CERIC

Central European
Research Infrastructure
Consortium

Introduction to Particle Accelerators

With Focus on Synchrotron Light Sources

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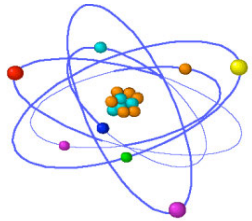
PaGES^3

Pianificazione,
Gestione ed
esecuzione di un
Esperimento Scientifico in
un centro di ricerca
internazionale

The project is funded by the Italian Region Friuli Venezia Giulia, within the program "Regional plan for the building up of the formative offer for the academic year 2017/2018", in the section "Special projects"

Ingredients



- **Charged particles:** electrons, protons, ions, anti-particles

$$E = \gamma(v) m_0 c^2$$

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

⇒ ***Special Relativity*** *is all we need. Includes kinematics and dynamics of relativistic charged particles.*

- Static and time-varying ***electric field*** increases the particle kinetic energy.

⇒ ***Radiofrequency (RF) accelerating structures***

- Static and time-varying ***magnetic field*** bounds the particle inside the vacuum chamber.

⇒ ***Magnetic elements*** *for controlling the particles direction (orbit) and beam size (focusing).*

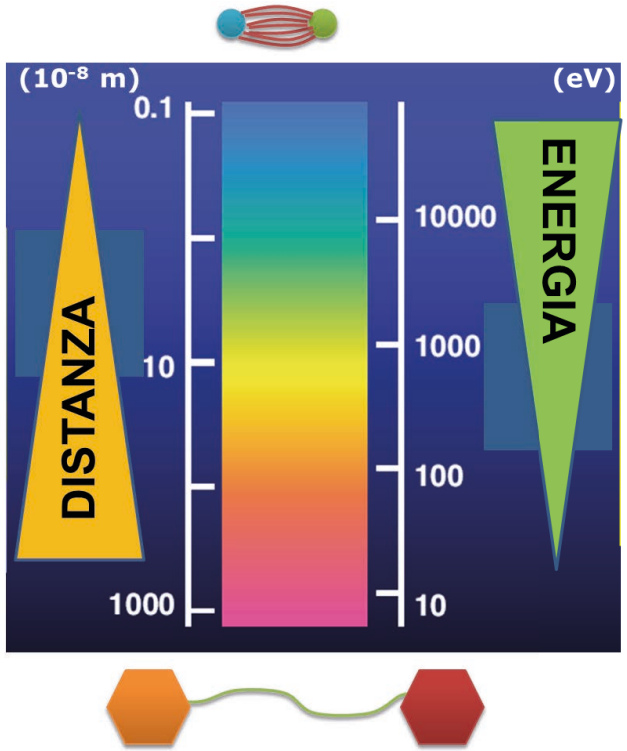
Why High Energy Particle Beams ?

LEGAMI ATOMICI

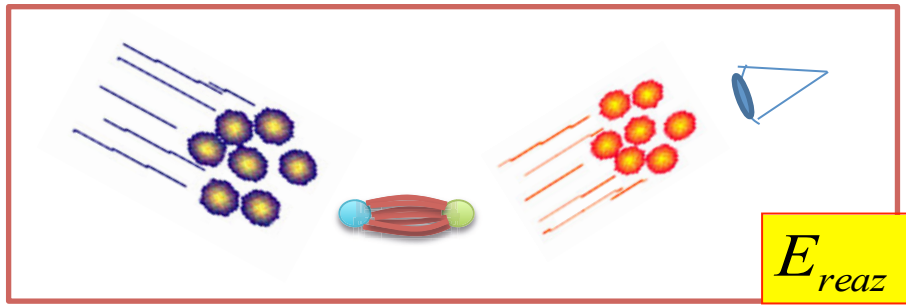
LEGAMI CHIMICI

MOLECOLE

PROTEINE

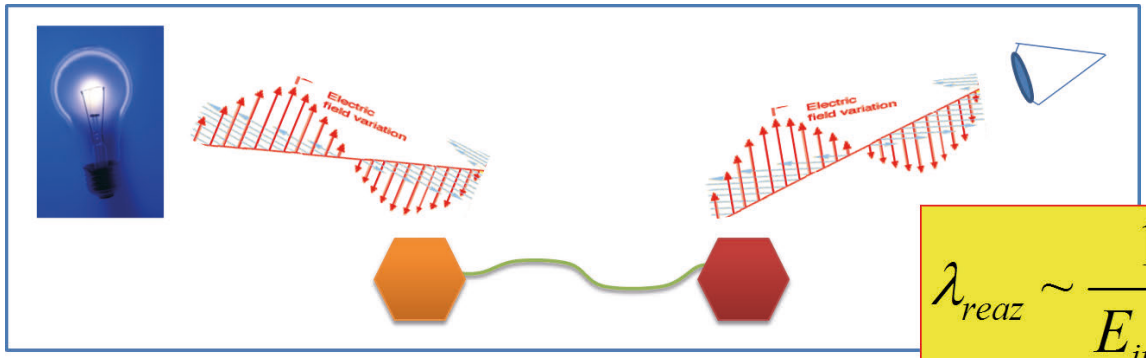


"Colliders" (LHC,…)



$$E_{reaz} \sim E_{incid}$$

"Synchrotron Light Sources" (Elettra,…)



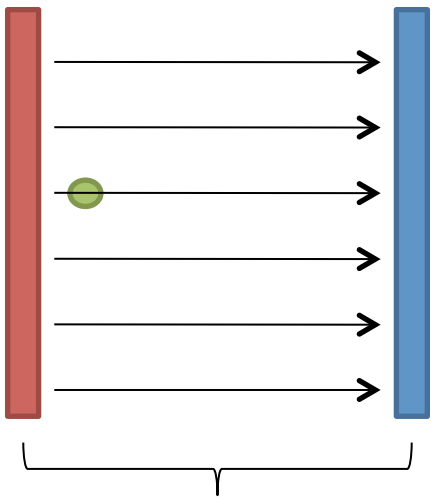
$$\lambda_{reaz} \sim \frac{1}{E_{incid}}$$

Acceleration, Particle Energy

$$L = \vec{F} \cdot \vec{s} = q\vec{E} \cdot \vec{s} = -q\Delta V$$

Electric field

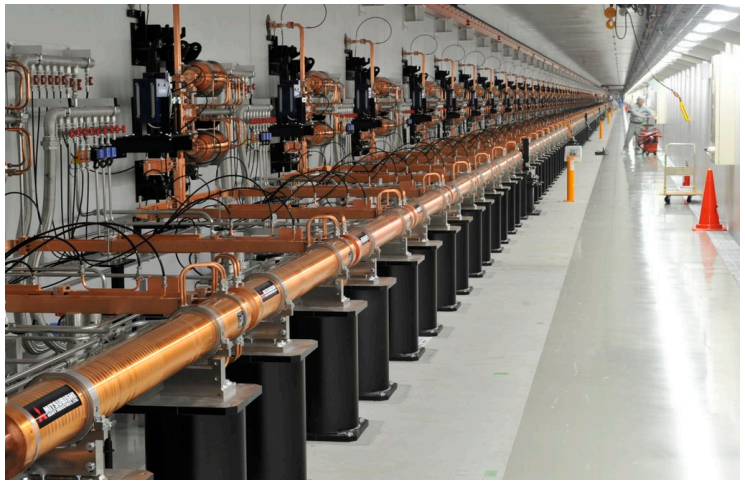
Energy



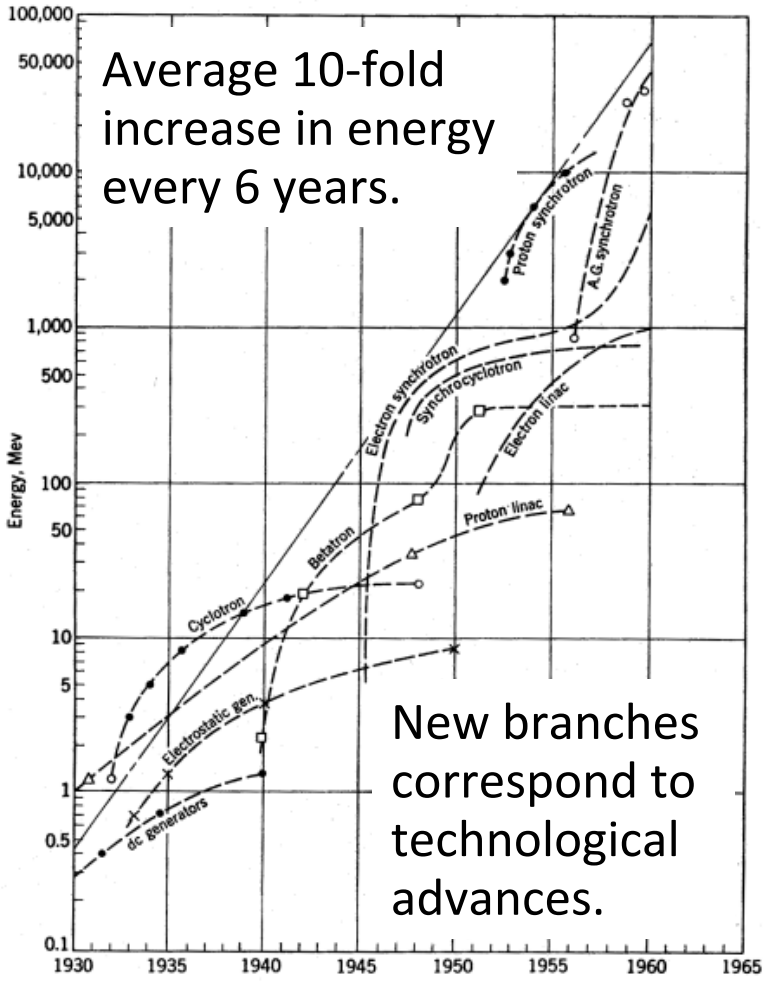
J = N x m = C x V

1 eV (electronvolt) = 1 e x 1 V

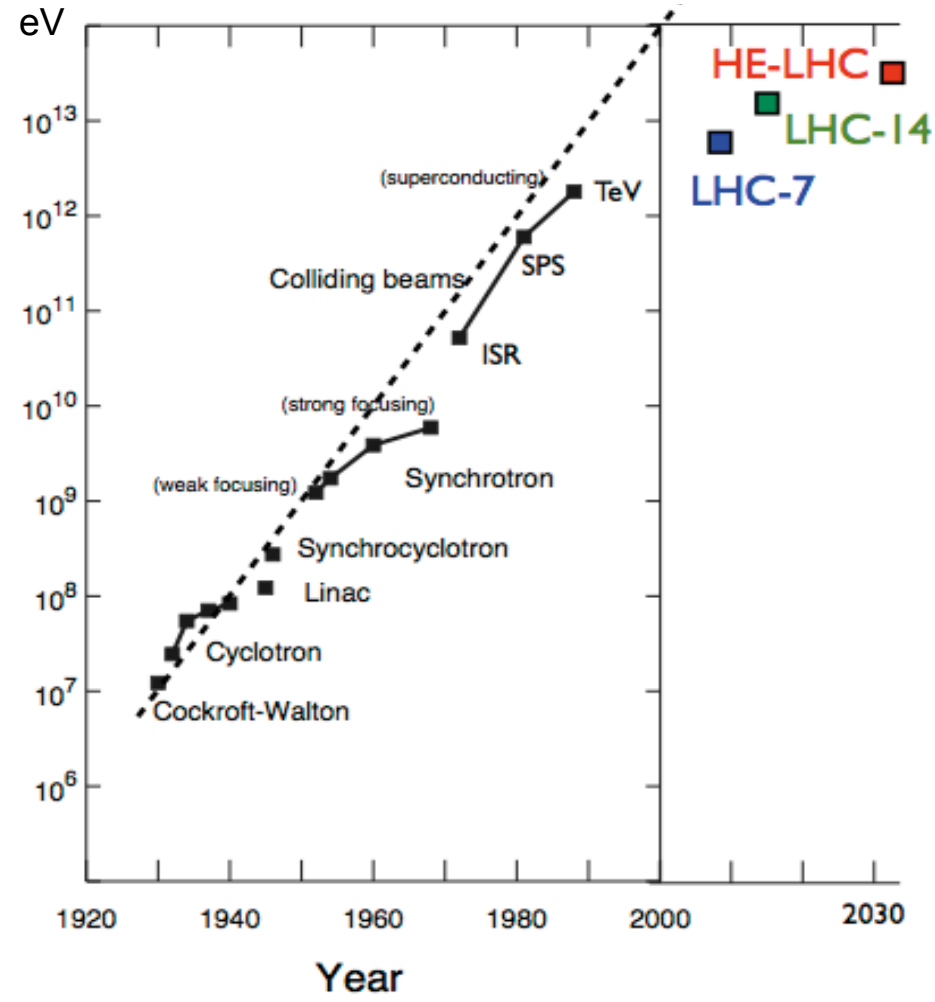
e = -1.6e-19 C



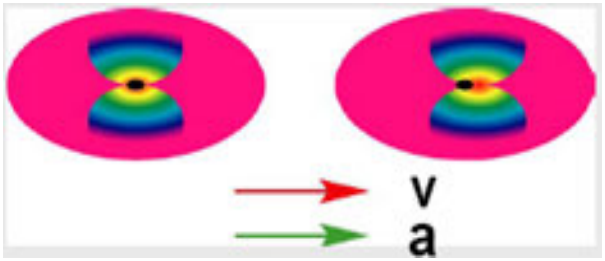
Livingstone Chart

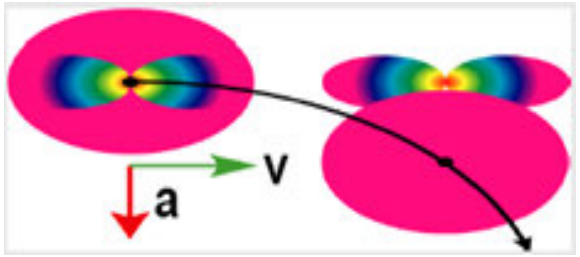


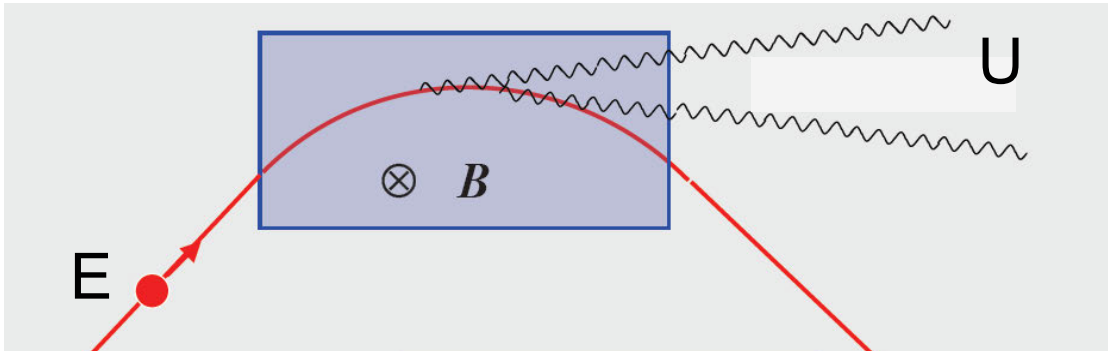
C.M. Energy (eV)



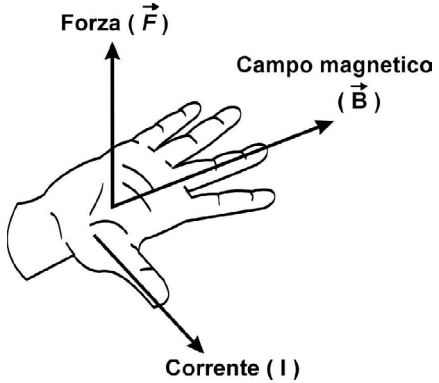
Synchrotron Radiation

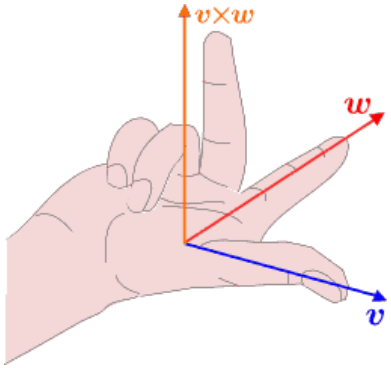


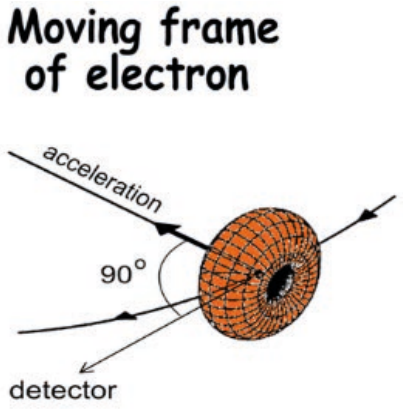


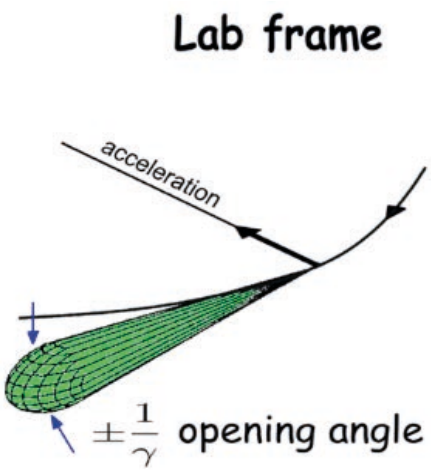


$$U_{turn}[keV] = 88.5 \frac{E_b^4\,[GeV]}{R\,[m]}$$



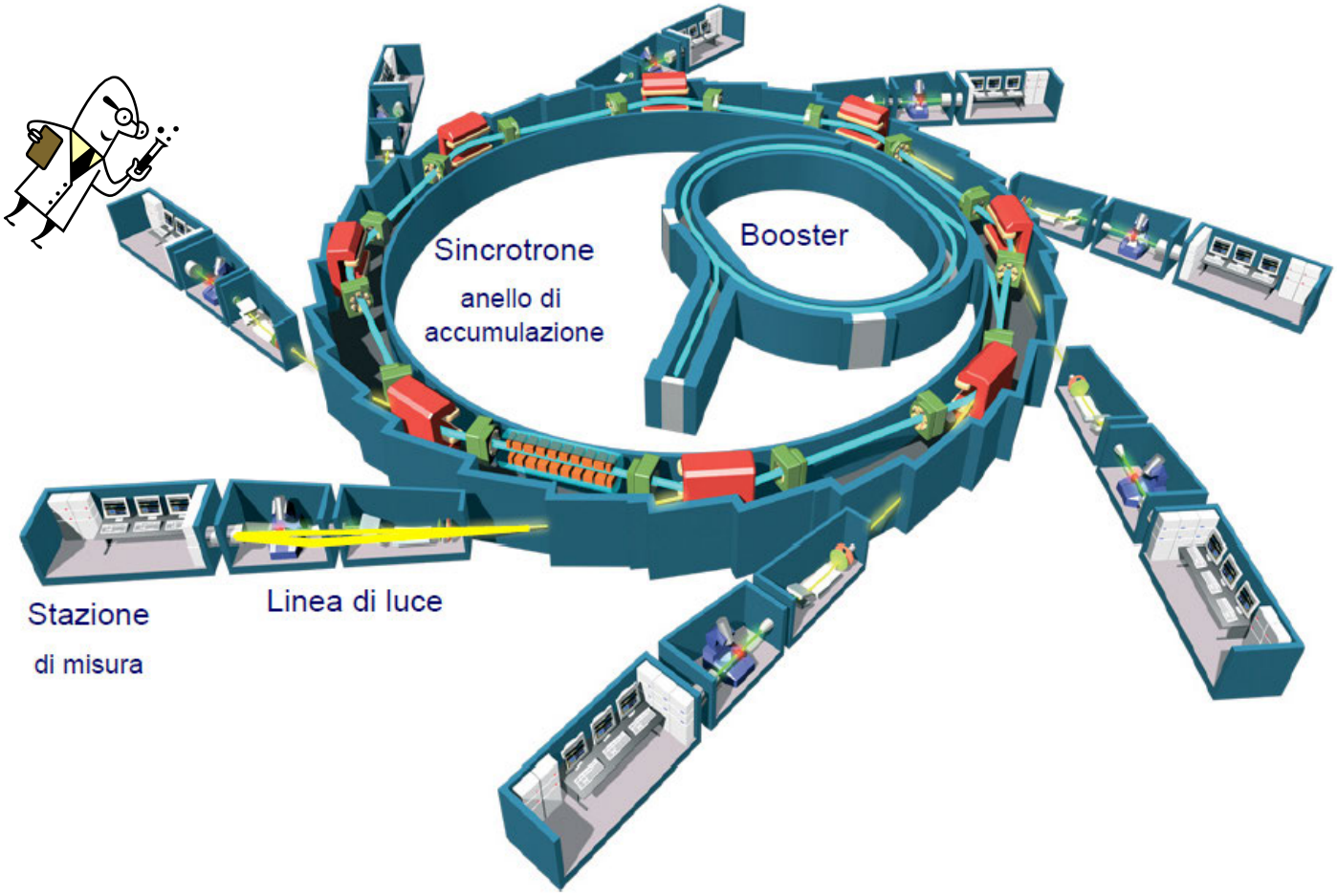


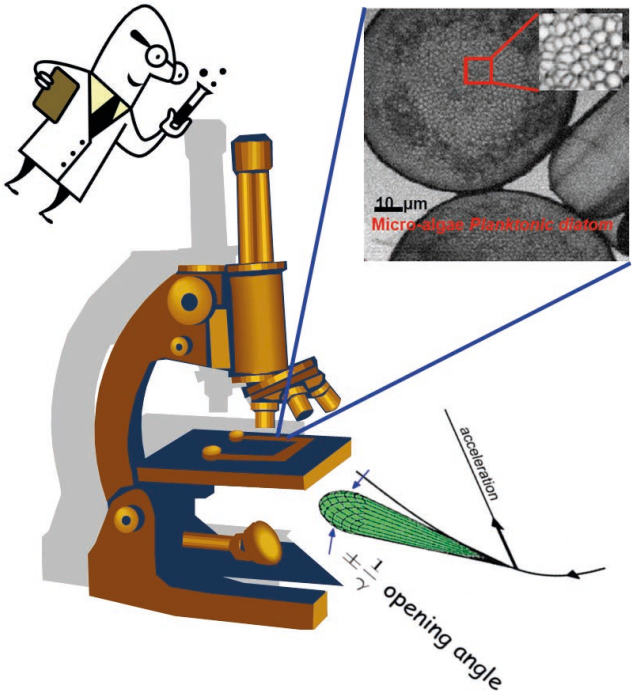




$$\frac{1}{\gamma} = \frac{m_o c^2}{E} = \sqrt{1 - (\frac{v}{c})^2}$$

Synchrotron Light Source





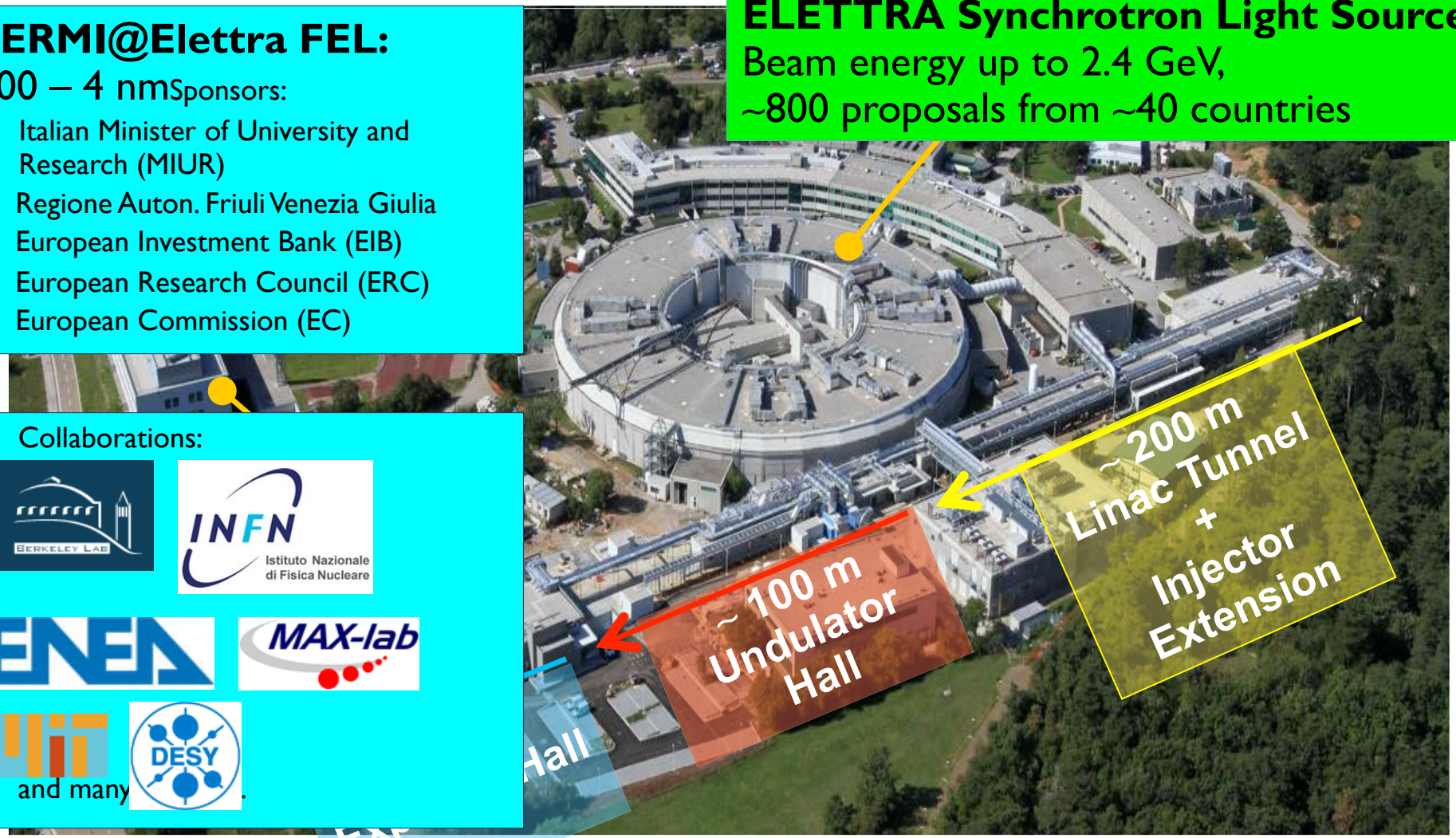
Elettra Sincrotrone Trieste

Elettra Sincrotrone Trieste is a nonprofit shareholder company of Italian national interest, established in 1987 to construct and manage synchrotron light sources as international facilities.

FERMI@Elettra FEL:
100 – 4 nm Sponsors:

- Italian Minister of University and Research (MIUR)
- Regione Auton. Friuli Venezia Giulia
- European Investment Bank (EIB)
- European Research Council (ERC)
- European Commission (EC)

ELETTRA Synchrotron Light Source:
Beam energy up to 2.4 GeV,
~800 proposals from ~40 countries



- Collaborations:
  - Berkeley Lab
  - INFN Istituto Nazionale di Fisica Nucleare
  - ENEA
  - MAX-lab
  - MIT
  - DESY
- and many .

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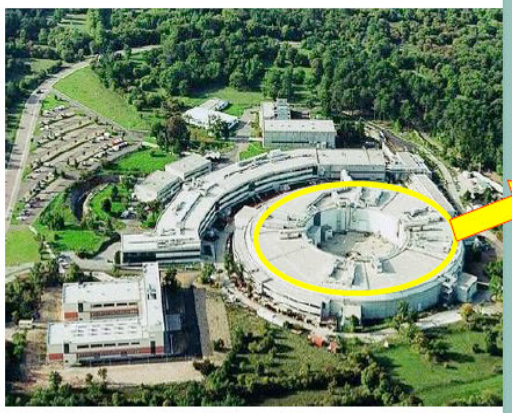
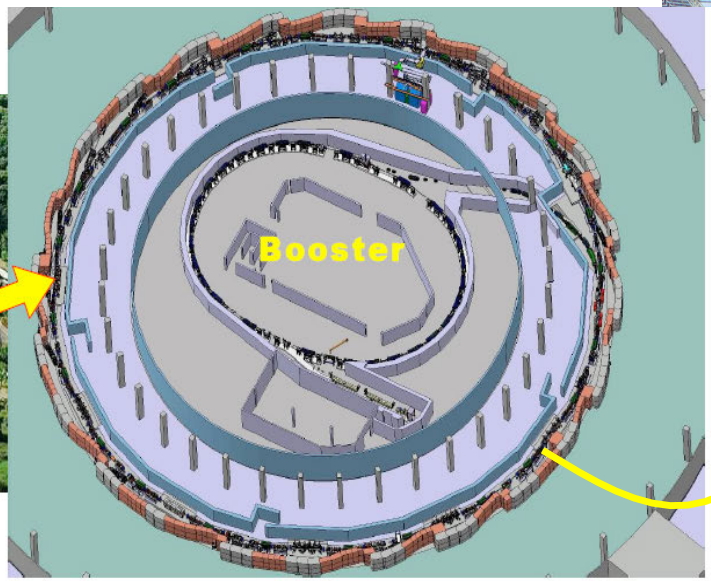
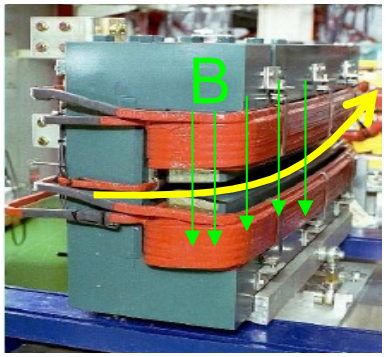
Elettra Synchrotron Light Source

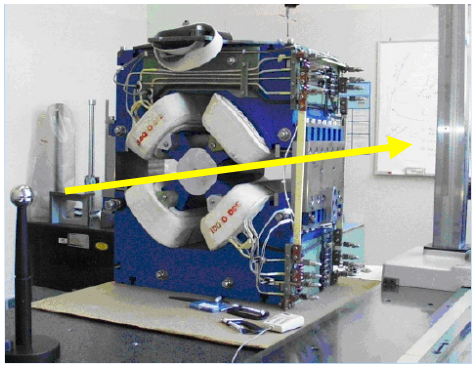




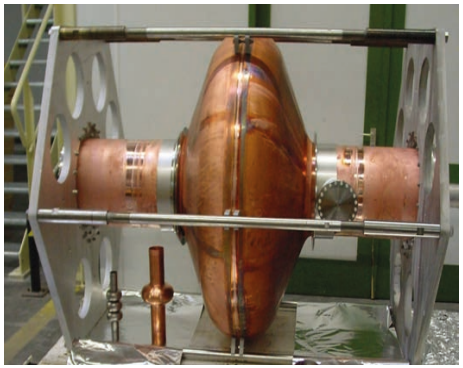
Dipole Magnet

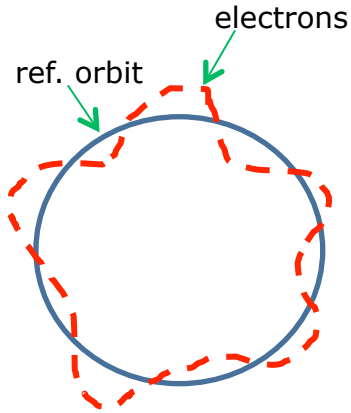


Quadrupole Magnet



RF cavity





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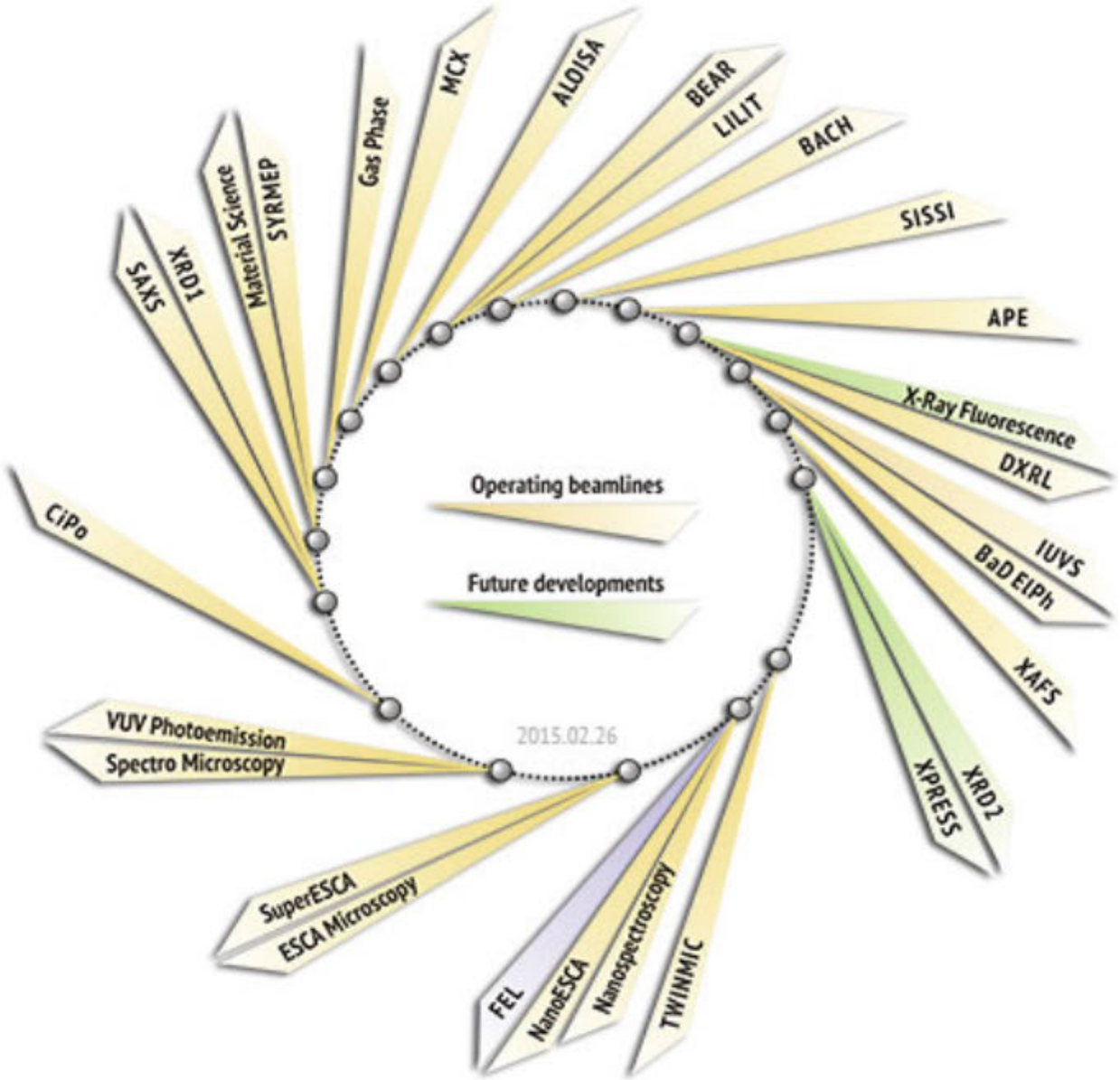
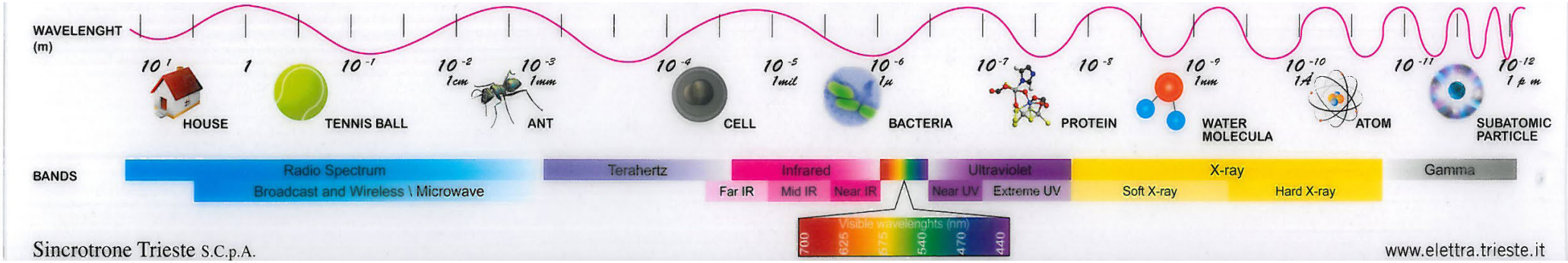
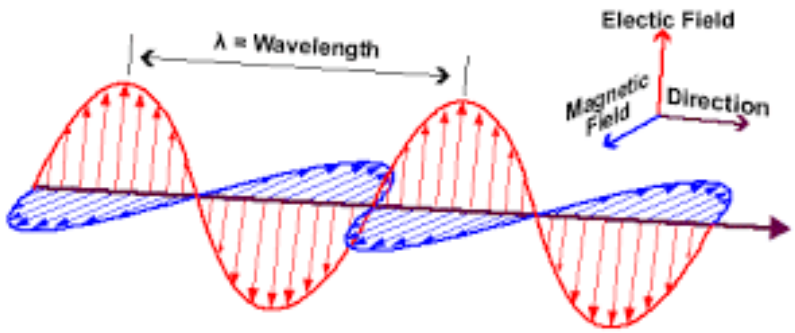
Elettra Photon Beamlines



- 24 beamlines open to Users
- 3 new beamlines in commissioning
- Physics of Matter, Biology, Chemistry, Medical Science, Technology Materials, Environment, etc…

Wavelength, Photon Energy





$$c\ [m/s] = \lambda \cdot \nu$$

$$f\ [Hz] = 2\pi\nu$$

$$E\ [J] = h \cdot \nu$$

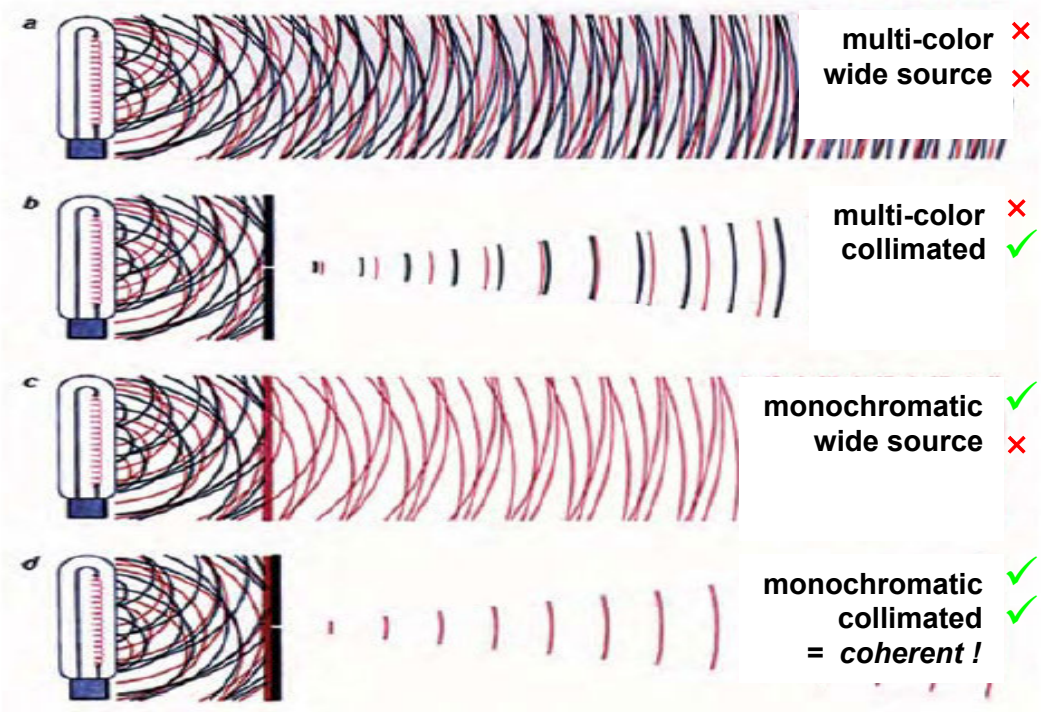
c = 2.998e8 m/s *Light speed in vacuum*

h = 6.626e-34 J s *Planck constant*

- An e.m. wave can be described also as a bunch of massless particles, named “photons”.
- Photons travel at speed *c* in vacuum.
- The energy of an e.m. wave (monochromatic) is the photon energy times the number of photons.

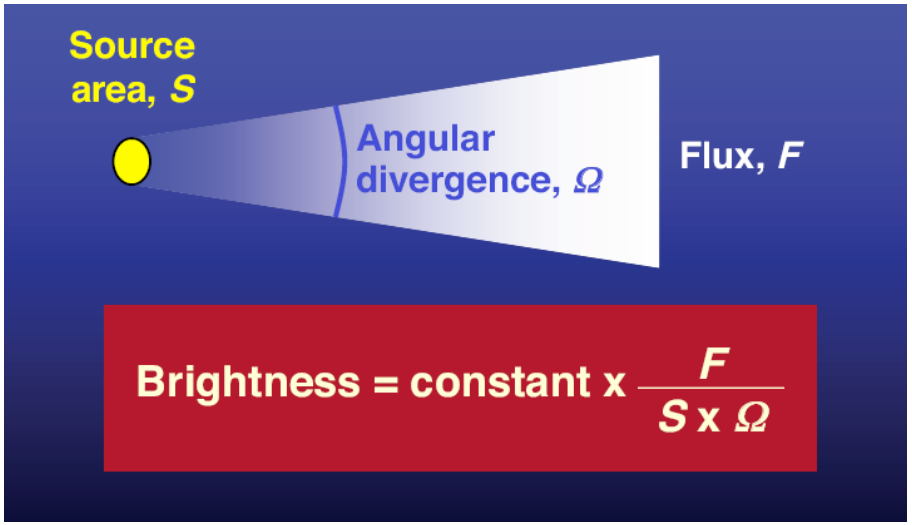
Radiation Properties

Transverse & Longitudinal Coherence

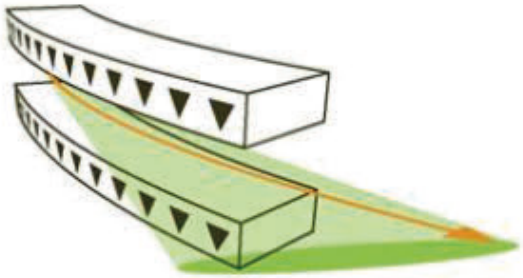


Courtesy of A. Schawlow, Stanford.

Brilliance



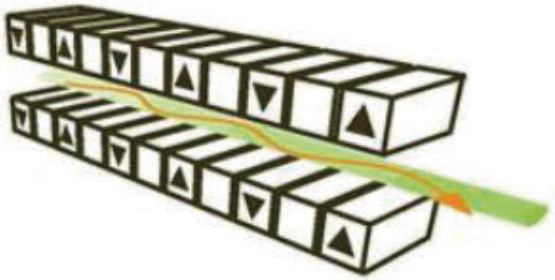
Radiation Sources



Magneti Curvanti

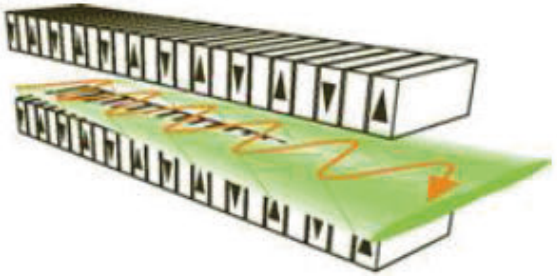
I magneti Curvanti mettono in connessione due sezioni diritte del sincrotrone: la luce è prodotta mediante la "bremesstralung radiations".

I Magneti di Inserzione (straight sections) sono nelle sezioni diritte e producono radiazione più intensa: gli elettroni fanno un moto a zig-zag, emettendo luce.



Ondulatore

La luce del raggio è coerente e collimata

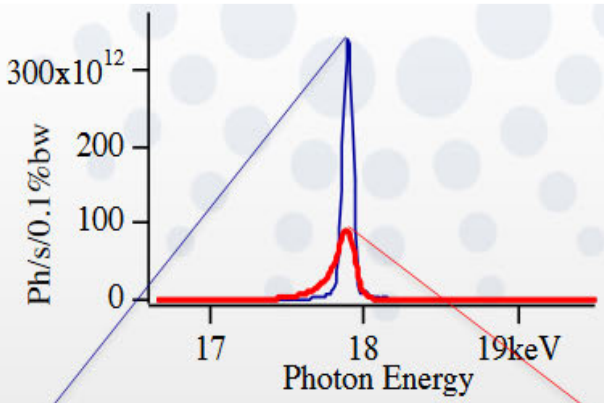


Wiggler

La luce del raggio è incorente e non collimata

Spectral Flux

Undulator:
Period λ_0= 22 mm
Number of period **N**=90
K=1.79
Harmonic **n**=3



Undulator resonance wavelength:

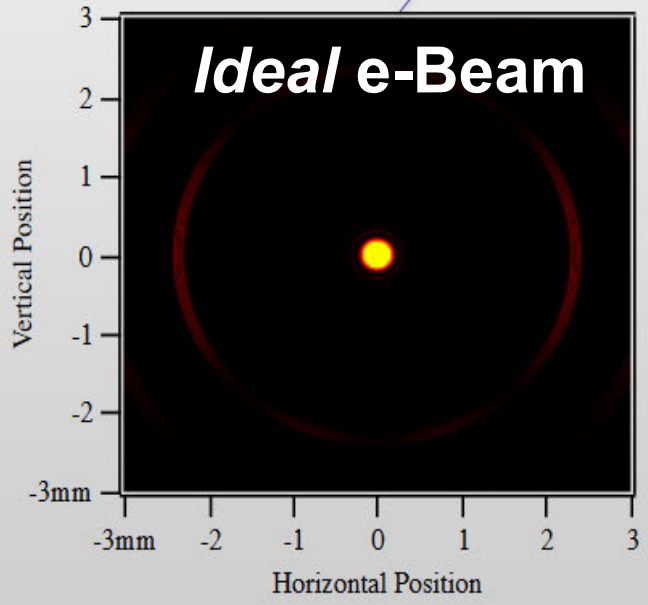
undulator period

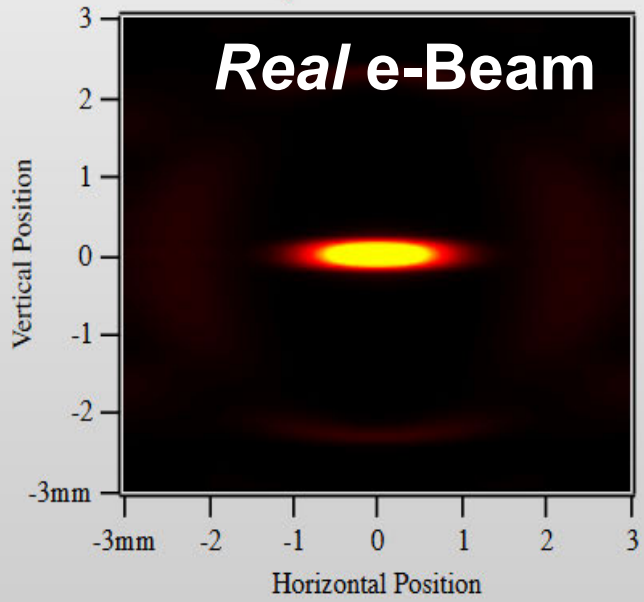
magnetic field

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + K^2/2 + \gamma^2\theta^2\right)$$

e-beam energy

e-beam divergence





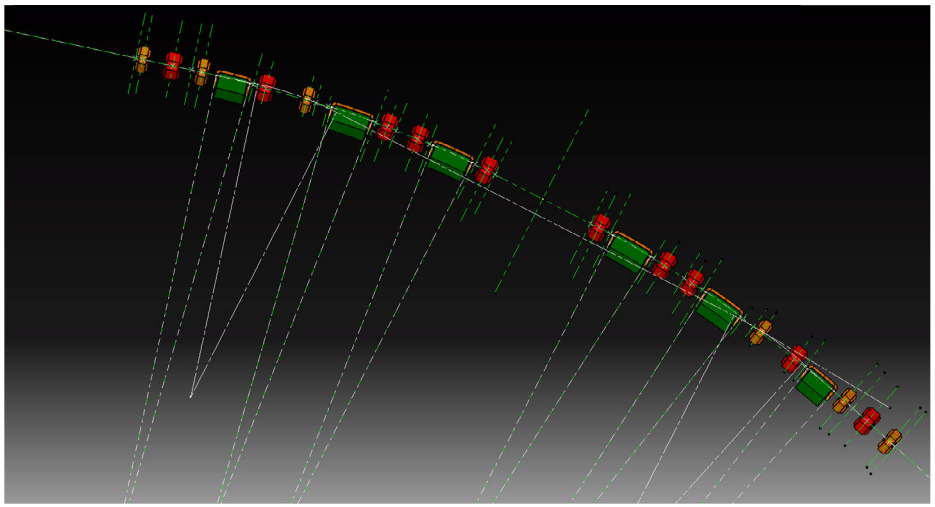
"undulator parameter", it is proportional to the undulator magnetic field: K ∝ B

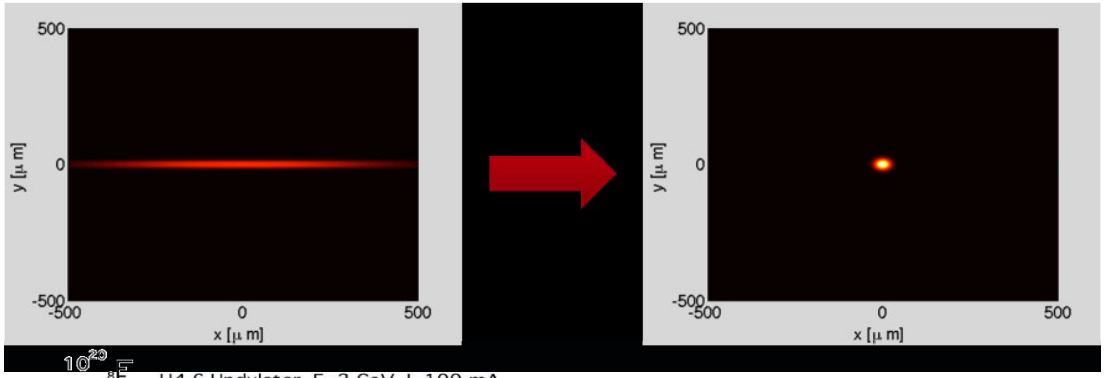
New Generation is Coming

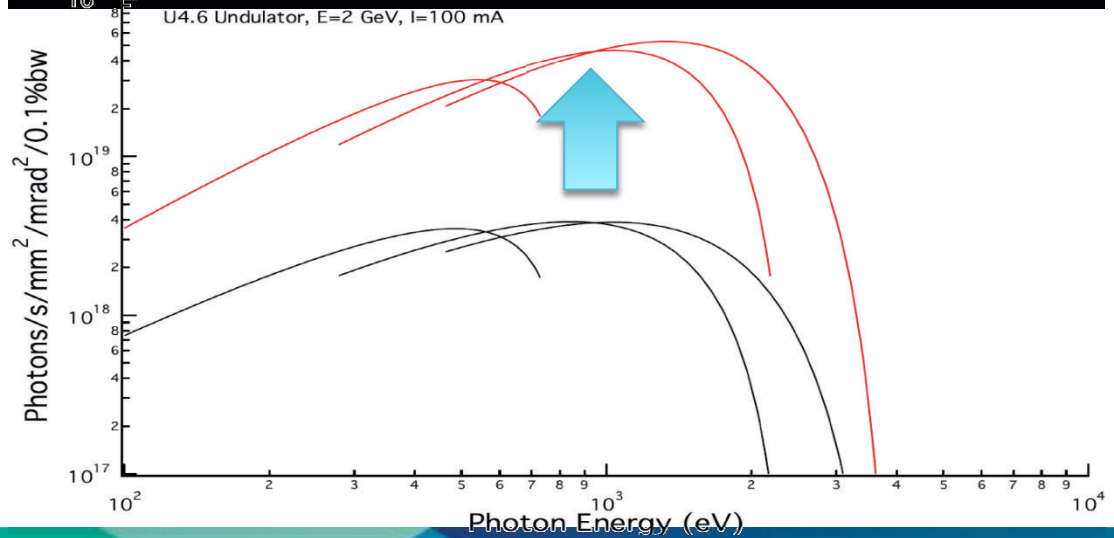
Upgrade of synchrotron light sources is planned worldwide, in order to reach a higher photon brilliance.

More dipoles, smaller bending angle, smaller e-beam sizes, higher charge density.

From Elettra to Elettra 2.0:

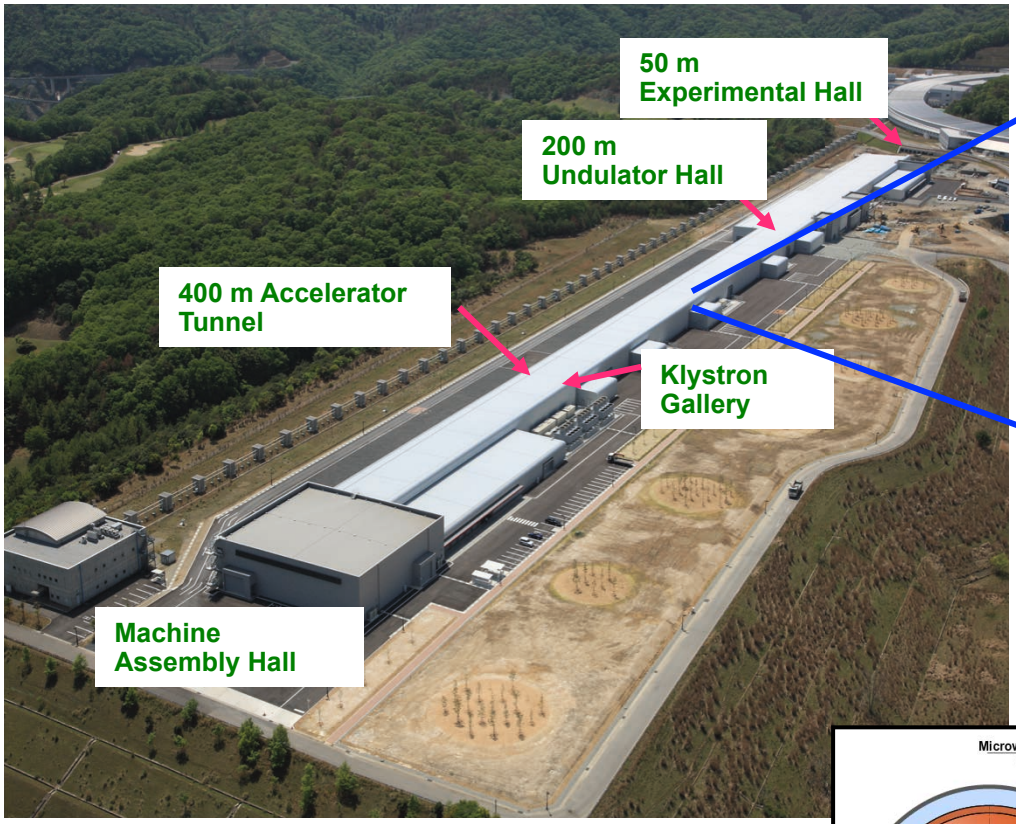




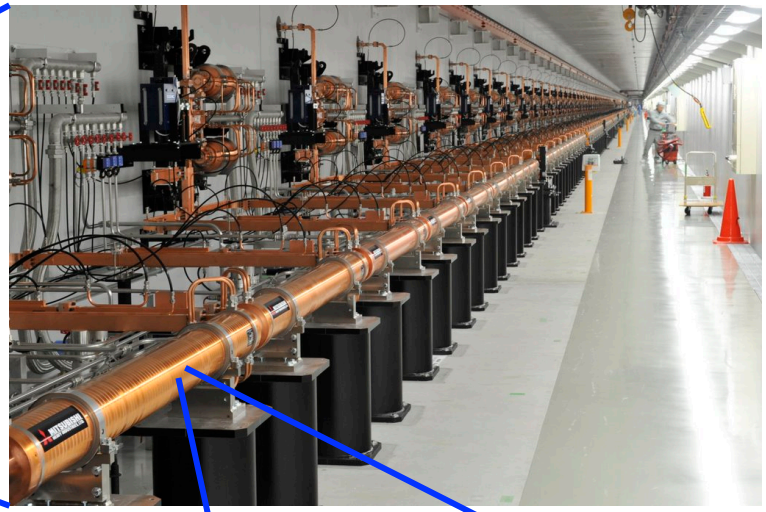


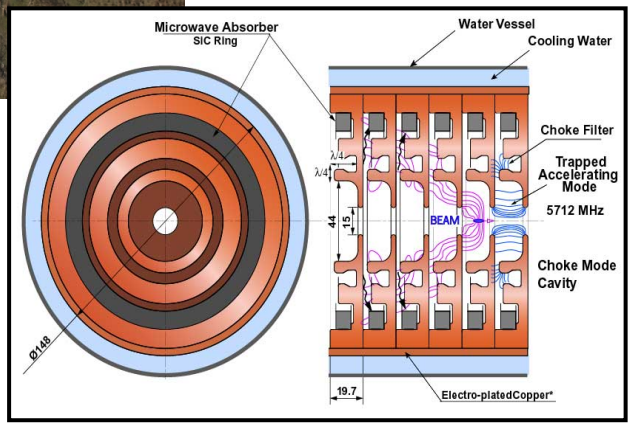
Back Slides Follow

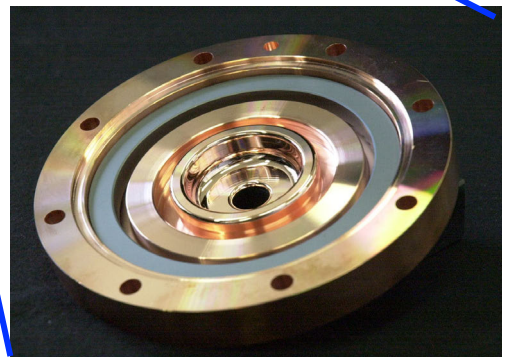
Radiofrequency Electron Linac



Source: T. Inagaki, T. Shintake

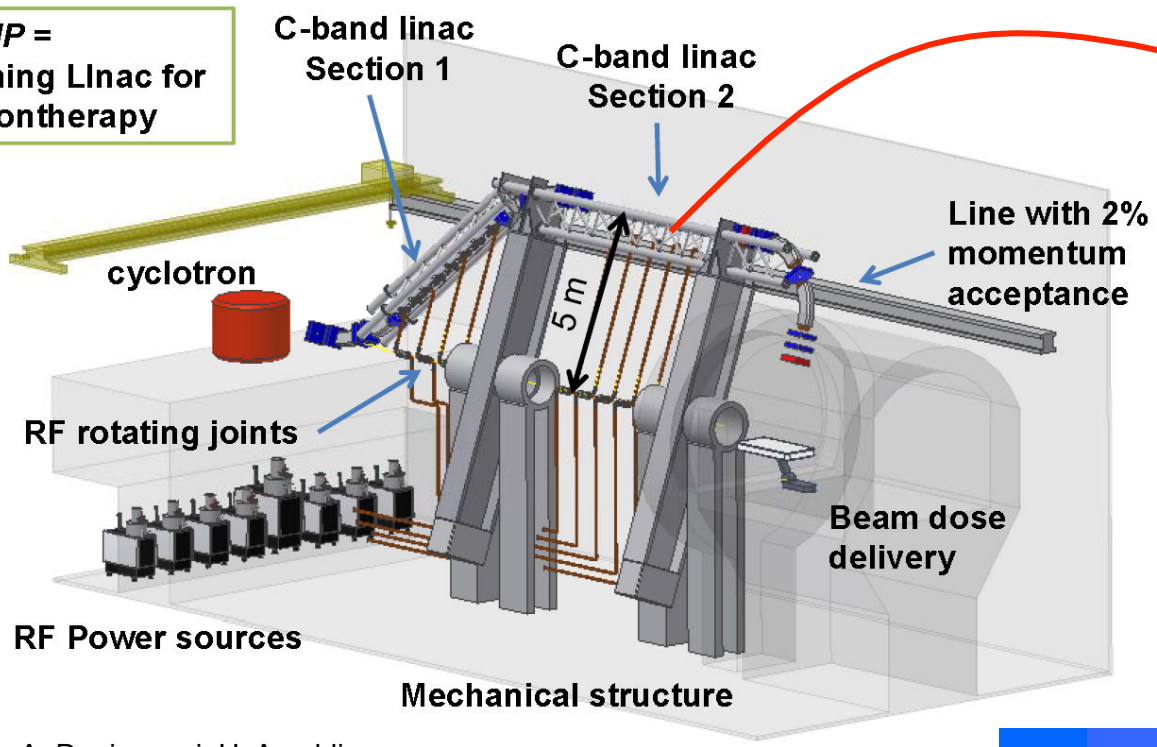




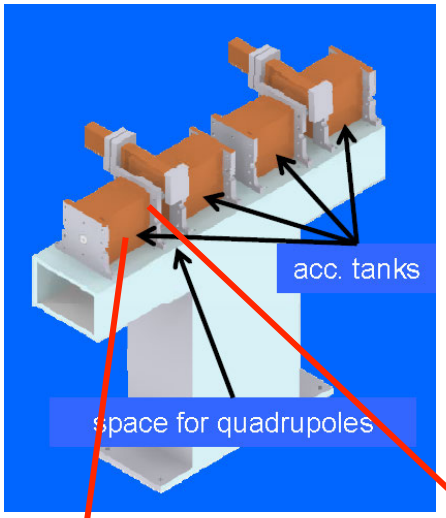


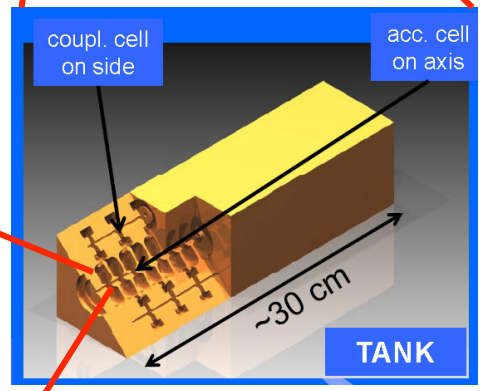
8 GeV e-linac
C-band (5.7 GHz)
35 MV/m acc. gradient
13000 cells mass production

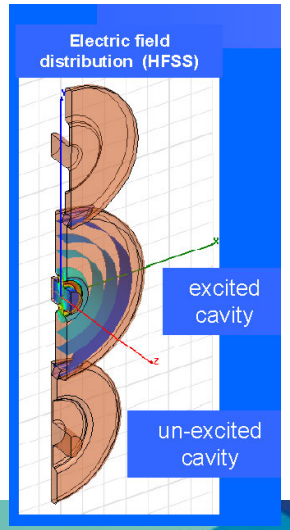
Radiofrequency Proton Linac



Source: A. Degiovanni, U. Amaldi

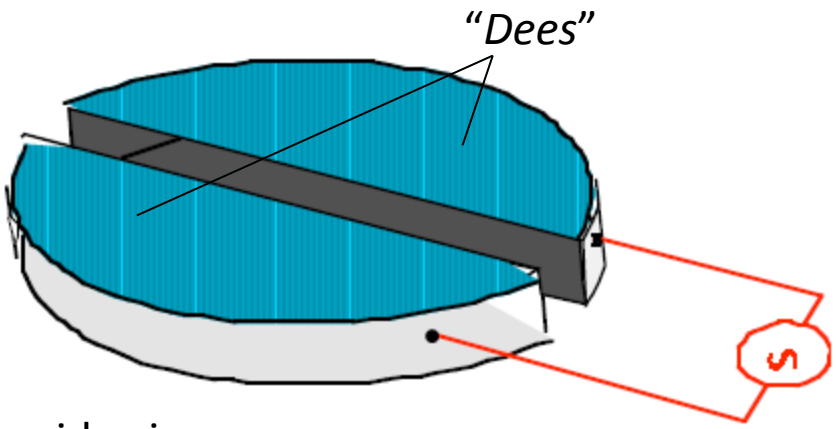




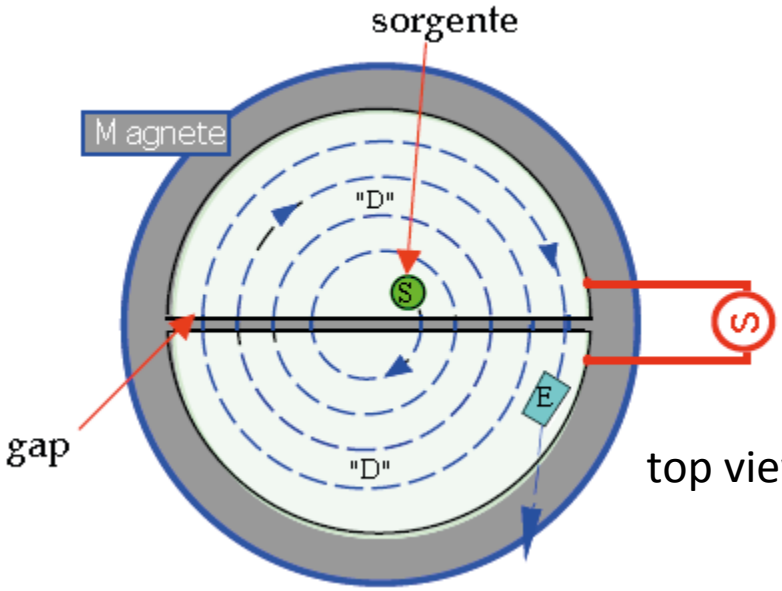


80–210 MeV p-linac
C-band (5.7 GHz)
<38 MV/m acc. gradient
Rep.rate, 200 Hz

Cyclotron *(E.O.Lawrence & M.S.Livingstone, Berkeley 1931)*



side view



top view

$$f_{RF} = (2n+1) f_C$$ Synchronism

$$\Delta T(t) = qV_o \sin(\omega_{RF} t + \varphi)$$ Energy gain / turn

$$\rho = \frac{P}{|q| B_o}$$ Lorentz force

$$P = \sqrt{2 m_o T}$$ Classical approximation (e.g., massive particles)

- Spiraling motion:

$$\Delta\rho = \rho \frac{1}{2} \frac{\Delta T}{T} = \frac{\Delta T}{|q| cB} \sqrt{\frac{m_0 c^2}{2T}}$$

- Maximum kinetic energy:

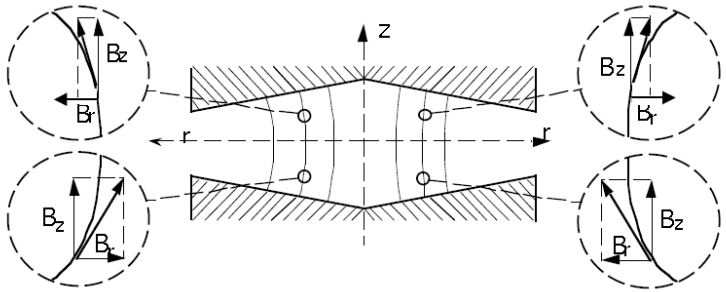
$$\frac{\sqrt{2 m_o T_{max}}}{|q| B} = R$$

Sinchro- and Sector- Cyclotron

$$\omega_c = \frac{B}{|q|m} = \frac{1}{\gamma}\frac{B}{|q|m_0} \equiv C\omega_{RF}$$

To maintain the synchronism, which ensures the multi/turn acceleration, one has two ways:

1. Increase B(t) synchronous to $\gamma(t)$, $\propto \rho(t)$ ⇨ *"sector cyclotron"*



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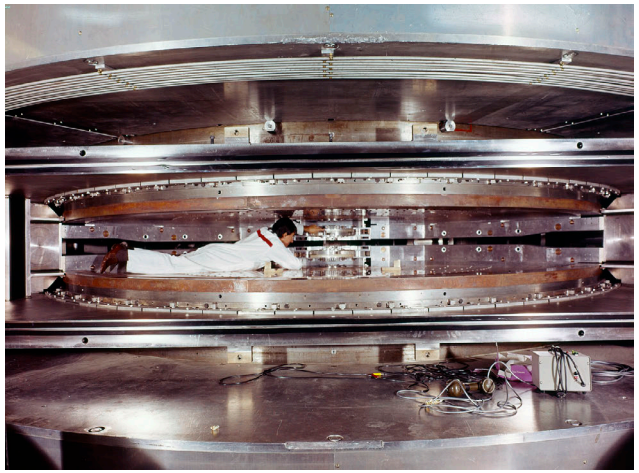
2. Increase ω_{RF} (t) synchronous to $\gamma(t)$

⇨ *"sincro-cyclotron"*

CERN SC



N.B.: here the beam is ***bunched***, over one period of modulation of ω_{RF} !!