Physics of Synchrotron Radiation

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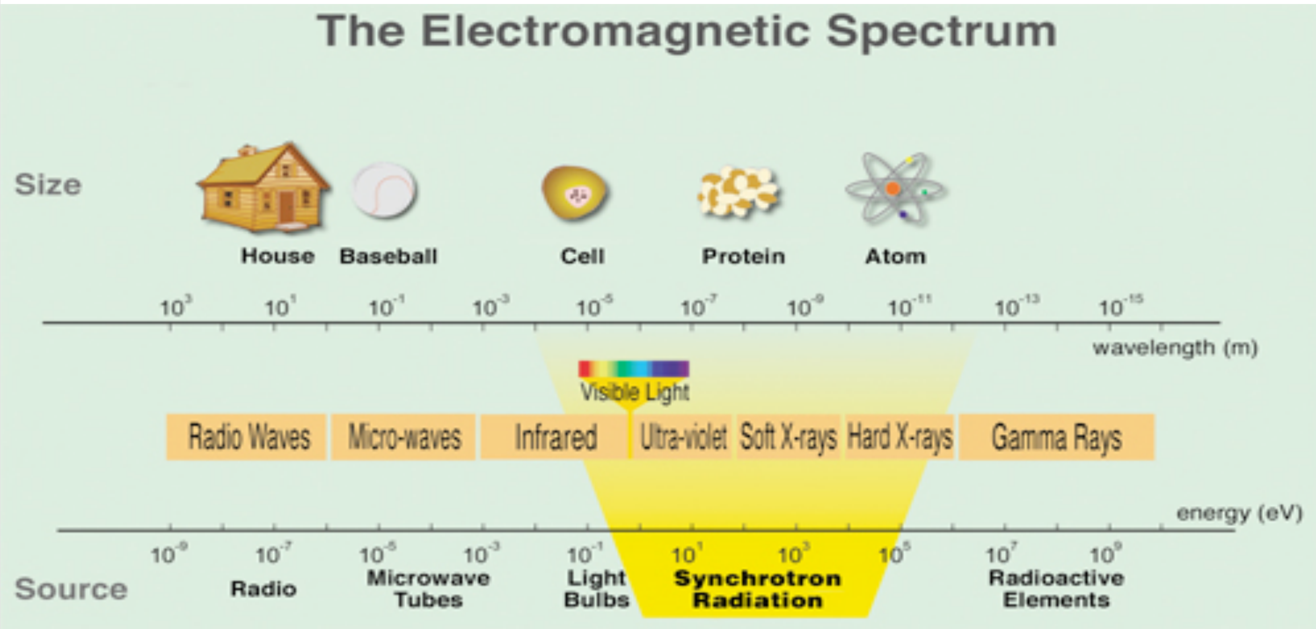
Outline

- Synchrotron light and radiation
- Typical storage ring - parameters
- Radiation power
- Characteristics of synchrotron radiation
  - Time compression
  - Angular collimation
  - Radiation spectrum
  - Flux and brilliance

Synchrotron light

Röntgen, 1895



J. P. Blewett, *Phys. Rev.* **69**, 87 (1946);
F. R. Elder, R. V. Langmuir, A. M. Gurewitsch, H. C. Pollock, *Phys. Rev.* **71**, 827 (1947)

The First Observation

The Crab nebula is the expanding remains of a star that was seen to explode by Chinese astronomers in the year 1054AD.

At the heart of the nebula is a rapidly-spinning neutron star, a pulsar, and it powers the strongly polarised bluish 'synchrotron' nebula.

Why X-rays are important

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

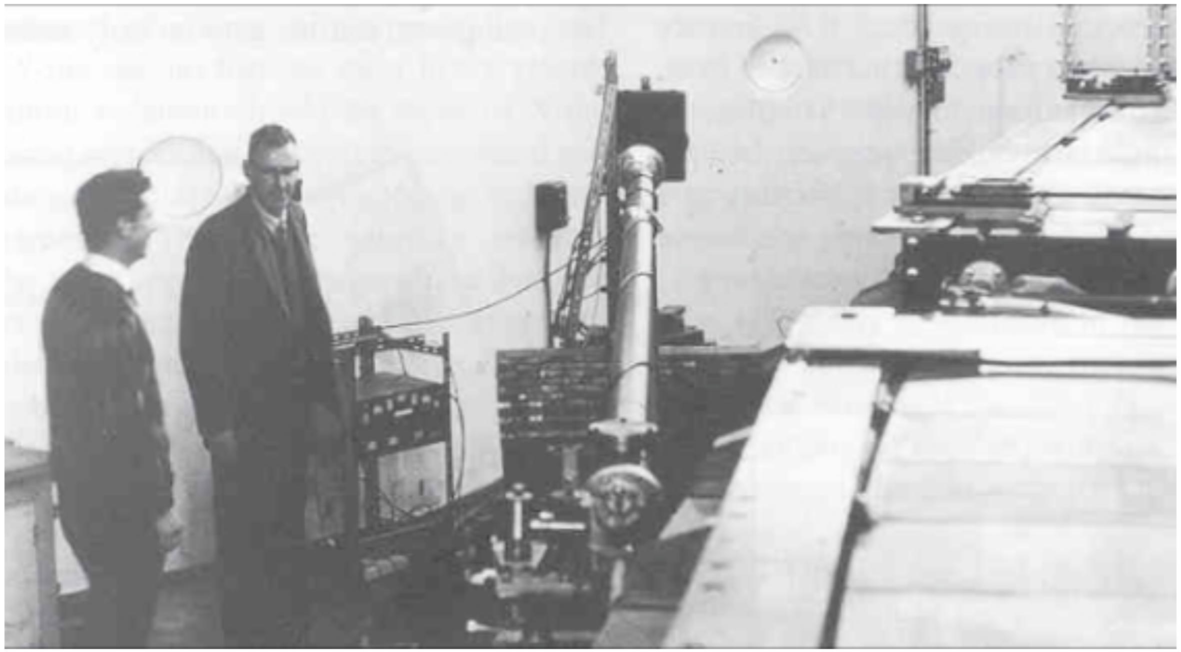
1962 Frances Crick, James Watson and Maurice Wilkins

1979 Alan Cormack and Godrey Hounsfield

Fernando Sannibale, USPAS, Jan 2006

A Brief History of SR – First Use

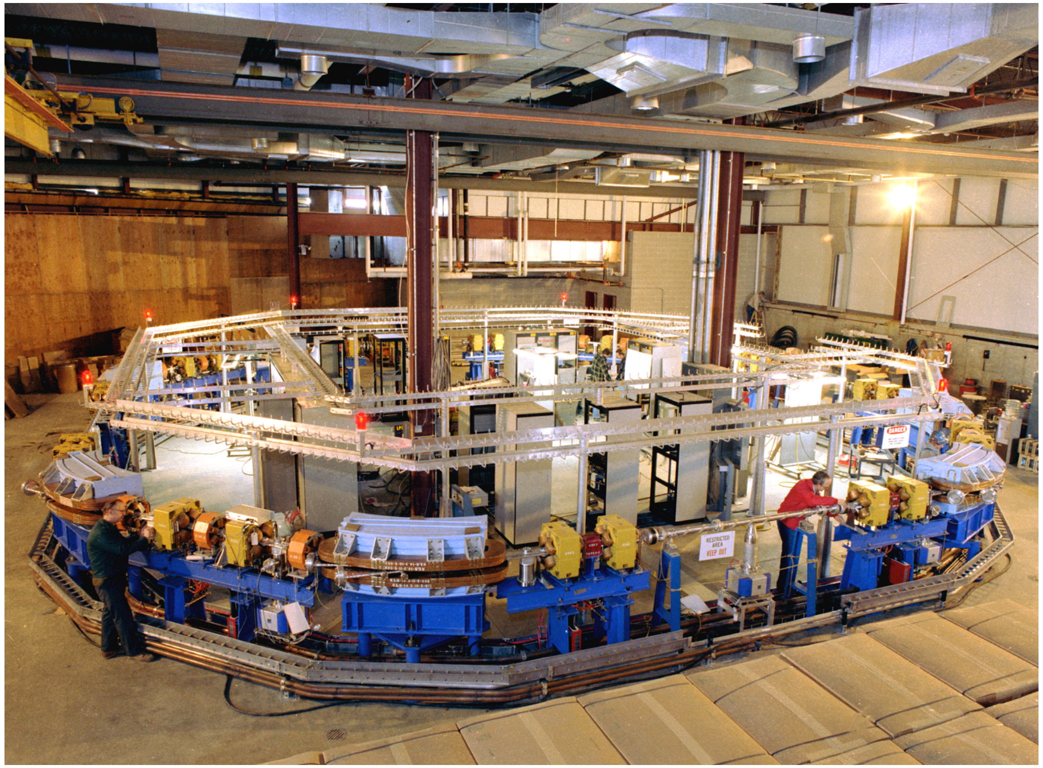
- 1st Generation SR sources
- Electron synchrotrons start to be built for high energy physics use (rapidly cycling accelerators not Storage Rings!)
- Interest from other physicists in using the "waste" SR
- First users are parasitic



The first beamline on NINA at Daresbury constructed in 1966/67 by Manchester University

NINA was a 6GeV electron synchrotron devoted to the study of particle physics

- 2nd Generation SR sources
- Purpose built accelerators start to be built – late 70's
- First users ~1980 (at SRS, Daresbury)
- Based primarily upon bending magnet radiation



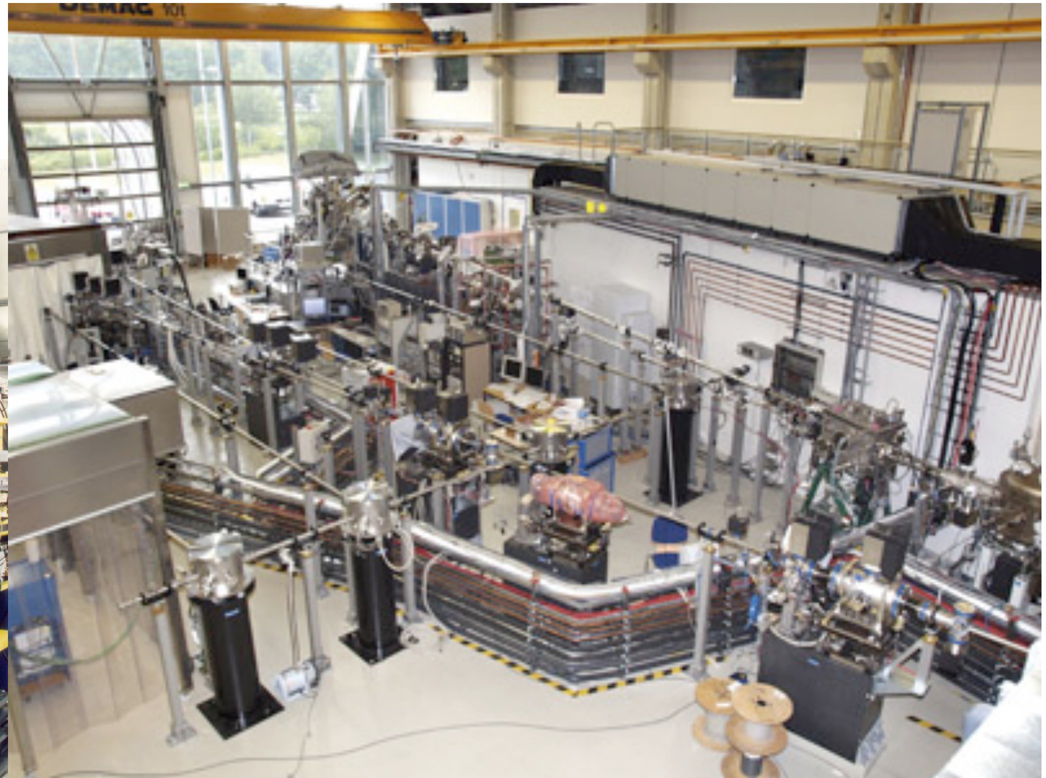
The VUV ring at Brookhaven in 1980 before the beamlines are fitted

Not much room for undulators!

A Brief History of SR – Enhanced Facilities

- 3rd Generation SR sources
- Primary light source is the undulator
- First built in the late 80's/early 90's
- First users ~1994

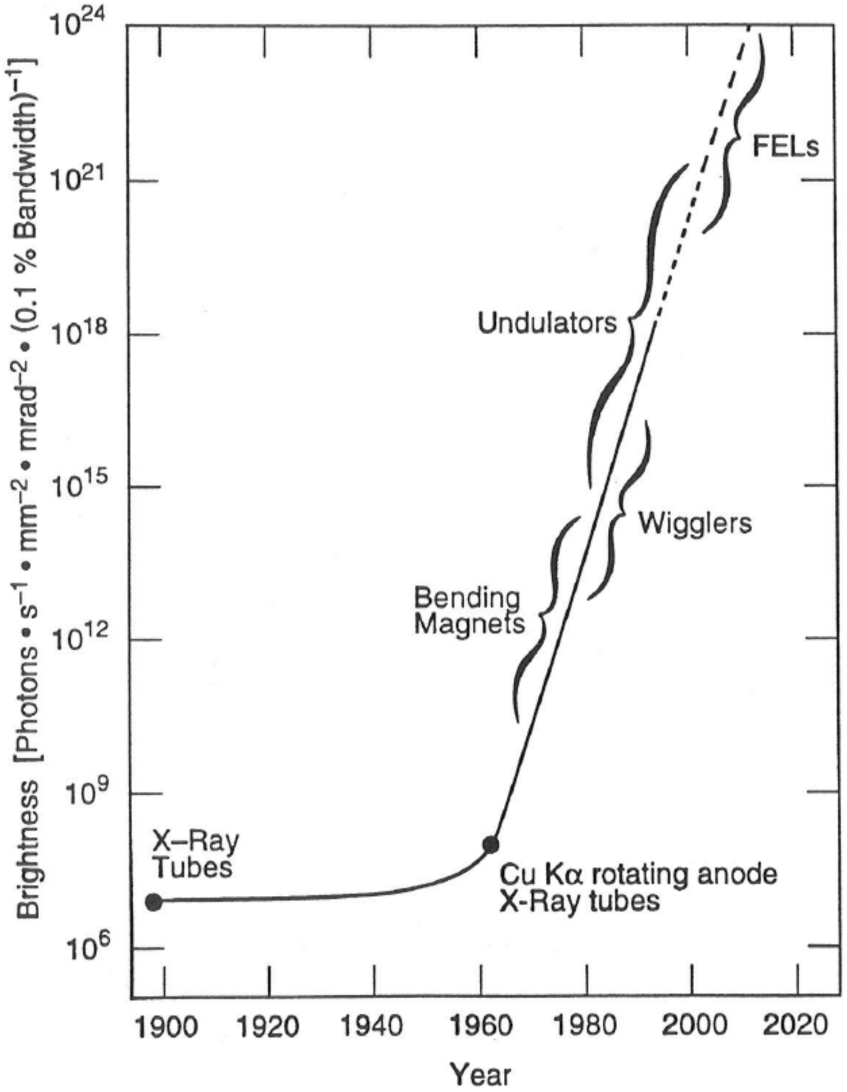
- 4th Generation SR sources
- Primary light source is the single pass Free Electron Laser
- First built ~2000
- First users ~2006



FLASH FEL facility at DESY

Synchrotron Radiation Sources

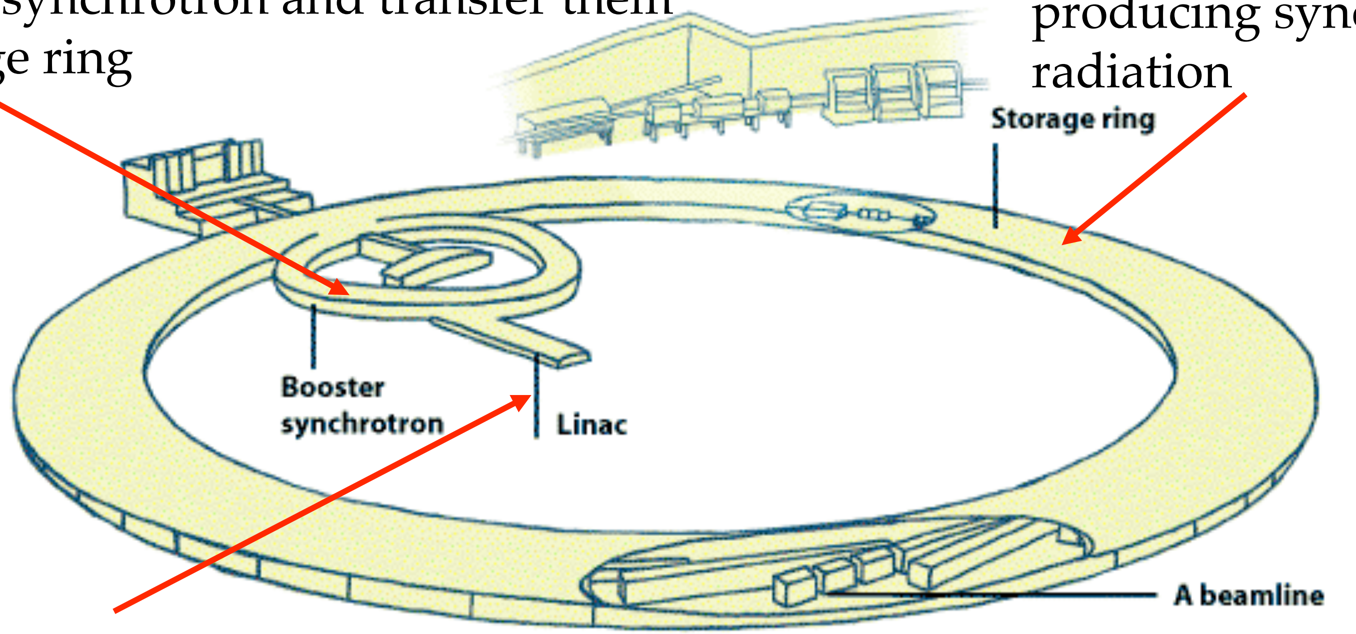
- **X-ray tubes** (early 20th century)
- **1st generation:** originally build for high-energy physics experiments and synchrotron radiation programs used parasitically
- **2nd generation:** dedicated synchrotron sources based on bending magnets
- **3rd generation:** synchrotron radiation is produced in undulators and wigglers
- **4th generation:** free electron lasers



Creating the light

Electrons are getting accumulated up to a high current (a few hundred mA) in the storage ring and they circulate freely producing synchrotron radiation

Accelerate electrons up to a few GeV in a few msec in the booster synchrotron and transfer them into the storage ring

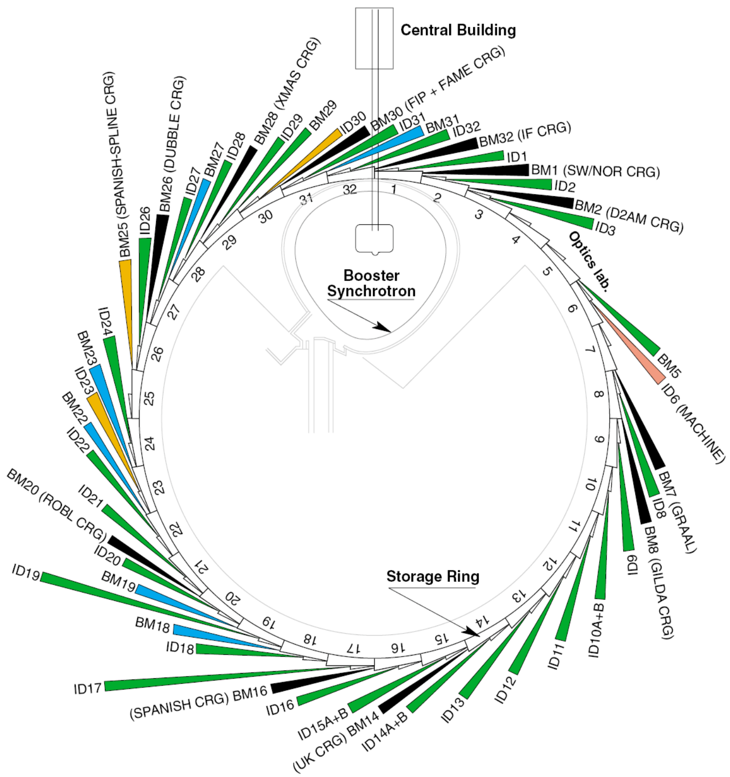


Produce electron in a thermionic gun, accelerate them up to a few MeV in a linac and transfer them into a booster

Procedure repeated periodically, depending on the beam lifetime

A typical storage ring – the ESRF

- The **first** and **most brilliant** 3rd generation light source in Europe
- **50 beam lines** collecting X-rays from insertion devices and bending magnets
- **3500 users/year** from **14 member countries** carrying X-ray spectroscopy experiments for material science, chemistry, biology, medicine, earth sciences, archeology, etc.
- The machine comprises an **e⁻ linac**, a 300m-**booster** and an 844m-**storage ring**
- The storage ring has a record **availability of 98%** with a **mean-time between failures** of more than **2 days**



ESRF parameters

Energy	GeV	6.03
Maximum Current	mA	200
Horizontal Emittance	nm	4
Vertical Emittance (*minimum achieved)	nm	0.025 (0.010*)
Coupling (*minimum achieved)	%	0.6 (0.25*)
Revolution frequency	kHz	355
Number of bunches		1 to 992
Time between bunches	ns	2816 to 2.82

Why circular machines?

$$\mathbf{p} = m_0 \mathbf{v} \qquad v << c$$

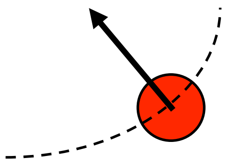
$$P_s = \frac{e^2}{6\pi\varepsilon_0 m_0^2 c^3}\left(\frac{d\mathbf{p}}{dt}\right)^2$$

Larmor Power radiated by non-relativistic particles is very small

$$\mathbf{p} = \gamma m_0 \mathbf{v} \qquad v \approx c$$

$$P_s = \frac{e^2}{6\pi\varepsilon_0 m_0^2 c^3}\left(\frac{dp}{dt}\right)^2$$

Power radiated by relativistic particle in linear accelerator is negligible

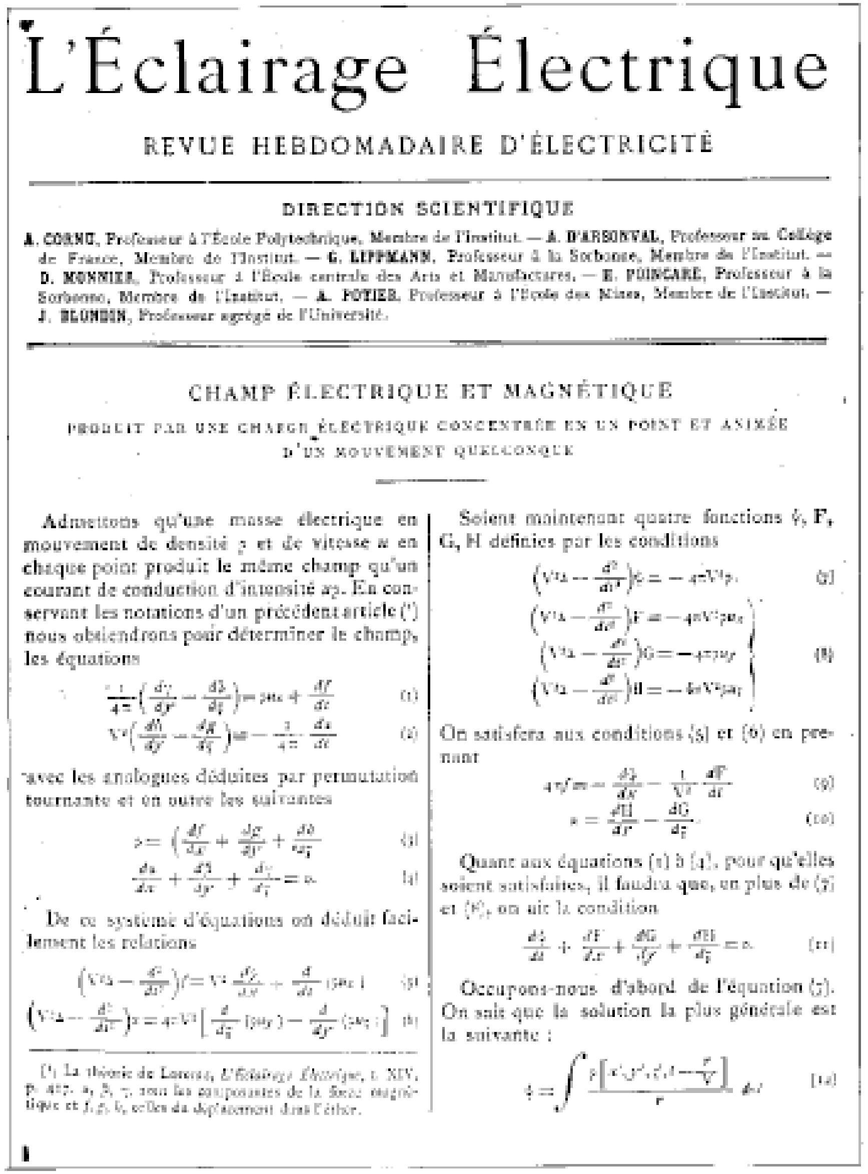


$$P_s = \frac{e^2 c}{6\pi\varepsilon_0 (m_0 c^2)^4}\frac{E^4}{\rho^2}$$

Power radiated by relativistic particle in circular accelerator is very strong (Liénard, 1898)

- "Electric and Magnetic Field produced by an electric charge concentrated at a point and travelling on an arbitrary path"

Prophetically published in the french journal "The Electric Light"



L'Éclairage Électrique

REVUE HEBDOMADAIRE D'ÉLECTRICITÉ

DIRECTION SCIENTIFIQUE

A. CORNU, Professeur à l'École Polytechnique, Membre de l'Institut. — **A. D'ARSONVAL**, Professeur au Collège de France, Membre de l'Institut. — **G. LIPPMANN**, Professeur à la Sorbonne, Membre de l'Institut. — **D. MONNIER**, Professeur à l'École centrale des Arts et Manufactures. — **H. POINCARÉ**, Professeur à la Sorbonne, Membre de l'Institut. — **A. POTIER**, Professeur à l'École des Mines, Membre de l'Institut. — **J. BLONDIN**, Professeur agrégé de l'Université.

CHAMP ÉLECTRIQUE ET MAGNÉTIQUE

PRODUIT PAR UNE CHARGE ÉLECTRIQUE CONCENTRÉE EN UN POINT ET ANIMÉE D'UN MOUVEMENT QUELCONQUE

Admettons qu'une masse électrique en mouvement de densité ρ et de vitesse ω en chaque point produit le même champ qu'un courant de conduction d'intensité ωρ. En conservant les notations d'un précédent article (¹) nous obtiendrons pour déterminer le champ, les équations

avec les analogues déduites par permutation tournante et en outre les suivantes

De ce système d'équations on déduit facilement les relations

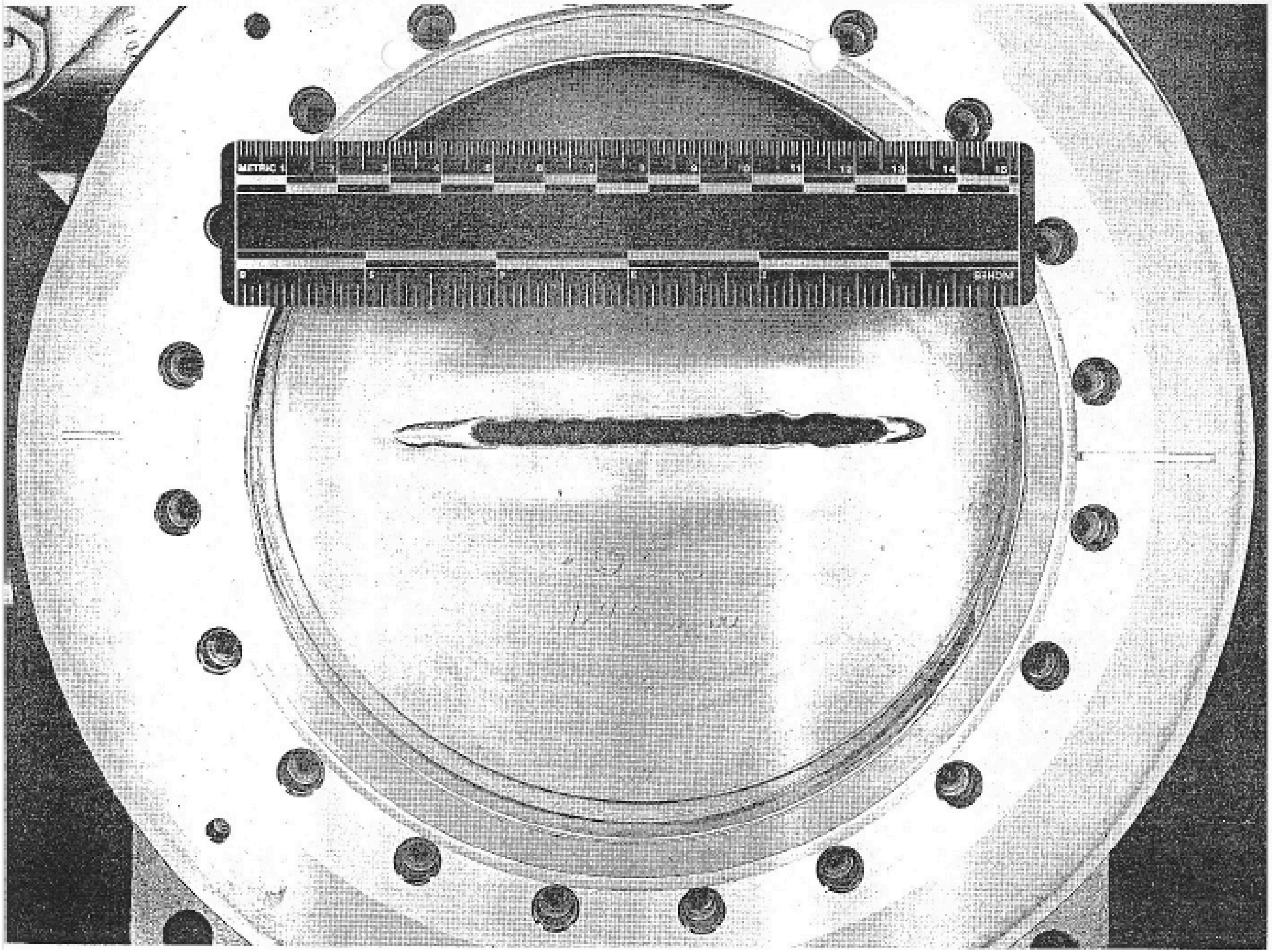
Soient maintenant quatre fonctions ψ, F, G, H définies par les conditions

On satisfera aux conditions (5) et (6) en prenant

Quant aux équations (1) à (4), pour qu'elles soient satisfaites, il faudra que, en plus de (7) et (8), on ait la condition

Occupons-nous d'abord de l'équation (7). On sait que la solution la plus générale est la suivante :

Power should be absorbed!



From L. Rivkin, CAS2003

Why electrons?

$$P_s = \frac{e^2 c}{6\pi\varepsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho^2}$$

Power inversely proportional to 4th power of rest mass (proton **2000 times** heavier than electron) On the other hand, for multi TeV hadron colliders (LHC) synchrotron radiation is an important issue (protection with absorbers)

$$\Delta E = \frac{e^2}{3\varepsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho}$$

For electrons:

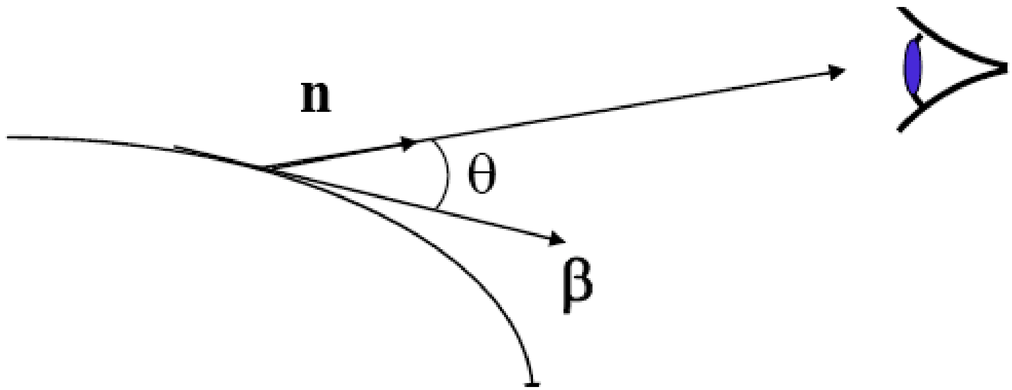
$$\Delta E[keV] = 88.5 \frac{E^4[GeV^4]}{\rho[m]}$$

By integrating around one revolution we get the **energy loss per turn.** For the ESRF is around 5 MeV/turn. On the other hand, for LEPII (**120 GeV**) it was 6GeV/turn, i.e. circular electron machines of more than 100GeV are not practical

Time compression

- Electron moving towards observer with normalized velocity $\boldsymbol{\beta}$ emits wave with period T_e while observer sees a different period T_o

$$T_o = (1 - \boldsymbol{n} \cdot \boldsymbol{\beta}) T_e$$

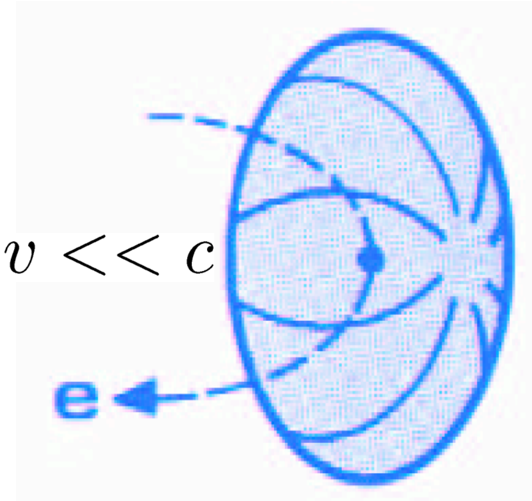


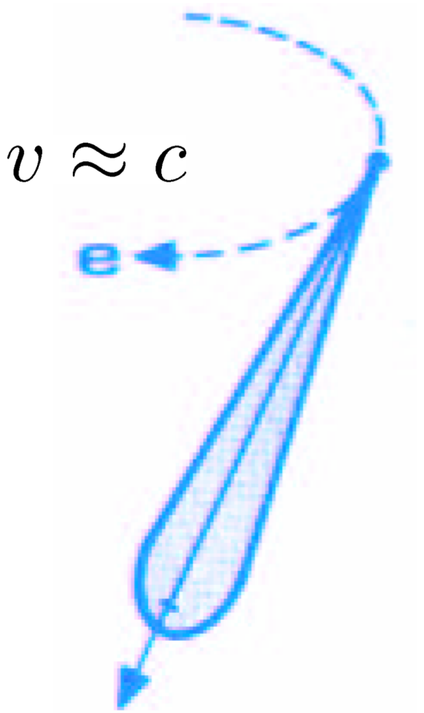
- The wavelength becomes in the same way

$$\lambda_o = (1 - \beta \cos\theta) \lambda_e$$

- Looking along the tangent of the trajectory $\theta = 0$ and by using $1 - \beta = \frac{1-\beta^2}{1+\beta} \approx \frac{1}{2\gamma^2}$ the wavelength is $\lambda_o = \frac{1}{2\gamma^2} \lambda_e$
- The emitted wavelength is compressed by a large factor
- Taking into account electrons of a few GeV, (γ of a few 10^3) with wavelengths of a few cm, provide radiation of a nm (X-rays)

Angular collimation





- For a non-relativistic source (or in the laboratory frame) radiation is axially symmetric, proportional to $\sin^2\theta_e$ (Herz dipole)
- For relativistic source, the observed angle with respect to the emission angle is

$$\tan\theta_o = \frac{\sin\theta_e}{\gamma(\cos\theta_e - \beta)}$$

- For small angles $\theta_o = \frac{1}{\gamma}\theta_e$
- The radiation is emitted into a narrow cone, perpendicular to the electron trajectory

Time dependence

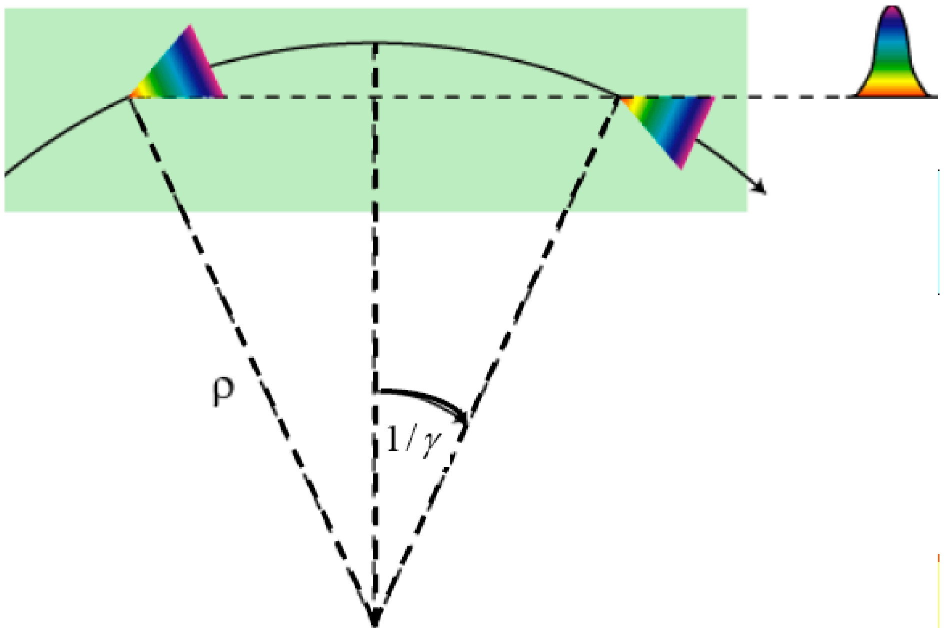
- Assume electrons moving in a ring of radius R
- Due to angle collimation, observer sees small fraction of electron trajectory $l = 2R/\gamma$
- The pulse length, defined as the time difference a photon and electron to cover this distance

$$\Delta t \approx \frac{l}{\beta c} - \frac{l}{c} = \frac{2R(1-\beta)}{\gamma\beta c}$$

- Finally, the pulse length is

$$\Delta t \approx \frac{R}{c\gamma^3}$$

- This is a very short pulse (typically fraction of ns) and thus the radiation can be produced with a time structure

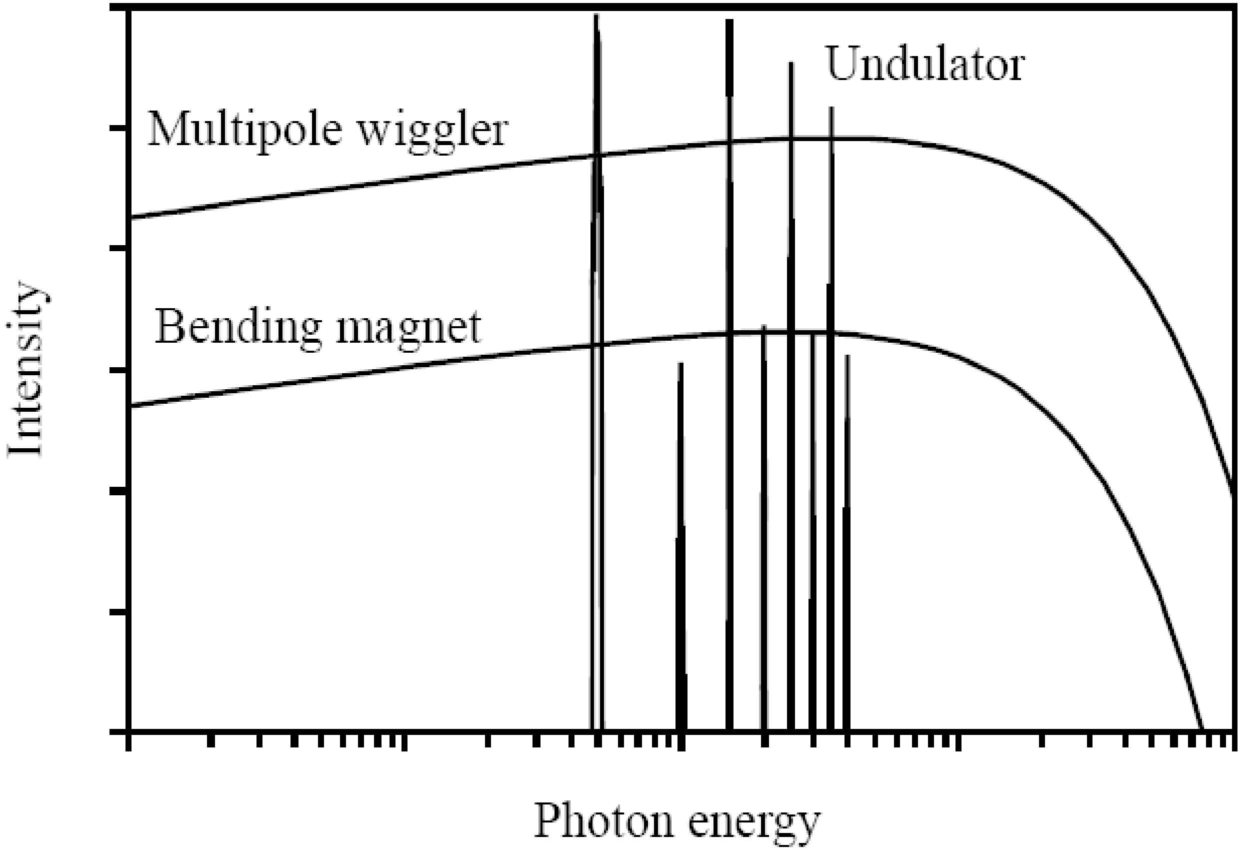


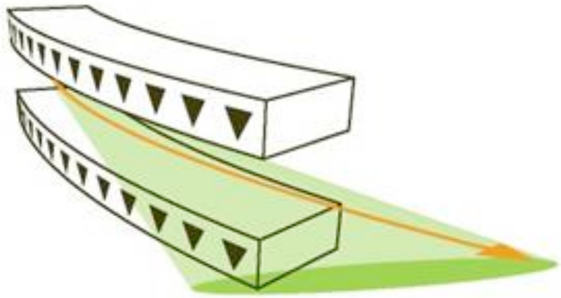
Synchrotron radiation spectrum

- The radiation comes in a series of flushes with a (critical or characteristic) frequency proportional to the revolution frequency

$$\omega_c \approx \gamma^3 \omega_0$$

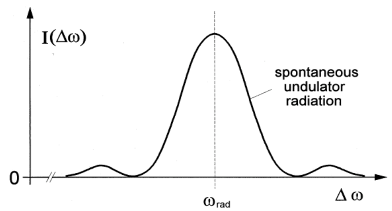
- This is almost a continuous spectrum, as the harmonics are so high that they overlap





Bending magnet (Sweeping searchlight)
At each deflection of the electron path a beam of radiation is produced.

Insertion devices

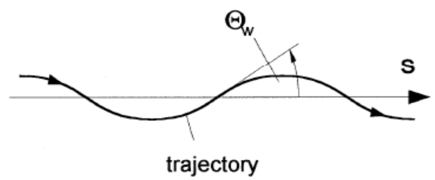


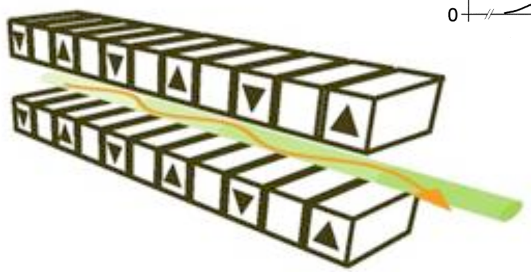
Undulator / wiggler parameter

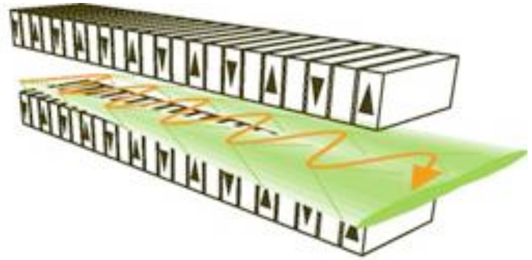
$$K = \frac{\lambda_u e \tilde{B}}{2\pi m_e c}$$

Deflection angle

$$\Theta_W = \frac{K}{\gamma}$$







Undulator (K≤1)
Produces a very narrow beam of coherent light

Wiggler (K>1)
Beams emitted at each pole reinforce each other and appear as a broad beam of incoherent light.

$$\frac{dF_n}{\frac{d\lambda}{\lambda}} = \int \frac{d\Phi_n}{d\theta_x d\theta_z \frac{d\lambda}{\lambda}}(\theta_x,\theta_z,\lambda_n)d\theta_x d\theta_z = \pi\alpha\frac{I}{e}NQ_n(K)$$

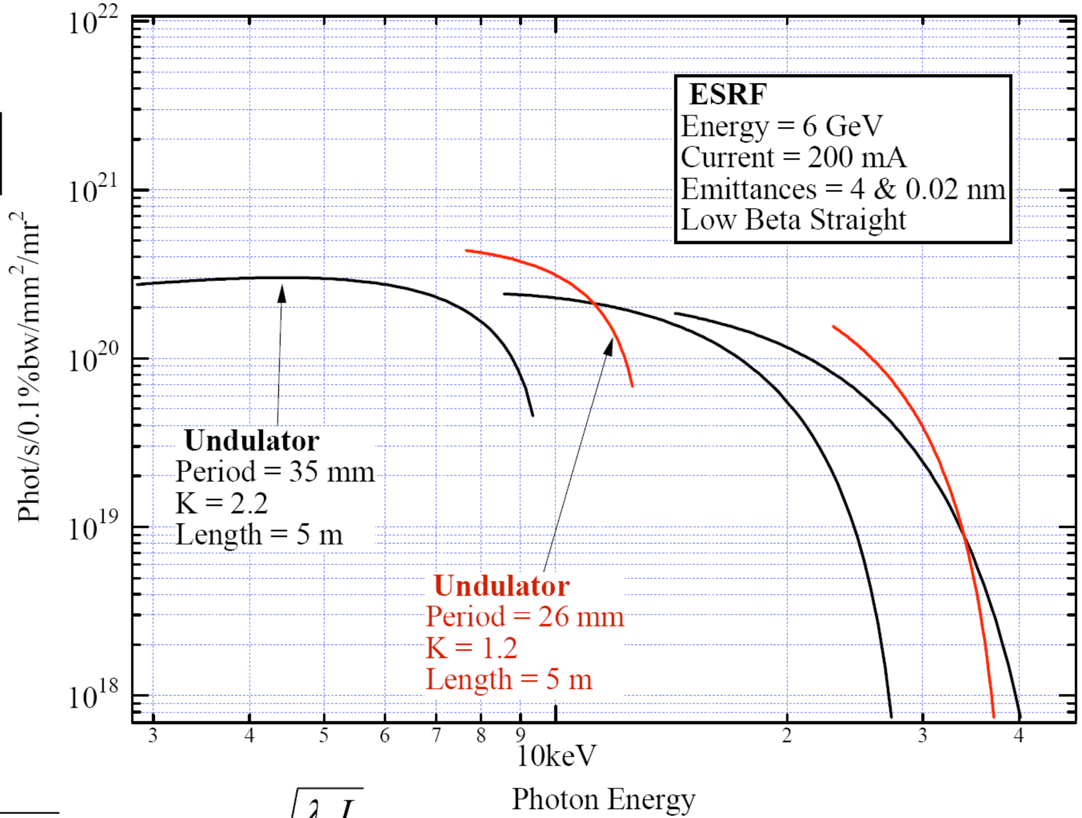
Maximum angular spectral flux

$$F_n\,[Ph/\sec/0.1\%] = 1.431\,10^{14}\; N\, I[A]\, Q_n(K)$$

N : Number of Undulator Periods

I : Ring Current

n : Harmonic Number



Spectral brilliance and brightness

$$B_n = \frac{F_n}{(2\pi)^2 \Sigma_x \Sigma'_x \Sigma_z \Sigma'_z}$$

$$\Sigma_x = \sqrt{\sigma_x^2 + \sigma_R^2}\;, \qquad \sigma_R = \frac{\sqrt{\lambda_n L}}{2\pi}$$

$$\Sigma'_x = \sqrt{\sigma'^2_x + \sigma'^2_R}\;, \qquad \sigma'_R = \frac{\lambda_n}{2L}$$

Σ_x, Σ_z : Photon beam sizes

Σ'_x, Σ'_z: Photon beam divergences