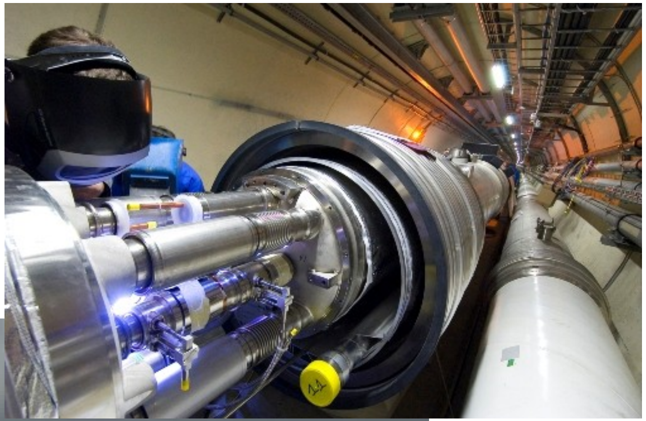
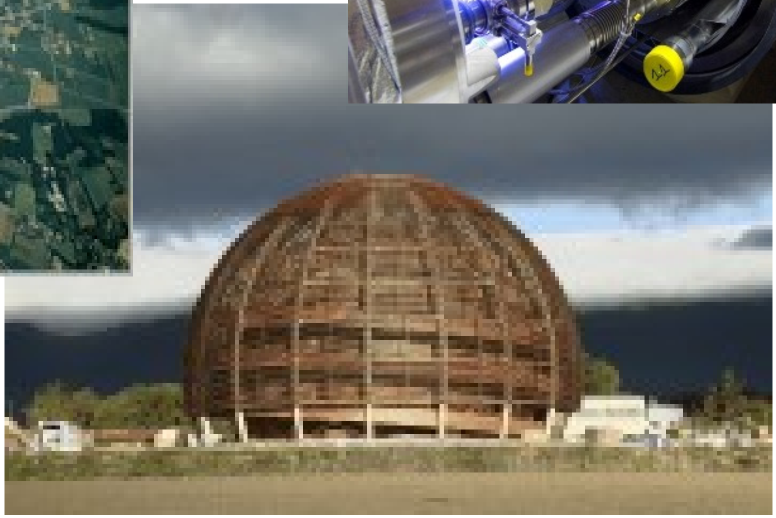
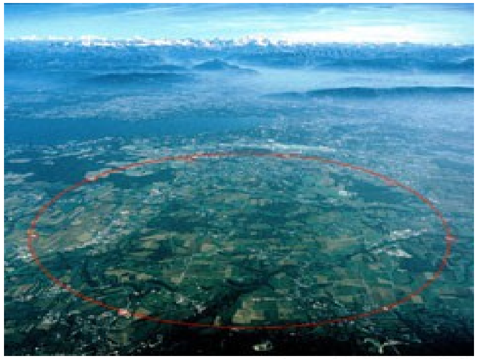
Introduction to Accelerators
Elena Wildner BE/ABP





Contents



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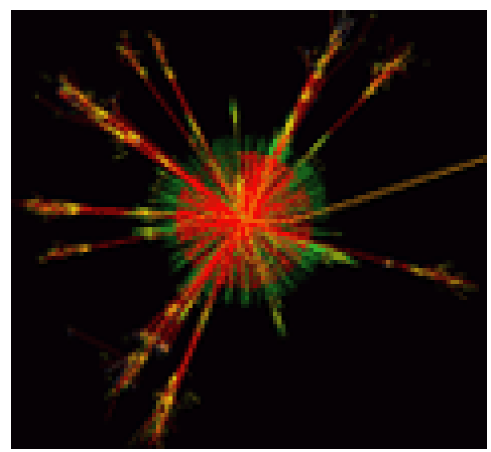
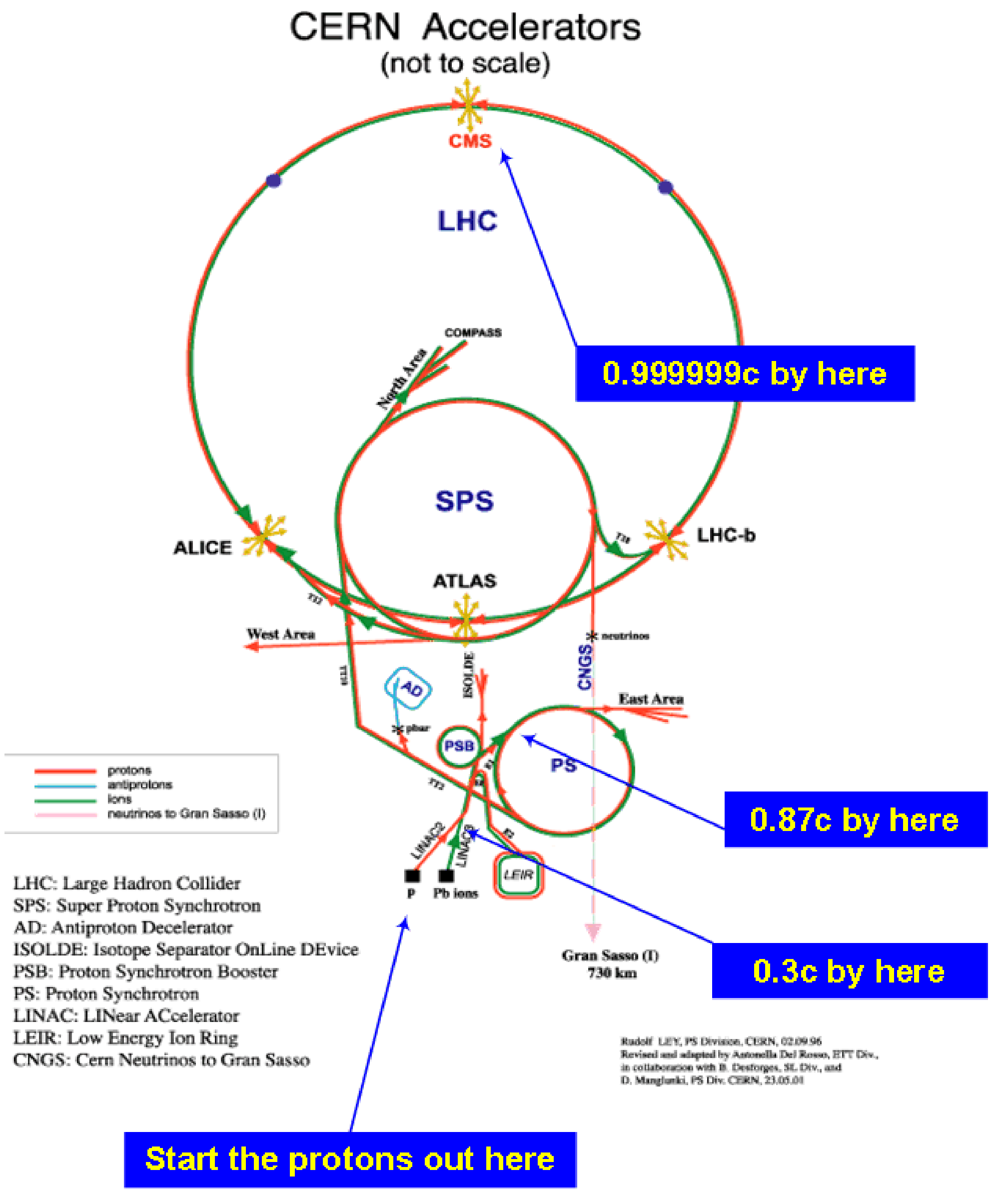
Application Areas

- In your old TV set: Cathode Tube
- Material Physics
  - Photons from Electrons,
  - Synchrotron Light
  - Material Surface
- Medicine
  - X-rays, synchrotron Radiation
  - Protons and Ions
- Food treatment
- Physics
- Etc.



Accelerators and LHC experiments at CERN

INTRODUCTION



Energies:

Linac 50 MeV

PSB 1.4 GeV

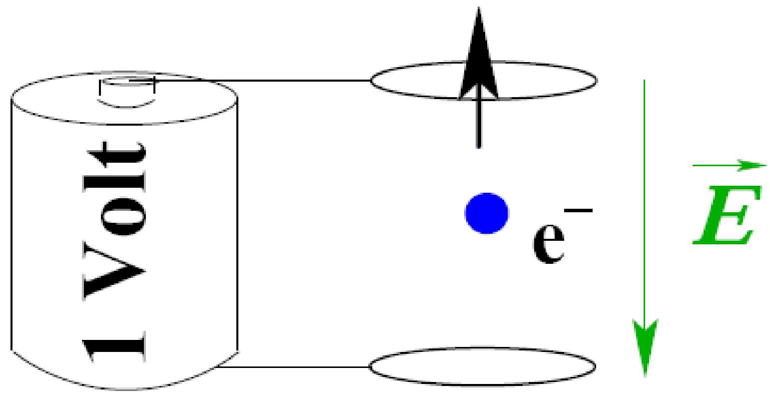
PS 28 GeV

SPS 450 GeV

LHC 7 TeV

Units?

Units: Electronvolt



Electronvolt, unit for energy denoted by eV, is used for small energies (joule)

1 eV is defined as the energy needed to move one electron, with charge e e (around $1.602 \cdot 10^{-19}$ C) in an electrical field with the strength 1 V/m a distance of 1 meter:

1 eV = $1.602 \cdot 10^{-19}$ joule.

Acceleration

In particle physics the unit eV is also used as a unit for mass since mass and energy are closely coupled through the relationship:
$E = mc^2$, $m=\gamma * m_0$
m is the particle mass and c the speed of light in vacuum.
The mass of one electron, having a speed of v << c is around 0.5 MeV.

Total energy

From Wikipedia

Relativity

When particles are accelerated to velocities (v) coming close to the velocity of light (c):

then we must consider relativistic effects

$$\boxed{\gamma = 1/\sqrt{1-\beta^2}\,;\quad \beta = v/c}$$

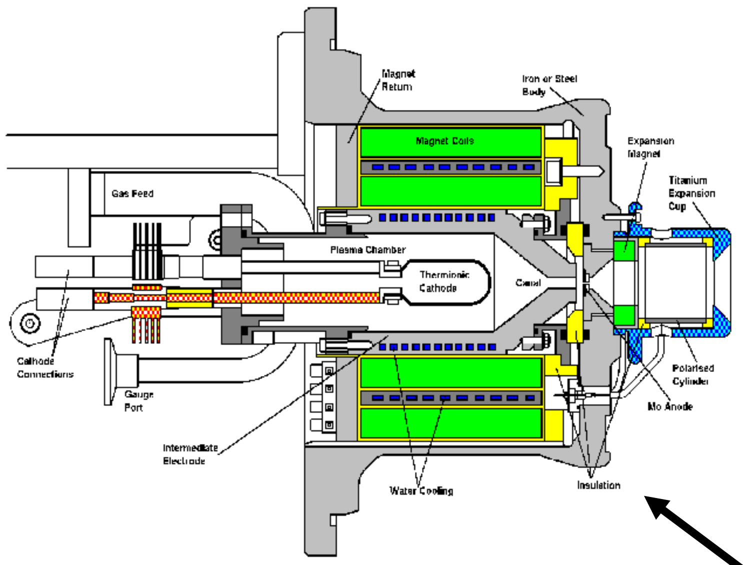
$$E = mc^2\,;\, m = \gamma * m_0$$

Total Energy **Rest Mass**

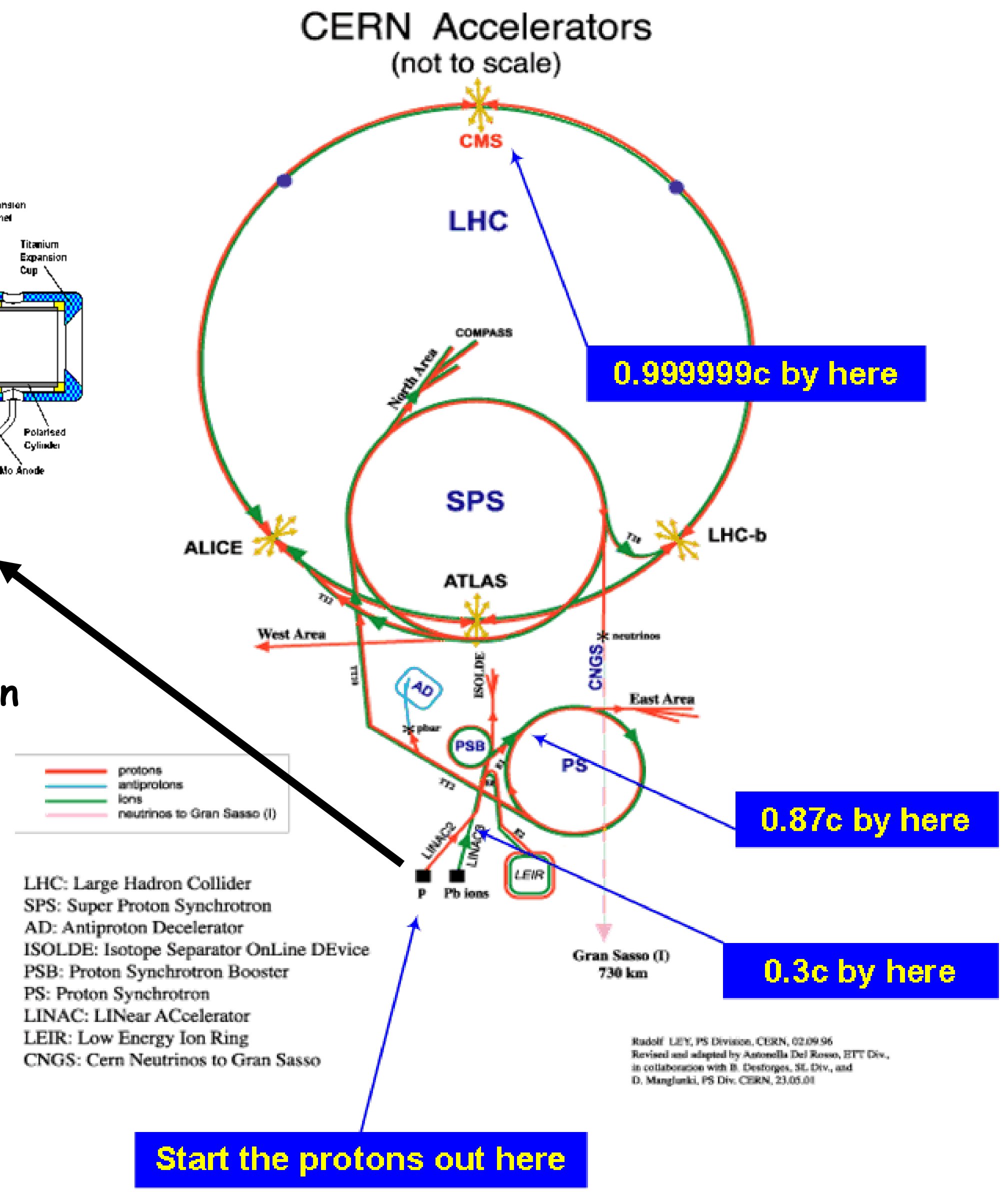
Particle Sources and acceleration

- Natural Radioactivity: alfa particles and electrons. Alfa particles have an energy of around 5 MeV (corresponds to a speed of ~15,000 km/s).
- Production of particles: Particle sources
- Electrostatic fields are used for the first acceleration step after the source
- Linear accelerators accelerate the particles using Radio Frequency (RF) Fields
- Circular accelerators use RF and electromagnetic fields. Protons are today (2007+) accelerated to an energy of 7 TeV
- The particles need to circulate in vacuum (tubes or tanks) not to collide with other particles disturbing their trajectories.

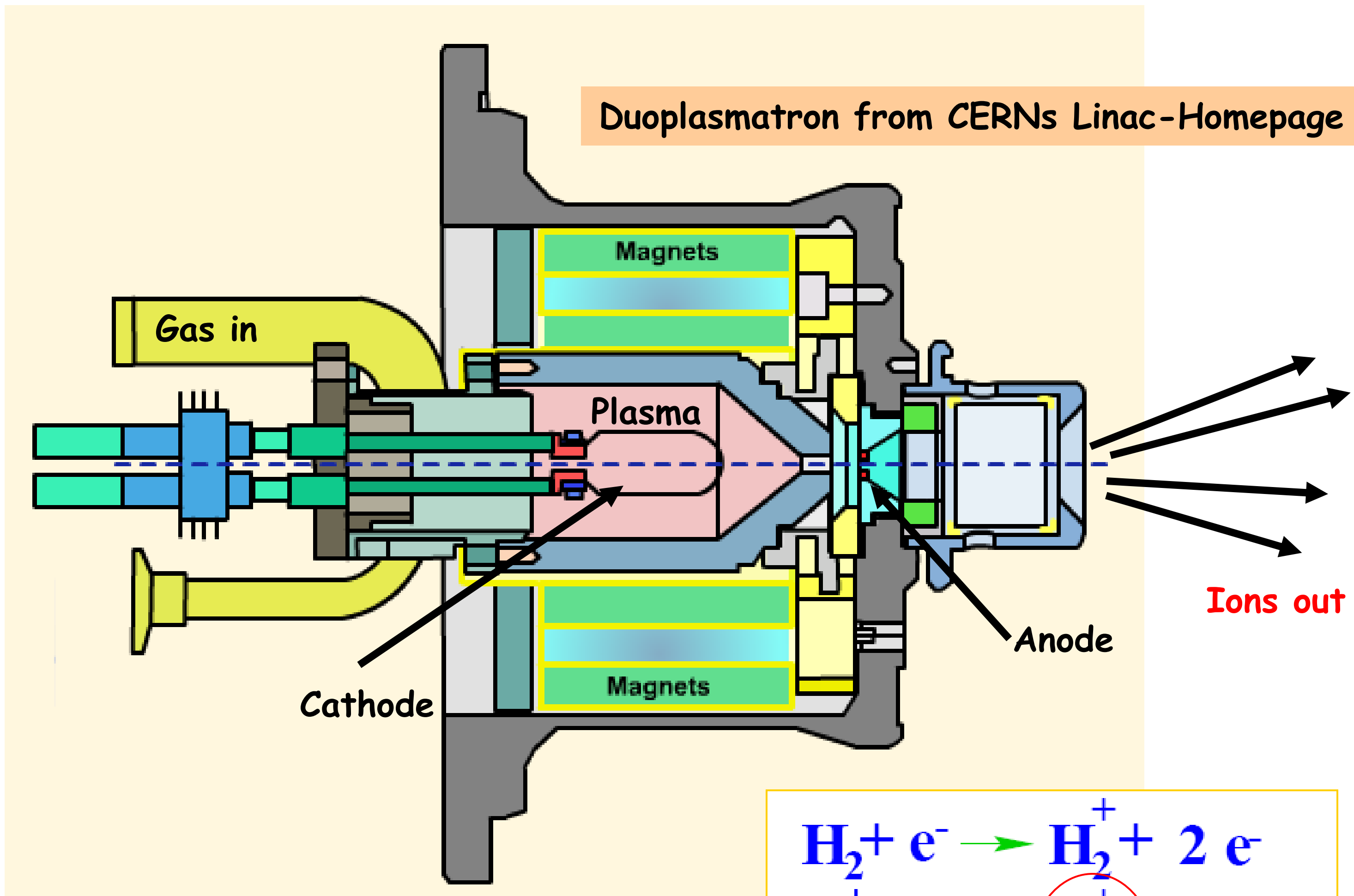
Particle Sources 1



Duoplasmatron for proton production



Particle Sources 2



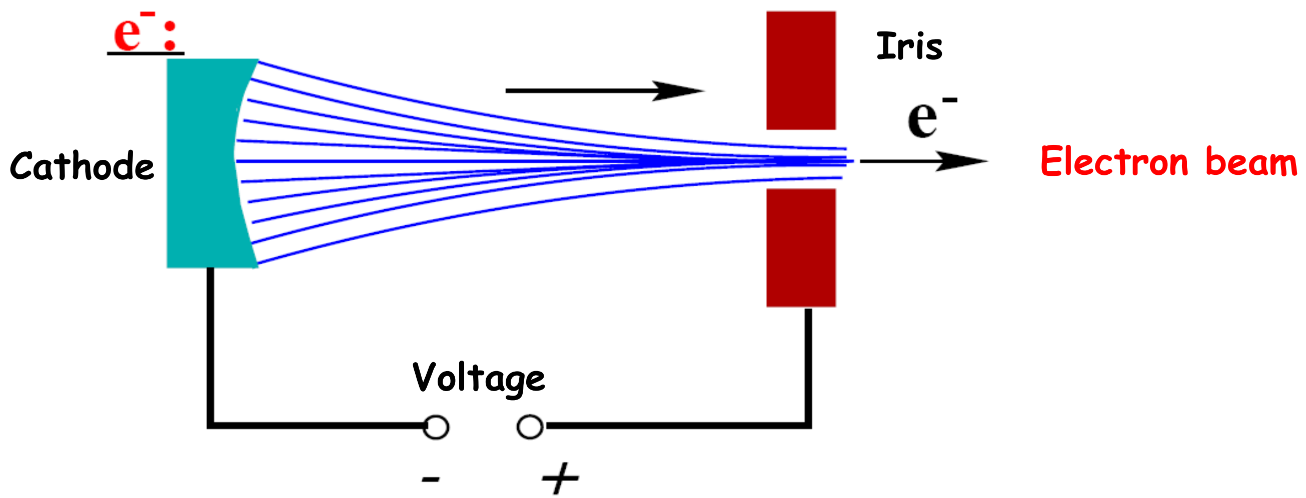
$$H_2 + e^- \rightarrow H_2^+ + 2\,e^-$$

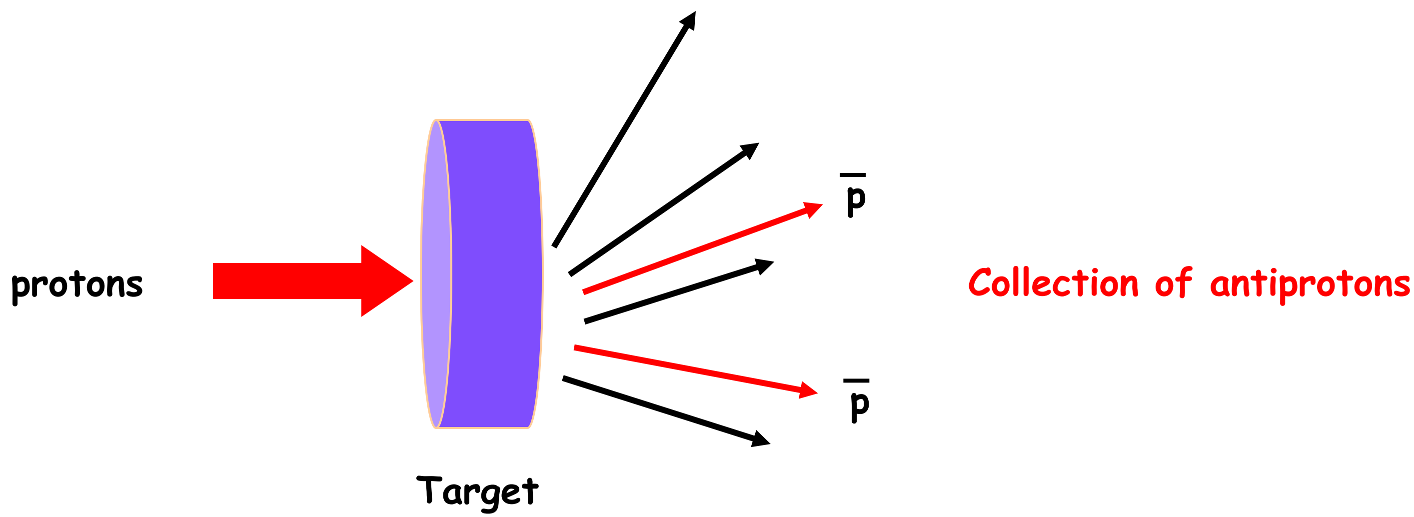
$$H_2^+ + e^- \rightarrow H^+ + H + e^-$$

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

Particle Sources 3

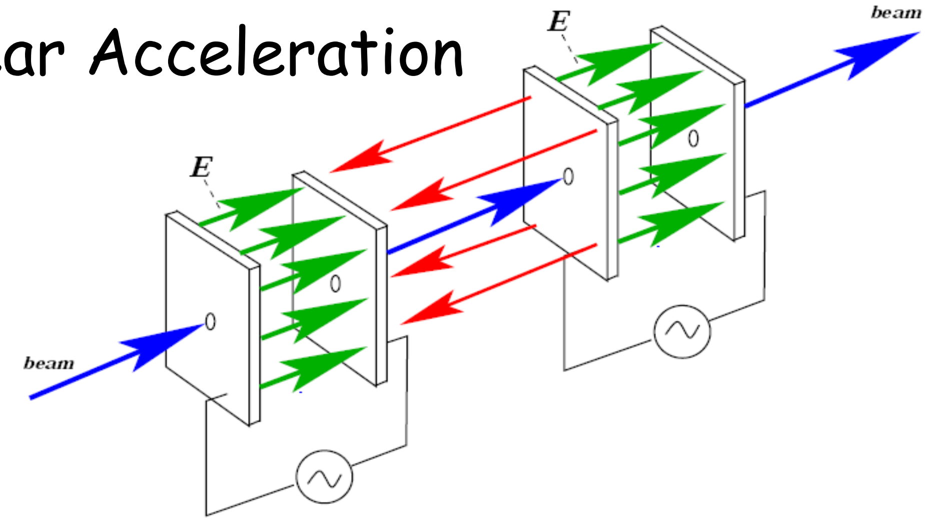
THE ACCELERATOR CHAIN



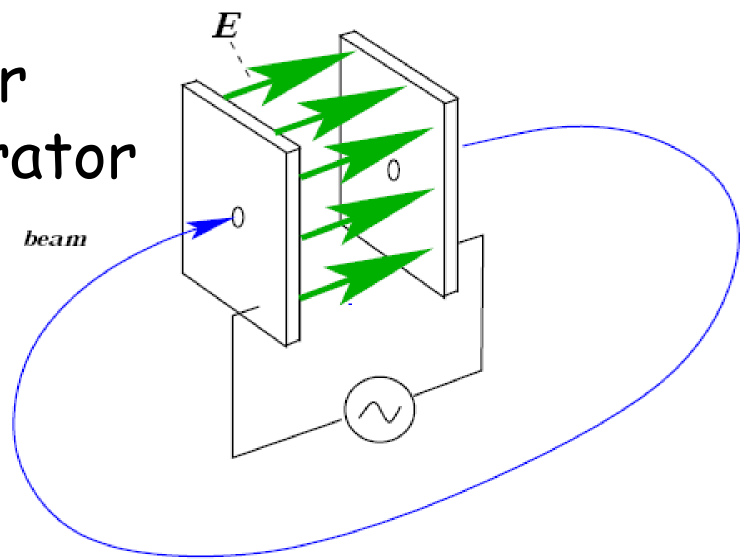


Time Varying Electrical Fields

Linear Acceleration



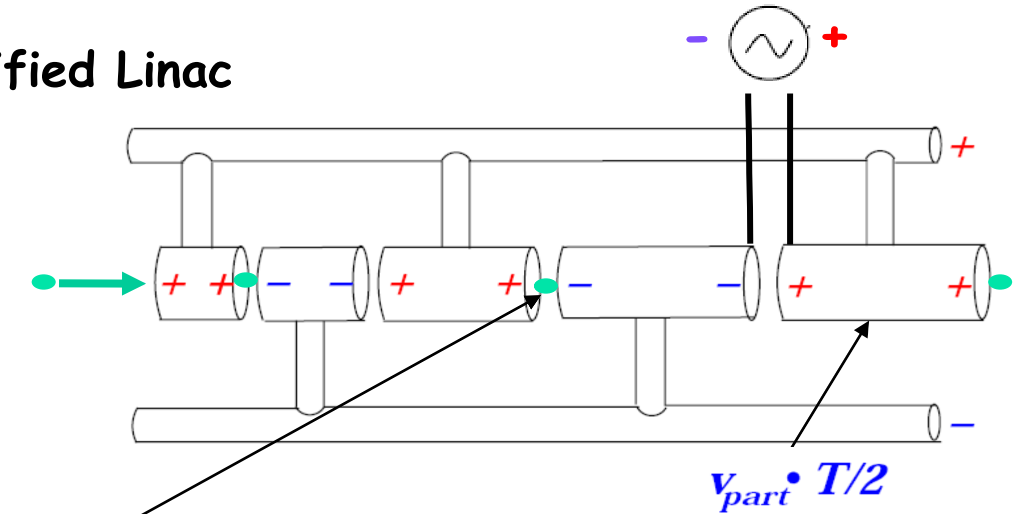
Circular accelerator



Linear accelerators

THE ACCELERATOR CHAIN

Simplified Linac

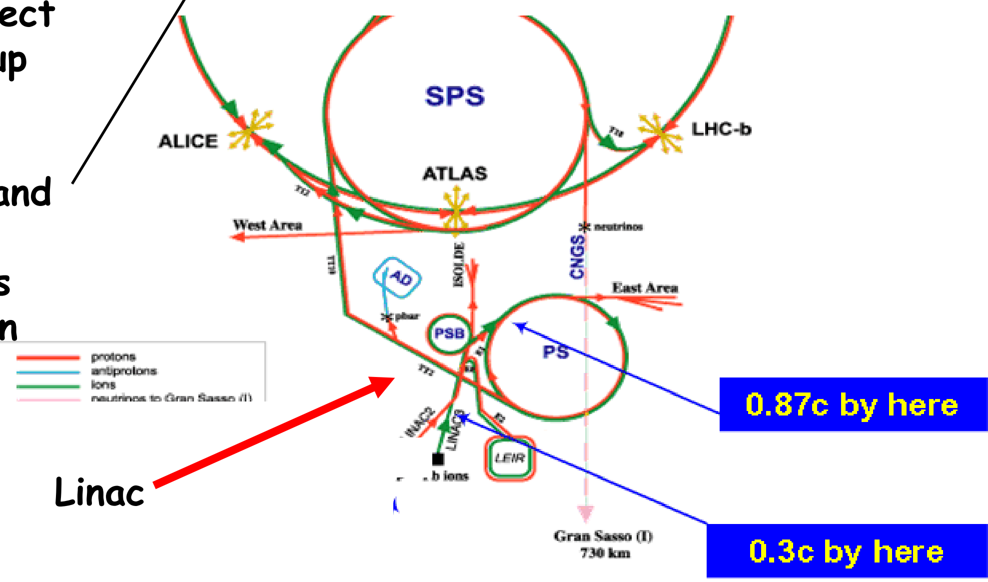


Wideroe

1928.

The particles are grouped together to make sure that the field has the 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



Alvarez: Resonance tank

The Cyclotron

Centripetal force=-Centrifugal force:

$$\frac{mv^2}{r} = Bqv$$

Continuous particle flux

Reorganizing:

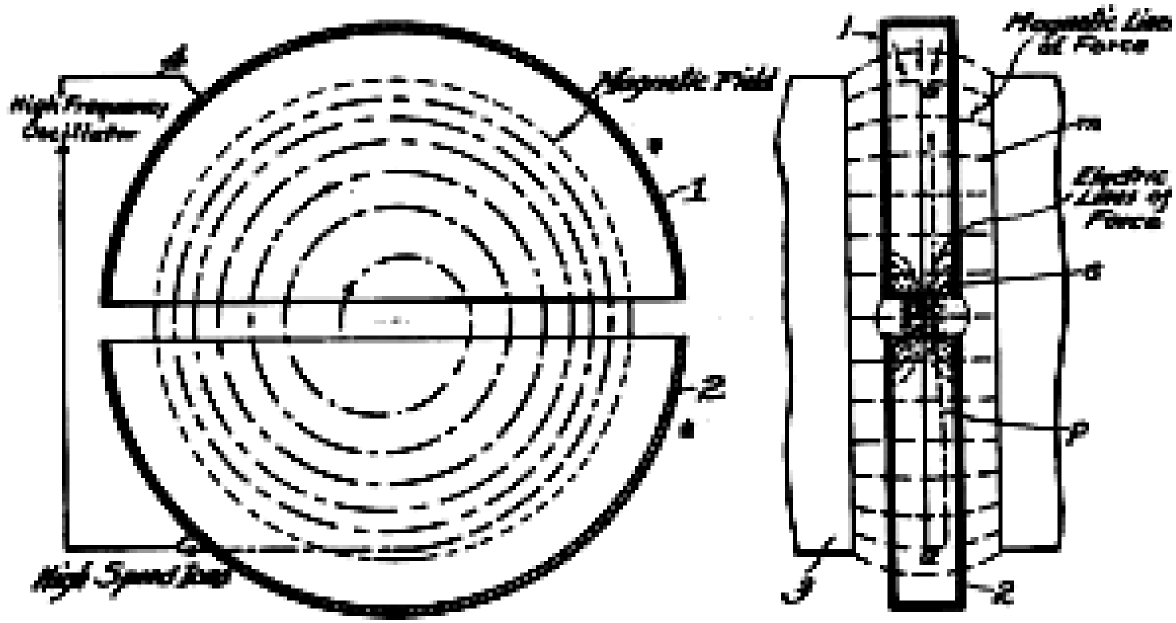
$$\frac{v}{r} = \frac{Bq}{m}$$

$$\downarrow$$

$$\omega = \frac{Bq}{m}$$

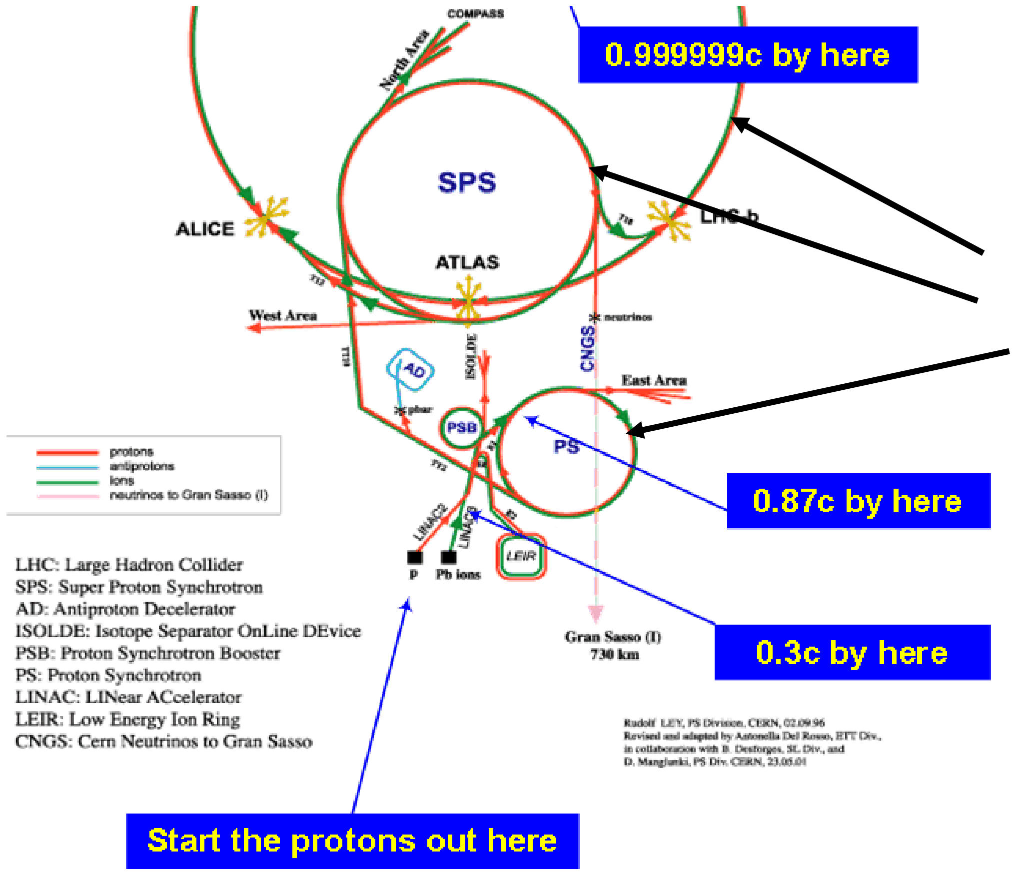
$$f = \frac{\omega}{2\pi}$$

$$f = \frac{Bq}{2m\pi}$$



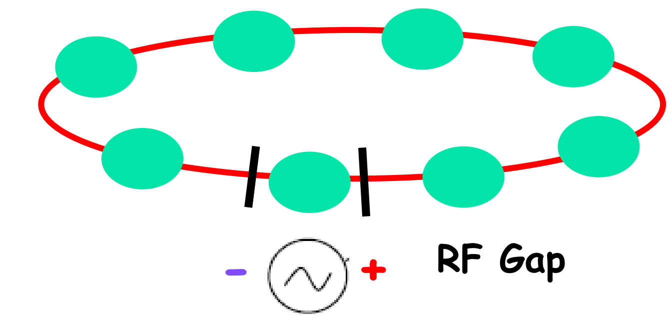
The frequency does not depend on the radius, if the mass is contant. When the particles become relativistic this is not valid any more. The frequency must change with the particle velocity: synchrcyclotron. The field can also change with the radius: isochronous cyclotron

Synchrotrons at CERN

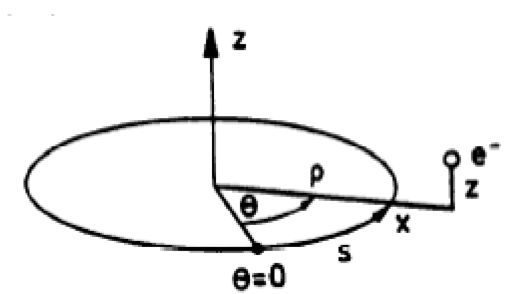


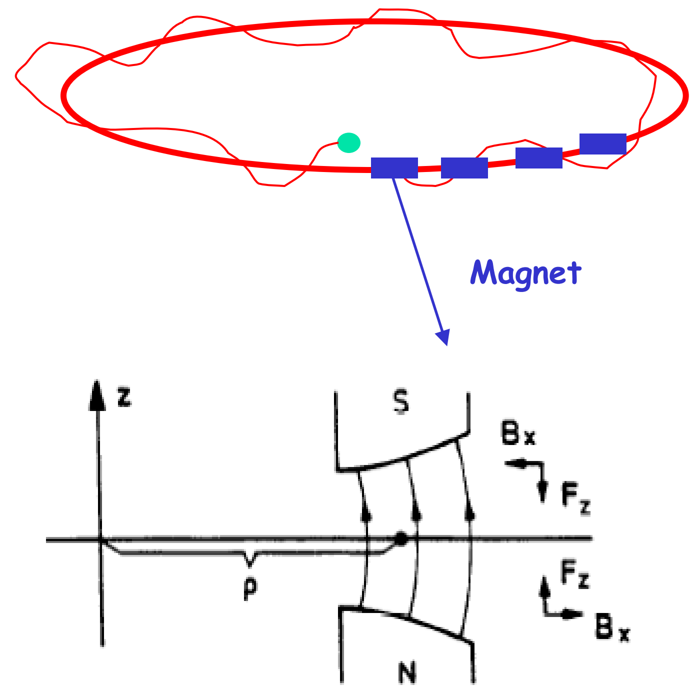
The Synchrotron

Groups of particles are circulating synchronously with the RF field in the acceleratoing cavities



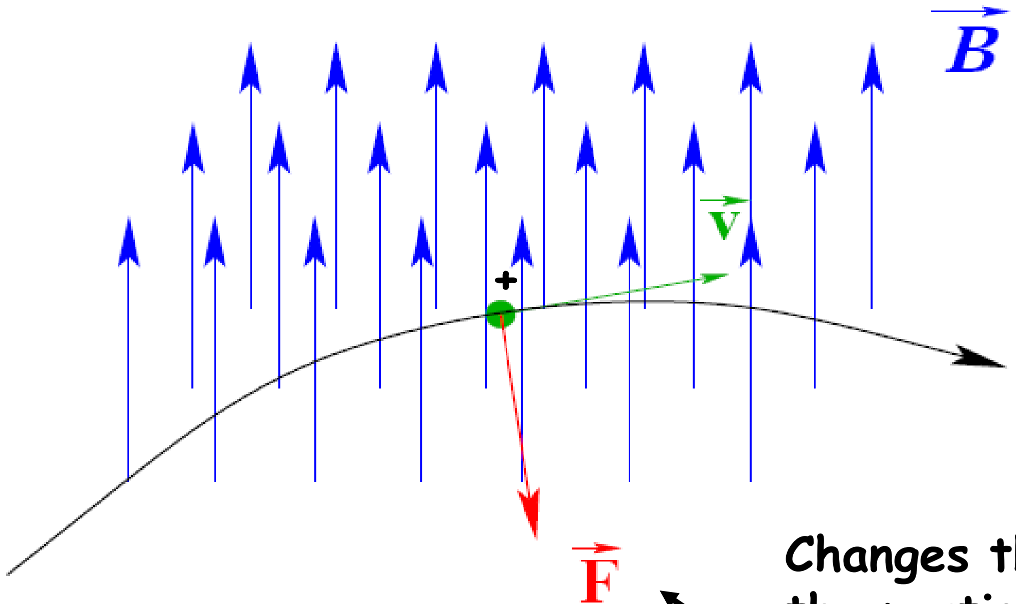
Each particle is circulating around an ideal (theoretical) orbit: for this to work out, acceleration and magnet fields must obey stability criteria!!





Forces on the particles

STEERING



Changes the direction of the particle

Lorentz:

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

Accelerates the particles

The Dipole

Dipole Magnet, bends the particle trajectory in the horizontal plane (vertical field). Exception: correctors...

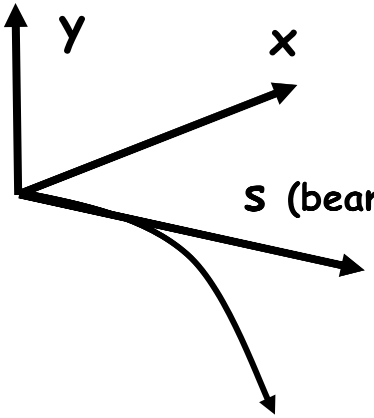
$$F_x = -ev_s B_y$$

$$F_r = mv_s^2 / \rho$$

$$p = mv_s$$

$$\frac{1}{\rho(x,y,s)} = \frac{e}{p} B_y(x,y,s)$$

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

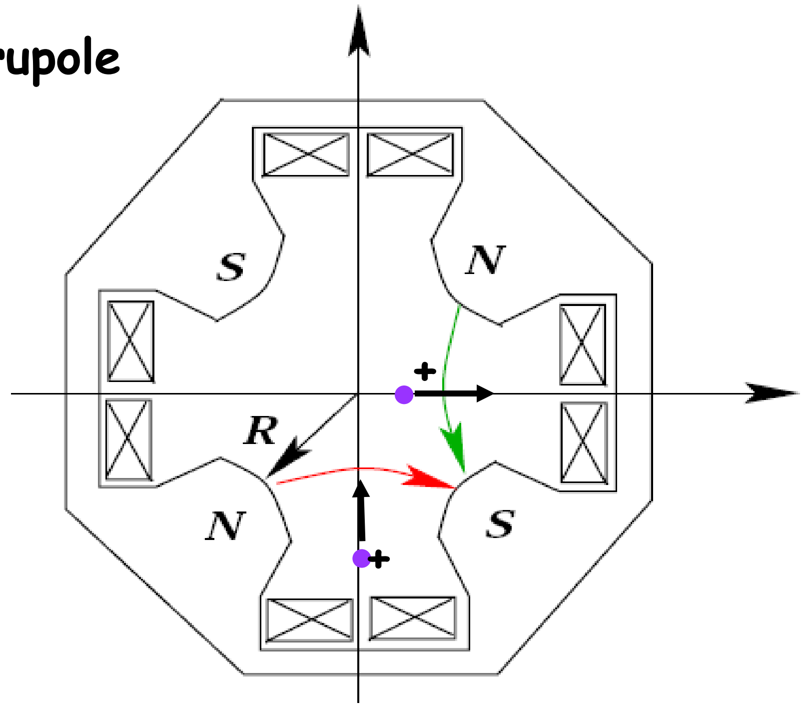


"Magnetic rigidity"

Focusing: The Quadrupole 1

The particles need to be focussed to stay in the accelerator. Similar principle as in optical systems.

Quadrupole



Positiv particle moving towards us: Defocussing in the horizontal plane, focussing the the vertical plane.

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

The Quadrupole 2

FOCUSING

$$B_x = -g \cdot y$$

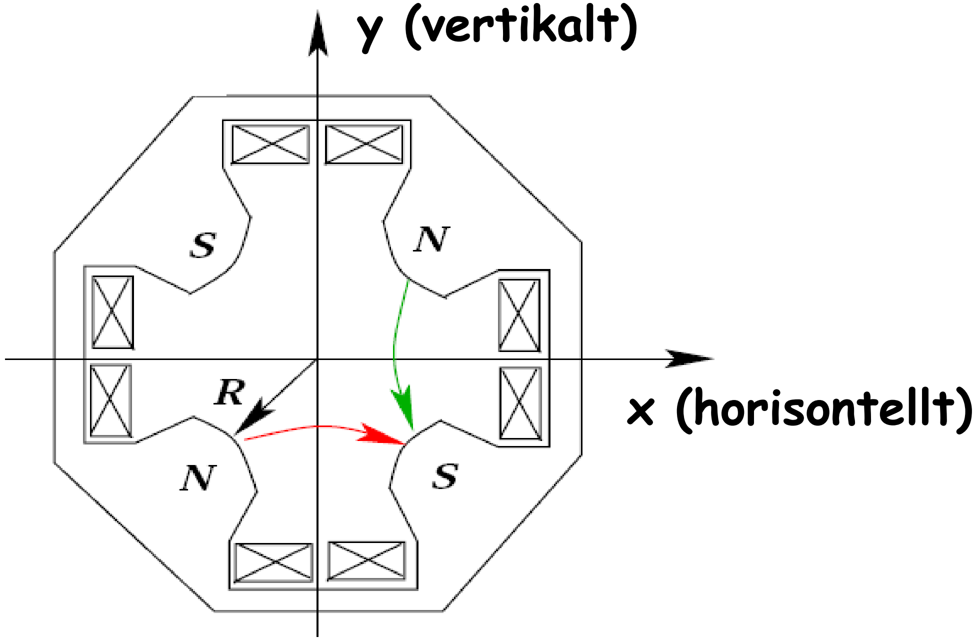
$$B_y = -g \cdot x$$

$$F_x = g \cdot x$$

$$F_y = -g \cdot y$$

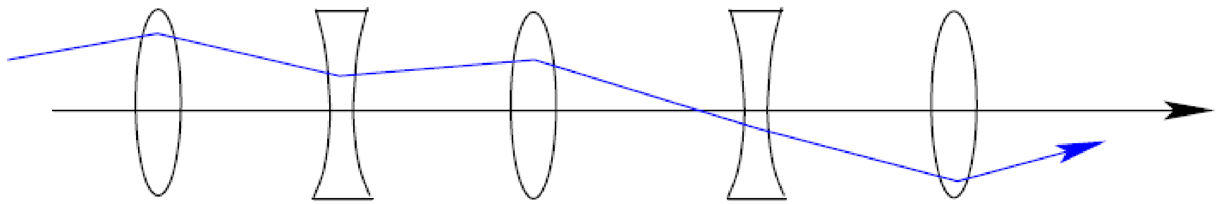
The force is proportional to x and to y:

Particles far from the center of the magnet are bent more, they get a more important corection.



The Focussing System

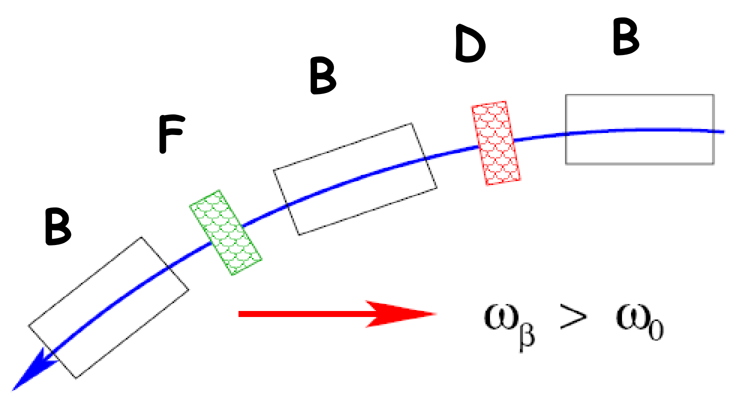
FOCUSSING



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

The beam takes up less space in the vacuum chamber, the amplitudes are smaller and for the same magnet aperture the field quality is better (cost optimization)

Synchrotron design: The magnets are of alternating field (focusing-defocusing)



The oscillating particles

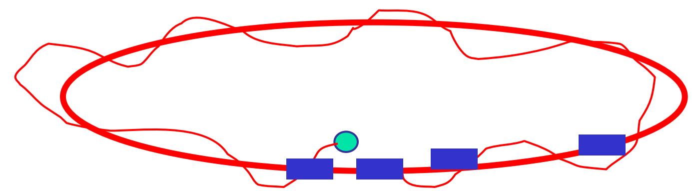
FOCUSSING

The following kind of differential equations can be derived, compare the simple pendulum:

g

$$x''(s) + \left(\frac{1}{\rho^2(s)} - k(s) \right) \cdot x(s) = \frac{1}{\rho(s)} \Delta p / p \quad ; \quad k = \frac{e}{p} \frac{\partial B_z}{\partial x}$$

$$z''(s) + k(s) \cdot z(s) = 0$$



$$x(s) = \sqrt{\varepsilon \beta_x}(s) \cos\left(\frac{2\pi}{L} Q \cdot s + \delta \right)$$

Oscillating movement with varying amplitude!

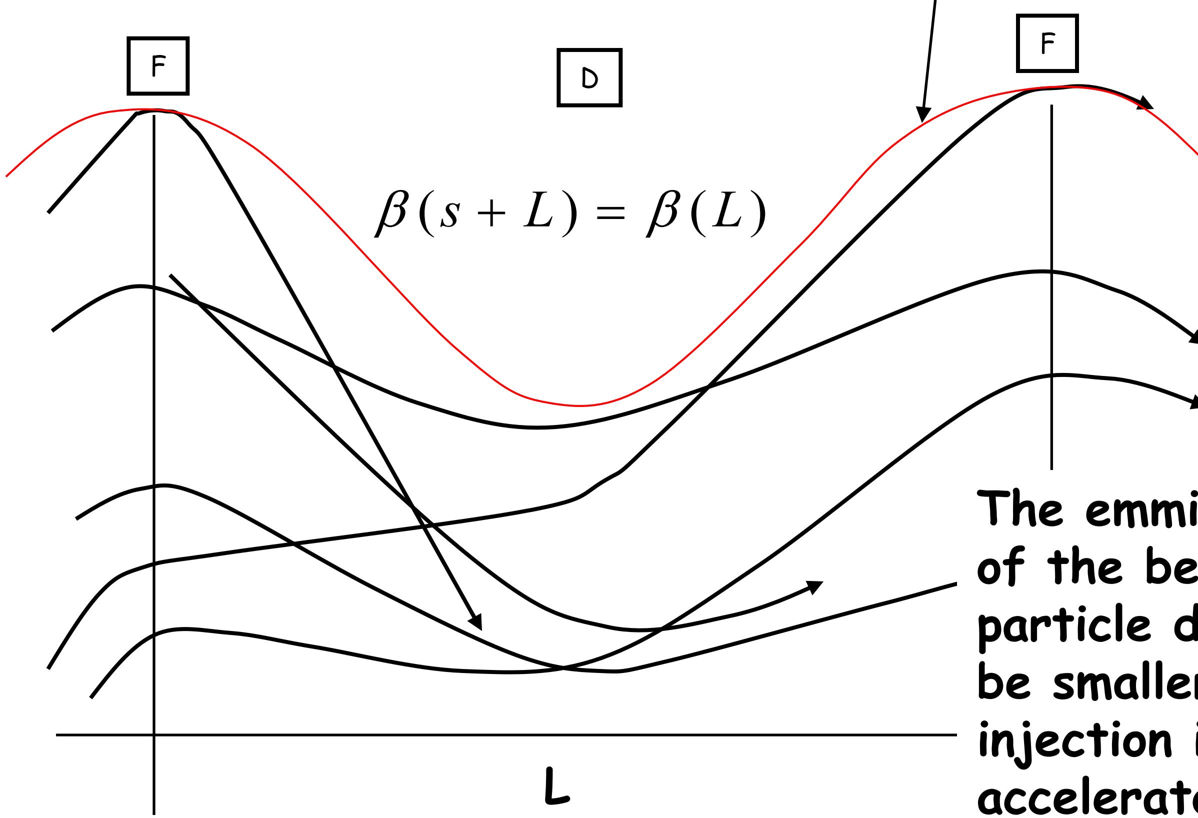
The number of oscillations the particle makes in one turn is called the "tune" and is denoted Q. The Q-value is slightly different in two planes (the horizontal and the vertical planes). L is the circumference of the ring.

The Beta Function

FOCUSSING

All particle excursions are confined by a function: the bsqare root of the the beta function and the emmittance.

$$x(s) = \sqrt{\varepsilon\beta_x}(s)\cos\left(\frac{2\pi}{L}Q \cdot s + \delta\right)$$

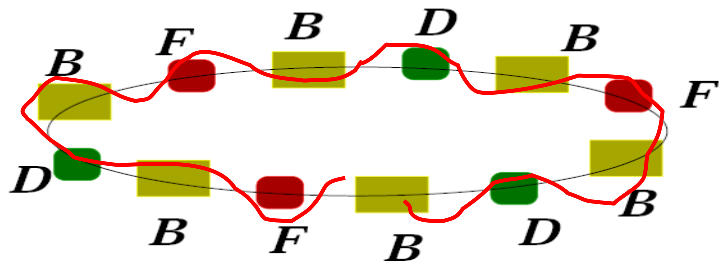


The emmittance,a measure of the beam size and the particle divirgences, cannot be smaller than after injection into the accelerator (normalized)

Closed orbit, och field errors

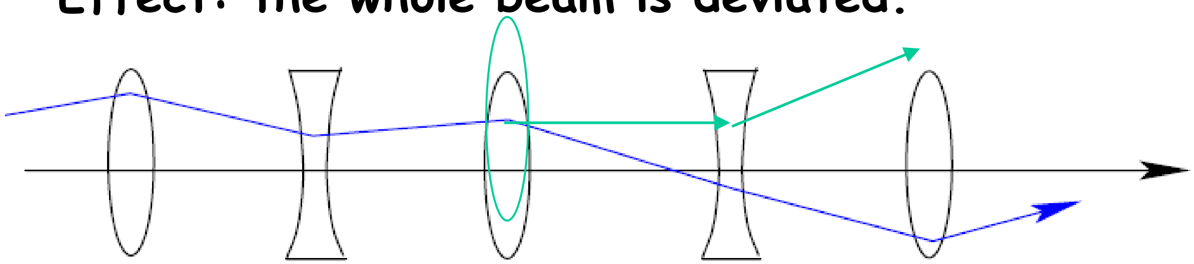
STEERING AND FOCUSSING

Theoretically the particles oscillate around a nominal, calculated orbit.



The magnets are not perfect, in addition they cannot be perfectly alined.

For the quadrupoles for example this means that 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.

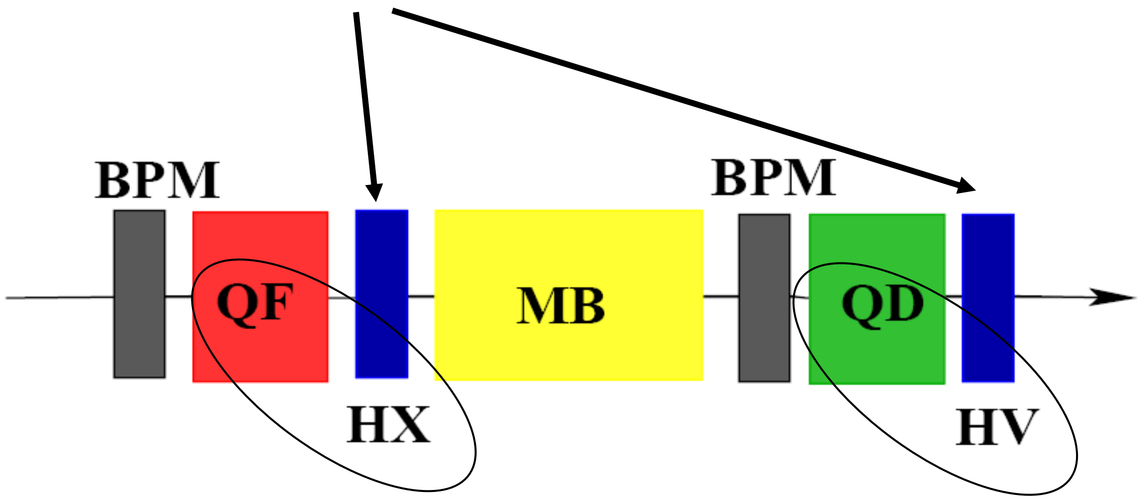


$$F_x = g \cdot x$$

$$F_y = -g \cdot y$$

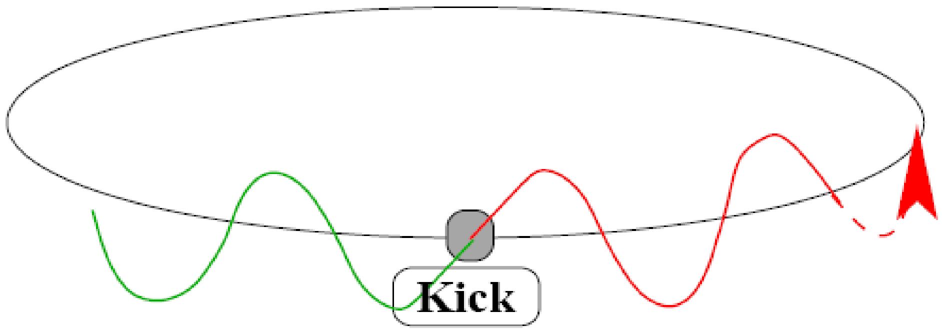
Correctors

Beam Position Monitors are used to measure the center of the beam near a quadrupole, the beam should be in the center at this position.
Small dipole magnets are used to correct possible beam position errors.



Other types of magnets are used to correct other types of errors for example non perfect magnetic fields.

Possible errors 1



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

The magnets have to be good enough so that resonace phenomena do not occur. Non wanted magnetic field components (sextupolar, octupolar etc.) are comparable to 10^{-4} relative to the main component of a magnet (dipole in a bending magnet, quadrupole in a focussing magnet etc.). This is valid for LHC

Possible errors 2

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

Movement of the surface of the earth
Trains
The moon
The seasons
Construction work
...

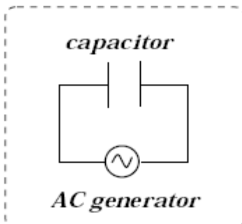
Calibration of the magnets is important
Current regulation in the magnets
...

The energy of the particles must correspond to the field in the magnets, to permit the particle to stay in their orbits. Control of the acceleration!

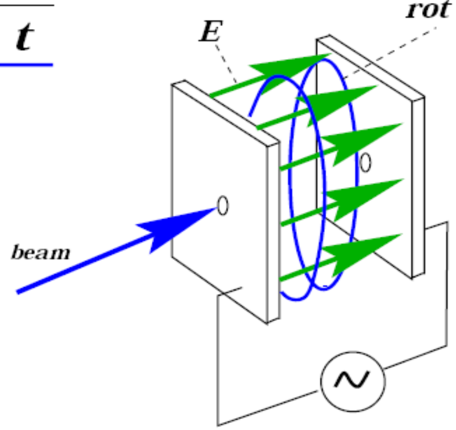
Electrical Fields for Acceleration

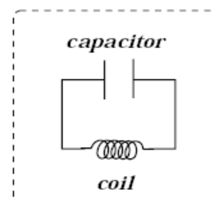
ACCELERATION

- $$E = -\frac{1}{c}\frac{\partial A}{\partial t}$$



$$rot\,B = \frac{\mu\varepsilon}{c}\frac{\partial E}{\partial t}$$

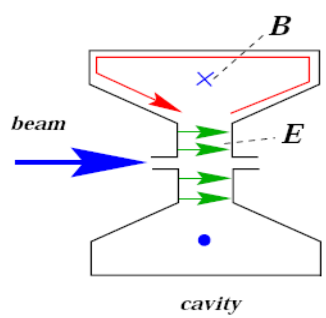


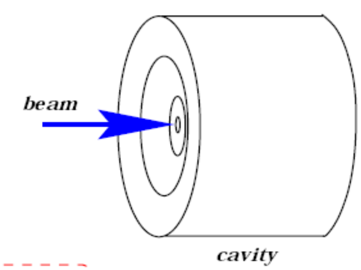


$$L = \frac{\mu_0 \cdot N^2 \cdot A}{l}$$

$$C = \frac{\varepsilon_0 \cdot A}{d}$$

Resonance circuit
Cavity for acceleration

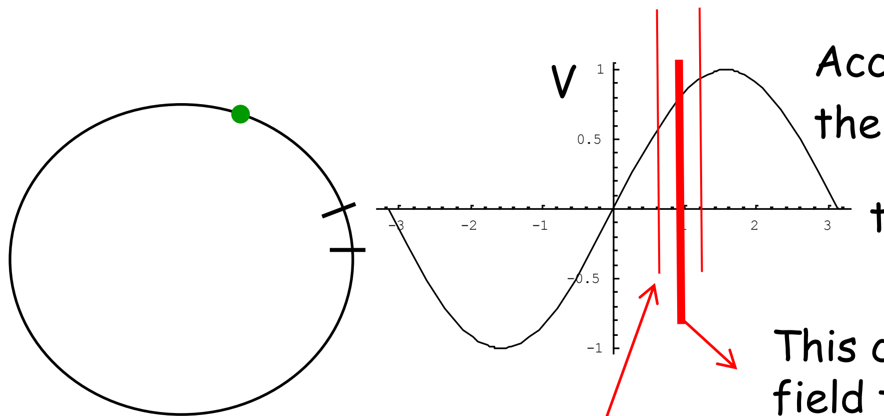




→ *f; Q; R*

The Synchrotron: Buckets

ACCELERATION

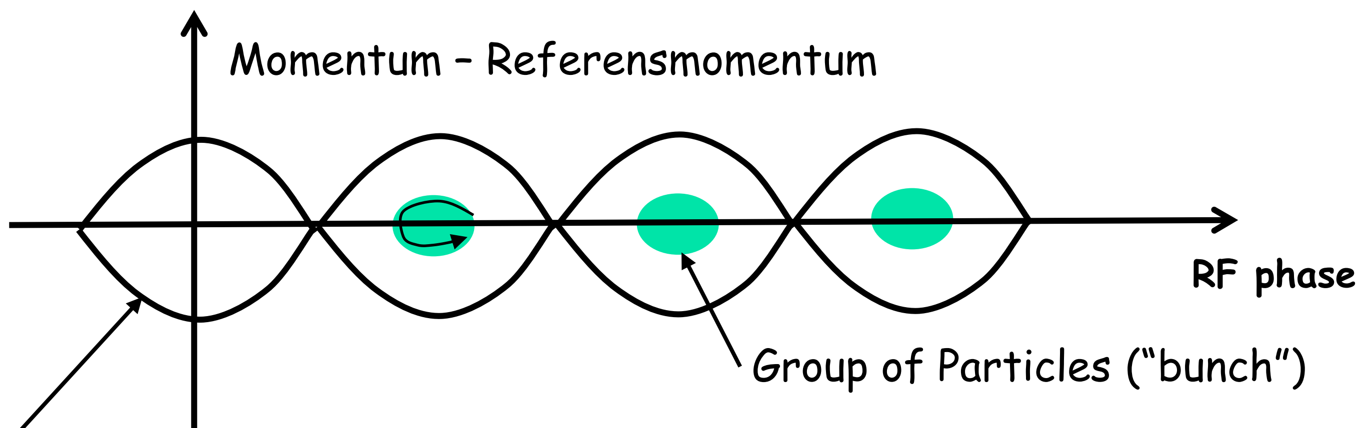


Accelerating gap with the RF voltage

This corresponds to the electical field the reference particle sees

An early particle gets less energy increase.

For Acceleration we change slightly the frequence for ecah passage.



"Bucket": Energy/phase condition for stability

Experiment

EXPERIMENT

Targets:

Bombarding material with a beam directed out of the accelerator.

Bubbelchamber

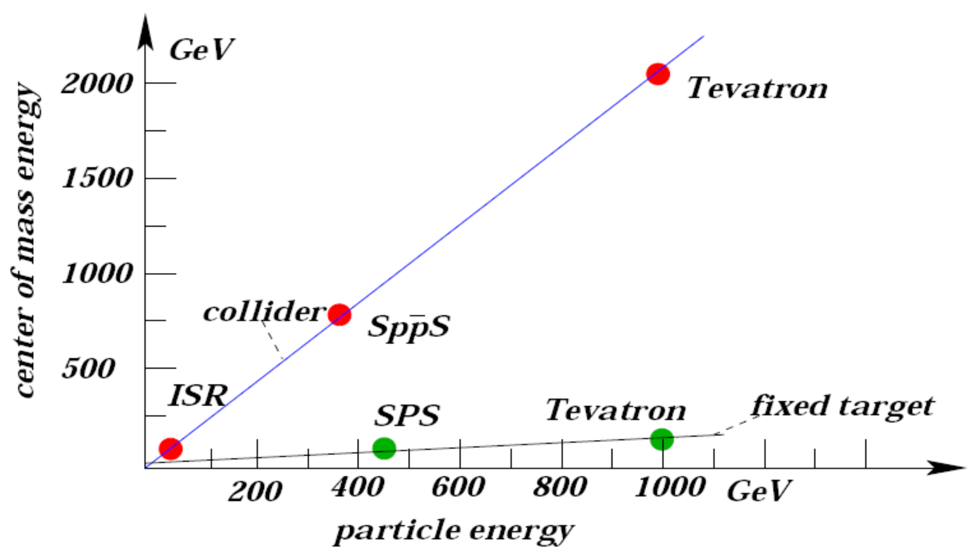
Avaliable energy is calculated in the center of mass of the system (colliding objects)

To collide particle more intersting

1960: electron/positron collider

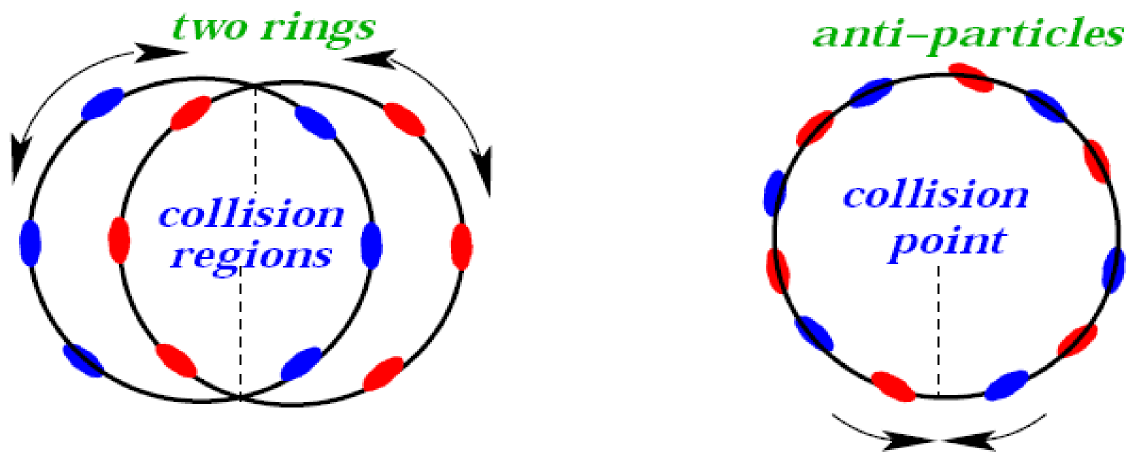
1970: proton antiproton collider

2000: ions, gold



Colliders

EXPERIMENT



- All particles do not collide at the same time -> long time is needed

- Two beams are needed

- Antiparticles are difficult (expensive) to produce (~1 antiproton/10^6 protons)

- The beams affect each other: the beams have to be separated when not colliding

Leptons/Hadrons

EXPERIMENT

Lepton versus Hadron Collider

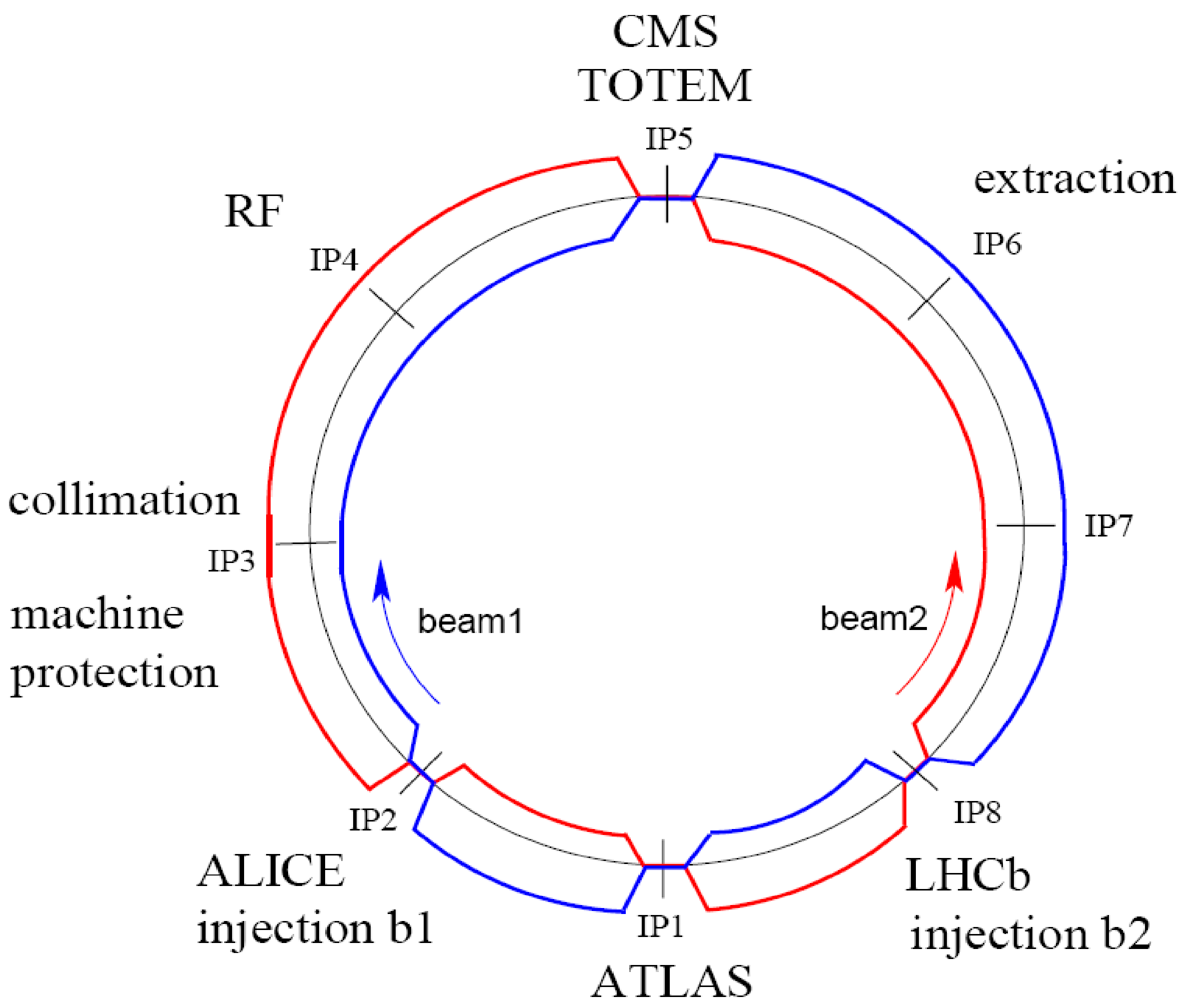
- ***Leptons:*** (e^+ / e^-)
  - ***elementary particles***
    - → ***well defined energy***
    - → ***precision experiments***

- ***Hadrons:*** (p^+ / $\bar{p}$)
  - ***multi particle collisions***
    - → ***energy spread***
    - → ***discovery potential***

- ***Example:***

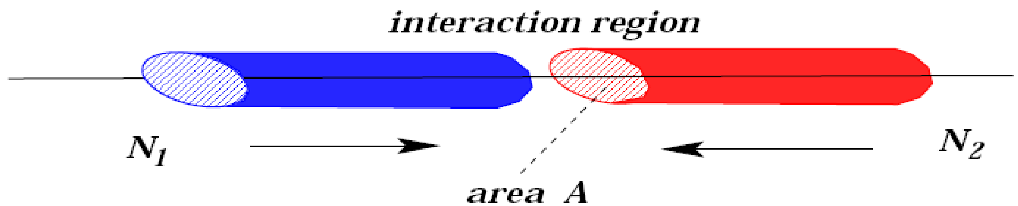
Z_0	*1985 $Sp\bar{p}S$*	p^+p^-
	1990 LEP	e^+e^-

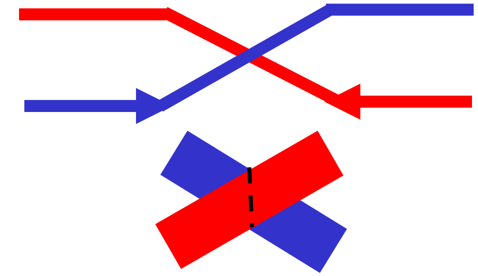
The LHC


CMS
TOTEM
IP5
extraction
IP6
RF
IP4
collimation
IP3
machine
protection
IP7
beam1
beam2
IP2
ALICE
injection b1
IP8
LHCb
injection b2
IP1
ATLAS

Luminosity

EXPERIMENT





$$\boxed{N_{ev}/sec = \sigma \cdot L}$$

$$A = \pi \varepsilon \beta *$$

$$x(s) = \sqrt{\varepsilon \beta_x}(s) \cos\left(\frac{2\pi}{L} Q \cdot s + \delta\right)$$

Number of particles per bunch (two beams)

Number of bunches per beam

Revolution frequency

$$L = \frac{N_b^2 n_b f_{rev}}{4 \pi \varepsilon \beta *} F$$

Formfactor from the crossing angle

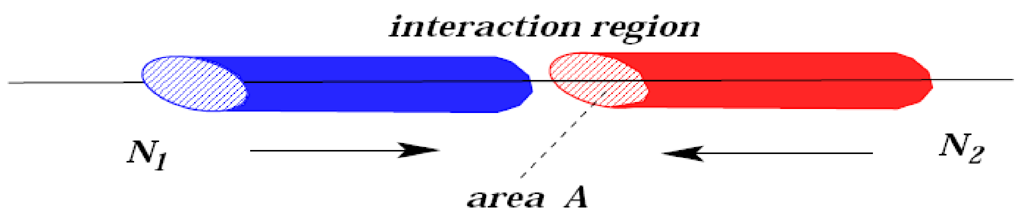
Emmittence

Optical beta function

Luminosity: the beam size

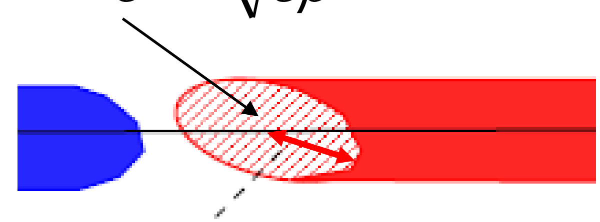
EXPERIMENT

We need a small beam in the collision point

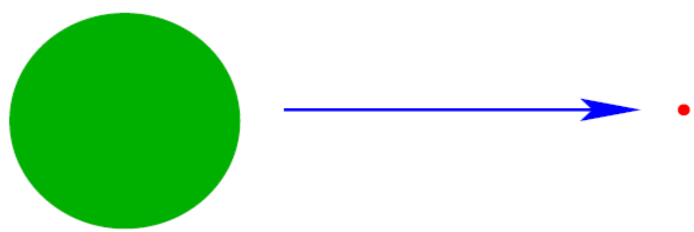


$$L = \frac{N_b^2 n_b f_{rev}}{4\pi\varepsilon\beta^*} F$$

$$\sigma = \sqrt{\varepsilon\beta^*}$$



LHC:



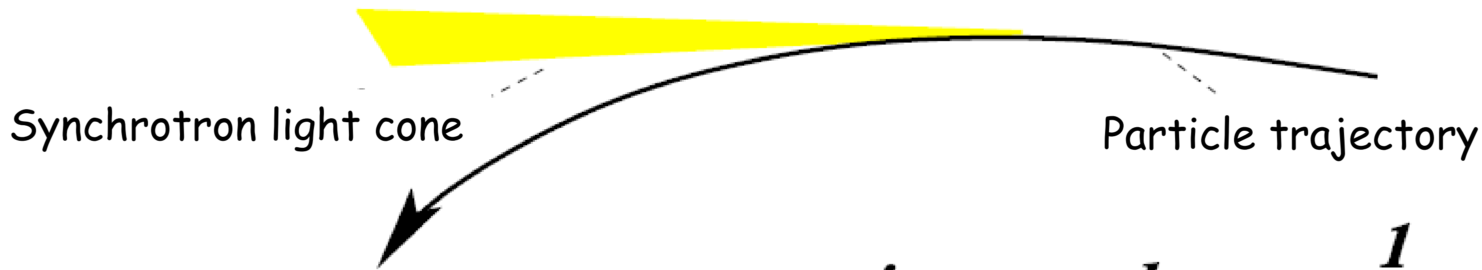
$\langle\beta\rangle_{arc}$ = *80 meter*

β_{IP} = *0.5 meter*

Limitation: **Available magnetic field**

Magnet aperture

Synchrotron light



$$\textit{opening angle} \propto \frac{1}{\gamma}$$

Electromagnetic waves

Accelerated charged particles emit photons

Radio signals and x-ray

$$P \propto \frac{\gamma^4}{\rho^2} \qquad E \propto \frac{\gamma^3}{\rho}$$

$$\text{LEP: } \gamma = 200000$$
$$\text{LHC: } \gamma = 7000$$

Vacuum

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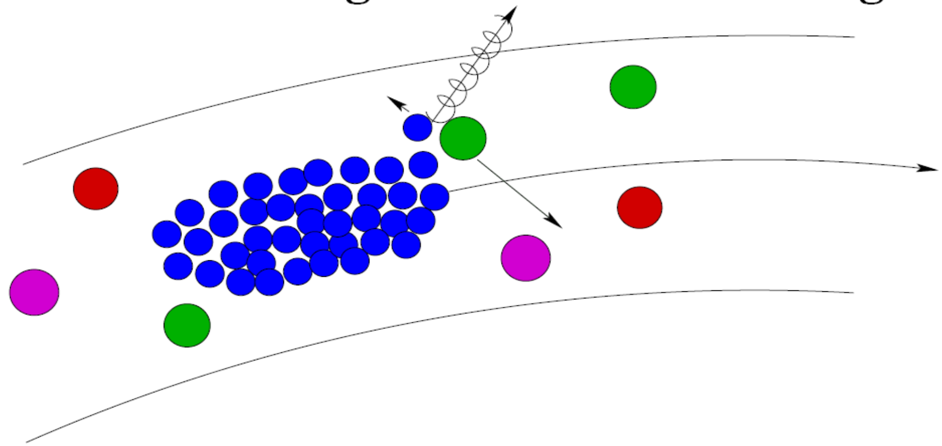
Bremsstrahlung + Coulomb Scattering



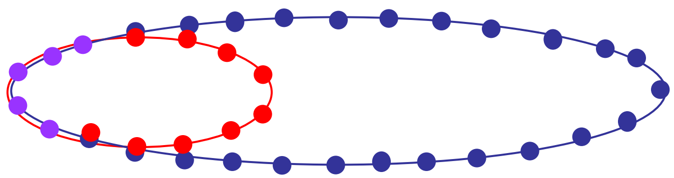
- "Blow up" of the beam
- Particle losses
- Non wanted collisions in the experiments
- Limits the Luminosity

Superconducting Technology 1

TEKNOLOGI

Why superconducting magnets?

Small radius, less number of particles in the machine, smaller machine



Energy saving, BUT infrastructure very complex

The Superconducting Dipole for LHC

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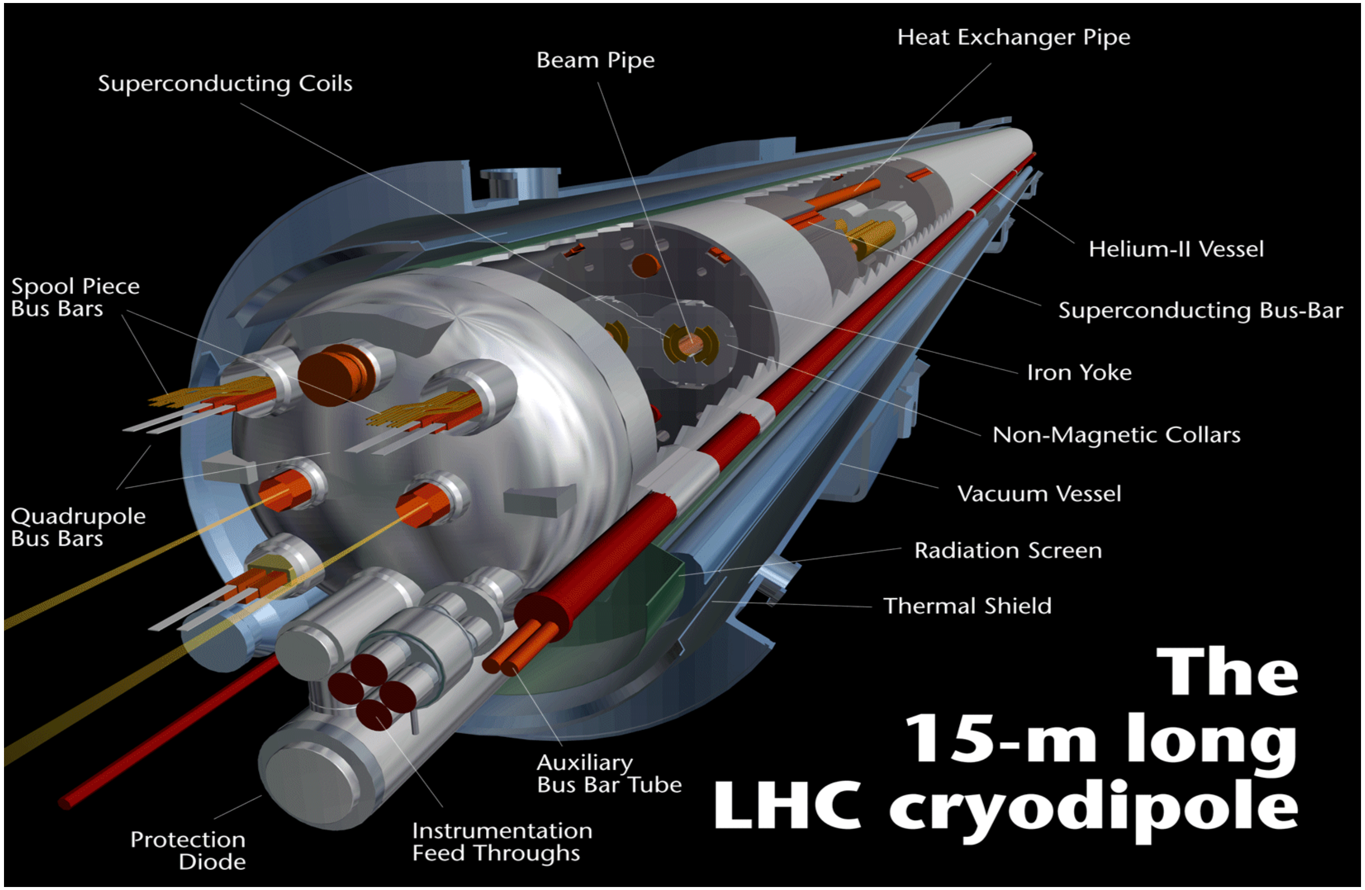
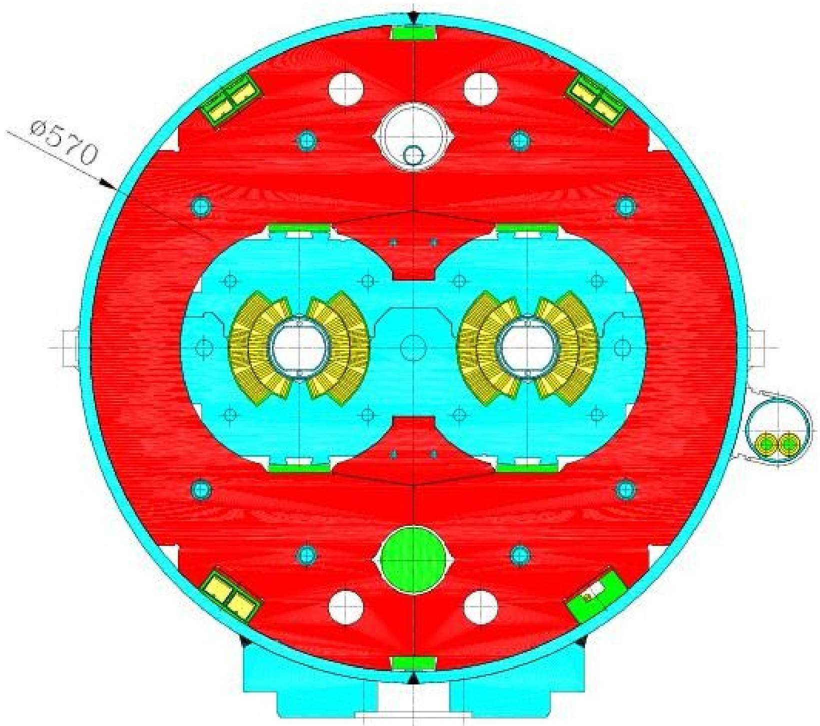
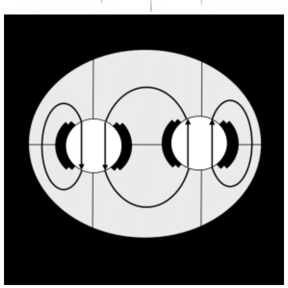
LHC dipole (1232 + reserves) built in 3 firms (Germany France and Italy, very large high tech project)



The LHC Dipole





"Two in one" construction

Working temperature
1.9 K !

Coldest spot i the universe...

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Physics Motivation 2

The Standard Model, "three generations"

Ordinary matter

What happens in our universe

How was created our universe

Generation 1 (ordinary matter)			
Fermion (Left-handed)	Symbol	Electric charge	Mas
Electron	e	? 1	0.511 MeV
Electron neutrino	ν_e	0	< 50 eV
Positron	e^c	+1	0.511 MeV
Electron antineutrino	ν_e^c	0	< 50 eV
Up quark	u	+2/3	~5 MeV
Down quark	d	? 1/3	~10 MeV
Anti-up antiquark	u^c	? 2/3	~5 MeV
Anti-down antiquark	d^c	+1/3	~10 MeV
Generation 2			
Fermion (Left-handed)	Symbol	Electric charge	Mass
Muon	μ	? 1	105.6 MeV
Muon neutrino	ν_μ	0	< 0.5 MeV
Anti-Muon	μ^c	+1	105.6 MeV
Muon antineutrino	ν_μ^c	0	< 0.5 MeV
Charm quark	c	+2/3	~1.5 GeV
Strange quark	s	? 1/3	~100 MeV
Anti-charm antiquark	c^c	? 2/3	~1.5 GeV
Anti-strange antiquark	s^c	+1/3	~100 MeV
Generation 3			
Fermion (Left-handed)	Symbol	Electric charge	Mass
Tau lepton	τ	? 1	1.784 GeV
Tau neutrino	ν_τ	0	< 70 MeV
Anti-Tau	τ^c	+1	1.784 GeV
Tau antineutrino	ν_τ^c	0	< 70 MeV
Top quark	t	+2/3	173 GeV
Bottom quark	b	? 1/3	~4.7 GeV
Anti-top antiquark	t^c	? 2/3	173 GeV
Anti-bottom antiquark	b^c	+1/3	~4.7 GeV

The CERN Laboratory

- Users contribute to the present large research project, the LHC, with in-kind services and equipment or directly with funding
- ALICE "A Large Ion Collider Experiment" will observe protons and lead ion collisions (strongly interacting matter, quark gluon plasma)
- ATLAS "A Toroidal LHC Apparatus" looks for Higgs bosons
- CMS "Compact Muon Solenoid" looks for Higgs bosons
- LHC-B, LHC Beauty experiment precise measurement on CP violation