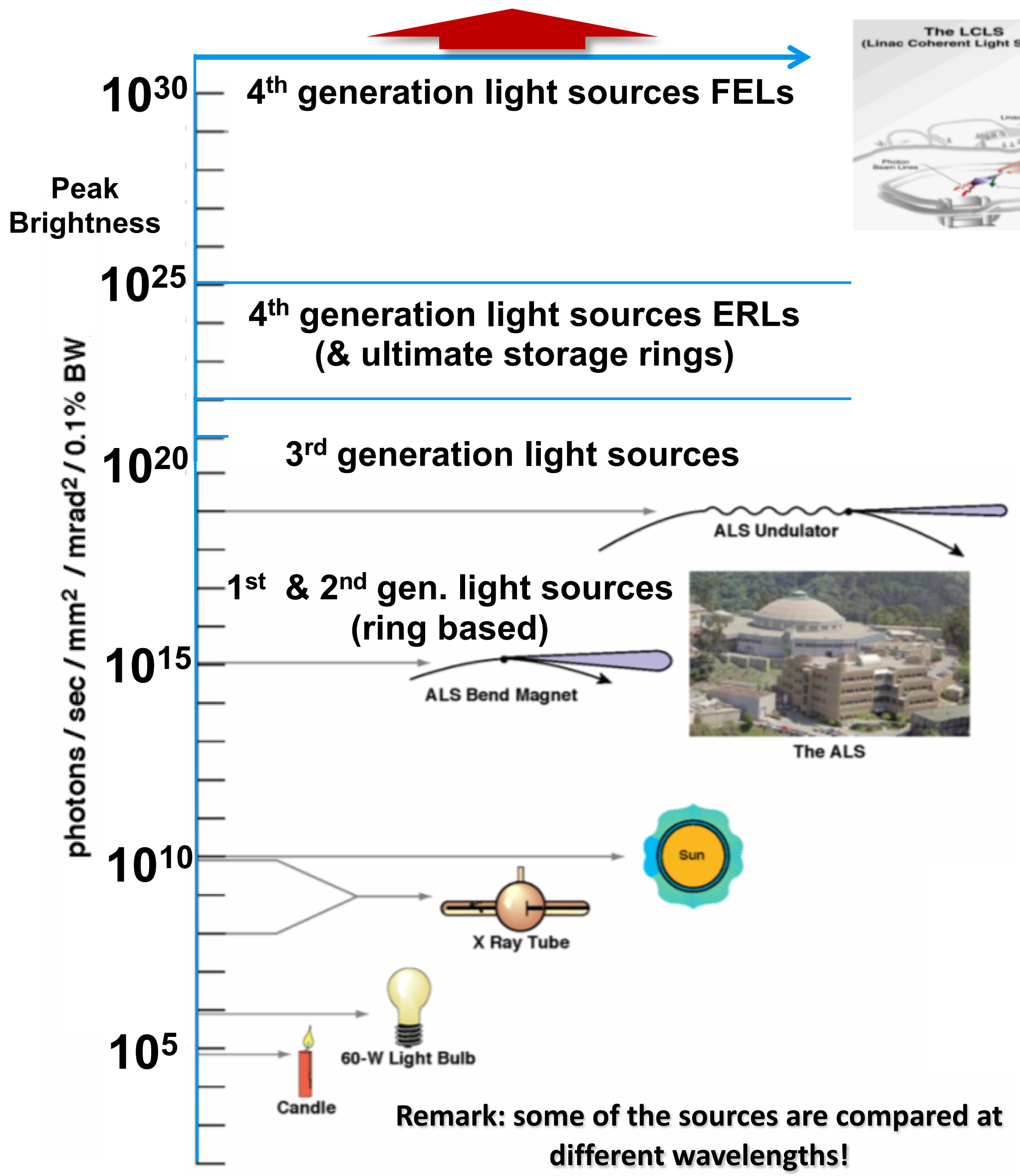
- From this definition, one can see that brightness represents the ***photon density in 4-D transverse phase space*** *within a bandwidth and averaged over a unit of time*

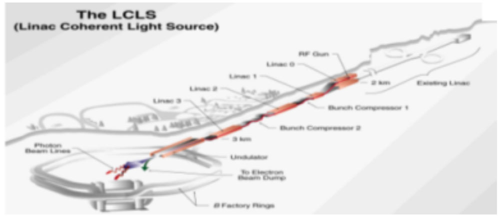
How Bright are Synchrotron Light Sources?

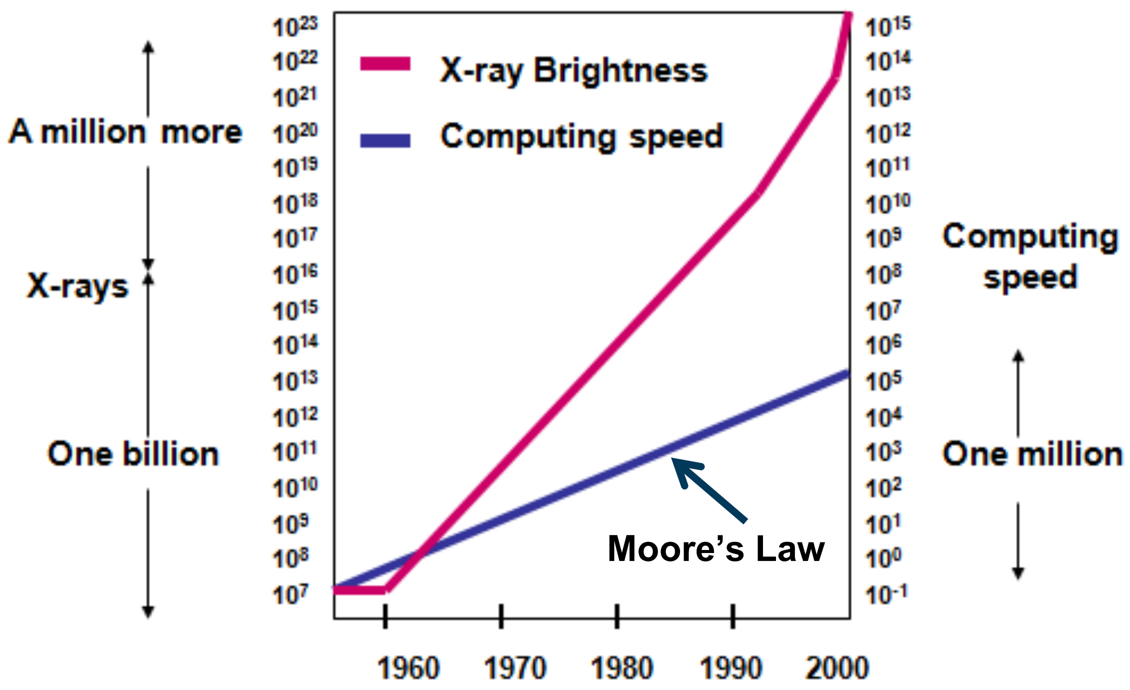




How Bright are Synchrotron Light Sources?





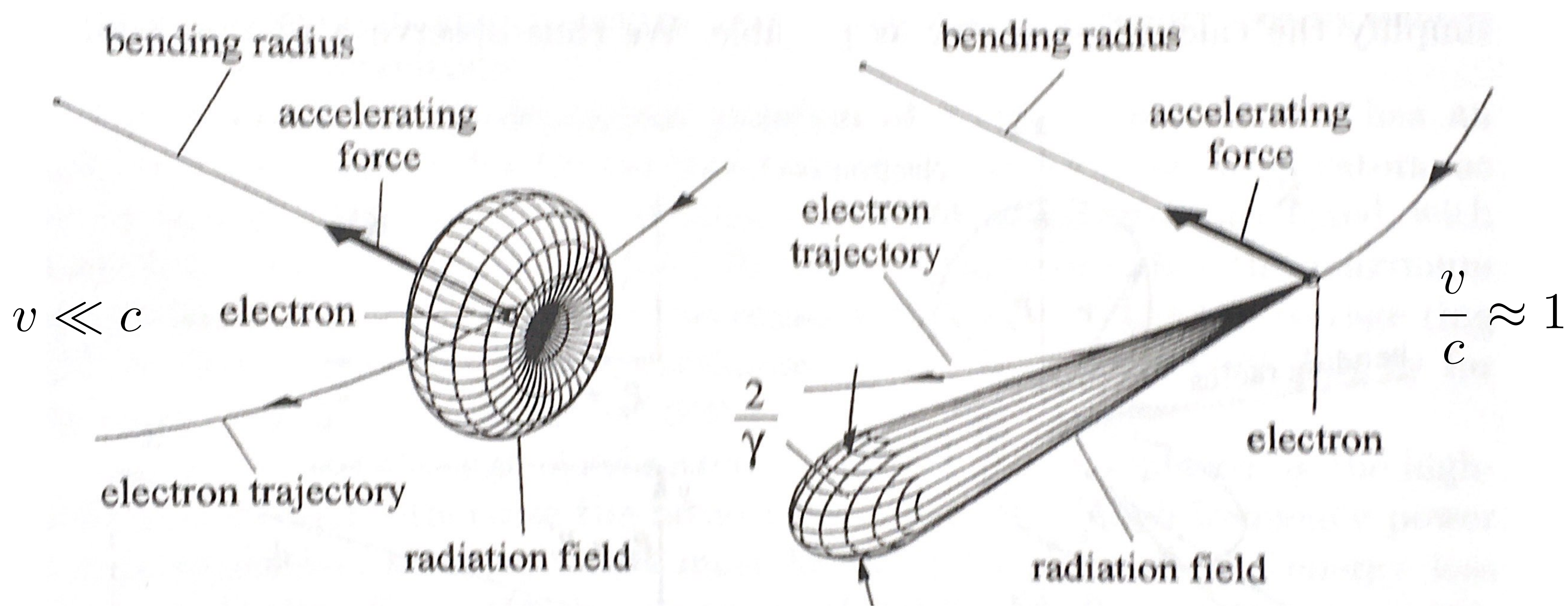


High brightness is very desirable:
faster experiments, higher coherence, improved spatial, time and energy resolutions in experiments, …

Properties of Synchr. Radiation: Angular Distribution

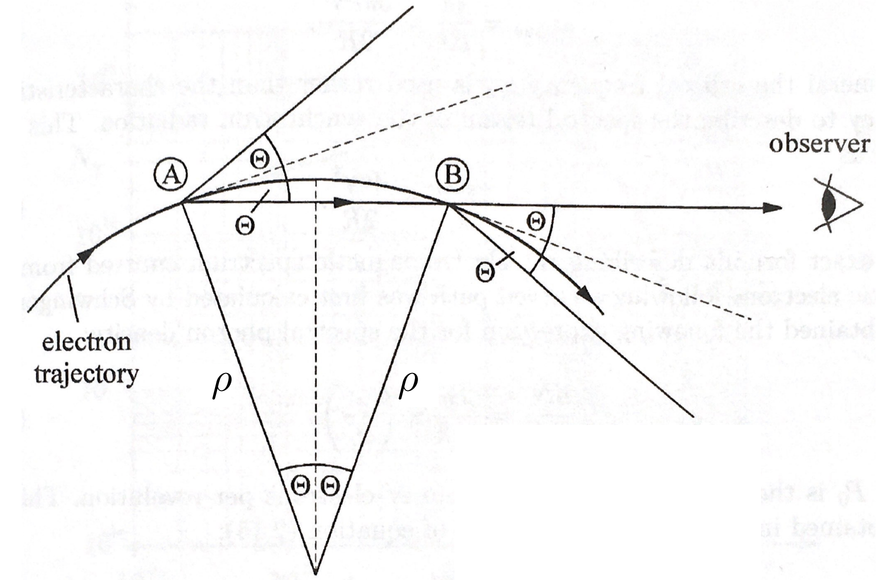
- At high energies synchrotron radiation becomes more focused

Co-moving Frame (Eigen Frame) **Lab Frame**



- This is a *relativistic effect*
- Can show that **cone angle scales like 1/γ** → for high-energy rings this forward-directed cone becomes extremely narrow

Properties of Synchr. Radiation: Bandwidth



- Since emission cone is so narrow, observer sees only very short section of electron trajectory (only few mm)

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

$$\Delta l_{A\to B} = 2\Theta\rho \approx \frac{2\rho}{\gamma}$$

- Think of a search light → pulse length is determined by path length difference between electron and photon

Relativistic Doppler boost

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

- This leads to **very short pulses** with **huge bandwidth**

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

  - Example: ALS at 1.9 GeV with 5-m bending radius

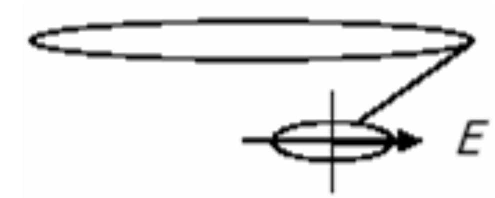
$$\Delta l \approx 2.70\ \mathrm{mm} \ \rightarrow \ \Delta t \approx 3.29\times 10^{-19}\ \mathrm{s} \ \rightarrow \ \Delta\omega \approx 3.04\times 10^{18}\ \mathrm{s}^{-1}$$

$$\boxed{f_{\max} \approx \frac{\Delta\omega}{2\pi} \approx 4.83\times 10^{17}\ \mathrm{Hz} \ \longrightarrow \ \lambda_{\min} = \frac{c}{f_{\max}} \approx 0.62\ \mathrm{nm}}$$

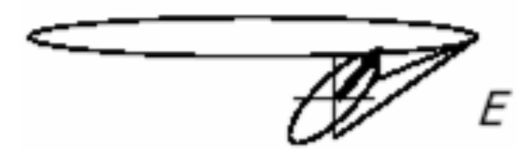
Very broad band!

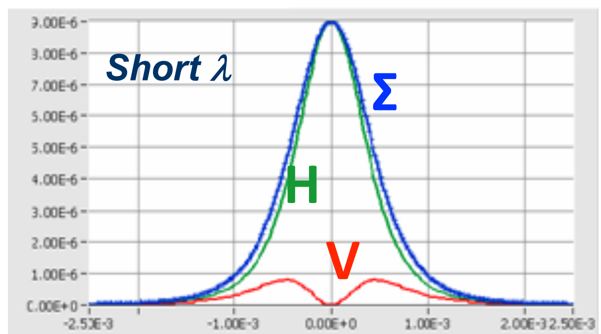
Properties of Synchr. Radiation: Polarization

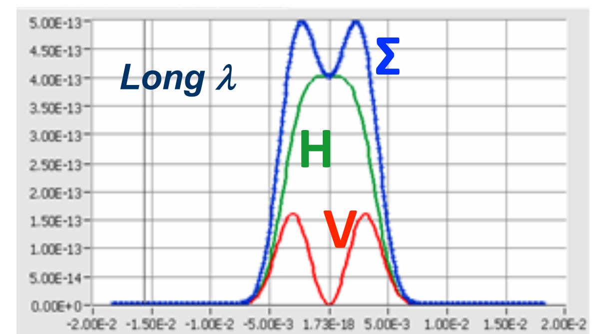
- Synchrotron radiation observed in the plane of the particle orbit is is **horizontally polarized**



- To an out-of-plane observer, synchrotron radiation is **elliptically polarized**







- This characteristic of synchrotron radiation is heavily exploited in experiments where polarization of the incident photons is important
- As we'll see later, there are **specific devices** we use to *control and optimize the polarization* of the generated synchrotron radiation for each individual experiment

Building the Accelerator: Main Ingredients

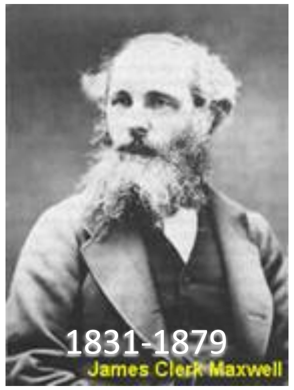
- Maxwell's equations (in vacuum, differential form, SI units)

$$\vec{\nabla}\vec{E} = \frac{\rho}{\epsilon_0}$$ **Gauss' law / Coulomb's law**

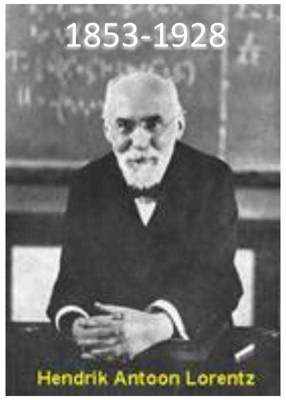
$$\vec{\nabla}\vec{B} = 0$$ **No-name law**

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$ **Faraday's law**

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{j} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$ **Ampère's law**



- Lorentz force $\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$



ρ : charge density
$\vec{j}$: current density

$\vec{j} = \sigma \vec{E}, \quad \sigma$: conductivity

$\epsilon_0 \mu_0 c^2 = 1$

$\epsilon_0 = 8.85 \times 10^{-12}\,\mathrm{F/m}\ \left[\mathrm{C^2/Nm^2}\right]$ Permittivity of free space
$\mu_0 = 4\pi \times 10^{-7}\,\mathrm{H/m}\ \left[\mathrm{N/A^2}\right]$ Permeability of free space

Building the Accelerator: Accelerating Particles

- Lorentz force tells us we'll use **electric fields** to **accelerate** particles (and **magnetic fields** will be used to **guide and deflect**) because *magnetic fields cannot perform work*

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

$$W = \int \vec{F}\, d\vec{s} = q \int \vec{E}\, d\vec{s} + q \int \left(\vec{v} \times \vec{B}\right) d\vec{s} = q \underbrace{\int \vec{E}\, d\vec{s}}_{\neq 0 \text{ unless } \vec{E} \perp \vec{s}} + q \underbrace{\int \left(\frac{d\vec{s}}{dt} \times \vec{B}\right) d\vec{s}}_{\text{always } = 0}$$

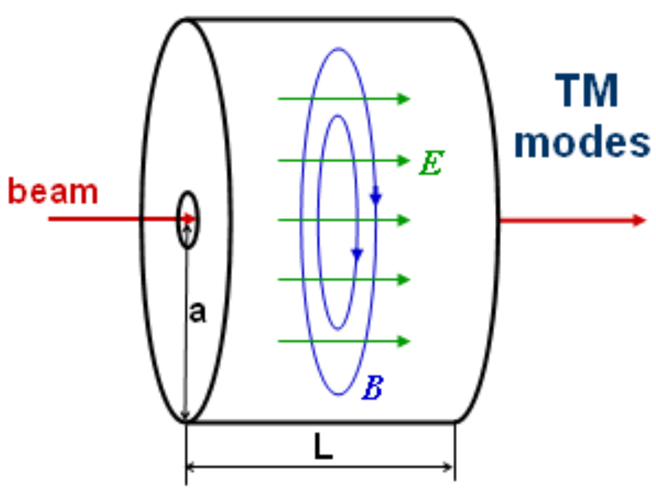
➡**Electric fields** can can modify particle energy ("*accelerate*")

- Most accelerators rely on **magnetic fields** to *steer*, eg. particle with momentum *p* and charge *q* in a uniform magnetic field *B* moves on a circle with radius

$$\rho = \frac{p}{qB} \quad \text{Larmor radius}$$

Electric Fields for Acceleration

- There are many ways to generate strong electric fields
- High efficiency and reliability in storage rings (=synchrotron operating at fixed energy) can be achieved with radio-frequency (RF) cavities



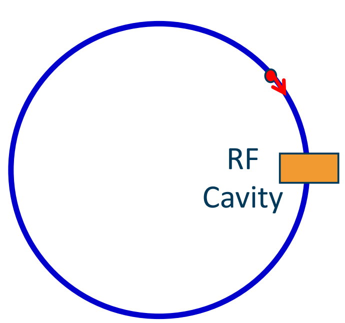
- For the TM_{010} mode in a metallic "pillbox" cavity:

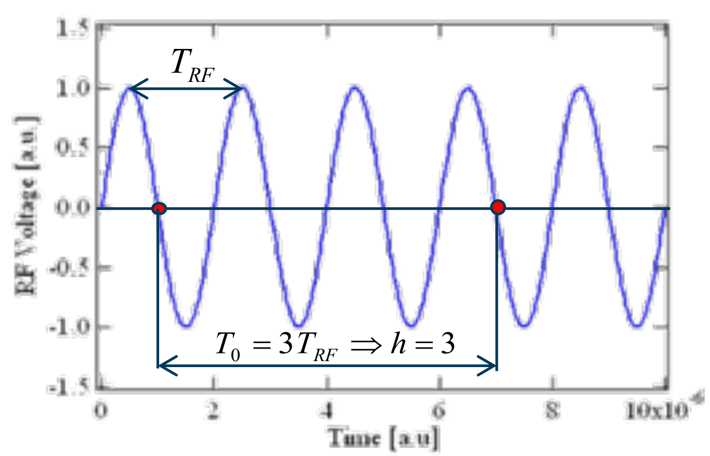
$$E_z^{\mathrm{TM}_{010}} = E_0(r)\cos(\omega_c t)$$

$$f_c = \frac{\omega_c}{2\pi} \approx \frac{2.405\,c}{2\pi\,a}$$

Example: ALS RF cavities at f_{rf} = 500 MHz → a = 229.5 mm

- RF fields need to be synchronized to particle's arrival time:



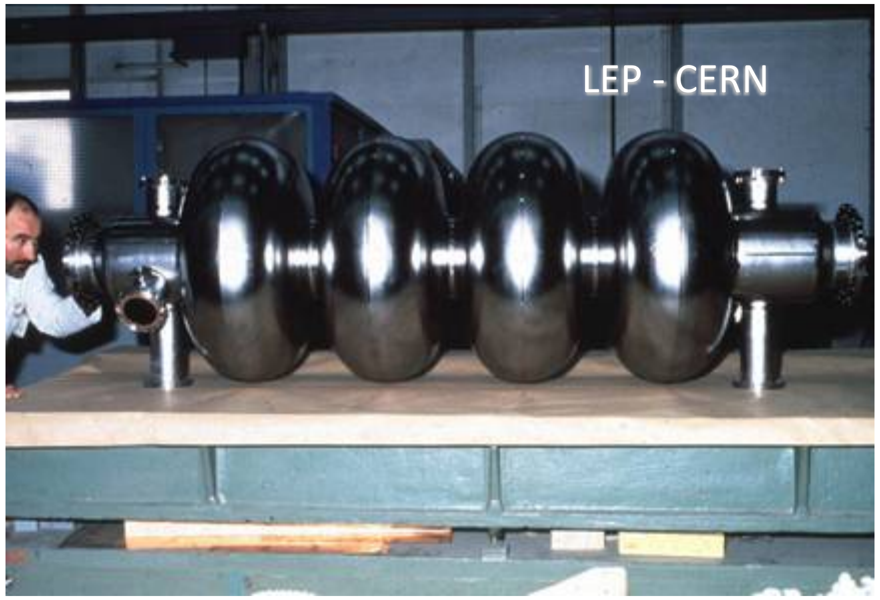


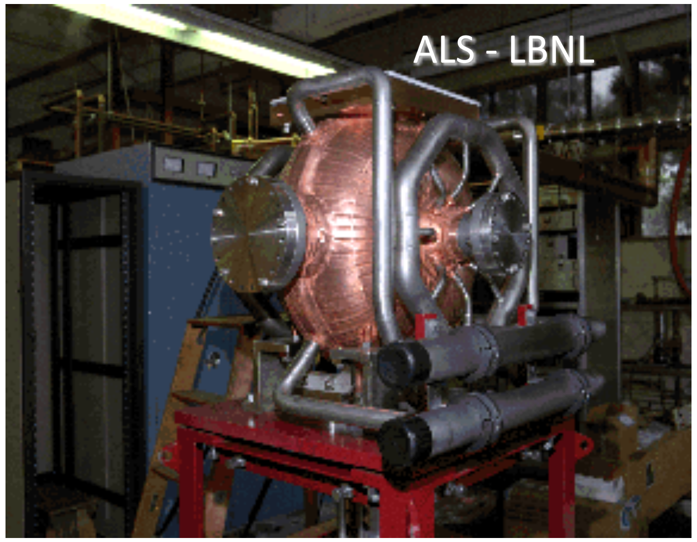
$$V_{\mathrm{rf}}(t) = V_0 \sin(2\pi f_{\mathrm{rf}} t)$$

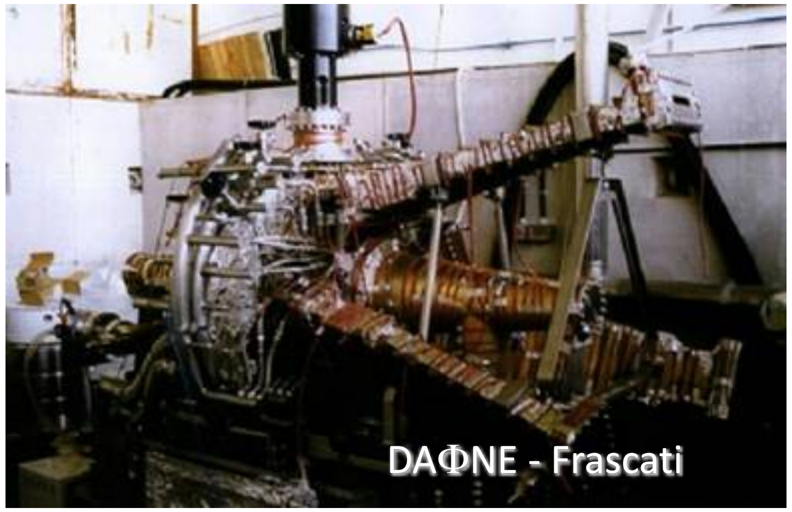
$$T_0 = h\,T_{\mathrm{rf}} \longrightarrow f_0 = \frac{f_{\mathrm{rf}}}{h}, \quad h \in \mathbb{N}$$

Synchronicity Condition

Electric Fields for Acceleration: Real RF Cavities



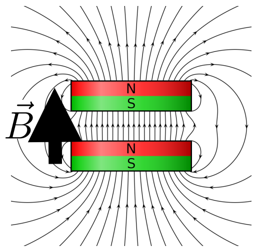




Most light sources rely on room temperature RF cavities, but sometimes we also encounter superconducting cavities (eg. CLS, DIAMOND, SLS 3HC).

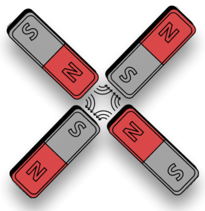
Magnetic Fields for Steering/Focusing

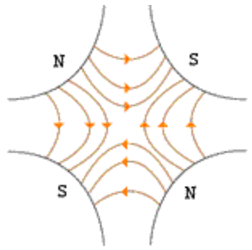
- Various types of magnets are used for **beam confinement**
  - **Dipoles** → used to *steer* and deflect beams



$$\vec{B} = \begin{pmatrix} 0 \\ B_y \\ 0 \end{pmatrix}, \quad B_y = \text{const}$$

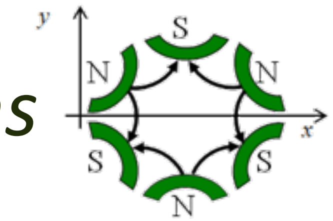
  - **Quadrupoles** → used to *focus* beams





$$\vec{B} = \begin{pmatrix} Ky \\ Kx \\ 0 \end{pmatrix}, \quad K = \text{const}$$

  - **Sextupoles** → apply *chromatic corrections*

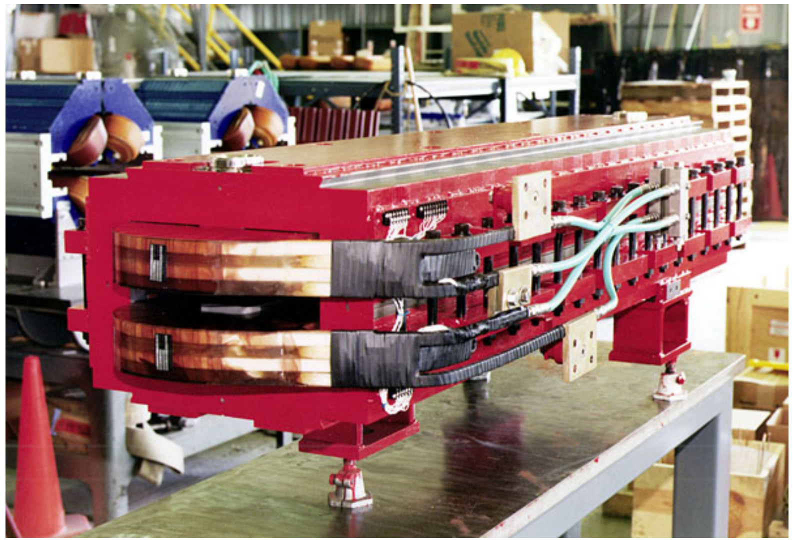


$$\vec{B} = \begin{pmatrix} Mxy \\ \frac{1}{2}M(x^2 - y^2) \\ 0 \end{pmatrix}, \quad M = \text{const}$$

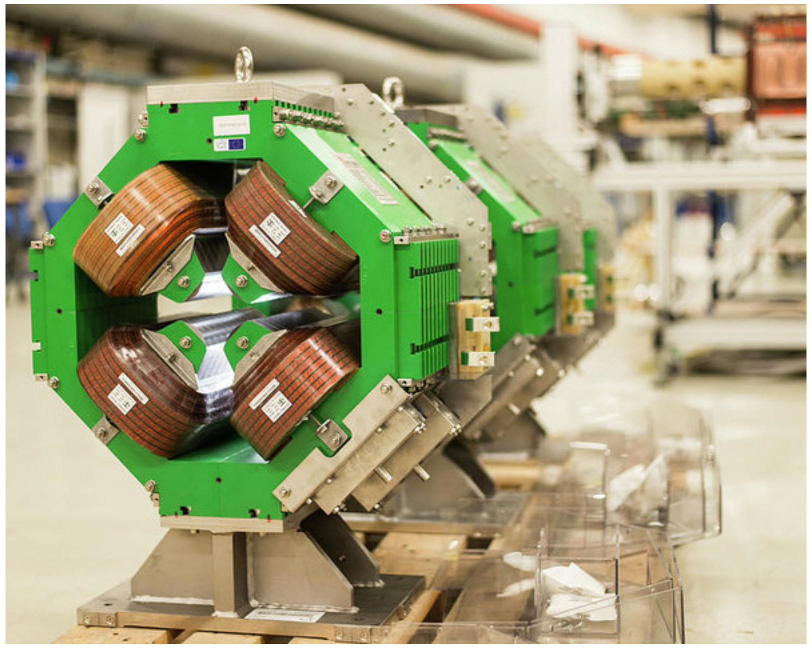
  - **Octupoles, Decapoles**, ... → correct higher-order *aberrations*

- And sometimes we use *hybrids*, i.e. **"combined-function magnets"**

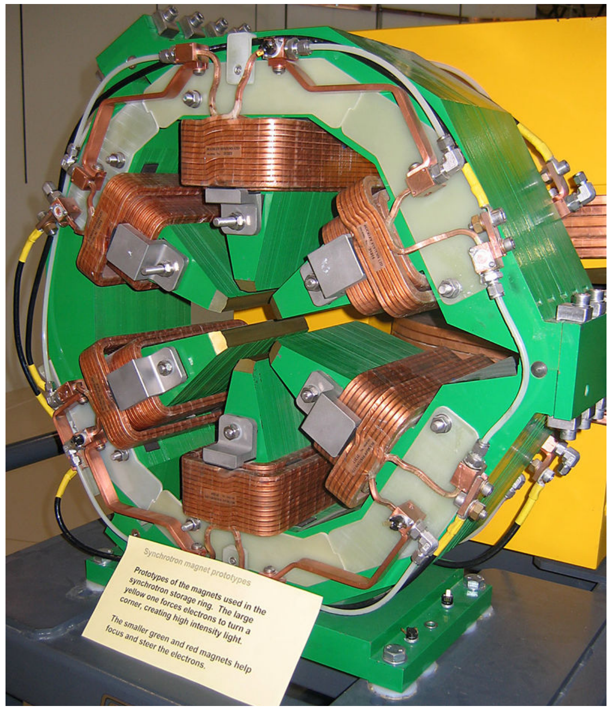
Magnetic Fields for Steering/Focusing: Real Magnets



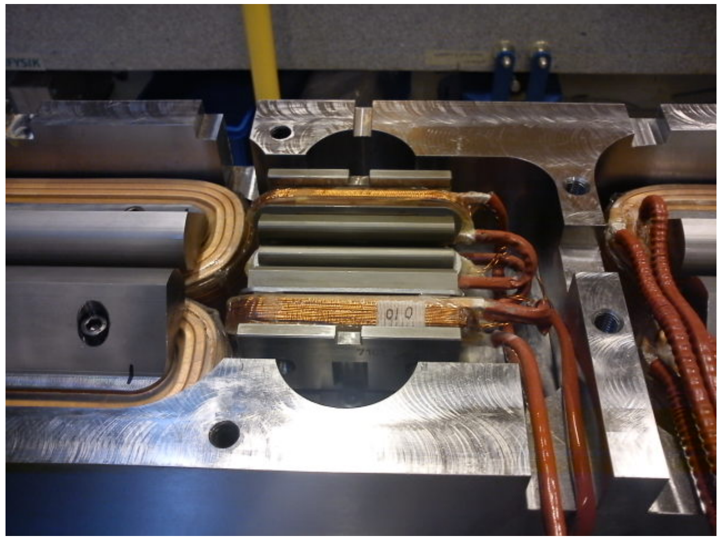
APS Dipole



SESAME Quadrupoles

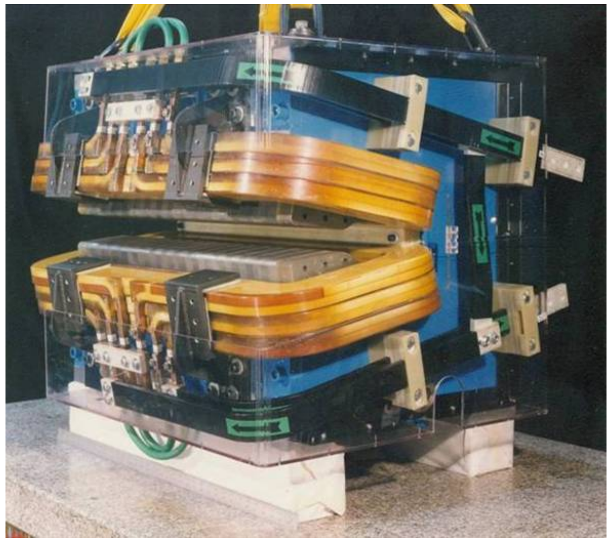


AS sextupole



MAX IV octupole (lower half)

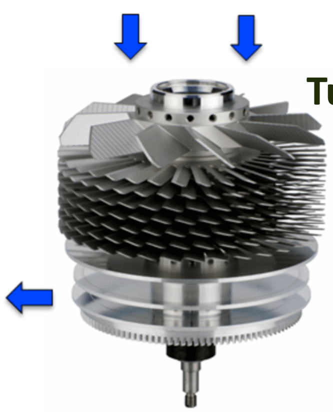
ALS Gradient Dipole



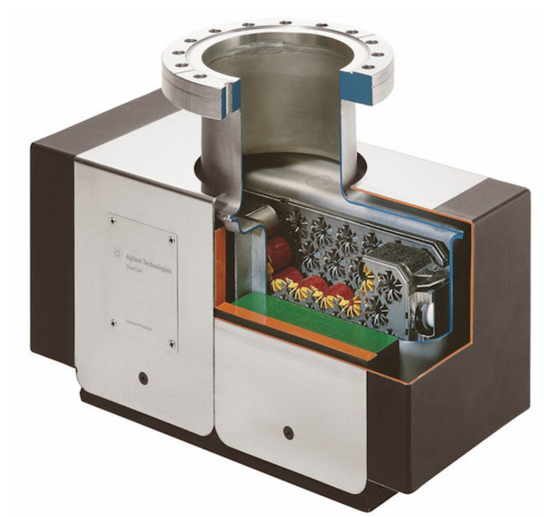
These are all room temperature electromagnets, but superconducting and permanent magnet-based schemes are also employed.

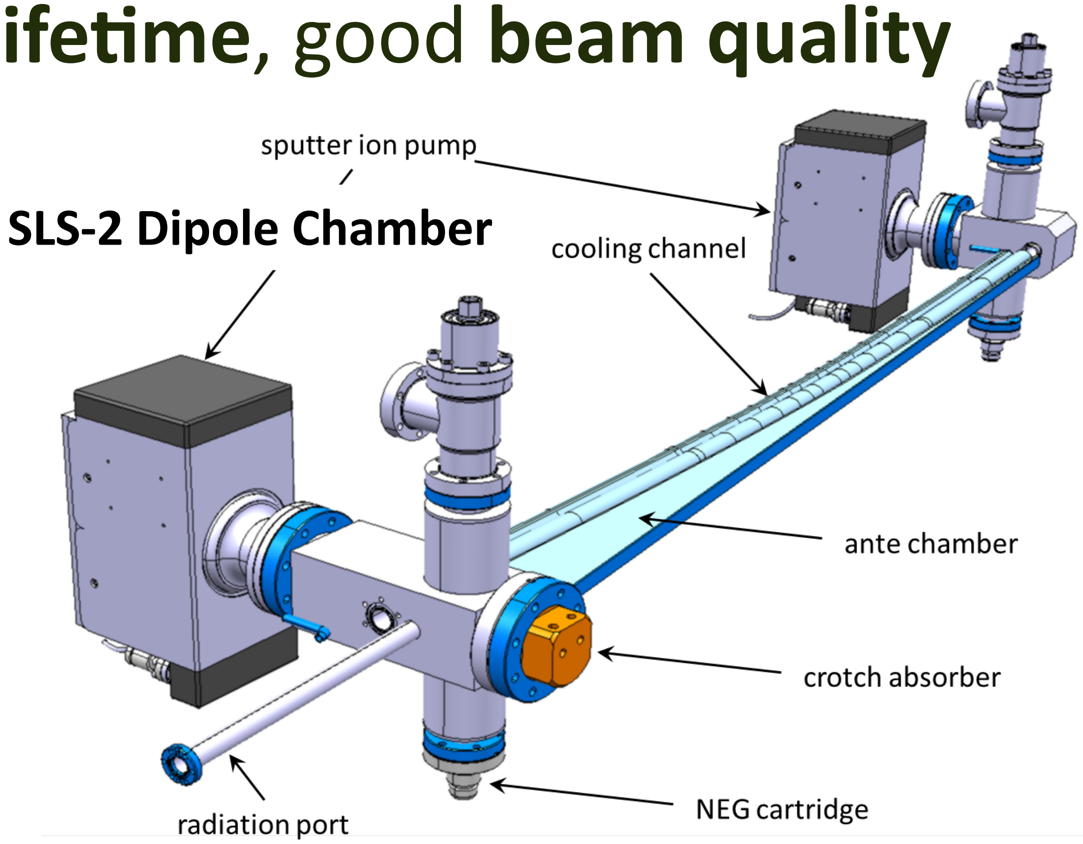
Vacuum Systems Ensure Beam Quality & Lifetime

- Vacuum systems consisting of **vacuum chambers** & **vacuum pumps** ensure UHV conditions (≈10^{-9} mbar or torr) for the stored electron beam → limit **scattering** → long **beam lifetime**, good **beam quality**


Turbomolecular Pump

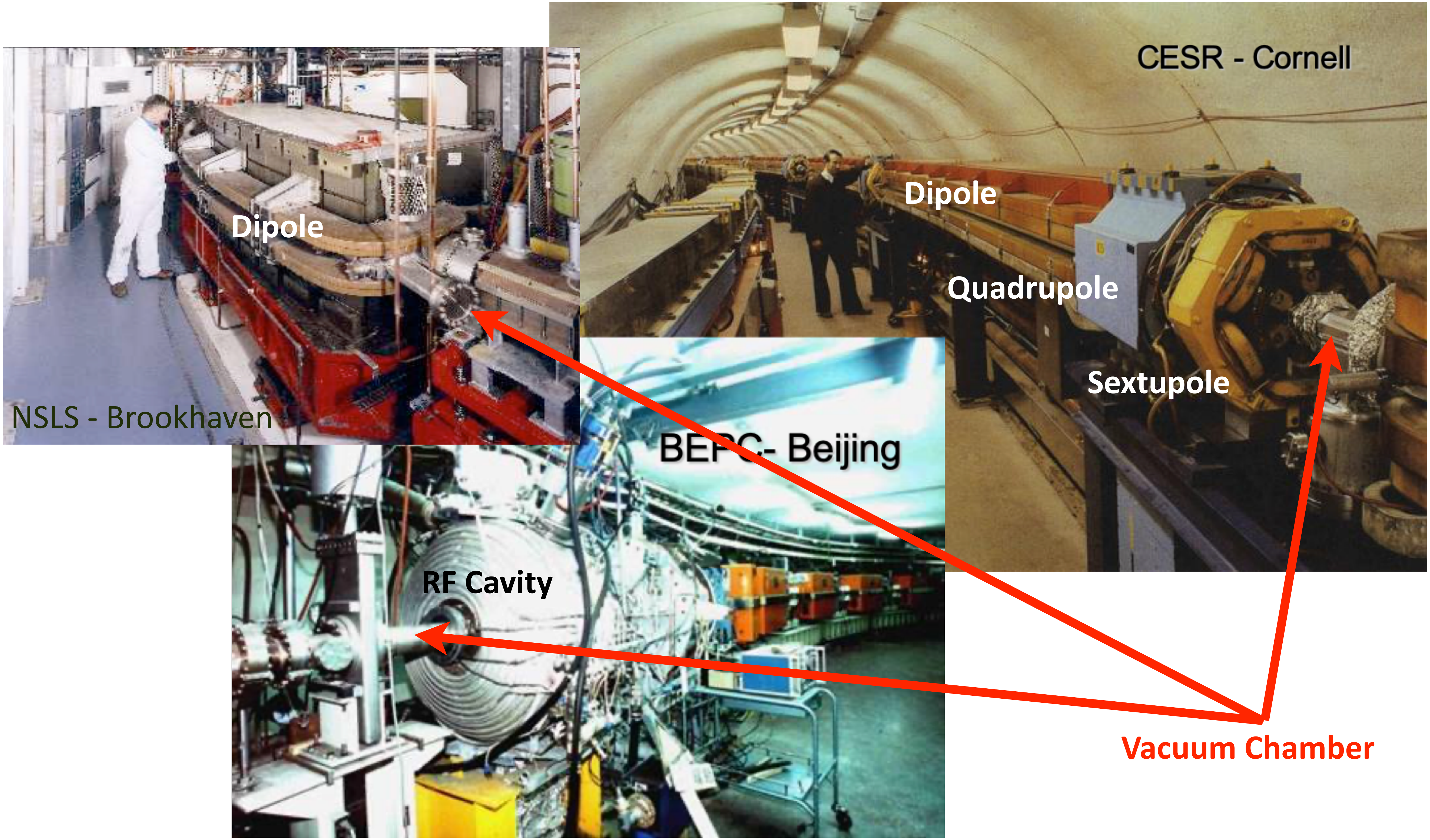

Roughing Pump


Ion Getter Pump



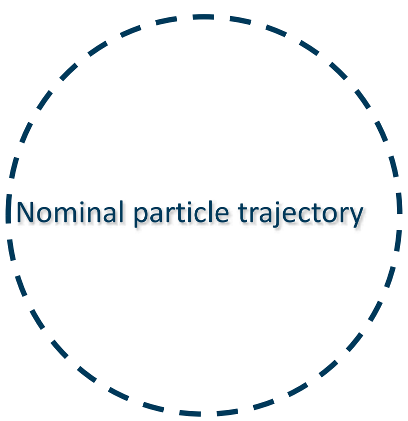
- Vacuum chambers also integrate many other integral pieces of equipment, eg. **beam diagnostics** (beam position monitors, current transformers, profile monitors [flags/screens], pressure gauges, etc.)

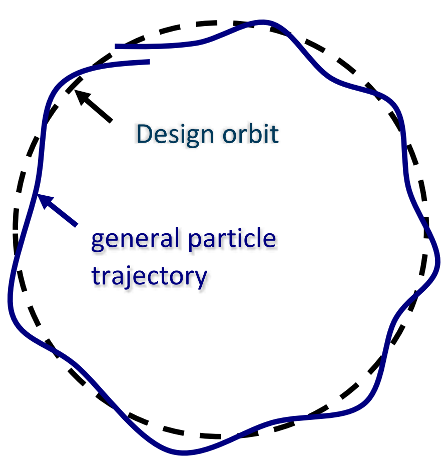
Putting it all together — real accelerators



At a Glance: Particle Dynamics in a Storage Ring

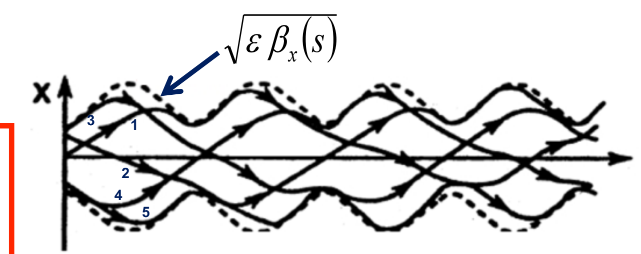
- Electrons **oscillate** around the nominal particle position and energy!
- **Damping** of these oscillations is due to the emission of synchrotron radiation
- Motion in the **transverse plane**:





$$x(s) = \sqrt{\varepsilon_x \beta_x(s)} \cos\left[\Psi_x(s) - \Psi_{x,0}\right]$$

$$y(s) = \sqrt{\varepsilon_y \beta_y(s)} \cos\left[\Psi_y(s) - \Psi_{y,0}\right]$$

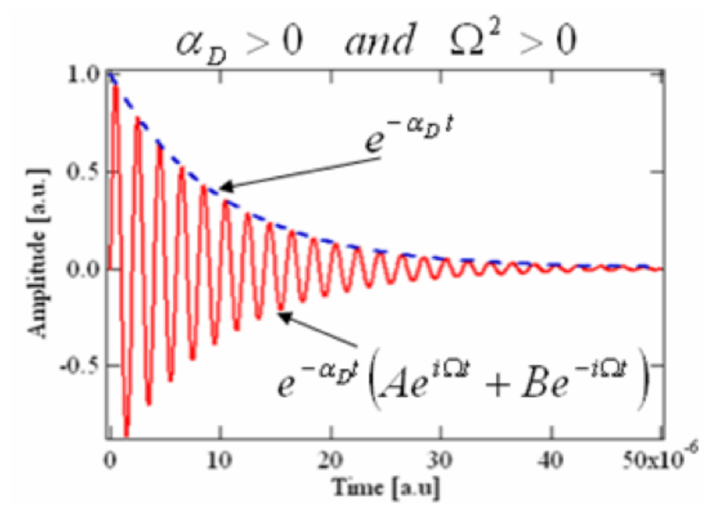


$$\Psi_{x,y}(s) = \int_0^s \frac{ds}{\beta_{x,y}(s)}$$

- **Longitudinal** motion:

$$\Delta s(t) = e^{-\alpha_D t}\left(Ae^{i\Omega t} + Be^{-i\Omega t}\right)$$

$$\Delta E(t) = -i\Omega \frac{p_0}{\eta_c} e^{-\alpha_D t}\left(Ae^{i\Omega t} - Be^{-i\Omega t}\right)$$

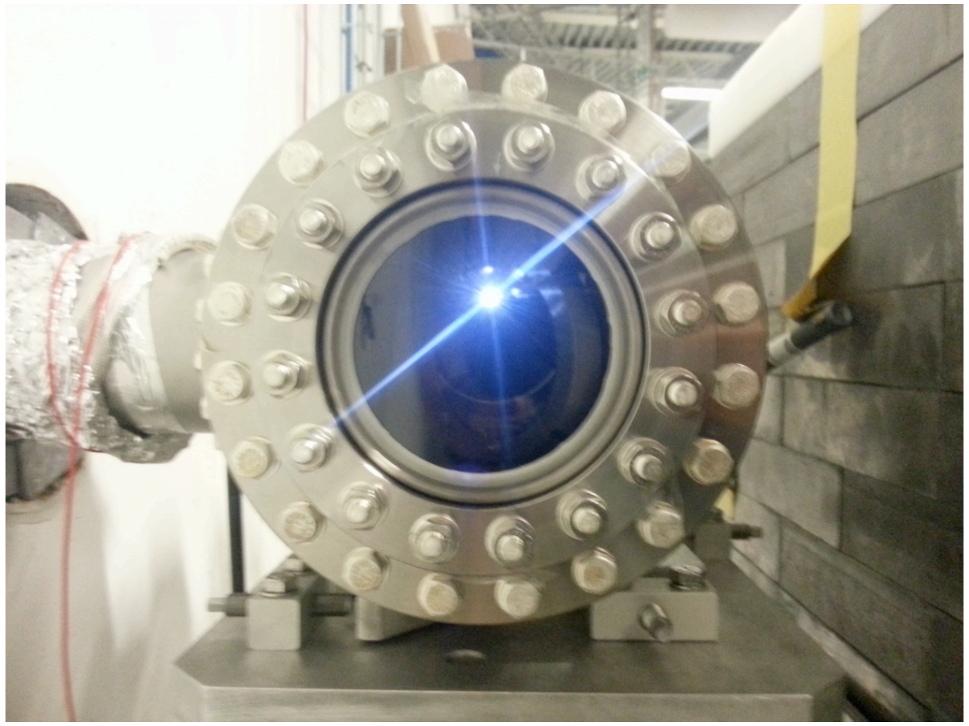


From Single Particle to Beam

- So far we have discussed the dynamics of a **single particle**, but in typical accelerators particles circulate in **bunches** (10^5–10^{13} particles per bunch) with many such bunches making up the entire **beam**
- Fortunately, **statistical mechanics** gives us well developed and highly suited tools for representing and understanding these large numbers of particles

➡ Particles lose their individuality and are instead represented by their distribution in **phase space** (position-momentum space)

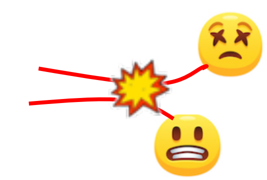
- The evolution of such a **phase space distribution** in the ring can be studied and the behavior of the whole beam characterized



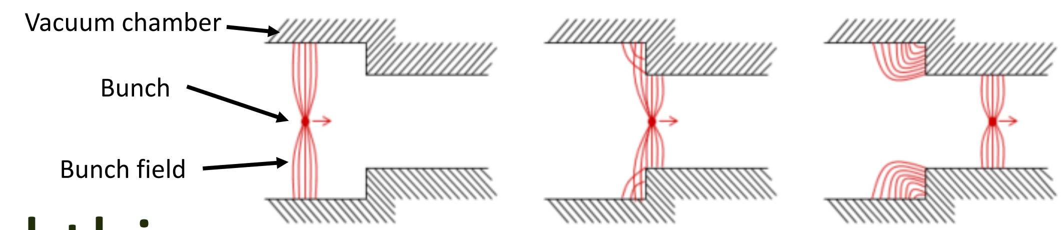
Visible synchrotron radiation at MAX IV

From Single Particle to Beam (cont.)

- Two important consequences follow: **collective effects** & **emittance**
- Collective effects

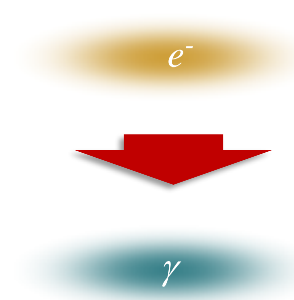


  – beam particles interact with other beam particles (**space charge**, **scattering**) as well as beam surroundings (**impedance**) → beam **instability**, particle **loss** → need to avoid this



  (such effects usually limit maximum current that can stably be stored)

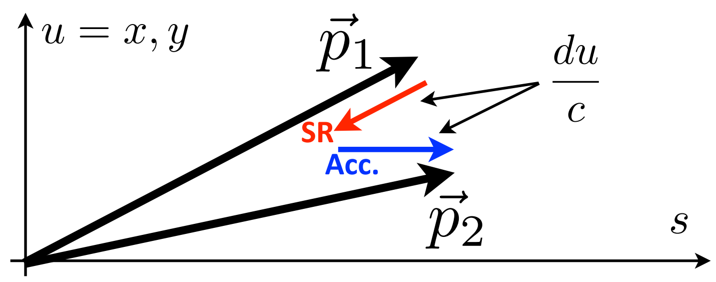
- Electron beam emittance
  – measure of **electron beam phase space density** directly related to brightness of the emitted synchrotron radiation



  ➡ in order to create **high-brightness photon sources**, the ultimate goal is therefore to design for **low-emittance beams** of high current (*"high-brightness electron beam"*)

Electron Beam Emittance in Storage Rings

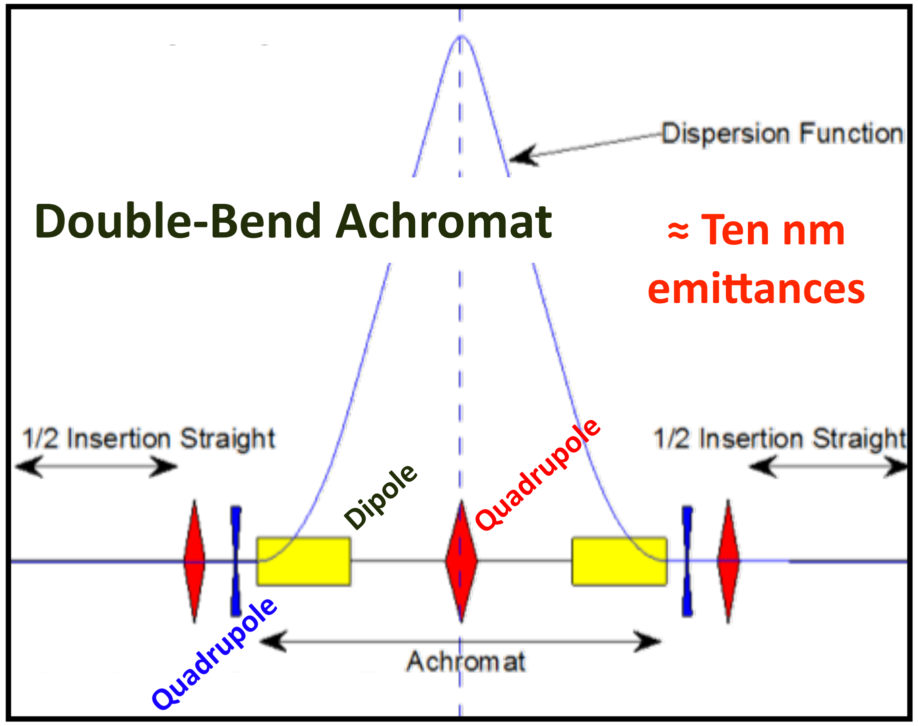
- Emittance in a ring is an **equilibrium state** that results primarily from two competing processes
  - *Recoil* during photon emission damps/reduces electron oscillations (**radiation damping**)
  - *Random energy loss* associated with photon emission induces/increases electron oscillations (**quantum excitation**)

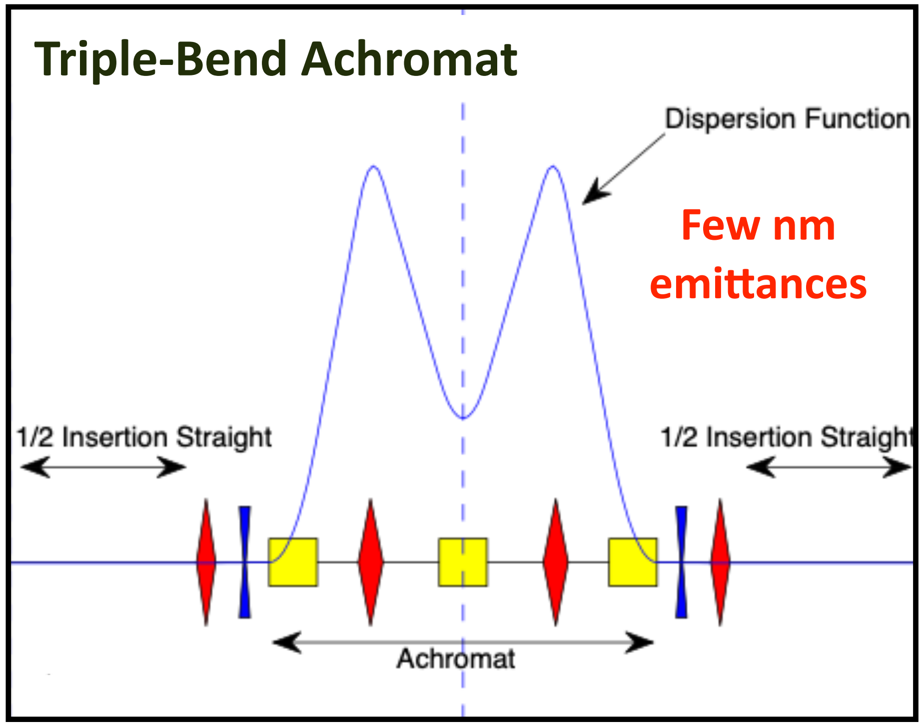


- Small emittances (small phase space volume) therefore require **large radiation damping** and **small quantum excitation**

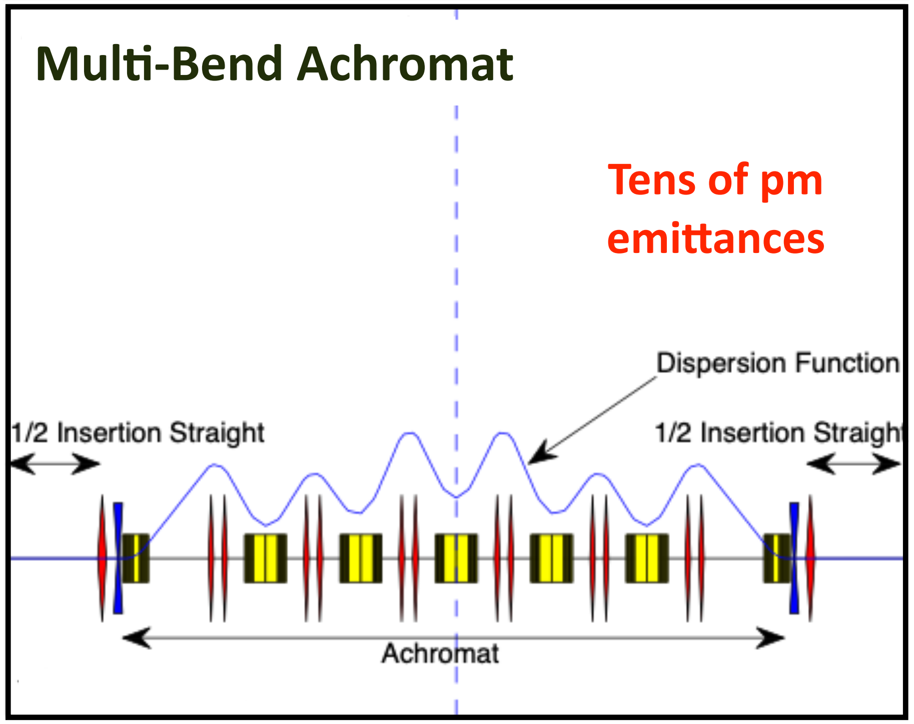
➡ It can be shown that in storage rings this is obtained by **increasing synchrotron radiation losses** and **minimizing the "dispersion"** (path difference between on- and off-energy electrons)

The Quest for Lower and Lower Emittance Lattices





Achromat = section of magnetic lattice with zero dispersion at both ends



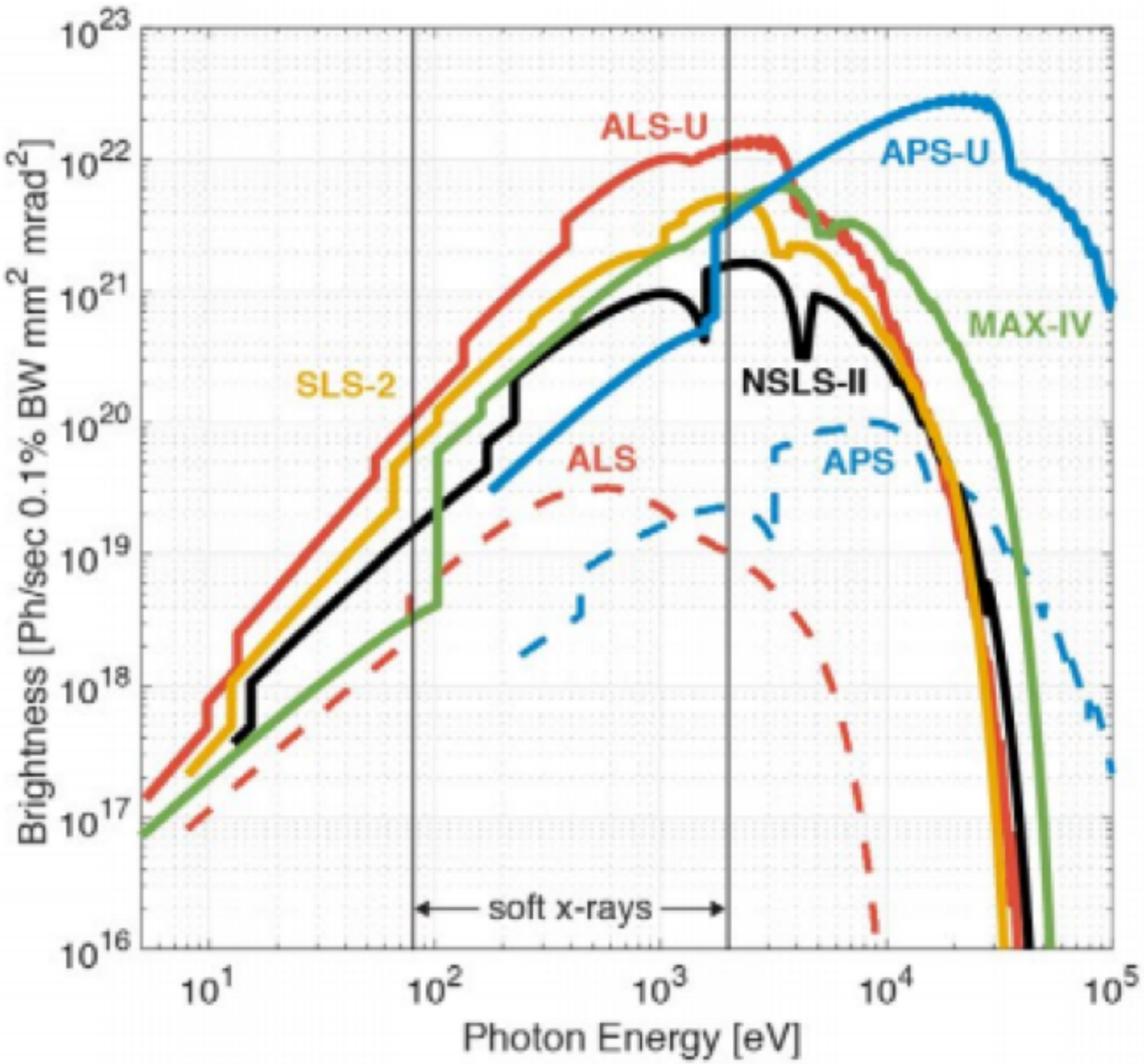
- Storage rings typically built from modular **cells** called "**sectors**"
- Sector is usually composed of **arc** (where most magnets are located) and **straight sections** to house insertion devices (IDs)
- Sector magnetic design is called **lattice** → most storage ring properties are determined by this magnetic lattice
- Latest *ultra-low emittance lattice designs* employ strong focusing lattices called "**multi-bend achromats**" (MBAs) where dispersion is focused to very lower values → **"4th-generation storage rings" (such as ALS-U)**

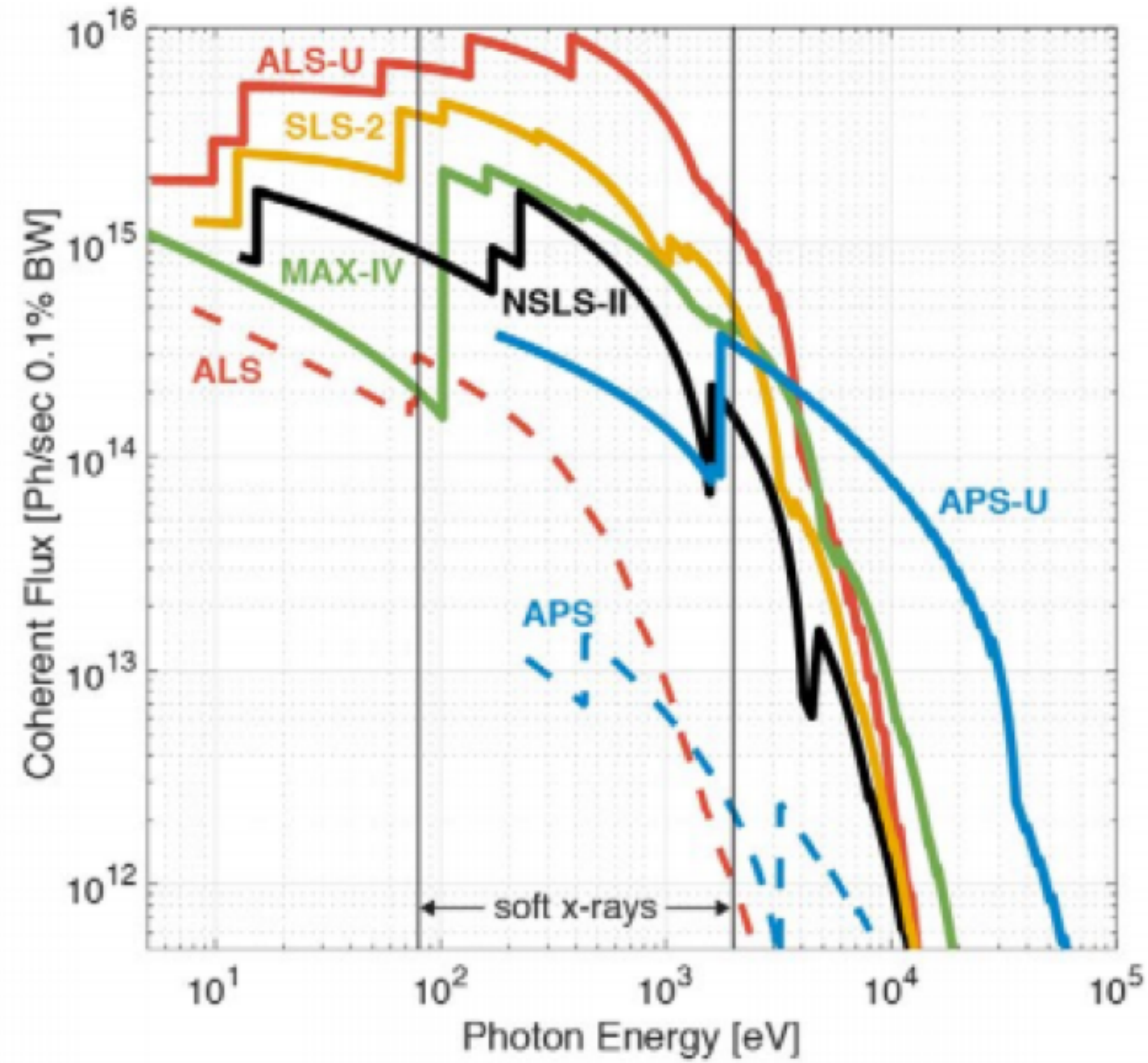
Ultralow Emittance & the Diffraction Limit

- Scientific case for a light source defines target photon wavelength region (eg. UV, soft, tender, hard x-rays)
- *Phase space area* (**emittance**) occupied by a photon of wavelength λ is: λ/4π (ALS optimized for ≈1 keV photons [λ≈1.2 nm] → ≈0.1 nm rad emittance)
- When electron beam emittance in storage ring is smaller than single-photon emittance → light source is **"diffraction limited"** (photons appear to emerge from point source)
- Example:
  - **ALS** electron beam emittance optimized over the years from ≈6 nm rad to ≈2 nm rad today
  - **ALS-U** emittance will reach ≈0.08 nm rad → diffraction limit achieved (by virtue of ambitious *multi-bend achromat* lattice design)

SOLEIL (Gif-sur-Yvette, France)

Ultralow Emittance & the Diffraction Limit (cont.)





- Achieving/surpassing diffraction limit → high **transverse coherence**

Optimizing the Photon Source

- The battle to **maximize photon brightness** is fought on two fronts:
  - In the **accelerator** → optimizing the design to get high stored current and smallest emittances (as just discussed)
  - In the accelerator elements where *synchrotron radiation* is actually generated: **dipole magnets** and **insertion devices** (IDs)
    → *This is what we'll discuss in the final part of this tutorial*

NSLS-II (Brookhaven, NY)

Bending Magnet Sources & Radiation

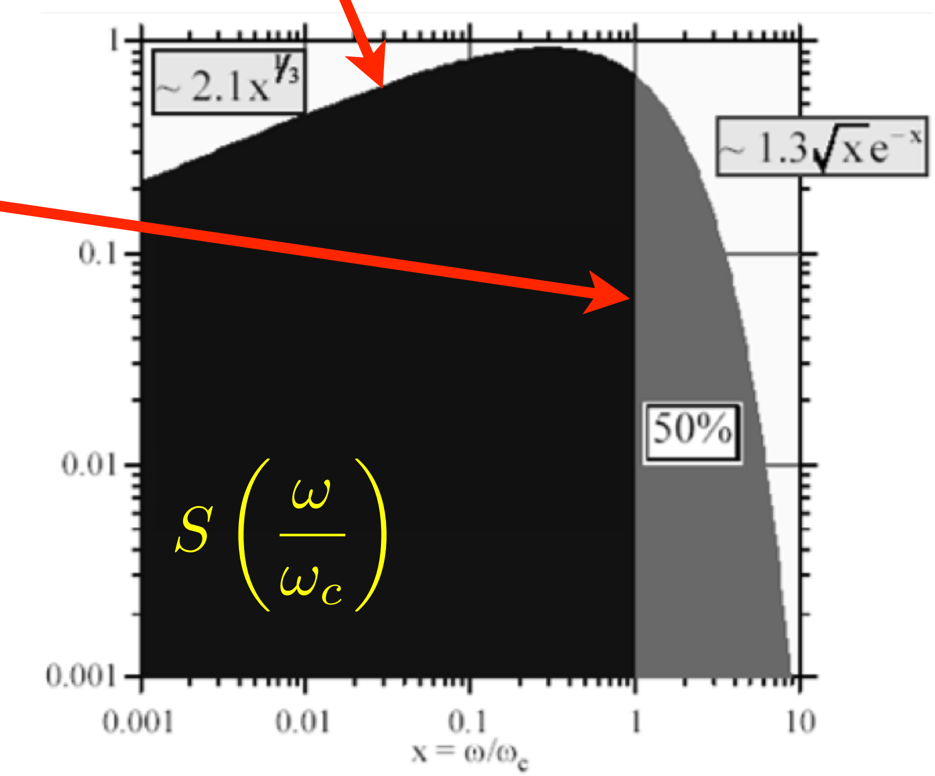
- Bend magnet **spectrum** is divided evenly (in power) at the **critical frequency**:

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

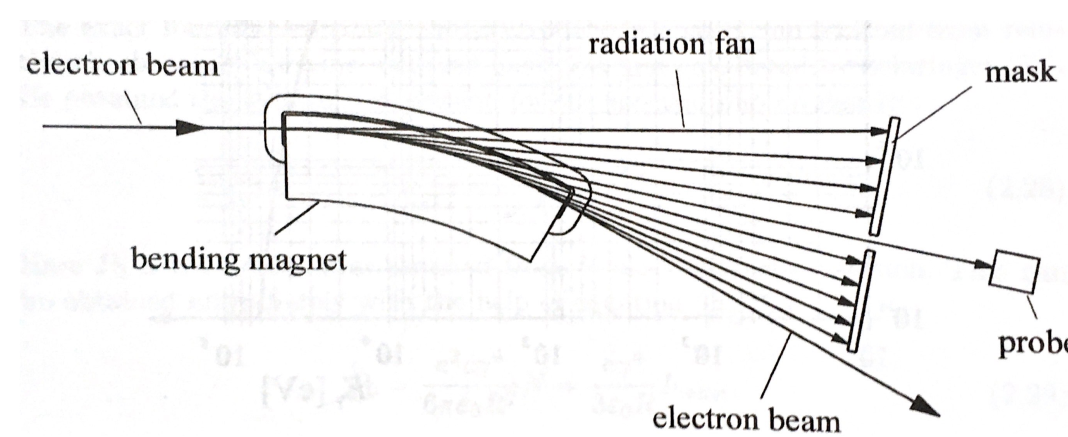
$$P_{\mathrm{tot}} = \frac{2}{3}\hbar c^2 \alpha \frac{\gamma^4}{\rho^2}$$

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

- This frequency corresponds to a **photon energy** we can express as a function of *electron beam energy* and *bend magnet field* alone: $E_c\,[\mathrm{eV}] = 665\,E^2\,[\mathrm{GeV}]\;B\,[\mathrm{T}]$

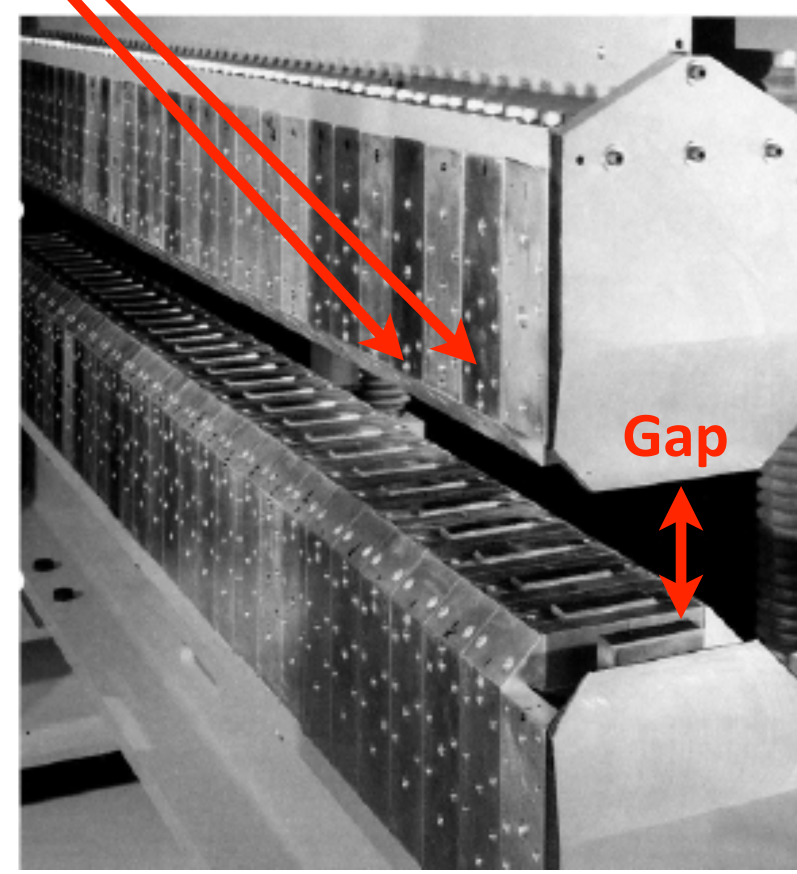


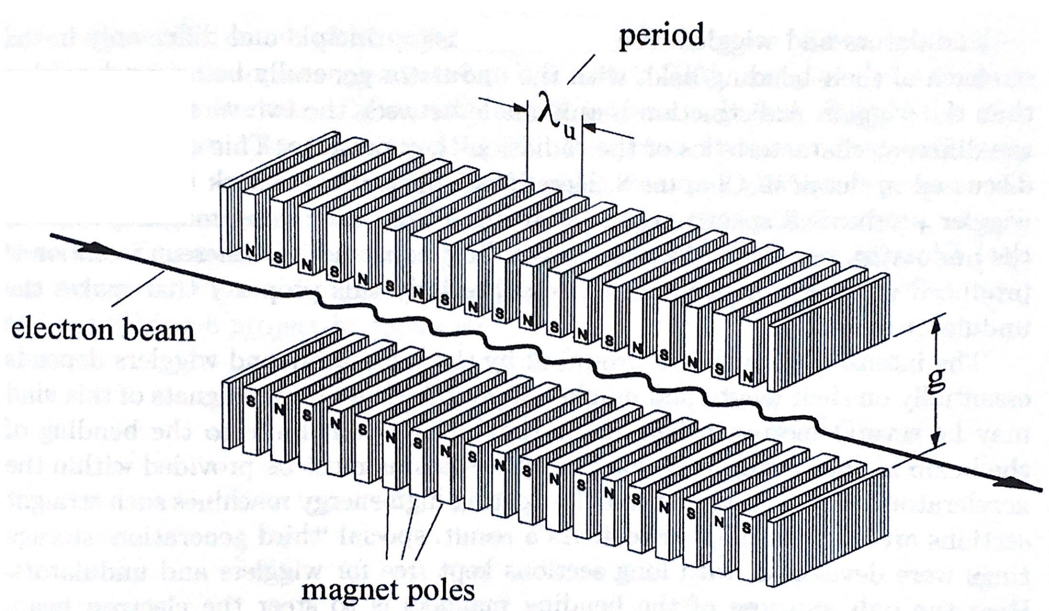
Bend Type	Beam Energy [GeV]	Bend Field [T]	Critical Energy [keV]
ALS	1.9	1.5	**3.6**
ALS superbends	1.9	5.0	**12.0**
ALS-U	2.0	0.86	**2.3**
ALS-U high-field bend	2.0	3.2	**8.5**

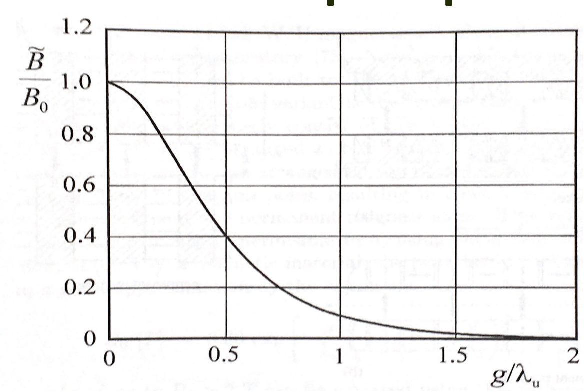


Insertion Devices: Undulators & Wigglers

- Arrays of alternating **permanent magnets** (invented by *K. Halbach* at LBNL, 1981) → as if electron beam traversed many small bending magnets and emitted synchrotron radiation at each
- Permanent magnet arrays installed on movable girders → by adjusting **magnetic gap** we modify the field at beam and therefore the properties of the emitted photons





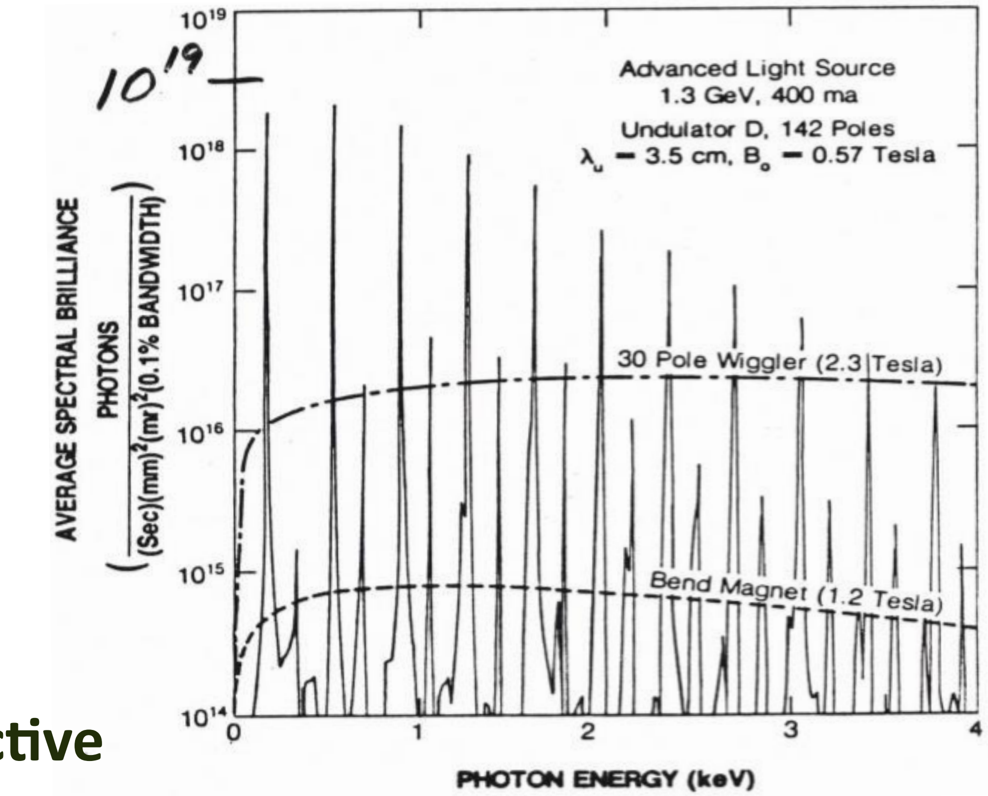


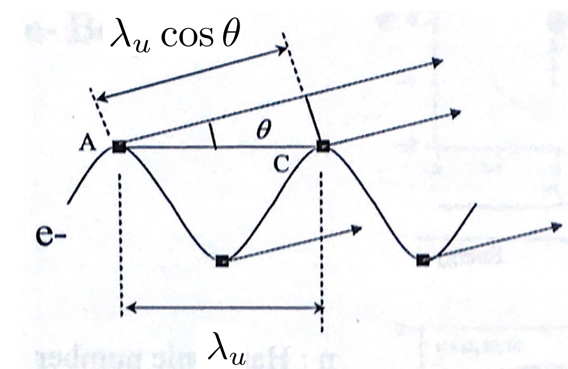
$$\tilde{B} = B_0 \cosh^{-1}\left(\pi \frac{g}{\lambda_u}\right)$$

$$\lambda_c = \frac{4\pi\rho}{3\gamma^3} = \frac{4\pi\,(mc^2)}{3qc\gamma^2}\frac{1}{\tilde{B}}$$

Undulator Radiation

- In a **wiggler** we get a lot of radiation in a broad bend magnet-like spectrum
- In an **undulator**
  - beam oscillates at much smaller amplitude → **constructive interference** between radiation emitted on different "wiggles" along device leads to **discrete peaks in spectrum**
  - we get **"higher harmonics"** because constructive interference satisfied for λ is obviously also satisfied for λ/N → undulators can emit high-energy photons (within narrow bandwidth) even in rings with low/medium beam energy





Red shift off axis

Fundamental (1st harmonic)

$$\boxed{\lambda = \lambda_u \cos\theta - ct_{\mathrm{AC}} \approx \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)}$$

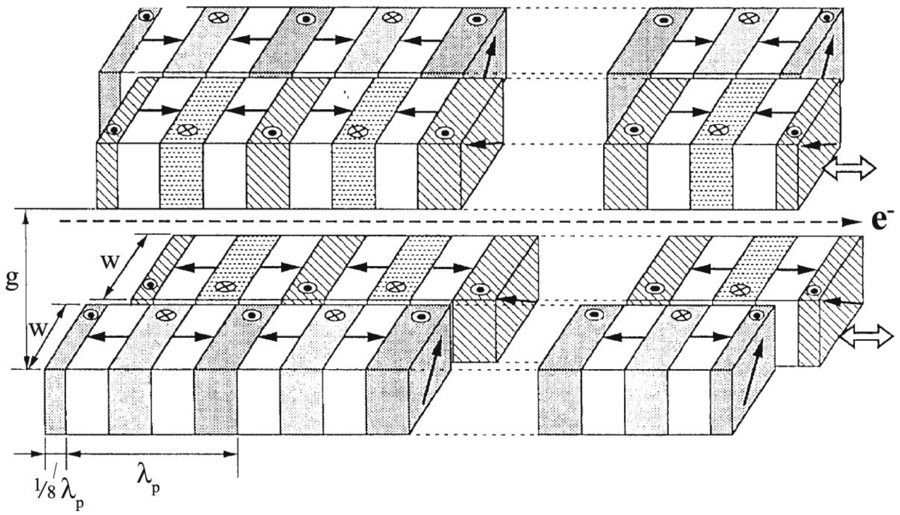
Lorentz boost

$$t_{\mathrm{AC}} = \frac{\lambda_u}{v} = \frac{\lambda_u}{c\left[1 - \frac{1}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)\right]}$$

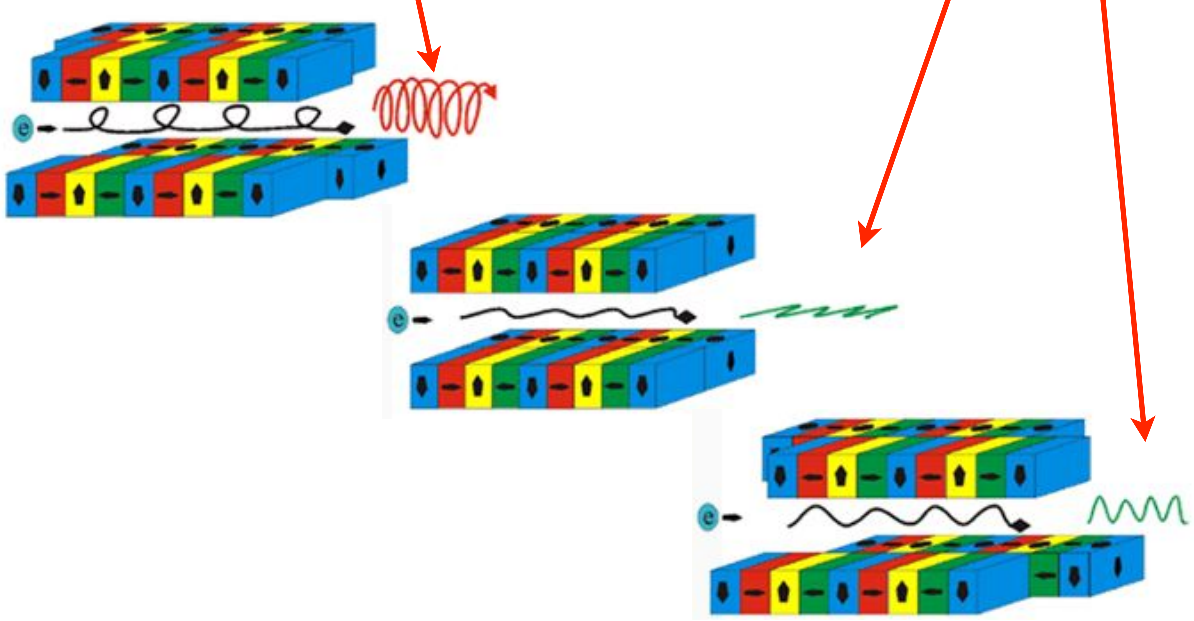
$$K = \frac{\lambda_u q \tilde{B}}{2\pi mc}, \quad \tilde{B} = B_0 \cosh^{-1}\left(\pi \frac{g}{\lambda_u}\right)$$

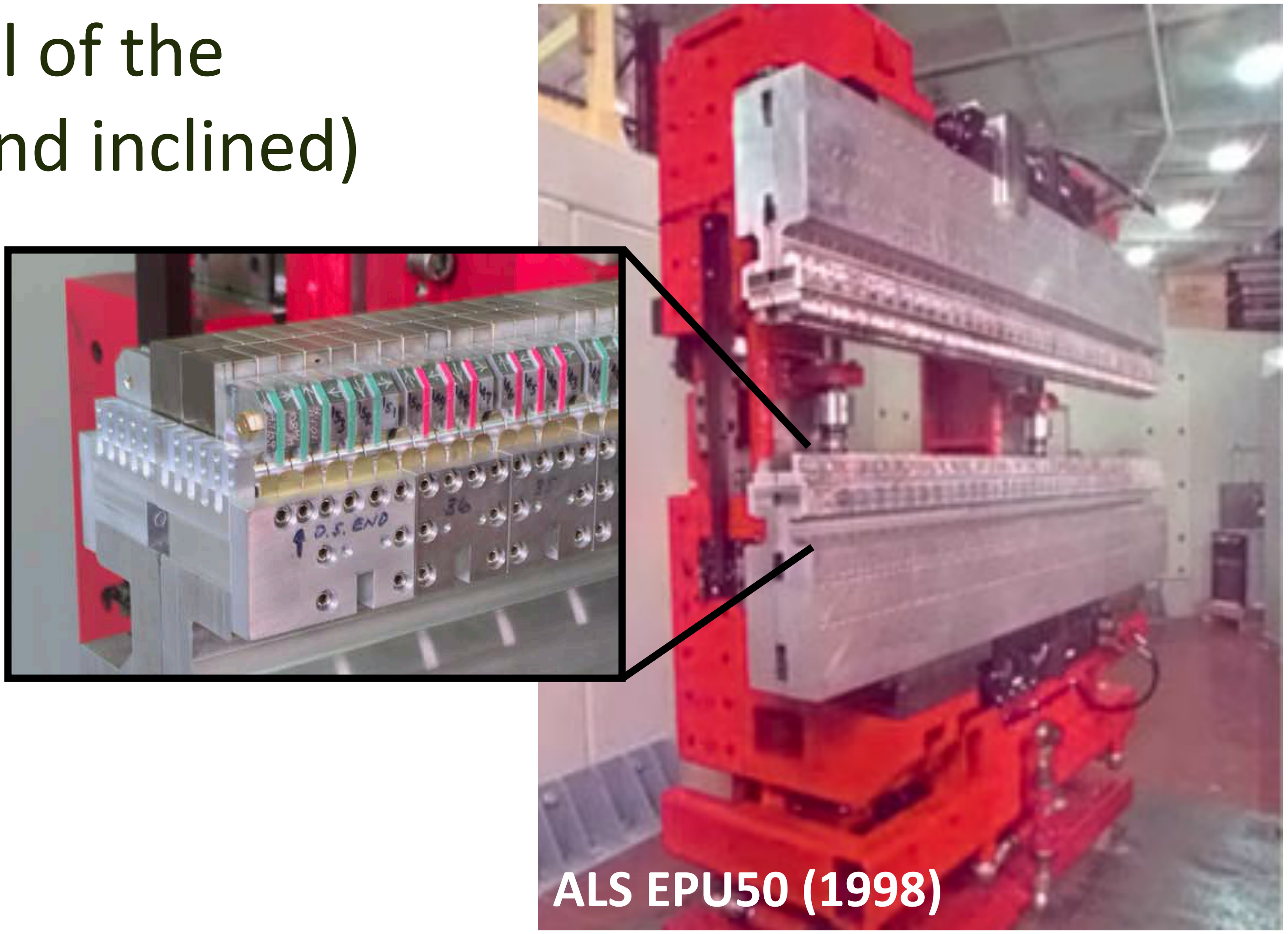
  - the **strength parameter** *K* determines the wavelength of the peaks in the spectrum → *K* is adjusted by varying the gap in the undulator → **wavelength-tunable device!**

Elliptically Polarizing Undulators (EPUs)

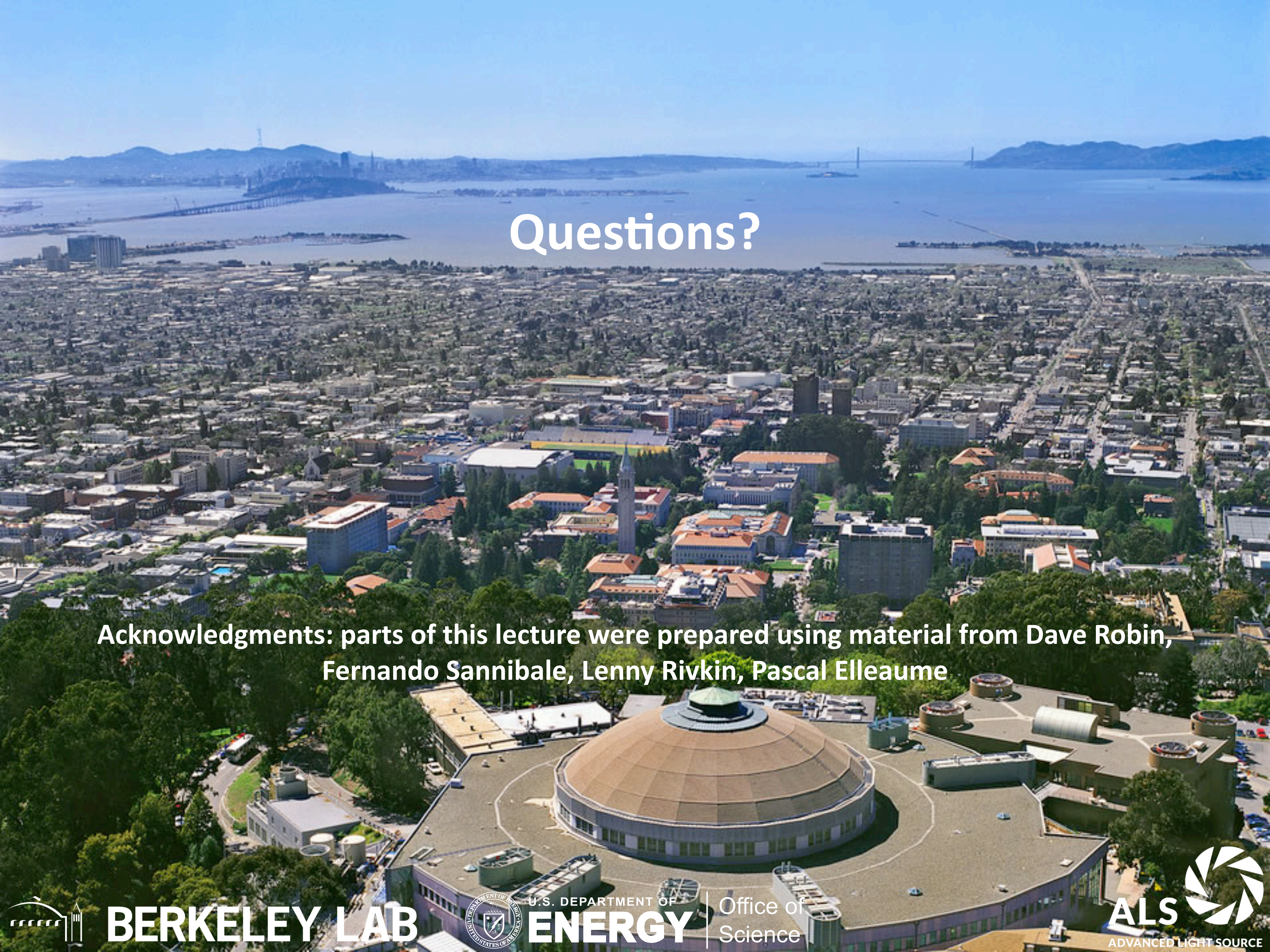


- Permanent magnet arrays are split and can be mechanically shifted (in the longitudinal direction) ➔ modifies plane of "wiggling" and thus the polarization of the emitted synchr. radiation
- EPUs allow for complete control of the polarization from linear (H, V, and inclined) to elliptical (incl. circular)





ALS EPU50 (1998)



Questions?

Acknowledgments: parts of this lecture were prepared using material from Dave Robin, Fernando Sannibale, Lenny Rivkin, Pascal Elleaume

Zoom Poll

Besides electrons, which of the following is best suited as source of synchrotron radiation?

A) Proton

B) Baseball

C) Positron

D) Higgs Boson

Zoom Poll

Besides electrons, which of the following is best suited as source of synchrotron radiation?

A) Proton
B) Baseball
C) Positron
D) Higgs Boson

➡ *C) is a suitable source of SR. Most light sources rely on electrons. But there are notable exceptions that use positrons (eg. PETRA III).*