# Accelerator Physics


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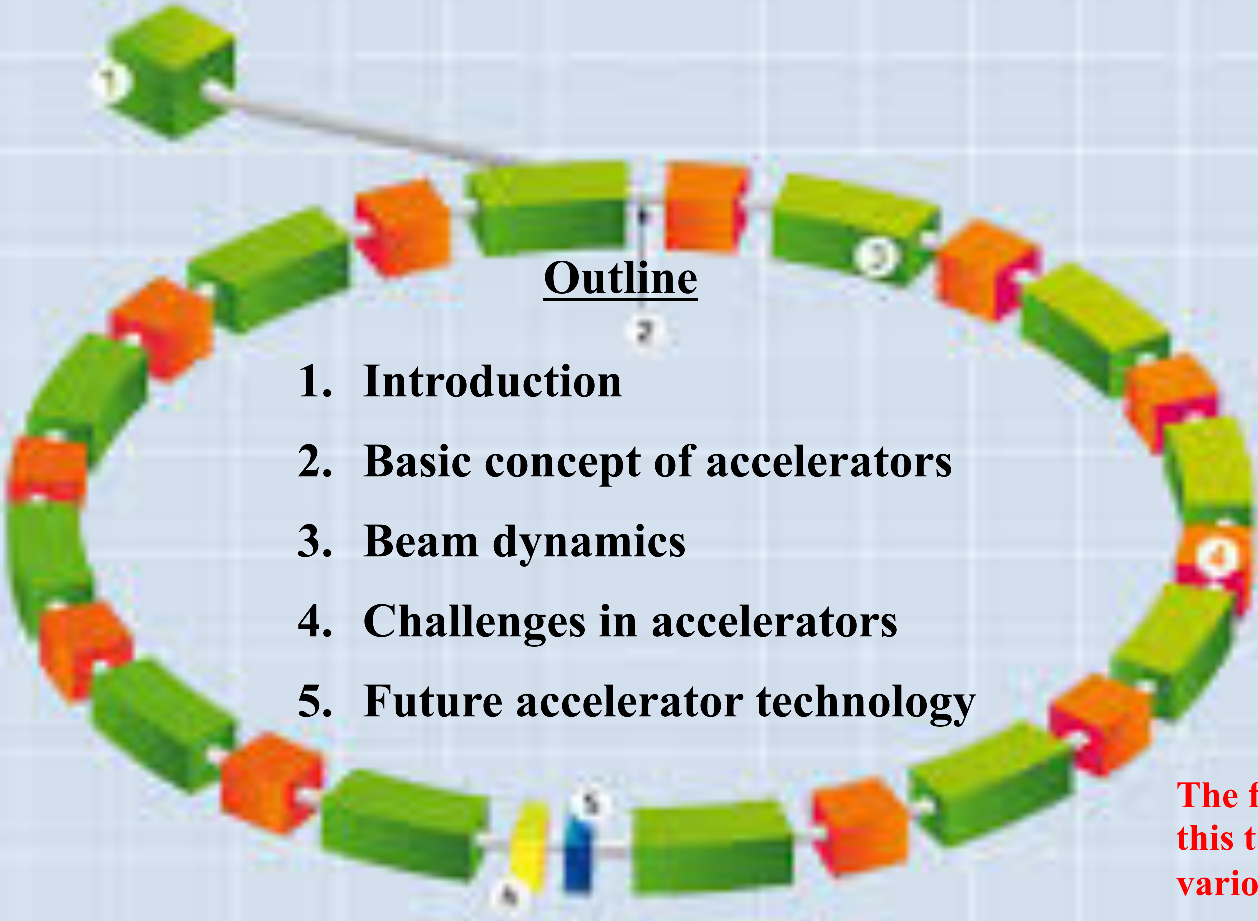
## NISER


*Workshop on Software Tools and Techniques used in EHEP and its Applications*

*MNIT Jaipur*

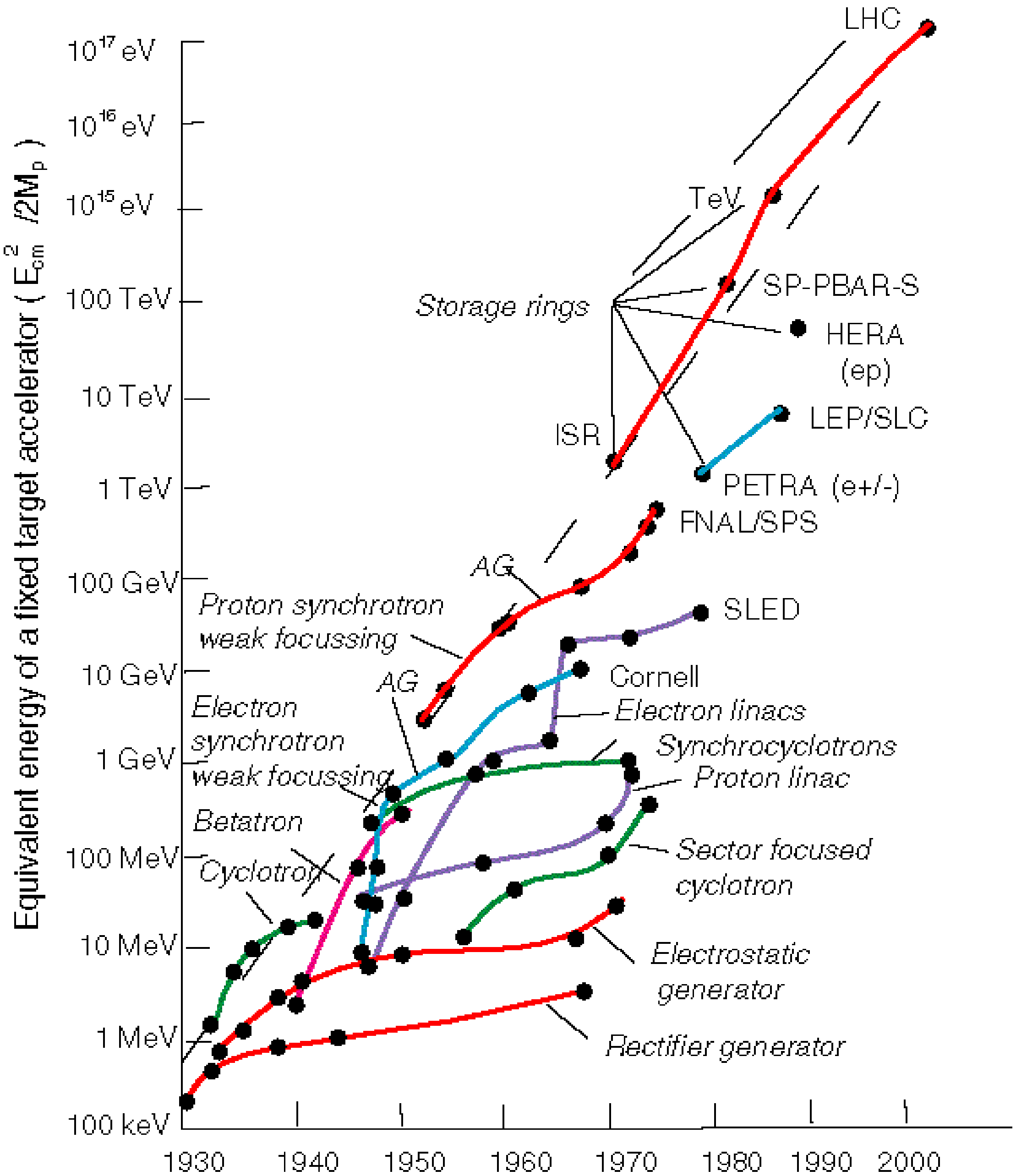


**Outline**

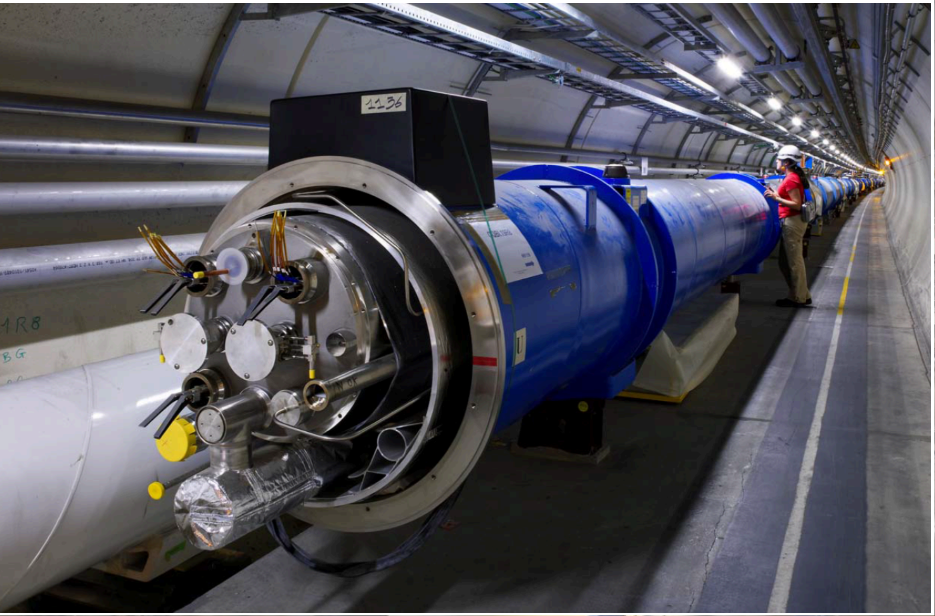
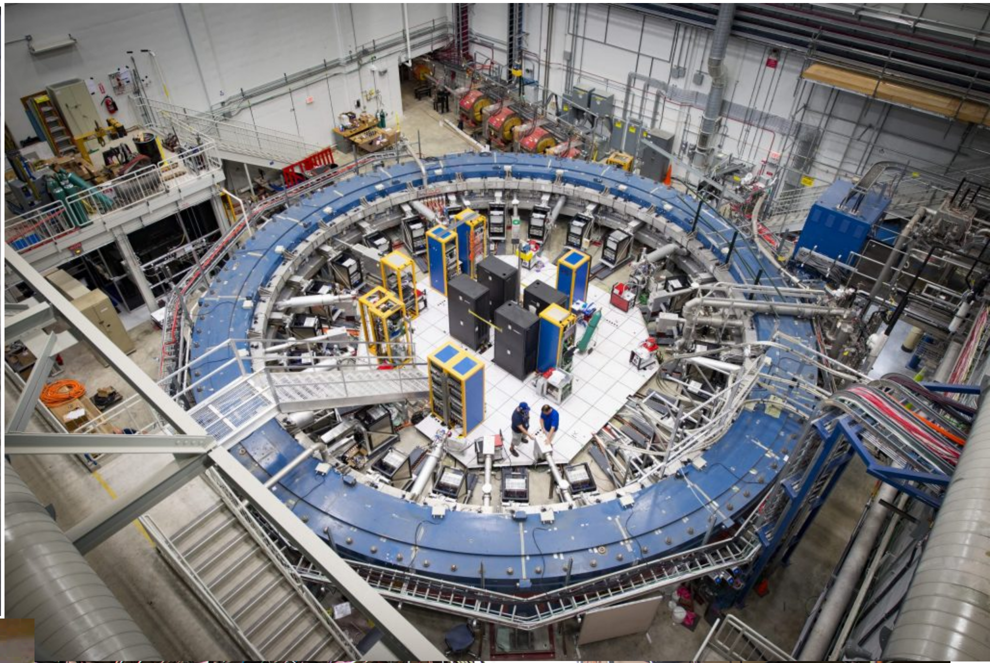
1. Introduction
2. Basic concept of accelerators
3. Beam dynamics
4. Challenges in accelerators
5. Future accelerator technology

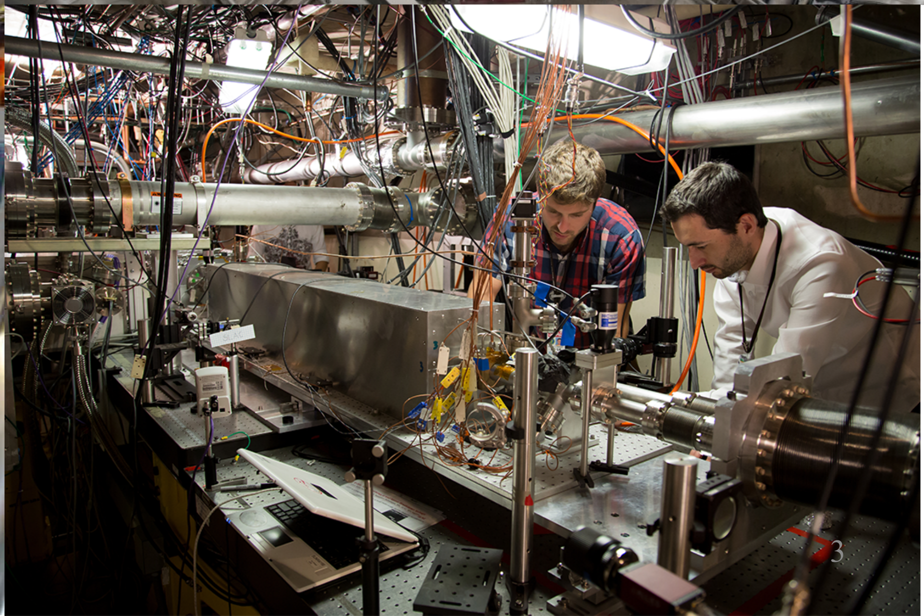
The figures/plots used in this talk are taken from various sources

# Particle accelerators since 1930s



# Few examples



# Accelerator – I

# Accelerator – II

# Why do you need accelerator?

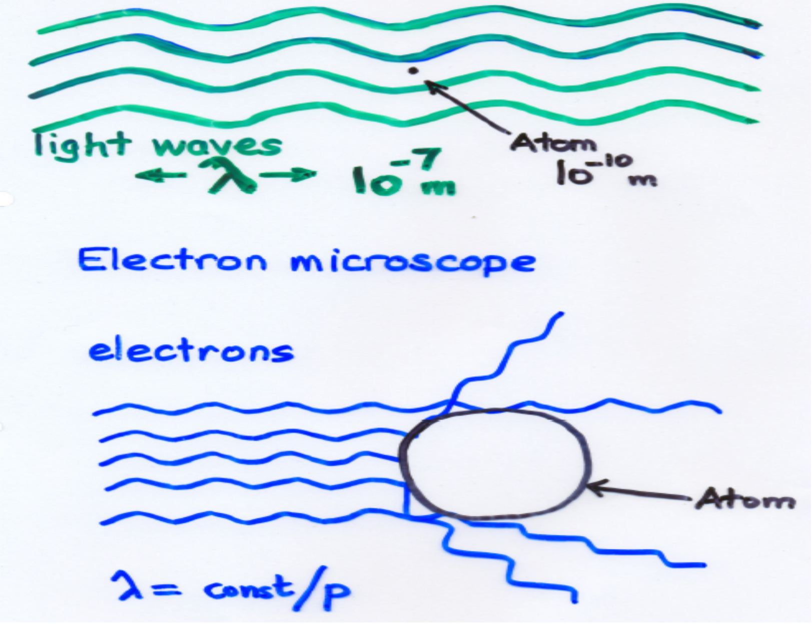
• Produce new massive unstable particle which would have existed in earlier time when universe was created. The concept is to use kinetic energy of a beam of particles to produce the new particles.

$$m = \frac{E}{C^2}$$ here E is the COM energy

Q: LHC has 14TeV COM energy, does it mean it will most likely produce particles with mass ~ 14TeV or even 7TeV?

Ans: No => why? (I will come back later)

• Probing smaller and smaller distance scales. One sends beam of particles to probe this small distance (e.g. to resolve two protons inside a He nucleus ). In order to do this, the de-Broglie wave length of the particle should be smaller than the particle size.

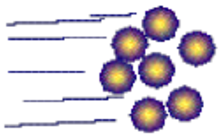


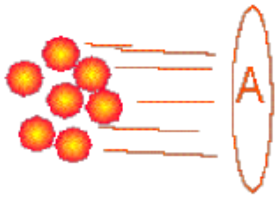

Q: AT LHC protons has 7TeV energy, how is equivalent de-Broglie wave length ?

$$\lambda = \frac{h}{p} = \frac{hc}{pc} \approx \frac{hc}{E} \approx \frac{200 MeV \bullet fm}{7000{,}000 MeV} \approx 10^{-17} - 10^{-18} cm$$

## Colliders vs fixed target experiements

- In Collider, say two beam with energy E and three momentum p ($E^2 = p^2+m^2$) travels in z-direction against each other





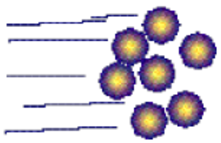

The Center of mass energy, $E_{cm}^2 = P^2 = (P_1 + P_2)^2 = P_1^2 + P_2^2 + 2P_1.P_2$

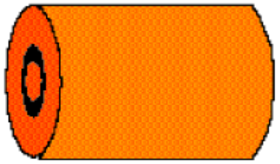
$$= m_1^2 + m_2^2 + 2(E_1E_2 - p_1.p_2)$$

$$\cong 2(E_1E_2 + p_1p_2) = 4E_1E_2$$

$\Rightarrow E_{cm} = 2\sqrt{(E_1E_2)}$, for LHC $E_1 = E_2 = 7$TeV $\Rightarrow E_{cm} = 14$TeV

- In fixed target experiment, say one beam with energy $E_{Lab}$ and three momentum $p_{Lab}$ travel in z-direction and hits target at rest.





Four momentums $P_1(E_{Lab}, 0,0, p)$ $P_2(m_T, 0,0,0)$

The Center of mass energy, $E_{cm}^2 = P^2 = (P_1 + P_2)^2 = P_1^2 + P_2^2 + 2P_1.P_2$

$$= m_1^2 + m_2^2 + 2E_{Lab}m_T \cong 2E_{Lab}m_T$$

To generate 14TeV $E_{cm}$, you need, $E_{Lab} = E_{cm}^2/2m_T = (14000)^2\text{GeV}^2/2\text{GeV}$

$$= 10^8\text{GeV}$$

# Examples of fixed target and Collider experiments

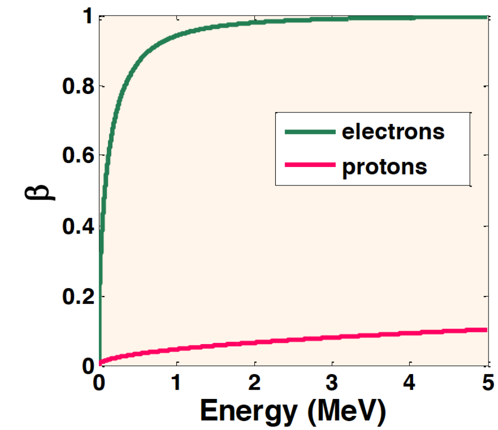
| Name | Type | $\sqrt{s}$ (GeV) | $L_{\text{int}}$ ($\text{pb}^{-1}$) | Years of operation | Detectors | Location |
|---|---|---|---|---|---|---|
| LEP | $e^+e^-$ | 91.2 (LEP-1)<br>130-209 (LEP-2) | ≈ 200 (LEP-1)<br>≈ 600 (LEP-2) | 1989-95 (LEP-1)<br>1996-2000 (LEP-2) | ALEPH, OPAL, DELPHI, L3 | CERN |
| SLC | $e^+e^-$ | 91.2 | 20 | 1992-98 | SLD | SLAC |
| HERA | $e^{\pm}p$ | 320 | 500 | 1992-2007 | ZEUS, H1 | DESY |
| Tevatron | $p\bar{p}$ | 1800 (Run-I)<br>1960 (Run-II) | 160 (Run-I)<br>6 K (Run-II, 06/09) | 1987-96 (Run-I)<br>2000-??? (Run-II) | CDF, DØ | FNAL |
| LHC | $pp$ | 14000 | 10 K/yr ("low-L")<br>100 K/yr ("high-L") | 2010? - 2013?<br>2013?? - 2016??? | ATLAS, CMS | CERN |
| ILC | $e^+e^-$ | 500-1000 | 1 M??? | ??? | ??? | ??? |

| Accelerator | Location | Years of operation | Shape and size | Accelerated Particle | Kinetic Energy | Notes and discoveries made |
|---|---|---|---|---|---|---|
| High Current Proton Accelerator Los Alamos Neutron Science Center (originally Los Alamos Meson Physics Facility) | Los Alamos National Laboratory | 1972–Present | Linear (800 m) and Circular (30 m) | Protons | 800 MeV | Neutron materials research, proton radiography, high energy neutron research, ultra cold neutrons |
| PSI, HIPA High Intensity 590 MeV Proton Accelerator | PSI, Villigen, Switzerland | 1974–present | 0.8 MeV CW, 72 MeV Injector 2, 590 MeV Ringcyclotron | Protons | 590 MeV, 2.4 mA, =1.4 MW | Highest beam power, used for meson and neutron production with applications in materials science |
| TRIUMF Cyclotron | TRIUMF, Vancouver BC | 1974–present | Circular | H- ion | 500 MeV | World's largest cyclotron, at 17.9m |
| ISIS neutron source | Rutherford Appleton Laboratory, Chilton, Oxfordshire, United Kingdom | 1984–present | H- Linac followed by proton RCS | Protons | 800 MeV | |
| Spallation Neutron Source | Oak Ridge National Laboratory | 2006–Present | Linear (335 m) and Circular (248 m) | Protons | 800 MeV - 1 GeV | Produces the most intense pulsed neutron beams in the world for scientific research and industrial development. |
| J-PARC RCS | Tōkai, Ibaraki | 2007–Present | Triangular, 348m | Protons | 3 GeV | Used for material and life sciences and input to J- |

# How fast protons travel in LHC?

*For LHC:*

**Proton mass ($m_0c^2$) = 938 MeV (to make it simple take it 1 GeV)**

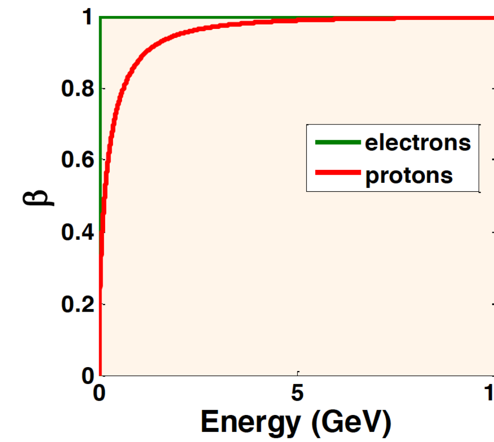



**Energy (E) of proton in LHC = 7TeV = 7000 GeV**

**We know $E = \gamma m_0 c^2$ => 7000 GeV = $\gamma$ x 1GeV => $\gamma$ = 7000**

$$\beta = 1 - \frac{1}{2 \times (7000)^2} = 0.99999999$$

**Velocity of proton = 0.99999999 c**




*For Tevatron:*

**Energy (E) of proton in LHC = 1.96 TeV = 1960 GeV**

**We know $E = \gamma m_0 c^2$ => 1960 GeV = $\gamma$ x 1GeV => $\gamma$ = 1960**

$$\beta = 1 - \frac{1}{2 \times (1960)^2} = 0.9999998$$

**Velocity of proton = 0.9999998 c**

***Even though it appears both cases protons travel very close to speed of light, they have very different effect when it comes to physics results/processes.***

# What particles to collide?

- If you want to collide them you better use circular path so that you can use the beam again. But what kind of particle to choose ?

**Stable charged particle** e.g. electron or proton

- Charged particles accelerating around the circular orbit radiate and the energy loss is

$$E_{loss} \alpha \frac{4\pi e^2}{R}\left(\frac{E}{mc^2}\right)^4$$

- So, the energy loss for proton as beam particle to electron as beam particle is

$$\left(\frac{m_e}{m_p}\right)^4 \approx 10^{-13}$$

Electron beams are not favorable if you are going to higher energ,y

So

Electrons/positrons:

- Well defined energy
- Precision experiment

Protons/antiprotons:

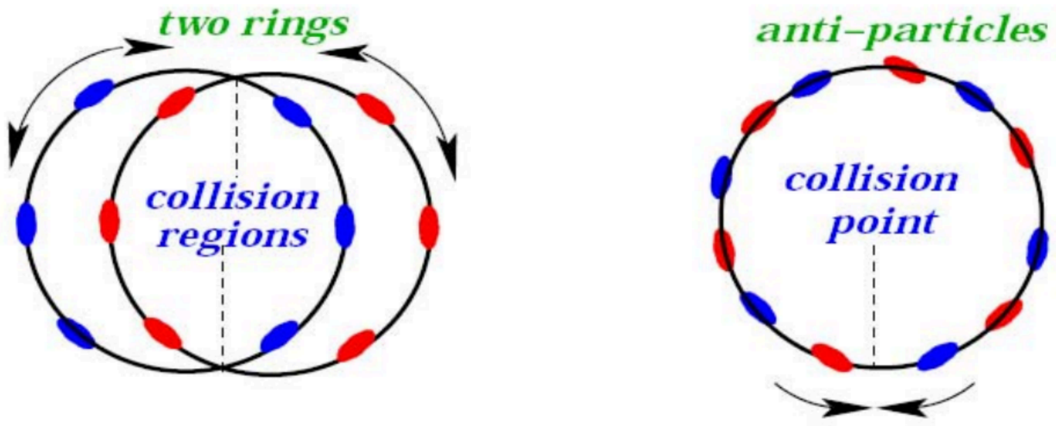
- Energy spread
- Discovery potential

What does this mean?

## proton-proton vs proton-anti-proton

- However, colliders like LHC and Tevatron choose different particles for collision. LHC used proton-proton beam collision whereas Tevatron used proton-antiproton, Even though antiparticles are difficult and expensive to produce ($\sim$ 1 antiproton/$10^6$ protons)

then why choose proton-antiproton ?




- In proton antiproton case, the highest energy collisions are between valence quarks and anti-quarks. It can produce high energy off shell gluons that can decay to new strongly interacting particles (as proton-antiproton has zero baryon number) or new gauge bosons. For LHC, the collision is dominated by gluon-gluon interaction. So it doesn't matter whether we collide proton-proton or proton-antiproton.
- One can use same vacuum pipe throughout beam-line (one can use same magnet to bend both proton and antiproton beams). One ring would do the job instead of two rings.

# pp vs $e^+e^-$ collison

Assume you want to produce top quark pairs using $e^+e^-$ and p-p colliders

In Collider, say two beam ($e^+$ and $e^-$) with energy E and three momentum p ($E^2 = p^2+m^2$) travels in z-direction against each other.

$\Rightarrow E_{cm} = 2\sqrt{(E_1E_2)} = 2E$
$\Rightarrow$ To produce top quark pairs you need $E_{CM} = 2 \times M_{top} = 350$ GeV => $E_1=E_2= E=175$GeV

However if the two beams are protons with energy E and three momentum p ($E^2 = p^2+m^2$) travels in z-direction against each other.

$\Rightarrow E_{cm} = 2\sqrt{(E_1E_2)} = 2E$. Its p-p COM energy, but protons are not elementary
$\Rightarrow$ Its gluon or quarks collide.
$\Rightarrow$ Assume gluons/quarks take fraction x of initial energy (or 4 mom) of proton

So the effect COM energy for quark-quark collision is $2\sqrt{(x_1E_1.x_2E_2)}$

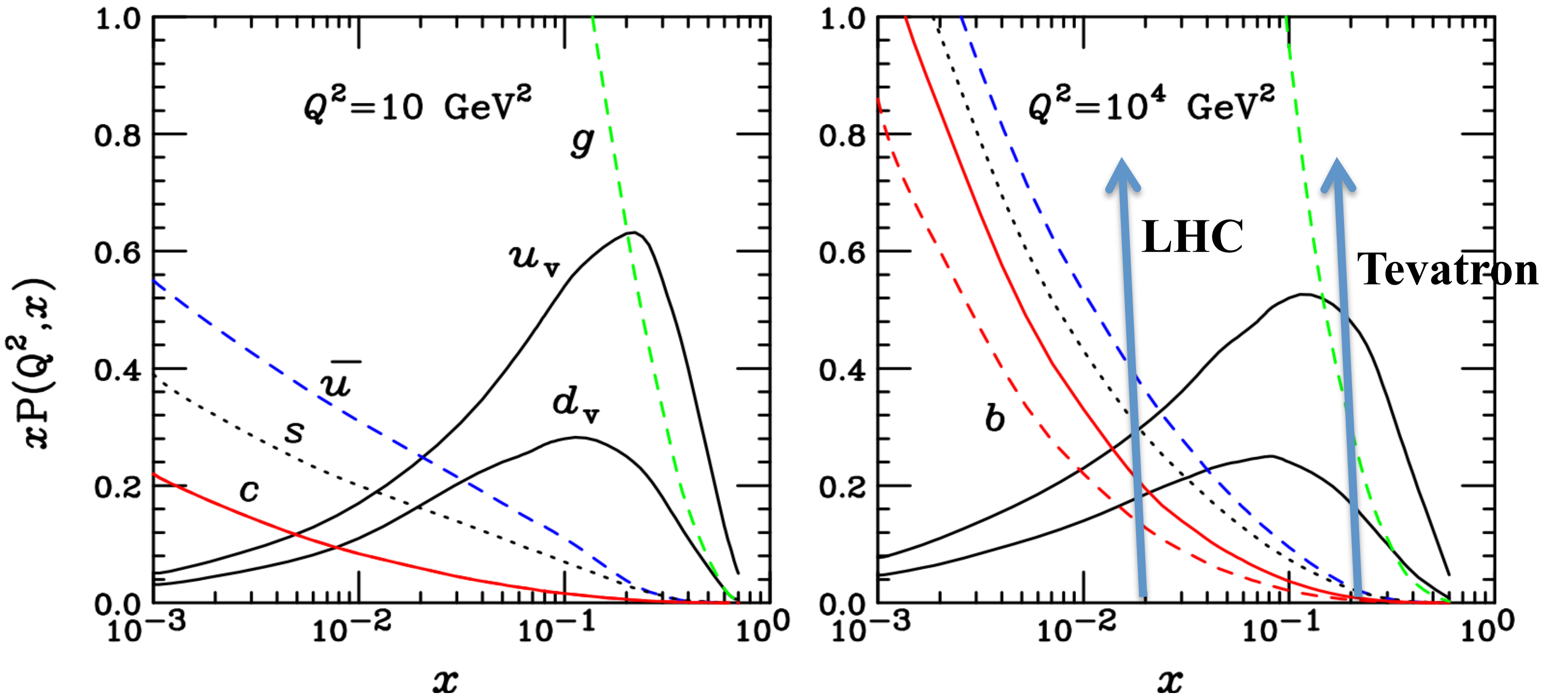
For simplicity take $x_1 = x_2 = x$, The quark-quark effective COM energy = x2E = $x.E_{cm}(pp)$

It is the quark-quark COM energy that produce top pairs

$x. 2E = 2 \times M_{top} = 350$ GeV => For LHC E = 7TeV => x = 350GeV/2*7000GeV = 0.025

For Tevatron, E = 2TeV => x = 350/2*1000 = 0.2

# pp vs $e^+e^-$ collison




$$\sigma(AB \to F\ X) = \sum_{a,b} \int dx_1 dx_2\ P_{a/A}(x_1, Q^2) P_{b/B}(x_2, Q^2)\ \hat{\sigma}(ab \to F),$$

**This is why the LHC is dominated by gluon-gluon process and Tevatron is dominated by quark-quark processes.**

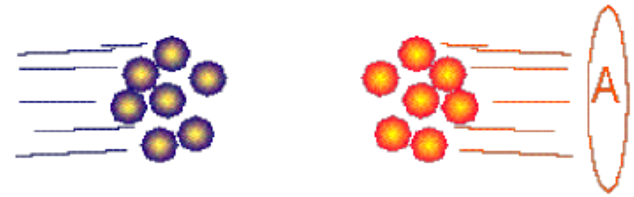
**As x varies in different collisions => The effective COM energy is different**
**=> Scans different energy region (energy is spread)**

**Now given that we know many basic needs to decide what kind of accelerator we should build, lets go to accelerator details.**

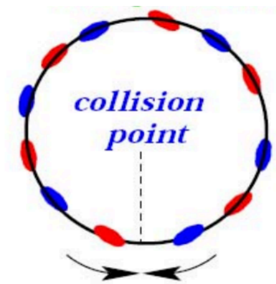
# Why the beam intensity is important for us and what is luminosity?

$$\dot{N} = L \cdot \sigma$$

Event Rate [Measured]; Luminosity [Machine parameter]; Cross Section

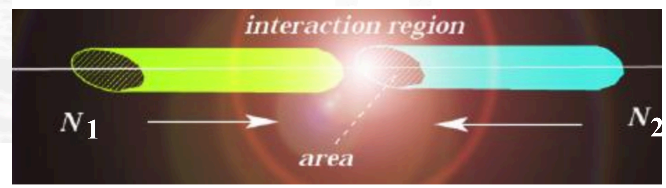



- The term luminosity was first coined by Dr. Bruno Toucschek to describe the interaction rate in a collider [http://arxiv.org/pdf/1103.2727.pdf ]
- In a collider, the detector at each collision point is designed to detect certain interaction events (for example Higg's event) when two beams are in collision and the events rate is the product of luminosity and cross-section of the interaction.




$$L = f\,\frac{N_1 N_2}{A}$$

\# of particles from beam 1 in collision ($N_1$); # of particles from beam 2 in collision ($N_2$); Frequency of collision ($f$); Area of collision, ie the product of beam size ($A$)




- The unit of instantaneous luminosity is $cm^{-2}\,sec^{-1}$.
- We sometimes talk about total integrated luminosity over certain period of time. The unit would be $cm^{-2}$ (normally we use $fb^{-1}$ (femto-barn) or $pb^{-1}$ (pico-barn) where 1 barn = $10^{-26}$ $cm^2$)

$$L_{int} = \int_0^{T_{store}} L(t)\,dt$$

# Why luminosity is so important?

Now, LHC runs with f= 40 MHz, $N^{1,2}$ = 1.5x $10^{11}$ and A = 3000 micron$^2$ =30x $10^{-6}$ cm$^2$

=> L ~ $10^{34}$cm$^{-2}$sec$^{-1}$

Assuming $10^7$ seconds running time per year, => L = $10^{41}$ cm$^{-2}$ , How much is this in fb$^{-1}$ ?

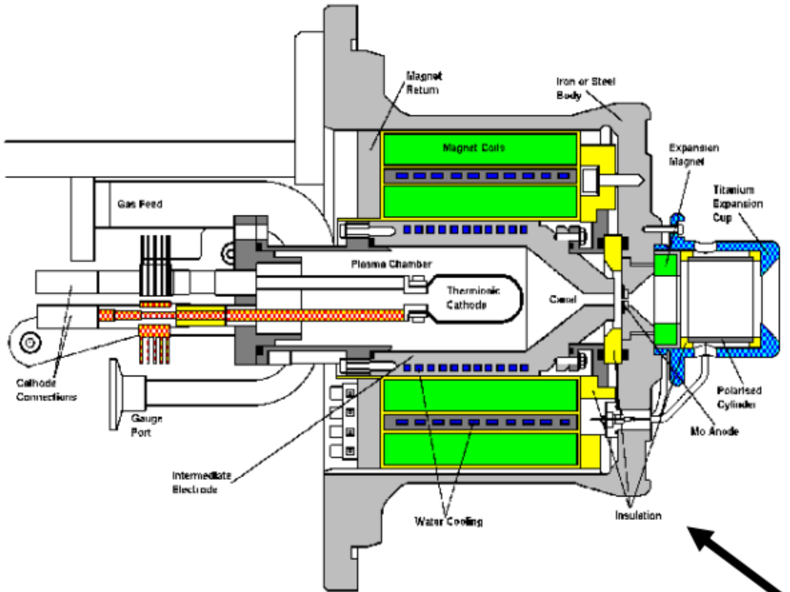
1fb = $10^{-15}$ x $10^{-24}$ cm$^2$ = $10^{-39}$cm$^2$ => 1 yr data = 100 fb$^{-1}$

Assume in LHC, Higgs are produced and decay to 4 leptons with production cross-section times the branching fraction ~ 1pb (this one we have no control over. Once the COM is fixed, the production cross-section is fixed. Similarly, the branching fraction depends on decay kinematics as well as follow the standard Feynman rules)

⇒ Then in one year time you get 100 fb$^{-1}$ x 1pb = 100K 4-lepton Higgs events

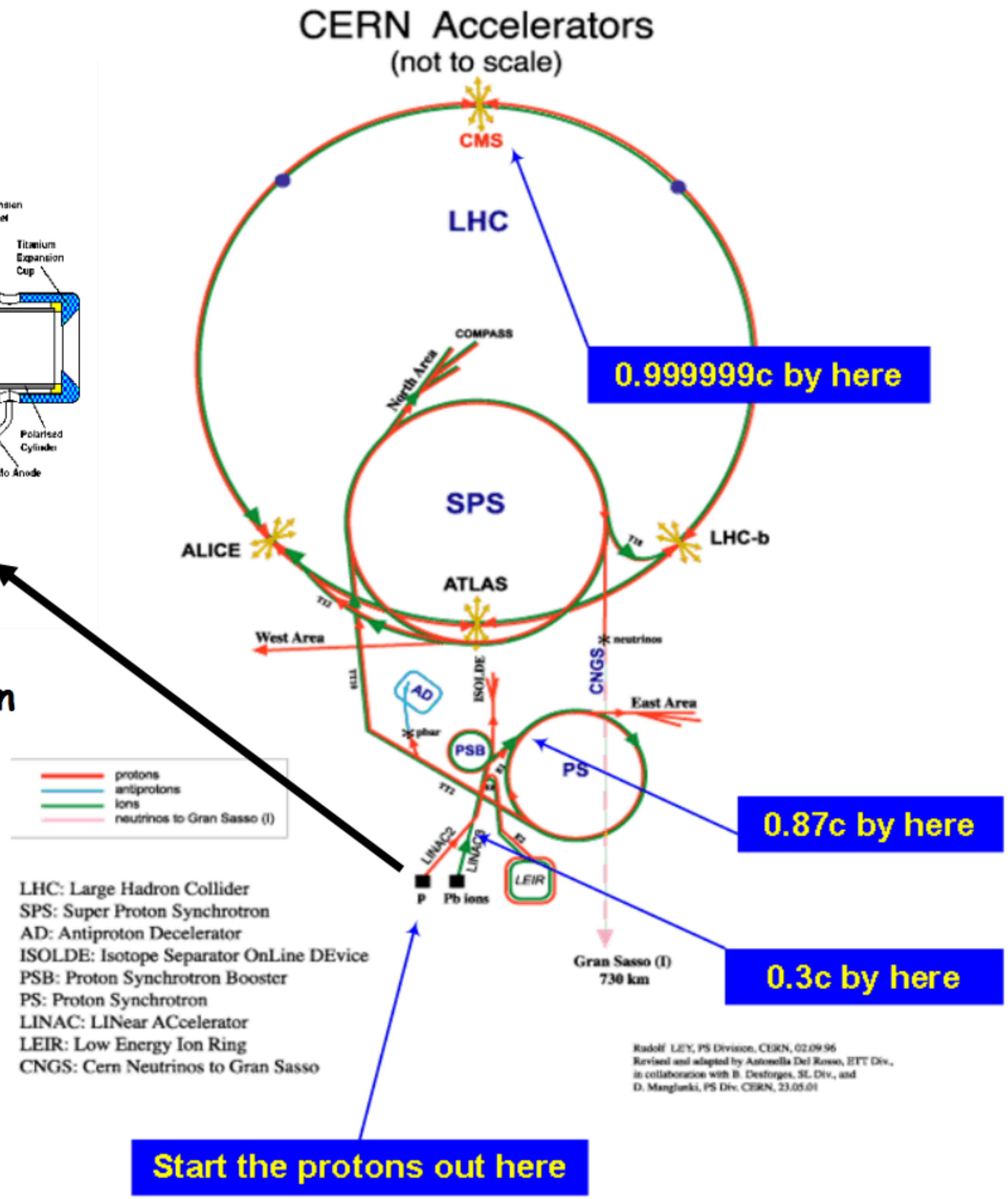
⇒ So in summary, one should try to increase the luminosity if you want to get more number of events which has small production cross-section.

# Basic principle of accelerator



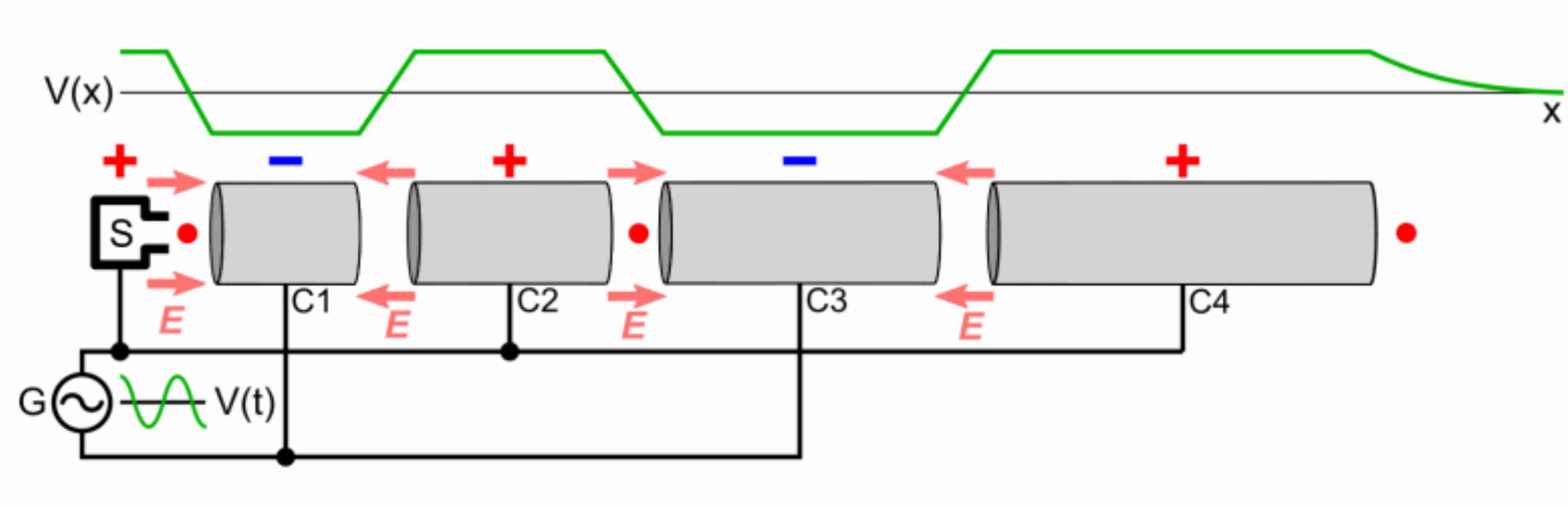

**Duoplasmatron for proton production**

$$H_2 + e^- \rightarrow H_2^+ + 2e^-$$
$$H_2^+ + e^- \rightarrow H^+ + H + e^-$$
$$H^+ + e^- \rightarrow H^+ + 2e-$$



# Basic principle of accelerator

- Accelerator has mainly two parts: (1) LINAC (2) Circular rings
- The concept of LINAC was first given by Wideroe in 1928
- Below shows very general working procedure of LINAC




- The particles are grouped together to make sure that the field has correct direction at the time the particle group passes the gap.

- The speed of the particles increases and the length of the modules change so that the particle's arrival in the gap is synchronized with the field direction in the gap

# The Synchrotron-I

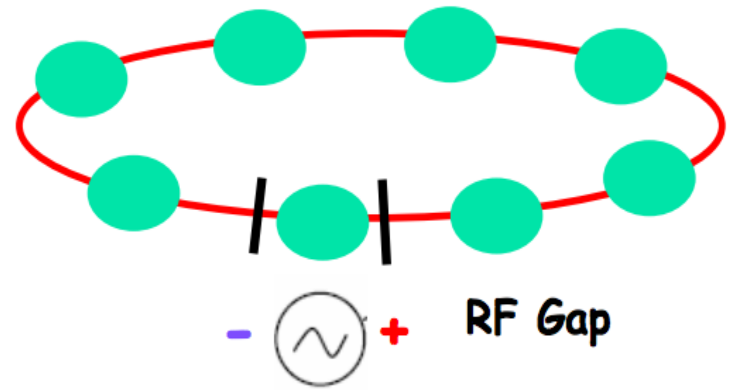
- **Bottom line: The particle motion is governed by Lorentz force law**

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

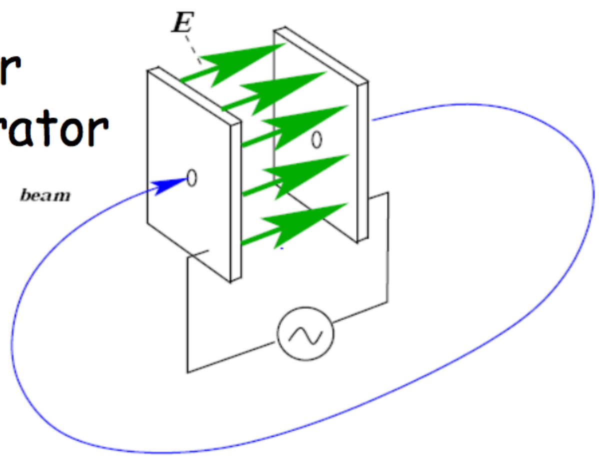
Electric field accelerates particles

Particles of different energy (speed) behave differently

Magnetic field confines particles on a given trajectory

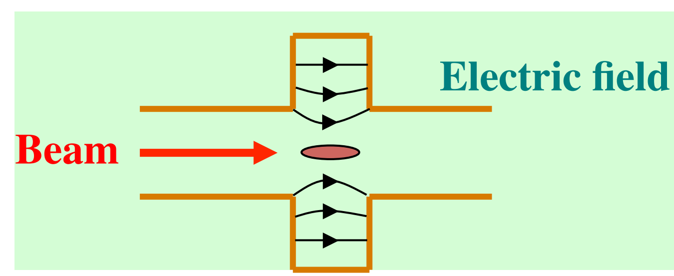



Circular accelerator




**Acceleration**

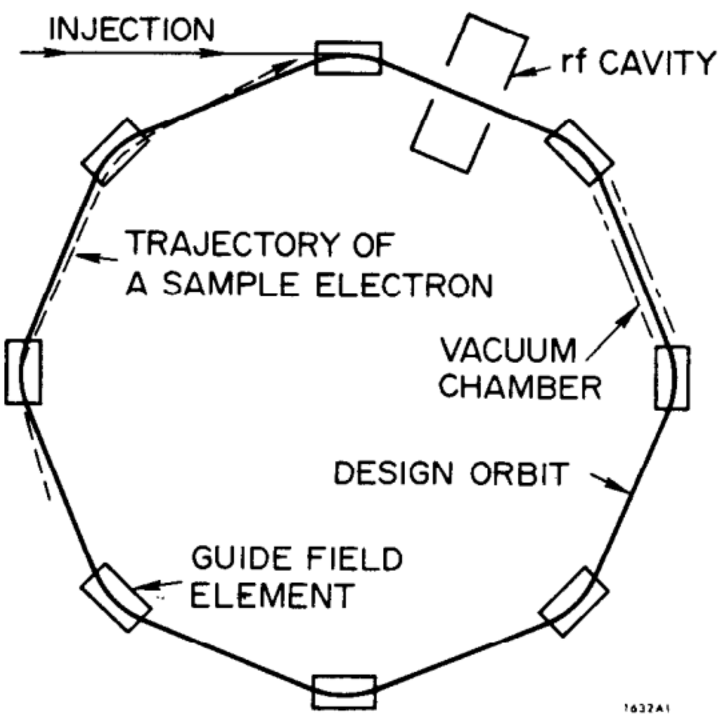
$\vec{E}$ = electric field

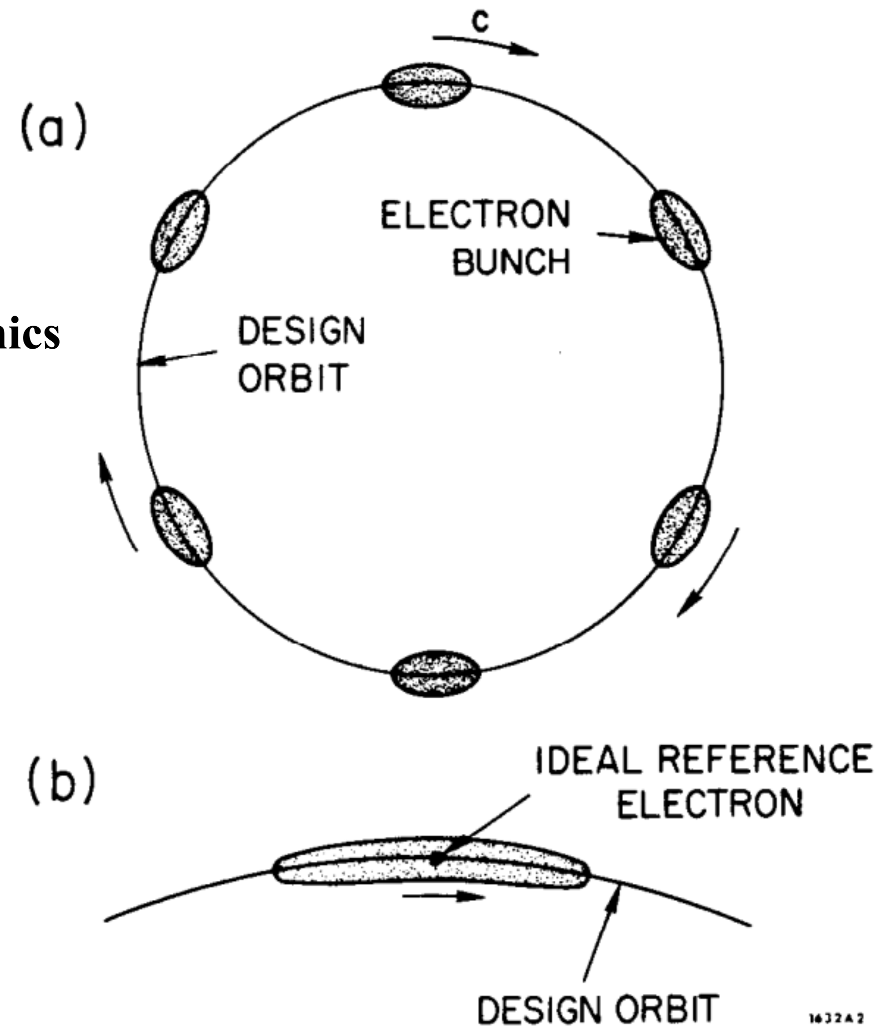



- **Groups of particle are circulating synchronously with the RF field in the accelerating cavities**
- **Each particle is circulating around the ideal (theoretical) orbit; for this to work out, acceleration and magnetic field must obey the stability criteria (come back to it later)**

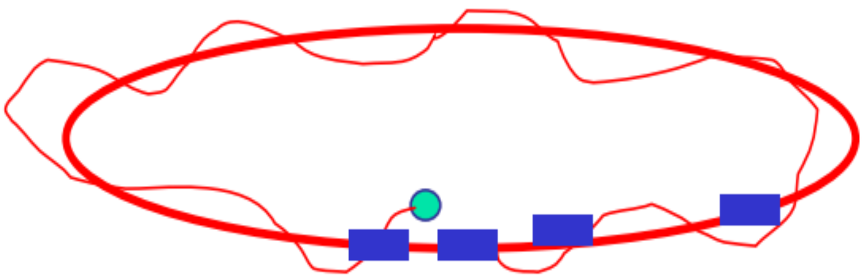
# The Synchrotron-II

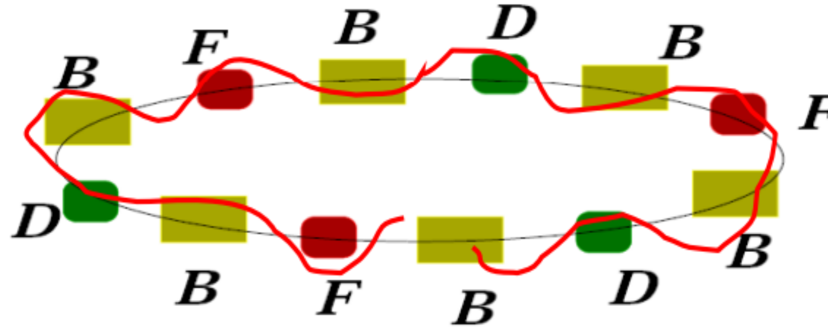
- ✓ In reality one never gets circular orbit
- ✓ The particle beam needs bending at few points to keep them on a circular orbit as shown below.
- ✓ In fact different kinds of magnets are used in practice to deal with complex beam dynamics



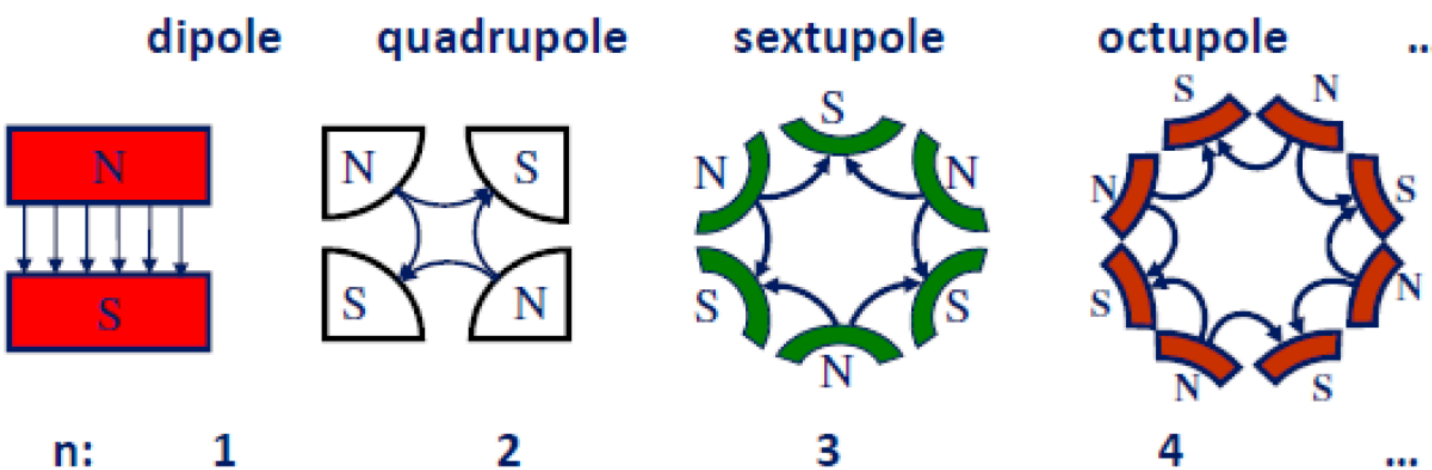
# Magnet configurations in a particle accelerator



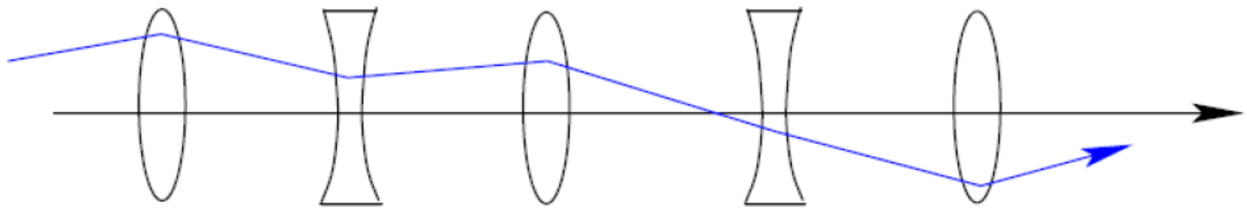



- **Main idea:**

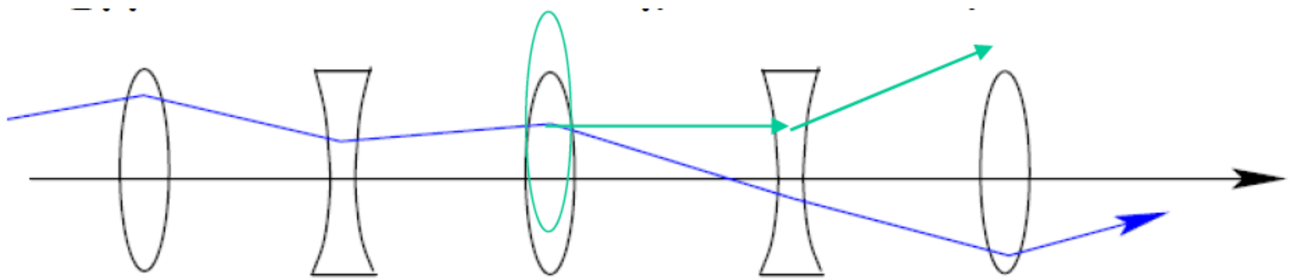
  **Bend the beam with dipoles (B) so that beam is constrained to closed path or orbit.**
  **Focus the beam in transverse directions using Focusing (F) and Di-focusing magnets(D), called (FODO lattice). These are quadrupole magnets.**
  **Several other higher order magnets are used as correcting magnets.**



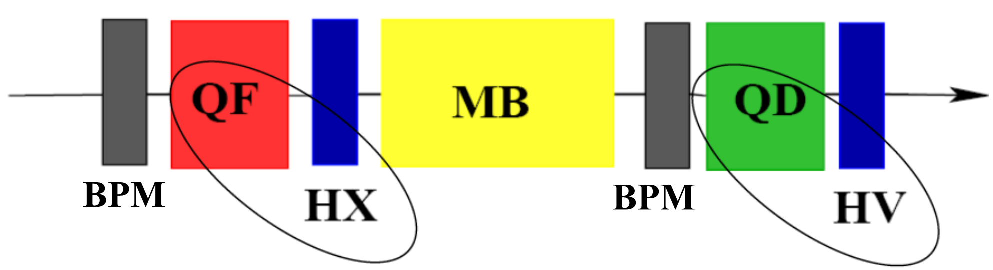
# Beam Dynamics



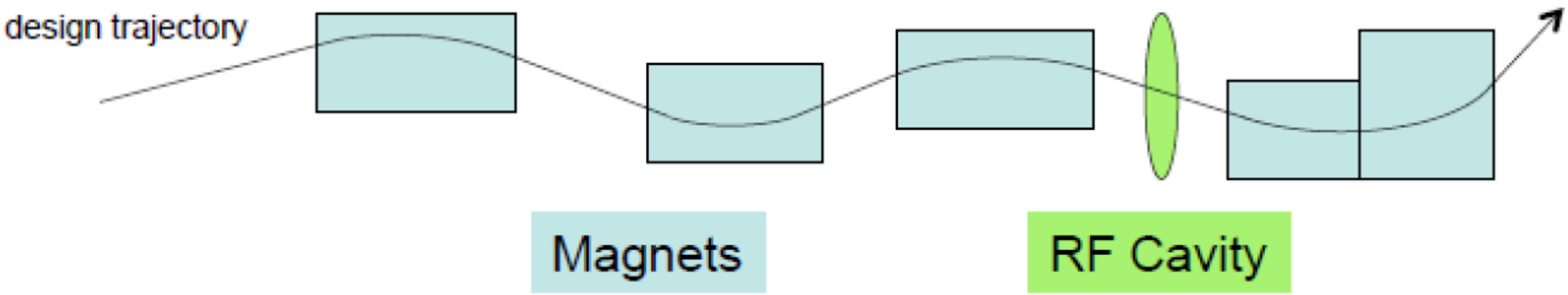
- Alternate gradient focusing gives an overall focusing effect
- The beam takes up less space in the vacuum chamber, the amplitudes are smaller
- However the magnets are not perfect; in addition they not be perfectly aligned
- For quadrupoles for example this means that the force the particles feel is either too large or too small => the whole beam is deviated



- Beam position monitors are used to measure the center of the beam near a quadrupole
- Also small dipole magnets are used to correct possible beam position error.



# Magnetic rigidity




**The most common term used in case of accelerators is magnetic rigidity:**

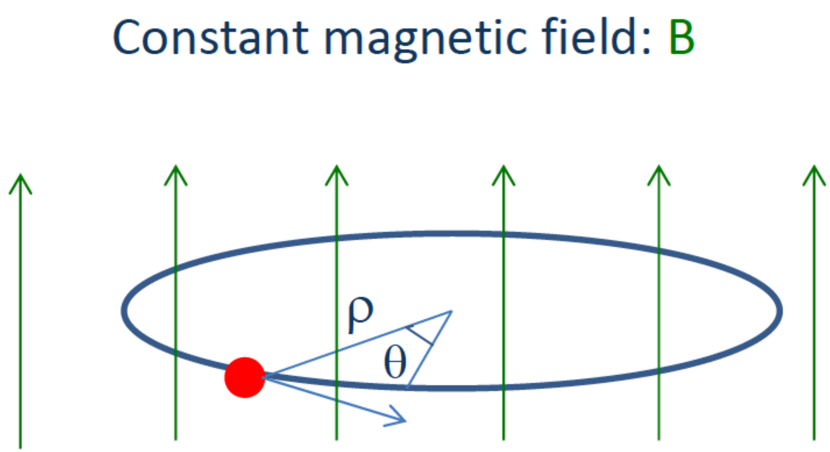
$$\Rightarrow \frac{mv^2}{\rho} = evB$$

$$\Rightarrow p = mv$$

$$\Rightarrow \frac{1}{\rho} = \frac{e}{p}B$$

$$\Rightarrow B\rho = \frac{p}{e}$$

$$B\rho[Tm] \approx 3.33 \frac{p[\frac{GeV}{c}]}{e}$$




- **This tells how hard or easy is a particle to deflect?**
- **High energy particles are harder to bend**

# Dipole bending

- **A dipole of uniform dipolar magnetic field deviates a particle by an angle θ**
- **The deviation θ depends on the length L and magnetic field B**

**The angle θ can be calculated:**

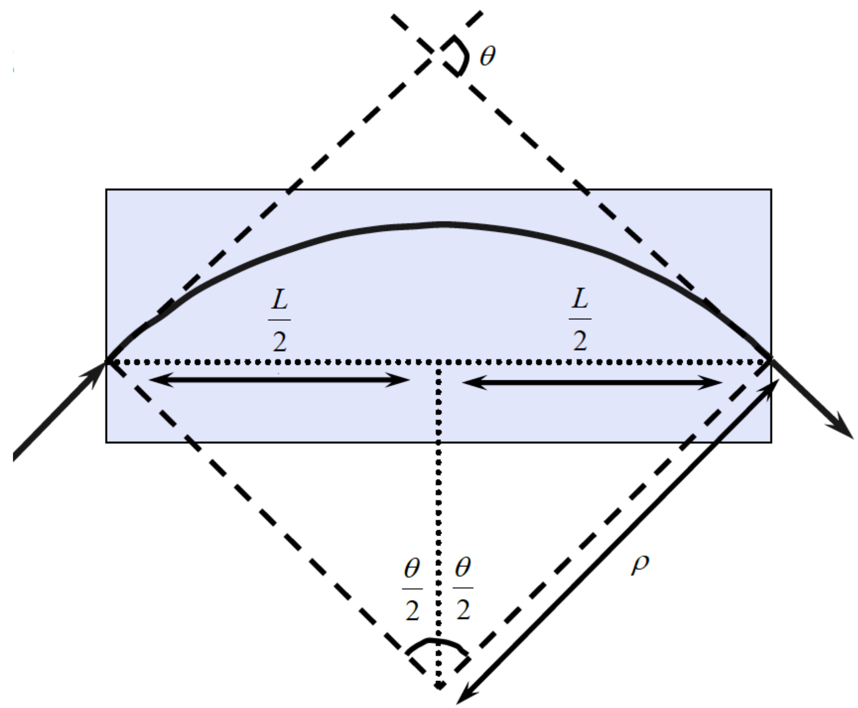
$$\sin\left(\frac{\theta}{2}\right) = \frac{L}{2\rho} = \frac{BL}{2(B\rho)}$$

**If θ is small:**

$$\sin\left(\frac{\theta}{2}\right) = \frac{\theta}{2}$$

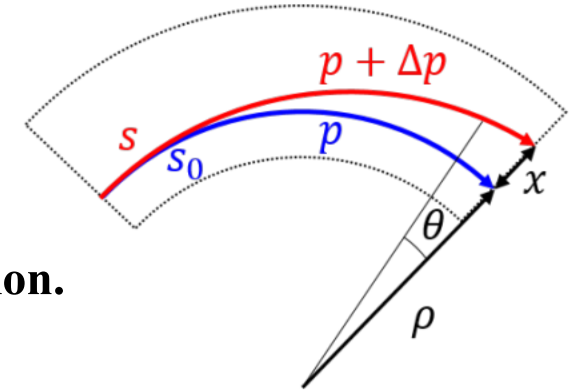
**So we can write:**

$$\theta = \frac{BL}{(B\rho)} = \frac{BL}{Rigidity}$$



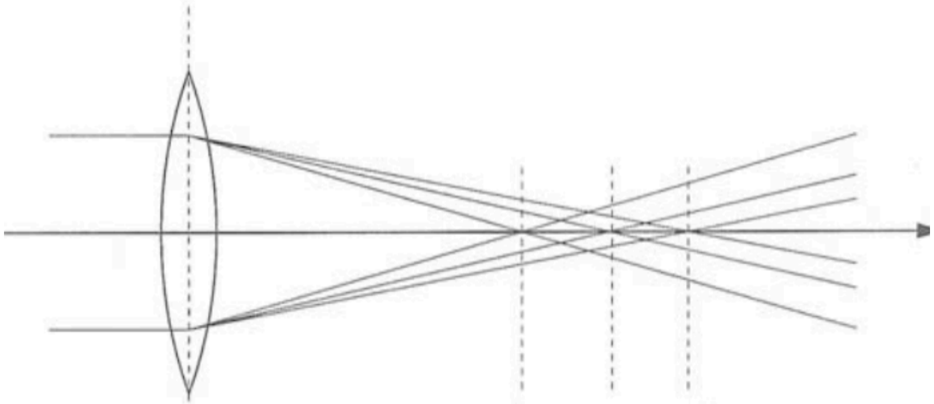

**LHC uses 15m long dipole magnets with magnetic field of 8.3Tesla. For LHC bending Angle per dipole is ~ 5 mrad.**

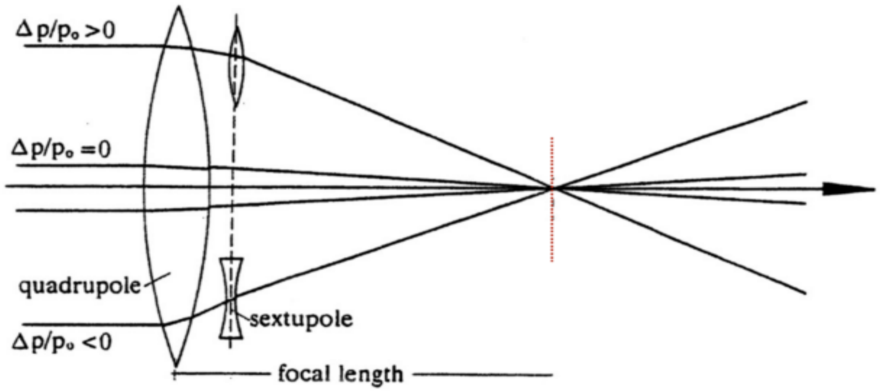
# Dispersion and Chromaticity




- ✓ **The bending angle inside the dipole depends on the energy/momentum of the particle. The particle in a beam with different momenta /energy have different bending inside the dipole magnet. This is called dispersion. The dispersion is suppressed by using the higher order magnets, such as quadrupoles.**

- ✓ **In addition to dispersion, a beam particle with momentum error Δ sees a focusing strength slightly different than that of a particle at the designed energy. This is called Chromaticity. One needs higher order magnets (specifically sextupoles) for correcting the chromaticity.**

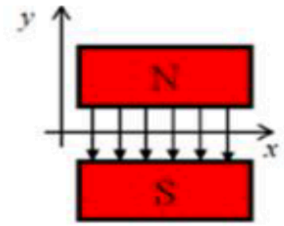


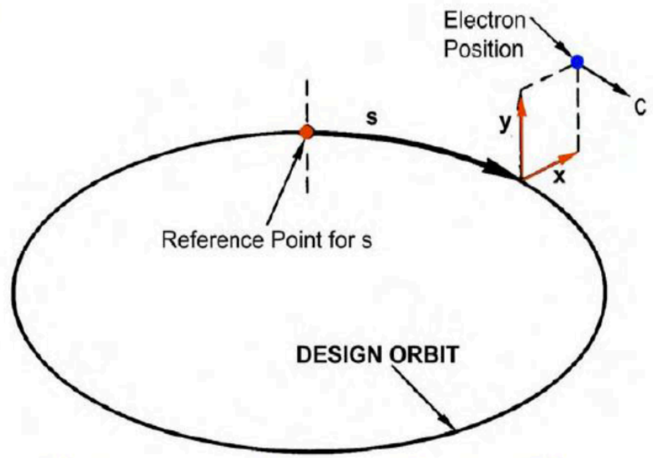


# Coordinate used for particle motion and magnets

**x: horizontal   y: vertical**
**s: longitudinal along the particle trajectory**

$\vec{B}$ = magnetic field

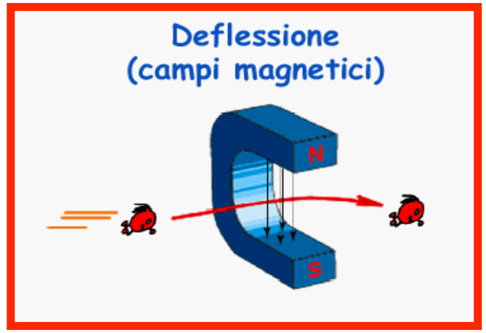


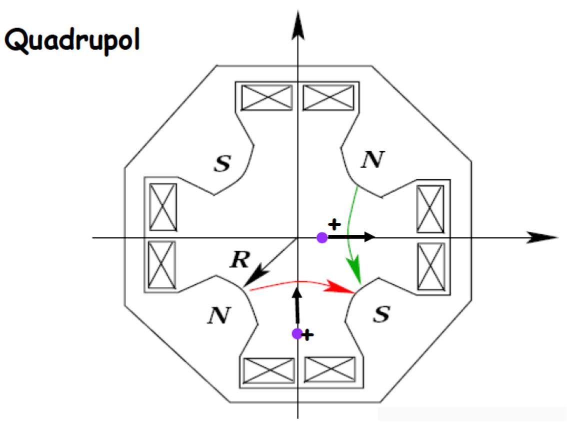




**Dipoles: used for guiding particle trajectory**

$B_x = 0$

$B_y = B_0 = constant$




**Quadrupole: focus the particle trajectory**

$B_x = Gy$

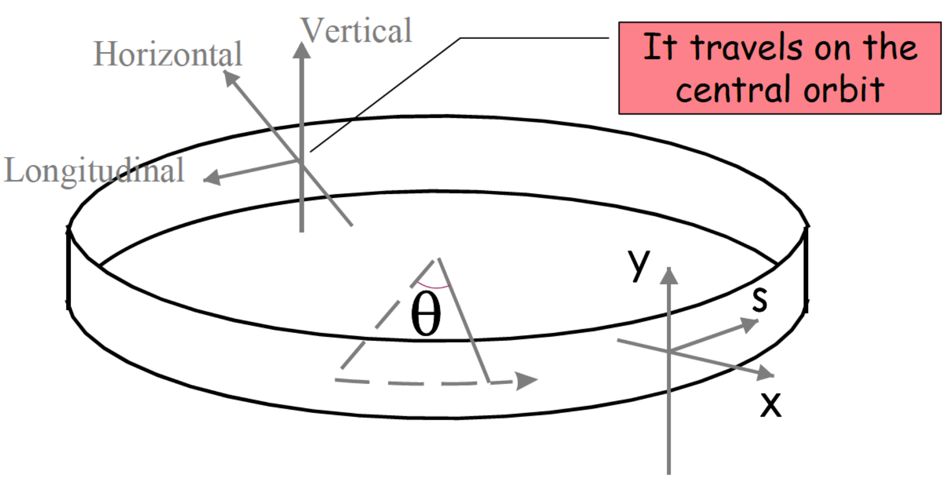
$B_y = -Gx$

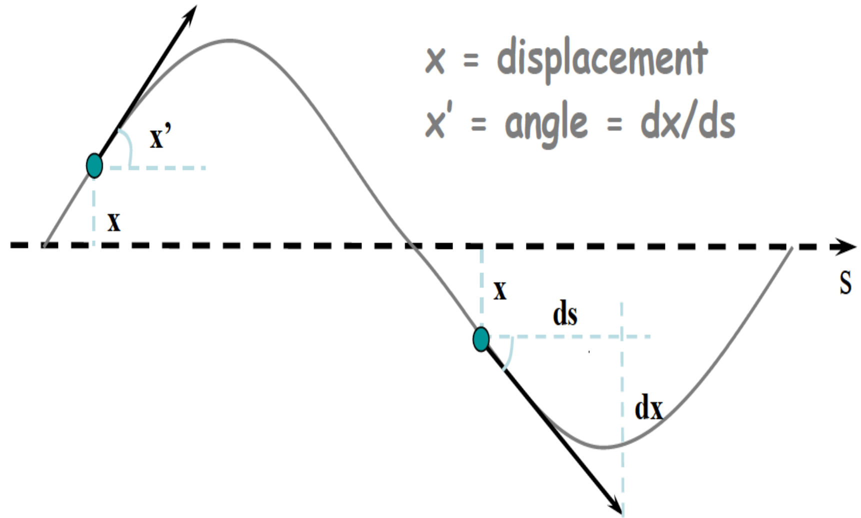
*G is a constant*

**Force is proportional to x or y => particle far from center of the magnet bent more. They get a more important correction.**

**In the above picture, a positive particle moving towards us gets defocussed in the horizontal plane and focused in the vertical plane. Its analogous to convex and Concave lenses.**

# Particle equation of motion in transverse direction-I




- A particle during its transverse motion in our accelerator is characterized by:
  -> Position or displacement from the central of designed orbit
  -> Angle with respect to central orbit
- Creates a oscillatory motion in transverse plane => Called Betatron Oscillation
- The number of oscillations/turn is $Q_x$ or $Q_y$ (called Betatron Tune)
- There are several ways to derive the transverse equations of motion. A particularly elegant method involves Hamiltonian dynamics but it is beyond the scope of this talk.

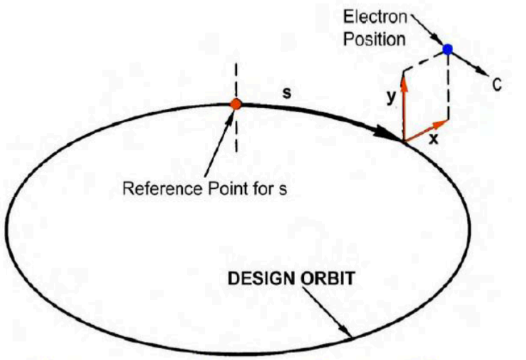
Here we will make some approximations and substitute into Lorentz Force equation.

# Hill's equation

**The particles satisfy the following equation while travelling inside the rings:**

**In horizontal plane:** $x'' + \left(\frac{1}{\rho^2} - k\right)x = 0$

**In vertical plane:** $y'' + ky = 0$




**1/ρ is the dipole bending radius and** $k = \frac{1}{B\rho}\frac{dB_y}{dx}$ **is the quadrupole focusing strength.**

**The above equations looks like:** $x'' + K(s)x = 0 \qquad y'' + K(s)y = 0$

**What does it tell us?**

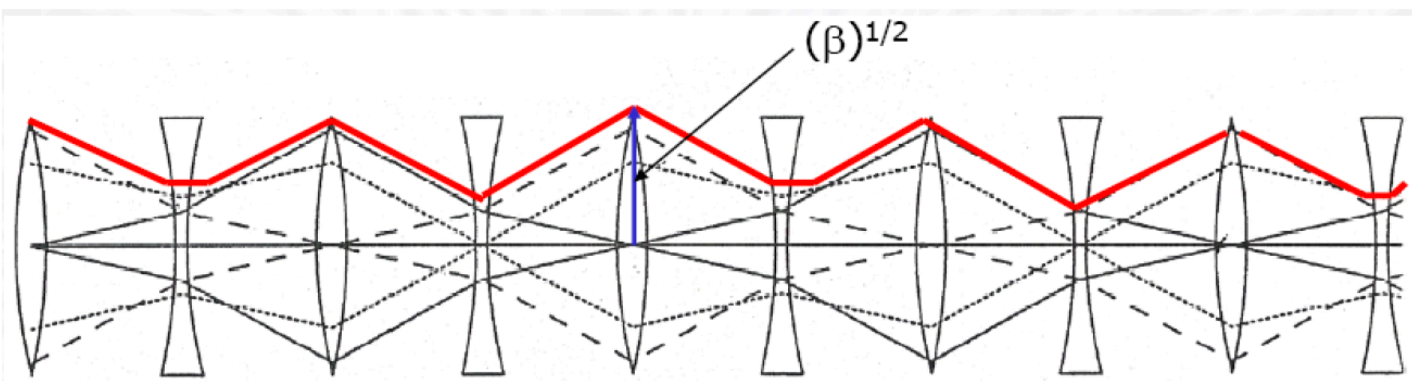
- ✓ **Particle motion about the reference trajectory is caused by normal dipoles and quadrupoles, whose strength varies with s.**
- ✓ **The k and ρ are constants and focusing with s, the motion is harmonic. Therefore we shouldn't be surprised later to find out that the motion has a "frequency". The total motion is s-dependence.**
- ✓ **The equation acts like a spring with "spring constant" or restoring force, K(s), which changes over the longitudinal distance of the accelerator**

# Solution to Hill's equation

$x'' + K(s)x = 0$ **is a second order differential equation**

**Guess a solution:** $x = \sqrt{\varepsilon.\beta(s)}\cos(\phi(s) + \phi_0)$

- **Here ε and $\phi_0$ are constants, which depend on the initial beam conditions**
- **β(s) is the amplitude modulation due to the changing focusing strength**
- **ϕ(s) is the phase advance, which also depends on the field strength.**
- **Lets define some parameters:**




$\alpha = -\beta'/2$  $\beta = \omega^2$  $\gamma = (1+\alpha^2)/\beta$  **and**  $\phi = (\phi(s) + \phi_0)$

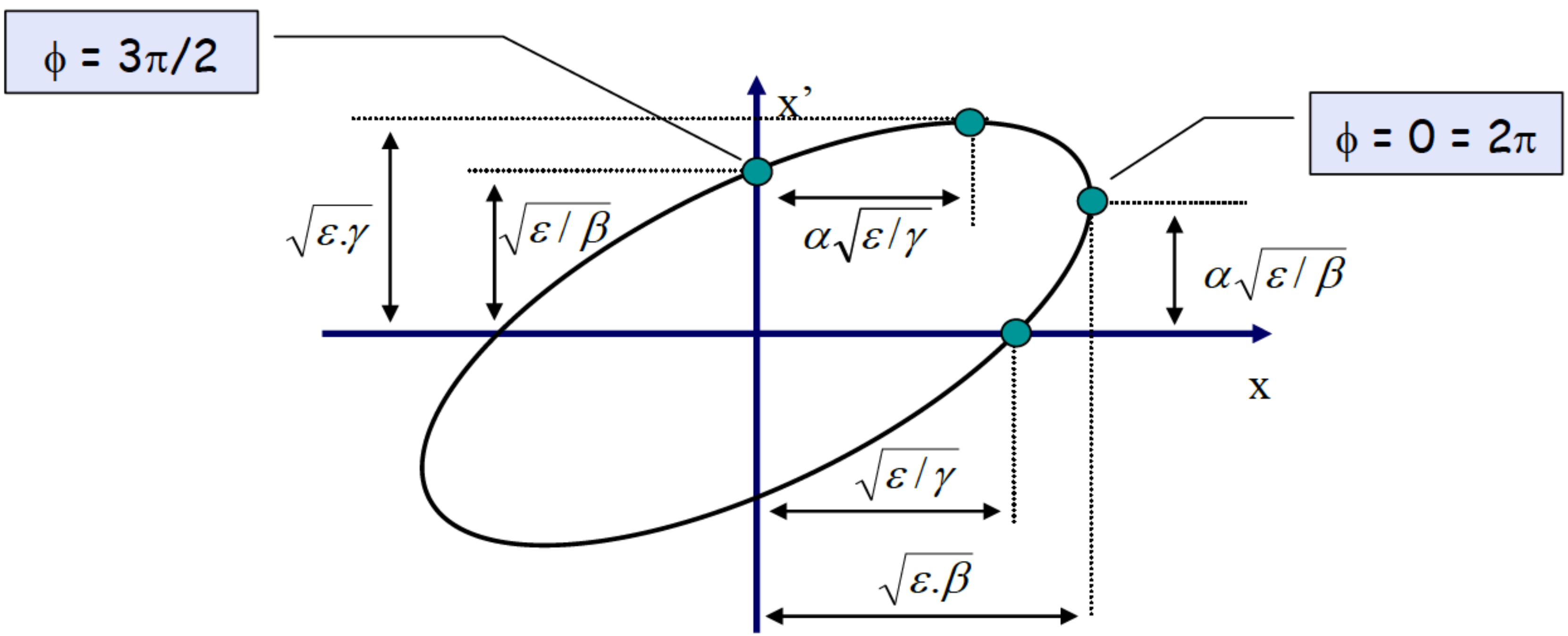
***α, β and γ are called twiss parameters (Courant-Snyder parameters)***

## Twiss parameters

So, now $x = \sqrt{\varepsilon.\beta(s)}\cos(\phi)$ and $x' = -\alpha\sqrt{\varepsilon / \beta(s)}\cos(\phi) - \sqrt{\varepsilon/\beta}\sin(\phi)$

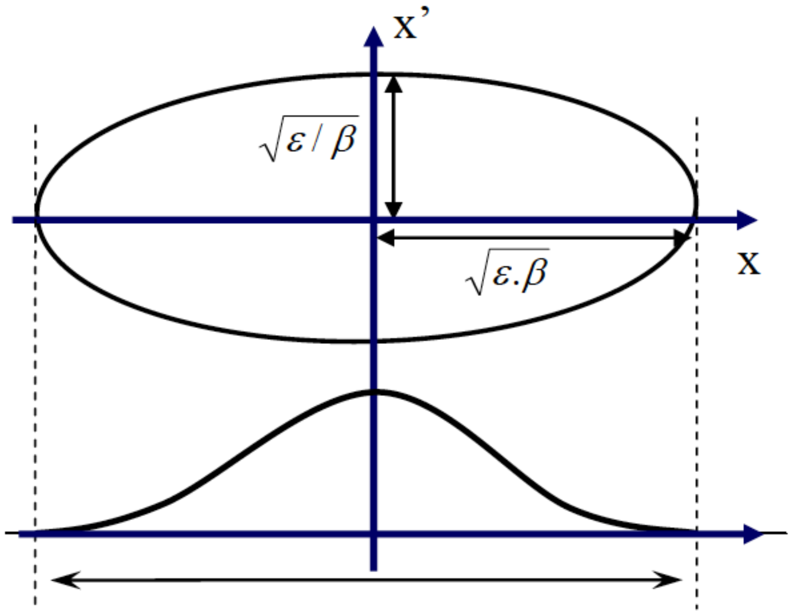
This gives rise to the relation: $\varepsilon = \gamma(s)x^2(s) + 2\alpha(s)x(s)x'(s) + \beta(s)x'^2(s)$

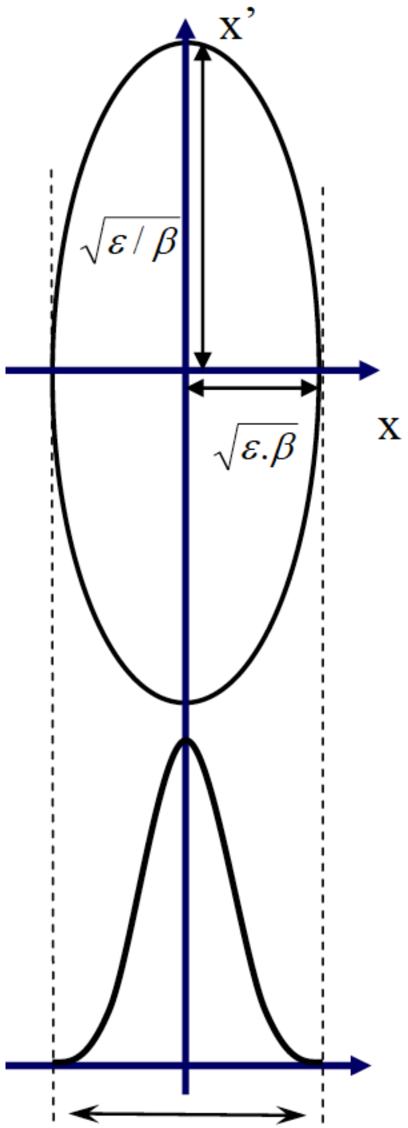
- Here ε is called the emittance (Courant-Snyder invariant), which is determined by initial conditions of the beam
- If we plot x' versus x, we get an ellipse which is called the phase space ellipse



# Phase space ellipse

- As we move around the machine the shape of the ellipse will change as β changes
- under the influence of quadrupoles.
- However the area of the ellipse (πε) does not change



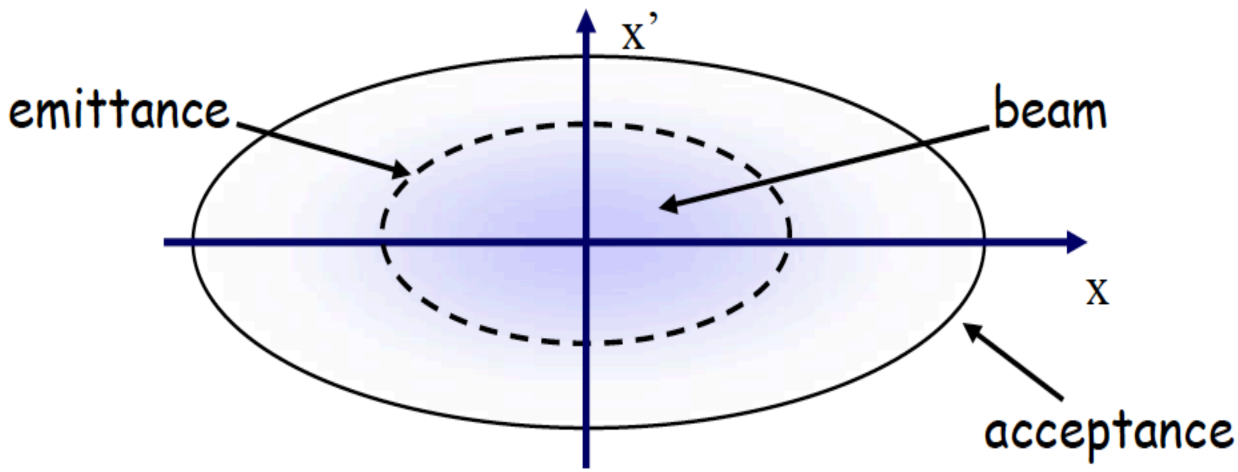




- The projection of the ellipse on the x-axis gives the physical transverse beam size.
- The variation of β(s) around the machine will tell you how the transverse beam size will vary

# Emittance and acceptance

**To be rigorous we should define the emittance slightly different**

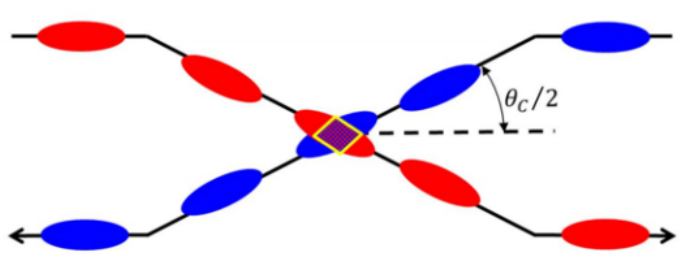
- ✓ **Observe all the particles at a single position on one turn and measure both their position and angle**
- ✓ **This will give large number of points in our phase space plot, each point representing a particle with its co-ordinate x, x'.**

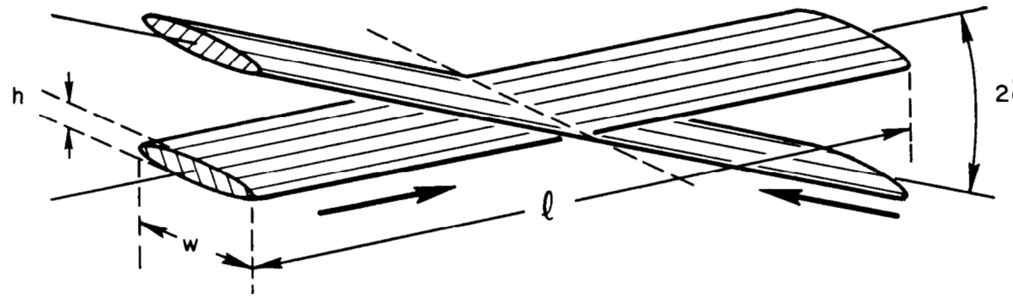



- ✓ **The emittance is the area of the ellipse which contains defined percentage, of the particles**
- ✓ **The acceptance is the maximum area of the ellipse, which the emittance can attain without losing particles.**

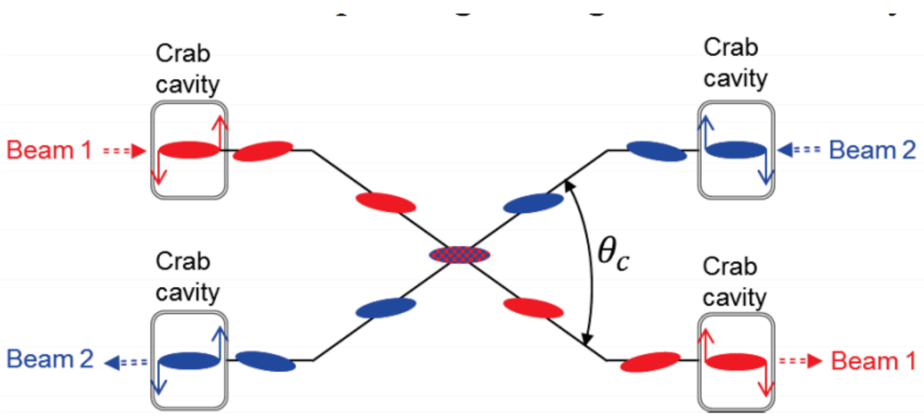
# Crab cavity

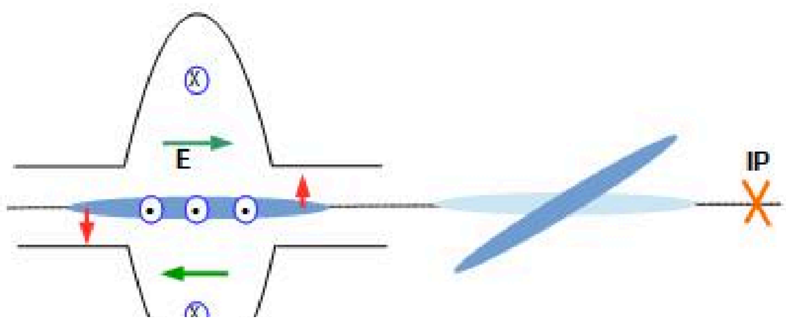
- Large crossing angles can reduce parasitic collisions. However, it also reduces the luminosity due to smaller overlap region between two bunches.



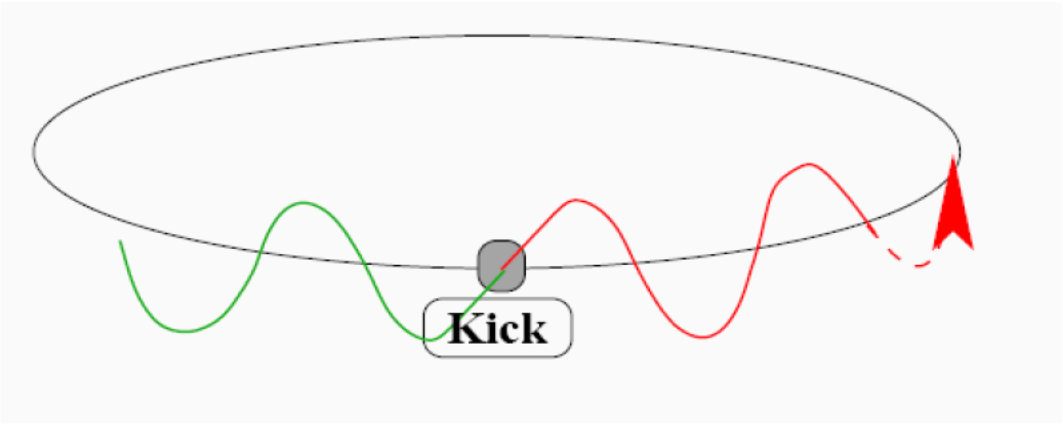




- Use RF cavity on either side of the collision point to align the bunch shape of two beams to recover luminosity reduction due to geometric factor. Such a cavity is called crab cavity. The RF device gives transverse kicks to tilt the bunches. First introduced by Dr. R Palmer (BNL) 1988 and first demonstrated at KEK B-factory



# Possible problems-I




- ✓ The Q-value gives the number of oscillations the particles make in one turn. If this value is an integer, the beam "sees" the same magnet-error (if there is any) over and over again and we may have a resonance phenomena. Therefore Q-value is not an integer.

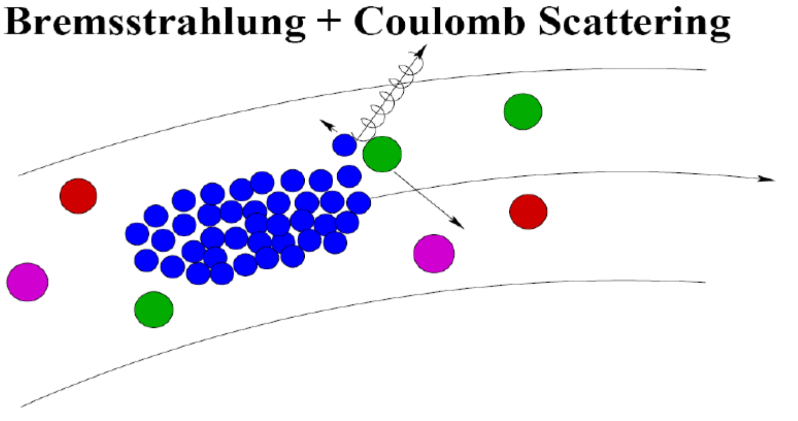
- ✓ The magnets have to be good enough so that resonance phenomena do not occur. Non wanted magnetic field components (sextupoles, octopoles etc) are comparable to $10^{-4}$ relative to the main component of the magnet (dipole is a bending magnet, quadrupole is a focusing magnet etc).

# Possible problems-II

Types of effect that may influence the accelerator performance and has to be taken into account:

- ✓ Blow up of beams
- ✓ Particle losses
- ✓ Beam gas
- ✓ Synchrotron radiation
- ✓ Movement of the surface of the earth
- ✓ Trains
- ✓ The moon
- ✓ Construction work

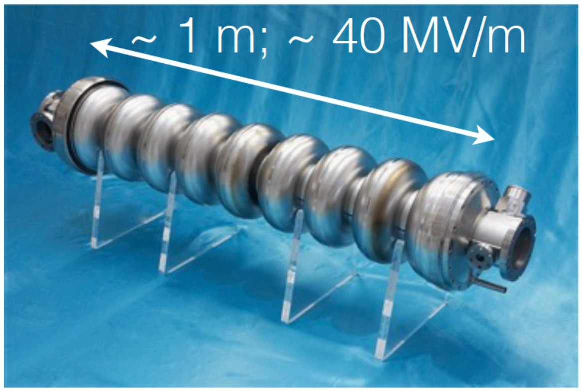
…..



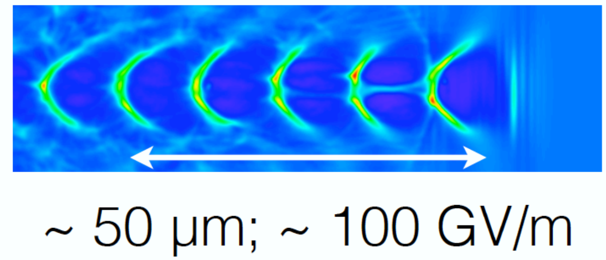

So calibration of the magnet is very important

# Plasma Wakefield Accelerator-I

- ✓ Conventional accelerators are large ( 100 meters to few kms) and expensive, 10-100M$
- ✓ Conventional accelerators can not achieve better than a few 10MV/m.
- ✓ Plasma waves are a possible compact alternatives and cheap.

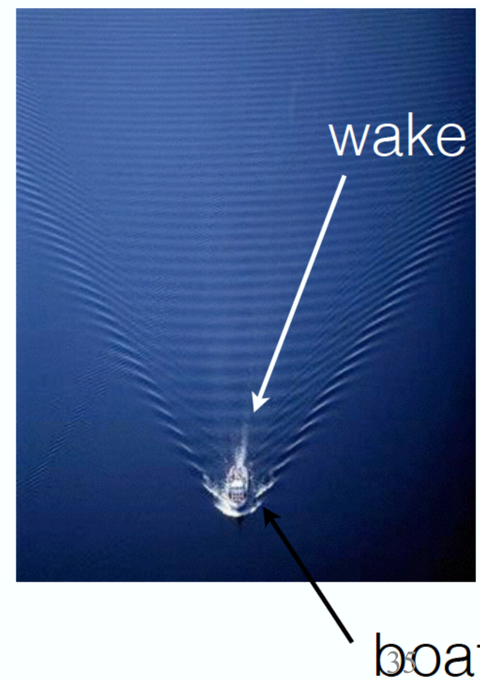



a section of RF cavity

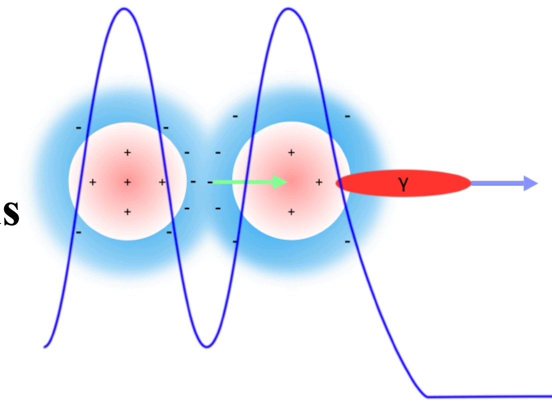



a plasma wave

- ✓ When a boat travels through water it produces a wave behind it – a “wake”
- ✓ The phase velocity of the wave is just the speed of the boat.
- ✓ So we can use a laser pulse travelling close to speed of light c in a plasma to drive a strong wave behind it.
- ✓ The drive pulse of an intense laser pulse pushes away electrons just like a boat pushes away the water
- ✓ The must heavier ions are left behind – this charge separation makes a very large electric field (as shown in next page)



# Plasma Wakefield Accelerator-II



- ✓ A laser pulse (red) when injected into the plasma medium, knocks away the plasma electrons (blue) and creates wakefields(pink) which are co-moving with the laser beam at the speed of light. The electrons behind are pulled towards by the positively charged wakefield hence accelerated.
- ✓ The blue line represents the ionization level.

- ✓ Its like surfer riding on the wave – if the electron catches the wave then it can travel
- ✓ Same speed as laser pulse.


- ✓ For surfer to ‘catch a wave’ he must swim to get to the speed before wave arrives, if he is too slow the wave will just pass over him
- ✓ We must find a way of accelerating electrons up to the correct speed for them to be trapped by the wave and accelerated
- ✓ Electrons travelling faster than the wave – eventually they stop being accelerated, this is called ‘de-phasing’

# Summary

- ✓ Accelerator plays a vital role in practical application to our understanding of nature. They are used in medicals as well as basic science research such as solid state and particle physics. We will not be able to test many theoretical models without inputs accelerator.
- ✓ As we go to higher and higher energy, the challenges are bigger, even maintaining small corrections.
- ✓ Over the time, accelerator design has improved multifold and still new techniques are being suggested or getting tested, for example International Linear Collider (ILC) plans to use plasma wakefield for accelerating electrons.
- ✓ India played big role in the area of accelerator hardware for LHC.
- ✓ Accelerator Physics is an open and active area of research . Students are encouraged to explore this area for development of science and technology.