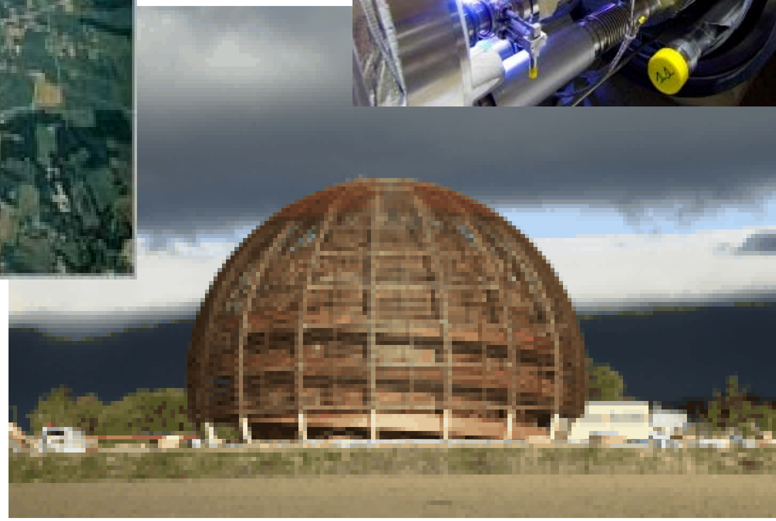
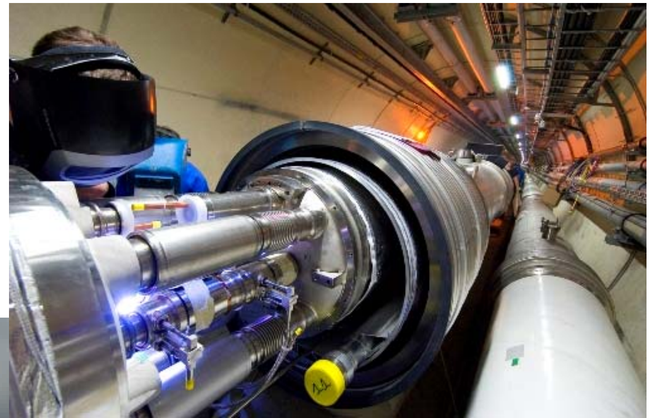
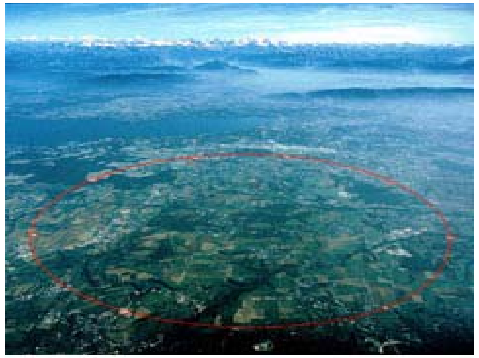
Introduction to Accelerators
Elena Wildner AT/MCS





Contents



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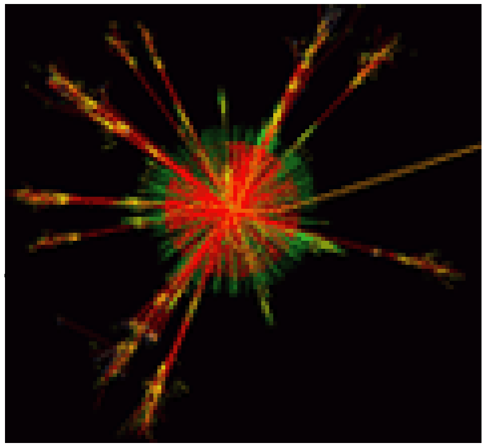
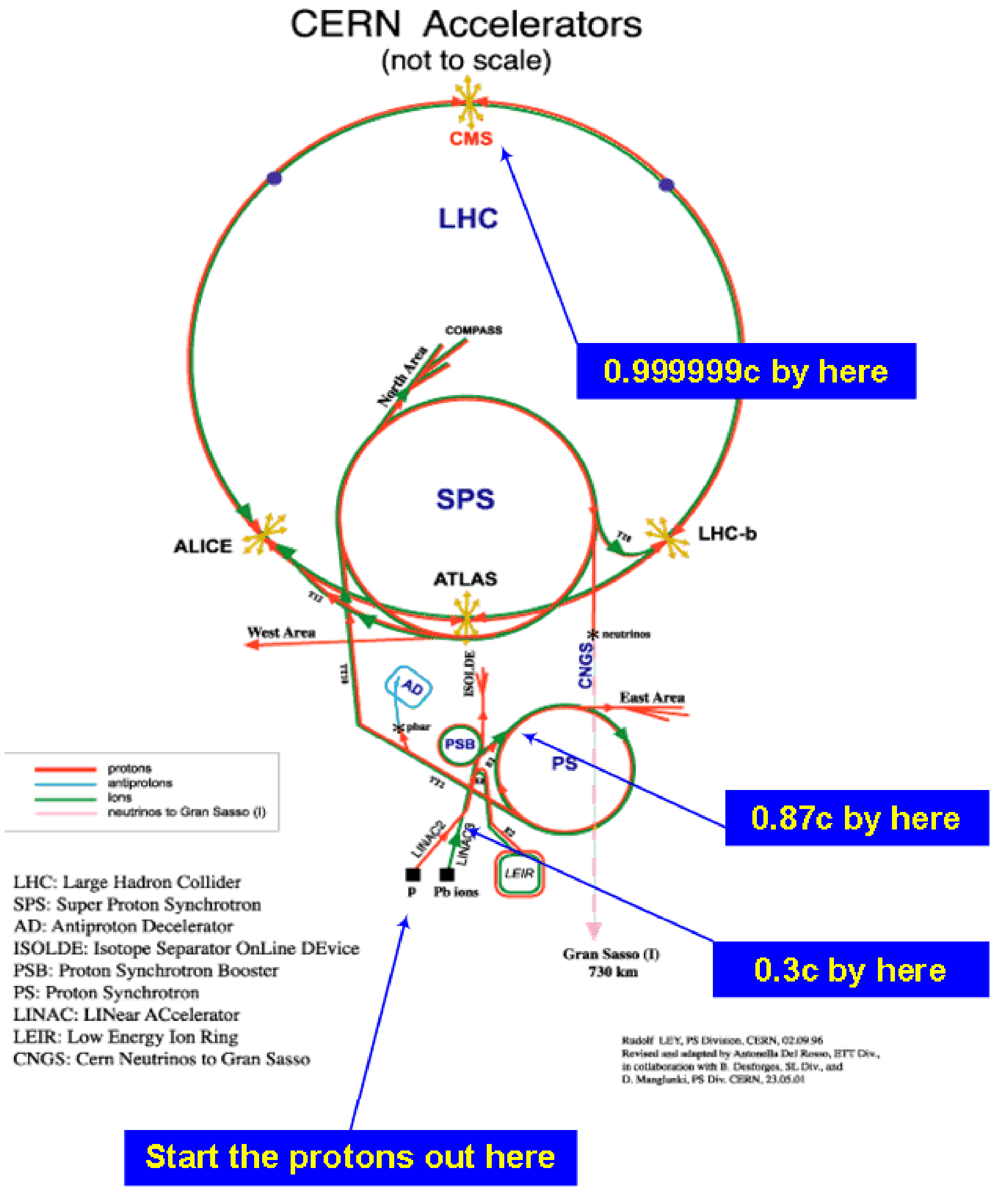
Application Areas

- 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
  - Nuclear physics
  - Isotope production
  - High energy physics
- Etc.



Accelerators and LHC experiments at CERN

INTRODUCTION



Energies:

Linac 50 MeV

PSB 1.4 GeV

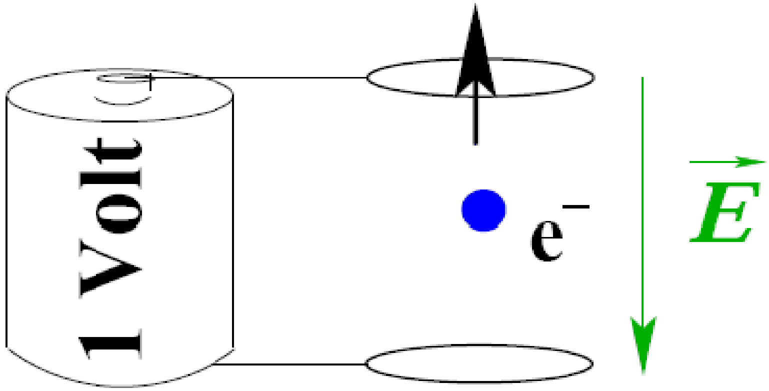
PS 28 GeV

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 (around $1.602 \cdot 10^{-19}$ C) in an electric 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

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

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

Total Energy (E) — **Rest Mass** (m_0)

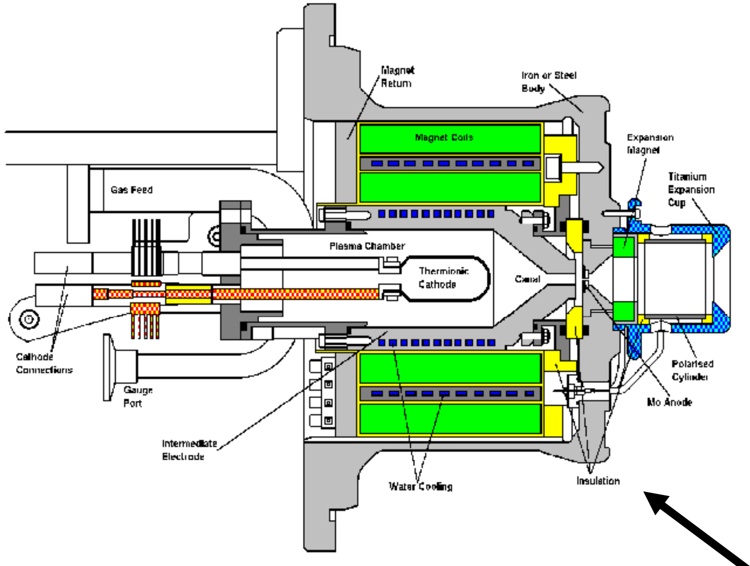
Particle Sources and acceleration

THE ACCELERATOR CHAIN

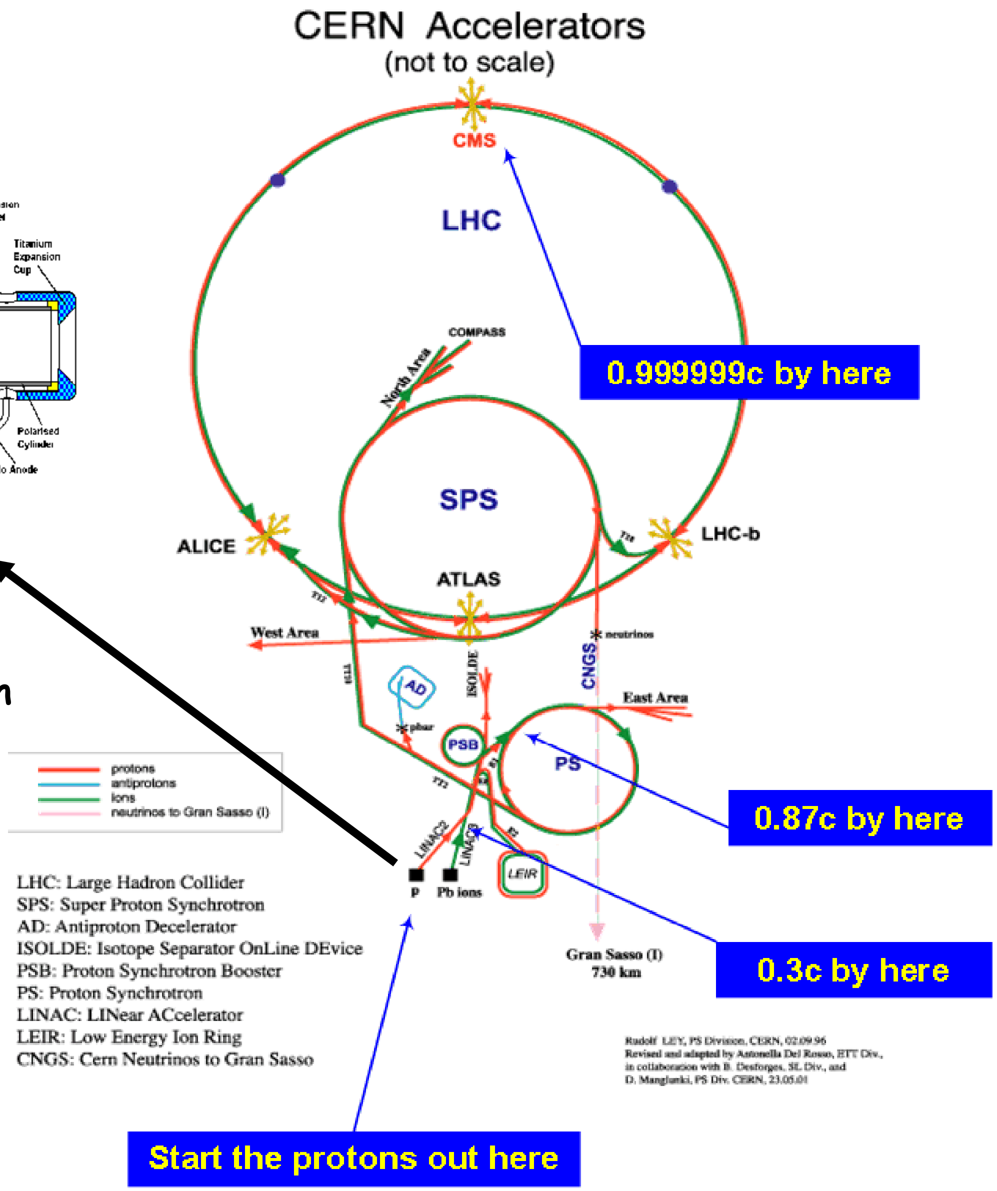
- Natural Radioactivity: alfa particles and electrons. Alfa particles have an energy of around 5 MeV (corresponds to a speed of ~15,000 km/s).
- Production of particles: Particle sources
- Electrostatic fields are used for the first acceleration step after the source
- Linear accelerators accelerate 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

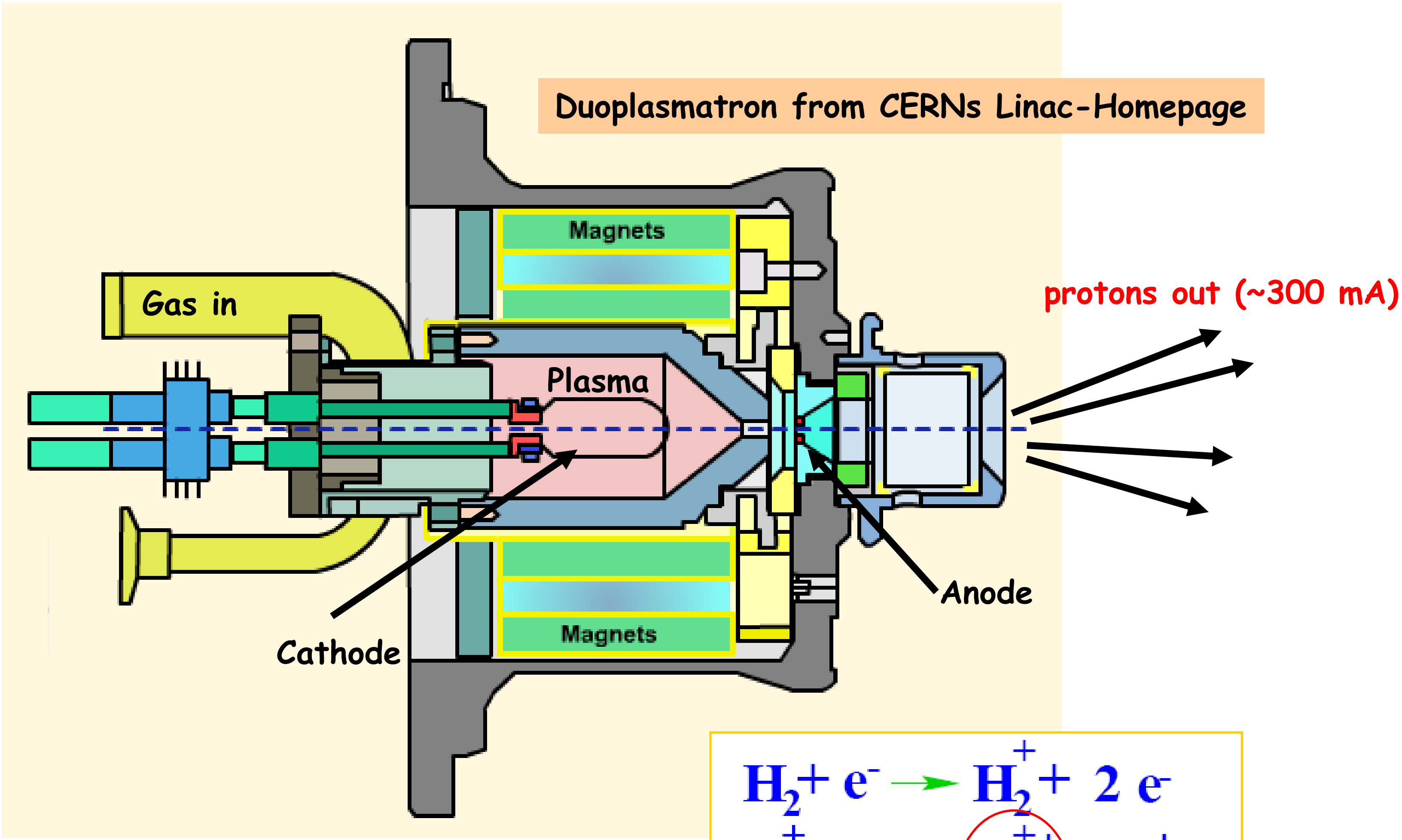
THE ACCELERATOR CHAIN



Duoplasmatron for proton production

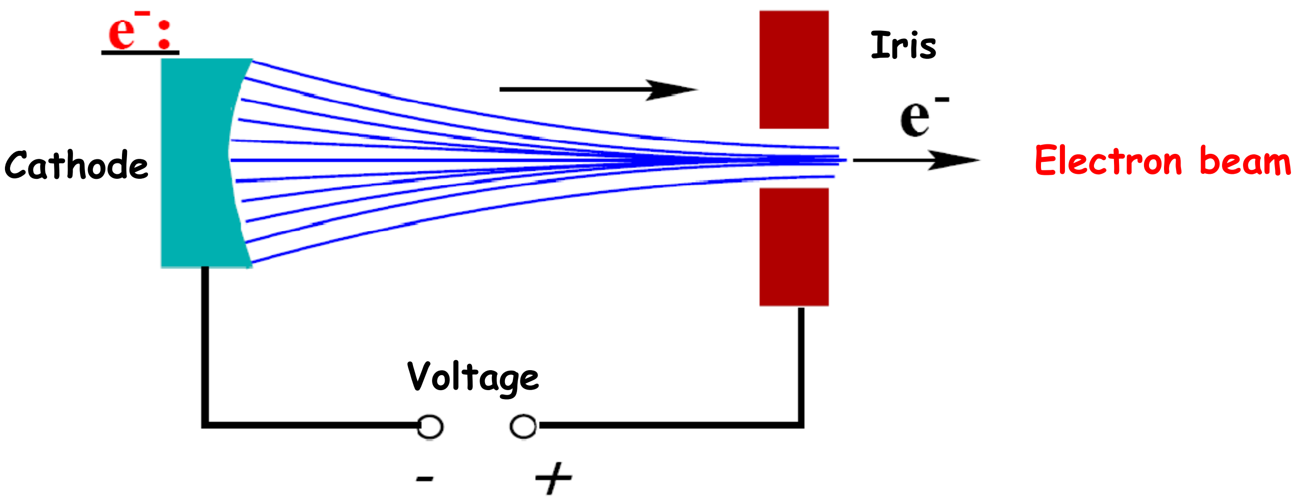


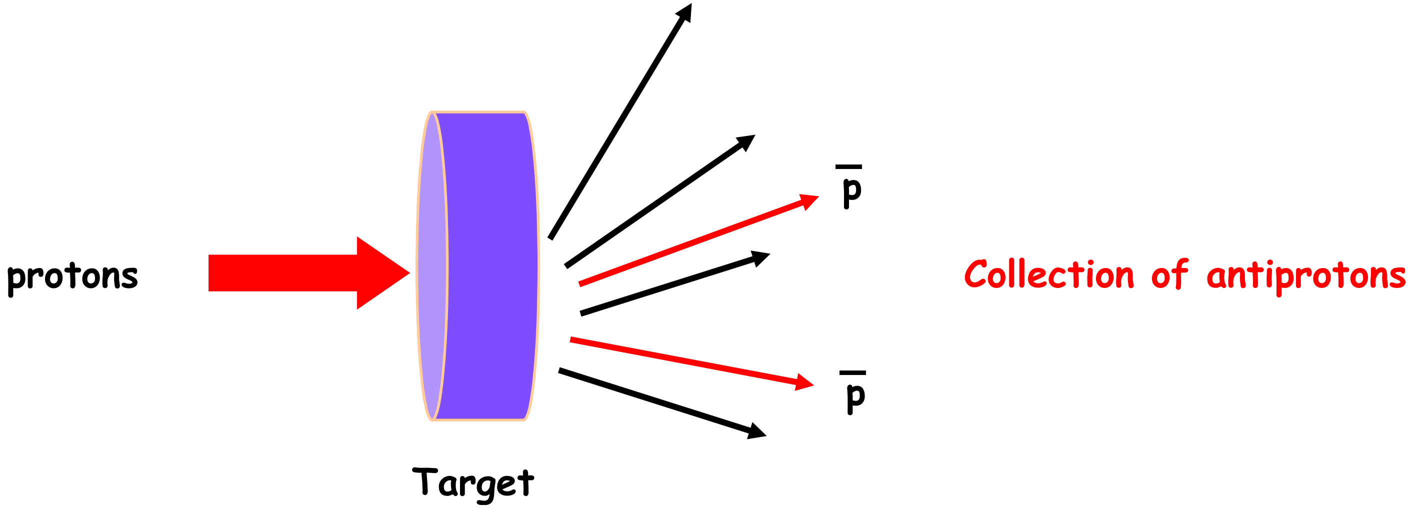
Particle Sources 2



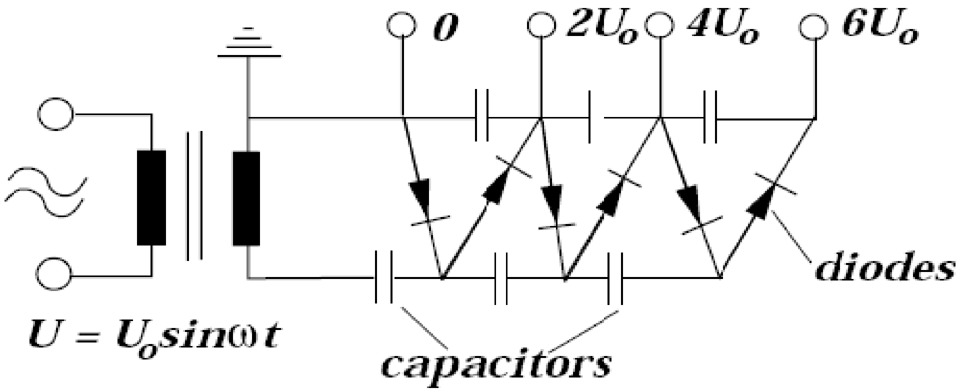
$$H_2 + e^- \rightarrow H_2^+ + 2\,e^-$$
$$H_2^+ + e^- \rightarrow H^+ + H + e^-$$
$$H + e^- \rightarrow H^+ + 2\,e^-$$

Particle Sources 3

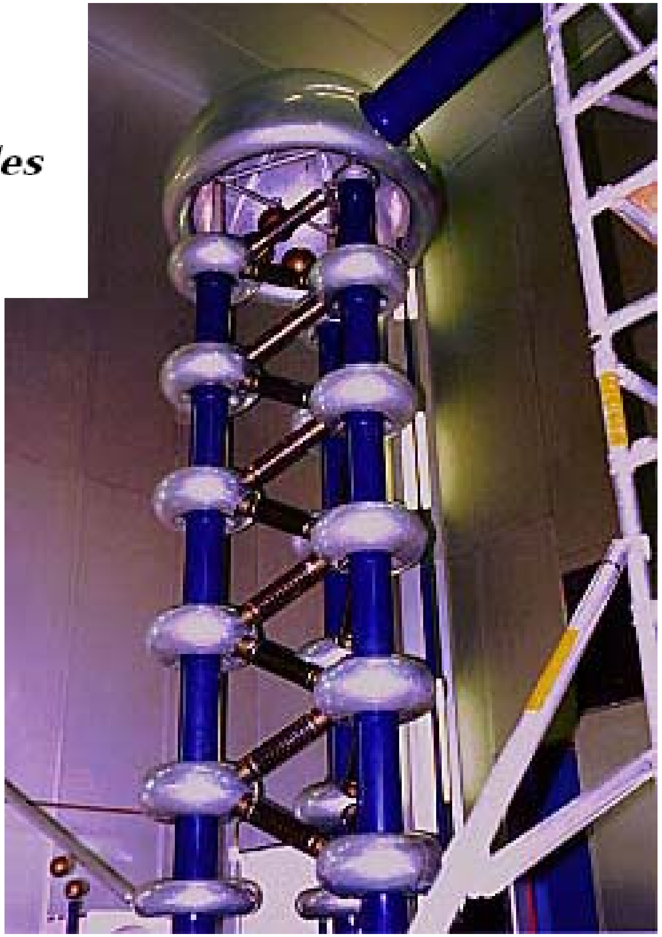




The Cascade Generator

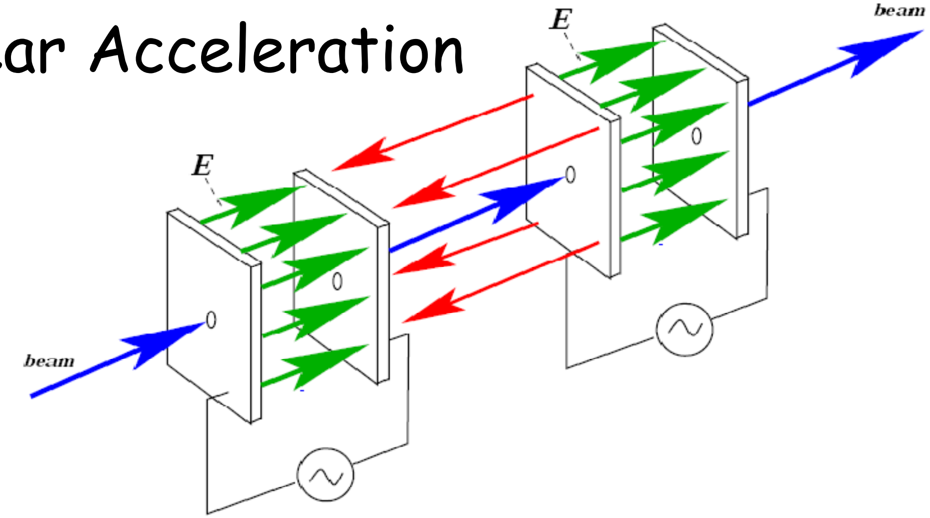


Cockroft Walton: 4MV

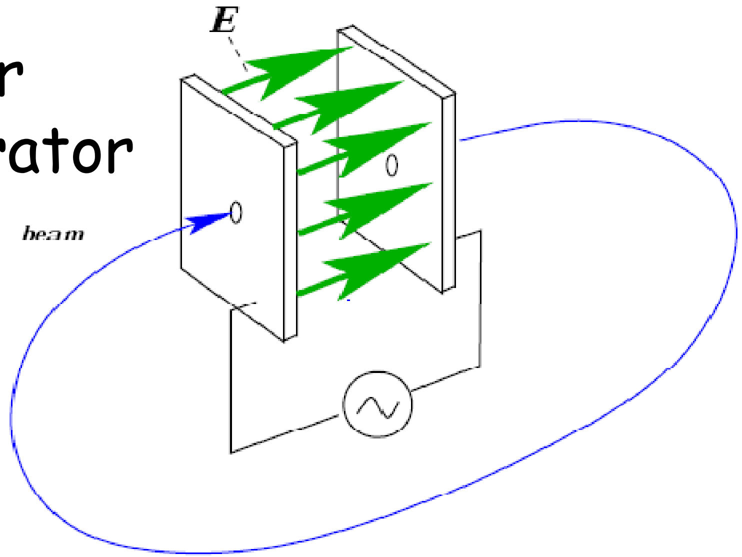


Time Varying Electrical Fields

Linear Acceleration

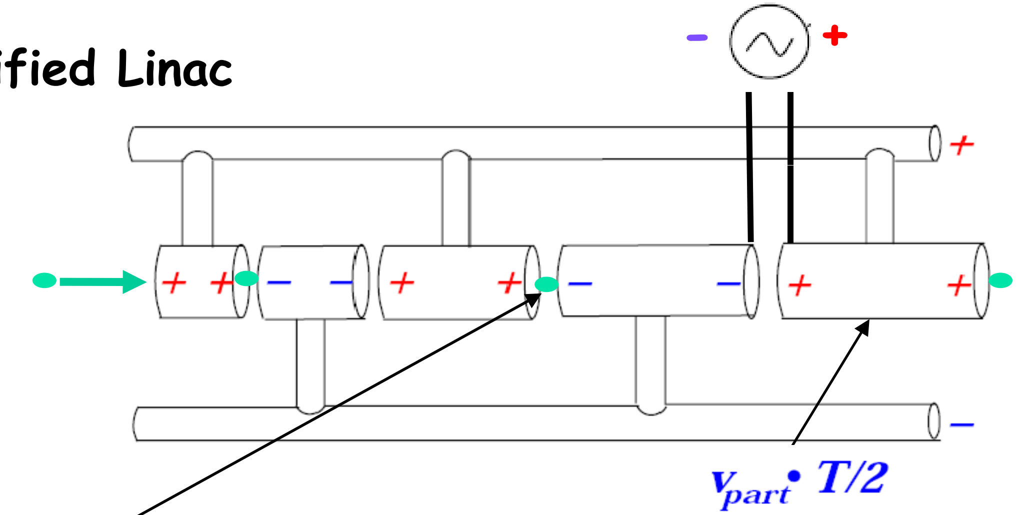


Circular accelerator



Linear accelerators

Simplified Linac

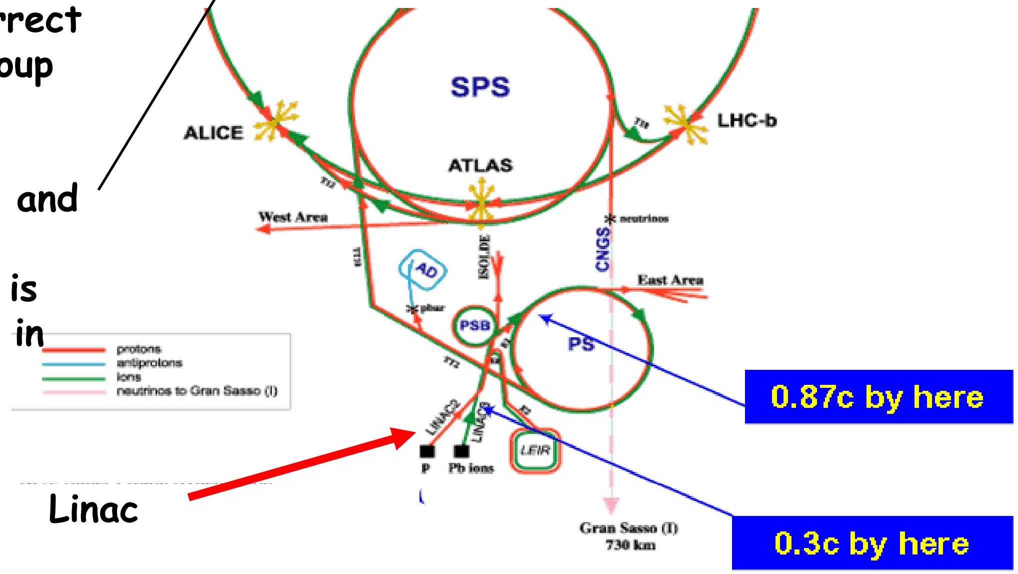


Wideroe

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:

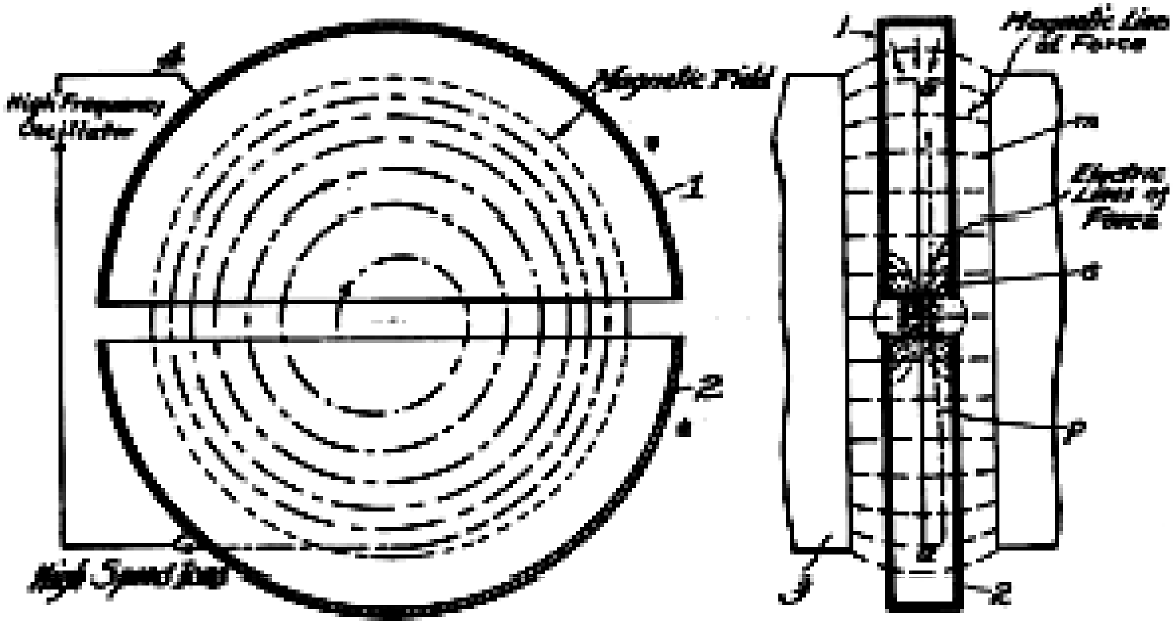
$$\frac{v}{r} = \frac{Bq}{m}$$

$$\downarrow$$

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

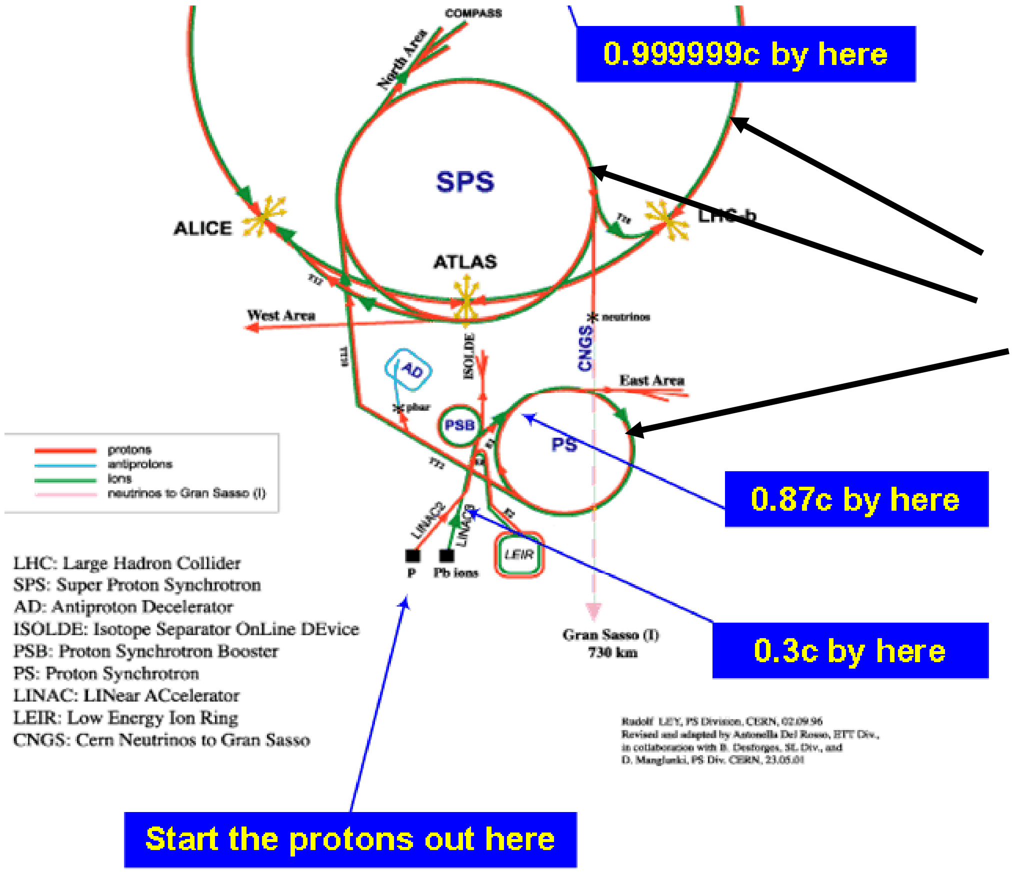
$$f = \frac{\omega}{2\pi}$$

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



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

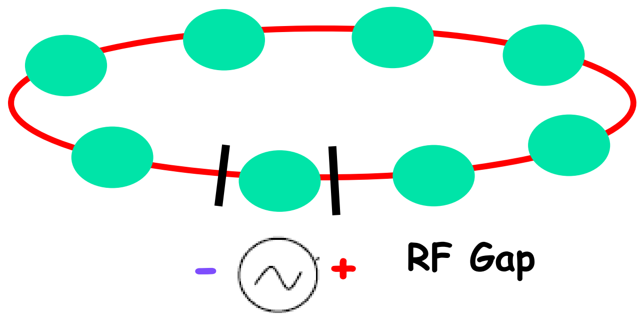
Synchrotrons at CERN



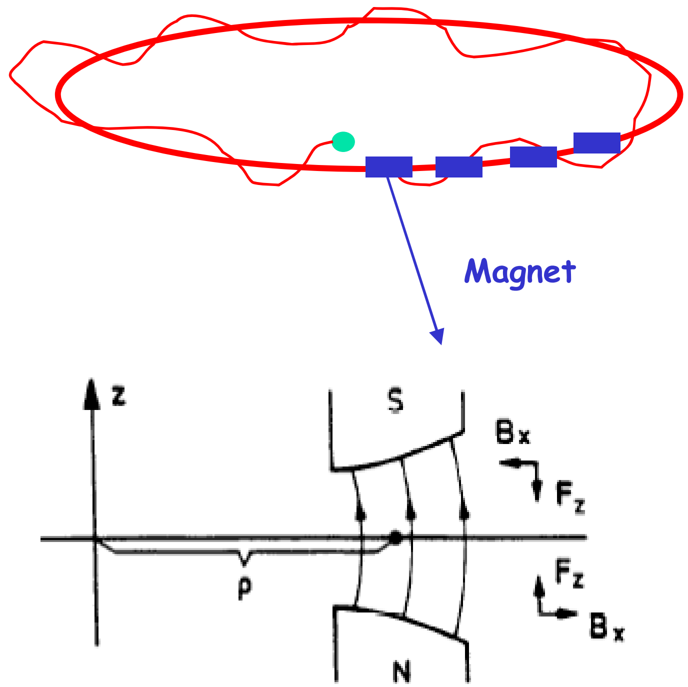
The Synchrotron

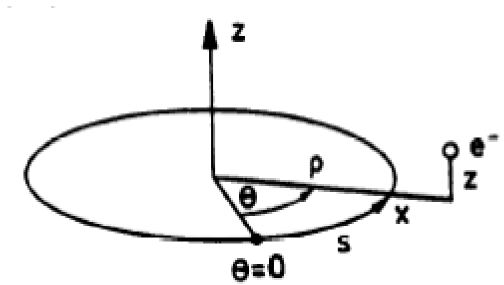
HOW TO KEEP THE BEAM IN PLACE

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



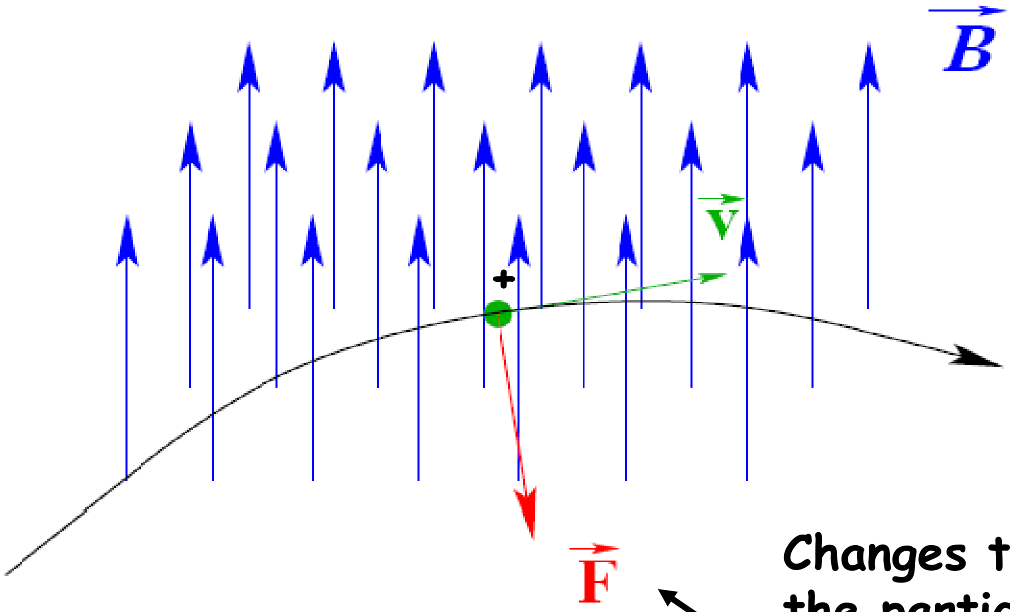
Each particle is circulating around an ideal (theoretical) orbit: for this to work out, acceleration and magnet fields must obey stability criteria!!





Forces on the particles

STEERING



Changes the direction of the particle

Lorentz:

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

Acceleration of the particles, field in the same direction as the velocity

The Dipole

STEERING

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

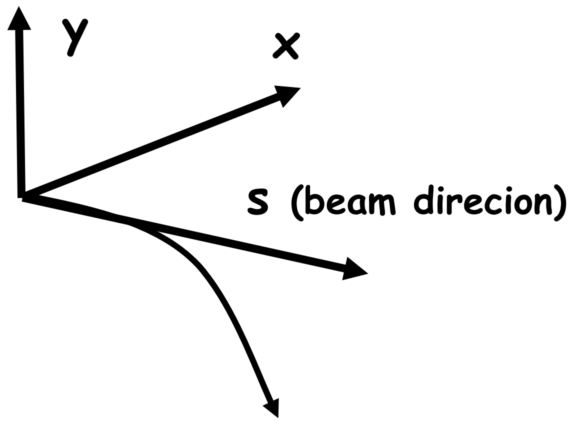
$$F_x = -ev_s B_y$$

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

$$p = mv_s$$

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

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



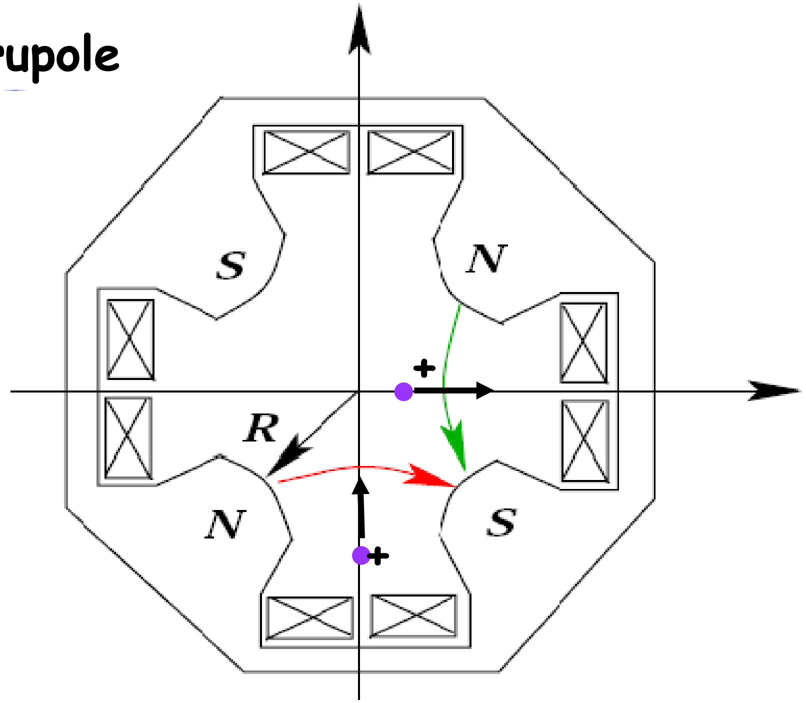
"Magnetic rigidity"

Focusing: The Quadrupole 1

FOCUSING

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

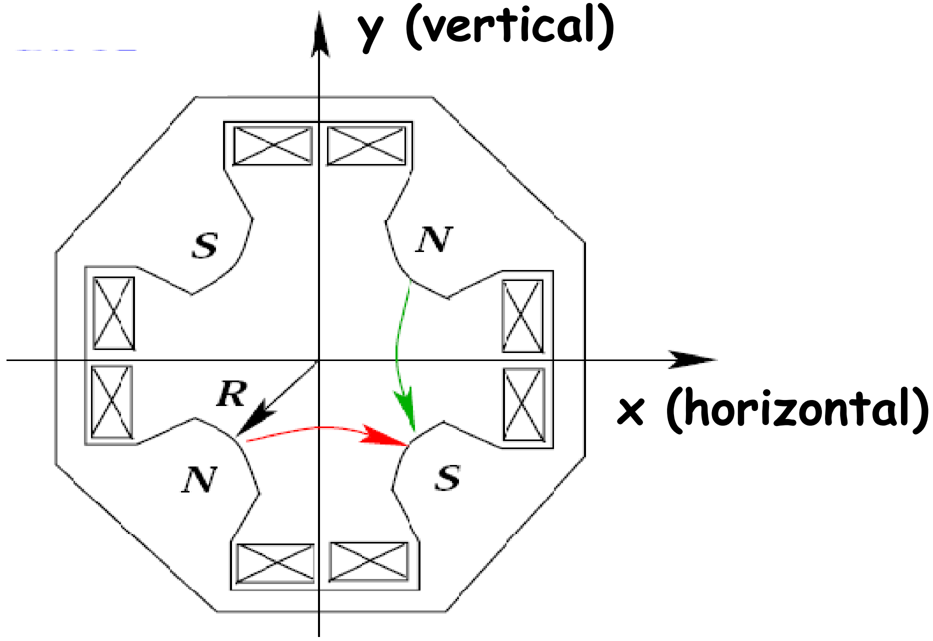
FOCUSING

$$B_x = -g \cdot y$$

$$B_y = -g \cdot x$$

$$F_x = g \cdot x$$

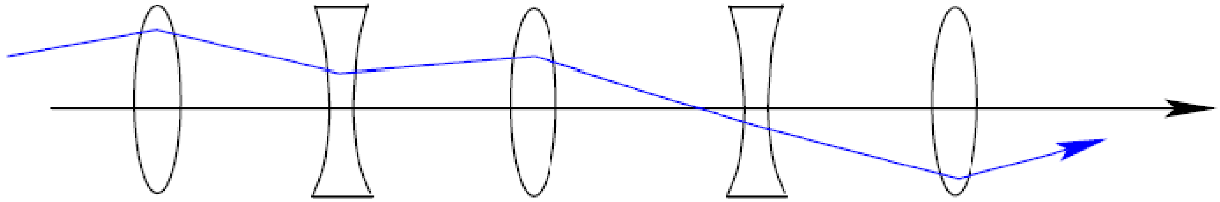
$$F_y = -g \cdot y$$



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 correction.

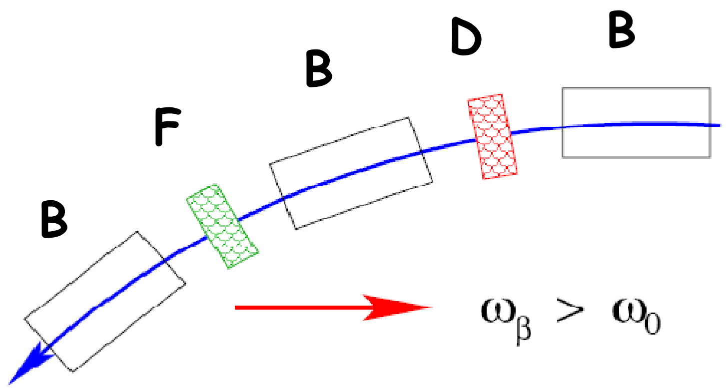
The Focusing System



"Alternate gradient focusing" gives an overall focusing 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

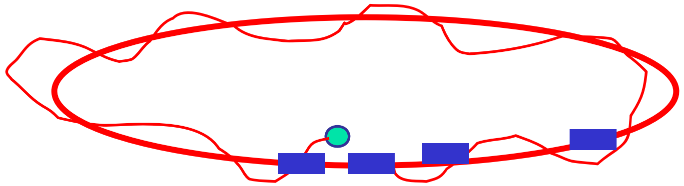
FOCUSING

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!

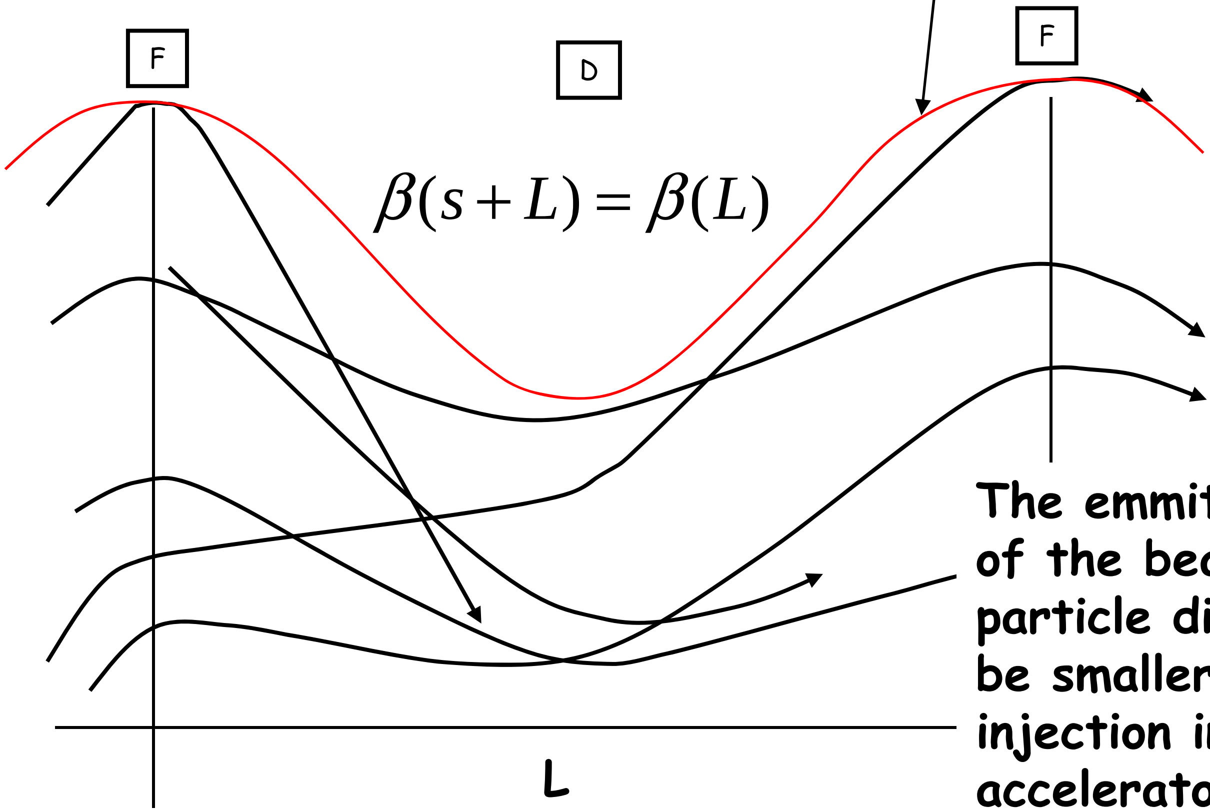
The number of oscillations the particle makes in one turn is called the "tune" and is denoted Q. The Q-value is slightly different in two planes (the horizontal and the vertical planes). L is the circumference of the ring.

The Beta Function

FOCUSING

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

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

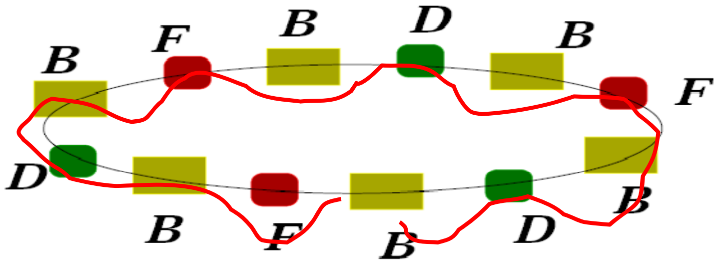


$$\beta(s+L) = \beta(L)$$

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

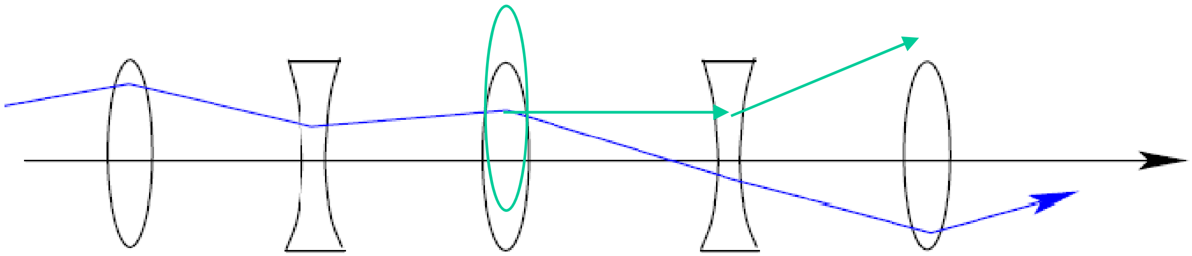
Closed orbit, and field errors

Theoretically the particles oscillate around a nominal, calculated orbit



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

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.



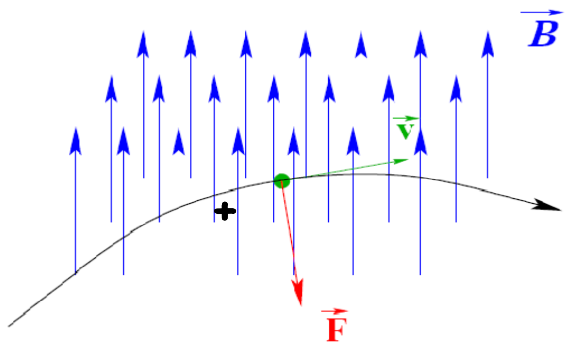
$$F_x = g \cdot x$$

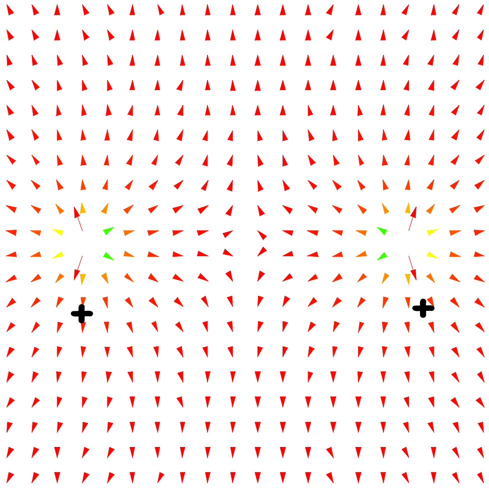
$$F_y = -g \cdot y$$

Effects from other particles: example, space charge

The field felt by a particle may come not only from the magnetic elements but also from the other particles.

If the beam is dense the influence of the coulomb field of other particles may be important.



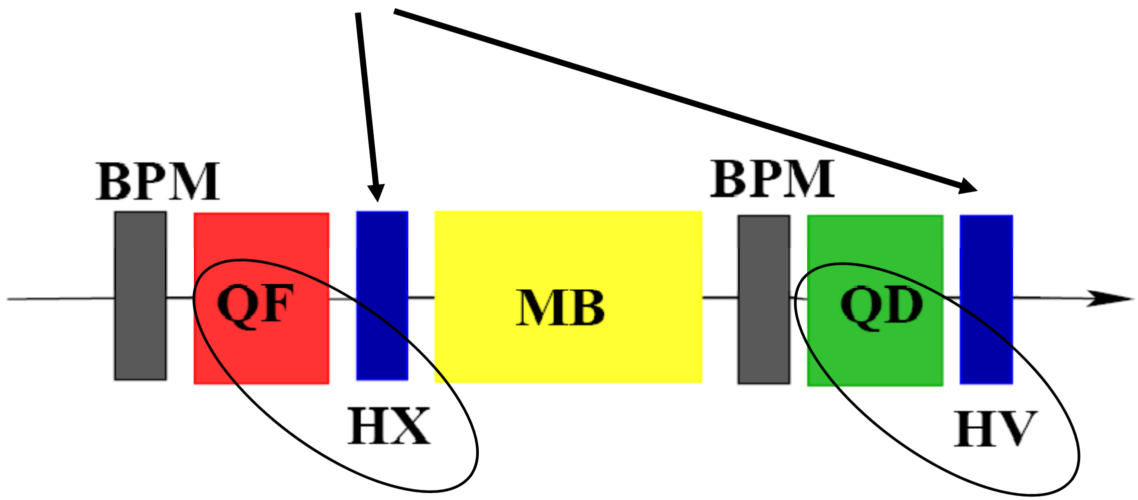


$$\frac{d\vec{p}}{dt} = Q * \left(\vec{E} + \vec{v} \times \vec{B} \right)$$

Correction of the field in the quadrupoles may be needed.

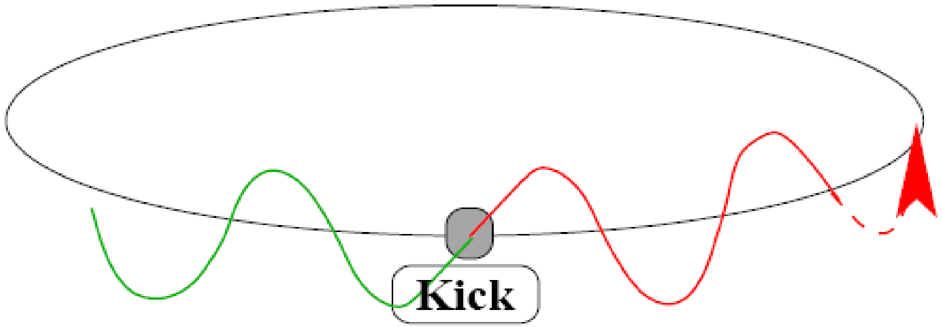
Correctors

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 resonance 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
...

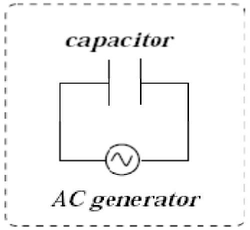
The energy of the particles must correspond to the field in the magnets, to permit the particle to stay in their orbits. Control of the acceleration!

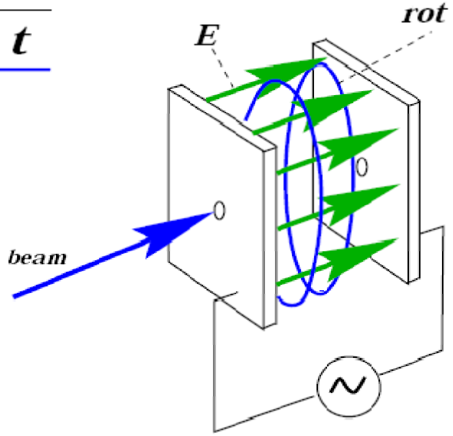
Electrical Fields for Acceleration

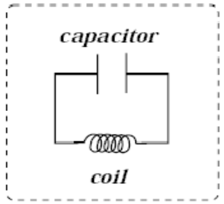
ACCELERATION

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

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



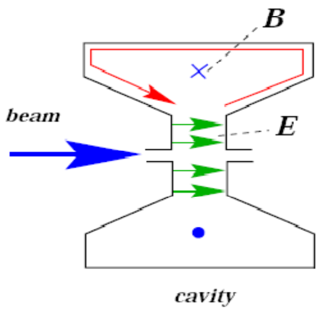


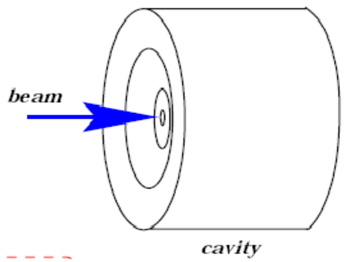


$$L = \frac{\mu_0 \cdot N^2 \cdot A}{l}$$

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

Resonance circuit
Cavity for acceleration

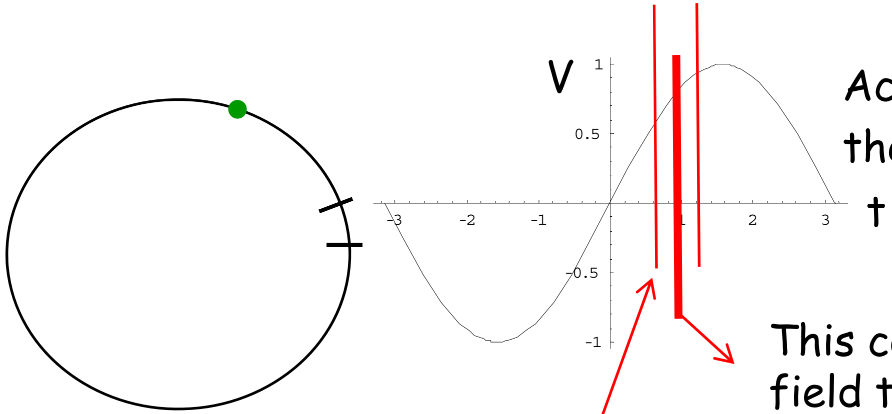




→ $f; Q; R$

The Synchrotron: grouping particles

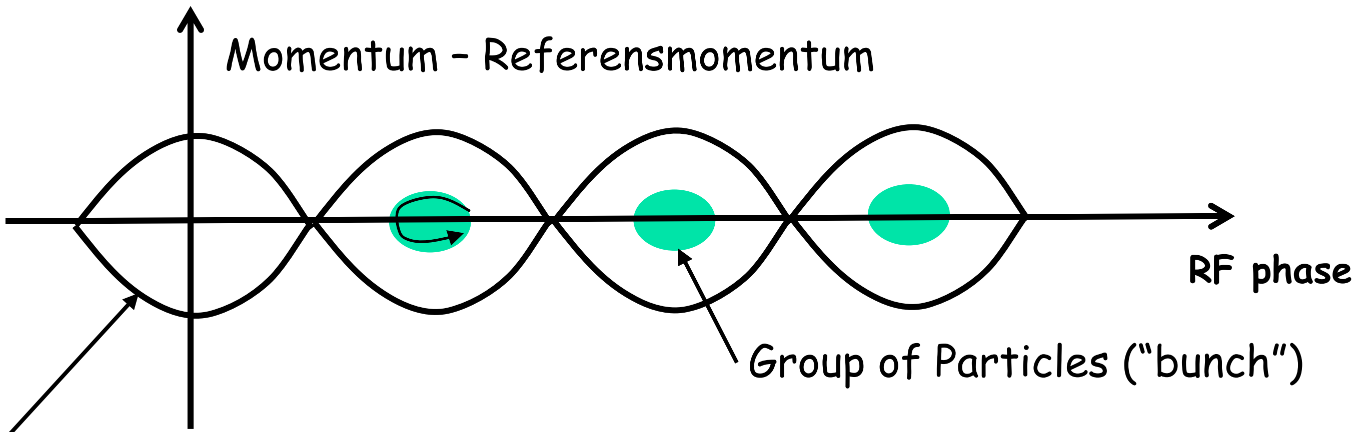
ACCELERATION



Accelerating gap with
the Radio Frequency (RF) voltage

This corresponds to the electical
field the reference particle sees

An early particle gets less energy
increase



Group of Particles ("bunch")

"Bucket": Energy/phase condition for stability

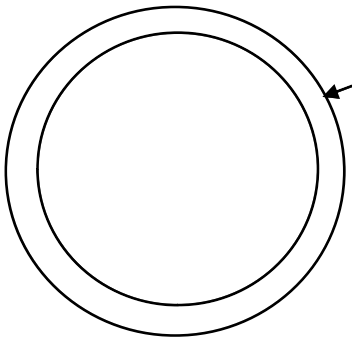
The Synchrotron: Acceleration

Magnetic field B and the velocity v

-> revolution path, the reference trajectory

-> revolution time

-> the time at which the particle enters the RF gap

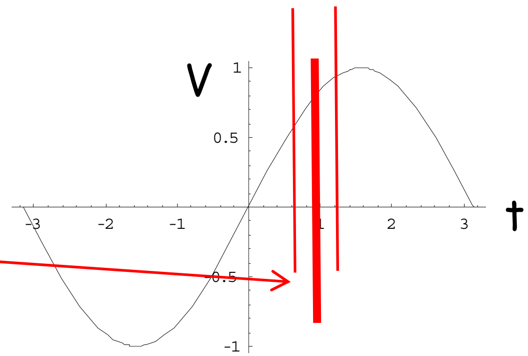


If v increases ->

Radius larger that the ref

Revolution time larger

Not adapted energy correction



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.

$$f = v/(2\pi R_0)$$

Experiment

Targets:

Bombarding material with a beam directed out of the accelerator.

Bubbelchamber

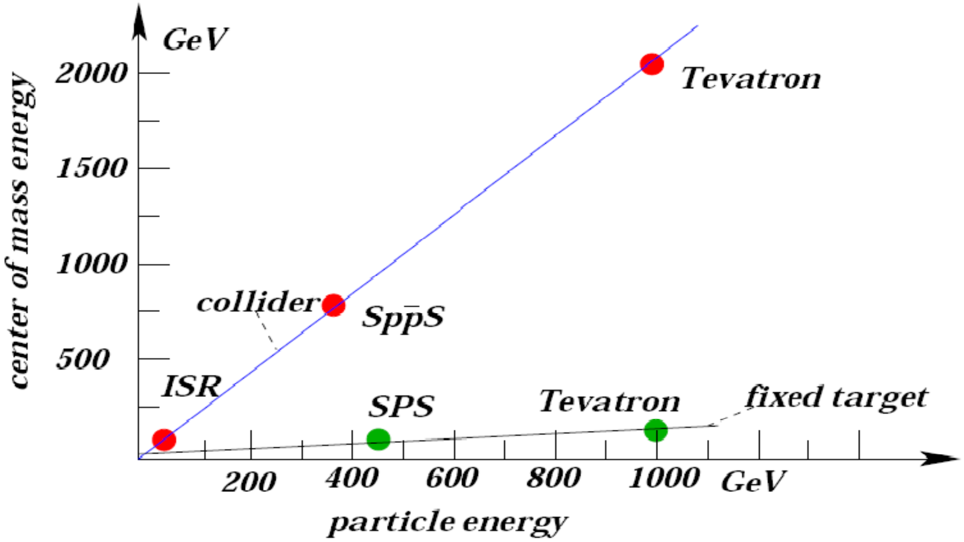
Avaliable energy is calculated in the center of mass of the system (colliding objects)

To collide particle more intersting

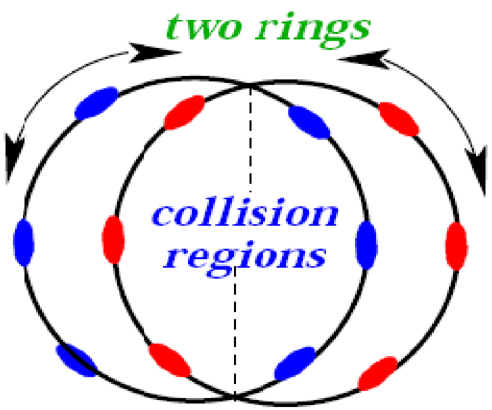
1960: electron/positron collider

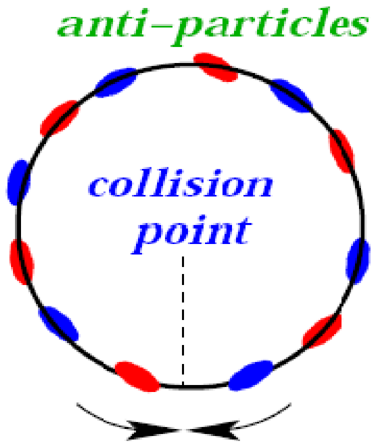
1970: proton antiproton collider

2000: ions, gold



Colliders





- ❑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

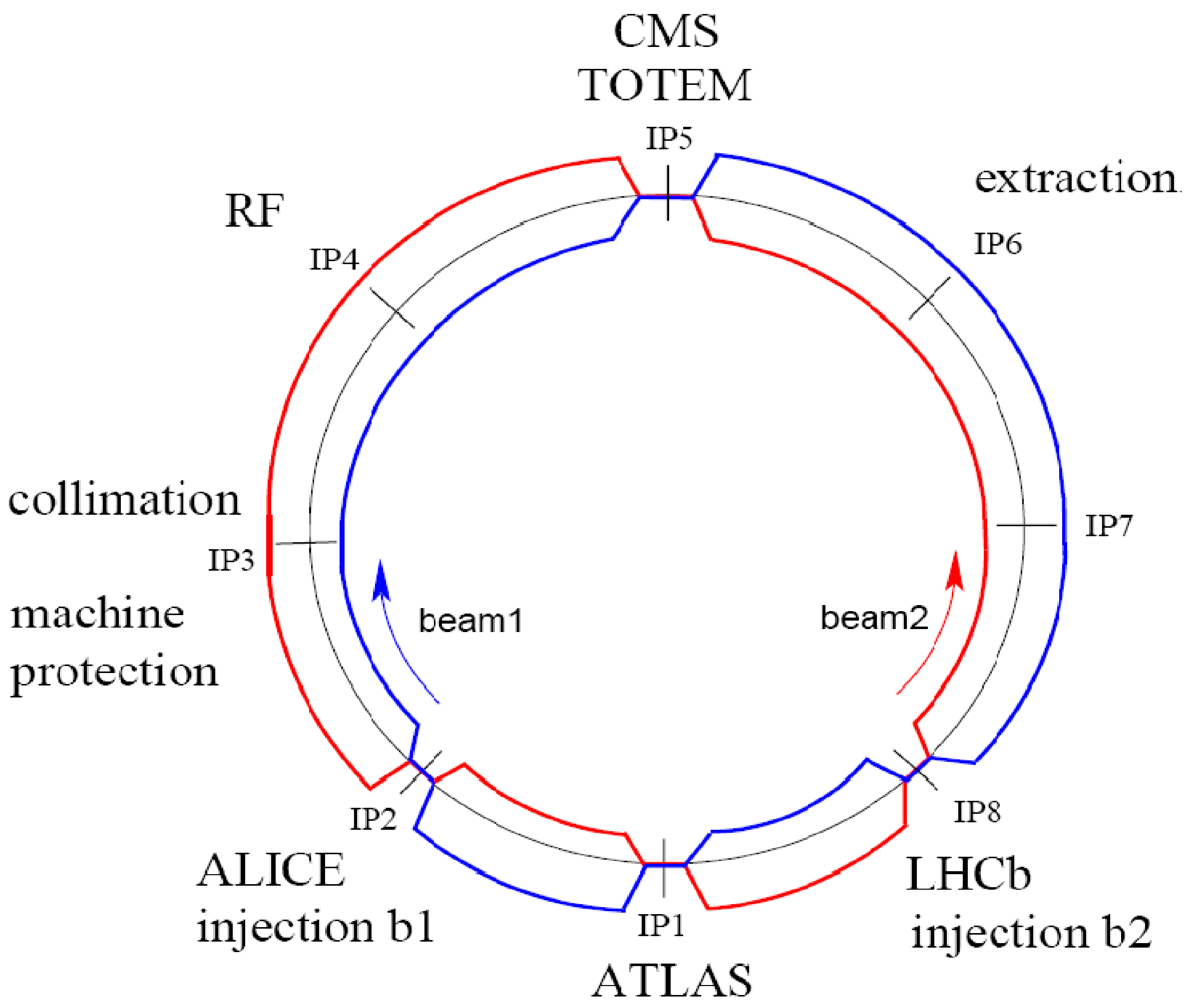
EXPERIMENT

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:**

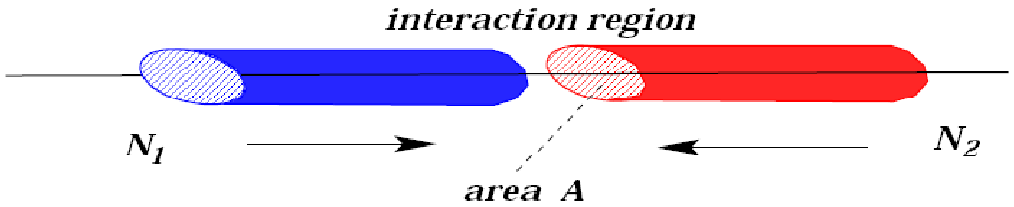
Z_0	1985 $Sp\bar{p}S$	p^+p^-
	1990 LEP	e^+e^-

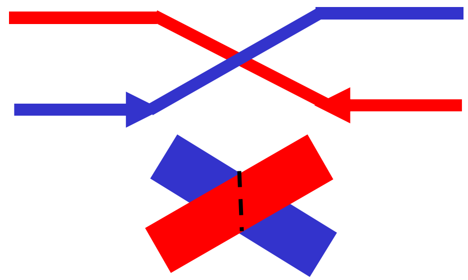
The LHC


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

Luminosity

EXPERIMENT





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

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

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

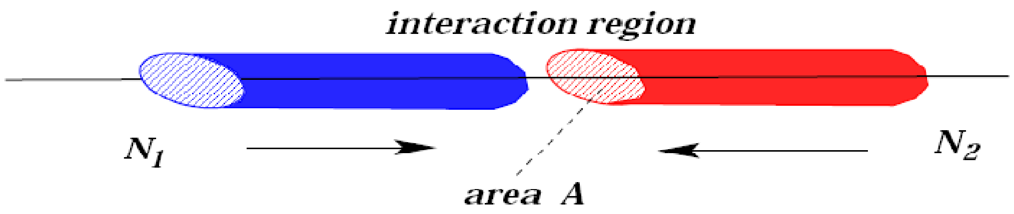
$$L = \frac{N_b^2 n_b f_{rev}}{4\pi \varepsilon \beta *} F$$

- N_b: Number of particles per bunch (two beams)
- n_b: Number of bunches per beam
- f_{rev}: Revolution frequency
- F: Formfactor from the crossing angle
- ε: Emmittence
- $\beta *$: Optical beta function

Luminosity: the beam size

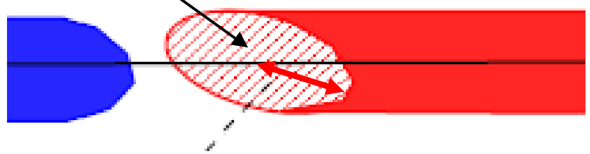
EXPERIMENT

We need a small beam in the collision point

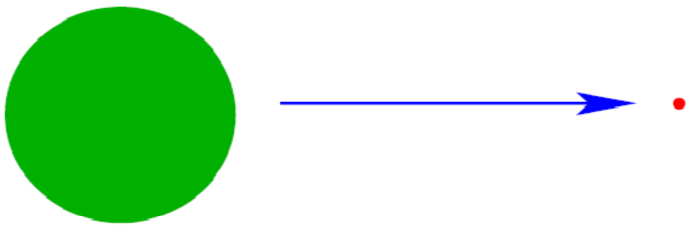


$$L = \frac{N_b^2 n_b f_{rev}}{4\pi\varepsilon\beta *} F$$

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



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

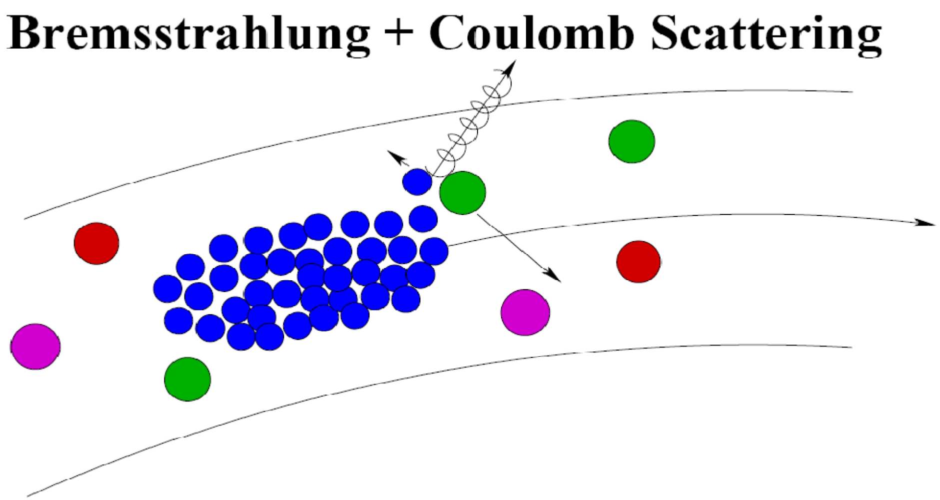
Radio signals and x-ray

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

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

Vacuum

TECHNOLOGY



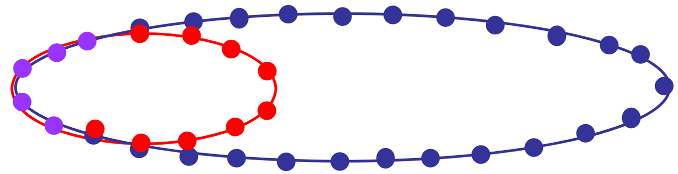
- "Blow up" of the beam
- Particle losses
- Non wanted collisions in the experiments
- Limits the Luminosity

Superconducting Technology 1

TECHNOLOGY

Why superconducting magnets?

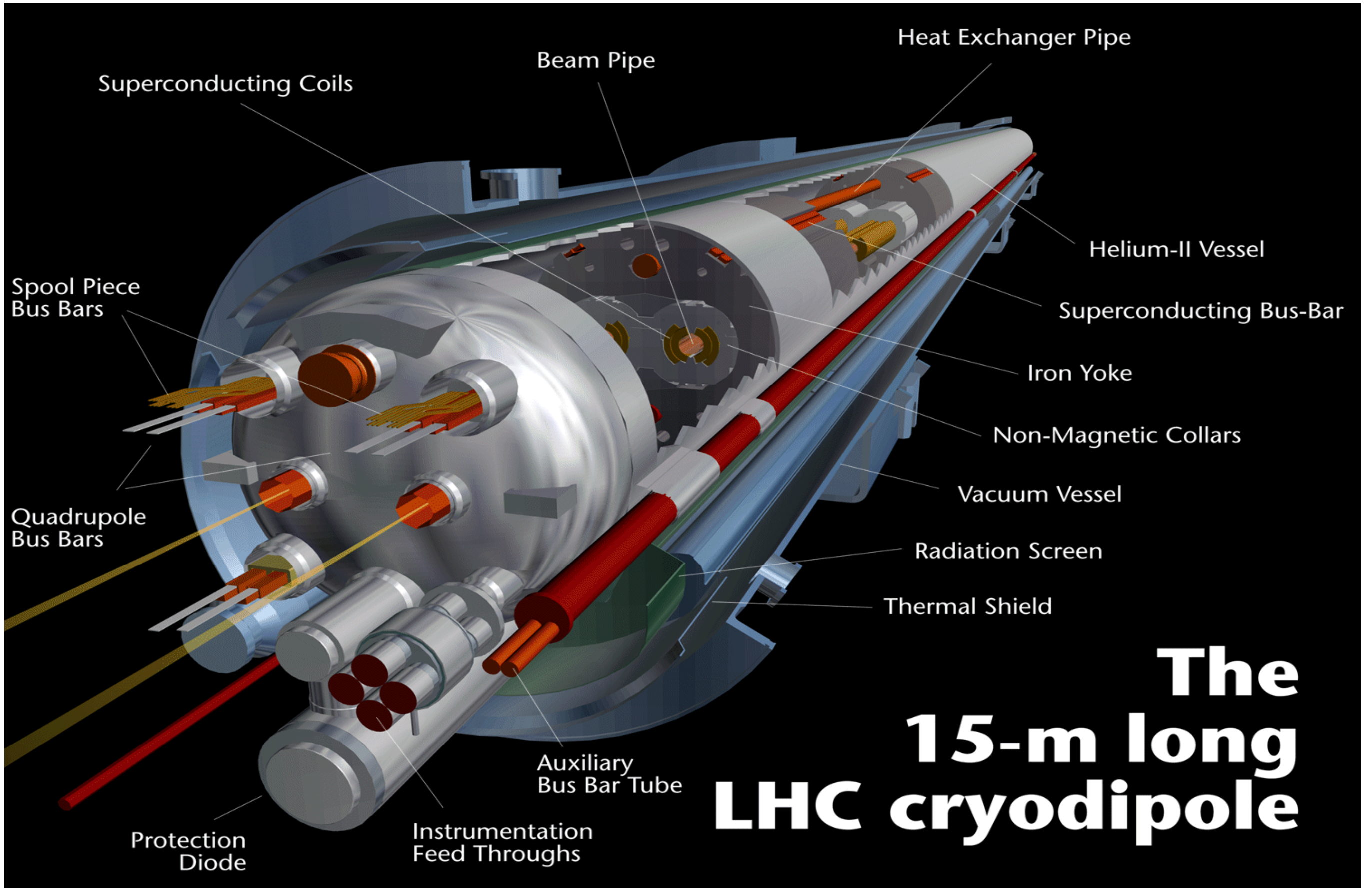
Small radius, less number of particles in the machine, smaller machine



Energy saving, BUT infrastructure very complex

The Superconducting Dipole for LHC

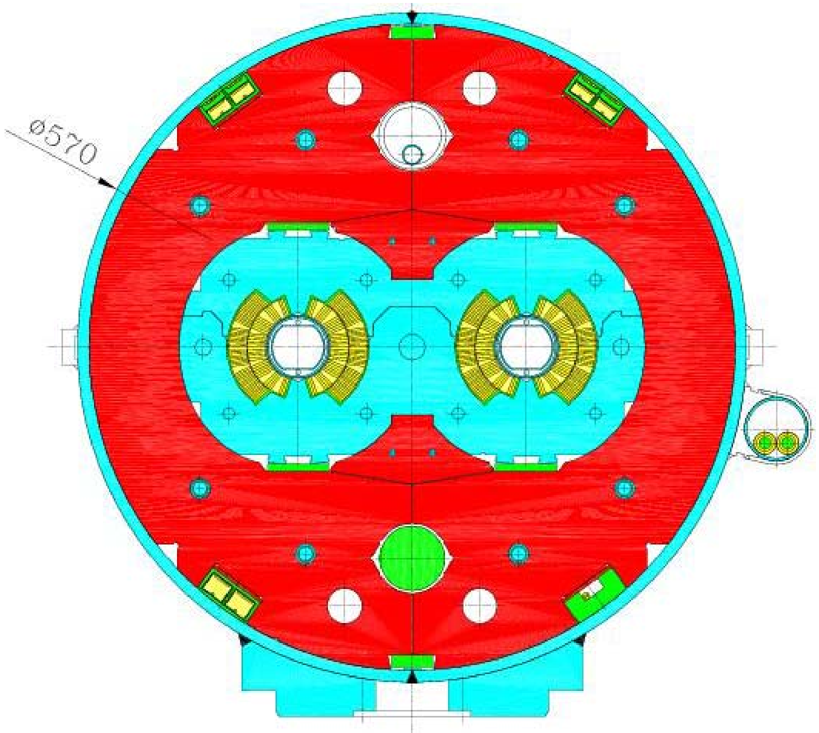
LHC dipole (1232 + reserves) built in 3 firms (Germany France and Italy, very large high tech project)

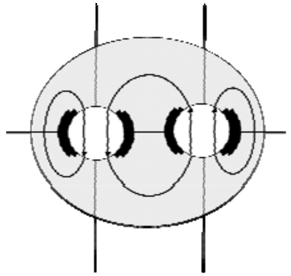


TECHNOLOGY

The LHC Dipole

TECHNOLOGY





"Two in one" construction

Working temperature
1.9 K !

Coldest spot i the universe...

Future accelerators

TECHNOLOGY

High Energy physics applications:

LHC upgrade

- Luminosity one order of magnitude higher
- Insertion regions will change
- Deposition in magnets of energy and debris
- New superconductors

Linear Colliders

- Cost proportional to beam energy, for circular machines proportional to the square of the beam energy
- International Linear Collider (ILC), 35 km, 500 GeV, electron-positron
- Compact Linear Collider (CLIC), 38 km, 3 TeV, electron-positron

Example: LHC 1

EXAMPLE: LHC

Table 2.1: LHC beam parameters relevant for the peak luminosity

		Injection	Collision
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5[a]
Transverse normalized emittance	[μm rad]	3.5[b]	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
Peak Luminosity Related Data			
RMS bunch length[c]	cm	11.24	7.55
RMS beam size at the IP1 and IP5[d]	μm	375.2	16.7
RMS beam size at the IP2 and IP8[e]	μm	279.6	70.9
Geometric luminosity reduction factor F[f]		-	0.836
Peak luminosity in IP1 and IP5	[$\mathrm{cm^{-2}sec^{-1}}$]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[$\mathrm{cm^{-2}sec^{-1}}$]	-	3.56×10^{30}

Exempel: LHC 2

EXEMPEL: LHC

Table 2.1: LHC beam parameters relevant for the peak luminosity

		Injection	Collision
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5^a
Transverse normalized emittance	[μm rad]	3.5^b	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
Peak Luminosity Related Data			
RMS bunch length^c	cm	11.24	7.55
RMS beam size at the IP1 and IP5^d	μm	375.2	16.7
RMS beam size at the IP2 and IP8^e	μm	279.6	70.9
Geometric luminosity reduction factor F^f		-	0.836
Peak luminosity in IP1 and IP5	[cm^{-2}sec^{-1}]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[cm^{-2}sec^{-1}]	-	3.56×10^{30}

Exempel: LHC 3

EXEMPEL: LHC

Table 2.1: LHC beam parameters relevant for the peak luminosity

		Injection	Collision
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5[a]
Transverse normalized emittance	[μm rad]	3.5[b]	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
Peak Luminosity Related Data			
RMS bunch length[c]	cm	11.24	7.55
RMS beam size at the IP1 and IP5[d]	μm	375.2	16.7
RMS beam size at the IP2 and IP8[e]	μm	279.6	70.9
Geometric luminosity reduction factor F[f]		-	0.836
Peak luminosity in IP1 and IP5	[$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	-	3.56×10^{30}

Exempel: LHC 4

EXEMPEL: LHC

Table 2.1: LHC beam parameters relevant for the peak luminosity

		Injection	Collision
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5[a]
Transverse normalized emittance	[μm rad]	3.5[b]	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
Peak Luminosity Related Data			
RMS bunch length[c]	cm	11.24	7.55
RMS beam size at the IP1 and IP5[d]	μm	375.2	16.7
RMS beam size at the IP2 and IP8[e]	μm	279.6	70.9
Geometric luminosity reduction factor F[f]		-	0.836
Peak luminosity in IP1 and IP5	[$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	-	3.56×10^{30}

Exempel: LHC 5

EXEMPEL: LHC

Table 2.1: LHC beam parameters relevant for the peak luminosity

		Injection	Collision
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5[a]
Transverse normalized emittance	[μm rad]	3.5[b]	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
Peak Luminosity Related Data			
RMS bunch length[c]	cm	11.24	7.55
RMS beam size at the IP1 and IP5[d]	μm	375.2	16.7
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Geometric luminosity reduction factor F[f]		-	0.836
Peak luminosity in IP1 and IP5	[$cm^{-2}sec^{-1}$]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[$cm^{-2}sec^{-1}$]	-	3.56×10^{30}

Arcs: ~ 1 mm transversellt

Exempel: LHC 6

Table 2.1: LHC beam parameters relevant for the peak luminosity

		Injection	Collision
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5[a]
Transverse normalized emittance	[μm rad]	3.5[b]	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
Peak Luminosity Related Data			
RMS bunch length[c]	cm	11.24	7.55
RMS beam size at the IP1 and IP5[d]	μm	375.2	16.7
RMS beam size at the IP2 and IP8[e]	μm	279.6	70.9
Geometric luminosity reduction factor F[f]		-	0.836
Peak luminosity in IP1 and IP5	[$cm^{-2}sec^{-1}$]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[$cm^{-2}sec^{-1}$]	-	3.56×10^{30}

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