

PaGES²

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

Introduction to Particle Accelerators

With Focus on Synchrotron Light Sources

Simone Di Mitri

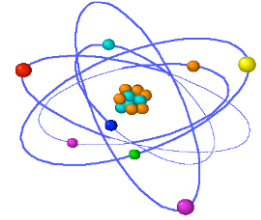
Elettra Sincrotrone Trieste

University of Trieste, Dept. of Physics

PaGES 2 è finanziato dalla Regione Autonoma Friuli Venezia Giulia, nell'ambito del Piano regionale per il potenziamento dell'offerta formativa (POF), anno 2016/2017: Progetto Speciali.



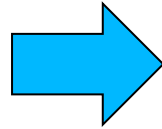
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- ❑ **Charged particles:** electrons, protons, ions, anti-particles

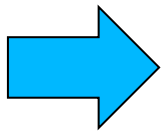
$$E = \gamma(v)m_0c^2$$

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



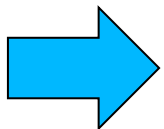
Special Relativity is all we need. Includes kinematics and dynamics of relativistic charged particles.

- ❑ 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.



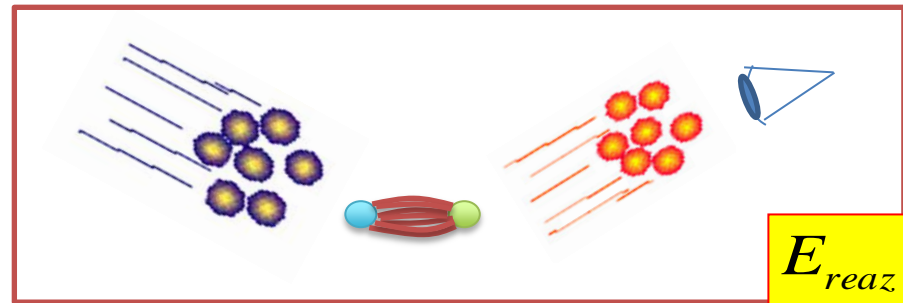
Magnetic elements for controlling the particles direction (orbit) and beam size (focusing).



eric

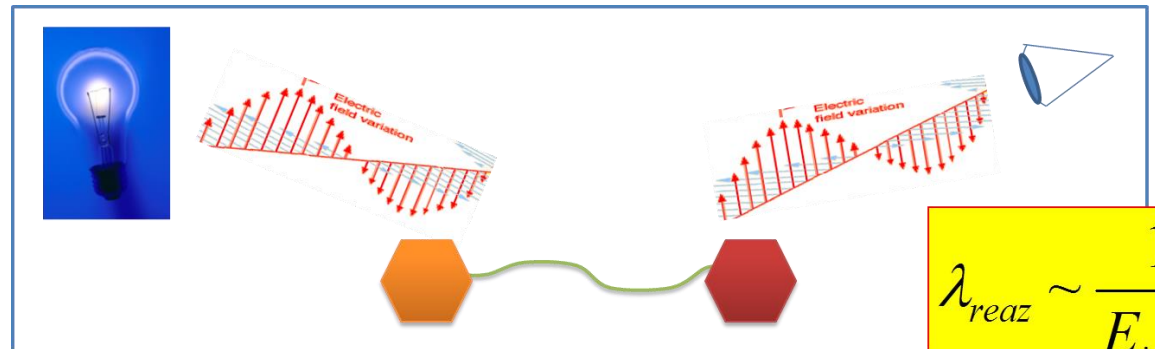
Why High Energy Particle Beams ?

“Colliders” (LHC,...)



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

“Synchrotron Light Sources” (Elettra,...)



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



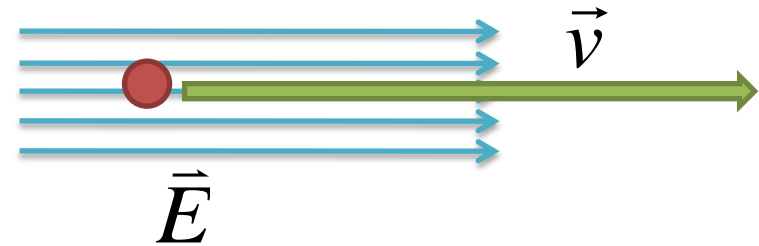
Elettra Sincrotrone Trieste

Acceleration, Particle Energy

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

Electric field

Energy

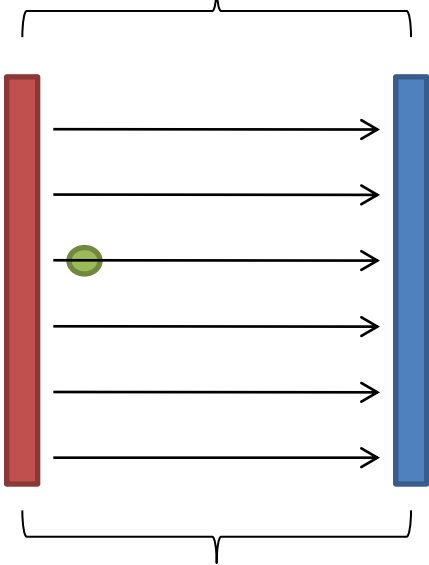


ΔV

$$J = N \times m = C \times V$$

$$1 \text{ eV (electronvolt)} = 1 \text{ e} \times 1 \text{ V}$$

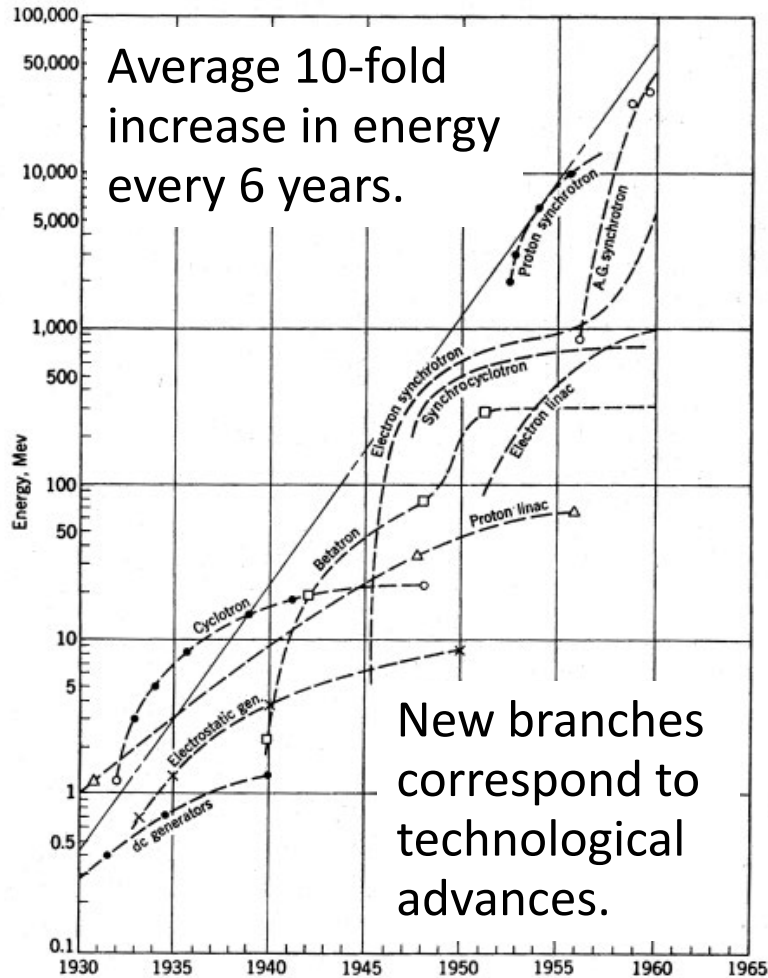
$$e = -1.6e-19 \text{ C}$$



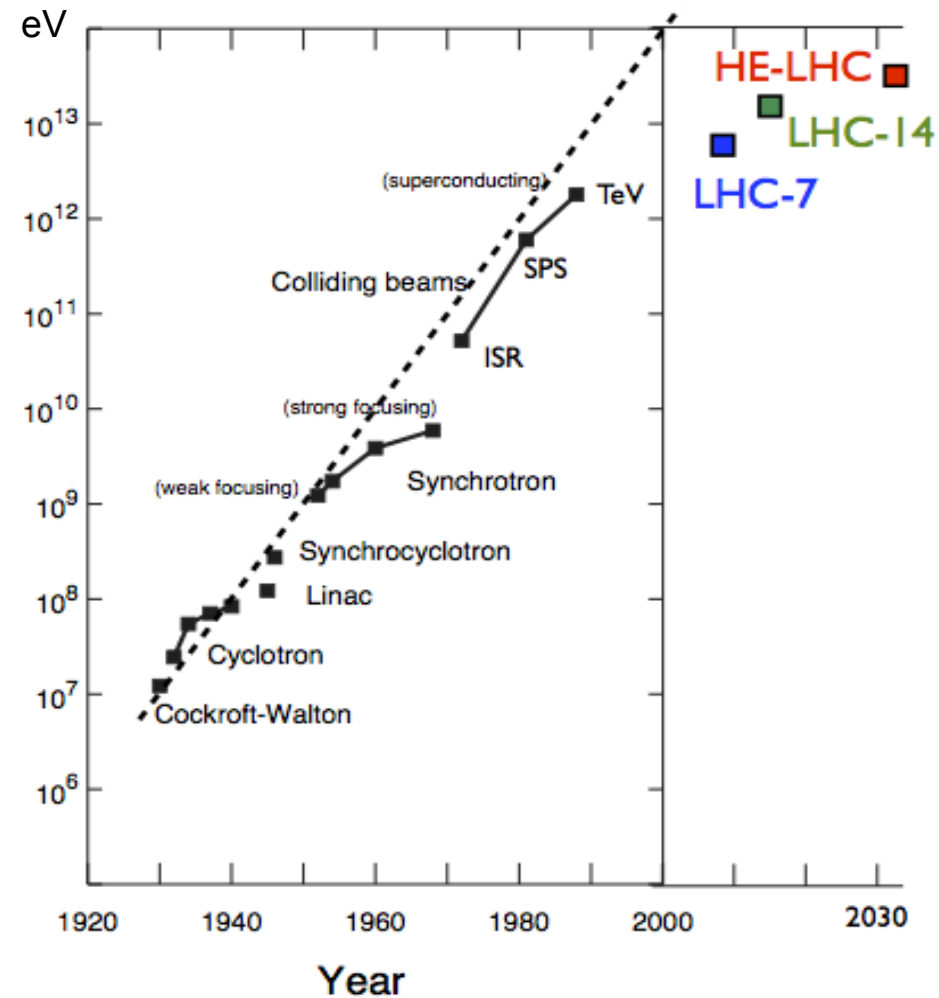
$$\Delta E = -q\Delta V$$



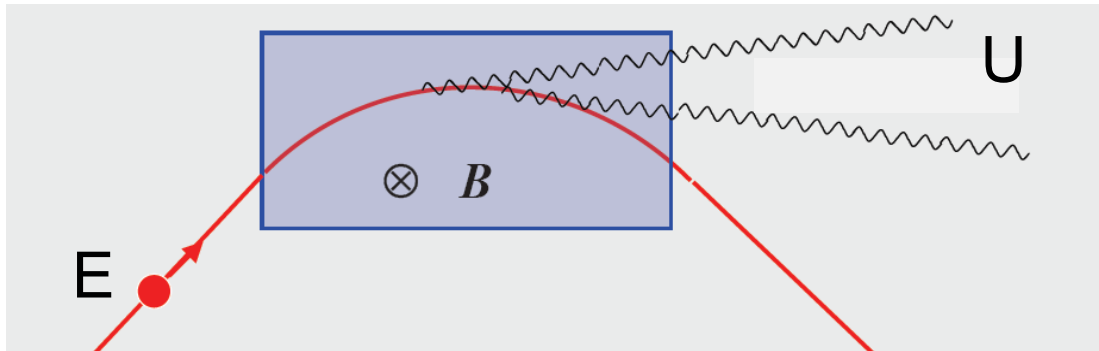
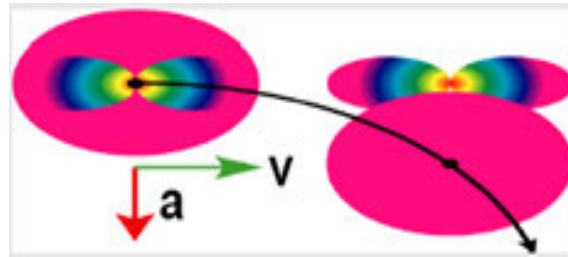
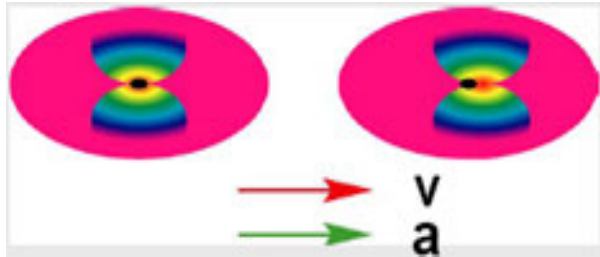
Livingstone Chart



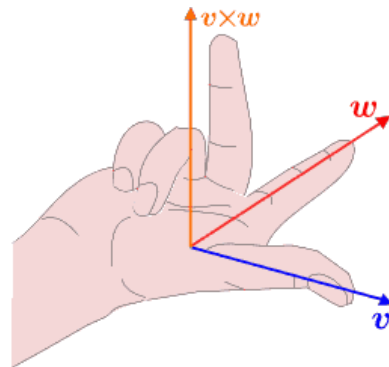
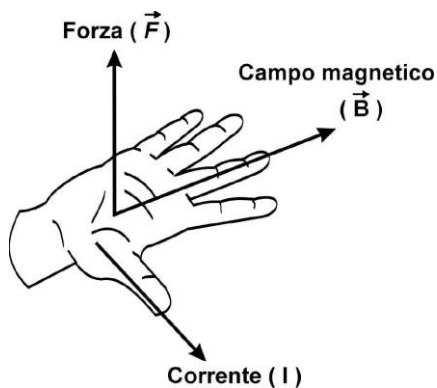
C.M. Energy
(eV)



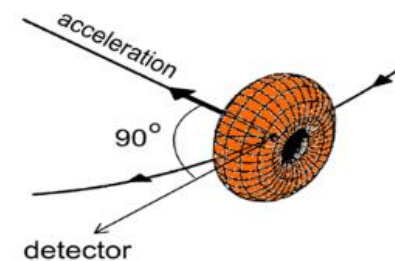
Synchrotron Radiation



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

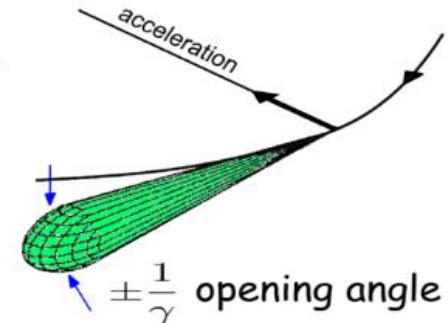


Moving frame
of electron

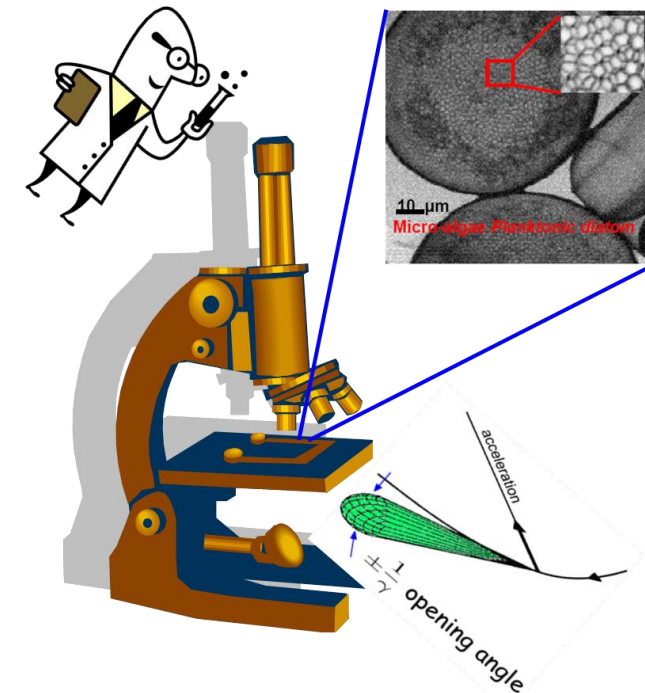
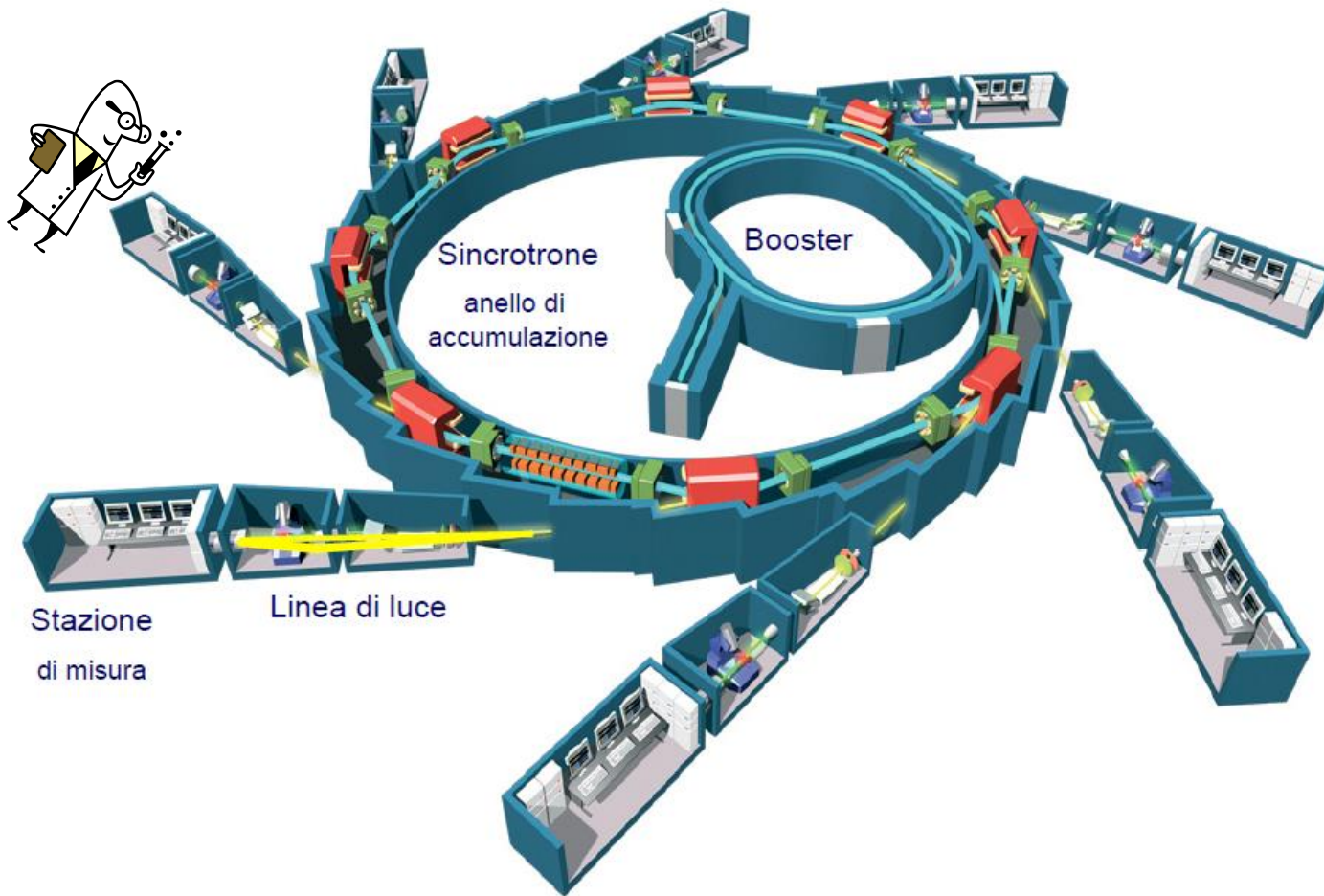


$$\frac{1}{\gamma} = \frac{m_0 c^2}{E} = \sqrt{1 - \left(\frac{v}{c}\right)^2}$$

Lab frame



Synchrotron Light Source



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 nmSponsors:

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

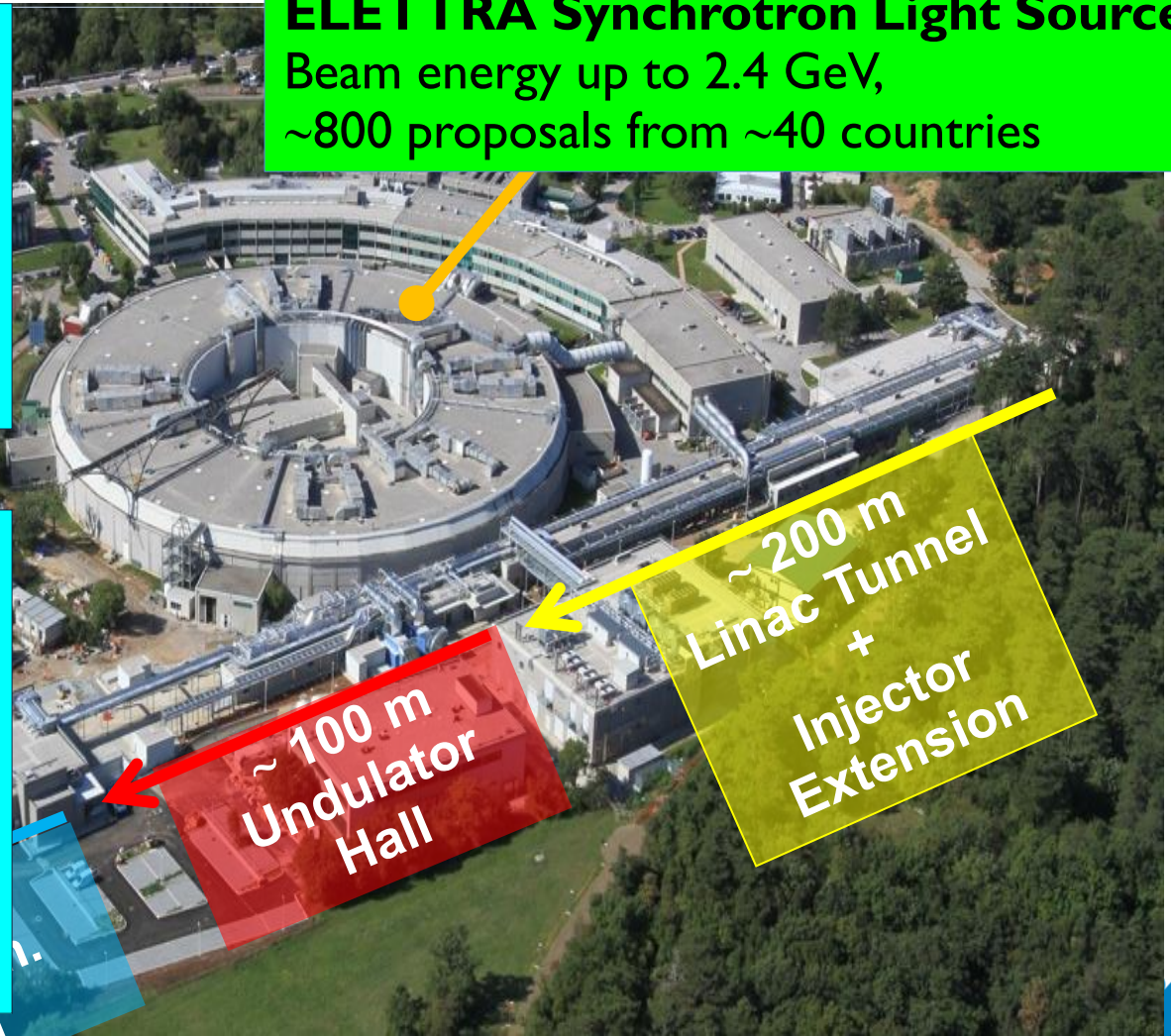
ELETTRA Synchrotron Light Source:

Beam energy up to 2.4 GeV,
 ~800 proposals from ~40 countries

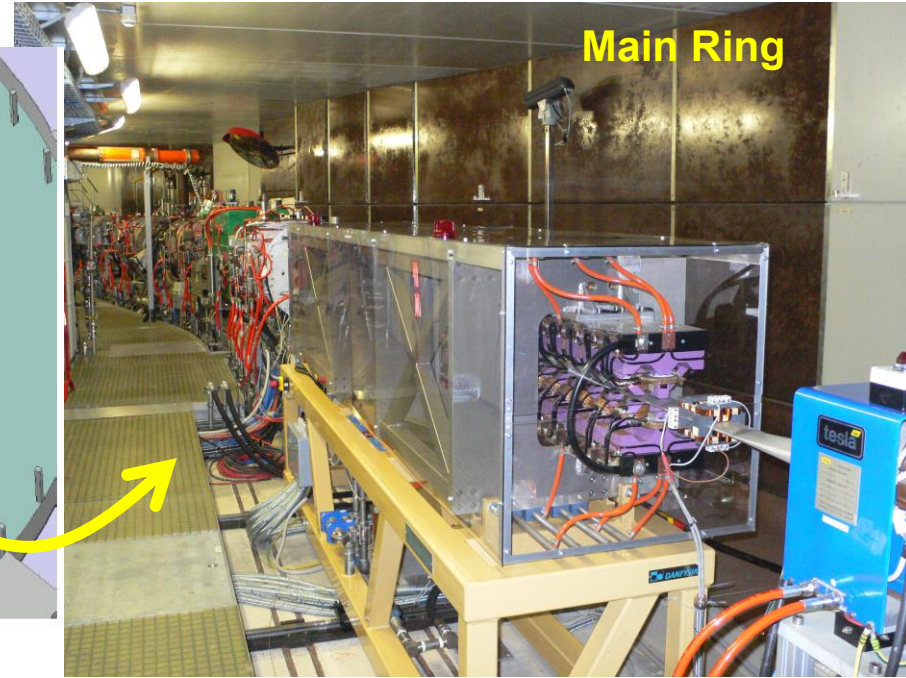
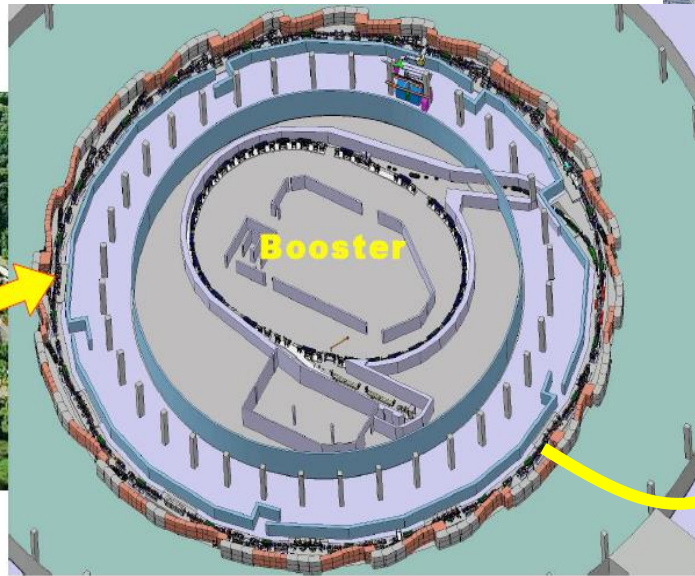
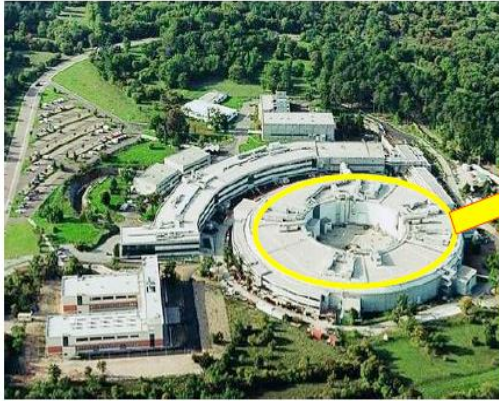
Collaborations:



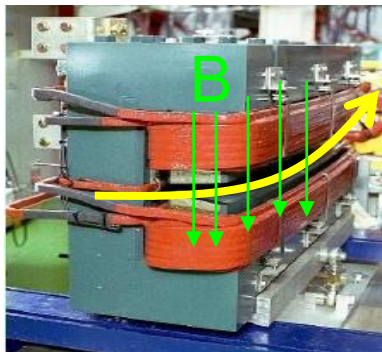
and many



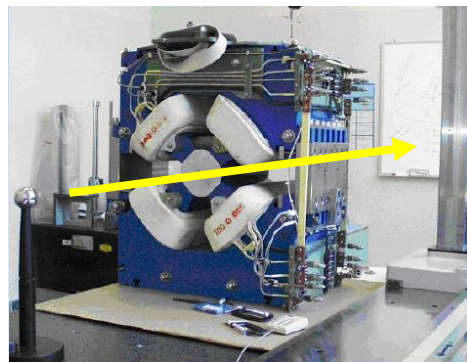
Elettra Synchrotron Light Source



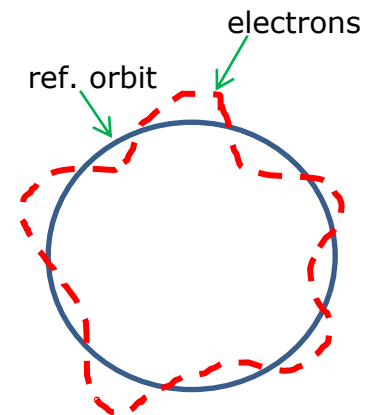
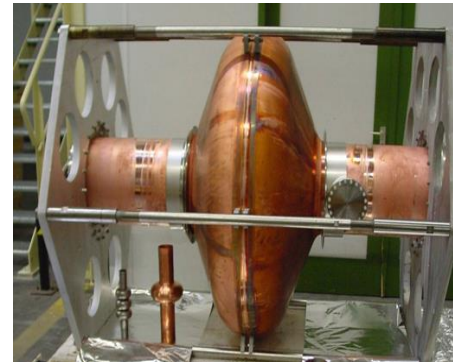
Dipole Magnet



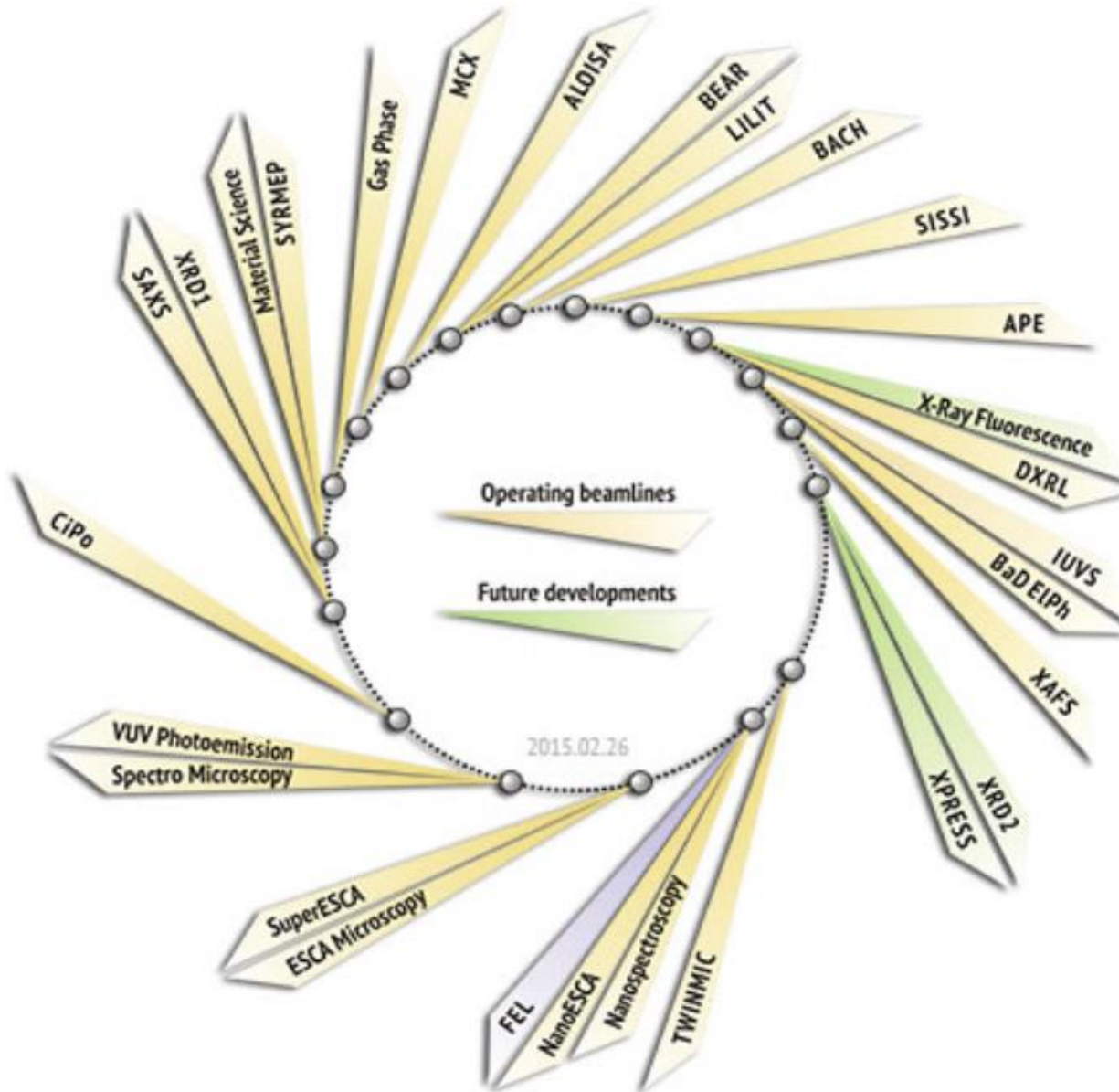
Quadrupole Magnet



RF cavity

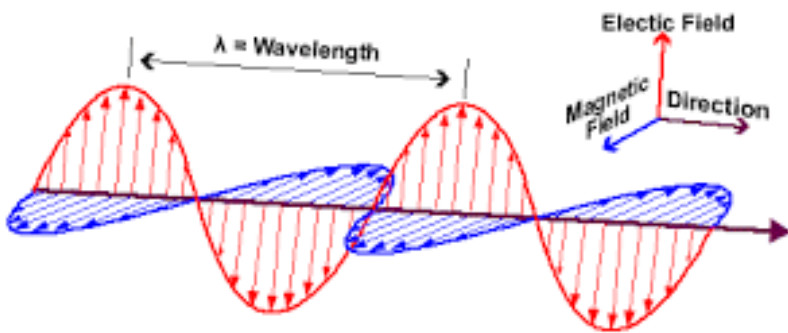
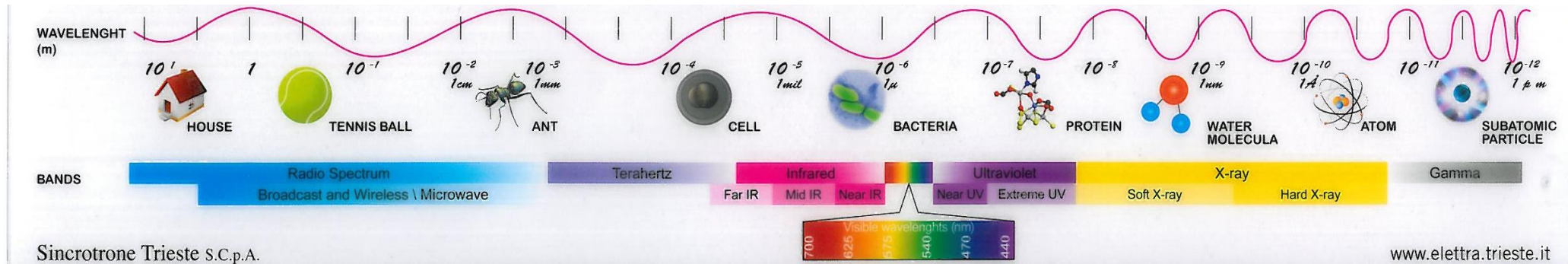


Elettra Photon Beamlines



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

Wavelength, Photon Energy



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

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

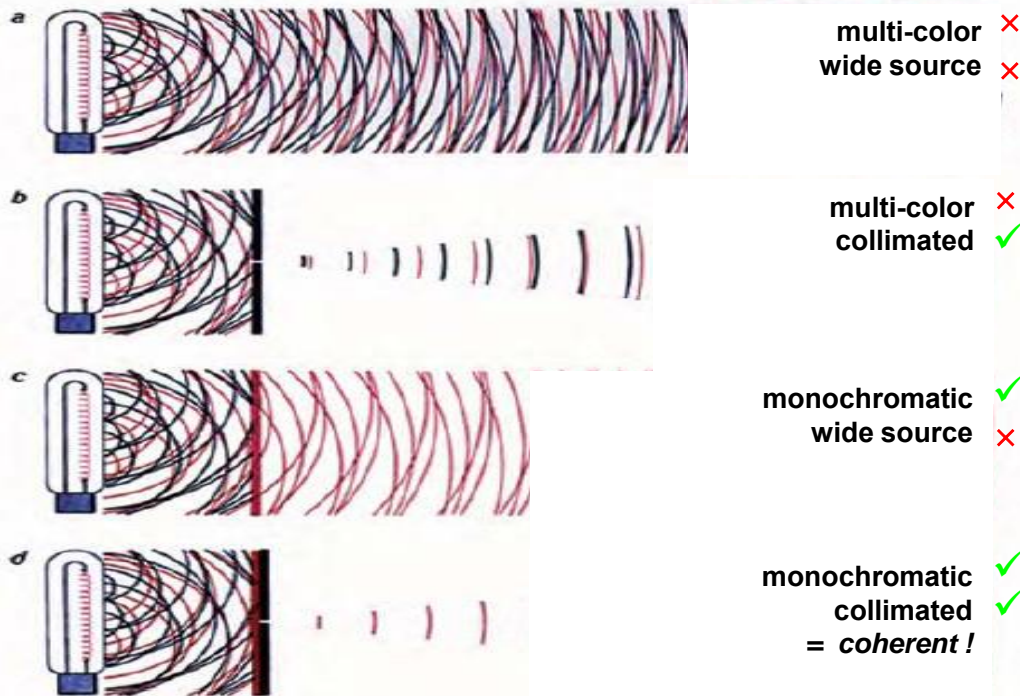
$$E [J] = h \cdot \nu$$

$c = 2.998 \times 10^8$ m/s *Light speed in vacuum*

$h = 6.626 \times 10^{-34}$ J s *Planck constant*

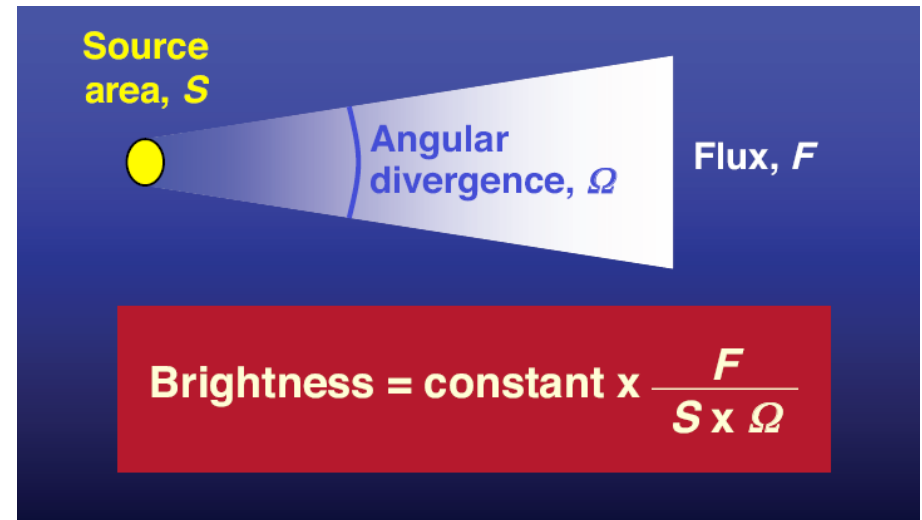
- An e.m. wave can be described also as a bunch of massless particles, named "photons".
- Photons travel at speed c in vacuum.
- The energy of an e.m. wave (monochromatic) is the photon energy times the number of photons.

Transverse & Longitudinal Coherence

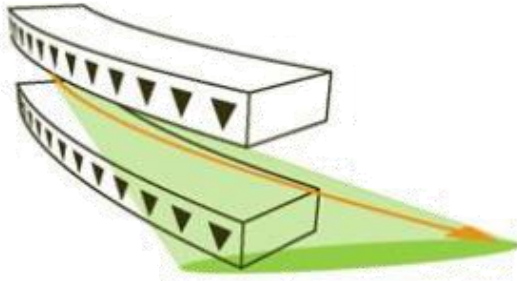


Courtesy of A. Schawlow, Stanford.

Brilliance



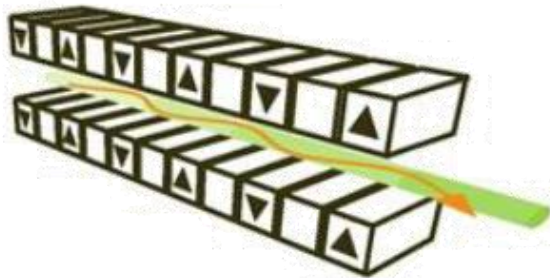
Radiation Sources



Magneti Curvanti

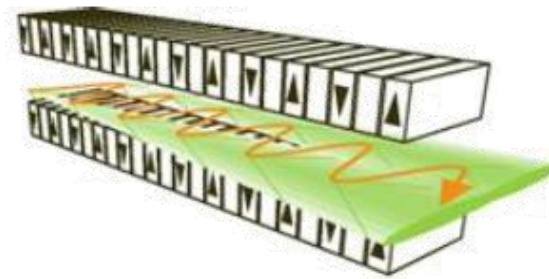
I magneti Curvanti mettono in connessione due sezioni diritte del sincrotrone: la luce è prodotta mediante la “bremesstrahlung radiations”.

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

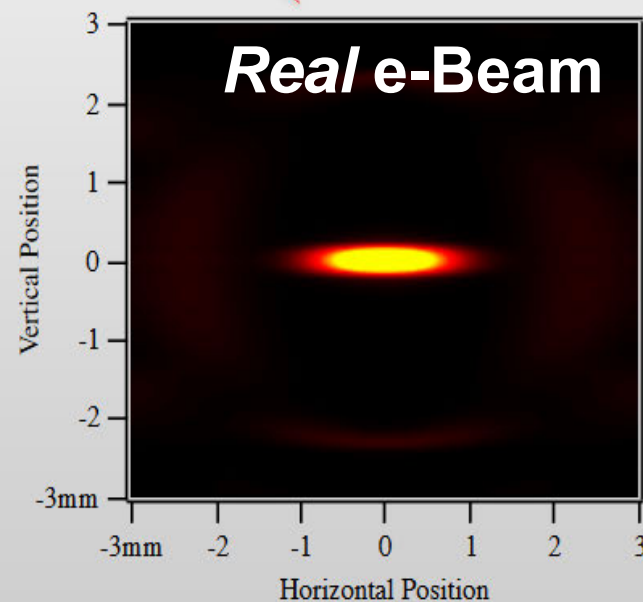
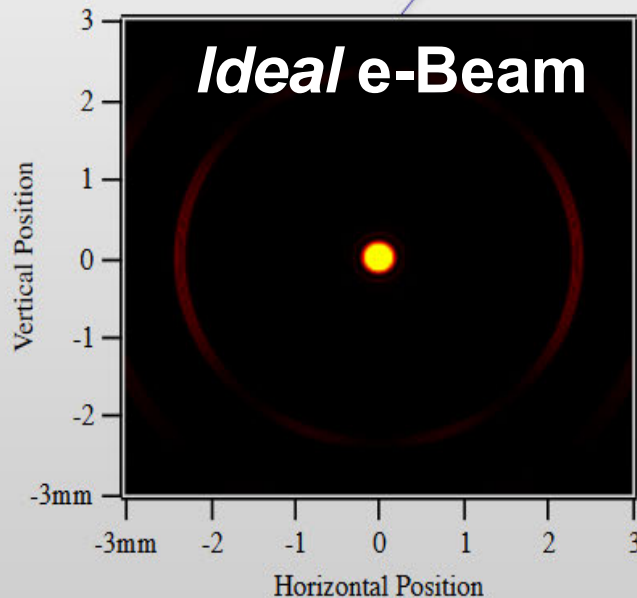
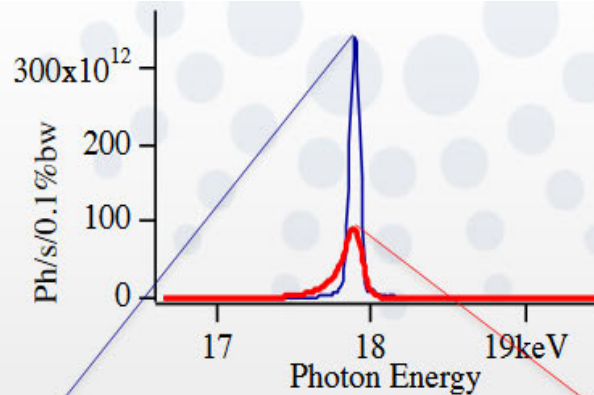


Wiggler

La luce del raggio è incoerente e non collimata

Spectral Flux

Undulator:
Period $\lambda_0 = 22$ 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

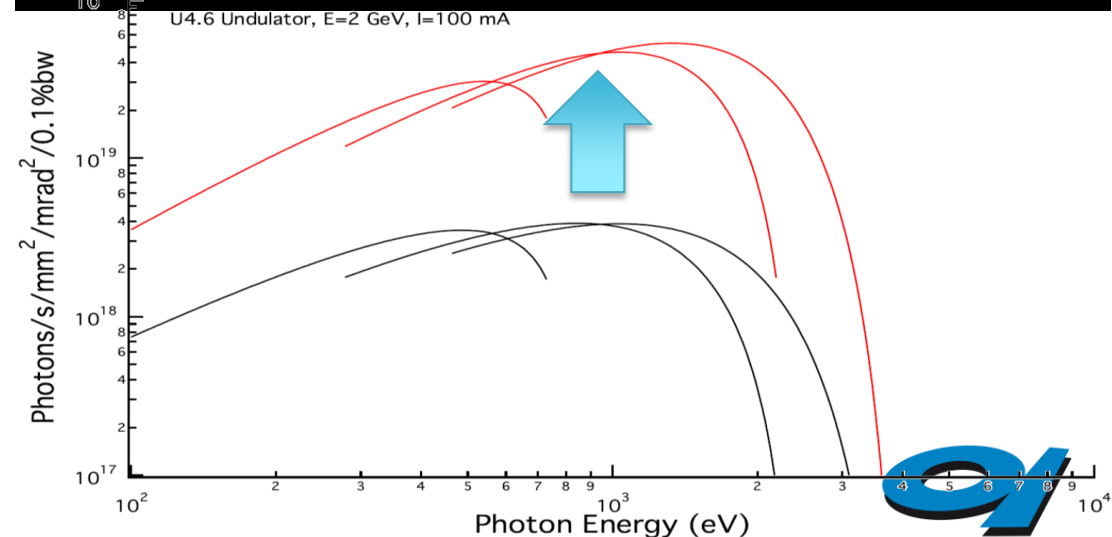
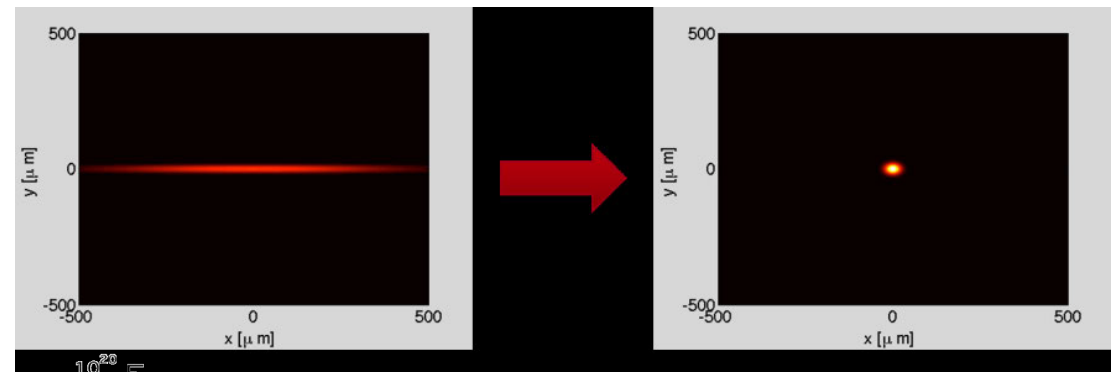
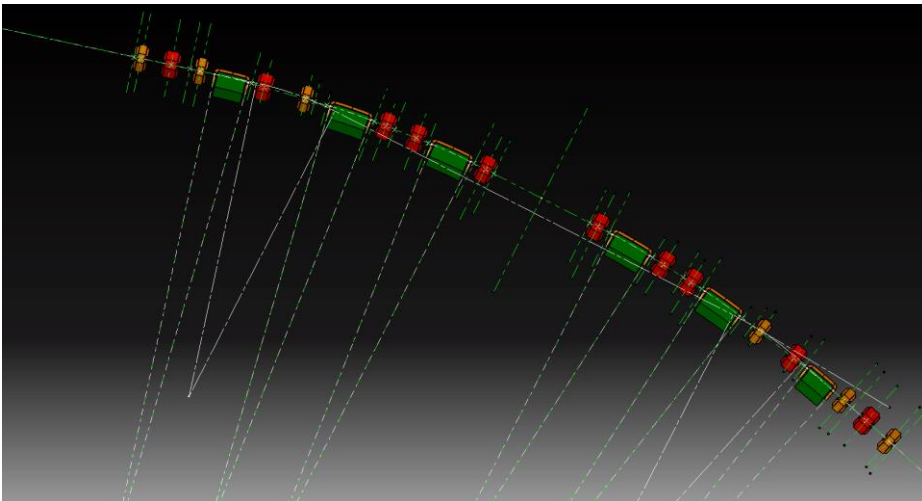
“undulator parameter”, it is proportional to the undulator magnetic field: $K \propto B$

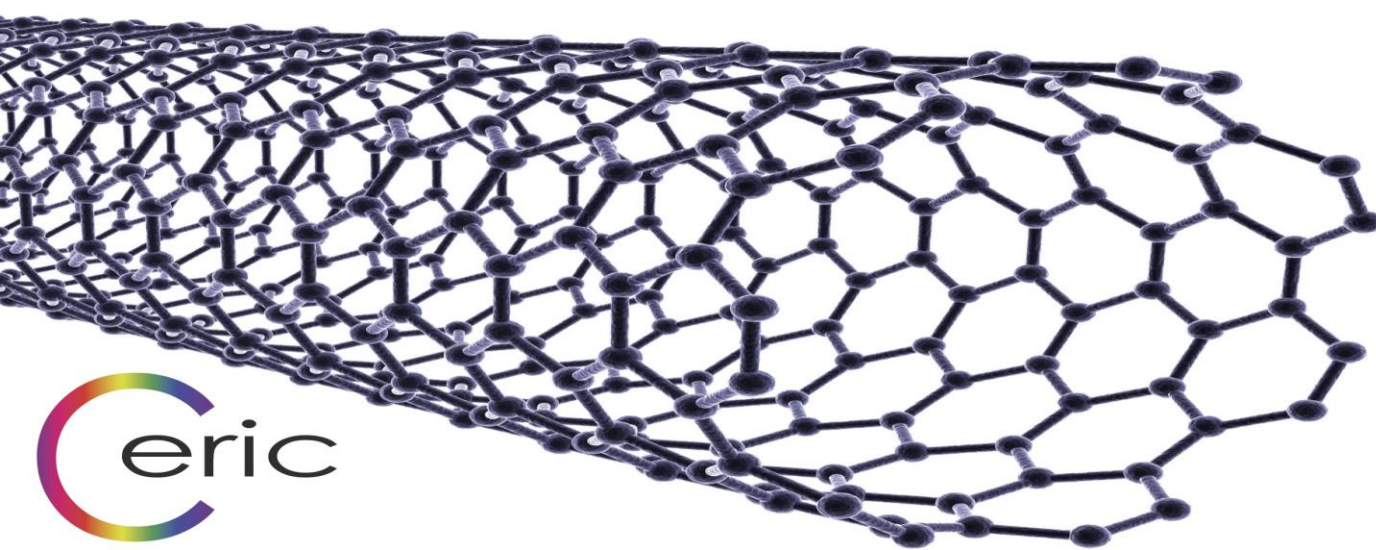
New Generation is Coming

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:





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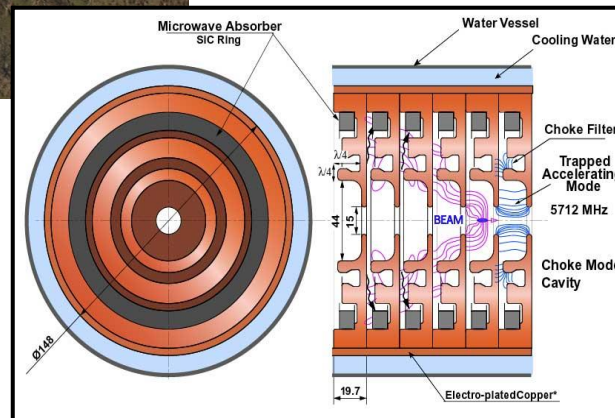
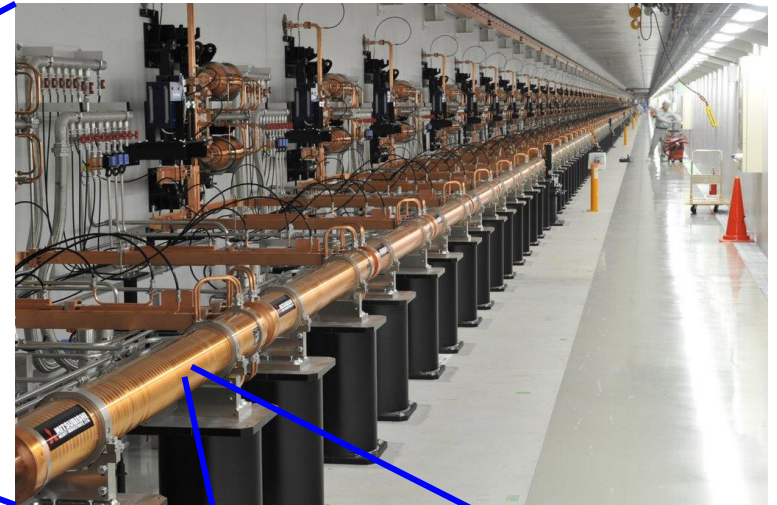
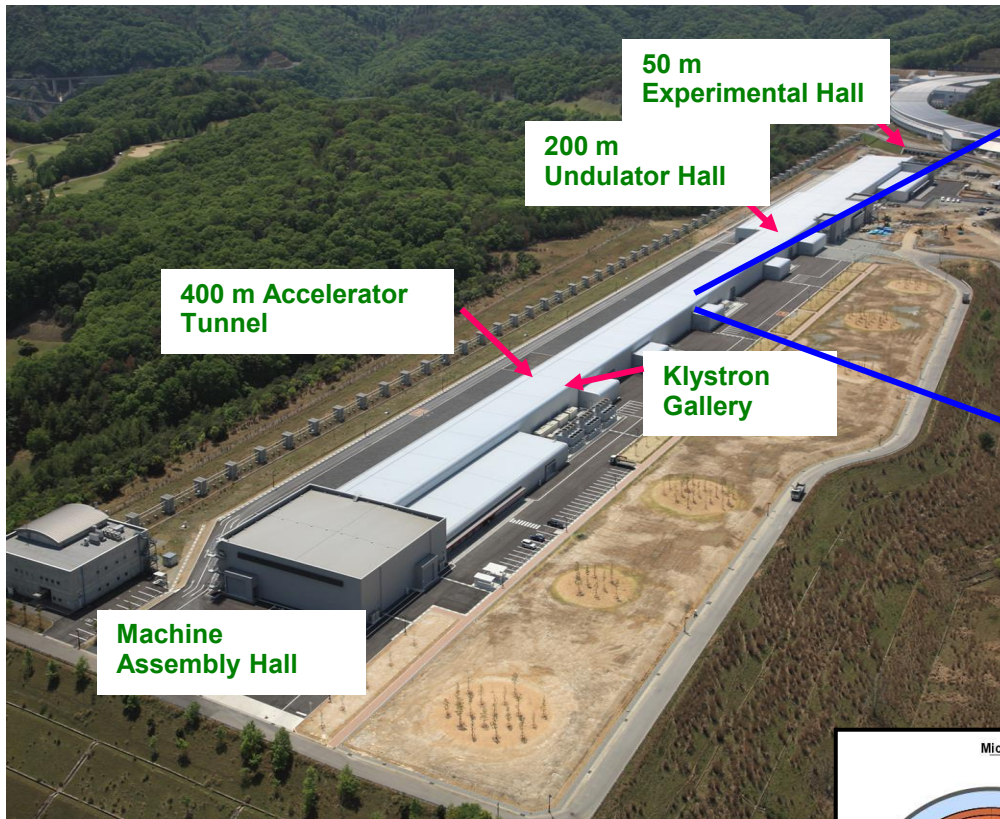
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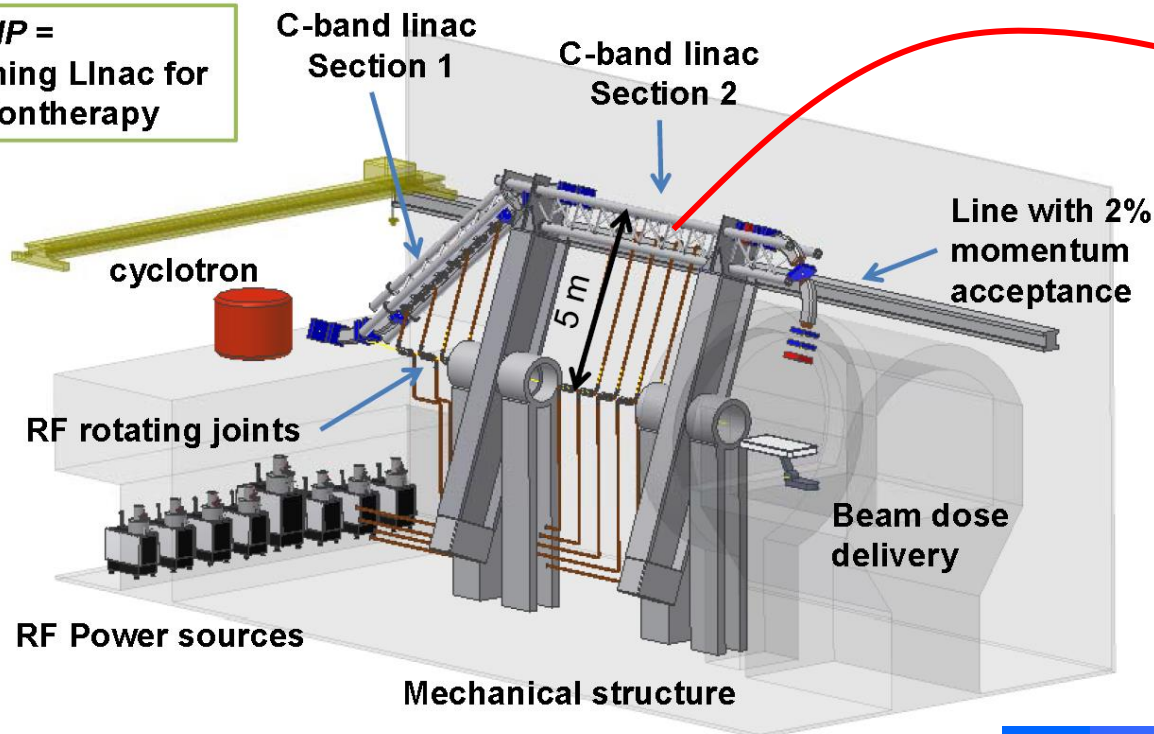
Source: T. Inagaki, T. Shintake

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

simone.dimitri@elettra.eu

Radiofrequency Proton Linac

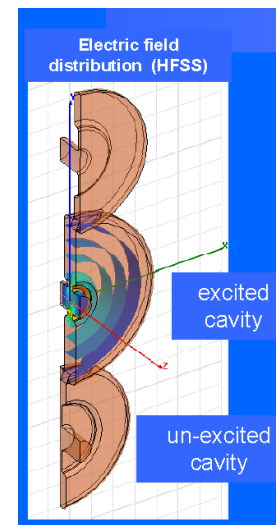
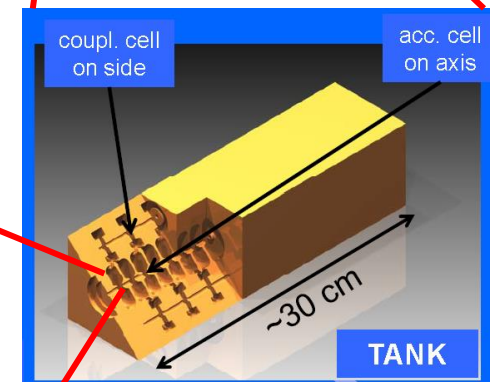
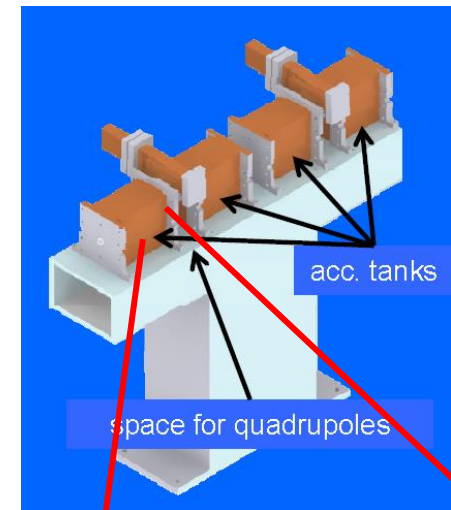
TULIP =
TURNING Linac for
Protontherapy



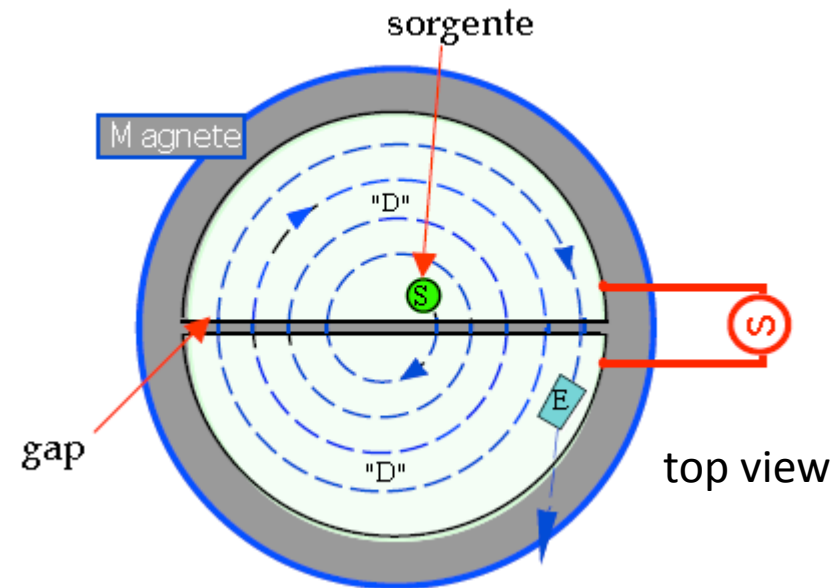
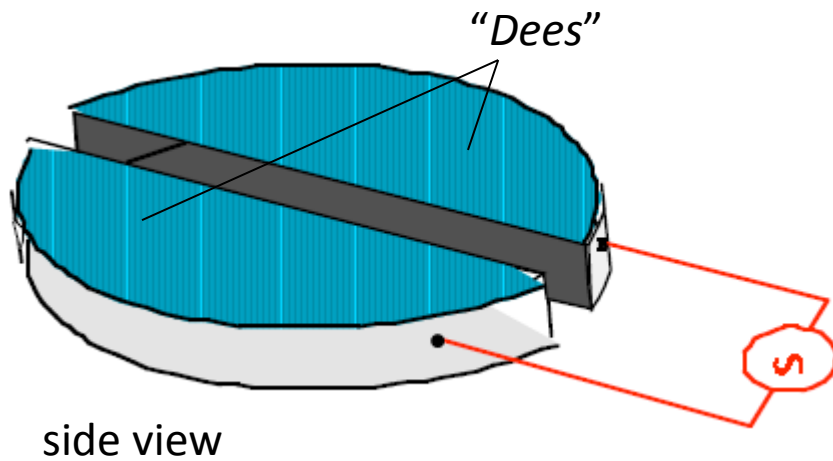
Source: A. Degiovanni, U. Amaldi

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

simone.dimitri@elettra.eu



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



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

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

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

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

- Spiraling motion:

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


- Maximum kinetic energy:

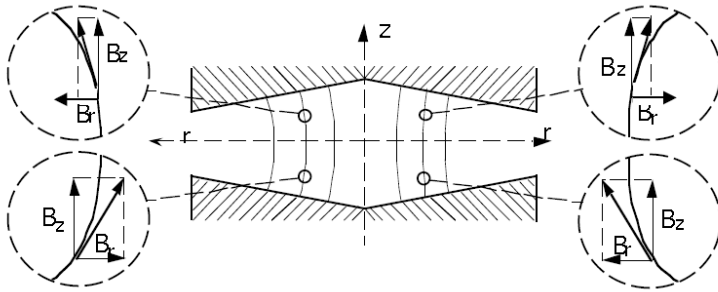
$$\frac{\sqrt{2m_o T_{\max}}}{|q|B} = R$$

Synchro- and Sector- Cyclotron

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

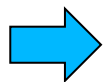
To maintain the synchronism, which ensures the multi/turn acceleration, one has two ways:

1. Increase $B(t)$ synchronous to $\gamma(t)$, $\propto \rho(t)$  “sector cyclotron”



TRIUMPH, Canada

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

 “sincro-cyclotron”

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

CERN SC

