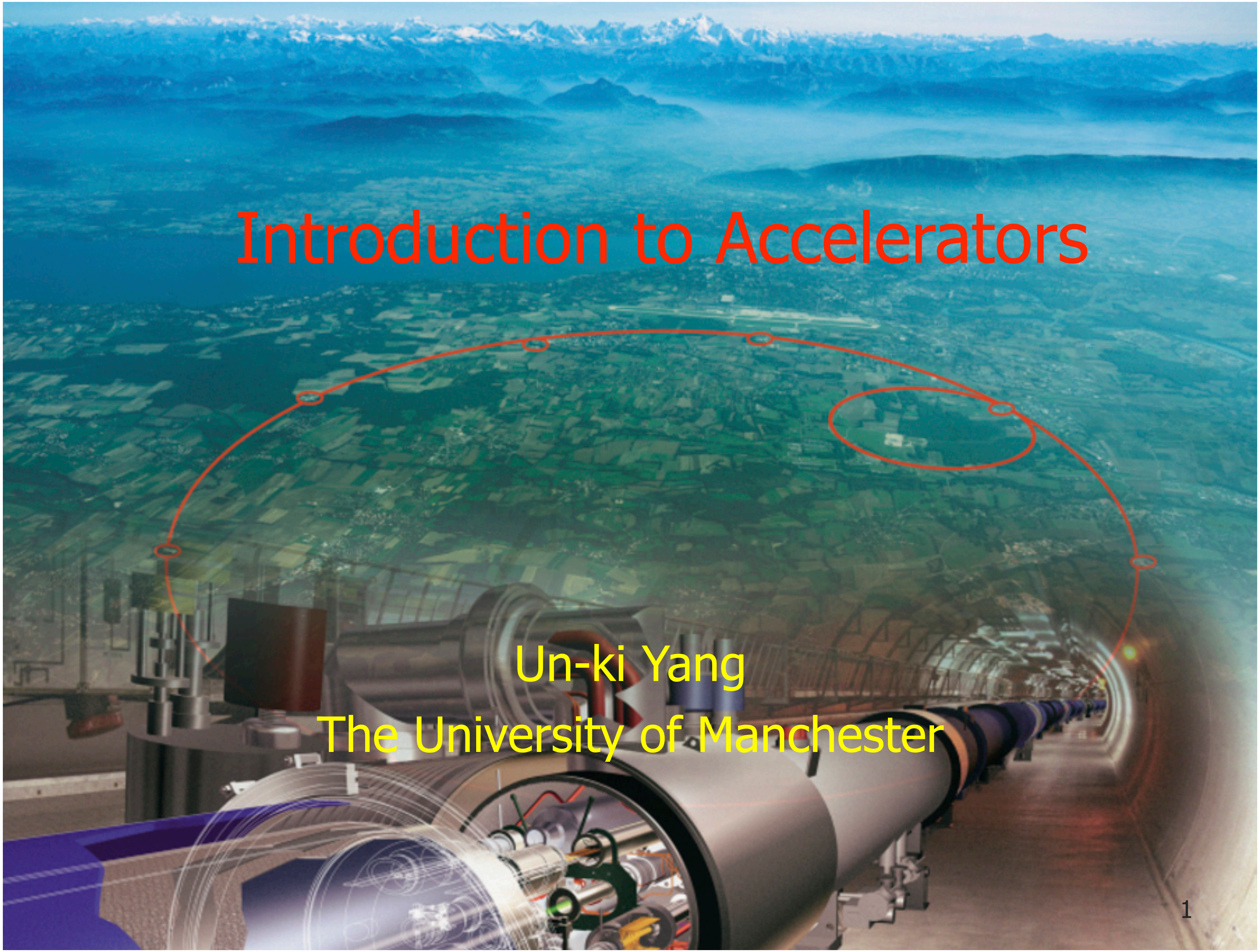


Introduction to Accelerators

Un-ki Yang
The University of Manchester

Outline

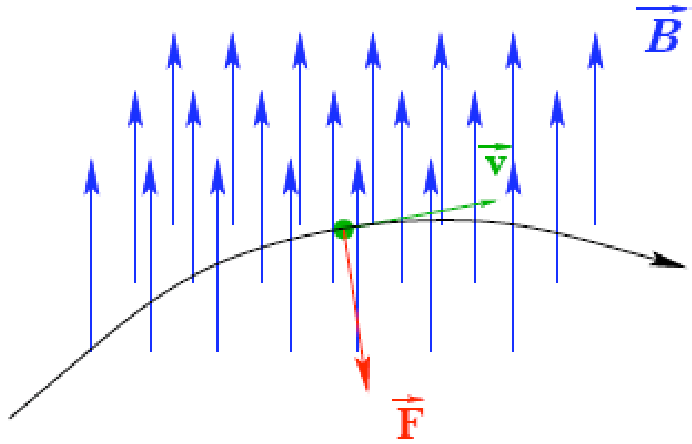
- Principles of particle accelerator
- How to control particle beam?
  - Longitudinal beam dynamics
  - Transverse beam dynamics
- Large Hadron Collider (LHC)
- Summary

Materials from the talks by D. Brandt
and E. Wildner talks

Principle of particle accelerator

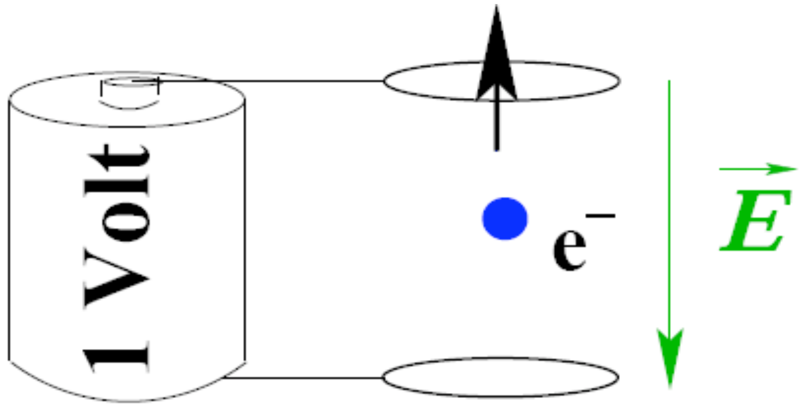
Lorentz Force:

$$\frac{d\vec{p}}{dt} = Q * (\vec{E} + \vec{v} \times \vec{B})$$



- Energy gain only due to E field
- Bending due to B field

Units: the electronvolt (eV)



The electronvolt (eV) is the energy gained by an electron travelling, in vacuum, between two points with a voltage difference of 1 Volt. 1 eV = 1.602 10^{-19} Joule

We also frequently use the electron volt to express masses:
1 eV/c^2 = 1.78 10^{-36} kg; electron 0.5 MeV/c^2 , proton 0.94 GeV/c^2

Relativity: $E=mc^2$; $m = \gamma m_0$, where $\gamma = 1/(1-\beta)^2$

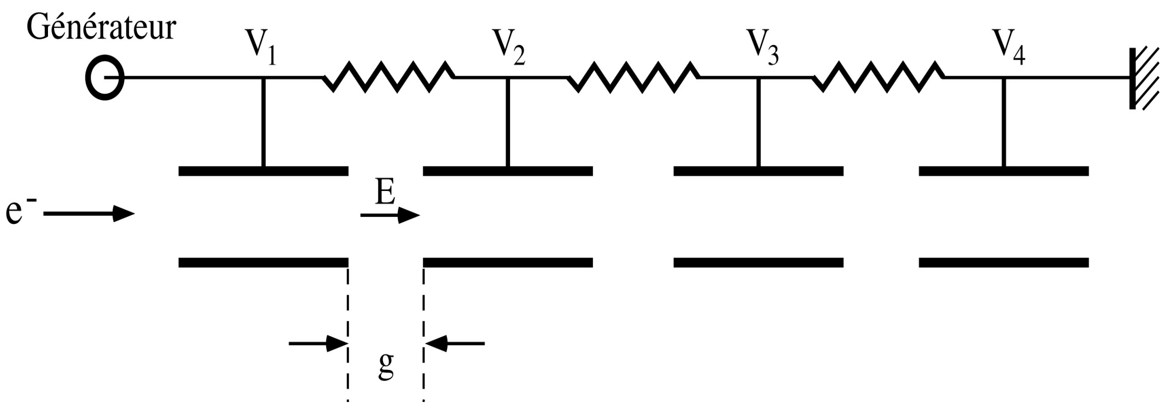
Acceleration

The accelerator has to provide kinetic energy to the charged particles, i.e. increase the momentum of the particles using an electric field E

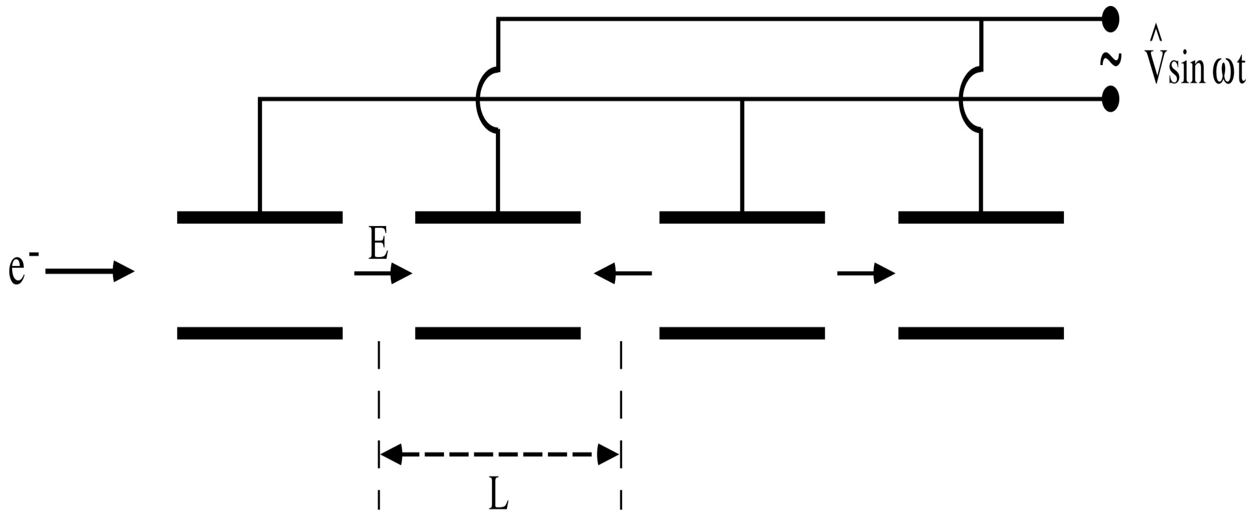
Electrostatic accelerator

Limit: $V_G = \Sigma V_i$

Rather use RF fields !



RF accelerating fields:

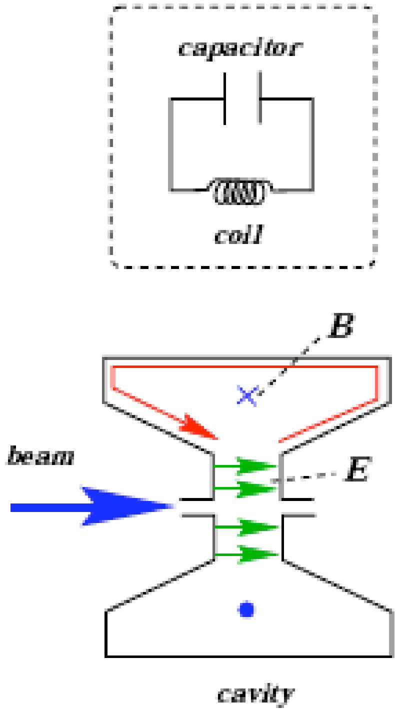


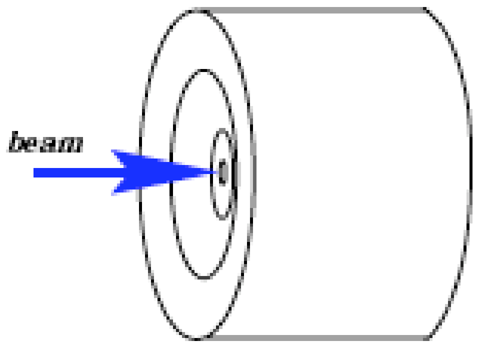
Synchronism: L = vT/2

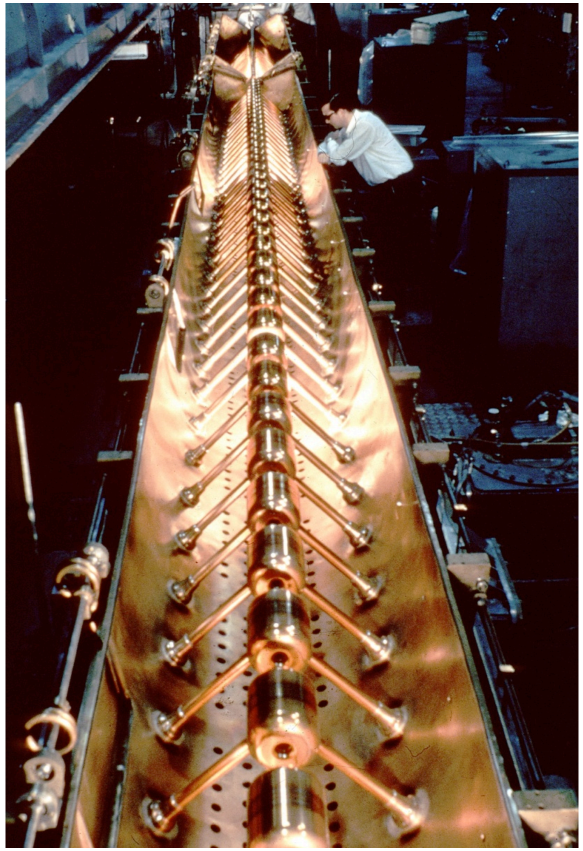
As the speed of the particles increases, the length of the drift tubes has to increase !

Resonant cavity

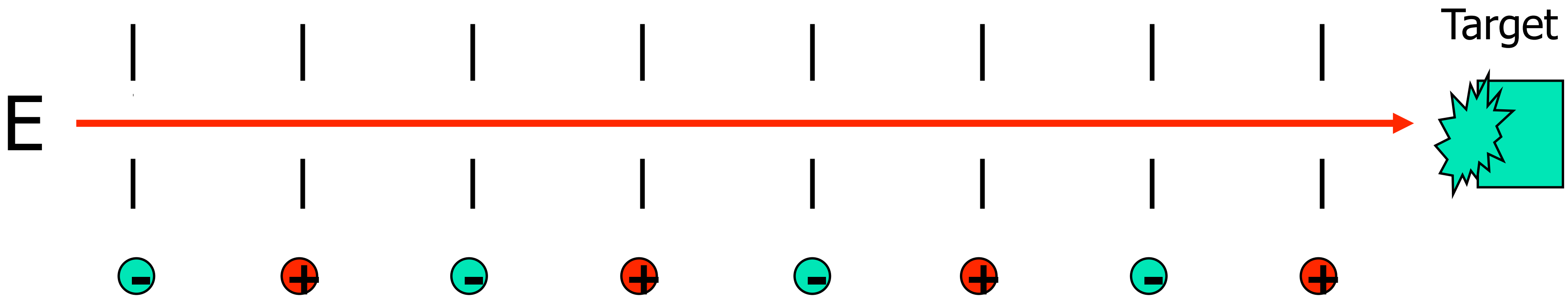
The resonance frequency of the cavity is adapted (matched) to the frequency of the RF generator







Ideal linear machines (linacs)



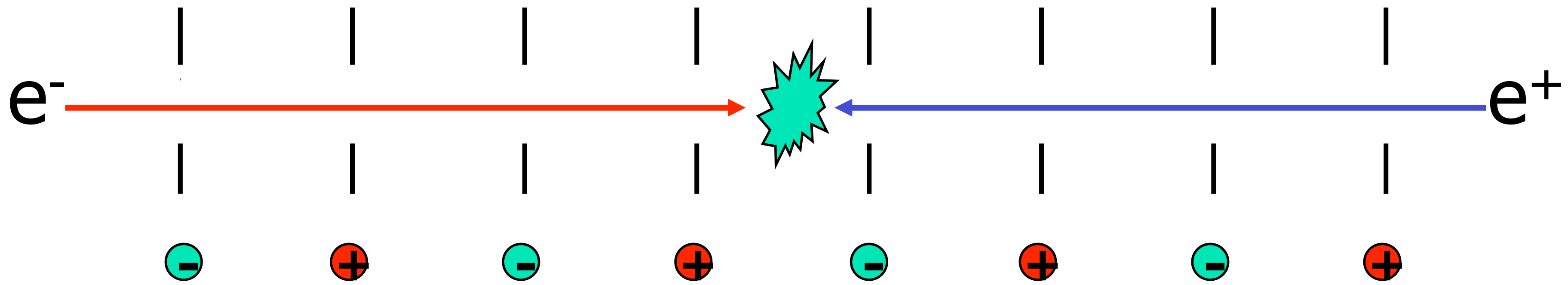
Available Energy : $E_{c.m.} = (2mE)^{1/2}$

Advantages: High intensity

Drawbacks: Single pass

Available Energy

Improved solution for $E_{c.m.}$



Available Energy : $E_{c.m.} = 2E$

Advantages: High intensity

Drawbacks: Single pass

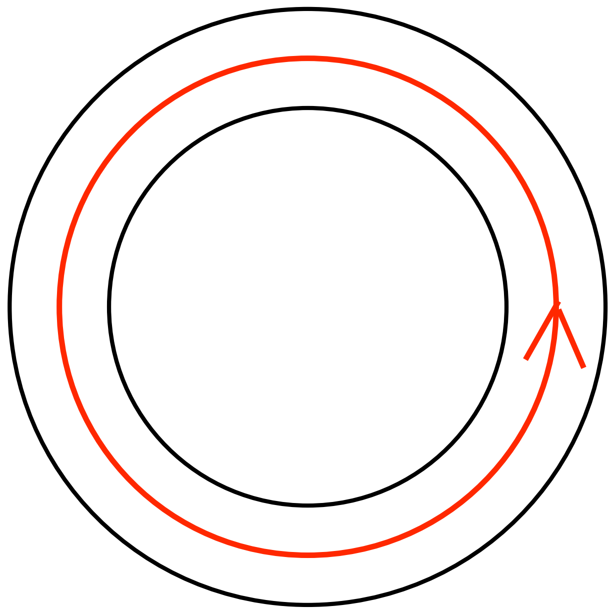
Space required

Keep particles: circular machines

Basic idea is to keep the particles in the machine for many turns.

Move from the linear design

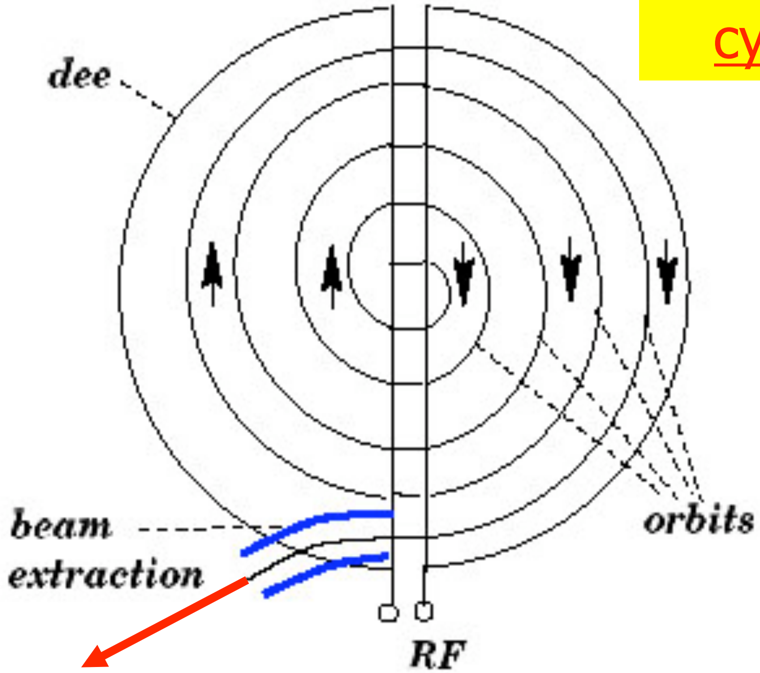
To a circular one:



- Need Bending
- Need Dipoles!

Circular machines

fixed
cyclotron



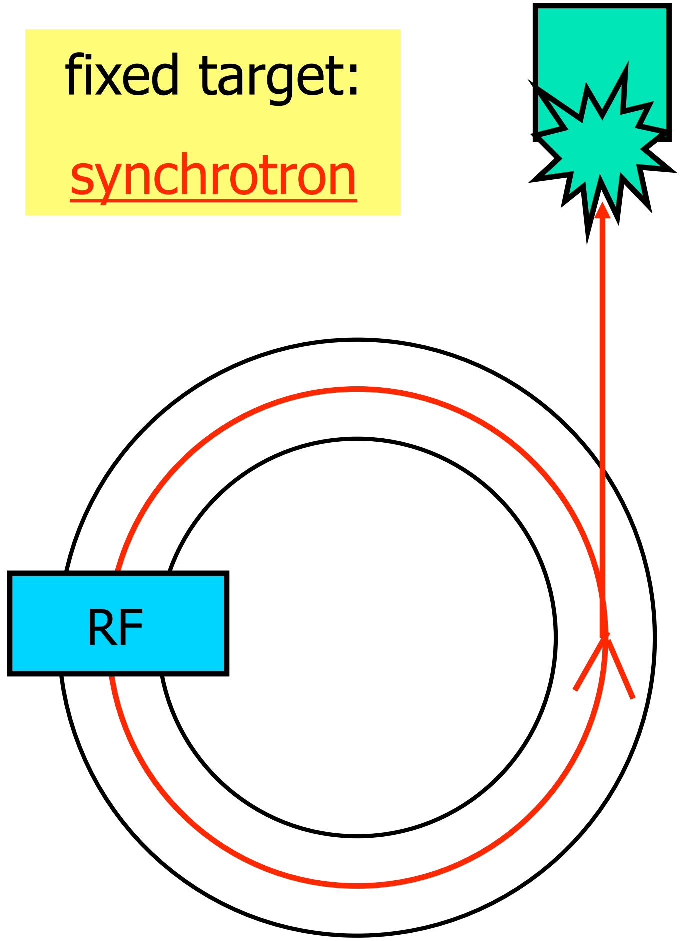
huge dipole, compact design,

B = constant

low energy, single pass.

fixed target:

synchrotron



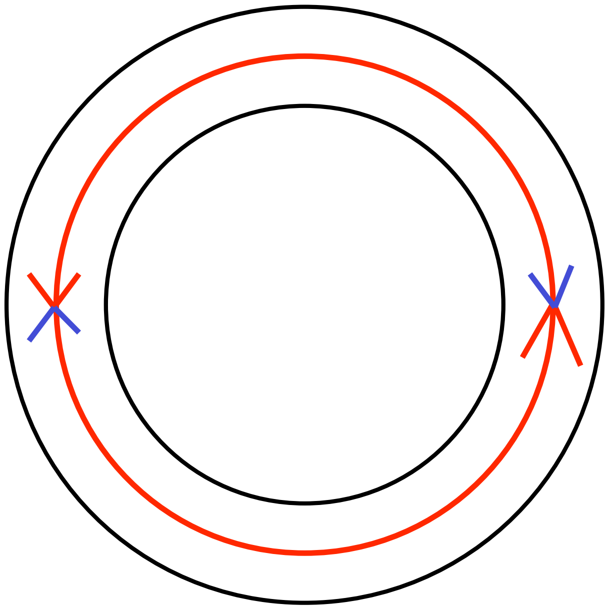
varying B, small magnets, high energy

Colliders ($E_{c.m.}$=2E)

<u>Colliders:</u>

electron – positron

proton - antiproton



Colliders with the same type of particles (e.g. p-p) require two separate chambers. The beam are brought into a common chamber around the interaction regions

Ex: LHC

4 interaction regions

How to control particle beam?

- How to accelerate particles?
  - Longitudinal beam dynamics
- How to bend particles?
  - Transverse beam dynamics
- How to make efficient collisions?

How to control particle beam?

- How to accelerate particles?
  - Longitudinal beam dynamics
- How to bend particles?
  - Transverse beam dynamics

Beam Dynamics

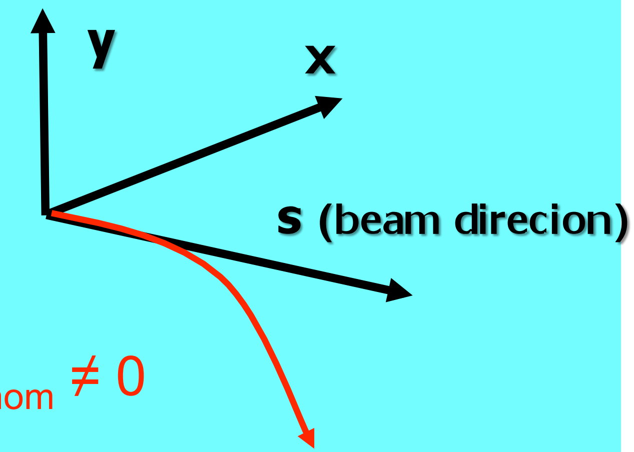
- In an accelerator designed to operate at the energy E_{nom}, all particles having $(s, E_{nom}, 0, 0, 0, 0)$ will happily fly through the center of the vacuum chamber without any problem. These are "ideal particles".

- The difficulties start when:

  - one introduces dipole magnets

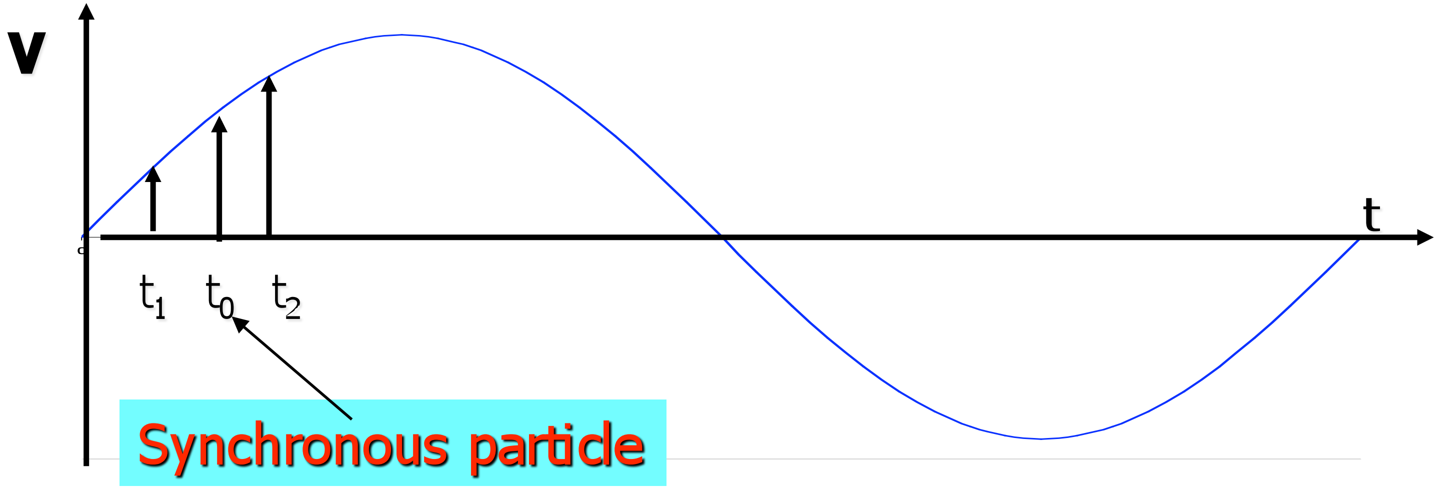
  - the energy $E \neq E_{nom}$ or $(p-p_{nom}/p_{nom}) = \Delta p/p_{nom} \neq 0$

  - either of $x, x', y, y' \neq 0$



Acceleration or compensation

- We have to provide energy to the particles either to accelerate them or to compensate for the losses accumulated during one turn.
- The ideal particle has to arrive at the cavity exactly at the same moment turn after turn (synchroneous particle).



Ideal particle arrives at t_0 ➔ $V = V_0$ ➔ o.k.

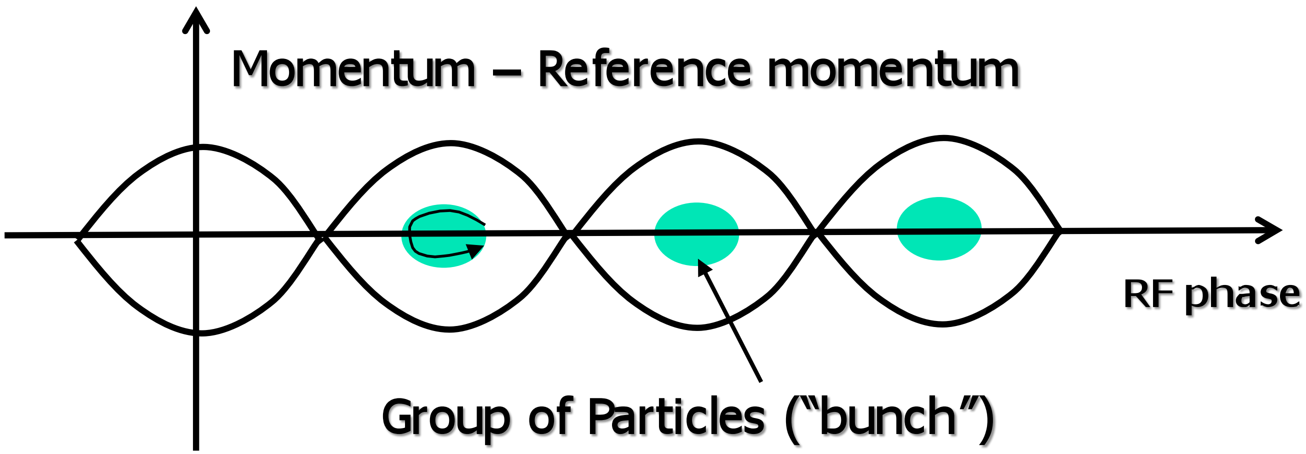
$\Delta p/p > 0$ ➔ t_1 ➔ $V_1 < V_0$ (smaller kick)

$\Delta p/p < 0$ ➔ t_2 ➔ $V_2 > V_0$ (bigger kick)

The bunches of particles:

The RF system creates bunches of particles

With $f_{RF} = h \cdot f_{rev}$, we could thus have "h" bunches of particles circulating in the machine.



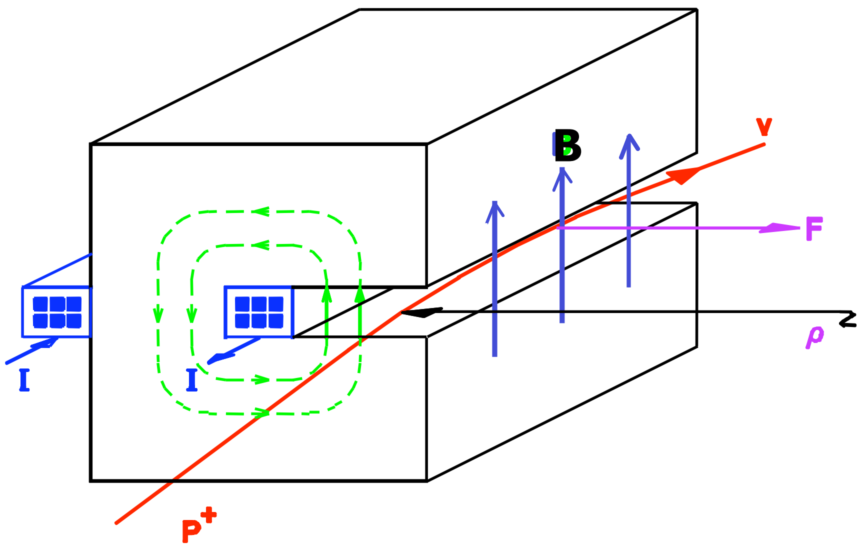
LHC: h= 35640

f_{RF} = 400 MHz

V_{RF} = 16 MV

2808 bunches per beam

Circular machines: Dipoles



Classical mechanics:

Equilibrium between two forces

Lorentz force

$F = e.(\underline{v} \times \underline{B})$

Centrifugal force

$F = mv^2/\rho$

$evB = mv^2/\rho$

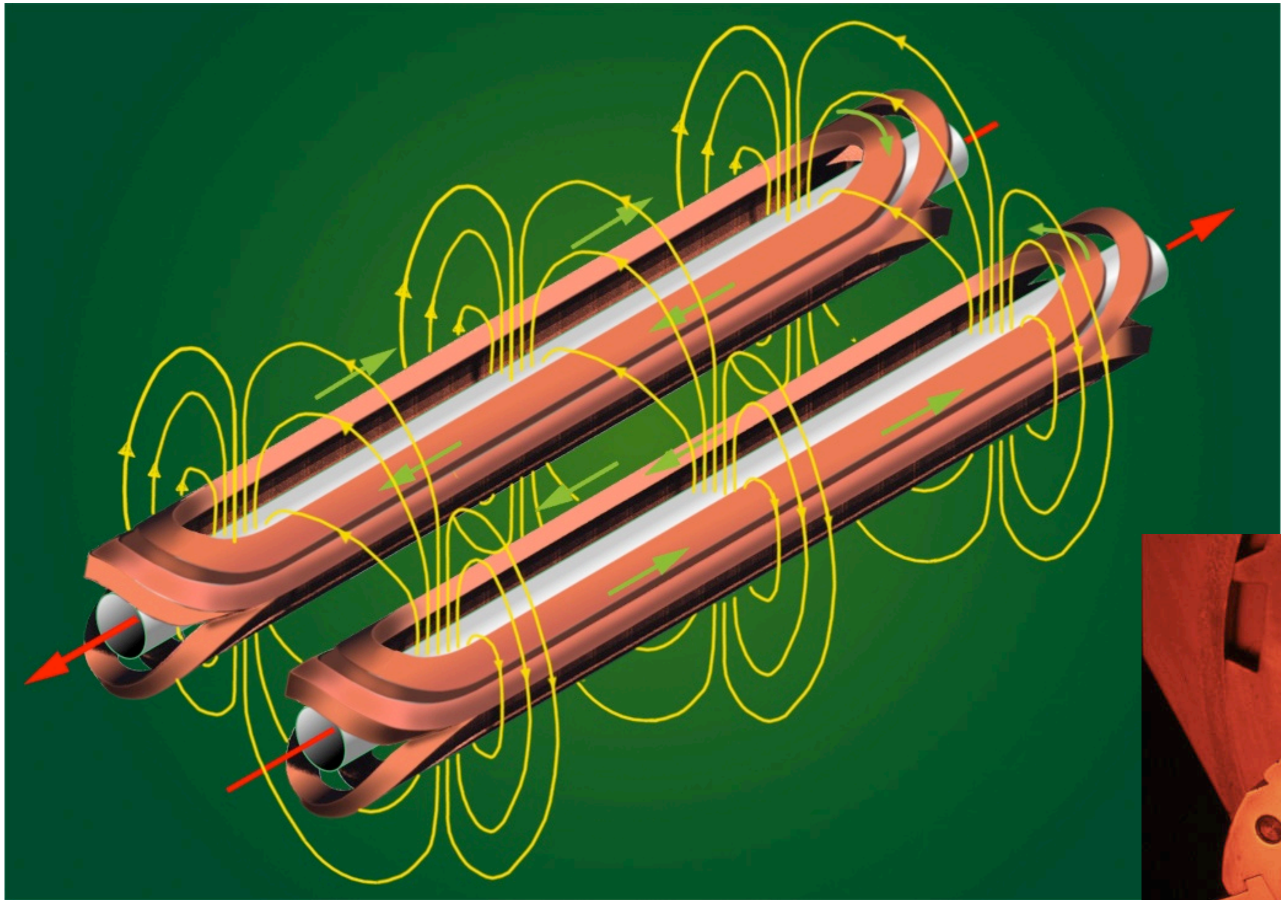
$p = m_0.c.(\beta\gamma)$

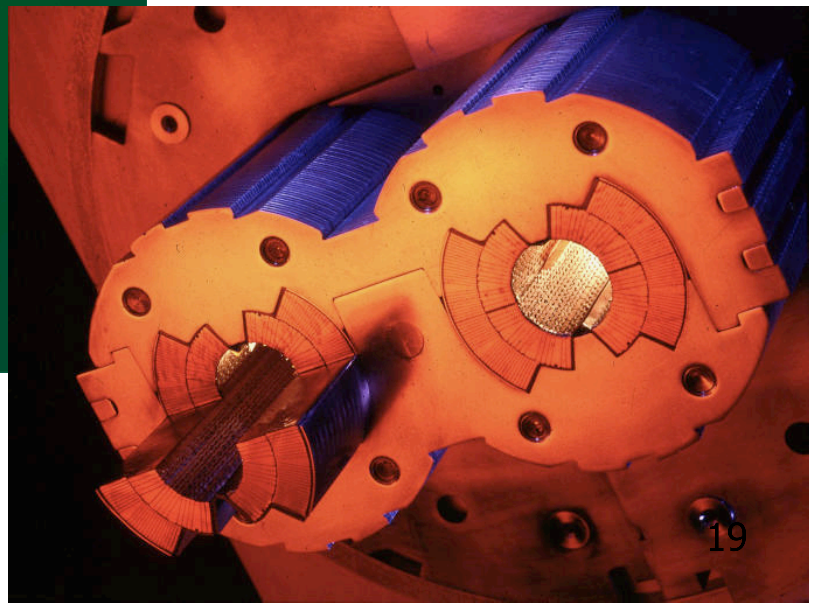
Magnetic rigidity:

$B\rho = mv/e = p/e$

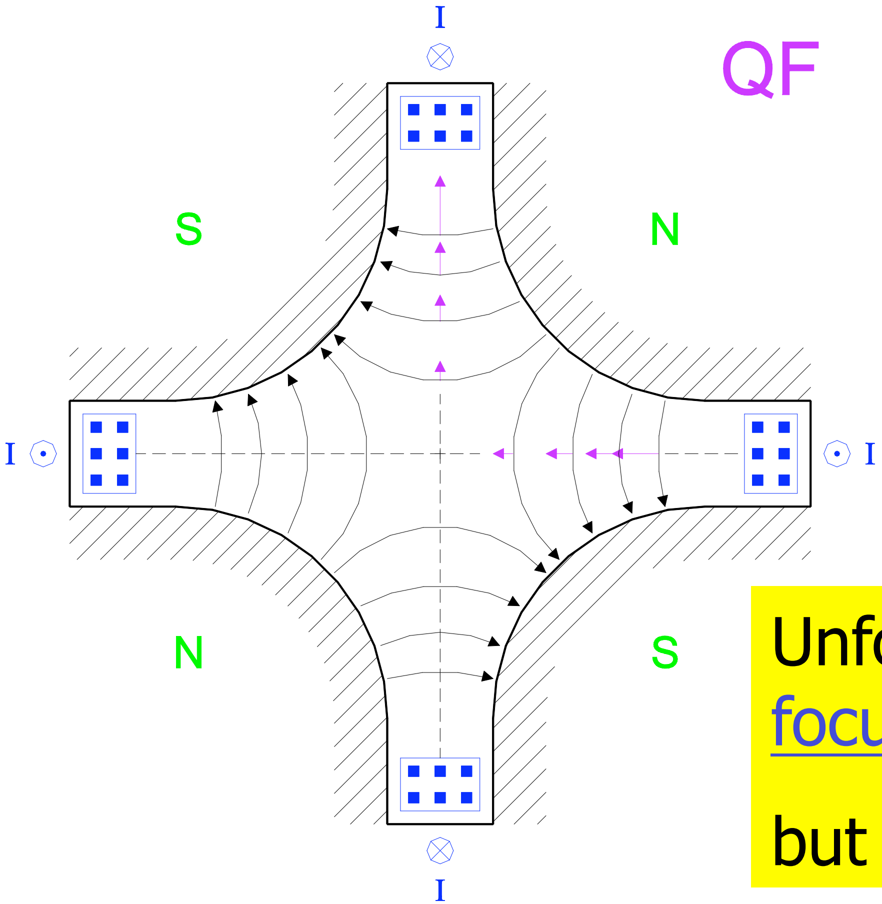
Relation also holds for relativistic case provided the classical momentum mv is replaced by the relativistic momentum p

Dipole magnet for the LHC





Focusing with quadrupoles



$F_x = -g.x$

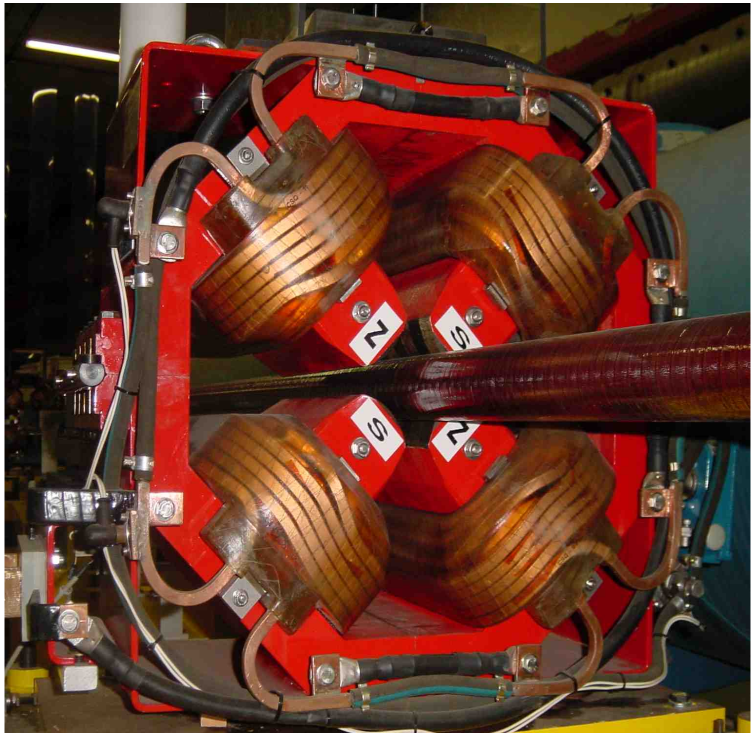
$F_y = g.y$

Force increases linearly with displacement

Unfortunately, this quadrupole is focusing in the horizontal plane

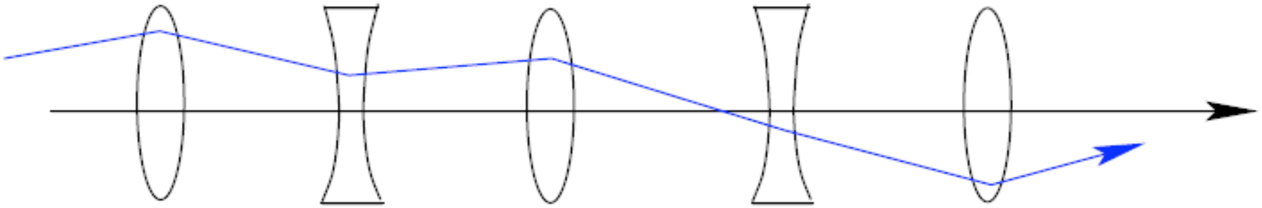
but defocusing in the vertical plane!

Quadrupoles:

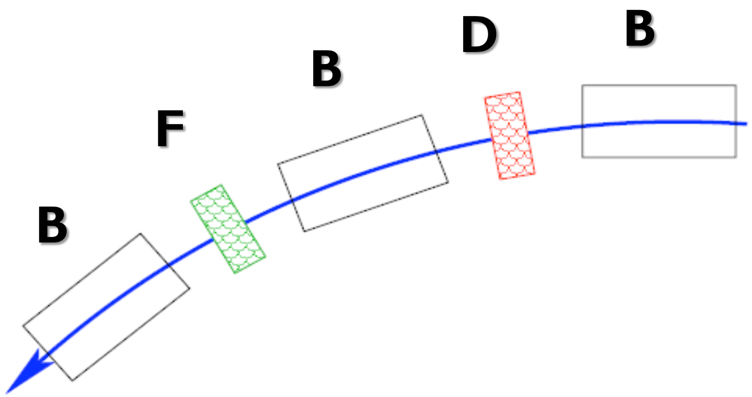


Alternating gradient focusing

"Alternate gradient focusing" gives an overall focusing effect (compare optical systems in cameras)



Synchrotron design: FODO



Synchrotron

- Energy depends on orbit and B field:

  To accelerate the particles, the magnetic field has to increase and the frequency has to be adjusted to keep the particles on the reference trajectory

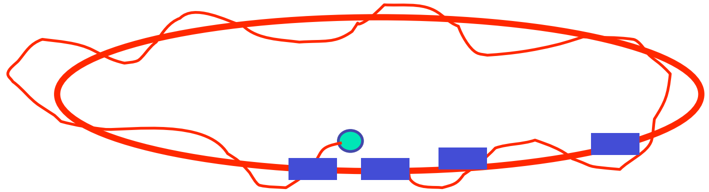
- The particles oscillate around the closed orbit

$$y(s) = \sqrt{A \cdot \beta} \cdot \sin\left(\frac{2\pi}{L} \cdot Q \cdot s + \phi_0\right)$$

amplitude term due to injector

amplitude term due to focusing

sorage ring circumference



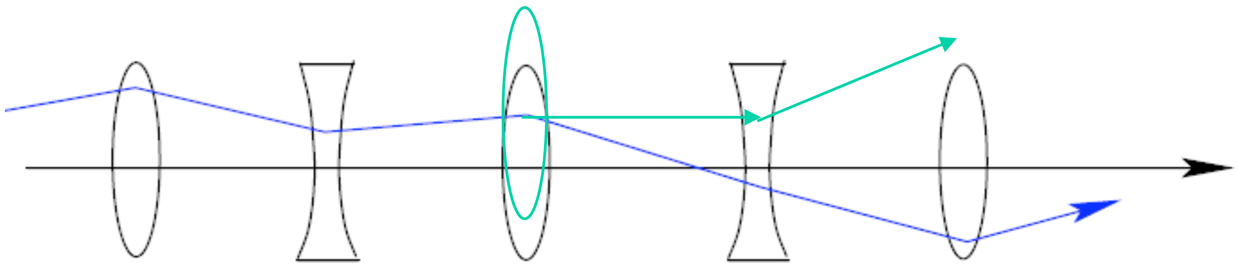
- Q ("tune"): number of oscillations per turn
- Q values are slightly different in two planes

LHC: Q_x = 64.31

Q_y = 59.32

Orbit Errors

- The magnets are not perfect, in addition they cannot be perfectly aligned
- For the quadrupoles, the force that the particles feel is either too large or too small with respect to the theoretically calculated force. Effect: the whole beam is deviated
- The field felt by a particle may come not only from the magnetic elements but also from the other particles (coulomb field): space charge
- Use small dipole magnets (or sextupole) to correct the orbit

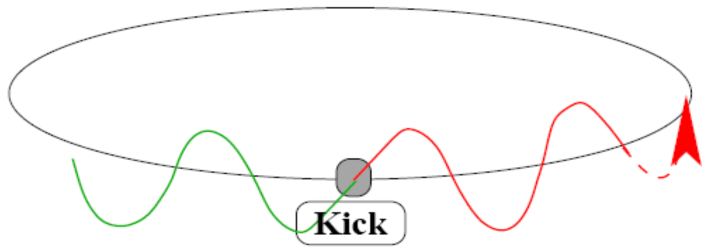


Sources for orbit errors

- Ground motions
  - Movement of the surface of the earth
  - Trains
  - The moon
  - The seasons
  - Construction work
- Error in magnet strength
- Error in particle energy

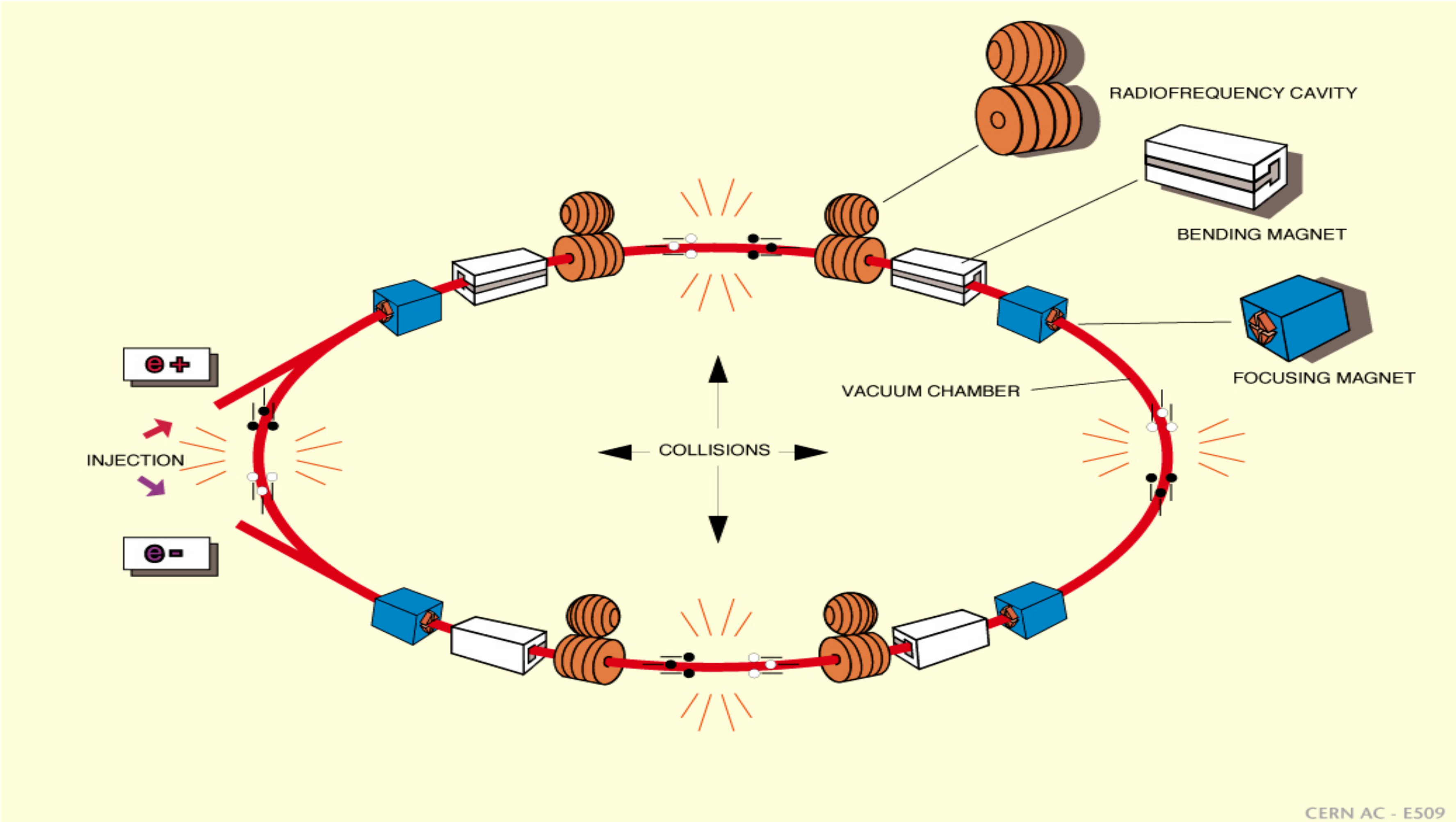
Orbit stability

- Dipole kick error:
  - The perturbations add up for Q=n(integer): need to avoid integer tune



  - Q=n+0.5: will this work?

Basic high energy collider:

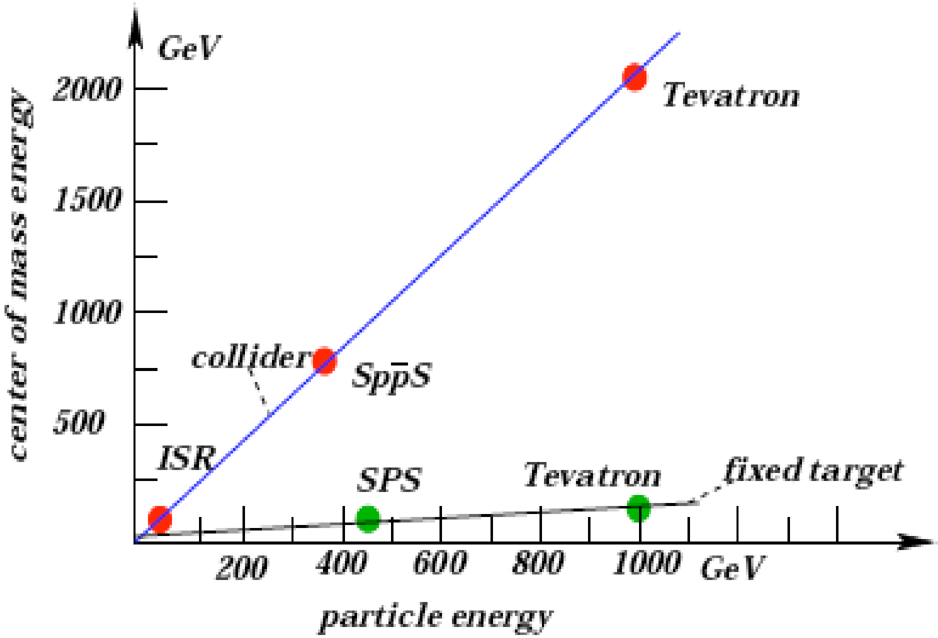


Lepton vs Hadron Collider

- *Leptons:* (e^+ / e^-)
  - *elementary particles*
    - → *well defined energy*
- *Hadrons:* (p^+ / $\bar{p}$)
  - *multi particle collisions*
    - → *energy spread*
    - → *discovery potential*
- *Example:*

Z_0	1985 $Sp\bar{p}S$	p^+p^-
	1990 LEP	e^+e^-

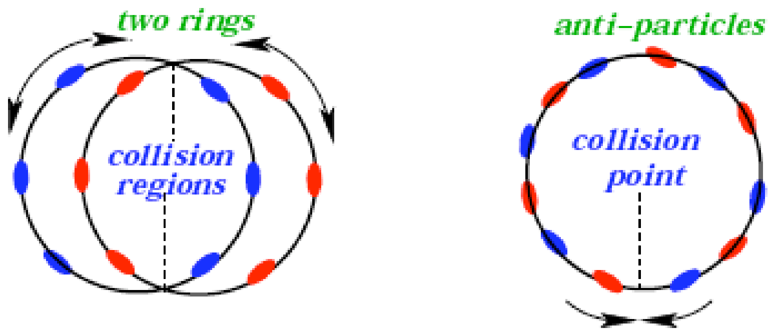
Particle colliders



not all particles collide in one crossing

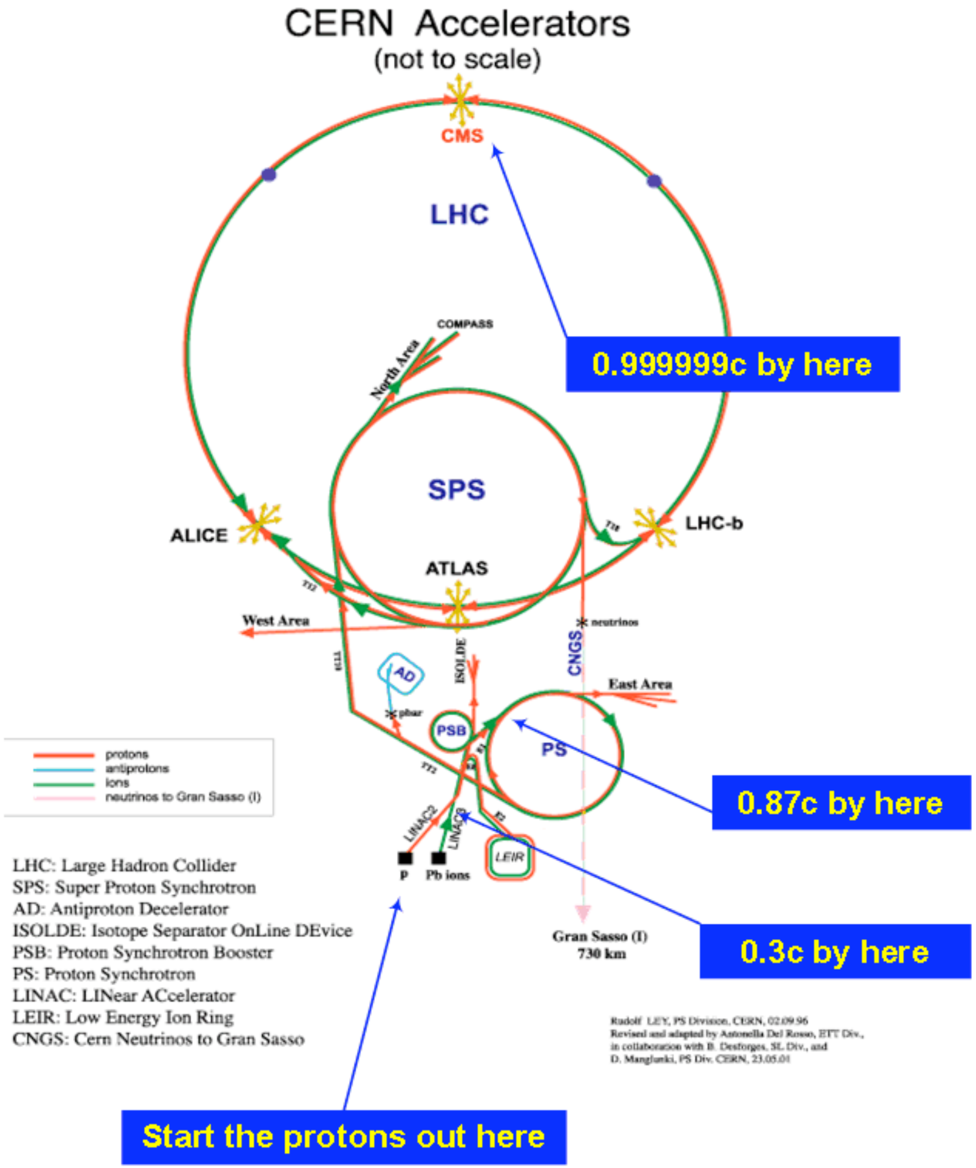
→ *long storage times*

requires 2 beams:



→ *anti-particles hard to produc*

LHC accelerator



Energies:

Linac	50 MeV
PSB	1.4 GeV
PS	28 GeV
SPS	450 GeV
LHC	7 TeV

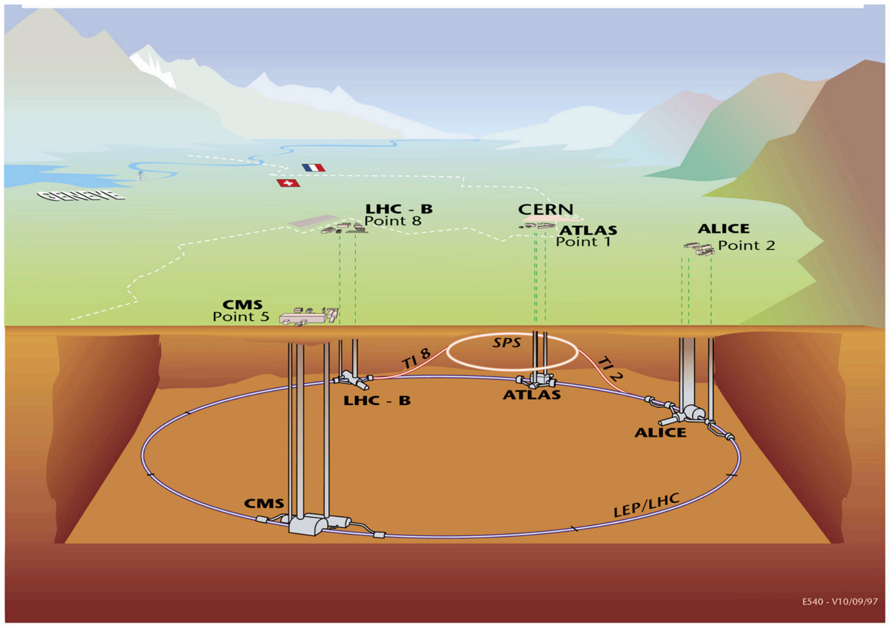
The LHC Project was started from the Lausanne Workshop in March 1984. The final approved in 1994

Choices for the LHC

- Proton-proton collider
- Super conducting RF
- R=2784 m:
- Super conducting magnet technology: B_{max} = 8.38T
- FODO lattice
- 2 beams in 1 magnet design
- 2808 bunches with 10^{11} particles per bunch:
  event rate = 10^9 events/second
- Cryo pump at 2K temperature

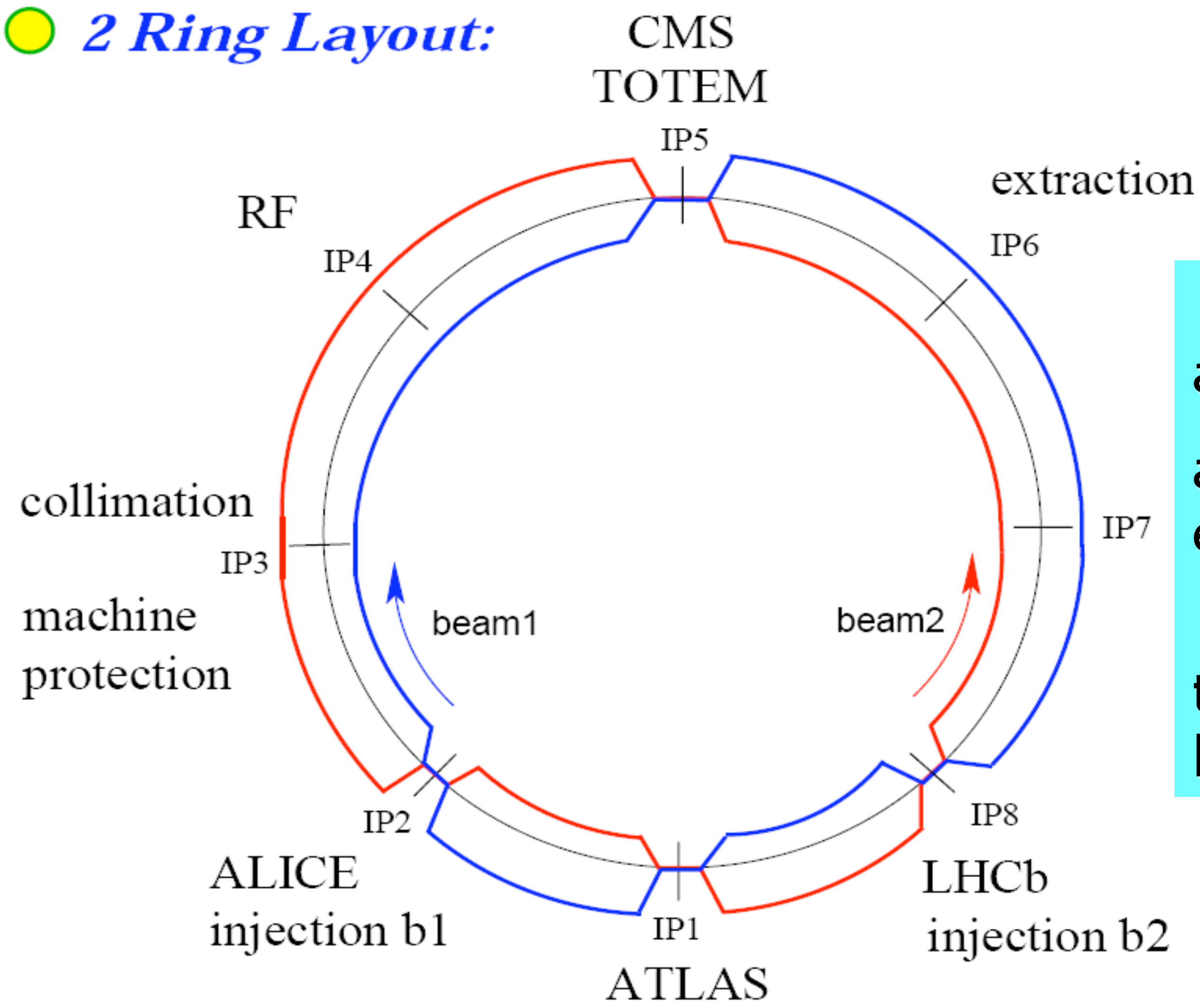
The LHC

- The largest machine that has even been built, and probably the most complex one: energy stored in one beam: 360 MJoule (10GJoule in the magnet system, like Airbus 380 with 700km/h)
- To make the LHC a reality: EM, relativity, mechanics thermodynamics, nonlinear physics, solid state physics, particle physics, and vacuum physics



LHC insertions:

- *2 Ring Layout:*



Create special zones around the experiments:

a straight section with the experiment in the middle

Section with quadrupoles to strongly squeeze the beam

Why Superconducting magnet?

- *LEP:*

B = 0.135 Tesla

$$P = R \cdot I^2$$

I = 4500A; R = 1mΩ → P = 20 kW / magnet

ca. 500 magnets → P = 10 MW

- *LHC:*

$$B \propto I$$

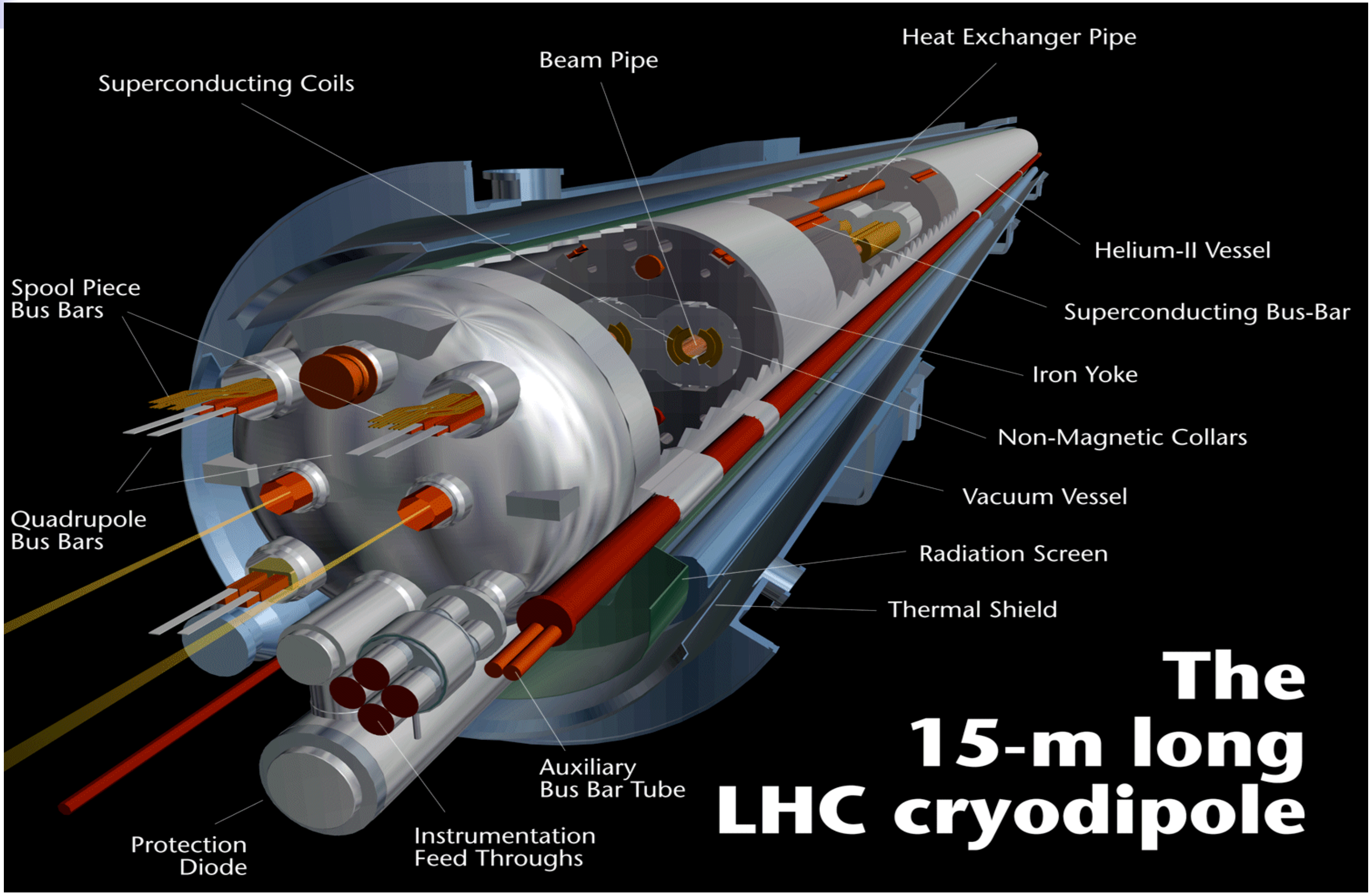
→ B_{max} = 8.38 T → I = 280000 A

→ P = 78 MW / magnet

ca. 500 magnets → P > 39 GW

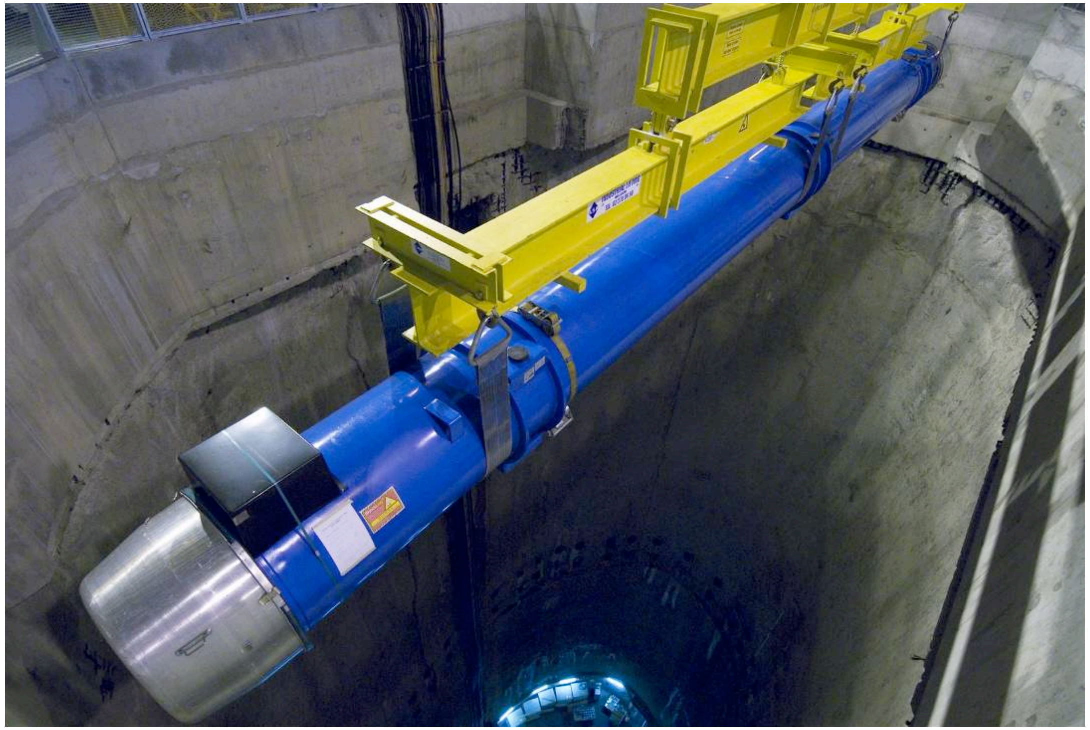
→ ***superconducting technology!***

The Superconducting Dipole for LHC

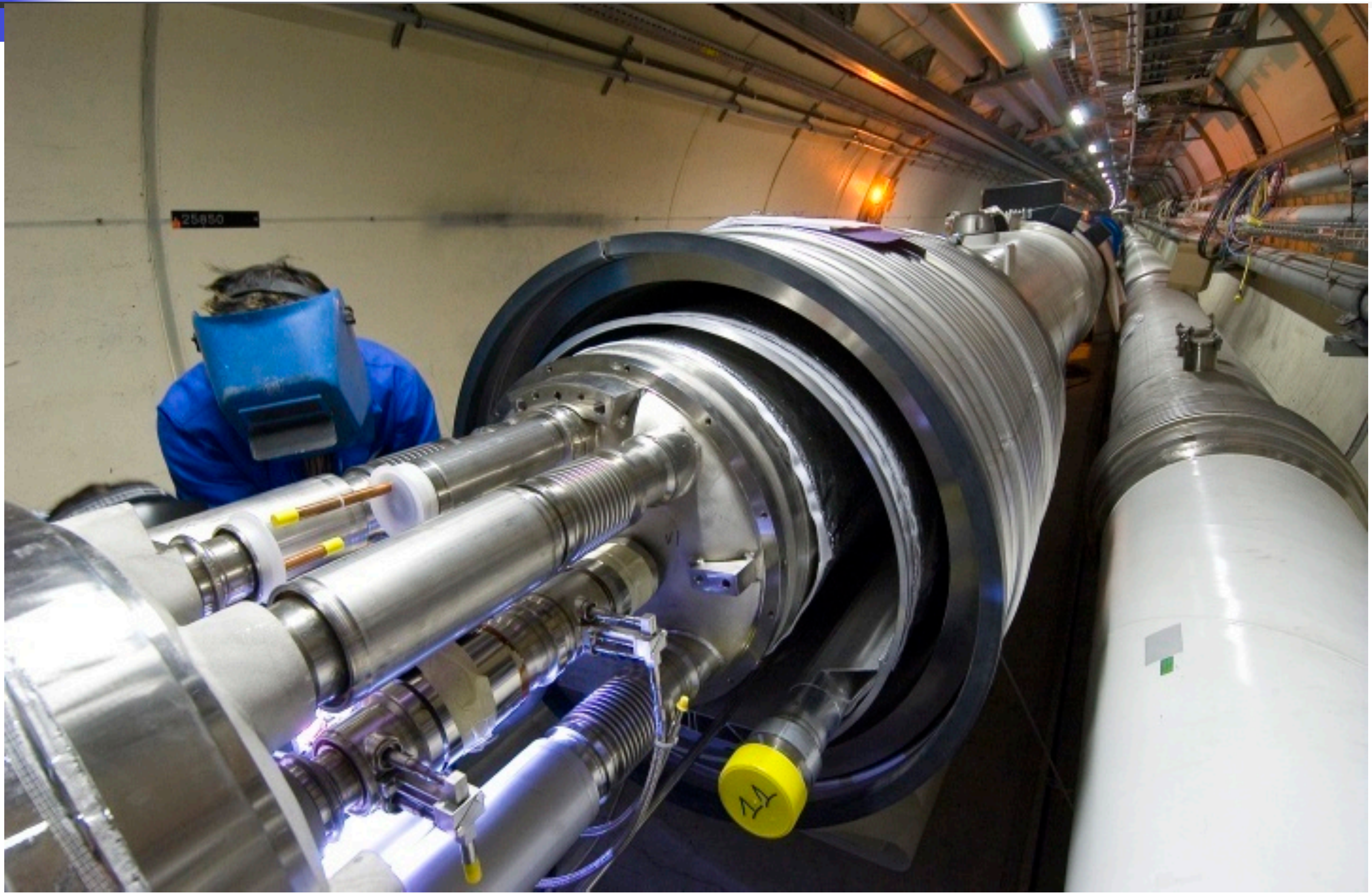


Working temperature 2.1 K
coldest spot in the galaxy

The last magnet 26 Apr. 2007



Dipole dipole interconnect



10 September 2008

Collider: the luminosity

$$dN/dt = L \times \sigma$$

$[1/s] = [1/(cm^2.s)] \times [cm^2]$

Beam sizes !

$$L = N_1.N_2.f.k/(4.\pi.\sigma_x.\sigma_y)$$

with:

$N_{1,2}$ = Number of particles per bunch (1.15×10^{11})

f = révolution frequency (11.245 kHz)

k = number of bunches (2808)

$\sigma_{x,y}$ = horizontal and vertical beam size (17 μm)

$L = 10^{34}\ 1/(cm^2.s)$

Synchrotron radiation

- Charged particles bent in a magnetic field emit synchrotron radiation!

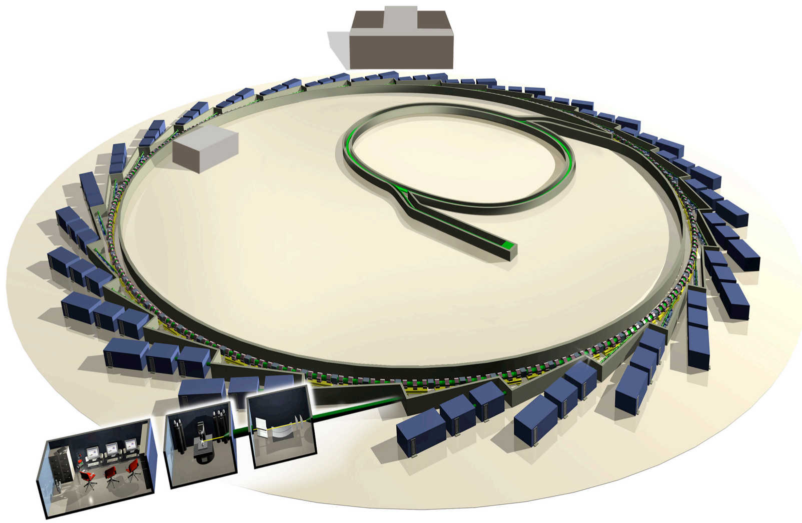
Energy loss:

$eU_0 = A \cdot \gamma^4 / \rho$

$(m_p/m_e)^4 = (1836)^4 \cong 10^{13}$

Collider	B (T)	E/beam (GeV)	γ	eU_0 (GeV)
LEP ($e^+ e^-$)	0.12	100	196000	2.92
LHC (p-p)	8.3	7000	7500	0.00001

Synchrotron Light Source



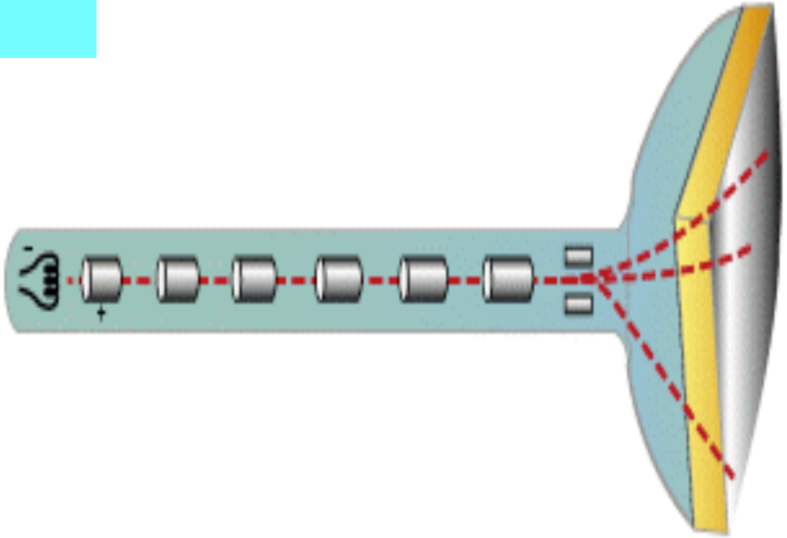
DIAMOND, Rutherford Lab

Future Accelerators

- LHC upgrade: higher beam E, one order of higher lum.
- Linear colliders:
  - International Linear Collider (ILC), 35 km, 500 GeV, electron-positron
  - Compact Linear Collider (CLIC), 38 km, 3 TeV, electron-positron
  - Muon collider

Domestic applications:

Your TV set…



is a small accelerator !

Medical applications

PET Tomography

University Hospital Geneva

Light Ion Cancer Therapy

Gantry at PSI , Villigen (CH)

Accelerators around the world

Basic and Applied Research		Medicine	
High-energy phys.	120	Radiotherapy	7500
S.R. sources	50	Isotope Product.	200
Non-nuclear Res.	1000	Hadron Therapy	20
Industry			
Ion Implanters	7000		
Industrial e- Accel.	1500	Total:	17390