An Introduction to 3rd Generation Light Sources

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Contents

Why Building Accelerators

Particle accelerators are devices producing beams of energetic particles such as ions, protons, neutrons, electrons, positrons, molecules, ...

Accelerators represent a fundamental research tool in science and technology that allowed for revolutionary progresses in many fields.

These include:

- **Ultra-precise electron microscopy**
- **Fundamental particle physics**
- **High brightness photon sources for material science, spectrometry, protein crystallography, … .**
- **Ion Implanters for surface modification, accelerators for sterilization and polymerization, …**
- **Radiation surgery and diagnostics, therapy of cancer, …**
- **…**

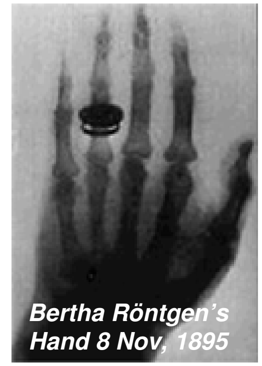
Accelerators in the World

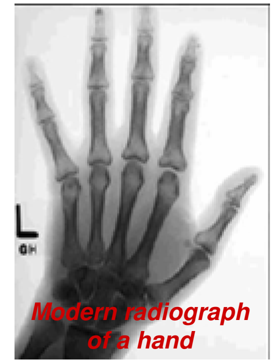
World wide inventory of accelerators, in total 15,000. Data collected by W. Scarf and W. Wiesczycka (See U. Amaldi Europhysics News, June 31, 2000)	
Category	**Number**
Ion implanters and surface modifications	7,000
Accelerators in industry	1,500
Accelerators in non-nuclear research	1,000
Radiotherapy	5,000
Medical isotopes production	200
Hadron therapy	20
Synchrotron radiation sources	70
Nuclear and particle physics research	110

- About half of the world's 15,000 accelerators are used as ion implanters, for surface modification and for sterilization and polymerization.
- The ionization arising when charged particles are stopped in matter is often utilized for example in radiation surgery and therapy of cancer. At hospitals about 5,000 electron accelerators are used for this purpose

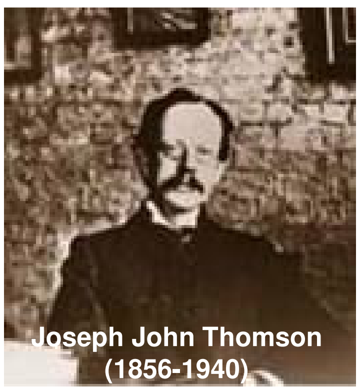
First Accelerator-Based Light Source


Wilhelm Conrad Röntgen
(1845-1923)

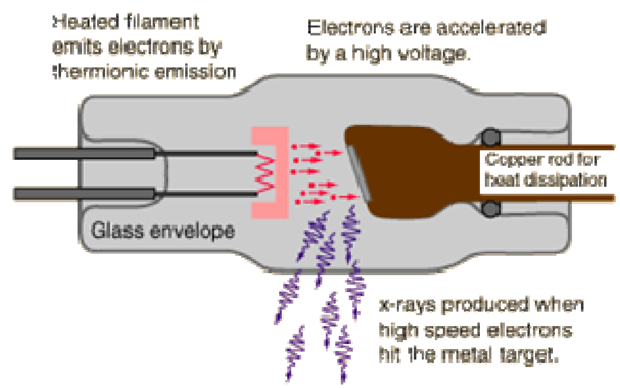

Bertha Röntgen's Hand 8 Nov, 1895


Modern radiograph of a hand

In 1895 Röntgen, using a cathode ray tube discovered the x-rays.
(1901 Nobel Prize)


Joseph John Thomson
(1856-1940)

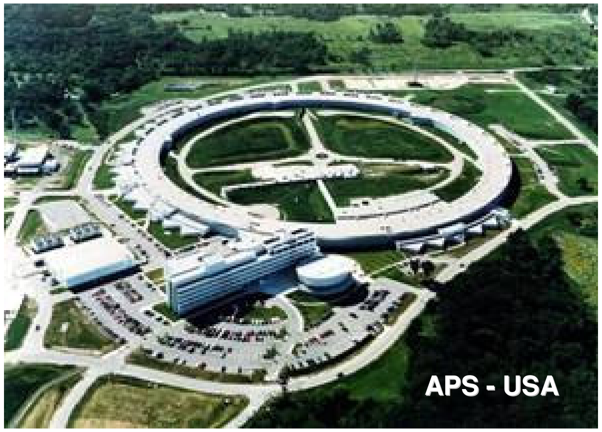
But it was only in 1897 that Thomson discovered the electron, showing that the cathode rays were these small negative charged particles being accelerated in the tube.
(1906 Nobel Prize)



From: hyperphysics.phy-astr.gsu.edu

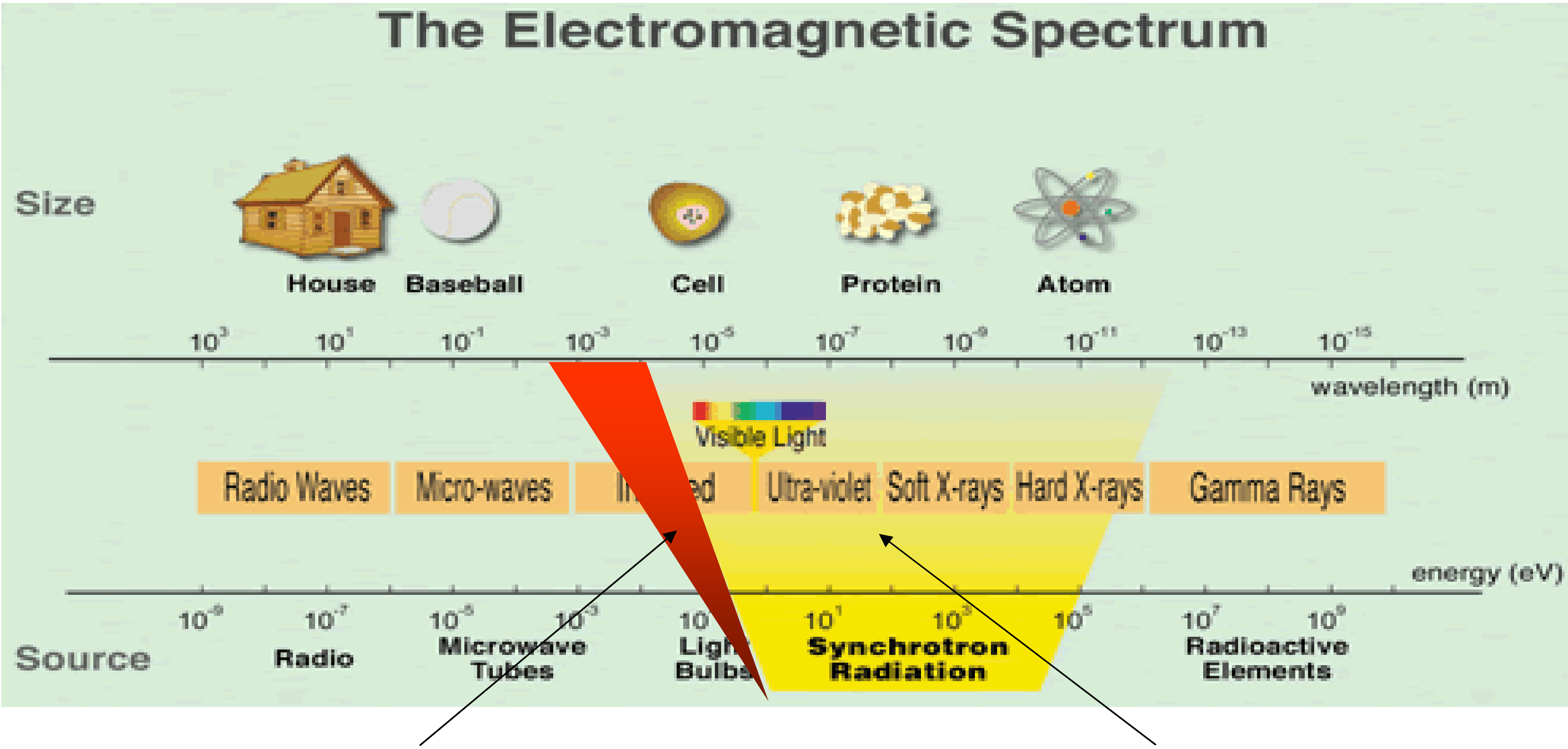
Particle accelerators were used even before being discovered!

Modern Storage Ring Based Light Sources



Modern synchrotron light sources are accelerators optimized for the production of synchrotron radiation.

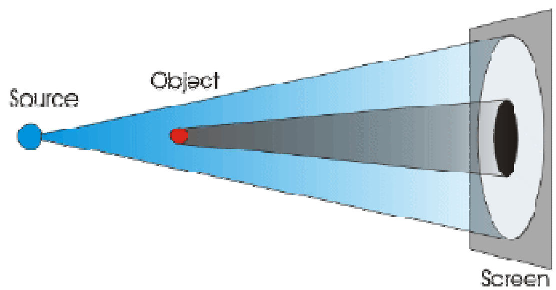
Synchrotron Radiation Electromagnetic Spectrum



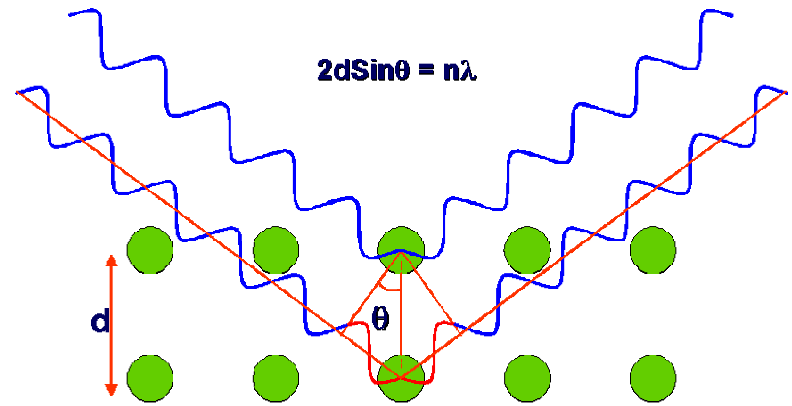
Coherent Synchrotron Radiation THz Synchrotron Generation Light Sources

Synchrotron Generation Light Sources

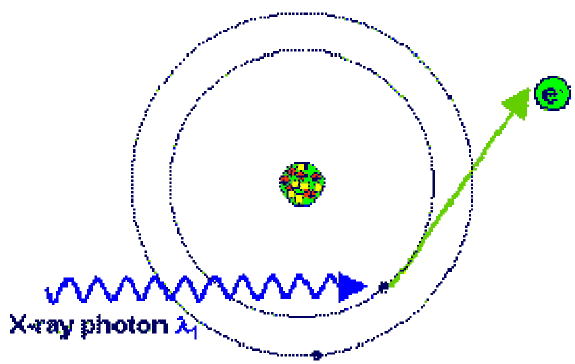
Interaction of Photon’s with Matter



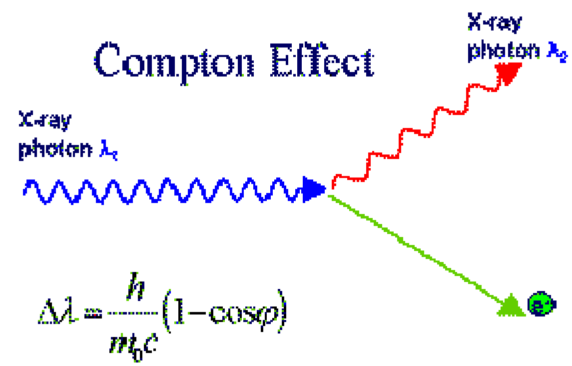
Radiography



Diffraction



Photoelectric Effect

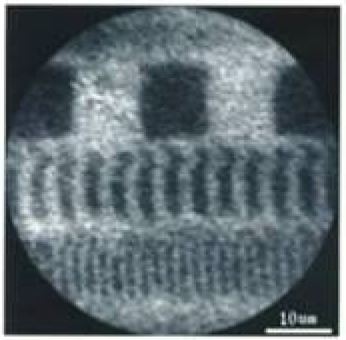


Compton Scattering

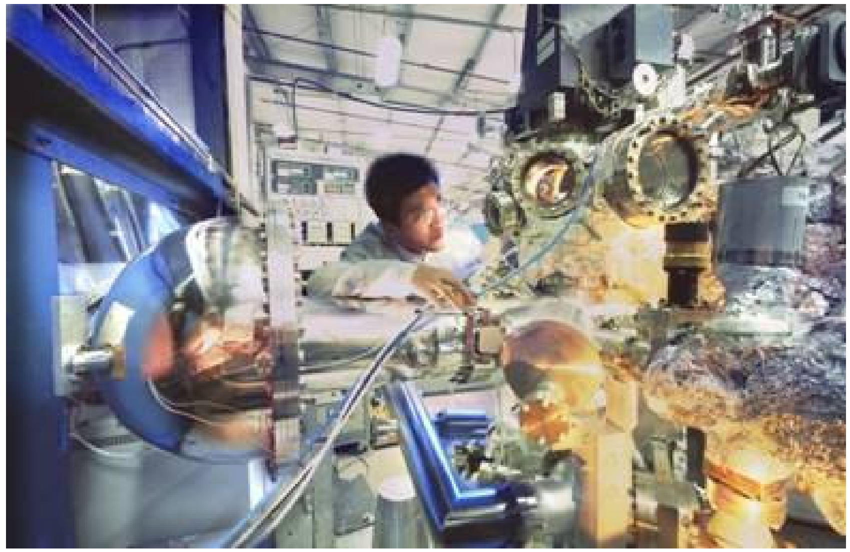
Applications

- Medicine
- Biology
- Chemistry
- Material Science
- Environmental Science
- and much more

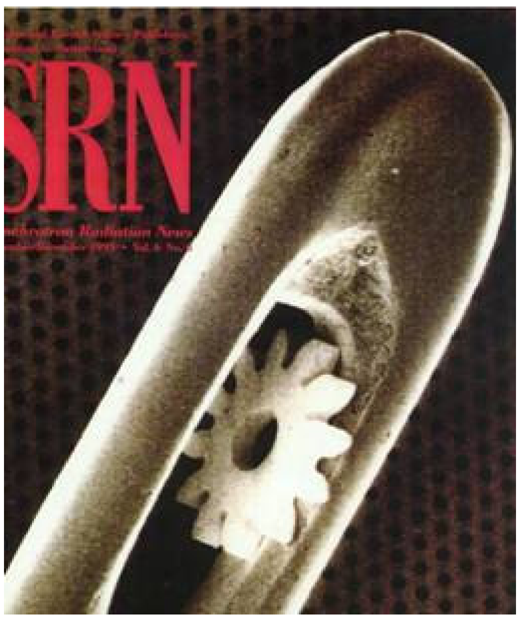
Materials Science



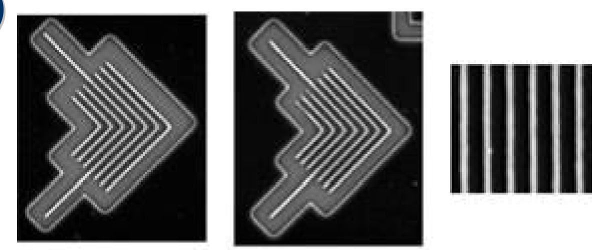
Visualizing magnetic bits on a computer hard drive



Using SR to learn how high temperature superconductors work



Using synchrotron radiation (SR) to make miniature mechanical and electromechanical devices and generating smaller and smaller chips devices by UV and EUV (13.5 nm) Lithography

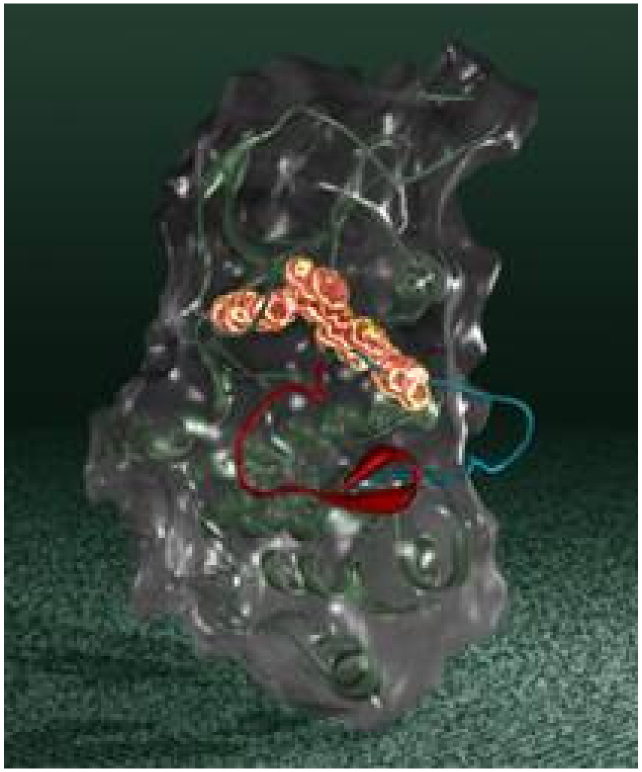


45 nm 3:1

39 nm 3:1

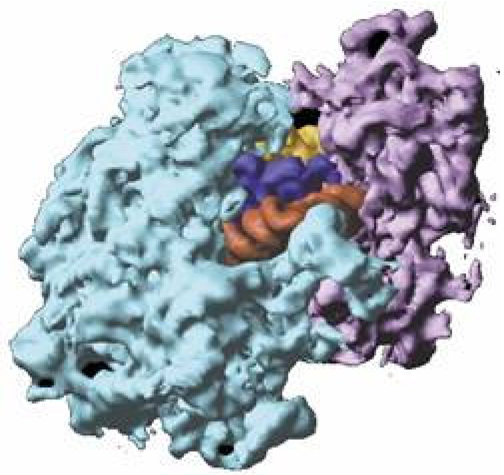
Protein Crystallography

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

Cellular Imaging and Biomedicine

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.

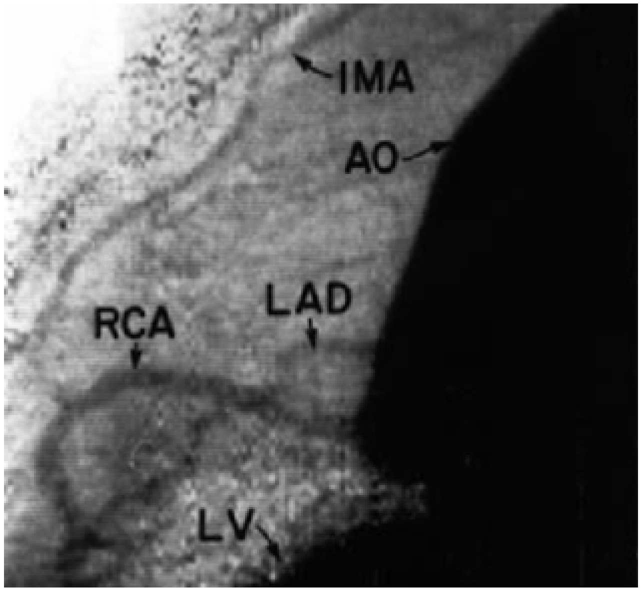
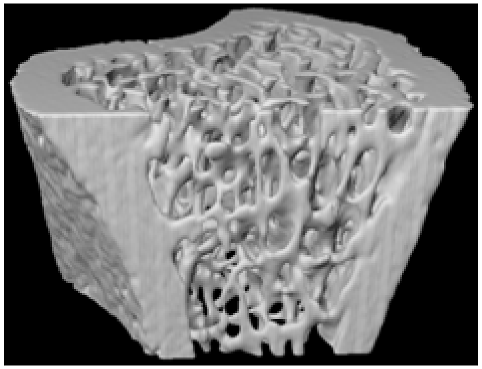
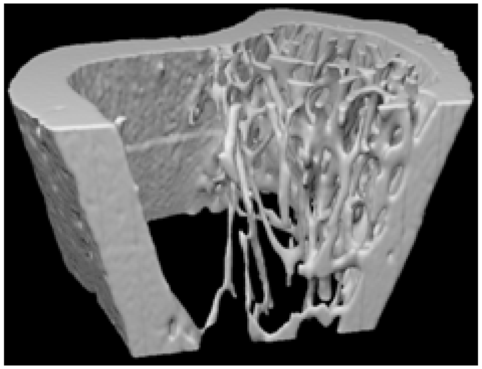


Image of a human coronary artery taken with synchrotron radiation at SSRL



before estrogen loss



after estrogen loss

Studies of osteoporosis at SSRL

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**

X-rays have enabled seminal scientific discoveries

BERKELEY LAB

18 Nobel Prizes
Based on X-ray Work

Chemistry

1936: Peter Debye

1962: Max Purutz and Sir John Kendrew

1976 William Lipscomb

1985 Herbert Hauptman and Jerome Karle

1988 Johann Deisenhofer, Robert Huber and Hartmut Michel

1997 Paul D. Boyer and John E. Walker

2003 Peter Agre and Roderick Mackinnon

Physics

1901 Wilhem Rontgen

1914 Max von Laue

1915 Sir William Bragg and son

1917 Charles Barkla

1924 Karl Siegbahm

1927 Arthur Compton

1981 Kai Siegbahn

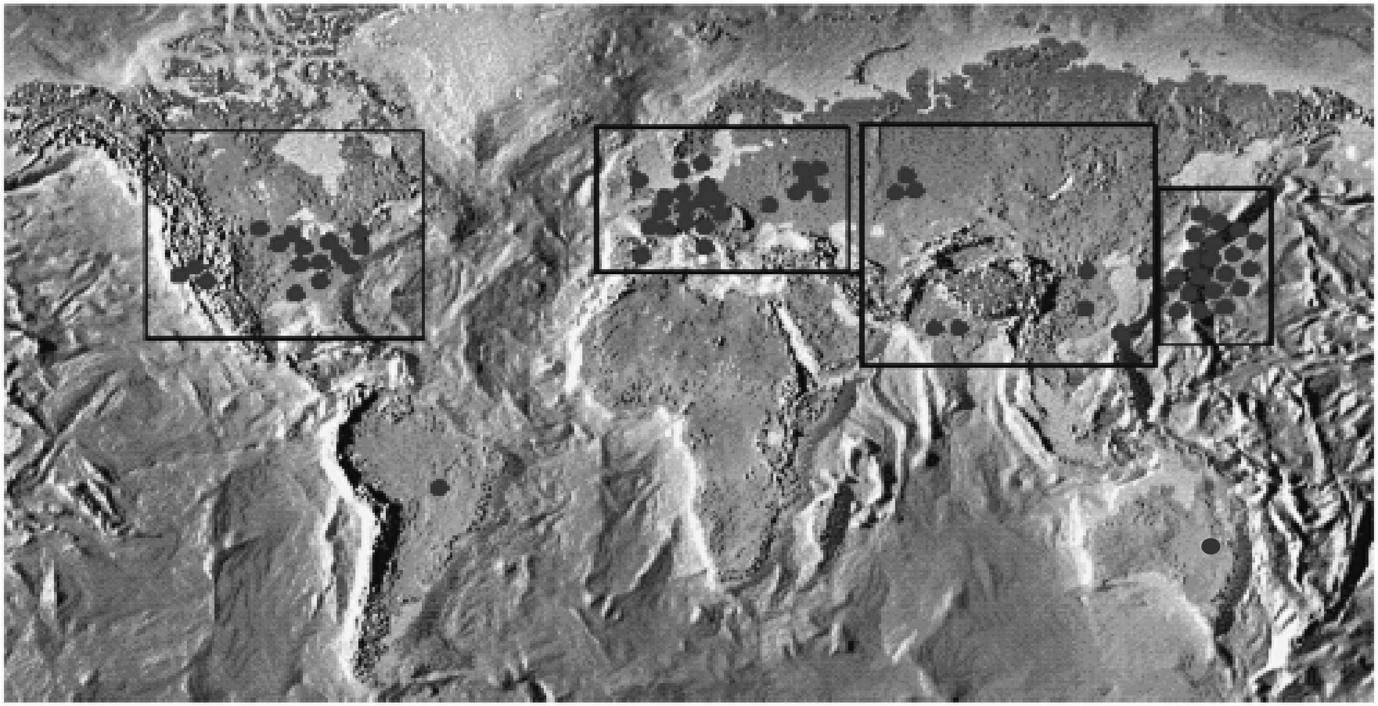
Medicine

1946 Hermann Muller

1962 Frances Crick, James Watson and Maurice Wilkins

1979 Alan Cormack and Godrey Hounsfield

20 000 Users World-Wide



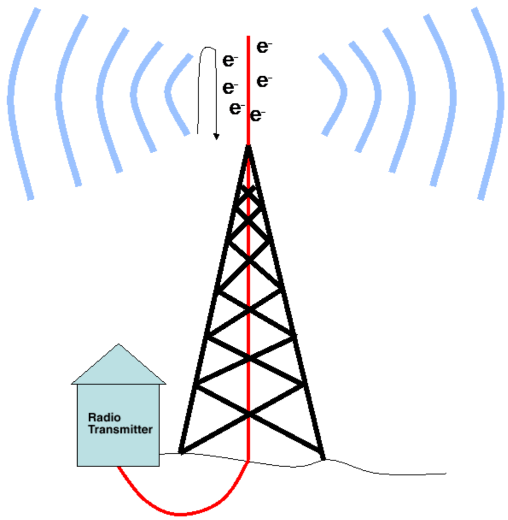
- **54 in operation in 19 countries used by more than 20,000 scientists**
- **8 in construction**
- **11 in design/planning**

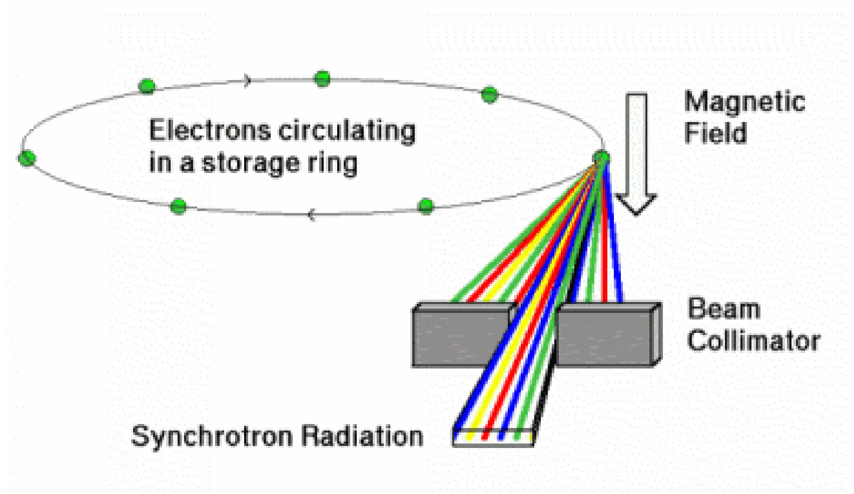
For a list of SR facilities around the world see
http://ssrl.slac.stanford.edu/SR_SOURCES.HTML
www.sesame.org.jo

How Accelerators Can Generate Light from Charged Particles?

Electrons accelerating by running up and down in a radio antenna emit radio waves (long wavelength electromagnetic waves)

- Synchrotron radiation is electromagnetic radiation emitted when charged particles are radially accelerated (move on a curved path).



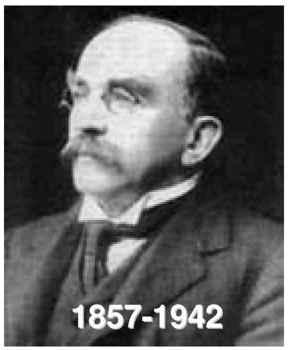


Both cases are manifestation of the same physical phenomenon:

Charged particles radiate when accelerated.

The Classical Picture

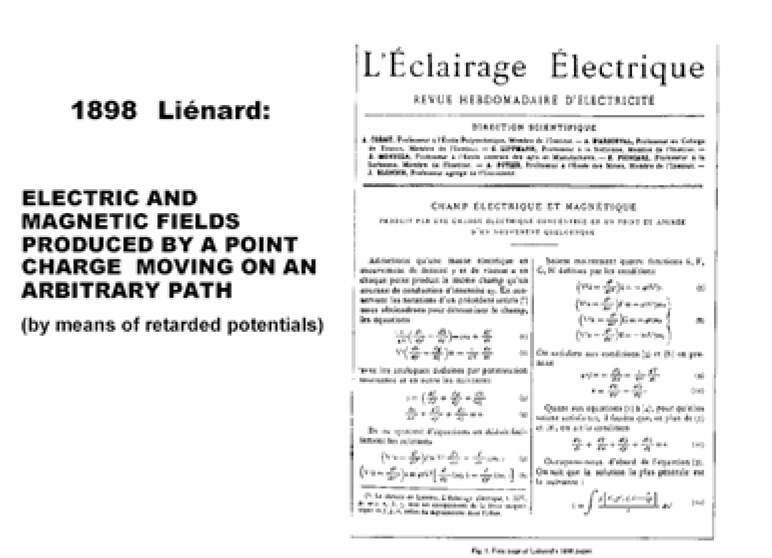
- **The theory for the radiation from charged particles can be derived in the framework of classical electromagnetism.**



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

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

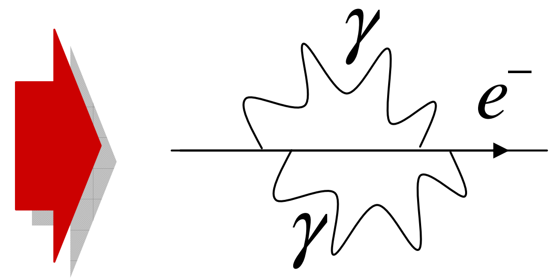
Larmor Power



- 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

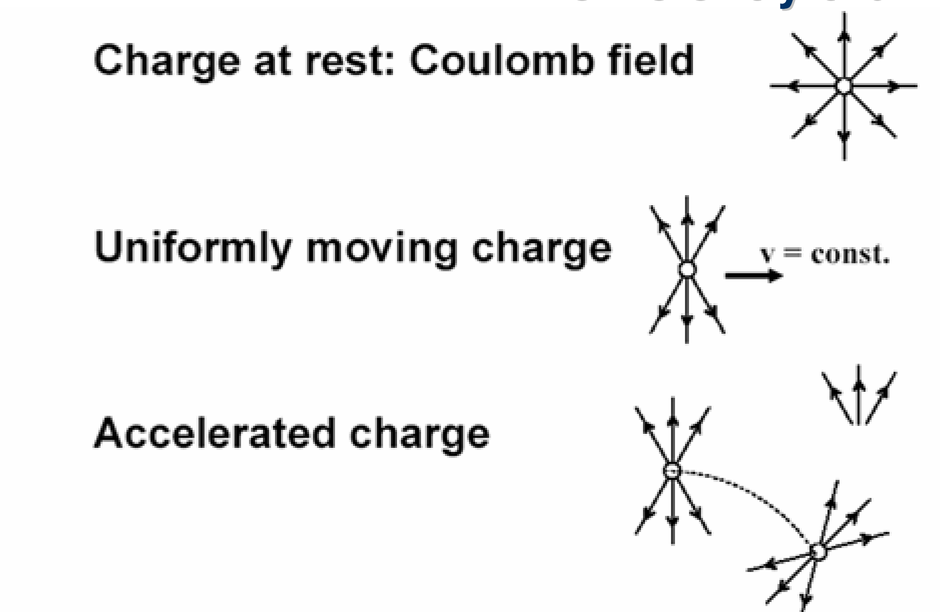
A Different Point of View

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



• The **acceleration** process acts as a "kick" that separates the particle from its photons that become real and independently observable.

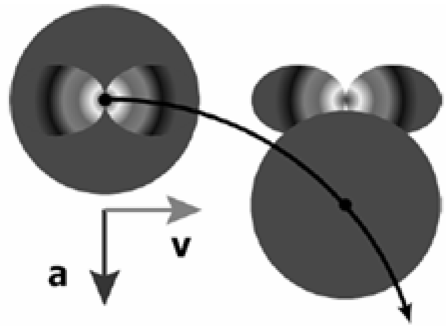
•Lighter particles are "easier" to accelerate and radiate photons more efficiently than heavier particles.



In the field of the magnets in a synchrotron, charged particles move on a curved trajectory. The transverse acceleration, if strong enough, allows for the separation and *synchrotron radiation* is generated.

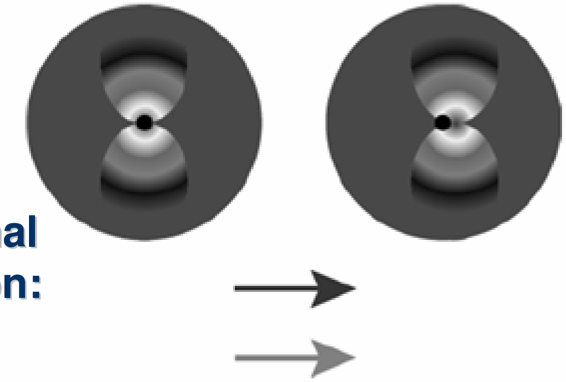
Longitudinal vs. Transverse Acceleration

Transverse acceleration:



Radiation field quickly separates itself from the Coulomb field

Longitudinal acceleration:



Radiation field cannot separate itself from the Coulomb field

$$If \quad v \approx c$$

$$\boxed{Radiated \;\; Power \propto \frac{E^4}{\rho^2}}$$

$$v \equiv particle \;\; speed, \;\; c \equiv speed \;\; of \;\; light, \;\; \rho \equiv curvature \;\; radius, \;\; E \equiv particle \;\; energy$$

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

Particle Accelerators for Generating Light

We just showed that if we accelerate charged particles to a velocity approaching the speed of light and that if we force them on curved trajectories we can generate high intensity radiation.

We also saw that the lighter the particle the easier is to accelerate it to ~ speed of light.

$$Electron\ mass \cong 9.1095\times 10^{-31}\ kg \qquad Proton\ mass \cong 1.6726\times 10^{-27}\ kg$$

Electrons (positrons) storage rings are the ideal candidates for an accelerator-based light source!

Building an Accelerator: The Main Ingredients

- Maxwell Equations in vacuum (SI Units – differential form):

$$\nabla \cdot \overline{E} = \frac{\rho}{\varepsilon_0}$$

Coulomb's or Gauss' law for electricity

$$\nabla \times \overline{E} = -\frac{d\overline{B}}{dt}$$

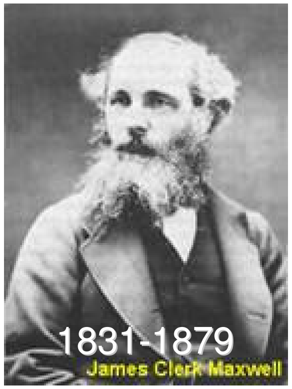
Faraday's law

$$\nabla \cdot \overline{B} = 0$$

Gauss' law for magnetism

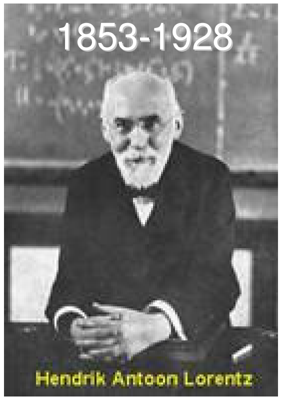
$$\nabla \times \overline{B} = \mu_0 \overline{J} + \mu_0 \varepsilon_0 \frac{d\overline{E}}{dt}$$

Ampere's law



- Lorentz Force:

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



Changing the Particle Energy

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

$$W = \int \overline{F} \cdot d\overline{l} = q\int \overline{E} \cdot d\overline{l} + \cancel{q\int \left(\overline{v} \times \overline{B}\right) \cdot d\overline{l}}$$

B fields can change the trajectory of a particle
But <u>cannot</u> do *work* and thus change its energy

$$\boxed{\overline{F} = q\overline{E} \qquad W = q\int \overline{E} \cdot d\overline{l}}$$

Charged particle energy can be modified by electric fields.

Confining Charged Particles on a Specific Trajectory

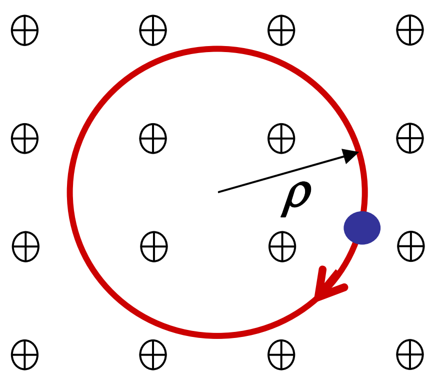
Both electric and magnetic field can be used for confining and steering charged particles.

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

$$\overline{F} = q\overline{v} \times \overline{B}$$

But in the great majority of particle accelerators is mainly the magnetic field used for the scope.

For example, it is well known that a particle with momentum p and charge q inside an uniform magnetic field B moves on a circle.



B field perpendicular to the viewgraph plane

$$\rho = \frac{p}{qB}$$

$$Larmor\ \ Radius$$

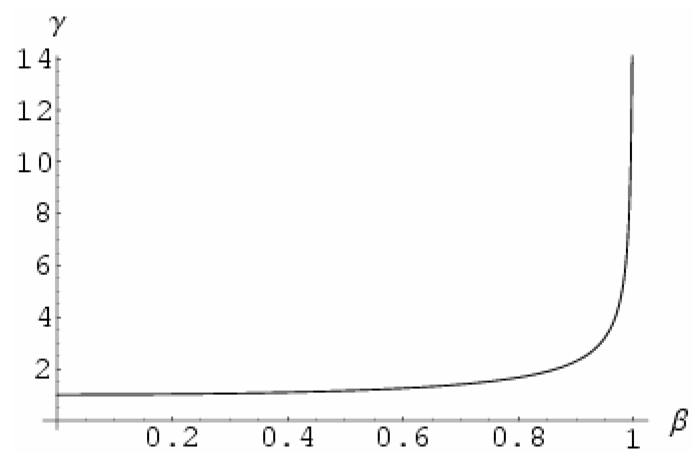
Approaching the Speed of Light

The special relativity states that the speed of light is a velocity limit:

$$\boxed{v \le c \quad always}$$

$$\beta = \frac{v}{c} \Rightarrow 0 \le \beta \le 1$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{E_T}{m_0 c^2}$$



The relativistic momentum:

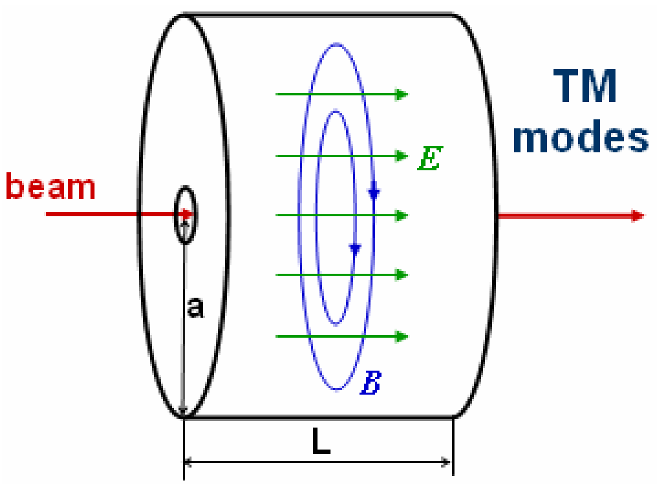
$$p = \gamma m_0 v \qquad p = m_0 v \quad v << c \qquad p \cong \gamma m_0 c \quad v \approx c$$

- The electron case:

$$\text{If} \quad E_T = 10 \ \text{MeV} \quad \Leftrightarrow \quad \gamma \cong 20.6 \quad \Leftrightarrow \quad \beta \cong 0.9988 \approx 1$$

For energies of ~ 10 MeV and above, electrons are "relativistic" particles traveling at the speed of light.

Controlling the Electric Field For Beam Acceleration



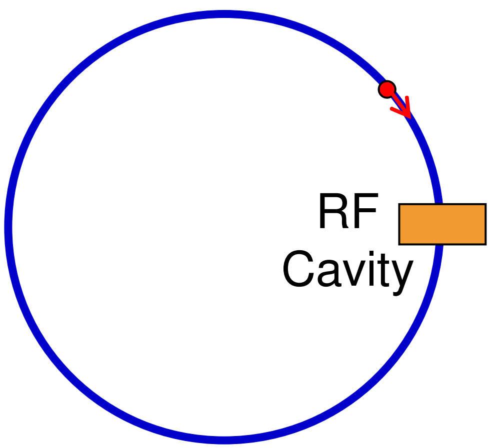
For the TM_{010} mode in metallic "pillbox":

$$E_z^{TM\,010} = E_0(r)\cos(\omega_C t)$$

$$f_C = \omega_C / 2\pi = 2.405\, c / 2\pi a$$

$$\text{Example} \quad f_0 = 500\, MHz \iff a = 229.5\, mm$$

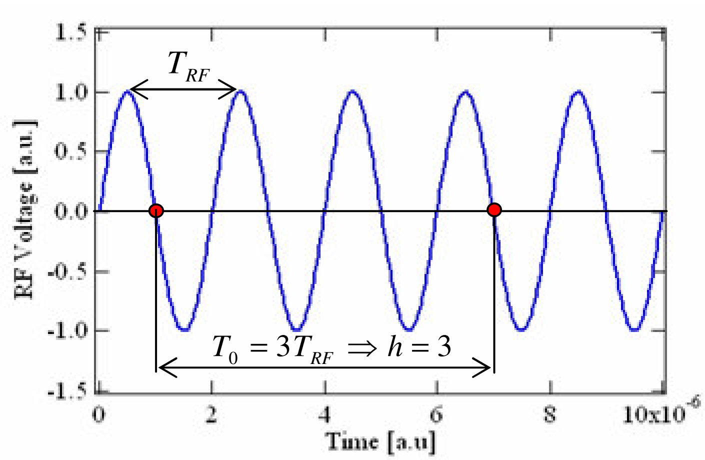
In a storage ring, the energy is controlled by one or more RF cavities:



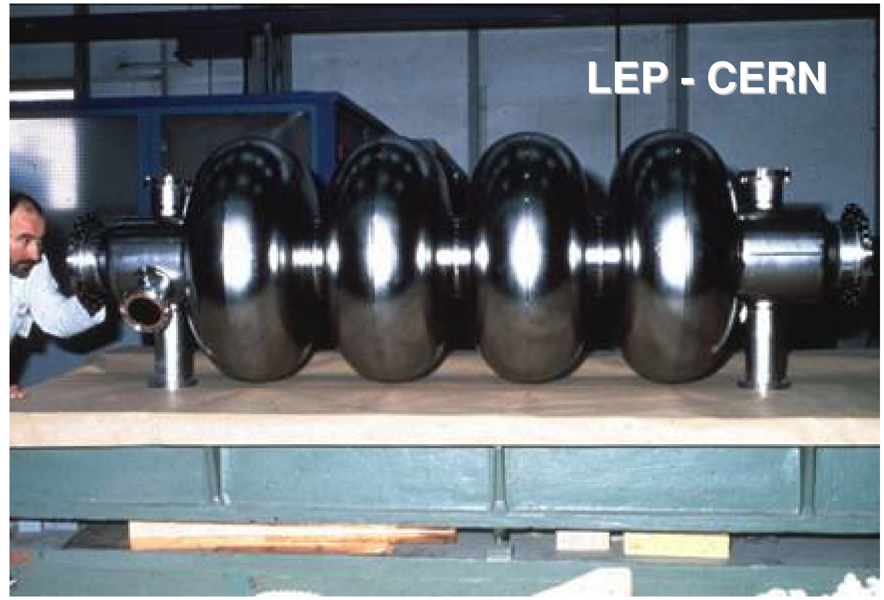
$$V_{RF}(t) = \hat{V}\sin(2\pi f_{RF} t)$$

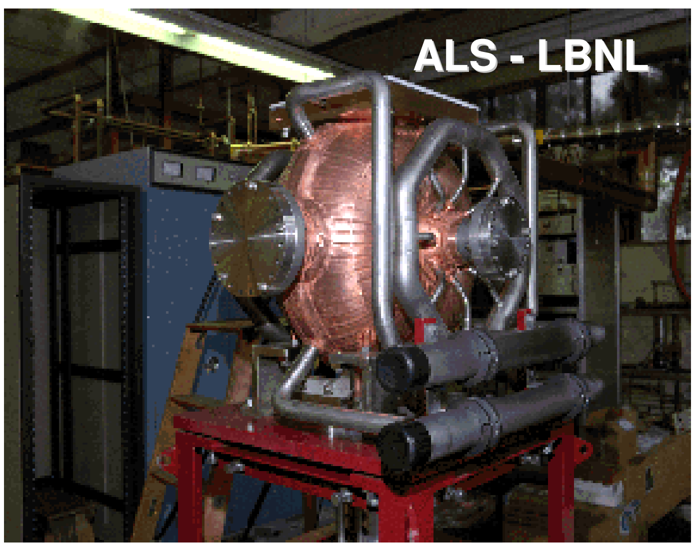
$$T_0 = hT_{RF} \Rightarrow f_0 = \frac{f_{RF}}{h}$$

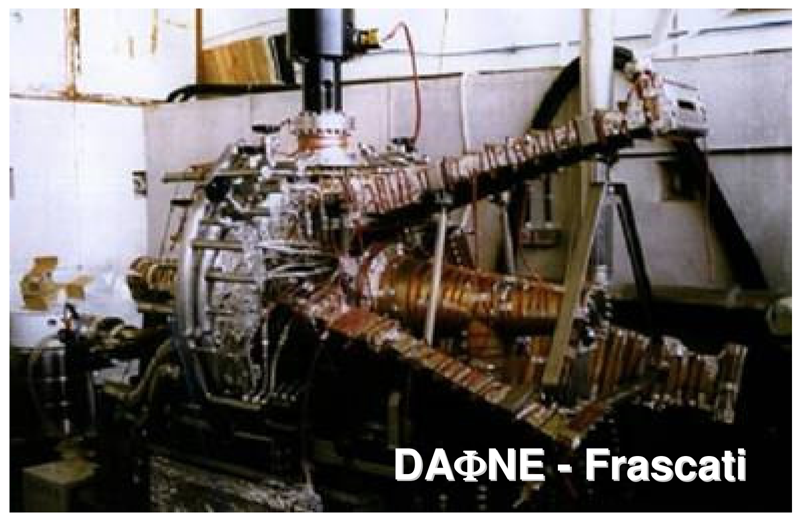
Synchronicity Condition



Real RF Cavities





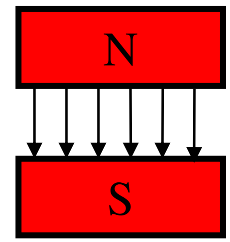


Using the Magnetic Field for Beam Confinement

There are several magnet types that are used in storage rings, for example:

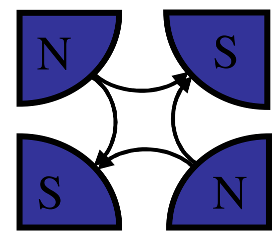
Dipoles → used for steering

$$B_x = 0$$
$$B_y = B_o$$



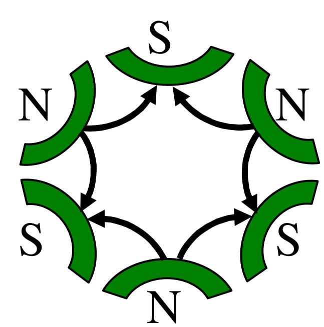
Quadrupoles → used for focusing

$$B_x = K\,y$$
$$B_y = K\,x$$

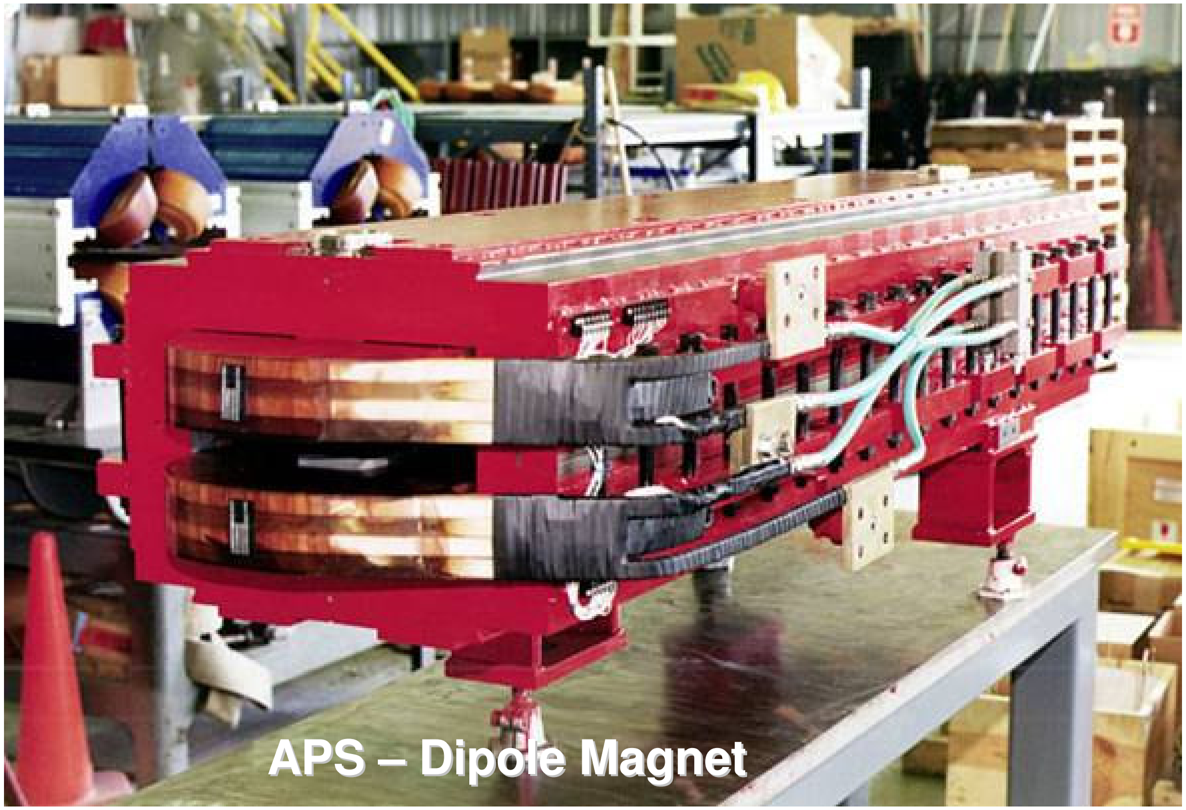


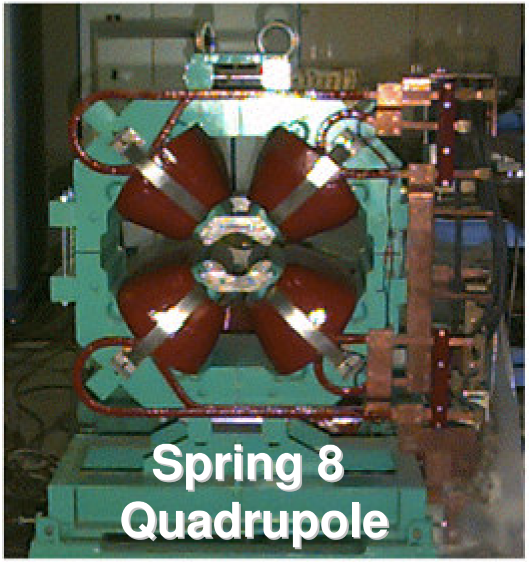
Sextupoles → used for chromatic correction

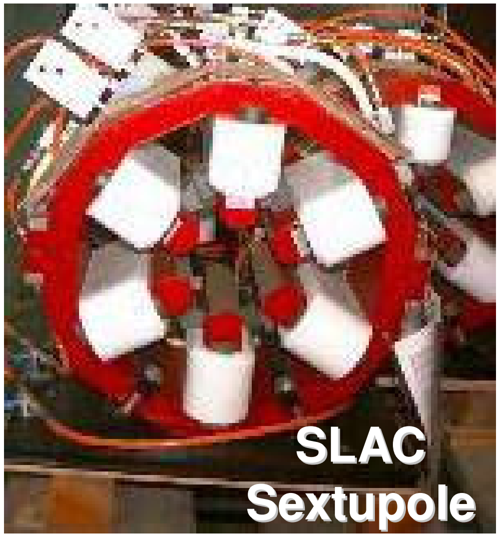
$$B_x = 2S\,xy$$
$$B_y = S\,(x^2 - y^2)$$



Real Magnets

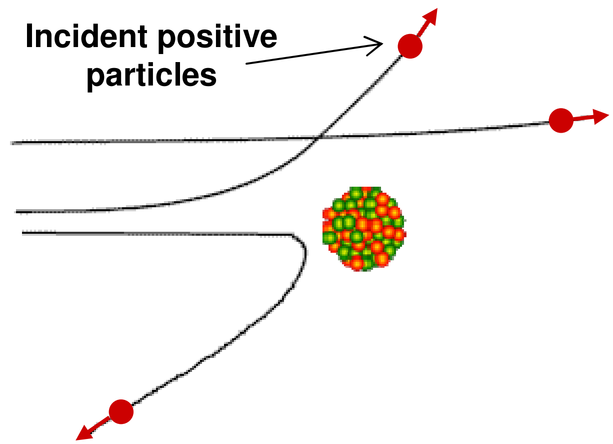






Residual Gas Scattering

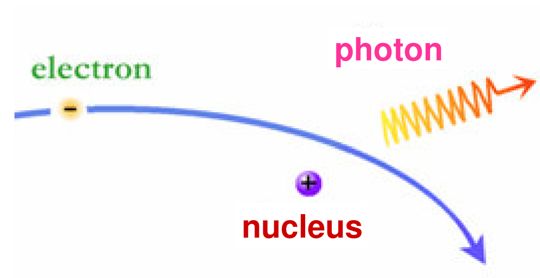
- **When an electron passes close to a residual gas molecule, it interacts with the molecule nucleus. Two cases are important for electron rings:**



- **Rutherford or elastic scattering, when the interaction changes the electron trajectory but does not change its energy:**

$$\frac{d\sigma_R}{d\Omega} = \frac{1}{(4\pi\varepsilon_0)^2}\left(\frac{Z_{Inc} Z e^2}{2\beta c\, p}\right)^2 \frac{1}{\sin^4(\theta/2)} \quad [MKS]$$

- **Gas Bremsstrahlung or inelastic scattering, when the interaction includes also the emission of a photon (Bethe and Heitler):**

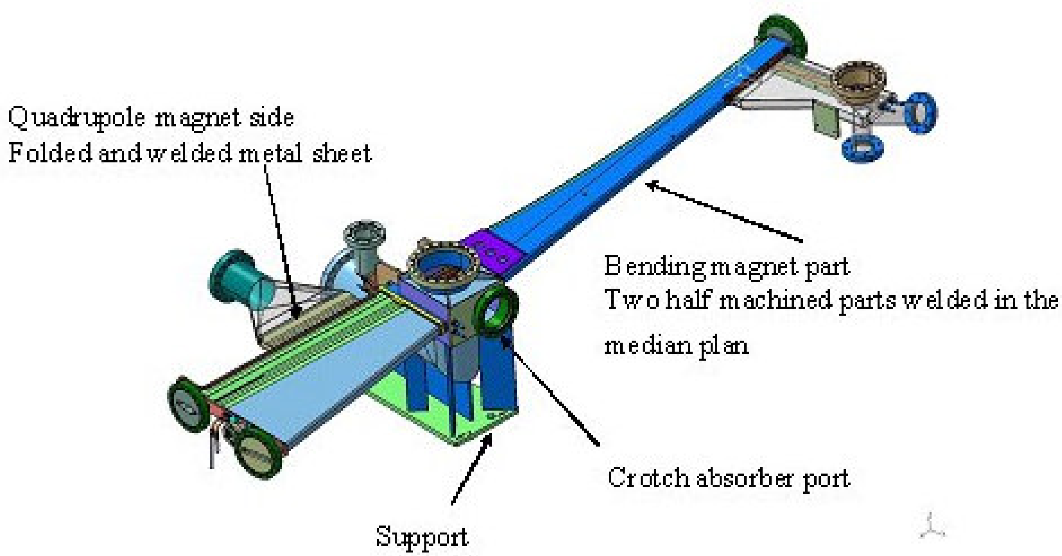


$$\frac{d\sigma_B}{d\kappa} = \alpha\frac{Z^2 r_0^2}{\kappa}\left\{\left[\frac{4}{3}\left(1-\frac{\kappa}{E_0}\right)+\left(\frac{\kappa}{E_0}\right)^2\right]\left[\varphi_1(\kappa_1)-\frac{4}{3}\ln Z\right]+\frac{2}{3}\left(1-\frac{\kappa}{E_0}\right)\left[\varphi_2(\kappa_1)-\varphi_1(\kappa_1)\right]\right\}$$

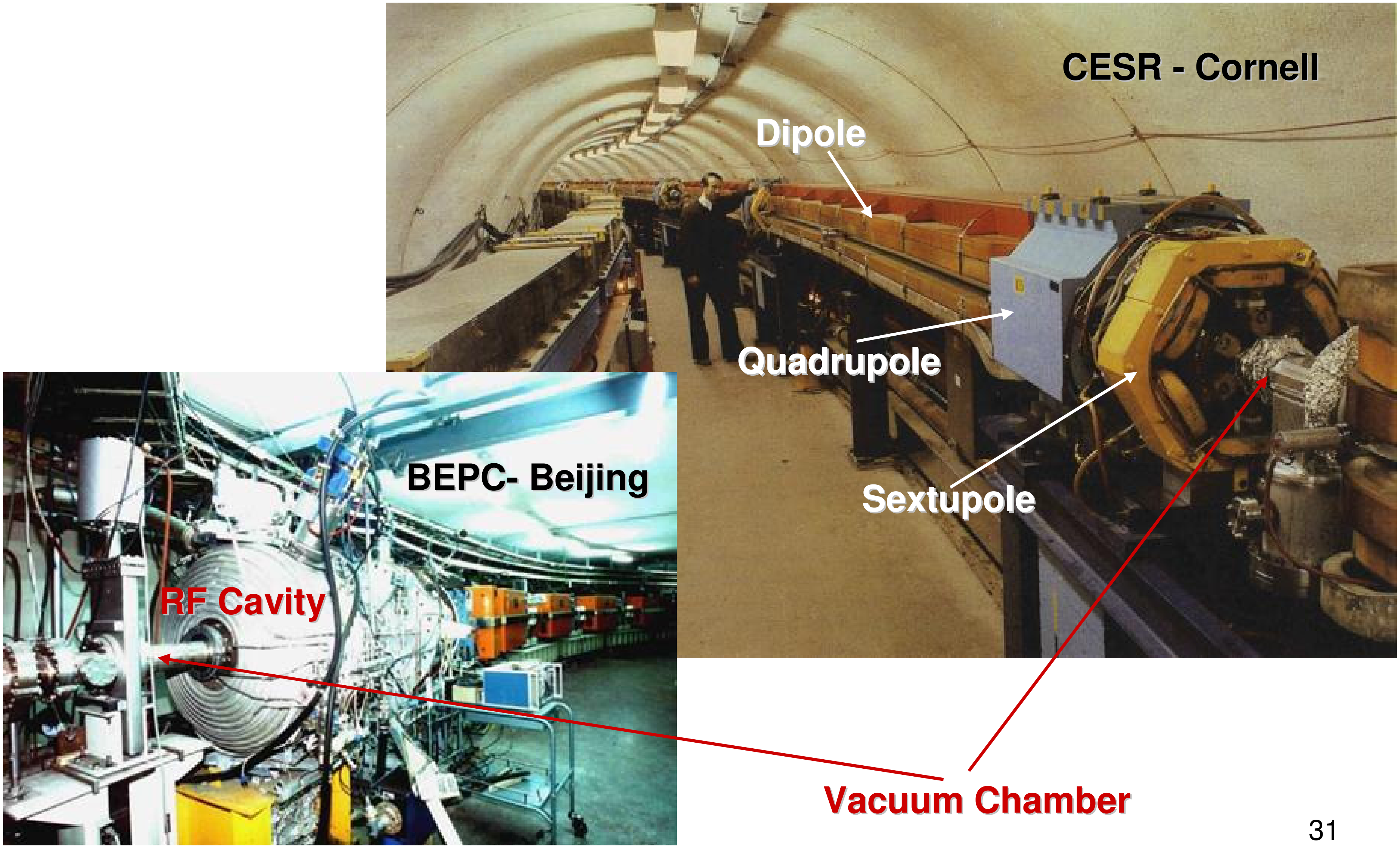
Vacuum Requirements

• Evaluating the loss rate of particles due to residual gas scattering for the typical electron ring case, one finds that **a vacuum pressure as small as 10^{-9} Torr is typically required** for ensuring many hours of beam lifetime.

• This can be achieved only by enclosing the beam inside a vacuum chamber and using a sophisticate pumping system for *ultra high vacuum* (UHV).

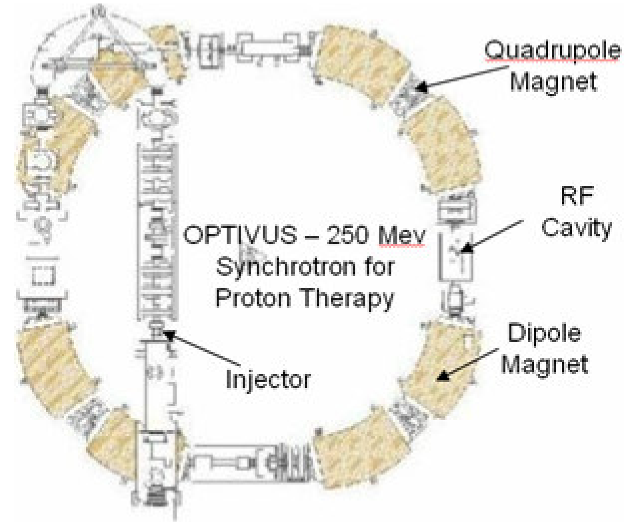


All Things Together



Synchrotrons & Storage Rings

- **In 1943 M. Oliphant conceived the synchrotron where the radius is fixed and all the fields can be confined only around the fixed orbit.**



$$\boxed{R = \frac{\gamma m_0 \beta c}{ZeB} = \text{constant} \;\Rightarrow B \;\text{ must scale} \propto \;\text{to}\; \beta\gamma}$$

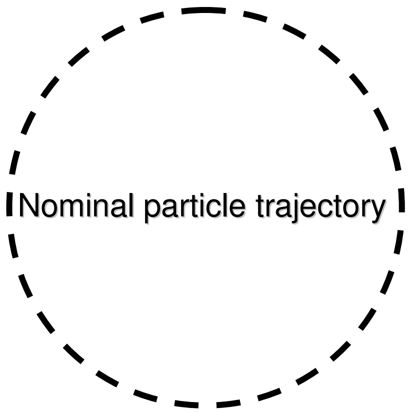
- **Synchrotrons have achieved energy as high as 100 GeV for electrons and 1000 GeV for protons**

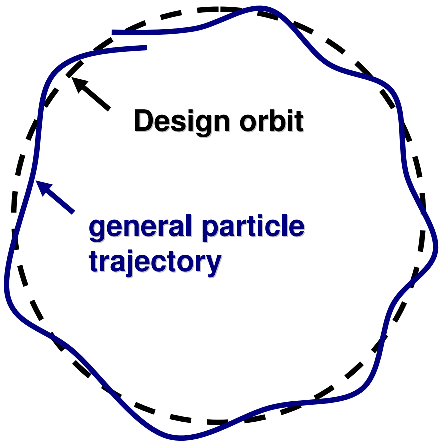
- **A synchrotron operates as a storage ring when the particles are not accelerated but just stored at a fixed energy for a relatively long time. Colliders, synchrotron light sources, …**

A Glance to the Particle Motion in a Storage RIng

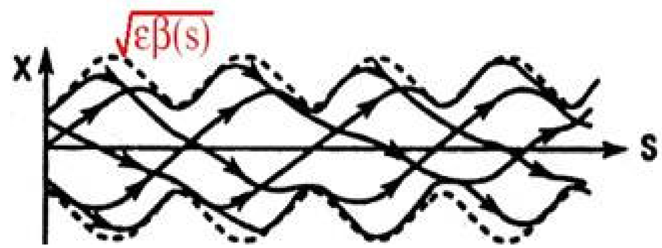
BERKELEY LAB

Transverse Plane Motion:





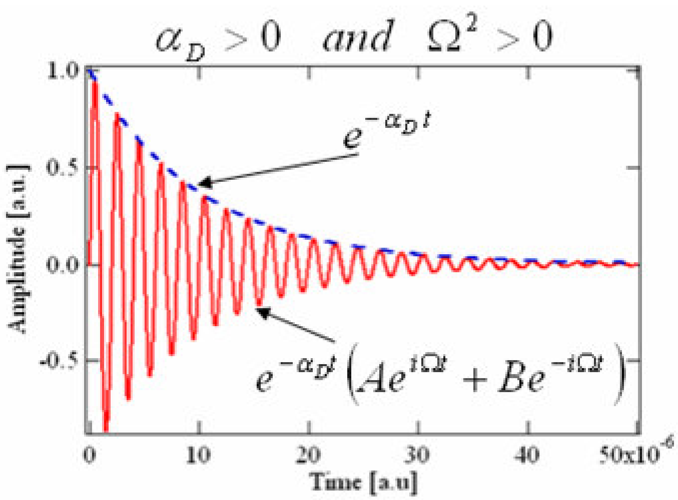
$$u(s) = a\sqrt{\beta_{Tu}(s)}\cos[\psi(s) - \psi_0]$$
$$u = x, y$$



Longitudinal Motion:

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

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



The electrons oscillate around the nominal particle position and energy!
Damping of the oscillation is due to the emission of synchrotron radiation.

Time Scale in Storage Rings

Now that we have briefly discussed the motion of a particle in an accelerator for all the planes. It can be useful remarking the time scale for the different phenomena governing the particle dynamics in a storage ring.

Revolution period: ~ hundreds of ns to μs

Transverse (betatron) oscillations: ~ tens of ns

Longitudinal (synchrotron) oscillations: ~ tens of μs

From Single Particle to a Beam

- So far we have discussed the dynamics of a single particle.
The **number of particles** per bunch in most accelerators is typically between 10^5 to 10^{13}.

- Integrating the particle motion for such a large number of particles along long accelerators can prove to be a quite tough task!

- Fortunately, *statistical mechanics* gives us very developed tools for representing and dealing with sets of large number of particles.

- The particles loose their individuality and are now represented by their distribution in the coordinate-momentum space (phase space).
The evolution of such a distribution in the ring can be studied and the behaviour of the whole beam can be characterized.

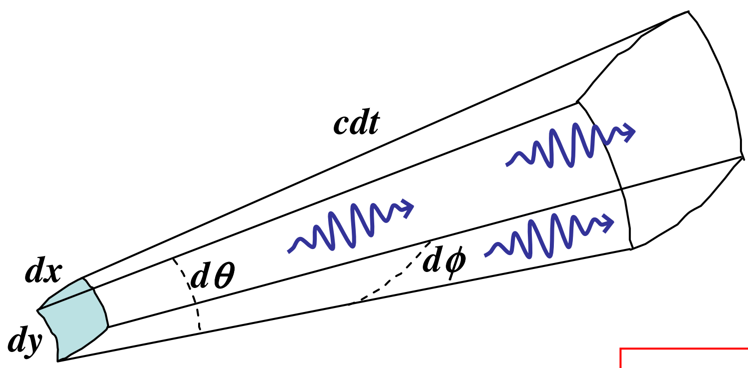
Flux and Brightness of a Light Source

- **The Photon Flux of a light source is defined as:**

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

•**Brightness is the main parameter characterizing the performance of a light source.**

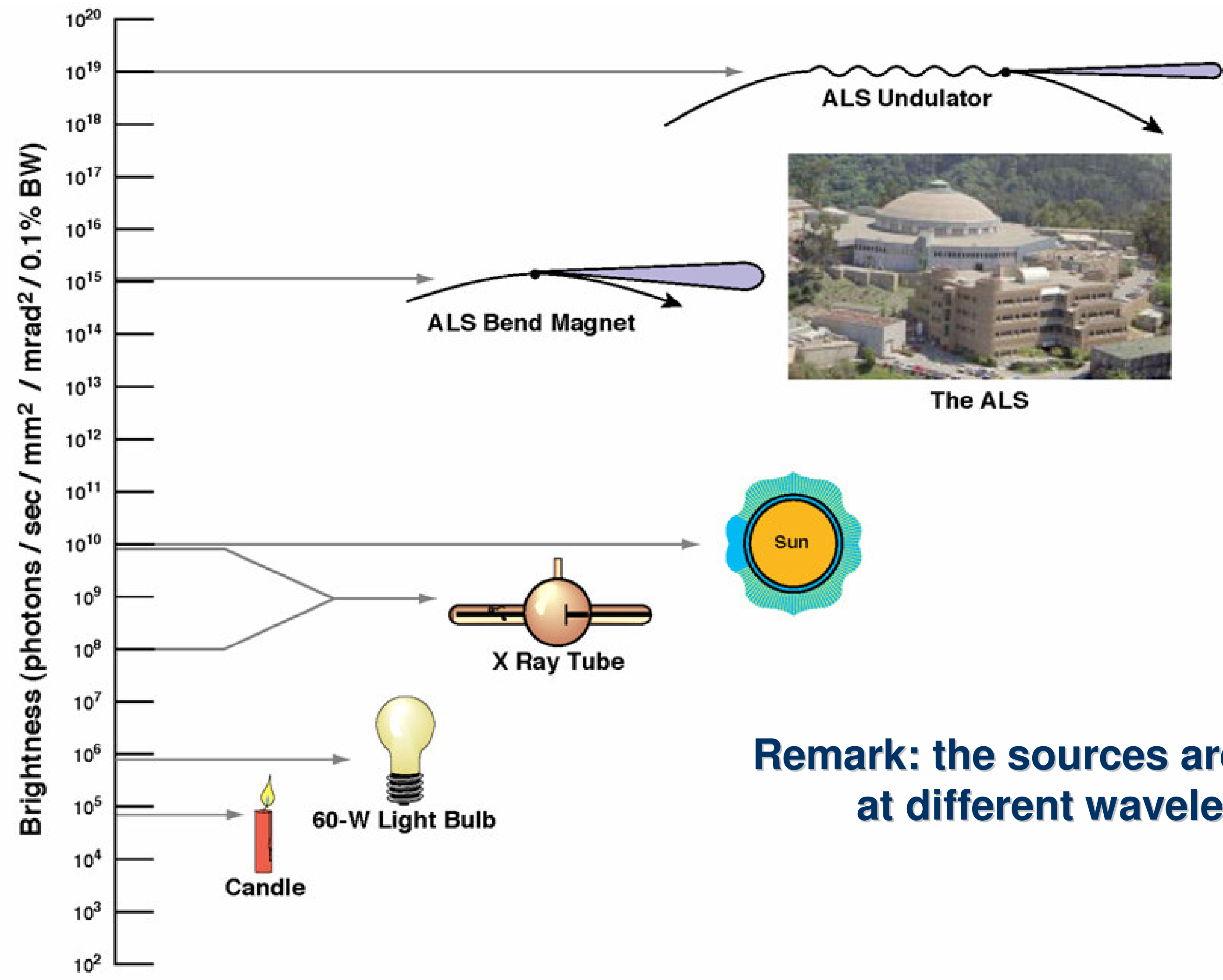
- ***Brightness is defined as the number of photons in bandwidth in the elementary volume:***



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

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

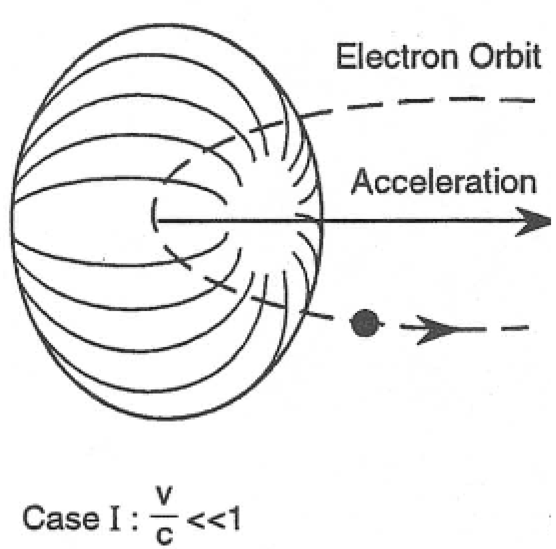
How Bright is a Synchrotron Light Source?



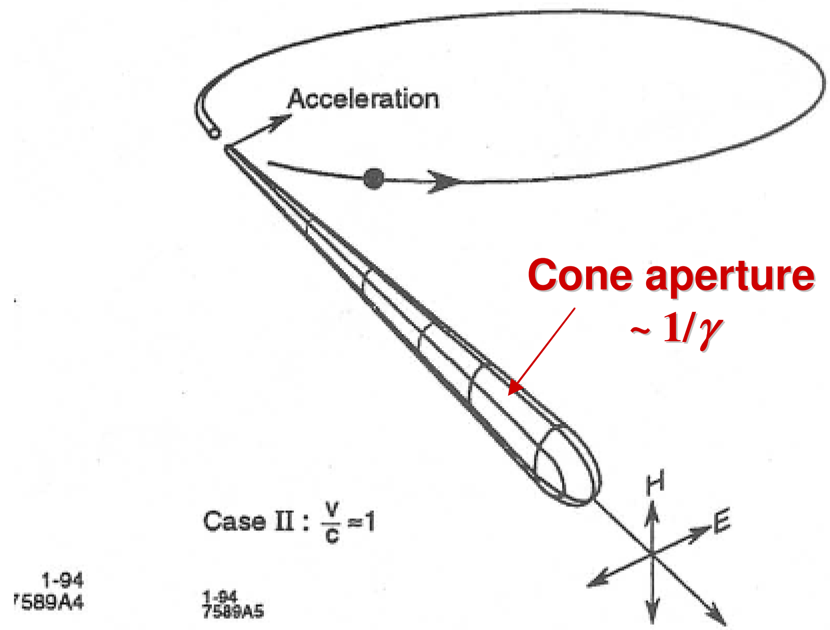
Remark: the sources are compared at different wavelengths!

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.

How to Optimize a Synchrotron Light Source

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

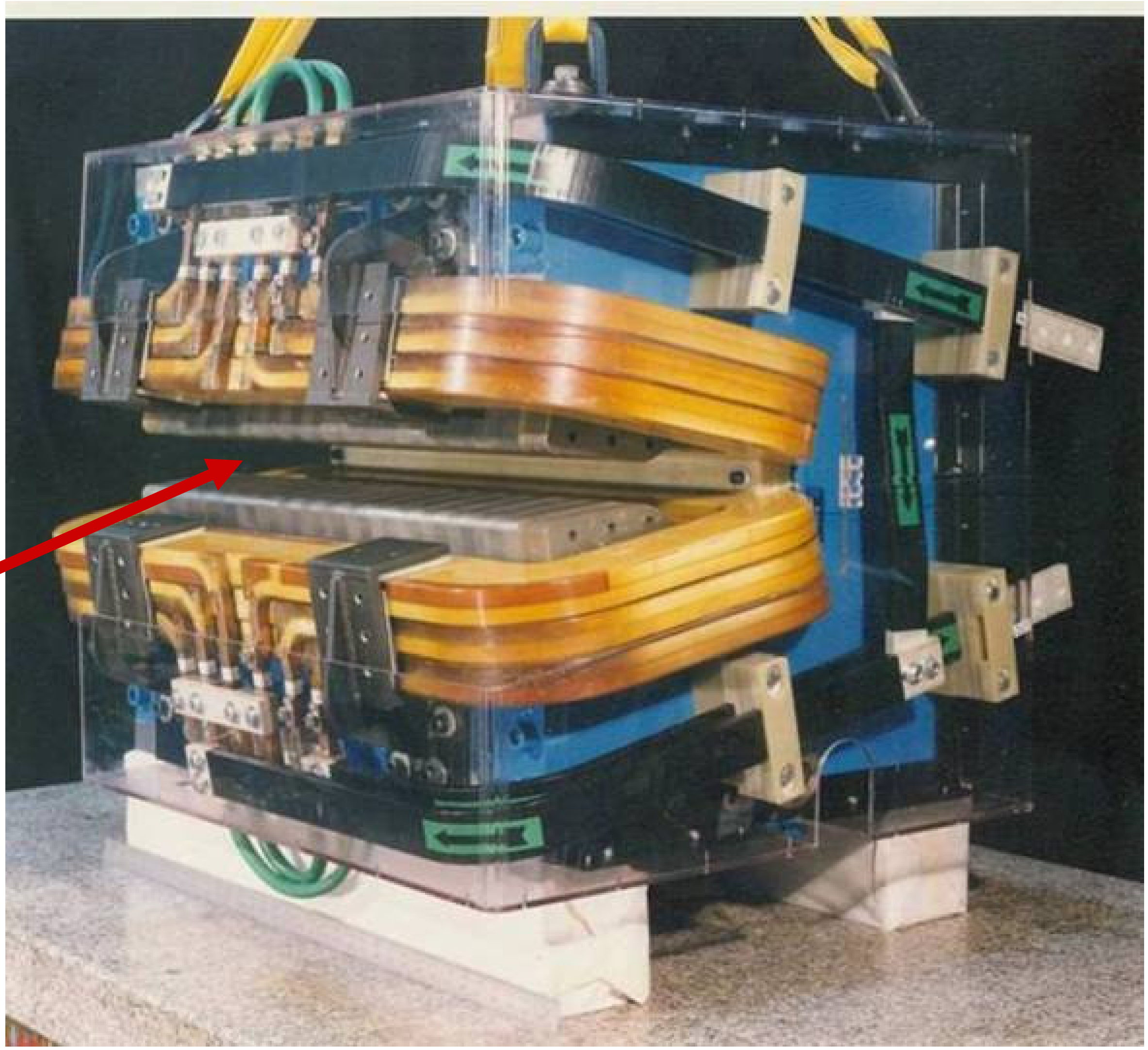
- **The battle for the brightness maximization is fought in two fronts:**
  - **In the storage ring parameters, by increasing the current and designing new lattices capable of smaller emittances (phase space volume occupied by the particles). Currents of hundreds of mA and lattices with ~ 1 nm emittance are typically used.**
  - **In the ring elements where the synchrotron radiation is actually generated: dipole magnets and insertion devices. And this is where spectacular improvements have been achieved!**

- **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 light ports in dipoles**
  - ***3rd generation*: dedicated storage rings with insertion devices**
  - ***4th generation*: free electron lasers, …**

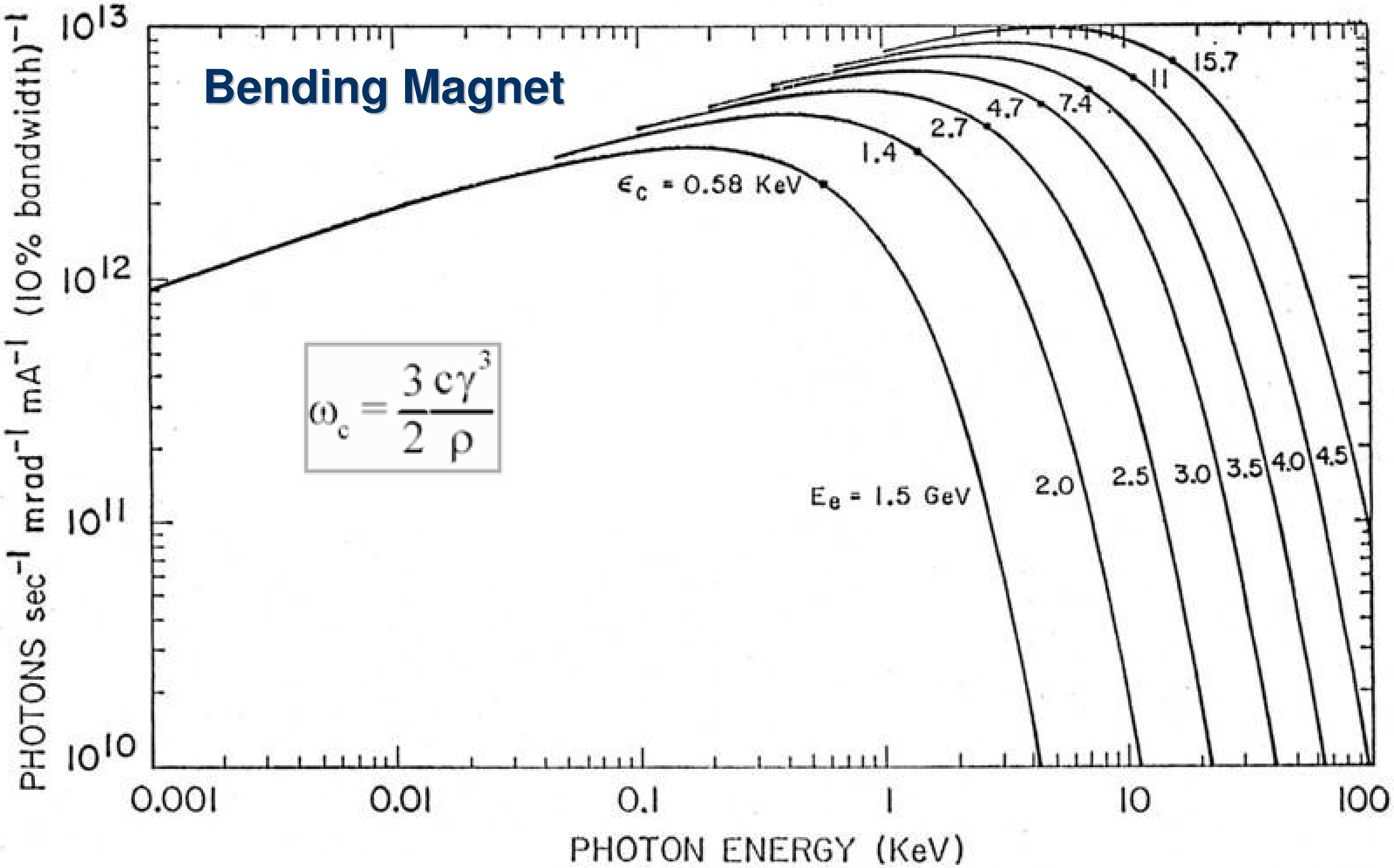
Bend Magnet

**Normal-Conductive
~ 1.5 T Max**

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



Spectrum Energy from a Dipole Source



Higher beam energies and smaller bending radii extend the spectrum of the photons towards higher frequencies

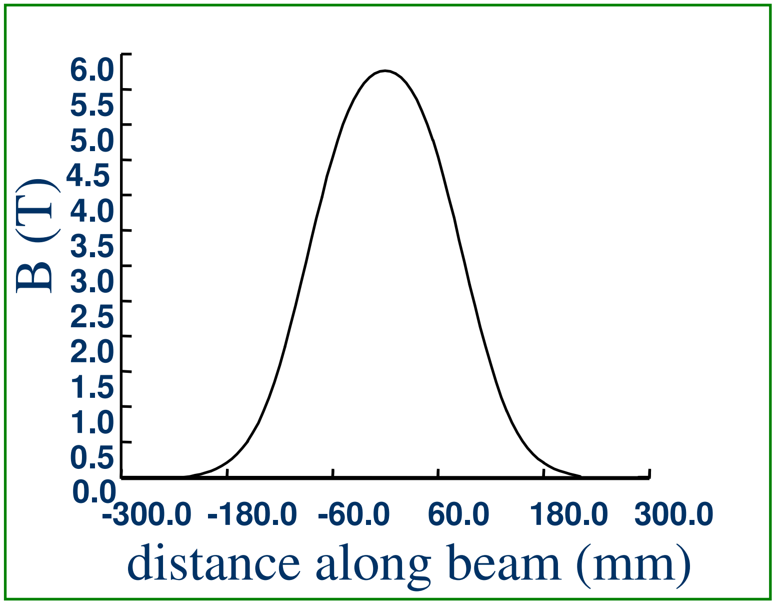
Dipoles for Hard X-rays

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 KeV photons).

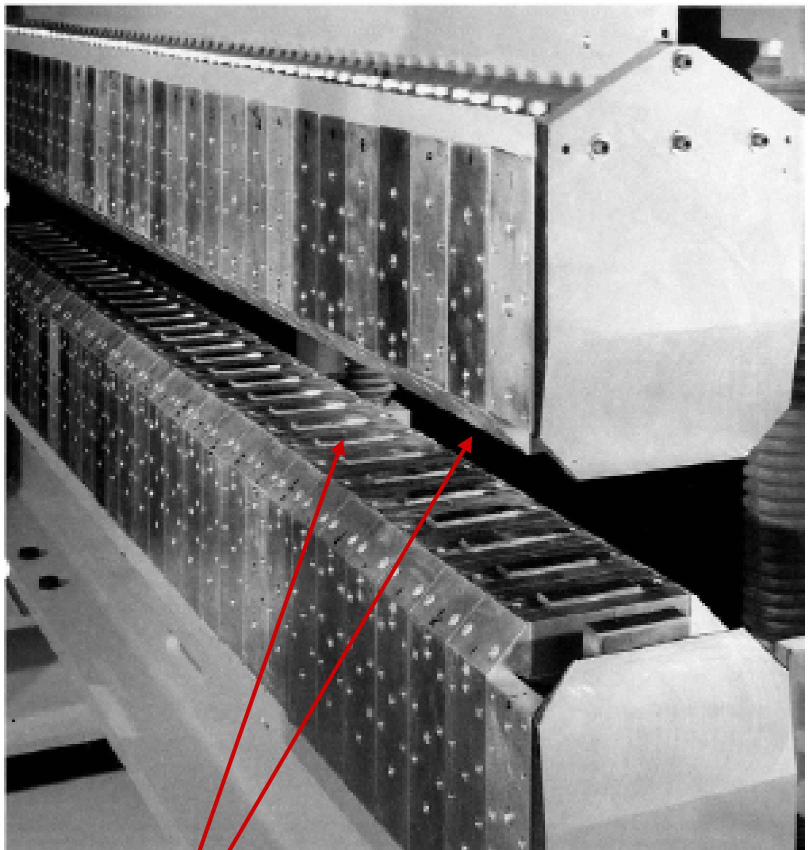
Superbend with cryostat

Superbend without cryostat

Superbend magnetic field

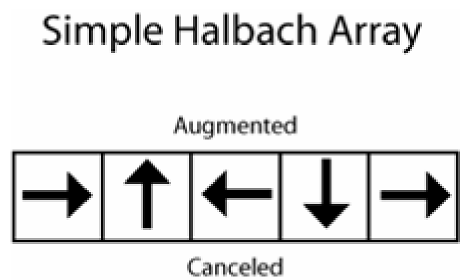


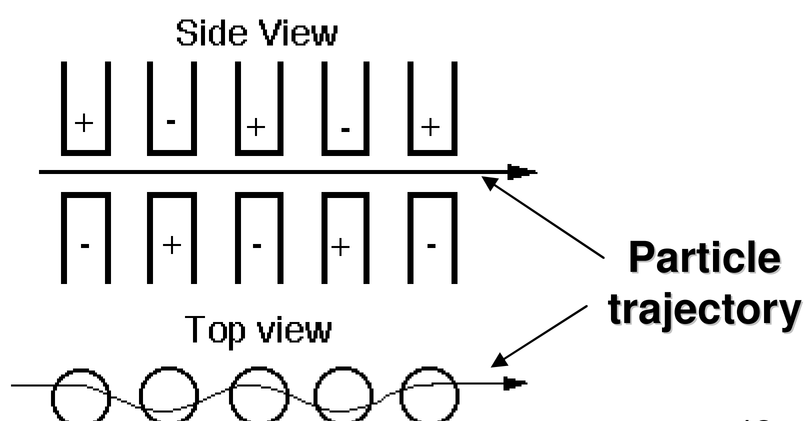
Undulators and Wigglers



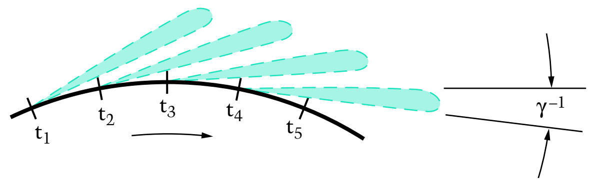
Permanent Magnets

Invented by Klaus Halbach





How Synchrotron Radiation is Generated in Storage Rings



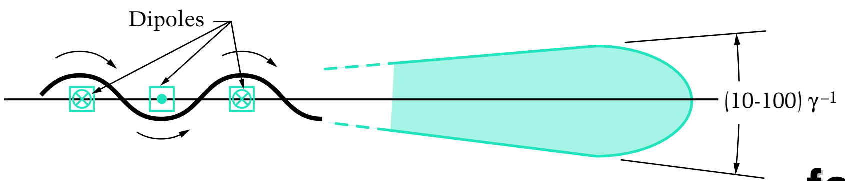
bending magnet

Continuous spectrum characterized by ε_c = critical energy

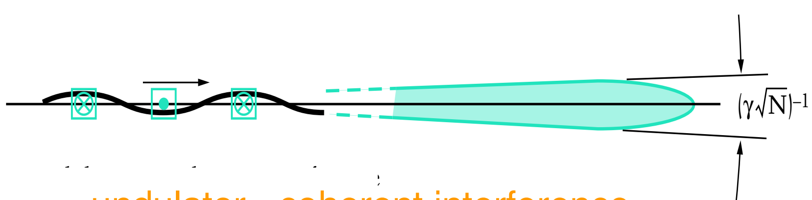
ε_c(keV) = 0.665 B(T)E²(GeV)

***For example*:**

for B = 1.35 T E = 2 GeV ε_c = 3.6keV



wiggler - incoherent superposition



undulator - coherent interference

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

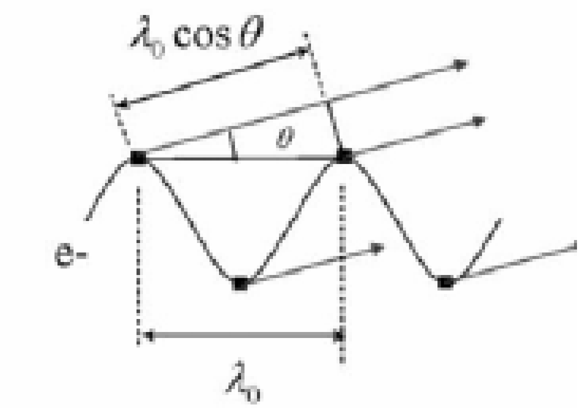
$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \sim \frac{\lambda_U}{\gamma^2} \quad \textbf{(fundamental)}$$

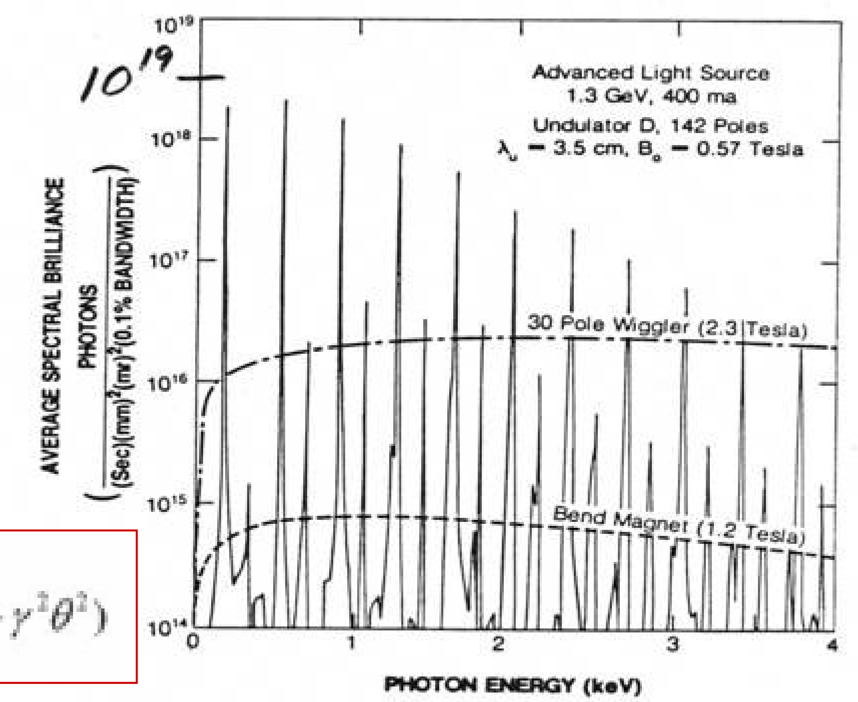
$$\varepsilon_1\,(\text{keV}) = \frac{0.95\,E^2\,(\text{GeV})}{\lambda_u^{(\text{cm})}\left(1 + \frac{K^2}{2}\right)}$$

$K = \gamma\varphi$ **where φ is the angle in each pole**

+ harmonics at higher energy

Undulator Radiation





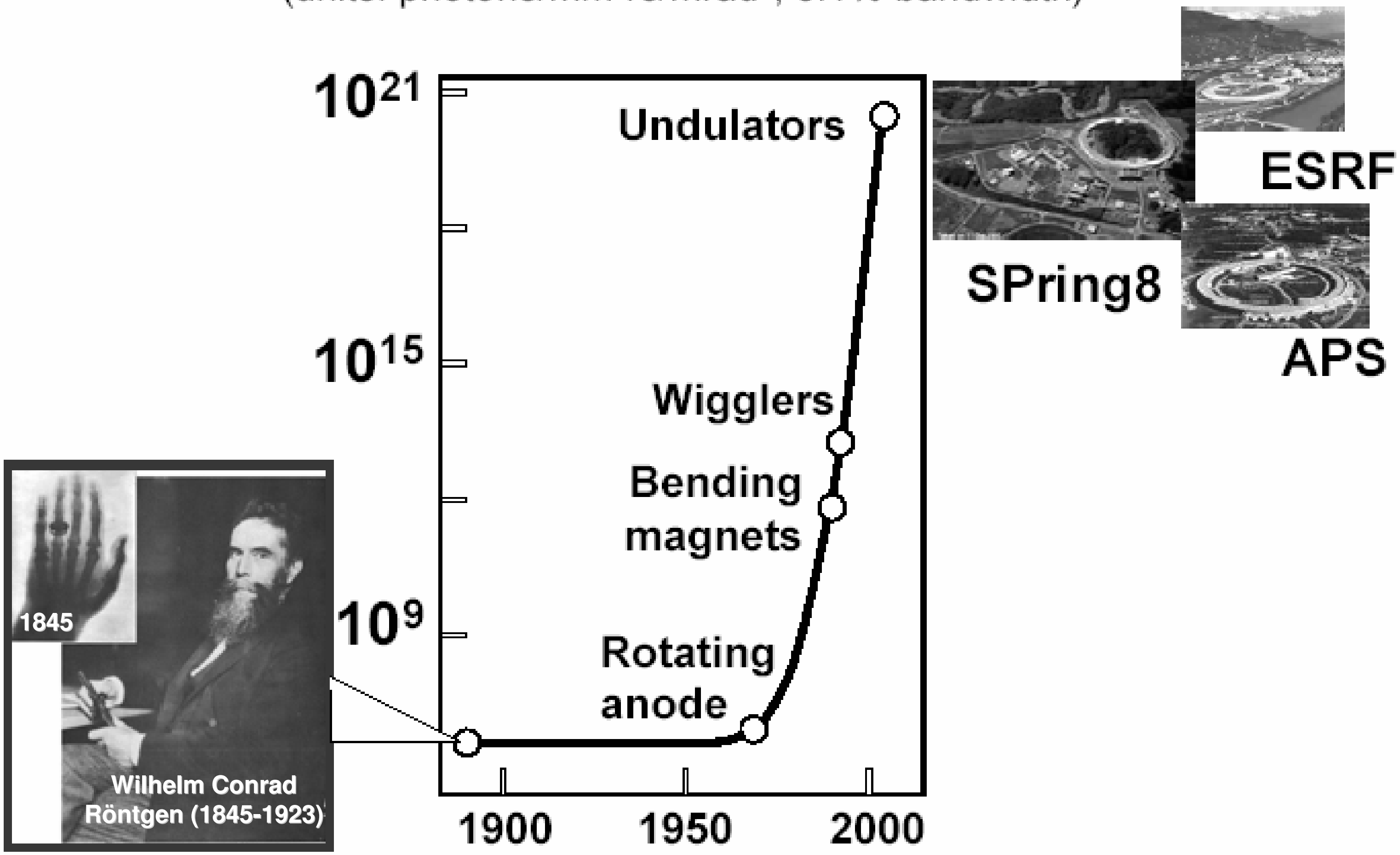
$$\lambda = c\left(\frac{\lambda_0}{v_z} - \frac{\lambda_0}{c}\cos\theta\right) \cong \lambda_0\left(1 - \frac{v_z}{c} + \frac{\theta^2}{2}\right) \cong \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

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

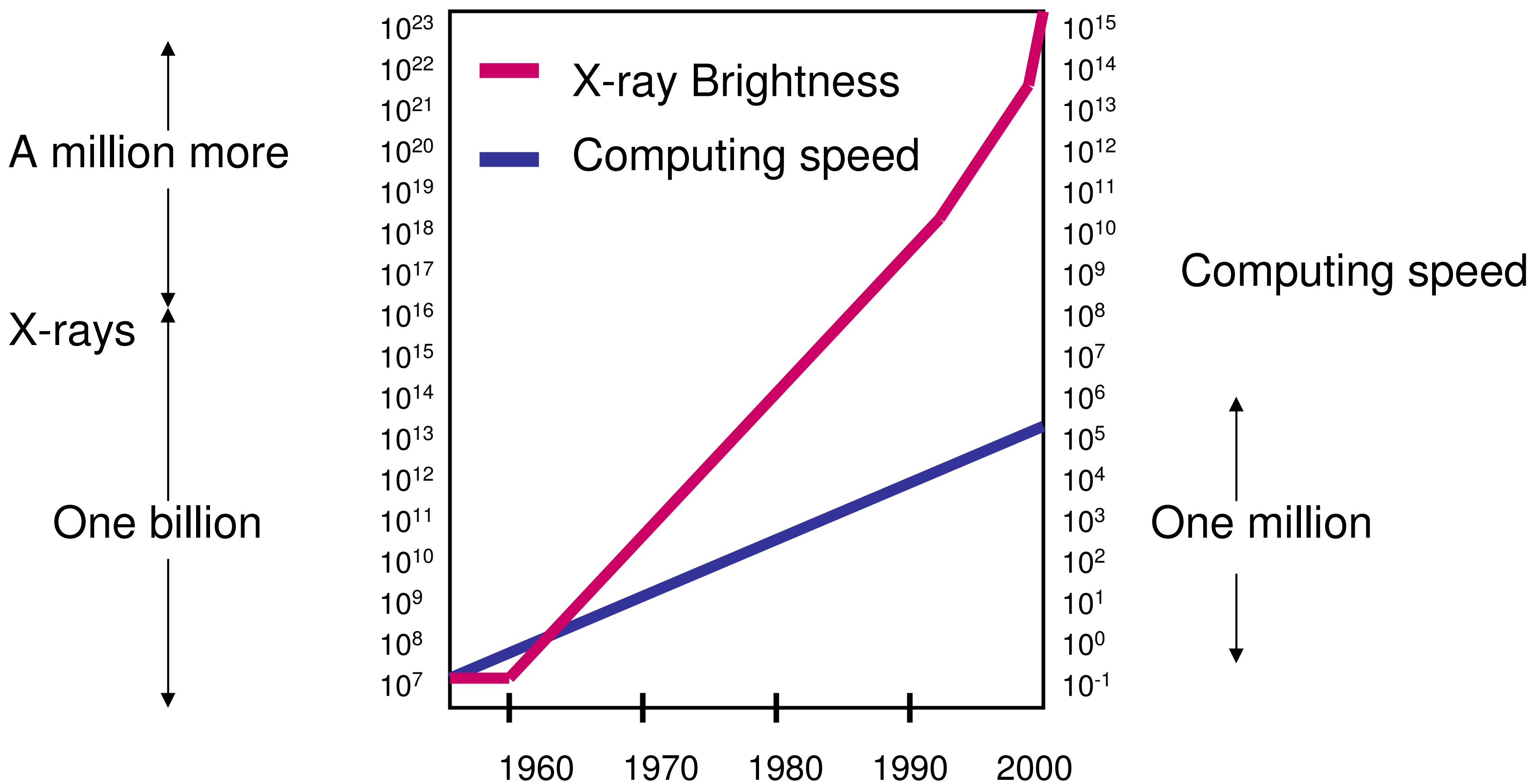
The condition for <u>constructive interference</u> requires that, while traveling along one period of the undulator, the electrons slip by one radiation wavelength with respect to the (faster) photon.

Steep Growth in Brightness

(units: photons/mm^2/s/mrad^2, 0.1% bandwidth)



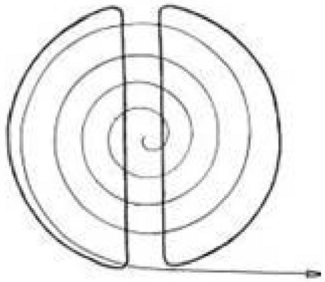
Growth in X-ray Brightness vs. Growth in Computing Speed

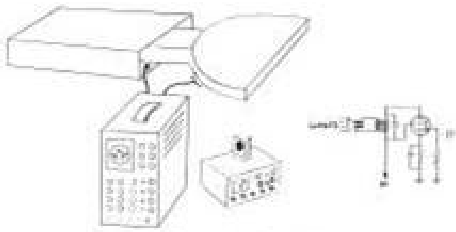


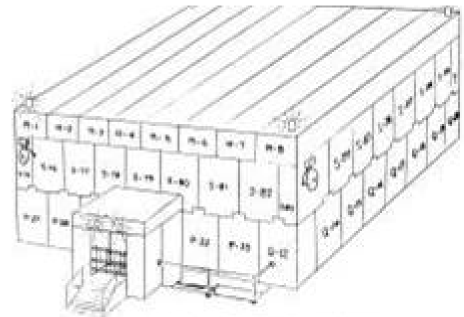
An Introduction to 3rd Generation Light Sources
F.Sannibale

The Cyclotron: Different Points of View

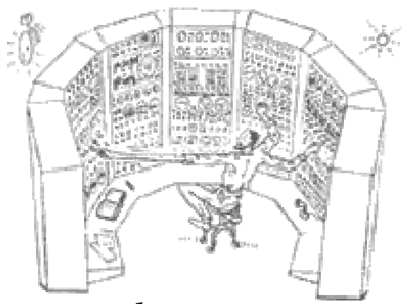
The Cyclotron, as seen by...


... the inventor


... the electrical engineer


... the health physicist


... the experimental physicist


...the operator

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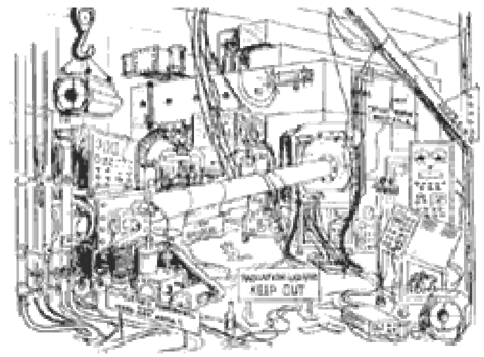
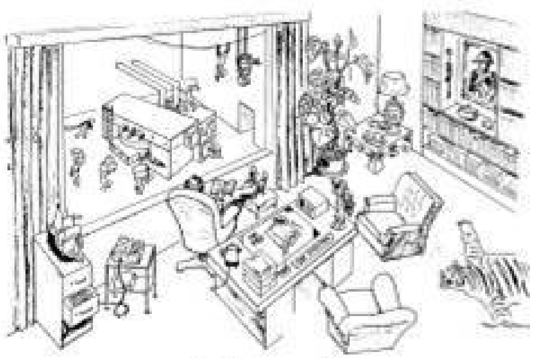
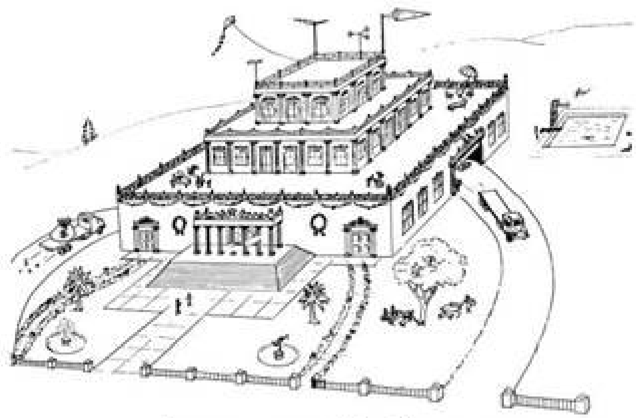
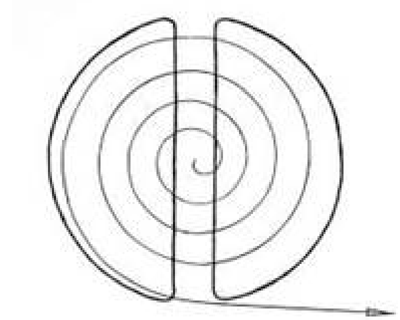
By Dave Judd and Ronn MacKenzie


...the visitor


... the laboratory director


... the governmental funding agency


... the student