Circular colliders
The DAΦNE Φ-Factor
Part I

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Outline

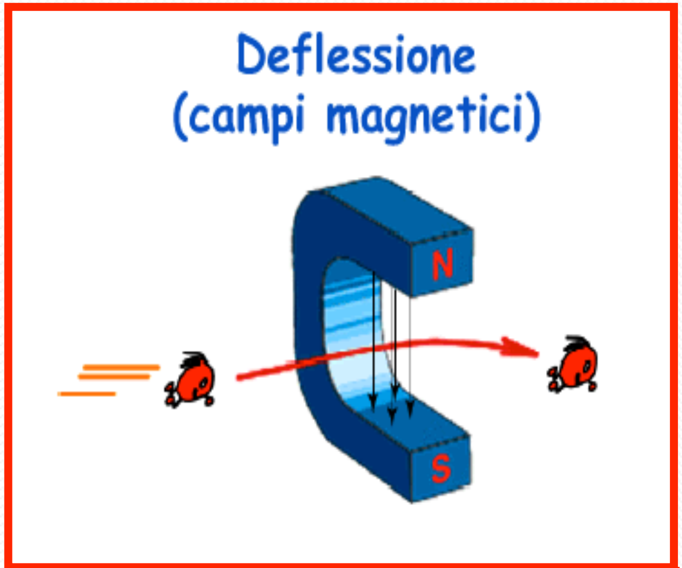
- Few concepts of accelerators physics
- Accelerator components
- Storage rings colliders
- Luminosity and beam-beam
- The DAΦNE collider
- The Large Piwinski Angle and Crab Waist concept
- Interaction Region design
- Some results of the new collision scheme
- Wigglers, beam pipe
- Examples of collective effects
- Conclusions

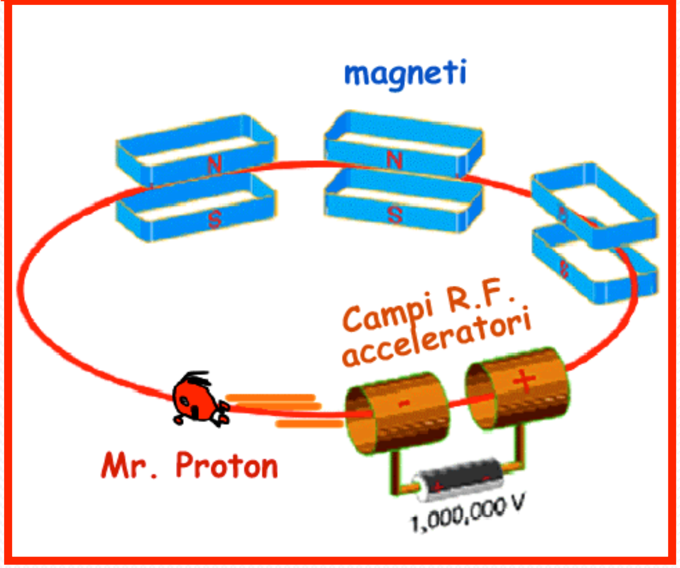
Circular Accelerators

- E.O.Lawrence (1930) was the first to think of bending the particles in a circular trajectory and make them pass many times in the same Radio Frequency cavity (RF)
- In circular accelerators the magnetic field B is vertical; if a relativistic particle with momentum p travels in a perpendicular magnetic field the momentum variation is:

$$\frac{dp}{dt} = ev \times B$$

- The curvature radius ρ of the particle trajectory depends on the charge and the Energy of the particle





Basic equation of particles motion in a circular accelerator

Charged particles motion is modified by the e.m. fields

$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

$\vec{E} = electric\ field$

$\vec{B} = magnetic\ field$

$\vec{p} = m\vec{v} =$ momentum

$m = m_o\gamma =$ invariant mass

$\vec{v} =$ velocity

$q =$ charge

$\beta \approx 1$

$v \approx c$

$s \approx ct$

Unit of particle Energy is the electronvolt [eV]: 1 eV is the energy of a particle with a unit charge accelerated by a 1 Volt elettrostatic potential:

1 eV=1.6x10^{-19} Joules

In accelerators multiples [keV, MeV, GeV] are most used !

Relativistic particle

- Follows relativistic kinematics

$$E = mc^2 = \frac{m_o c^2}{\sqrt{1-\beta^2}} = \gamma E_o$$

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

- If accelerated $\beta \to 1$ $m \to \infty$

- For ultra-relativistic particles (electrons) $p \approx \frac{E}{c}$

Electrical fields

$$\vec{\mathbf{F}} = m_o \vec{\mathbf{a}} = q\vec{\mathbf{E}}$$

Acceleration: increase in velocity

+ increase in energy

(as in Linear accelerators, with the RF cavities)

Magnetic fields

- A charged particle in a uniform magnetic field B describes a circle with radius ρ
- From the Lorentz force

$$q\rho B = m_o \gamma v$$

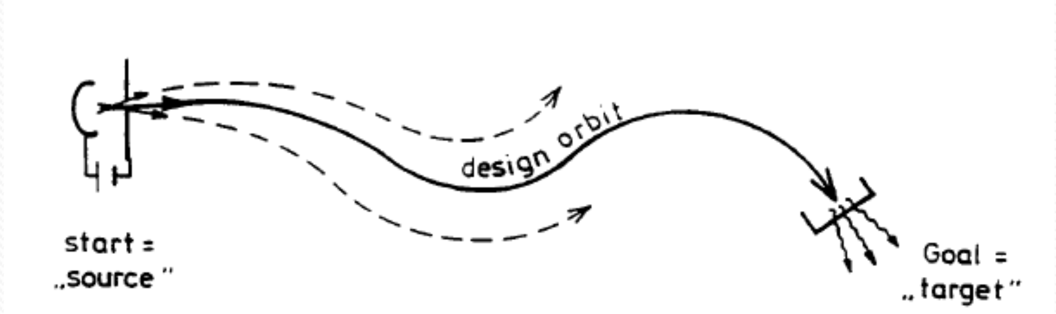
$$B(T)\rho(m) = 3.3\, E(GeV)$$

Magnetic rigidity

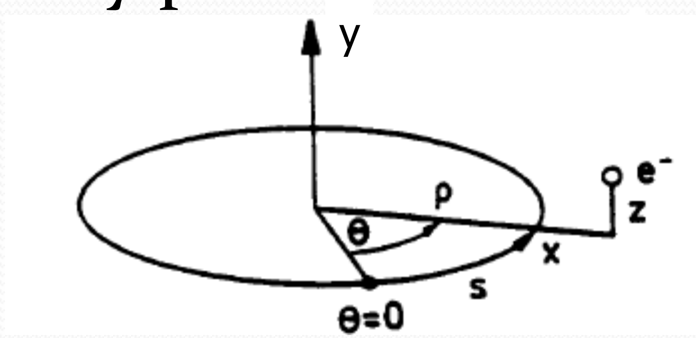
- Magnetic fields are used in circular accelerators to guide charged particles in circular trajectories in the beam pipe

Reference trajectory

In each accelerator exists a reference trajectory for the nominal particle (nominal energy, zero transverse displacement)

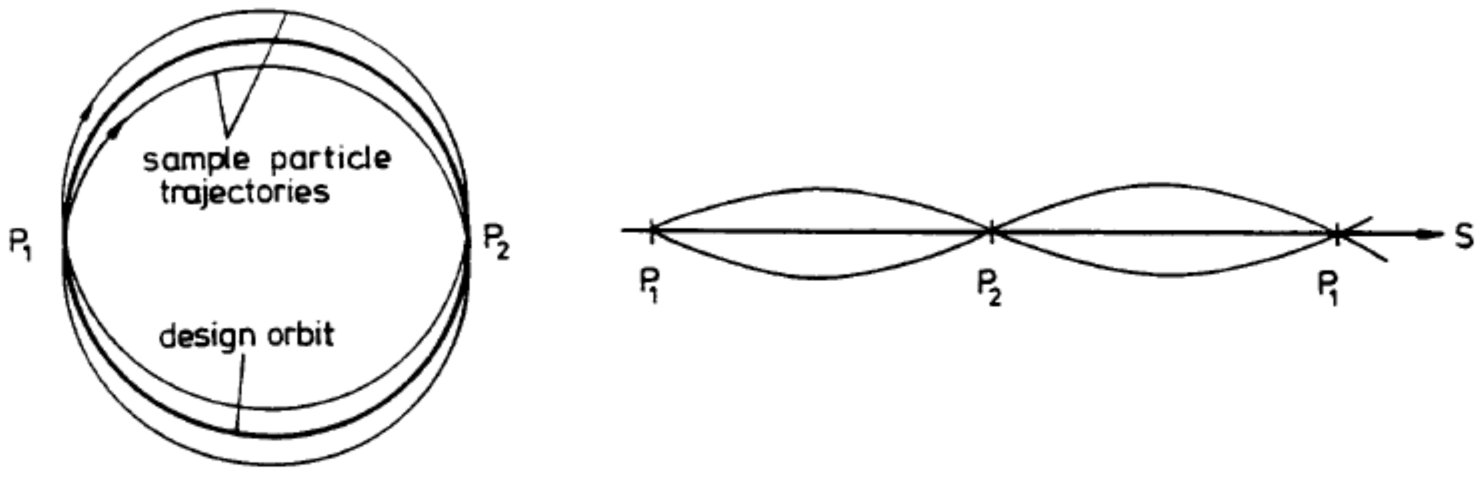


In a circular accelerator this trajectory is a closed orbit formed by pieces of arcs and drift spaces



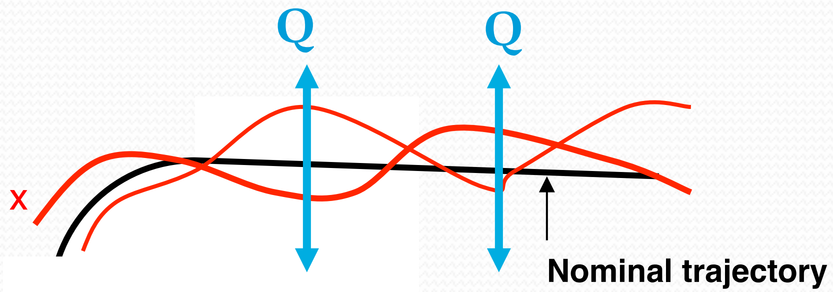
Focusing

- Since particles have in general deviated trajectories with respect to this orbit, focusing forces are needed to keep all trajectories close to the nominal one
- Focusing is provided by quadrupole magnets



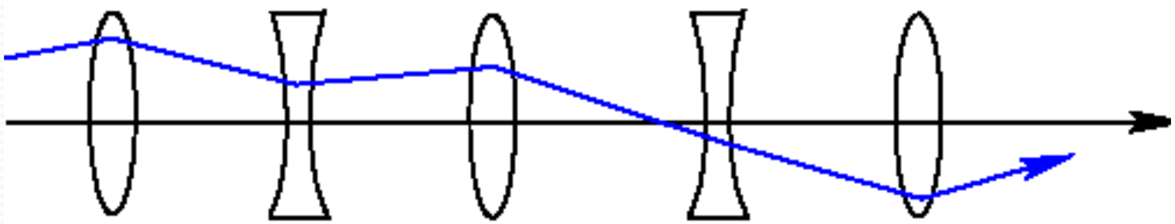
Betatron oscillations

- A particle with nominal energy E and coordinates $x=x'=y=y'=0$ follows the nominal trajectory and goes through the centre of the quadrupoles (Q) where the magnetic field is zero

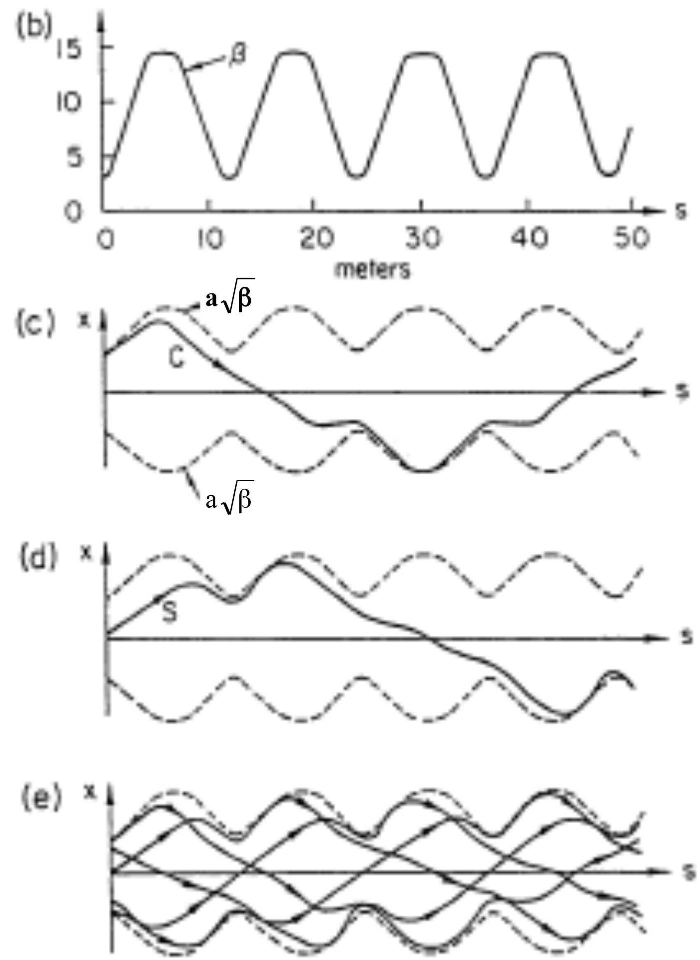


- If for any reason its position changes, it goes off axis in the quadrupoles and starts to oscillate around the nominal trajectory: these are called "betatron oscillations"

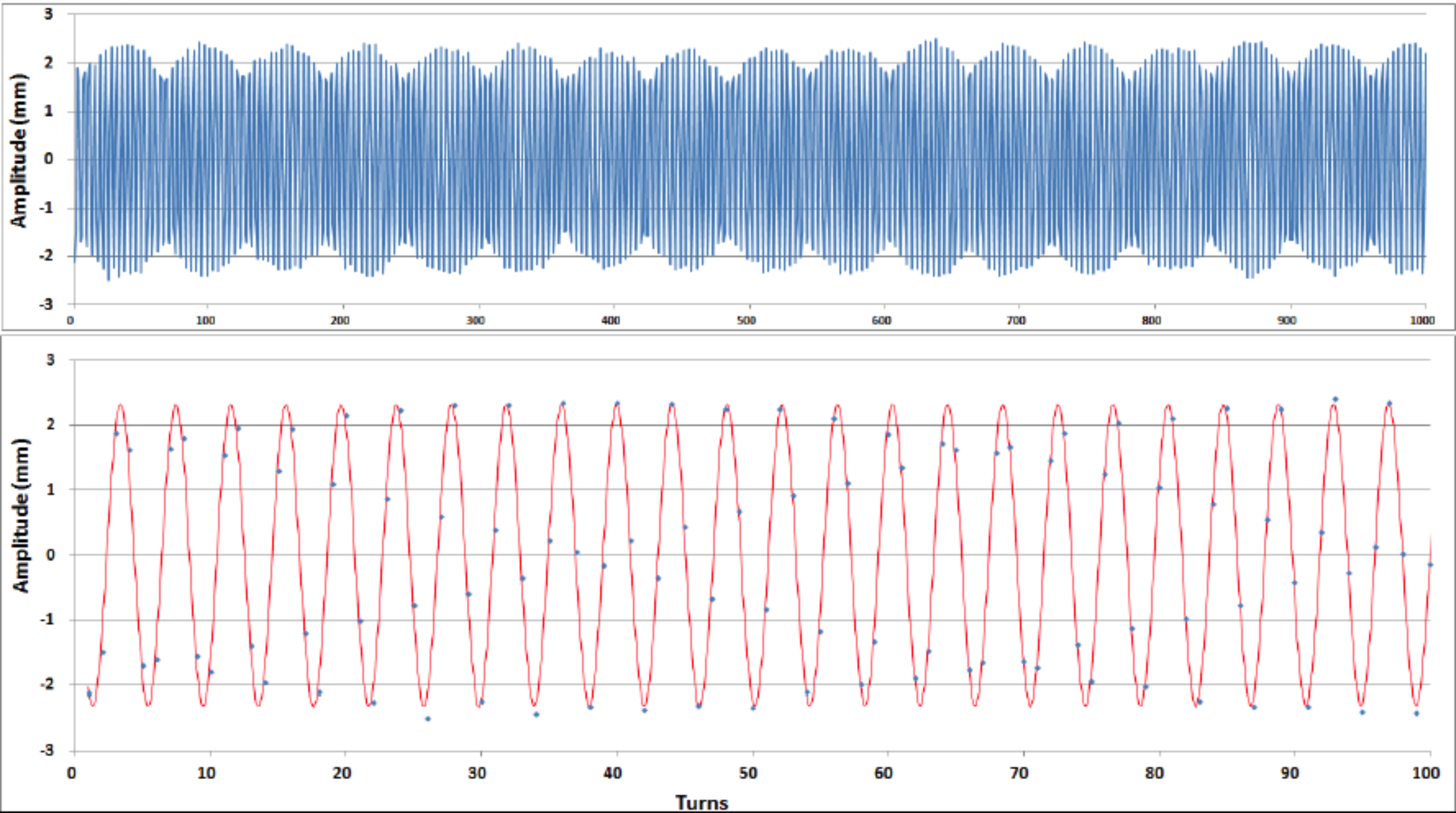
Transverse trajectory described by each particle inside the bunch is pseudo-sinusoidal



The envelope in which all particles in the bunch are confined is proportional to the β function

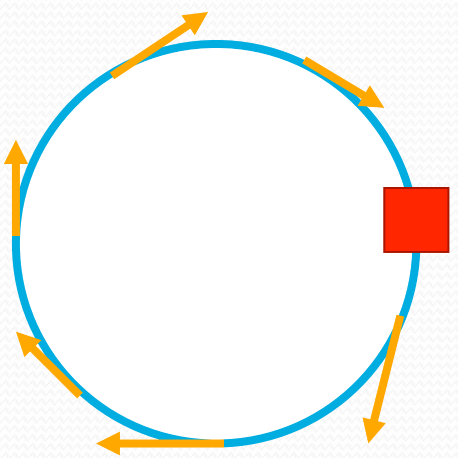


Example of coherent betatron oscillations as measured by Beam Position Monitors (BPM)



Synchrotron Radiation

- A charged particle travelling along a curved trajectory emits photons, whose energy depends from the particle's mass and energy and from the trajectory bending radius
- A charged particle travelling along a curved trajectory loses energy
- In a storage ring lost energy is replaced by the RF cavities

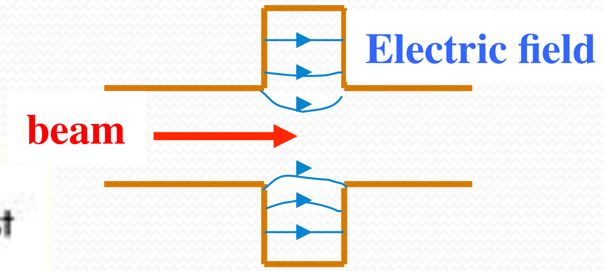


$$U = \frac{4\pi}{3} \frac{r_o}{\left(mc^2\right)^3} \frac{E^4}{\rho}$$

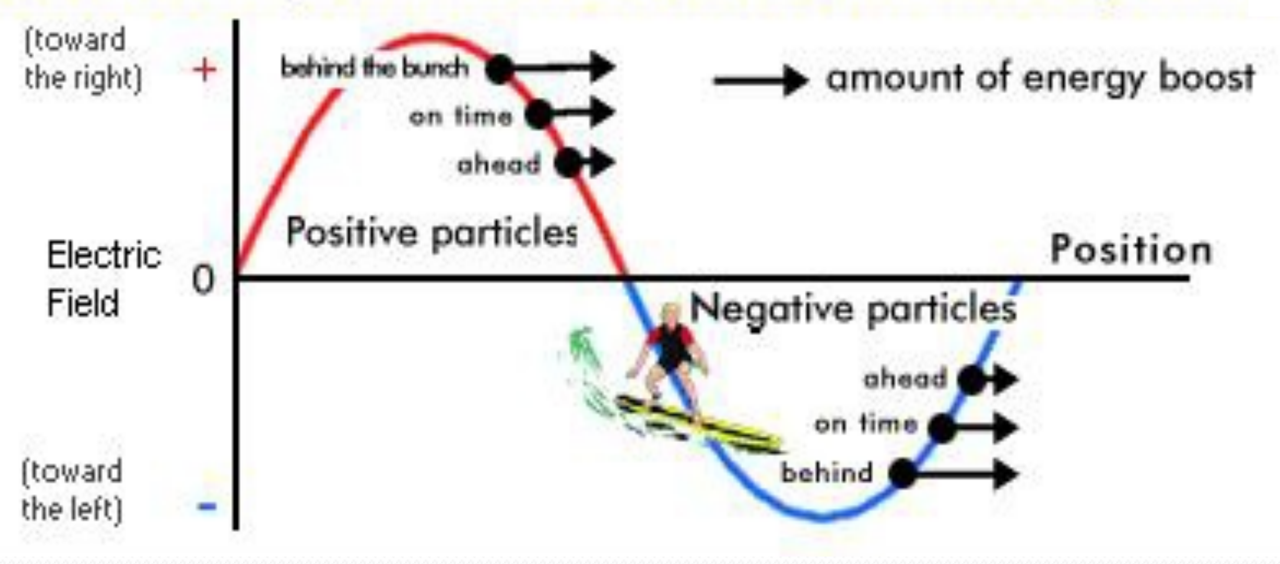
Energy lost per turn

Radio Frequency cavity

- In the RF cavity the accelerating field is sinusoidal and accelerates or decelerates depending on the arrival time of the particle
- Principle of phase stability: the particle ahead of time with respect to the "synchronous" particle will be less accelerated, the one late more accelerated
- Particles will oscillate around the synchronous phase and will be "bunched"
- These are called "synchrotron oscillations"

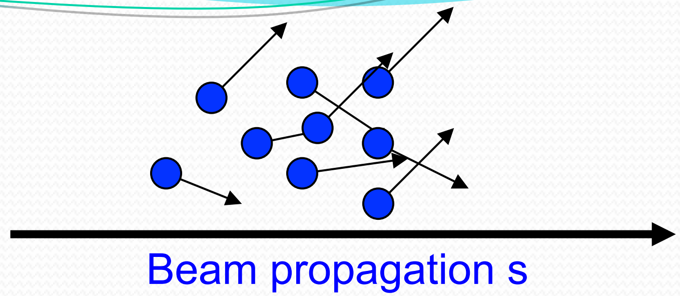


RF cavity

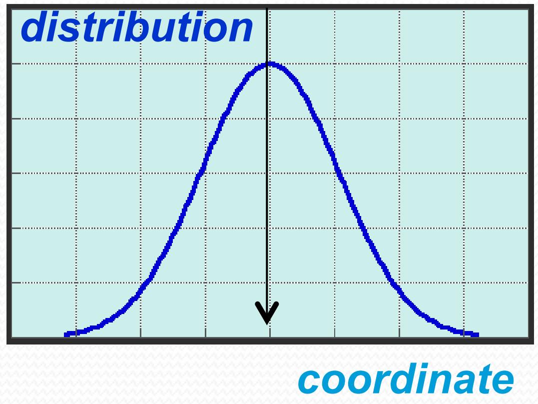


Particles phase space

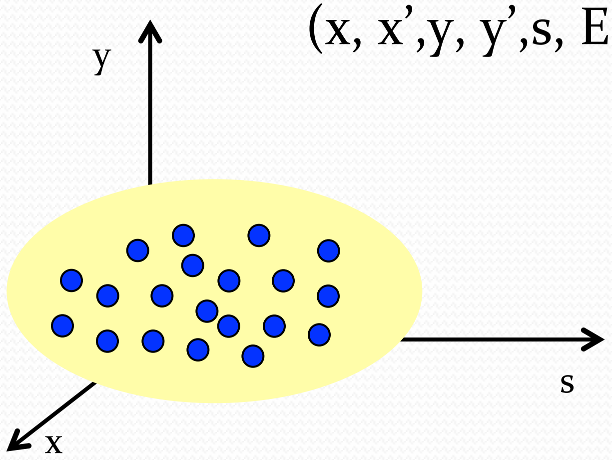
Particles in a beam
don't have all the same
energy, position, angle



energy, position and angle
Have Gaussian distributions



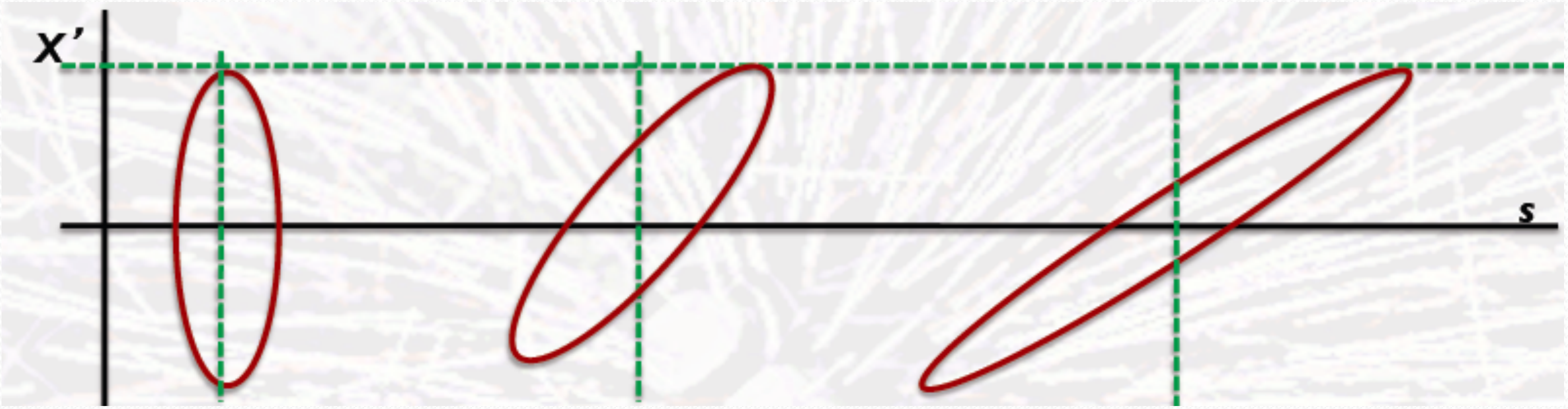
The bunch is a Gaussian
at 6 dimensions in the phase space
(x, x',y, y',s, E)



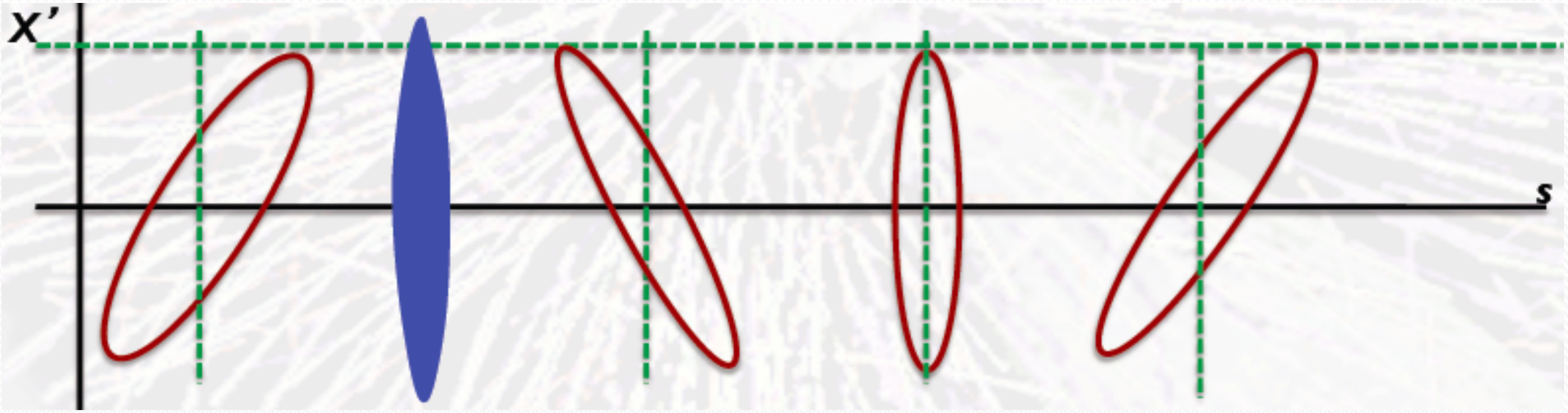
Each plane, ex. (x,x') or (y,y') is called
PHASE SPACE
Area occupied by particles in each phase space
is called **EMITTANCE**

Transformations in phase space

- In a drift space (no fields) from point 1 to point 2:

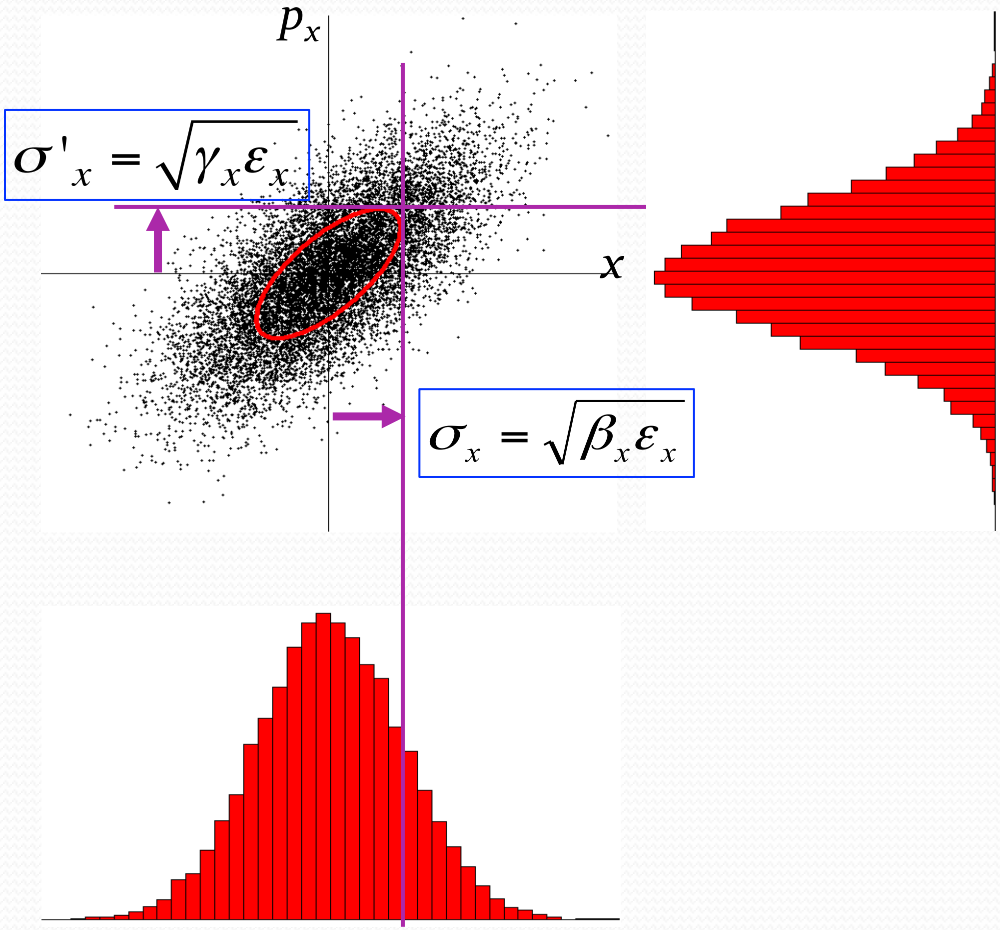


- Effect of a focusing quadrupole:



Emittance and bunch dimensions

- Emittance is the area of the phase space occupied by particles
- From the emittance, knowing the function β in the point, the transverse beam dimensions $\sigma_{x,y}$ and $\sigma'_{x,y}$ can be derived



$$\varepsilon_x = \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle x p_x \rangle^2}$$

Area of the ellipse = $\pi \varepsilon_x$

$$\langle x^2 \rangle = \beta_x \varepsilon_x$$

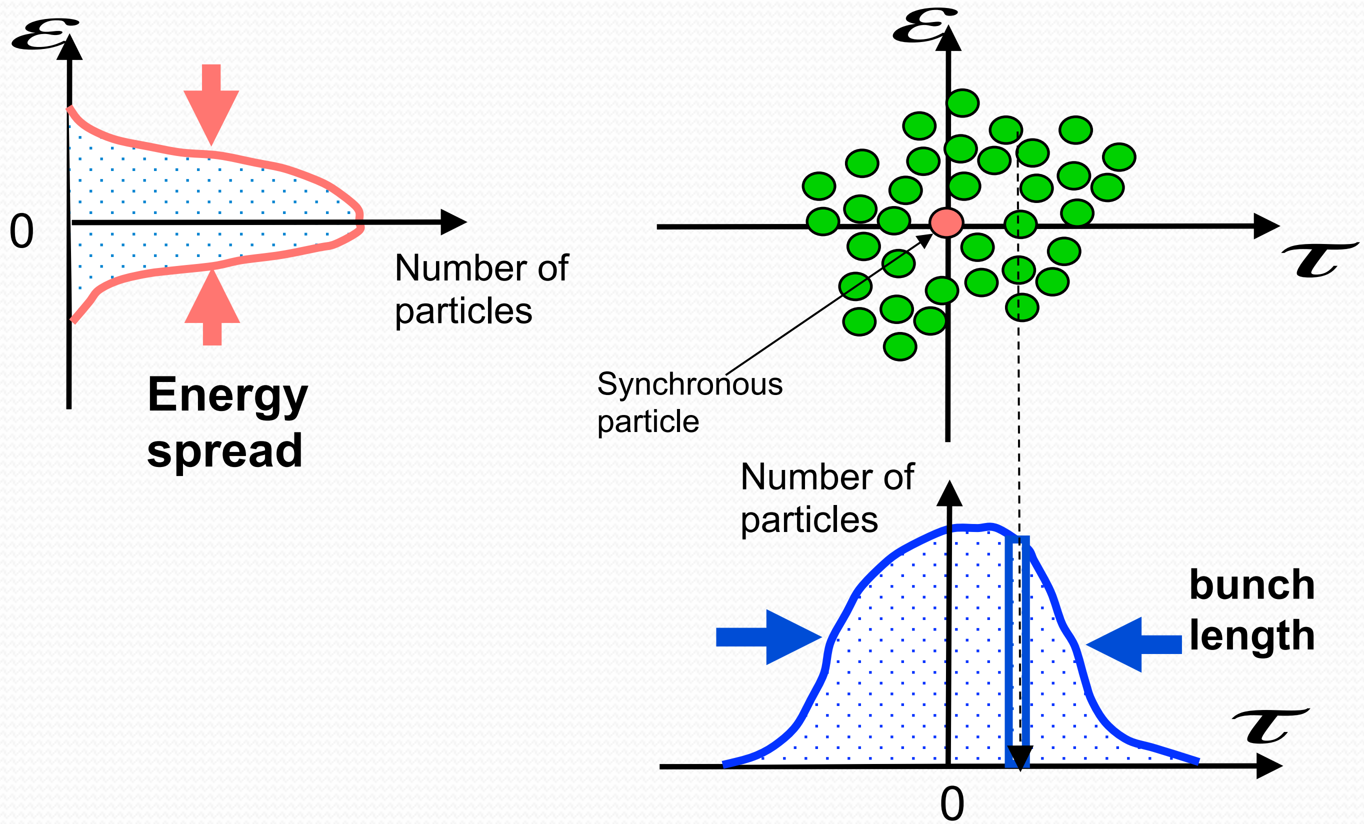
$$\langle p_x^2 \rangle = \gamma_x \varepsilon_x$$

$$\langle x p_x \rangle = -\alpha_x \varepsilon_x$$

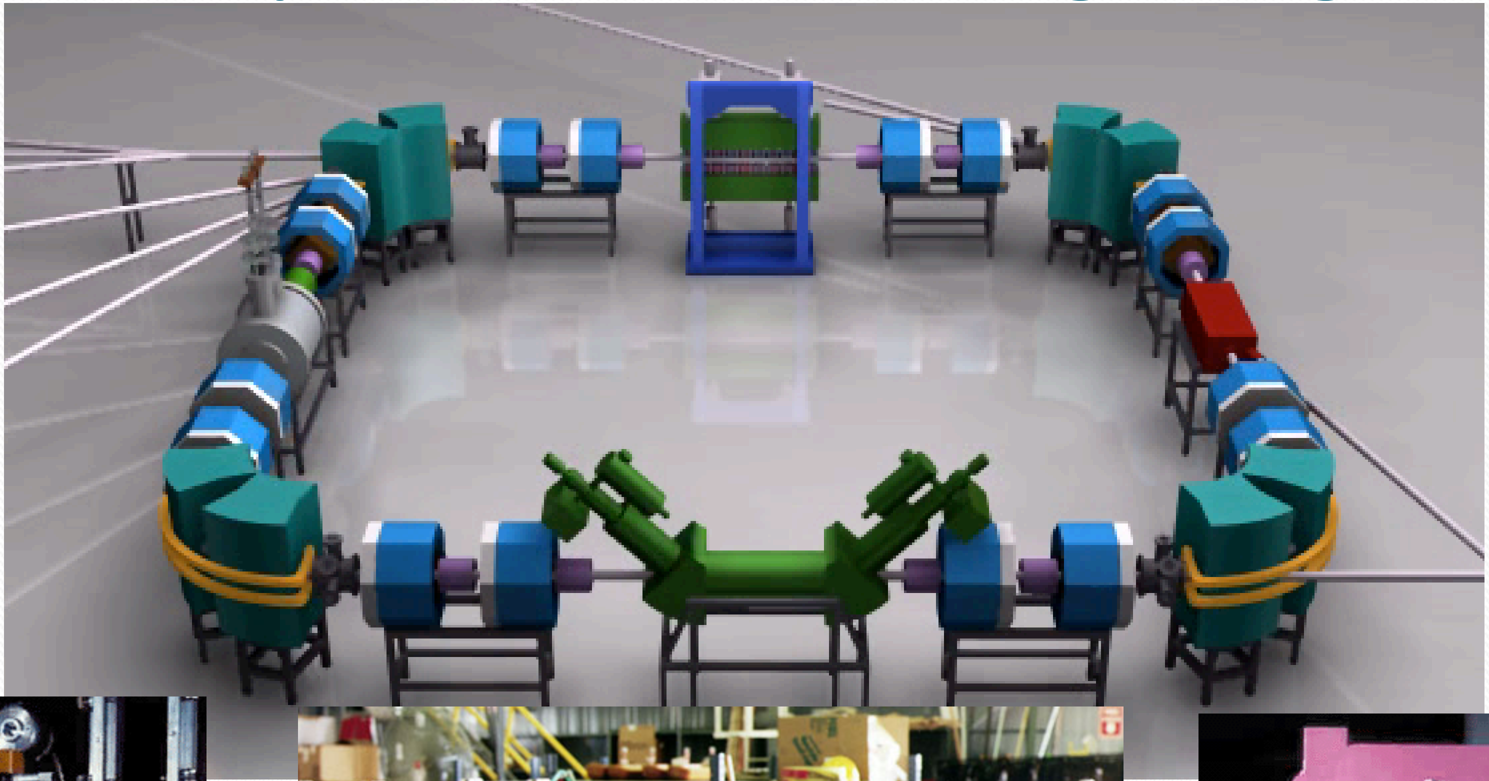
$$\beta_x \gamma_x - \alpha_x^2 = 1$$

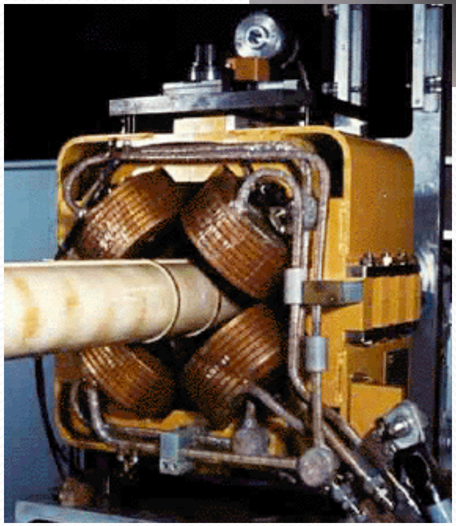
Bunch length and energy spread

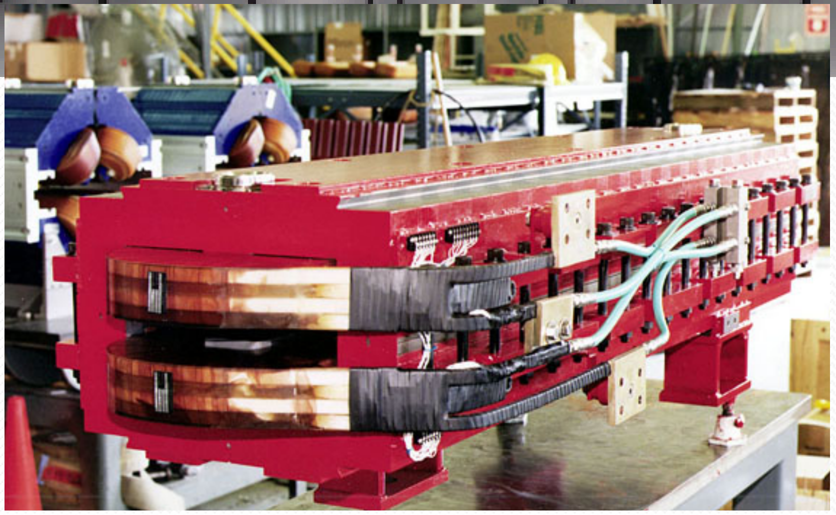
- At each moment the **N** particles in a bunch are distributed around the synchronous particle and oscillate around with the same frequency describing ellipses of different area in the phase space

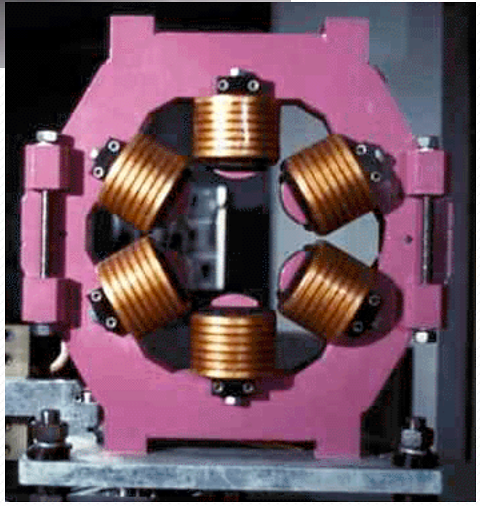


Components of a storage ring









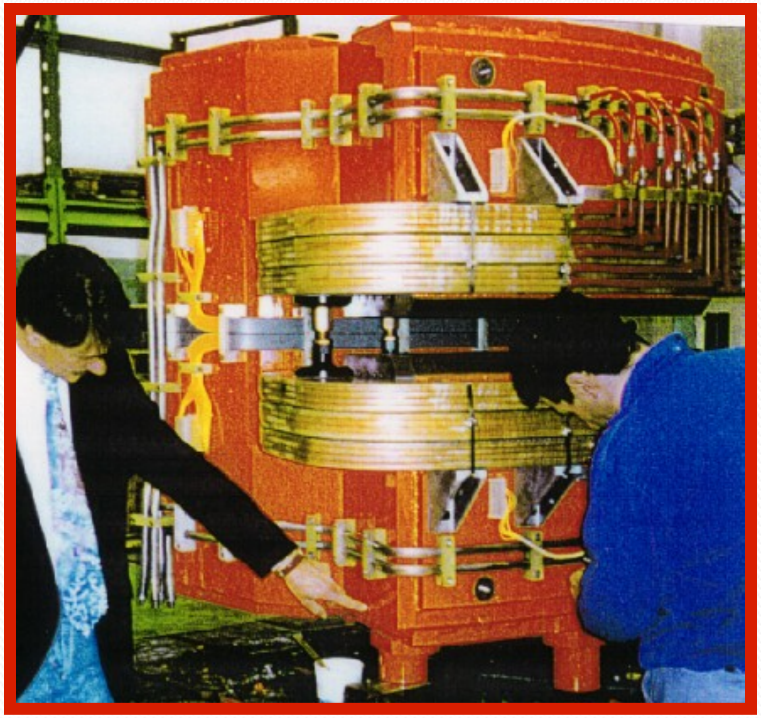
Components of a storage ring (I)

- To accelerate and maintain a beam in a circular accelerator magnets are used, with different properties:
  - Dipoles: to guide the beam along the circular trajectory, to correct deviations from the ideal orbit
  - Quadrupoles: to focus the beam
  - Sextupoles, octupoles, etc: magnets with non linear magnetic field to correct unwanted effects (chromatism, etc…)
  - Wigglers, undulators: magnets with many poles of small dimensions and alternate polarity, used to get photon beams with different wavelengths in synchrotron light sources
- Since particles lose their energy when curved in the dipoles, a RF cavity will restore it, to avoid that the beam is lost in few turns

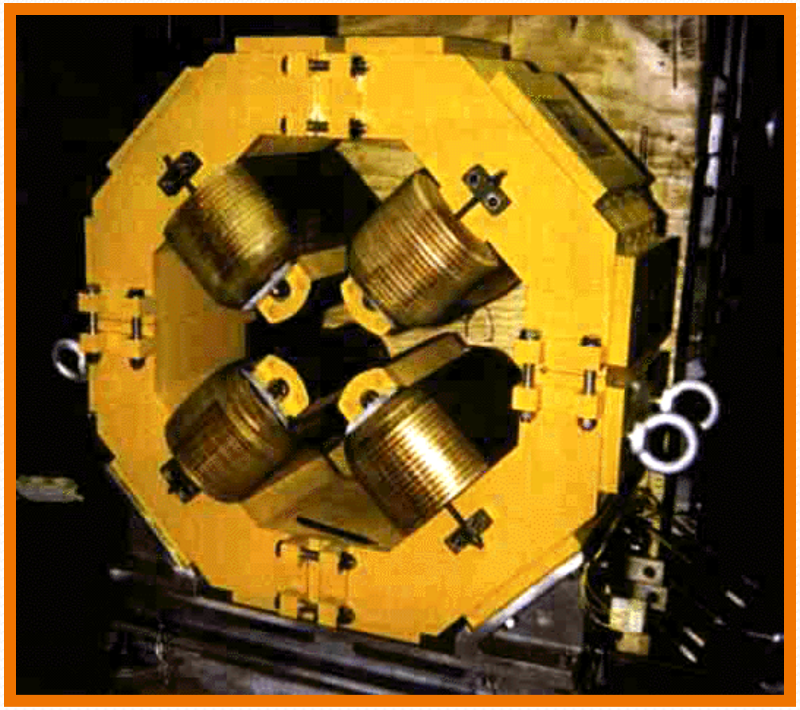
Components of a storage ring (II)

- The beam must travel in a beam pipe (circular or elliptical) where there is a very low vacuum
- A cooling system is needed for magnets and RF cavity
- To monitor beam properties and improve the performances of the accelerator diagnostics is needed
- To inject (and extract) the beam special pulsed magnets are needed
- Collimators and/or masks are used to avoid "background" particles in the beam pipe arrive to the detector
- A control system manages the operation of all the above

Example of ring magnets



dipole



quadrupole

Intensity of the magnetic field is changed by changing the current in the coils

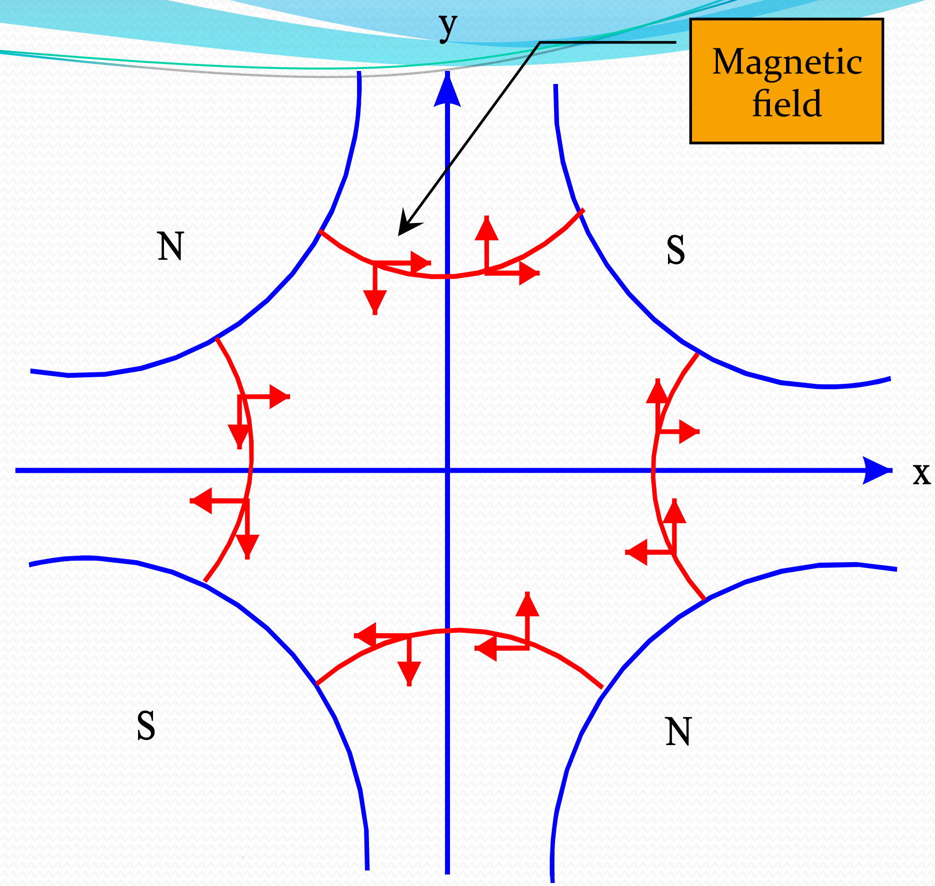
Quadrupole

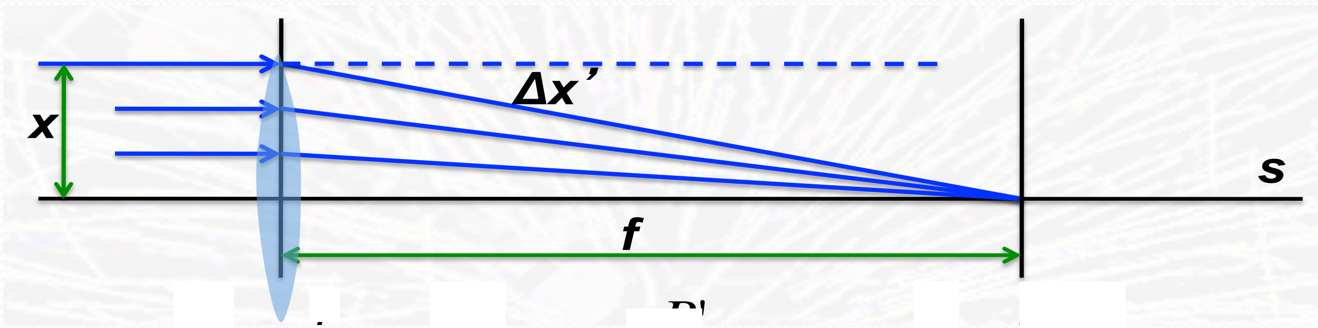
- Used to focus particles
- 4 poles, 2 North, 2 South
- Zero field on the axis
- Kick to particles is linear:

$$\Delta x' = -Klx$$
$$\Delta y' = Kly$$

- Focal length depends on energy (G=gradient):

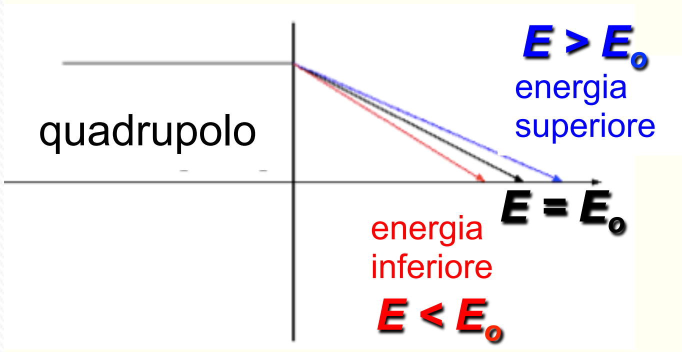
$$f = \frac{B\rho}{GL_q} \quad [m]$$

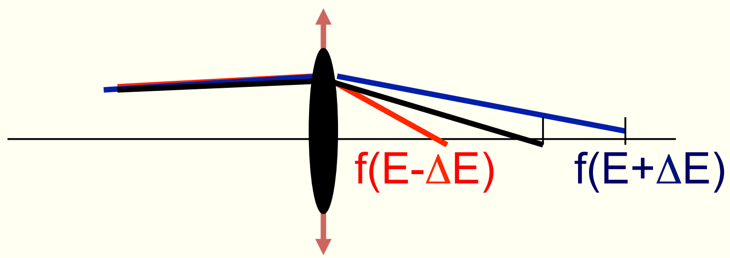




Sextupole

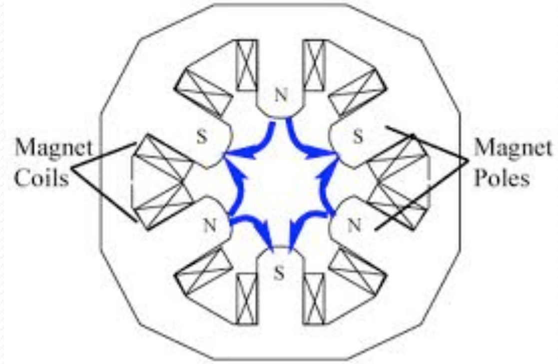
- Focusing in quadrupoles depend on particle energy, so some particles will be more focused and other less focused (larger E → longer *f* and vice versa, chromatism)





- Solution: sextupoles, which act like a quadrupole with a gradient proportional to the particle transverse displacement
- Kick (m=gradient) is non linear:

$$\Delta x' = -mx^2, \Delta y' = 2mxy$$



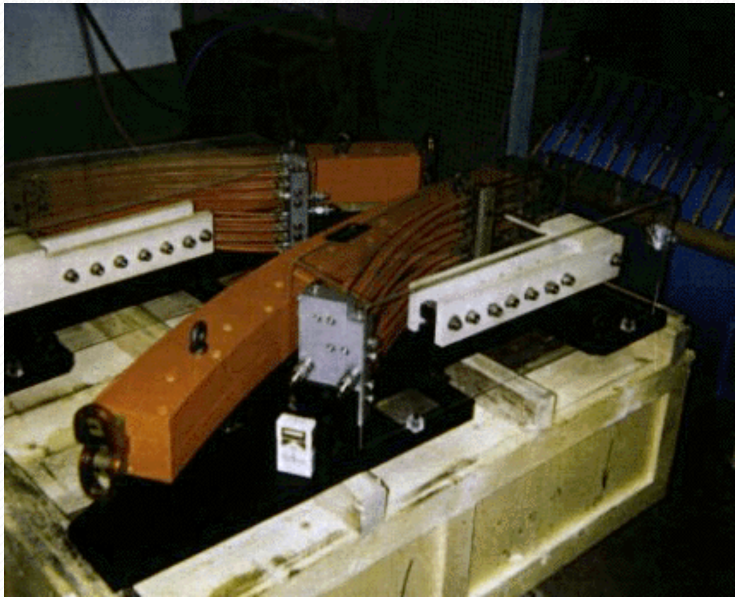
Other magnets

- To improve the accelerator performances other types of magnets are also used, for example:
  - Correctors (2 poles) are small dipoles to correct particles position and keep them closer to the ideal orbit
  - Octupoles (8 poles) can cure some instabilities and non-linearities
  - Decapoles, dodecapoles (10, 12 poles) are used in some cases to increase the dynamic aperture (stable area occupied by beam particles) since they correct the high order multipolar effects always present in dipoles and quadrupoles
  - Skew Quadrupoles (4 poles, tilted by 45°) can cure the coupling between X and Y planes, that increases the beam vertical dimensions and must be corrected
  - Solenoids produce an axial field, are used by the particle detectors and for some specific applications (ex. e-cloud instability)

Pulsed magnets

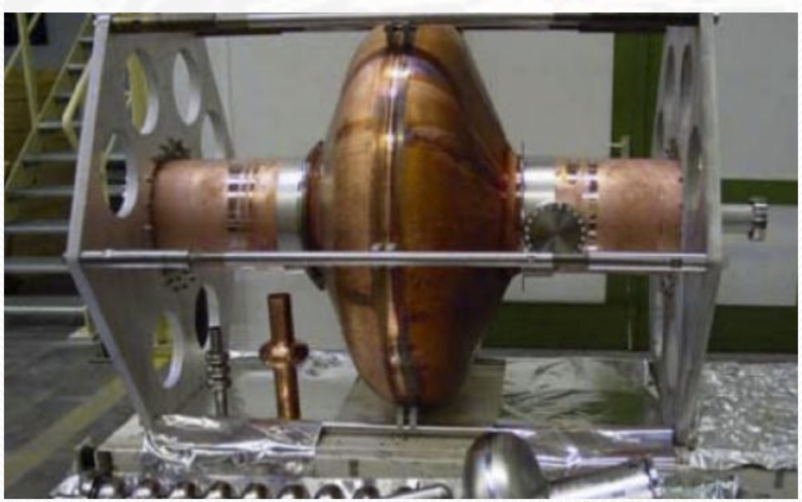
- Pulsed magnets are used to inject, they are ON for just a fraction of time of the order of nanoseconds and then put OFF
- Most used pulsed magnets are:
  - Septum: a magnet which provides a small kick to the beam to be injected, so that it can enter the beam pipe, possibly without perturbing the stored beam
  - Kickers: devices which use e.m. fields to give to the injected beam the kick needed to put it on the stored beam orbit

DAΦNE 34° septum



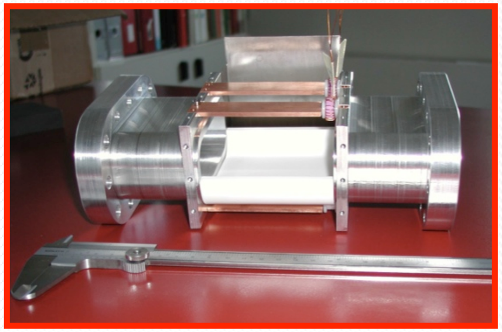
RF Cavity

- A metallic chamber in which is stored an oscillating e.m. field at RF (MHz) that can be varied so that particles can gain energy
- In a storage ring provides also for the particles "bunching"



Diagnostics

- To control the accelerator performances it is necessary to measure the beam properties during operation
- Special devices are used (in general in a non destructive way) to measure:
  - Transverse beam dimensions
  - Bunch length
  - Beam position along the ring (orbit)
  - Number of β-tron oscillations per turn ("tune")
  - Beam current
  - Luminosity (in colliders)



DAΦNE
Beam Position Monitor

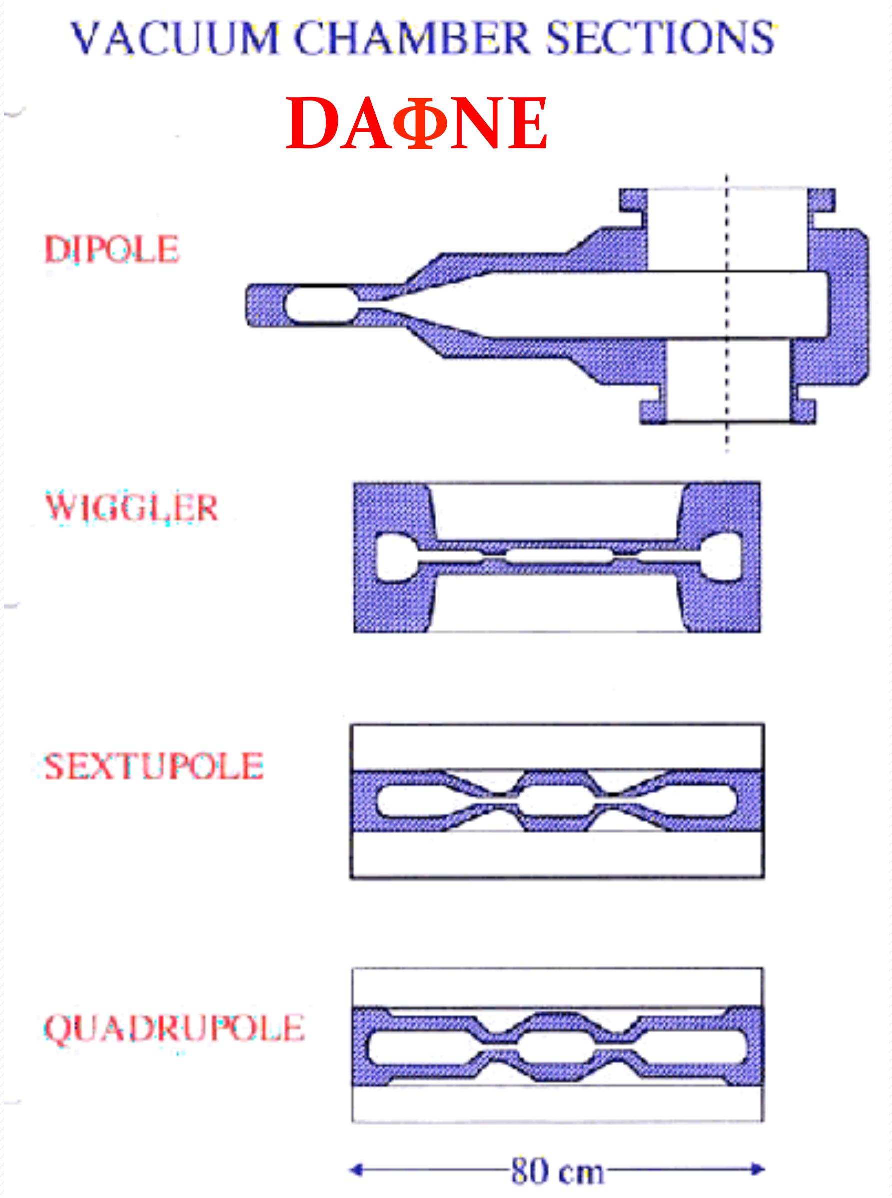
- Other devices are used to stabilize the beam and cure instabilities:
  - Feedbacks (transverse, longitudinal)
  - Electrodes for "ion clearing"
  - Electrodes for "e-cloud clearing"

Beam pipe

- The beam circulates in a tube (vacuum chamber or beam pipe) where ultra-low vacuum, order of 10^{-9} - 10^{-11} Torr, is done by means of vacuum pumps
- It is extremely important that the vacuum is very low, since every residual gas particle interacting with the beam can degrade its properties or create instabilities and beam loss
- There are many kind of pumps: ion, Non Evaporable Getters (NEG), sublimation, …
- Beam particles which are lost on the beam pipe and emitted photons are absorbed by special “absorbers”, usually installed in dipoles where the radiation is emitted

Beam pipe

- The beam pipe must be designed to:
  - be able to support the ultra-low vacuum needed
  - be as smooth as possible
  - have ante-chamber for the photons emitted
  - be of a material suitable to support heating from the beam and mitigate instabilities (such as electron-cloud)



Collimators and masks

- Collimators and masks can limit damages that lost particles (“backgrounds”) can cause to the particles detectors, for several reasons (residual gas scattering, Touschek effect, etc…)
- In proton machines (ex. LHC) they are also used to collimate the beam (less focused than electron beam)
- In electron machines the power collected by masks is generally few MW, while in proton machines the design of the collimators is crucial both for the material used and their cooling

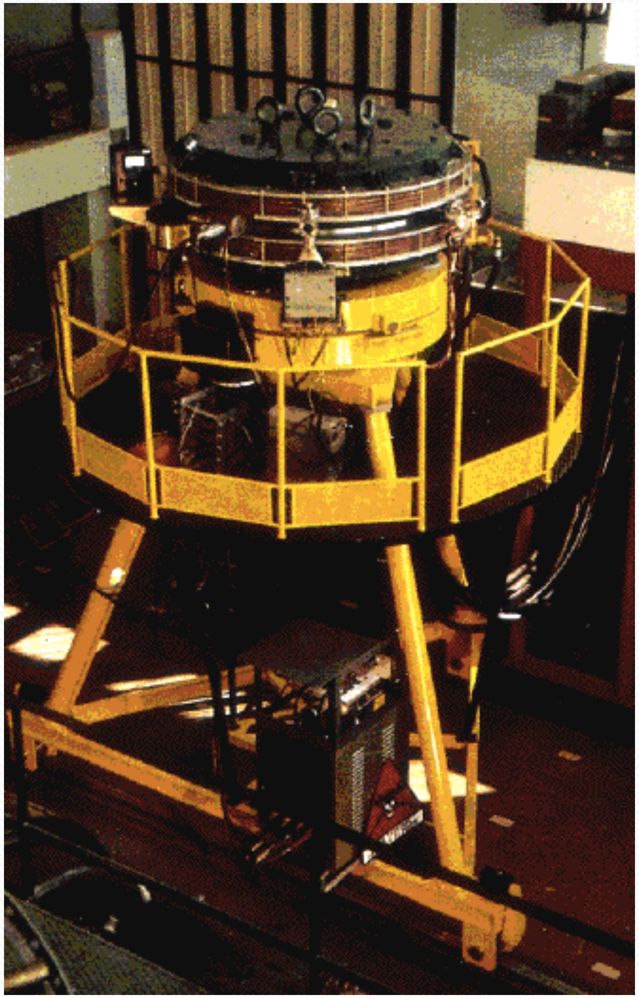
Feedback systems

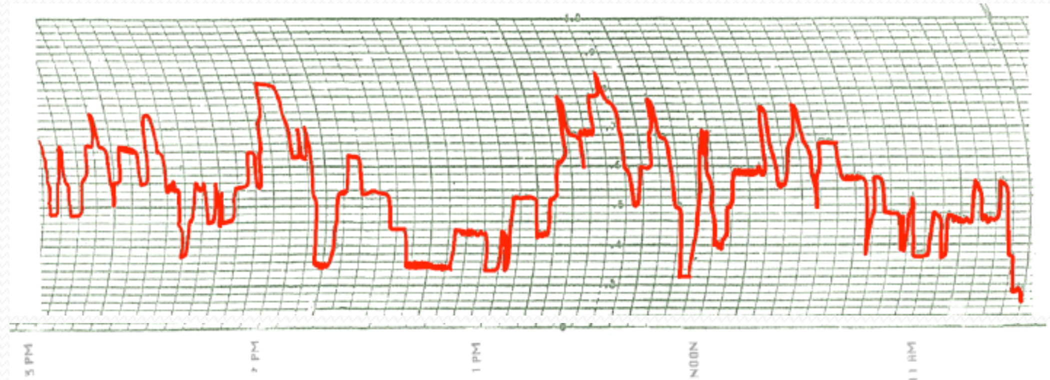
- To keep the beams stable bunch-by-bunch feedback systems are used
- These systems use a *pick-up* to detect the position of each bunch and then apply a correction "kick" to each bunch to correct for the long range wake fields effects
- The bunch-by-bunch feedback effects add to the natural instability damping due to the damping phenomenon. Modern digital systems can have damping times of about 20 turns
- At DAΦNE a last generation feedback allows for beam stabilization at currents > 2 A

Storage ring colliders

- Two beams travel in opposite way in the same or in two different vacuum chambers
- They meet ("annihilate") in one or more points, where particles detectors are installed to collect events produced in the annihilation
- AdA (Anello di Accumulazione) was the first, 250 MeV, conceived and built at Laboratori Nazionali di Frascati by Bruno Touschek and collaborators
- For the test it was moved to the Orsay Laboratory (France) where a Linac for electrons and positrons was operational
- The AdA success gave birth to ACO (France), SPEAR (SLAC) and Adone (Frascati) and started the physics of storage ring colliders

AdA (Anello di Accumulazione) 1961-1965





Il Nuovo Cimento
Vol. XVIII, n. 6
16 Dicembre 1960

Registrazione dei primi elettroni accumulati in Ada. La vita media era di 21 sec, il numero medio di 2.3.

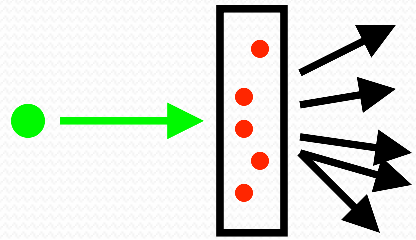
Record of the first electrons stored in AdA. Their half life was 21 sec, the average number was 2.3.

Recording of the first accumulated electrons in AdA. Lifetime was 21 sec, average number of electrons was 2.3

Advantages of a collider

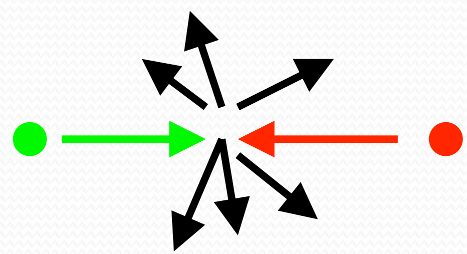
- Fixed target experiments: beam is extracted from the accelerator and hits a fixed target where other particles are produced by decay. The available Energy for the production is:

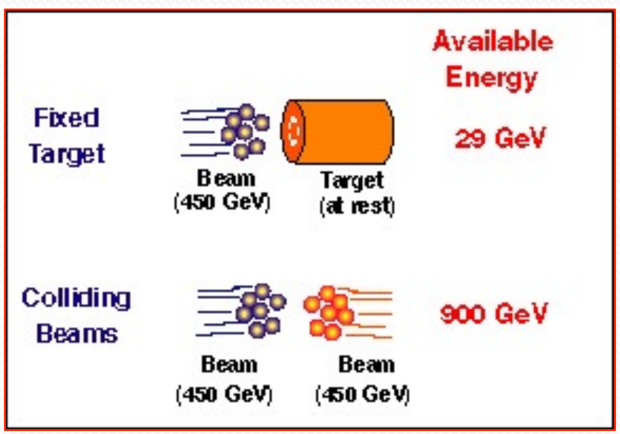
$$E_{c.m.} = \sqrt{2E_{beam}m_{target}c^2}$$



- Colliders: two beams (same particles or particle/antiparticle) circulate opposite and collide in one or more points. All the beams Energy is available for production:

$$E_{c.m.} = 2E_{beam}$$





Luminosity

- Luminosity **L** is a measurement of probability of particles colliding per unit area per second
- Given the cross section of a physical process σ_{phys} the counting rate of events is:

$$\mathbf{R}\ [s^{-1}] = \boldsymbol{\sigma}_{\mathbf{phys}}\ [cm^{-2}]\ \mathbf{L}\ [cm^{-2}s^{-1}]$$

Luminosity

- In "*head-on*" collisions (no crossing angle) with *bunched* beams of opposite charge and Gaussian distributions, Luminosity is defined:

$$L = \frac{f_{coll}}{4\pi} \frac{N^+ N^-}{\sigma_x^* \sigma_y^*}$$

$f_{coll} = N_b f_o$ = collision frequency, N_b= number of bunches, f_o= revolution frequency
N^+, N^- bunch population
σ^*_x, σ^*_y transverse beam dimensions at Interaction Point (IP)
$4\pi\sigma^*_x\sigma^*_y$ area of colliding beams

- To get high luminosity:
  - Increase collision frequency
  - Decrease bunch dimensions (small β)
  - Increase bunch density

BUT...

Beam-beam effects limit maximum bunch density → bb tune shift

Beam-beam effects

- Beam-beam effects are a limitation for the maximum particles density in the bunch
- Particles in a bunch are strongly influenced by the non linear fields of the opposite traveling bunches
- Increase bunch density can produce beam blow-up and particles loss
- A measurement of the force of the beam-beam interaction is the linear beam-beam tune shift ξ_x, ξ_y
- Exists an empirical upper limit of ξ_x, ξ_y

Lepton Factories

- Precision measurements (ex. in weak interactions) demand for the construction of high luminosity colliders to collect a huge number of events
- Asymmetric B-Factories (E_{cm}=10.58 GeV) like **PEP-II** (SLAC) and **KEKB** (KEK) have reached unprecedented record luminosities (KEKB = 2.1×10^{35} cm^{-2} s^{-1}) and high beam currents
- At Frascati the **DAΦNE Φ–Factory** (E_{cm}= 1.02 GeV) has reached a record luminosity (4.5×10^{32} cm^{-2} s^{-1}) at this low energy
- At Novosibirsk **VEPP2000** is a Φ-Factory for testing "*round beams*" collisions (equal emittances and beam sizes)
- A **τ-charm Factory BEPCII** (E_{cm}= 3-4 GeV) is running in Beijing ($L=8 \times 10^{32}$ cm^{-2} s^{-1})
- An upgrade of KEKB (**SuperKEKB**) to reach L= 8×10^{35} cm^{-2} s^{-1} is presently under construction in Japan