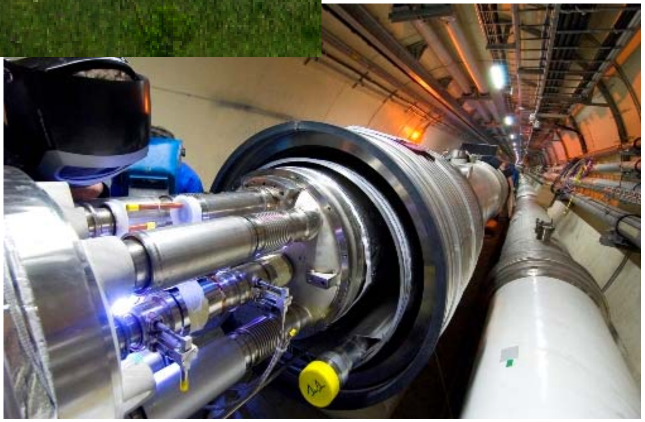
Introduction to Accelerators
Overview



Elena Wildner

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Application Areas

INTRODUCTION

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    Synchrotron Light
    Material Surface
- Medicine
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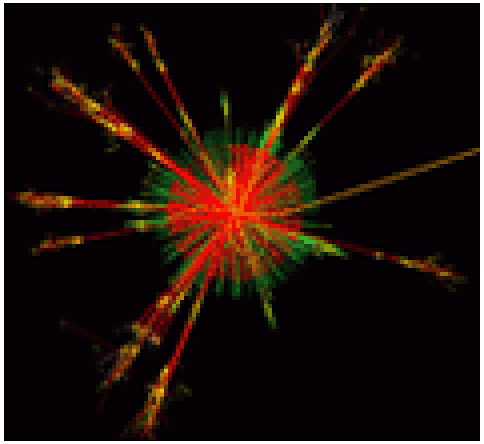
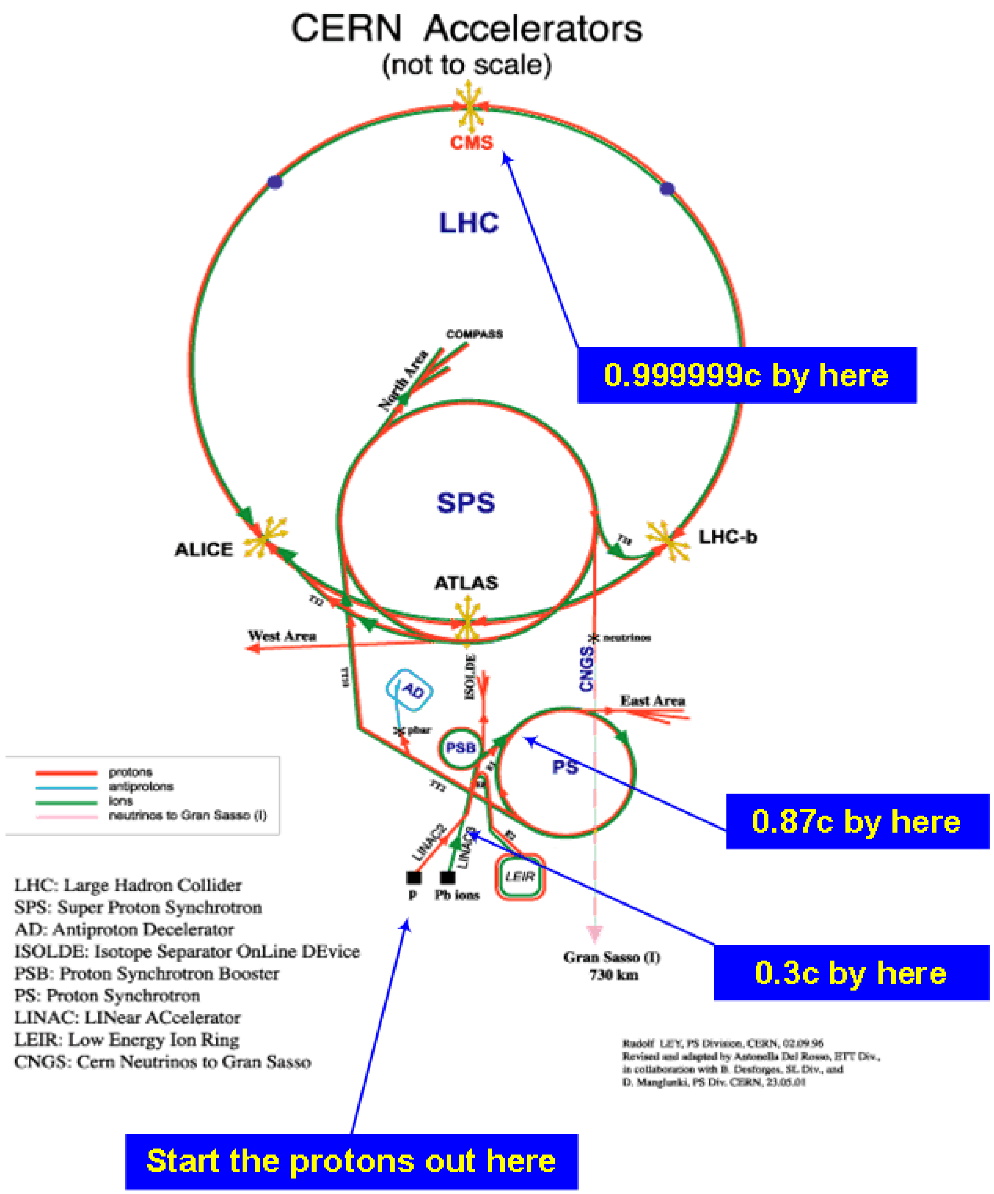
  - Protons and Ions
- Food treatment
- Physics
  - Collisions
  - Neutrino production…
- Etc.



Accelerators and LHC experiments at CERN



Energies:

Linac 50 MeV

PSB 1.4 GeV

PS 28 GeV

SPS 450 GeV

LHC 7 TeV

Units?

Units, Energy and Momentum

Einstein's relativity formula:We all might know the units **Joules** and **Newton meter** but here we are talking about **eV**….!?

If we push a block over a distance of **1 meter** with a force of **1 Newton**, we use **1 Joule** of energy.

Thus : **1 Nm = 1 Joule**

The **energy** acquired by an **electron** in a potential of **1 Volt** is defined as being **1 eV**.

1 eV is **1 elementary charge** 'pushed' by **1 Volt**.

Thus : **1 eV = 1.6 x 10^{-19} Joules**.

The unit eV is too small to be used currently, we use:

1 KeV = 10^3 eV; 1MeV = 10^6 eV; 1GeV=10^9…………

Relativity

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

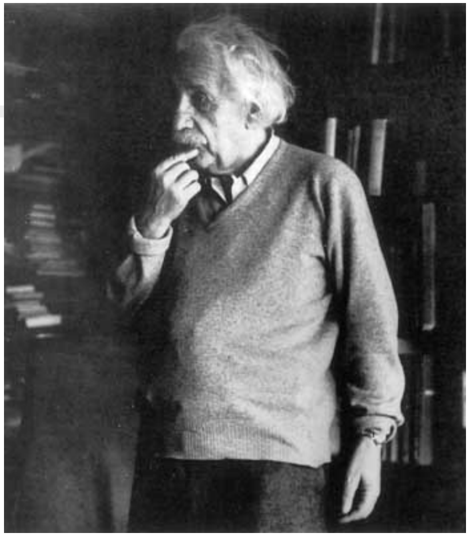
then we must consider relativistic effects

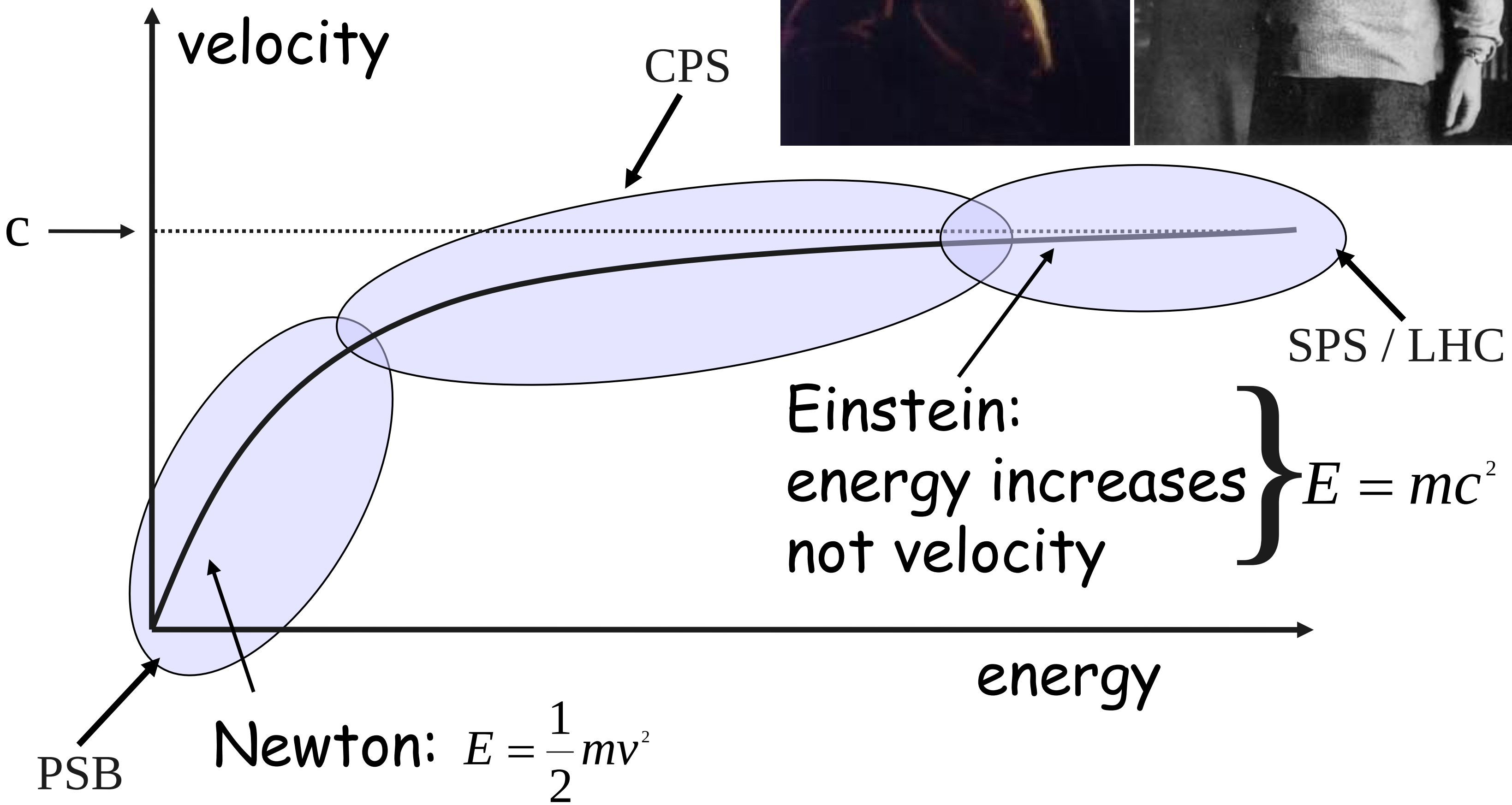
$$\gamma = 1/\sqrt{1-\beta^2}; \quad \beta = v/c$$

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

Total Energy **Rest Mass**

Relativity




velocity
CPS
c
SPS / LHC
Einstein:
energy increases
not velocity
$E = mc^2$
energy
PSB
Newton: $E = \frac{1}{2}mv^2$

Energy and Momentum

Einstein's relativity formula: $E = mc^2$

- For a mass at rest this will be: $E_0 = m_0 c^2$

Rest mass

Rest energy

- Define: $\gamma = \frac{E}{E_0}$ As being the ratio between the total energy and the rest energy
- Then the mass of a moving particle is: $m = \gamma m_0$
- Define: $\beta = \frac{v}{c}$,then we can write: $\beta = \frac{mvc}{mc^2}$
- $p = mv$,which is always true and gives: $\beta = \frac{pc}{E}$ or $p = \frac{E\beta}{c}$

Units, Energy and Momentum

However:

Energy

$$p = \frac{E\beta}{c}$$

Momentum

Therefore the **units** for **momentum** are GeV/c…etc.

Attention:

when **β=1** **energy** and **momentum** are **equal**,

when **β <1** the **energy** and **momentum** are **not equal**.

Units, Example PS injection

Kinetic energy at injection $E_{kinetic}$ = 1.4 GeV.

Proton rest energy E_0=938.27 MeV.

The total energy is then: $E = E_{kinetic} + E_0$ =**2.338GeV**.

We know that $\gamma = \frac{E}{E_0}$, which gives γ = 2.4921.

We can derive $\beta = \sqrt{1 - \frac{1}{\gamma^2}}$, which gives **β = 0.91597**.

Using $p = \frac{E\beta}{c}$ we get p = **2.14 GeV/c**

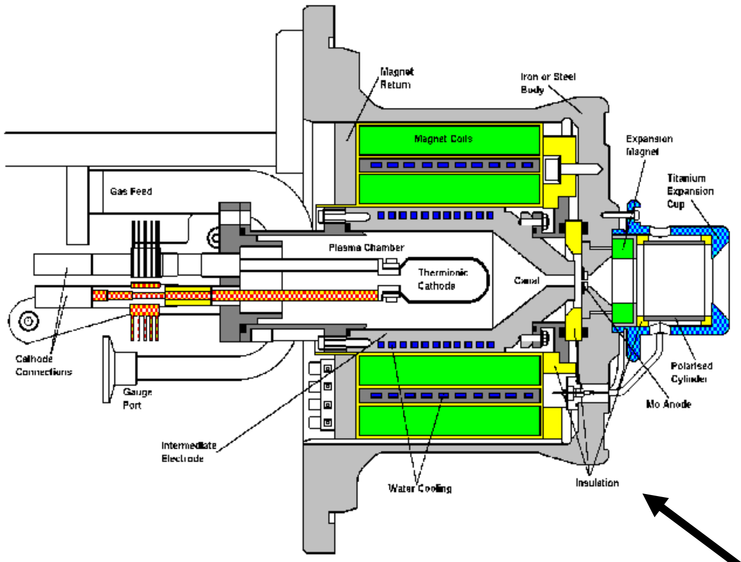
In this case: **Energy ≠ Momentum**

Particle Sources and acceleration

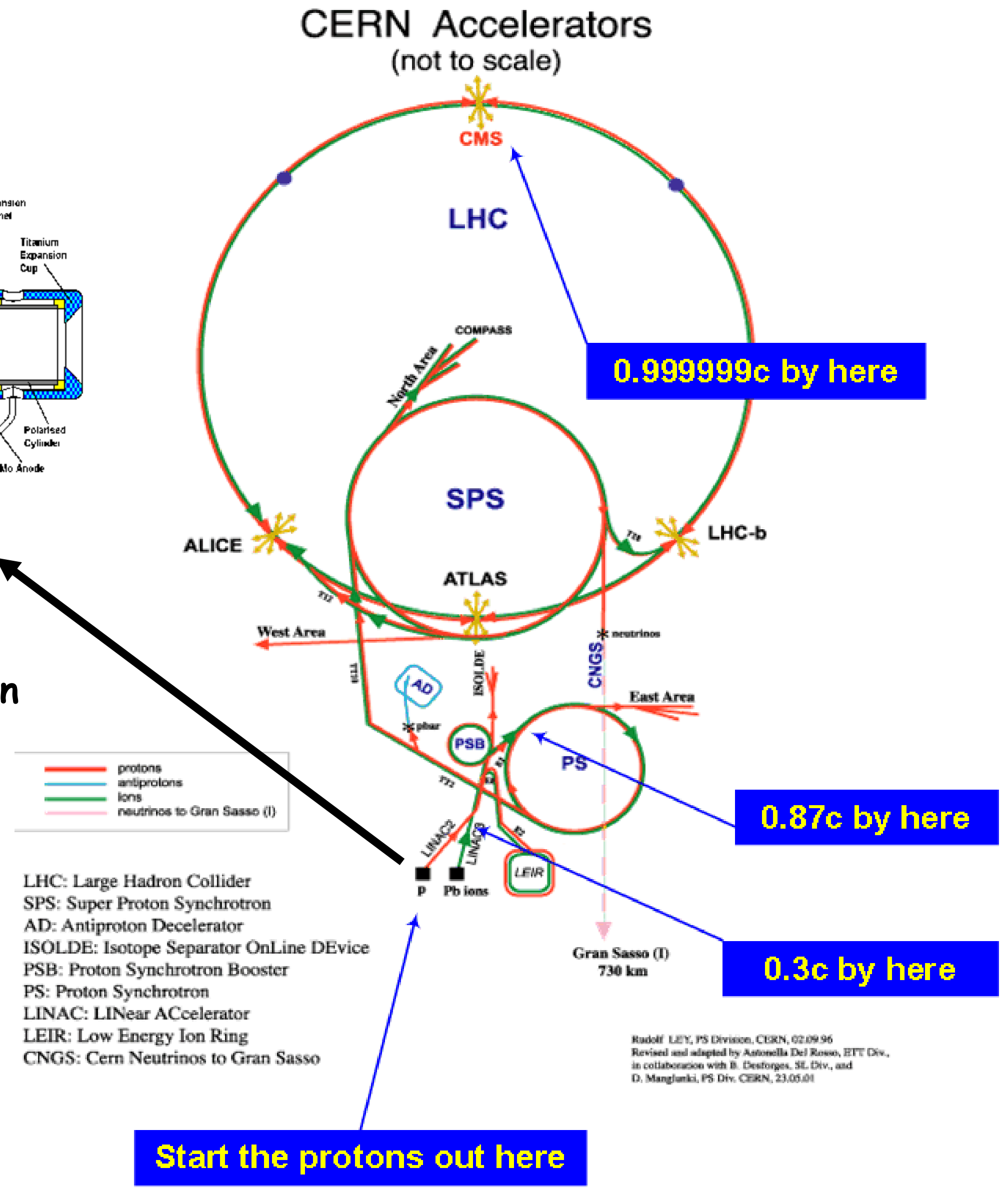
- Natural Radioactivity: alfa particles and electrons. Alfa particles have an energy of around 5 MeV (corresponds to a speed of ~15,000 km/s).
- Production of particles: Particle sources
- Electrostatic fields are used for the first acceleration step after the source
- Linear accelerators accelerate the particles using Radio Frequency (RF) Fields
- Circular accelerators use RF and electromagnetic fields. Protons are today (2008?) 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

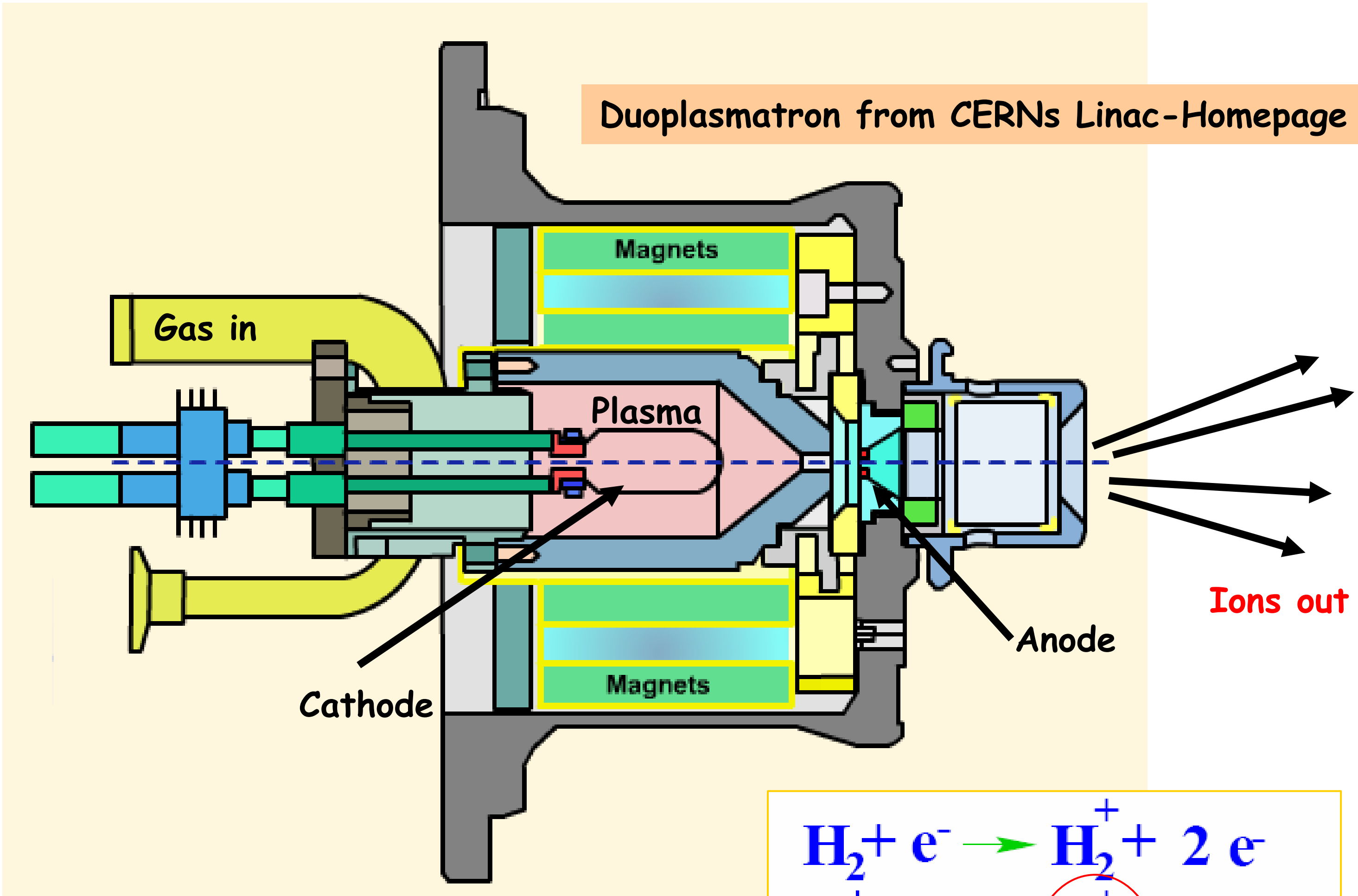
THE ACCELERATOR CHAIN



Duoplasmatron for proton production



Particle Sources 2

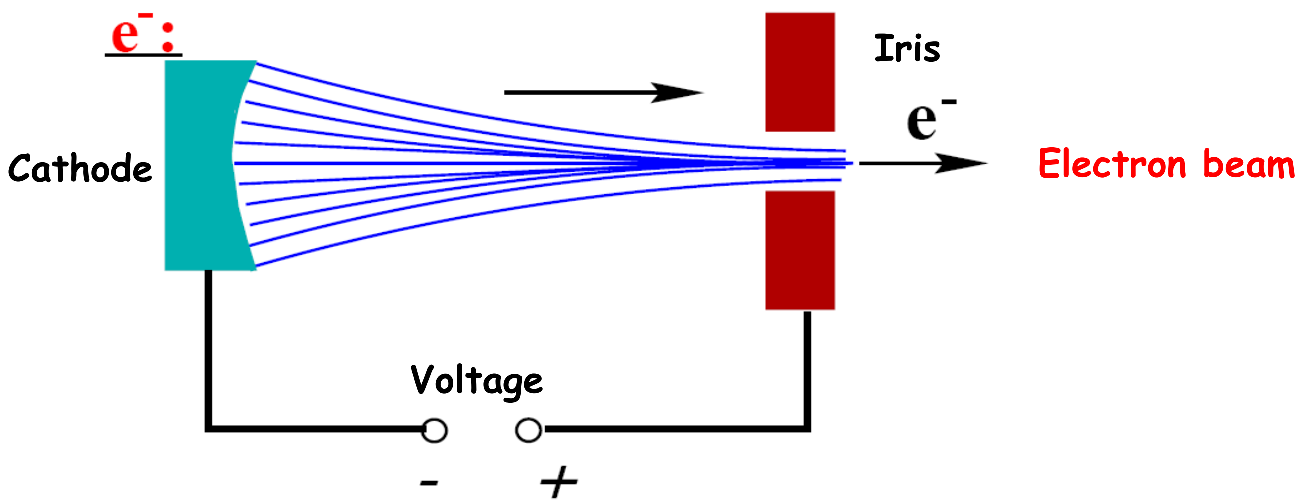


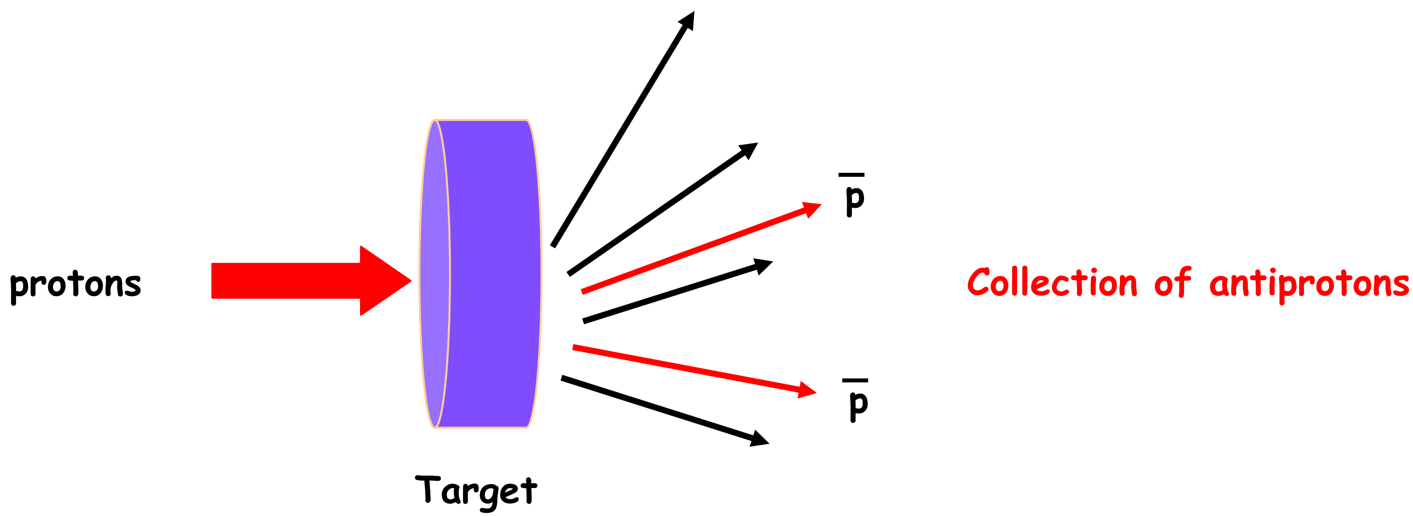
$$H_2 + e^- \rightarrow H_2^+ + 2e^-$$

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

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

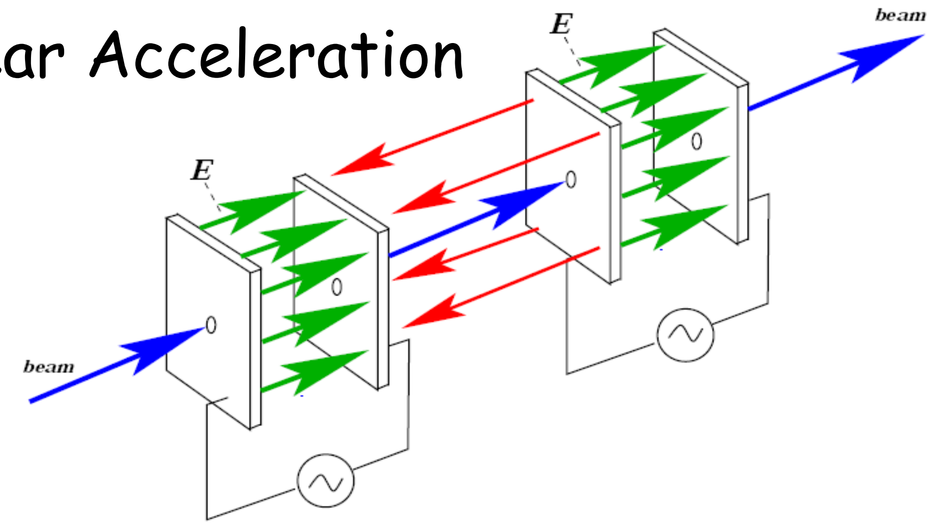
Particle Sources 3



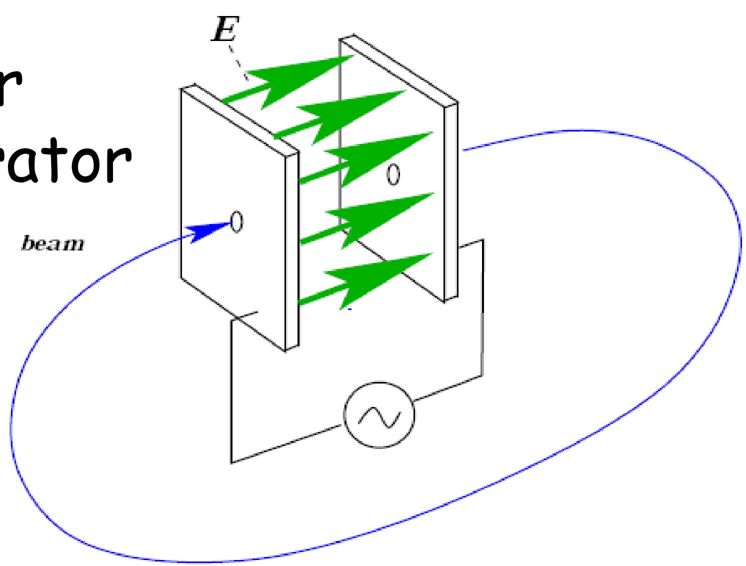


Time Varying Electrical Fields

Linear Acceleration



Circular accelerator

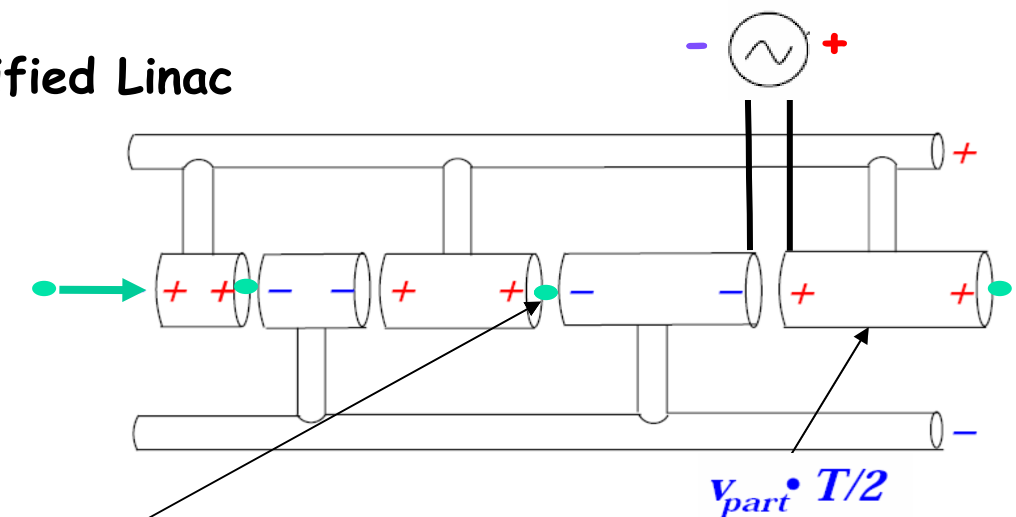


Linear accelerators

Simplified Linac

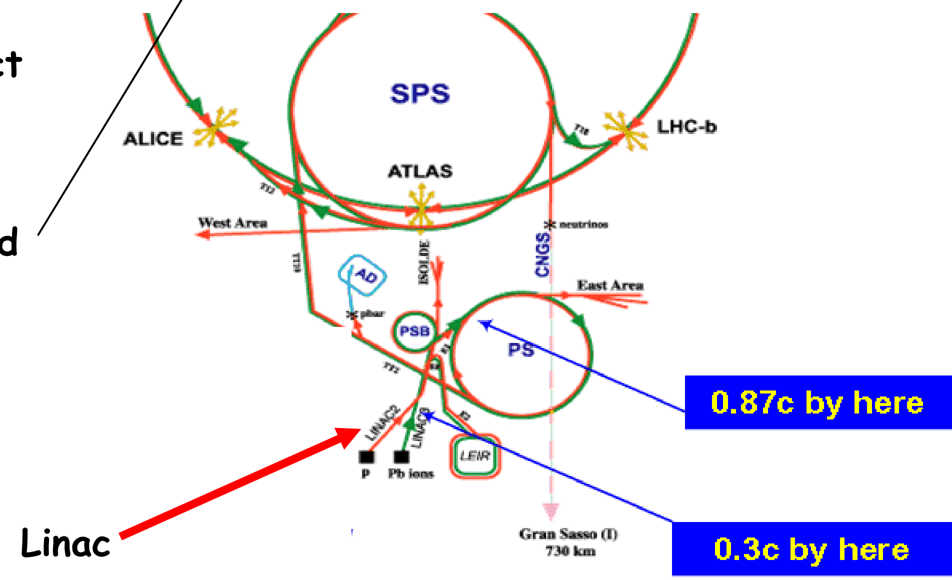
Wideroe

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:

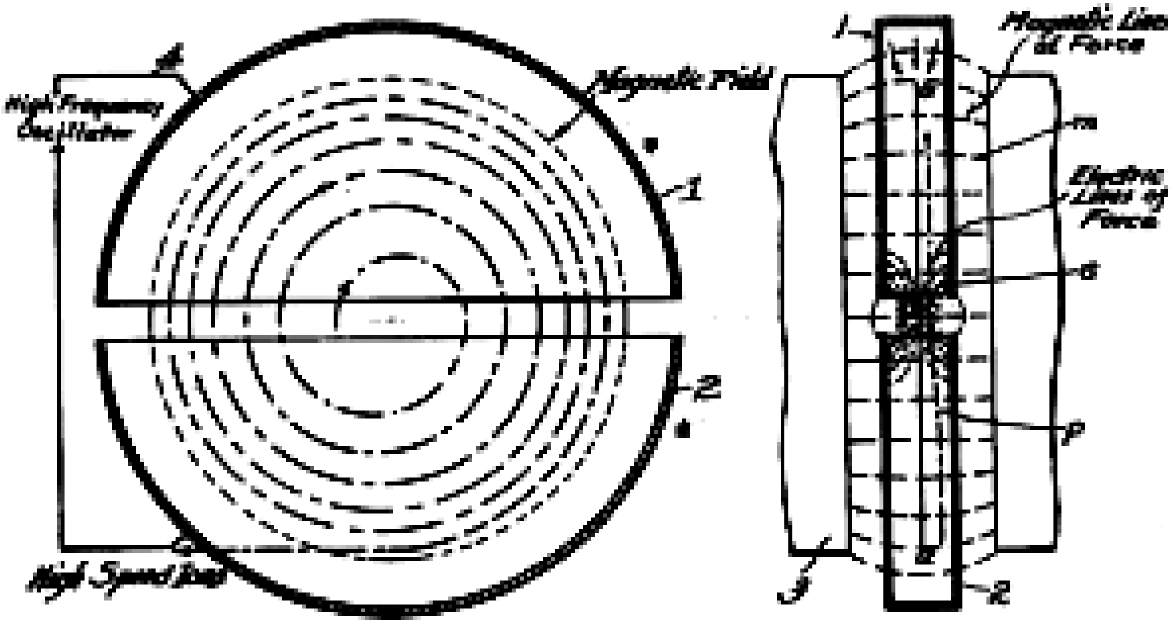
$$\frac{v}{r} = \frac{Bq}{m}$$

$$\downarrow$$

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

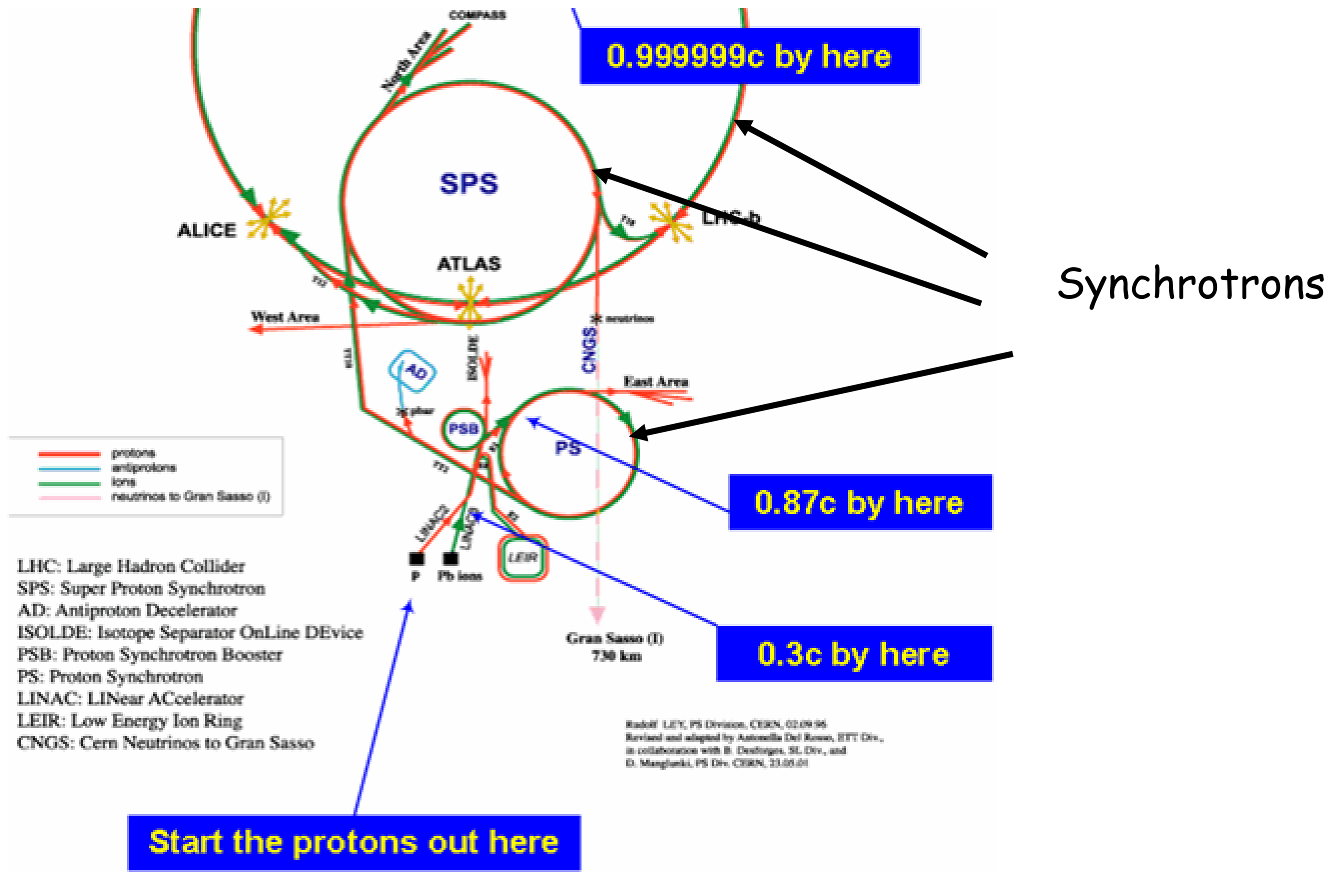
$$f = \frac{\omega}{2\pi}$$

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



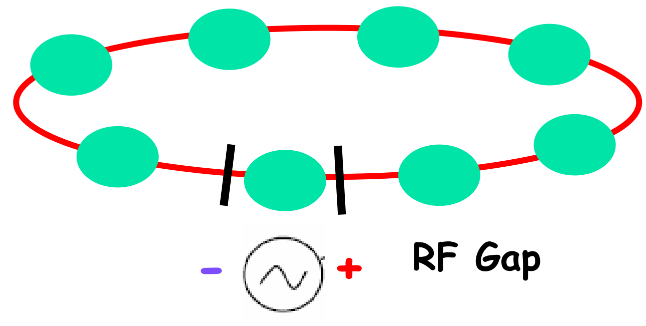
The frequency does not depend on the radius, if the mass is contant. When the particles become relativistic this is not valid any more. The frequency must change with the particle velocity: synchrocyclotron. The field can also change with the radius: isochronous cyclotron

Synchrotrons at CERN



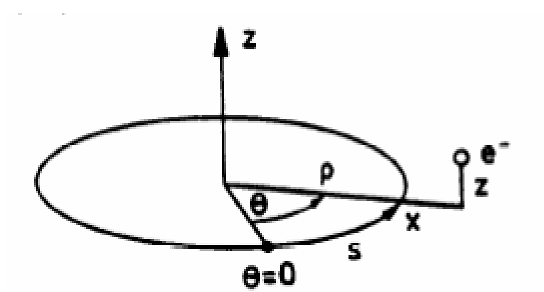
The Synchrotron

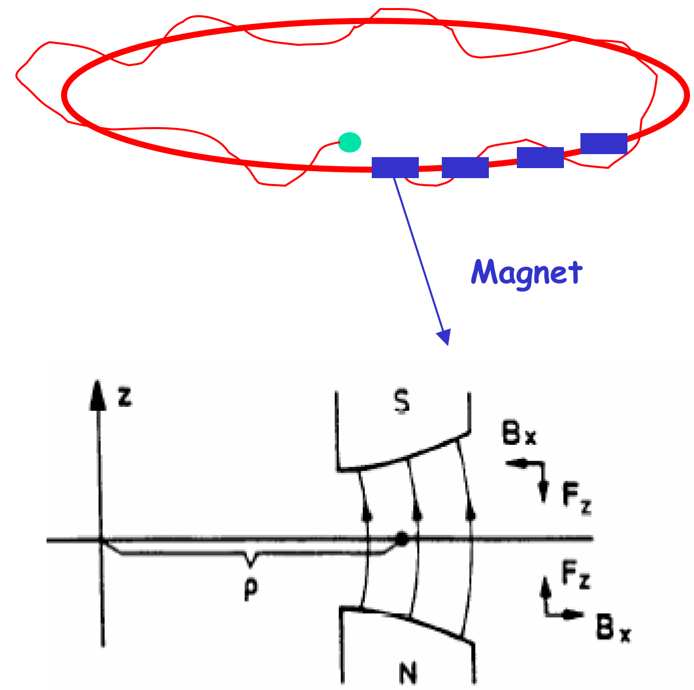
HOW TO KEEP THE BEAM IN PLACE



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

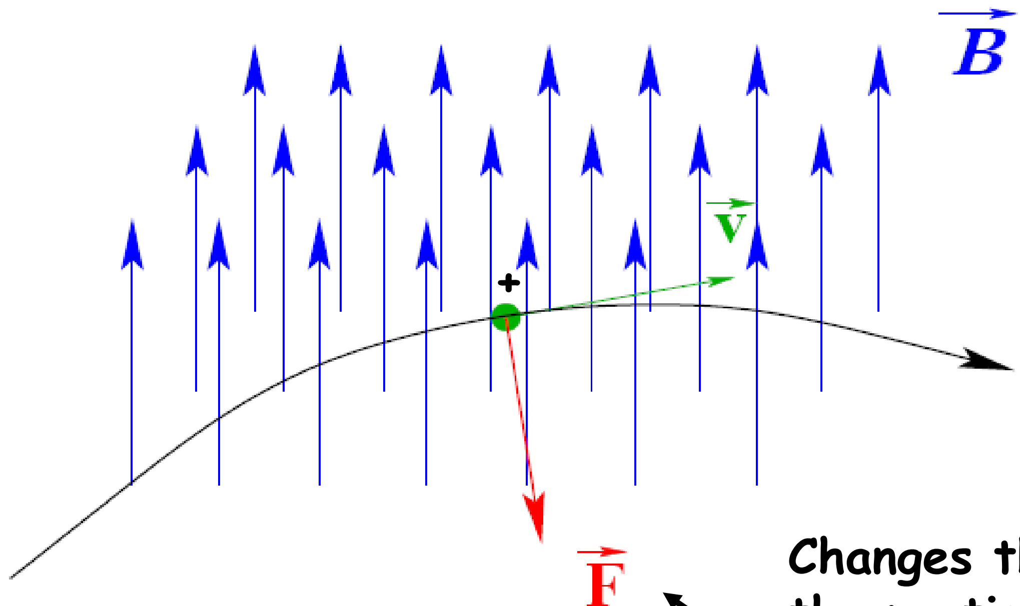
Each particle is circulating around an ideal (theoretical) orbit: for this to work out, acceleration and magnet fields must obey stability criteria!!





Forces on the particles

STEERING



Changes the direction of the particle

Lorentz:

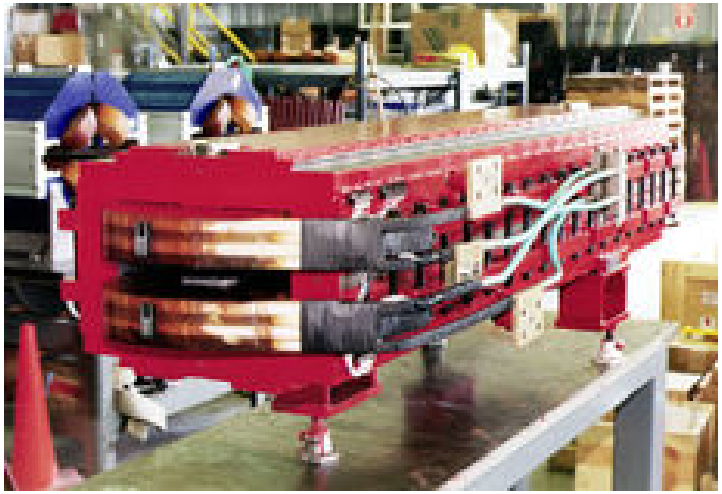
$$\frac{d\vec{p}}{dt} = Q * \left(\vec{E} + \vec{v} \times \vec{B} \right)$$

Accelerates the particles

The Dipole

STEERING

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



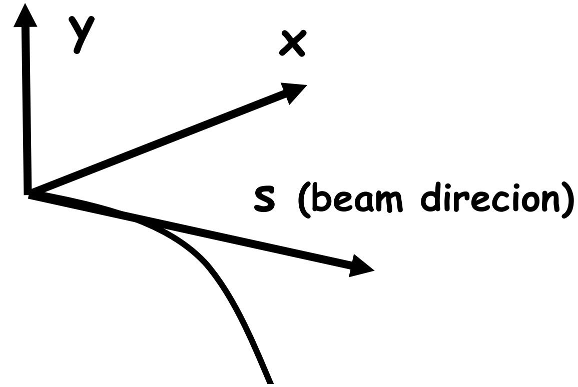
$$F_x = -ev_s B_y$$

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

$$p = mv_s$$

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

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



"Magnetic rigidity": 3.3356 p [Tm] with units GeV/c for momentum

Brho for ions

STEERING

Isotope	Mass excess keV	A	gamma	q=Z	Total electron binc eV	beta	m0 (atomic) GeV/c²	m0(fully stripped) GeV/c²
6He	17595.1	6	100	2	79.00474851	0.999949999	5.606559	5.605537
6Li	14086.793	6	100	3	203.4847994	0.999949999	5.603051	5.601518
18Ne	5317.17	18	100	10	3511.631932	0.999949999	16.772210	16.767103
18F	1121.36	18	100	9	2715.858189	0.999949999	16.768014	16.763418
19Ne	1751.44	19	100	10	3511.631932	0.999949999	17.700138	17.695031
19F	-1487.39	19	100	9	2715.858189	0.999949999	17.696899	17.692303
8Li	20946.84	8	100	3	203.4847994	0.999949999	7.472899	7.471366
4He	2425.9156	4	100	2	79.00474851	0.999949999	3.728402	3.727380
8B	22921.5	8	100	5	670.9817282	0.999949999	7.474874	7.472319
4He	2425.9156	4	100	2	79.00474851	0.999949999	3.728402	3.727380

dm/m0 (total)	dm/m0 (Eeb)	p GeV/c	B*rho T.m	T GeV	mass in nmu nmu	B T
1.8E-04	1.4E-08	560.525707	934.8563	554.948198	6.019441	6.00541757
2.7E-04	3.6E-08	560.123808	622.7906	554.550299	6.015125	4.00074111
3.0E-04	2.1E-07	1676.62648	559.2624	1659.94322	18.005158	3.59264241
2.7E-04	1.6E-07	1676.25794	621.2661	1659.57834	18.001200	3.99094745
2.9E-04	2.0E-07	1769.41467	590.2132	1751.80812	19.001602	3.79146713
2.6E-04	1.5E-07	1769.14182	655.6913	1751.53798	18.998672	4.21209164
2.1E-04	2.7E-08	747.099269	830.6850	739.665261	8.023039	5.33623231
2.7E-04	2.1E-08	372.719374	621.6290	369.010631	4.002604	3.99327889
3.4E-04	9.0E-08	747.194578	498.4746	739.759621	8.024063	3.20214783
2.7E-04	2.1E-08	372.719374	621.6290	369.010631	4.002604	3.99327889

The Dipole

STEERING

A dipole with a uniform dipolar field deviates a particle by an angle θ.

The deviation angle θ depends on the length L and the magnetic field B.

The angle θ can be calculated:

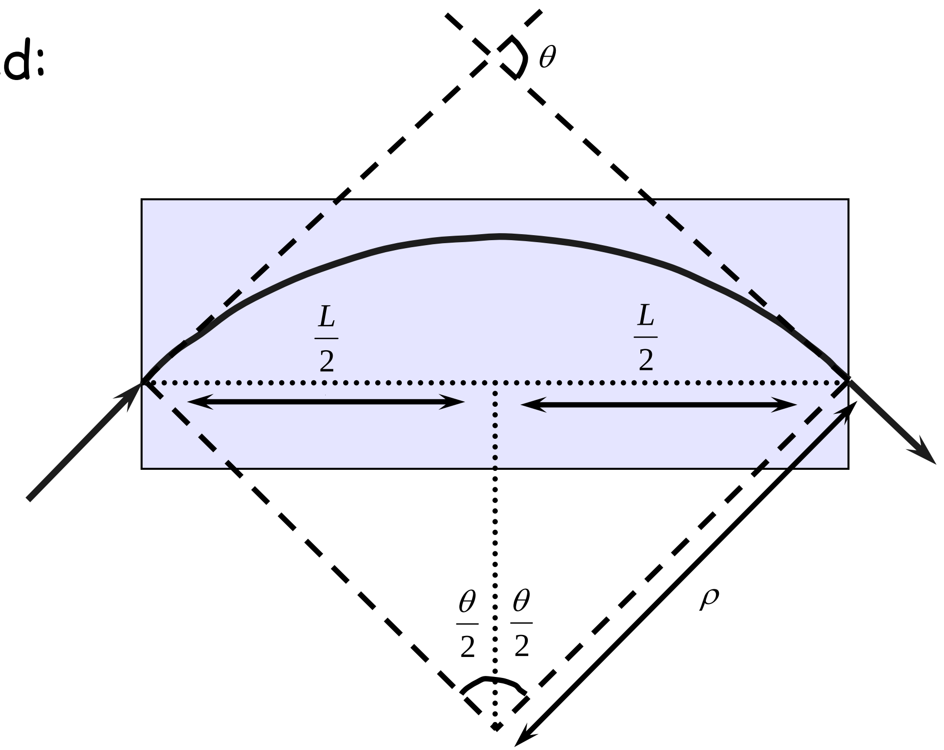
$$\sin\left(\frac{\theta}{2}\right) = \frac{L}{2\rho} = \frac{1}{2}\frac{LB}{(B\rho)}$$

If θ is small:

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

So we can write:

$$\theta = \frac{LB}{(B\rho)}$$

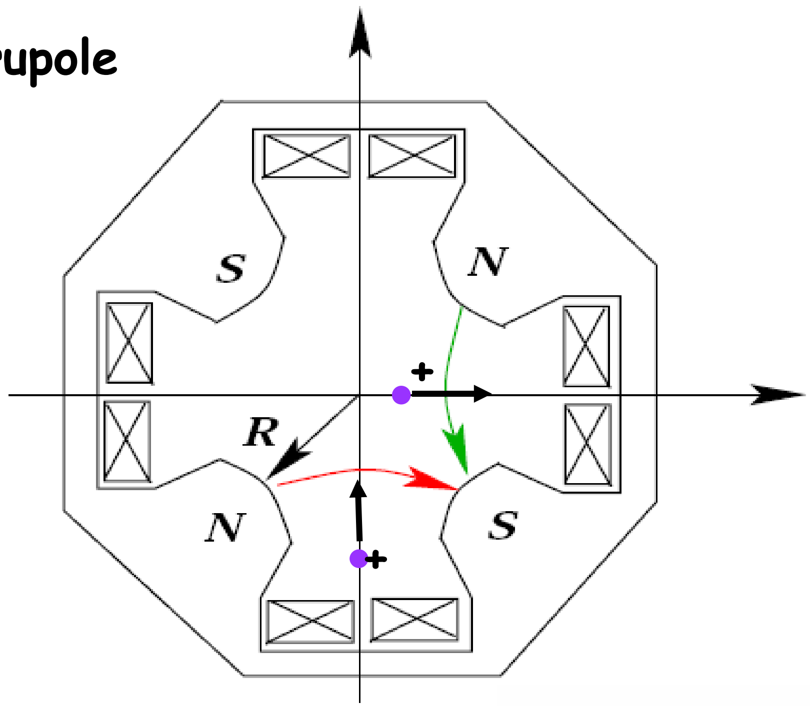


Focusing: The Quadrupole 1

FOCUSING

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

Quadrupole

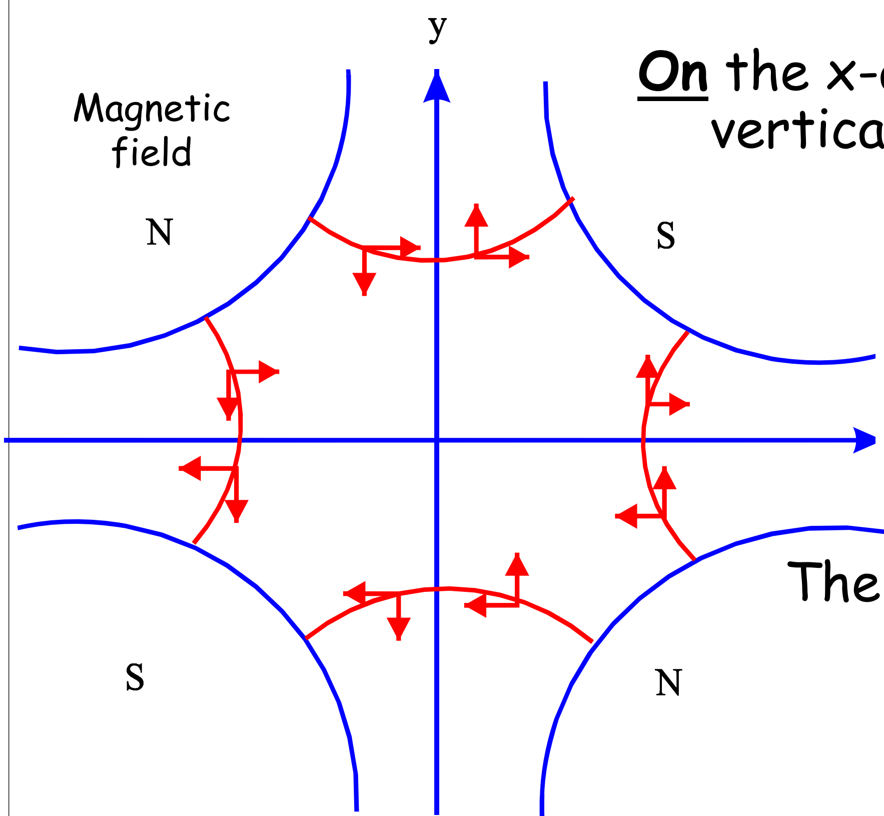


Positiv particle moving towards us:
Defocussing in the horizontal plane, focussing the the vertical plane.

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

The Quadrupole 2

FOCUSING



On the x-axis (horizontal) the field is vertical and given by:

$$\mathbf{B_y \propto x}$$

On the y-axis (vertical) the field is horizontal and given by:

$$\mathbf{B_x \propto y}$$

The field **gradient**, **K** is defined as:

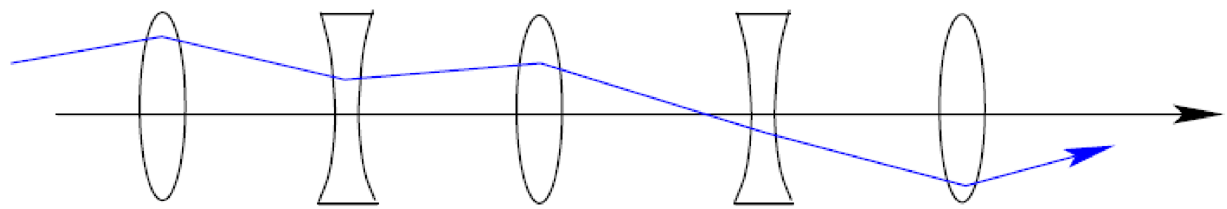
$$\frac{d(By)}{dx}\,(Tm^{-1})$$

The **'normalised gradient'**, **k** is defined as: $\frac{K}{(B\rho)}(m^{-2})$

Focal length: 1/kl where l is the length of the quadrupole

The Focusing System

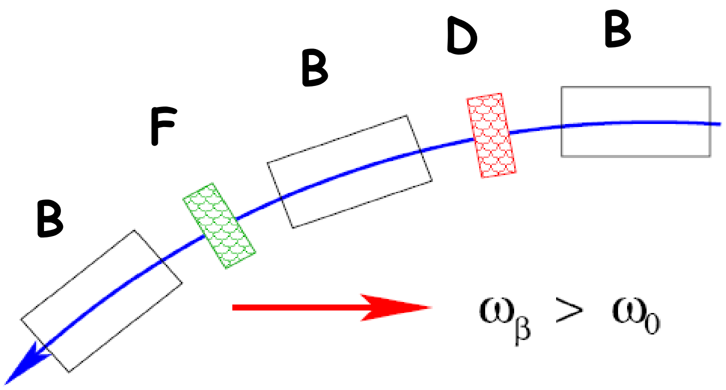
FOCUSSING



"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

FOCUSSING

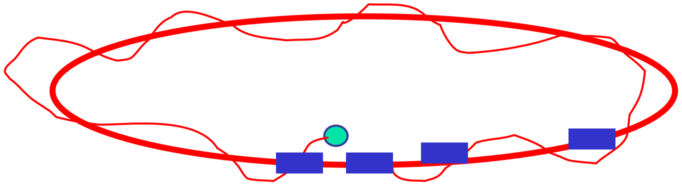
The following kind of differential equations can be derived, compare the simple pendulum:

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.

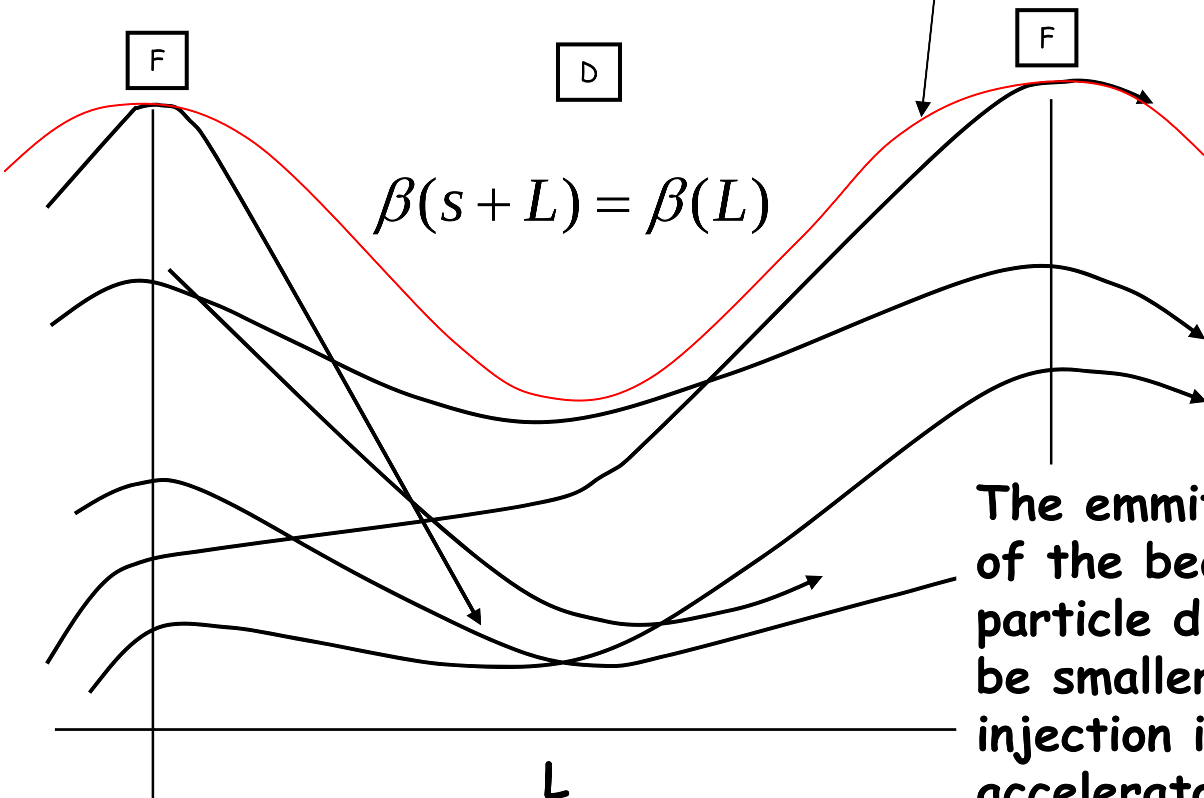
The Beta Function

FOCUSSING

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

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

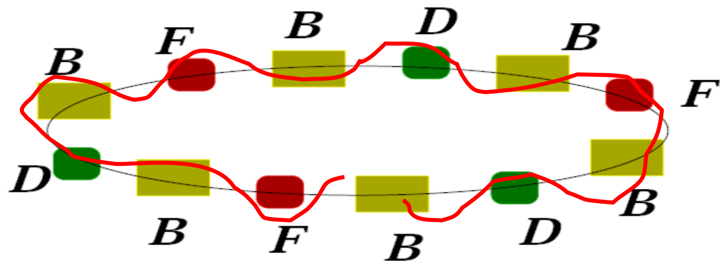
$$\beta(s+L)=\beta(L)$$



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

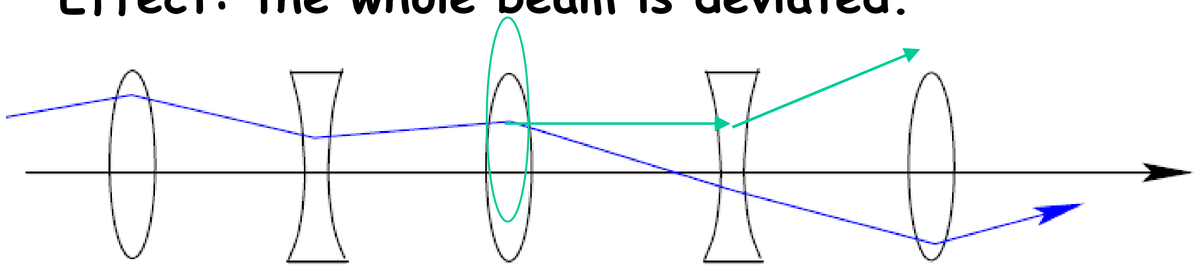
Closed orbit, and field errors

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.

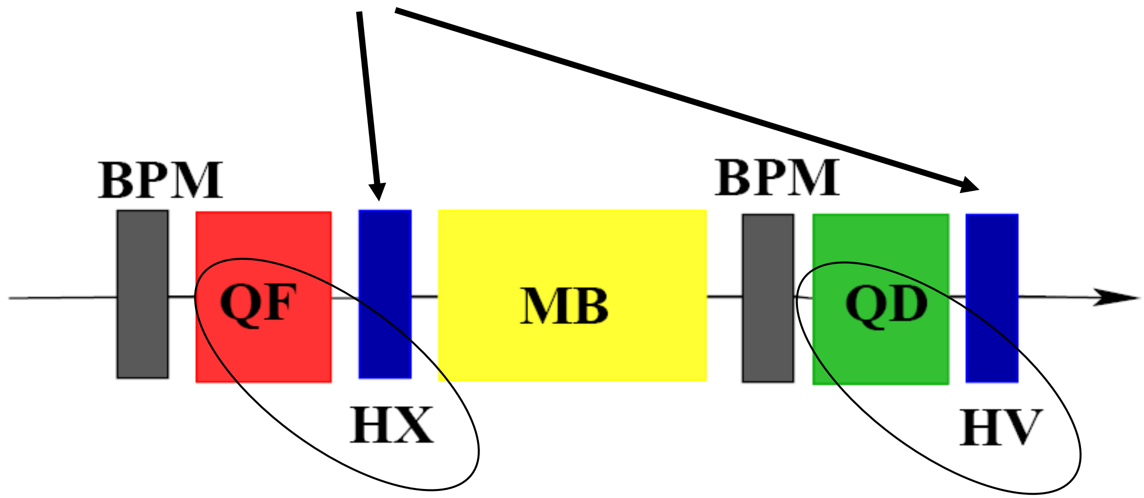


$$F_x = g \cdot x$$

$$F_y = -g \cdot y$$

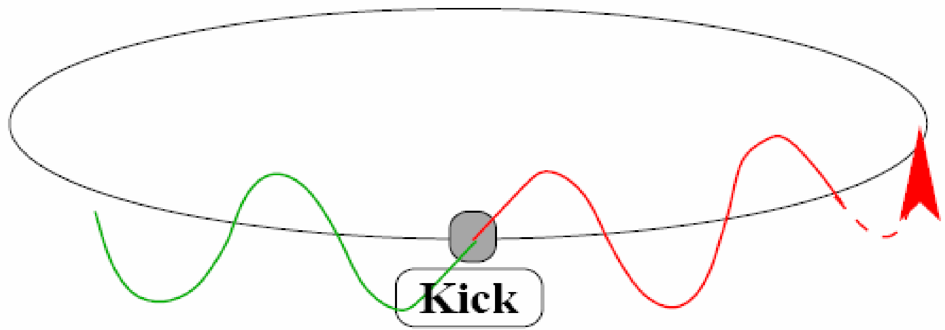
Correctors

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 (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.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
...

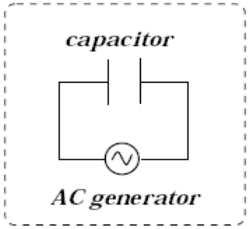
Calibration of the magnets is important
Current regulation in the magnets
...

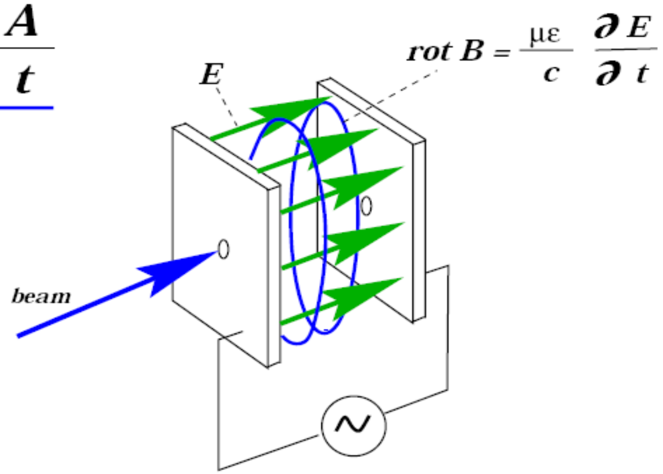
The energy of the particles must correspond to the field in the magnets, to permit the particle to stay in their orbits. Control of the acceleration!

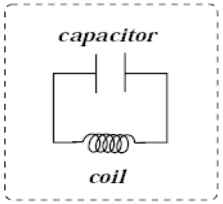
Electrical Fields for Acceleration

ACCELERATION

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



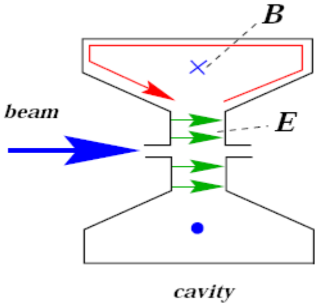


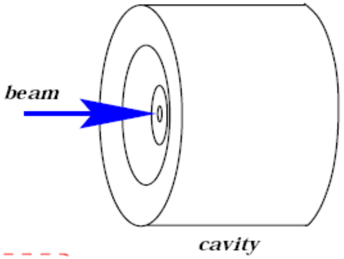


$$L = \frac{\mu_0 \cdot N^2 \cdot A}{l}$$

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

Resonance circuit
Cavity for acceleration

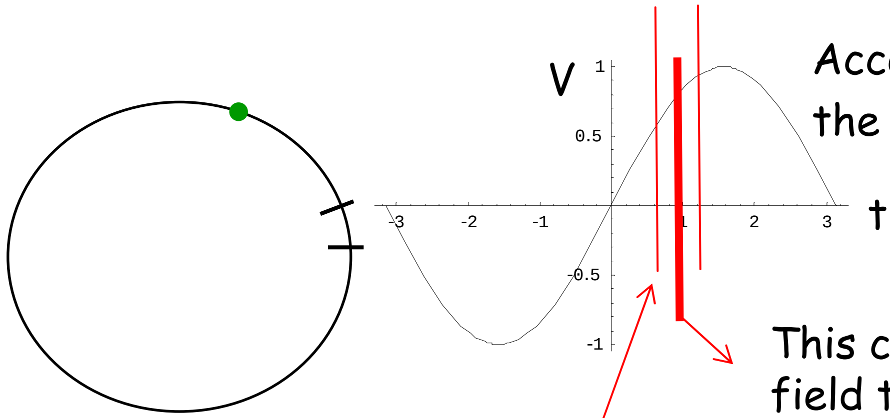


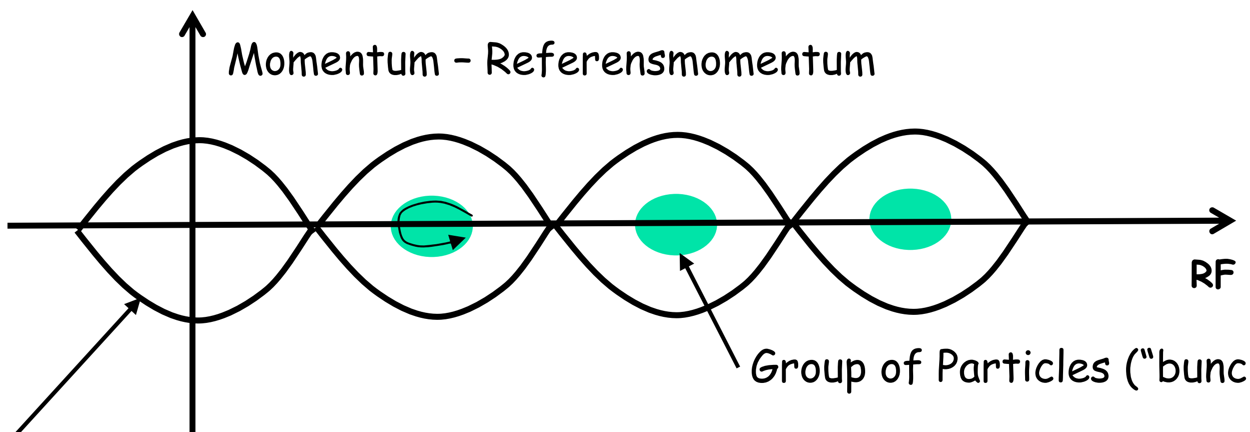


$\boxed{f;\ Q;\ R}$

The Synchrotron: Acceleration 0

ACCELERATION





Experiment

EXPERIMENT

Targets:

Bombarding material with a beam directed out of the accelerator.

Bubbelchamber

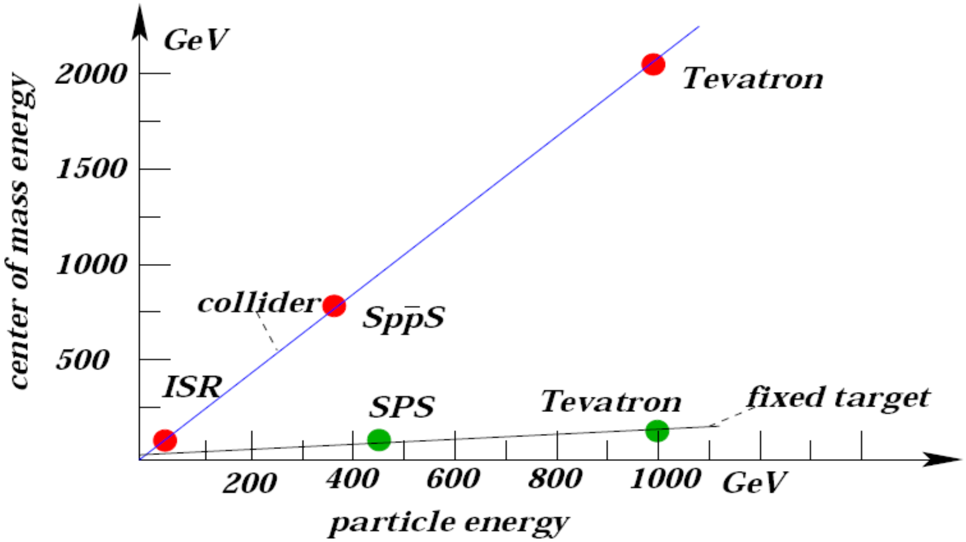
Available energy is calculated in the center of mass of the system (colliding objects)

To collide particle more interesting

1960: electron/positron collider

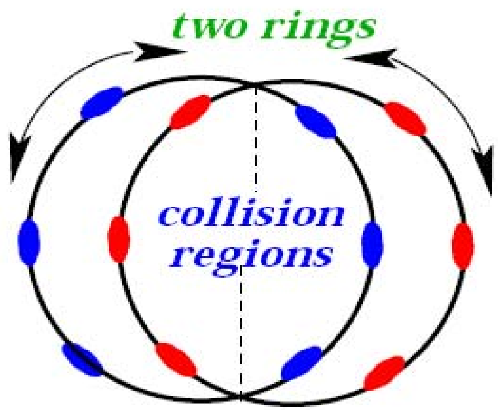
1970: proton antiproton collider

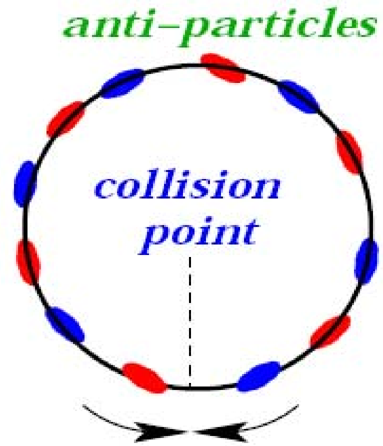
2000: ions, gold



Colliders

EXPERIMENT





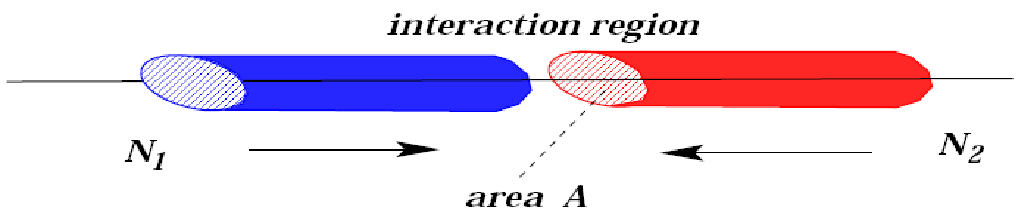
- All particles do not collide at the same time -> long time is needed

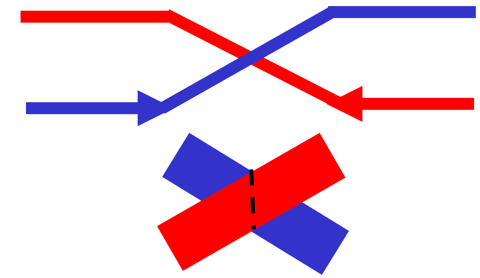
- Two beams are needed

- 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

Colliders: Luminosity





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

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

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

EXPERIMENT

Number of particles per bunch (two beams)

Number of bunches per beam

Revolution frequency

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

Form-factor from the crossing angle

Emmittance

Optical beta function

Synchrotron light

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

Electromagnetic waves

Accelerated charged particles emit photons

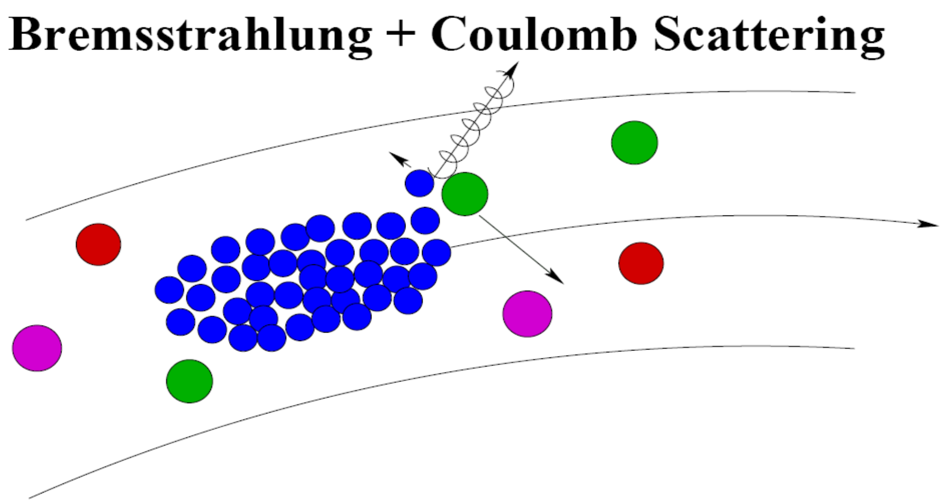
Radio signals and x-ray

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

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

Vacuum

TECHNOLOGY



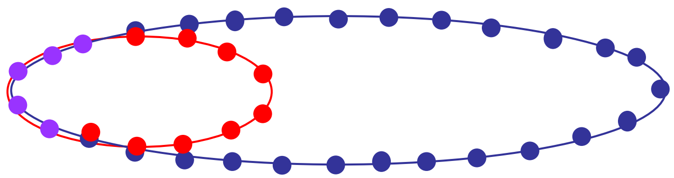
- "Blow up" of the beam
- Particle losses
- Non wanted collisions in the experiments
- Limits the Luminosity

Superconducting Technology 1

TECHNOLOGY

Why superconducting magnets?

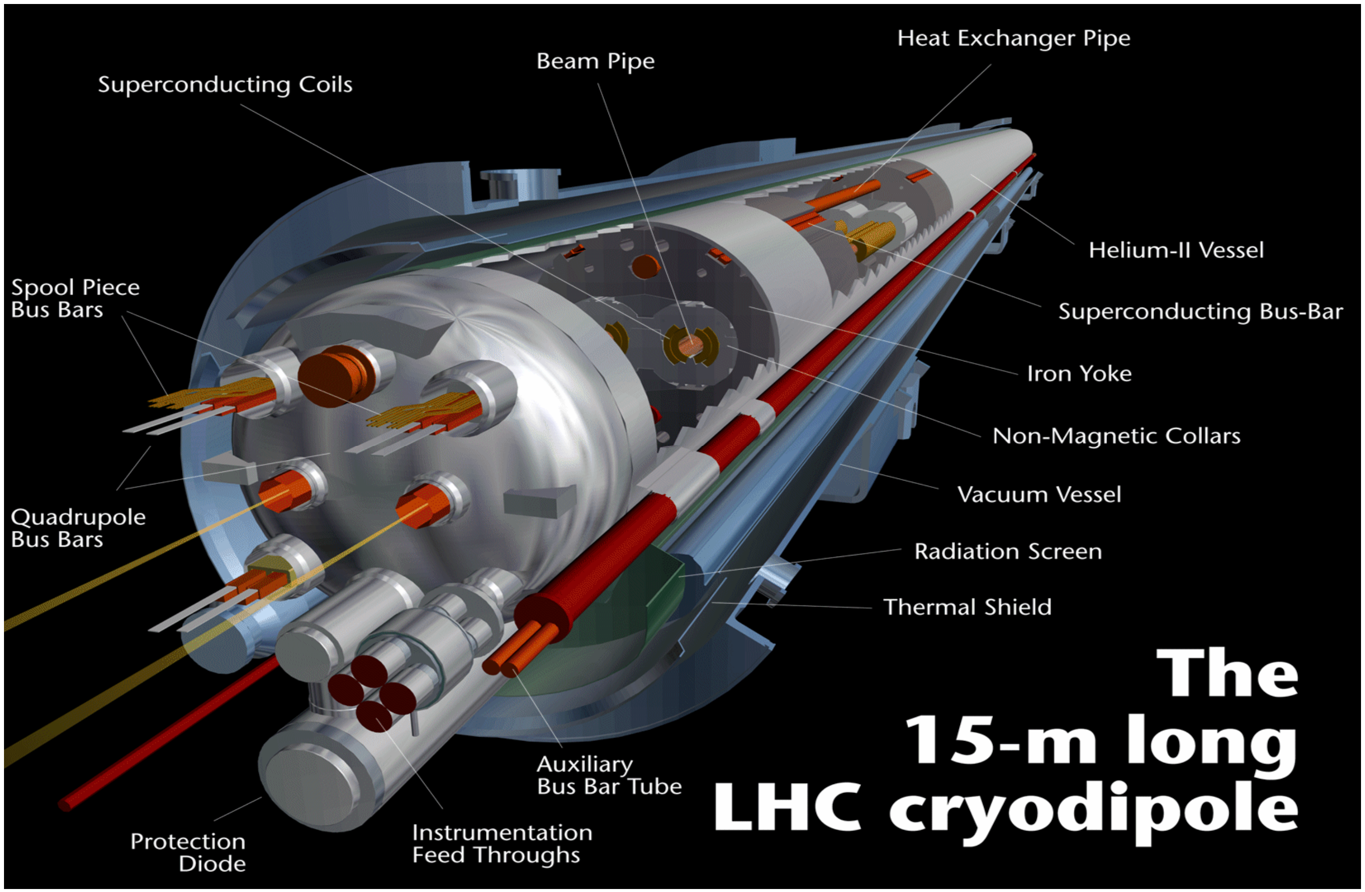
Small radius, less number of particles in the machine, smaller machine



Energy saving, BUT infrastructure very complex

The Superconducting Dipole for LHC

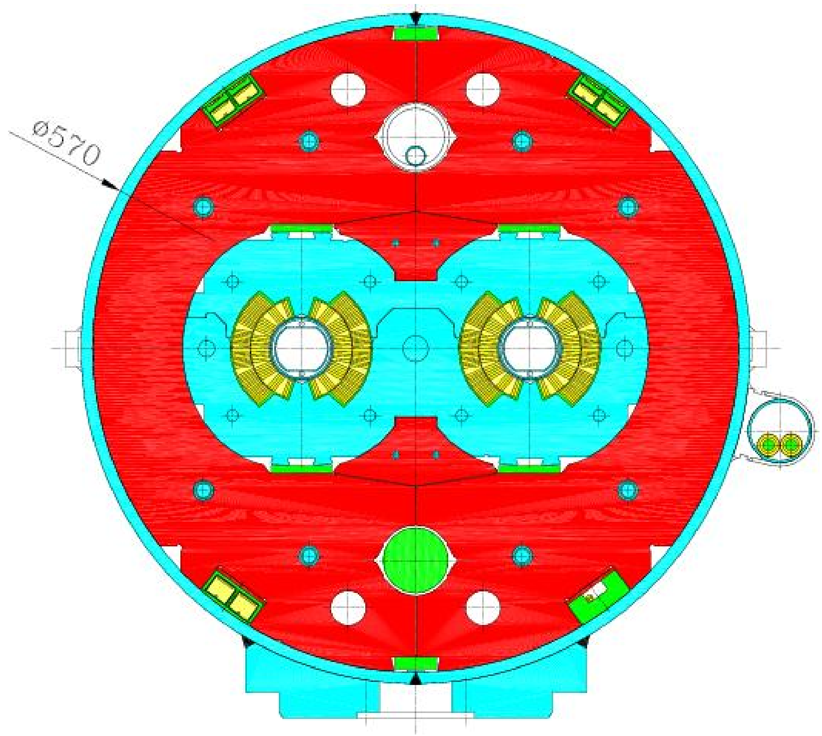
LHC dipole (1232 + reserves) built in 3 firms (Germany France and Italy, very large high tech project)

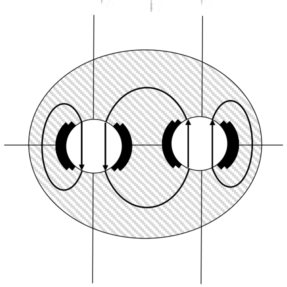


TECHNOLOGY

The LHC Dipole

TECHNOLOGY



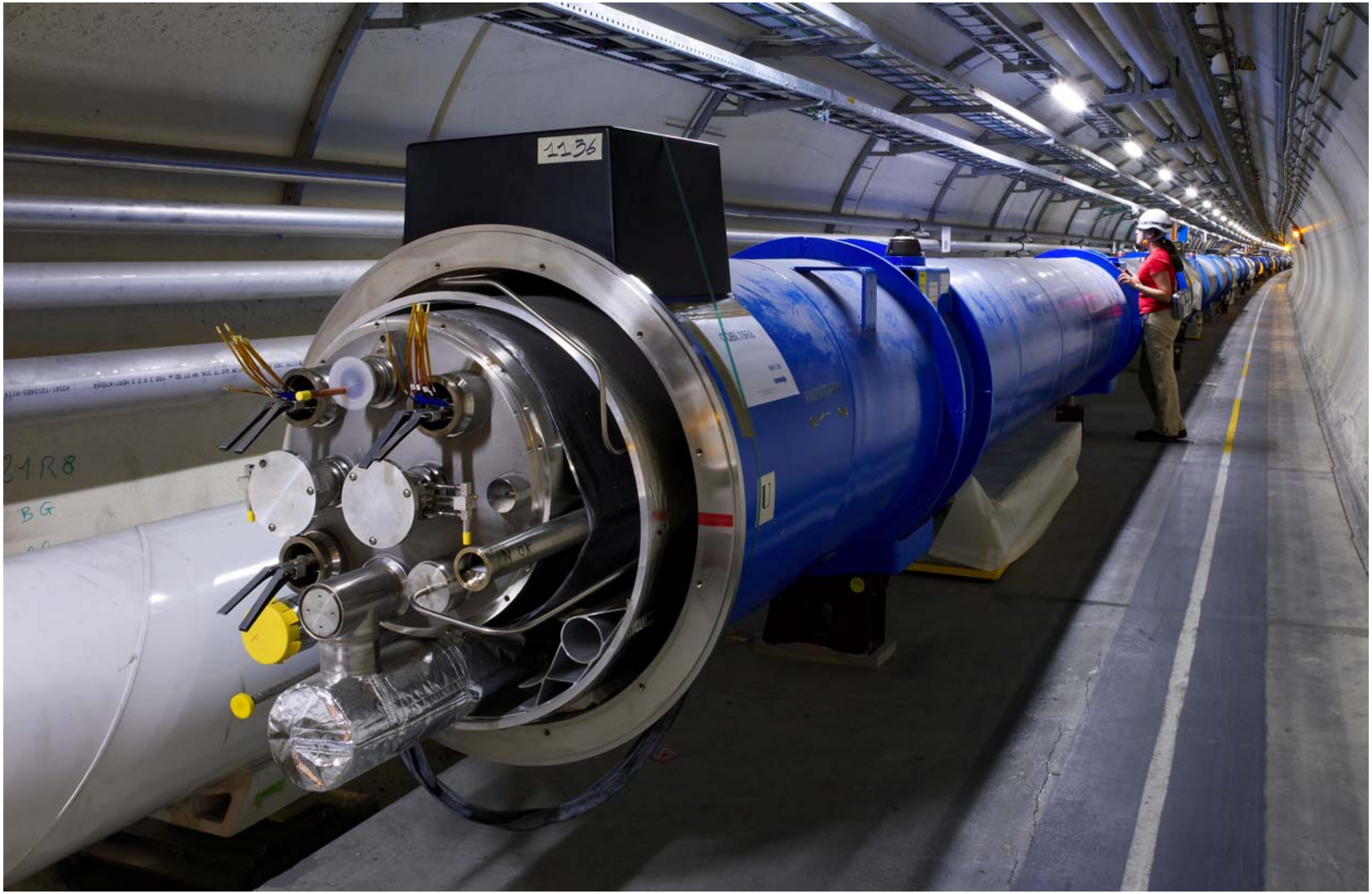


"Two in one" construction

Working temperature
1.9 K !

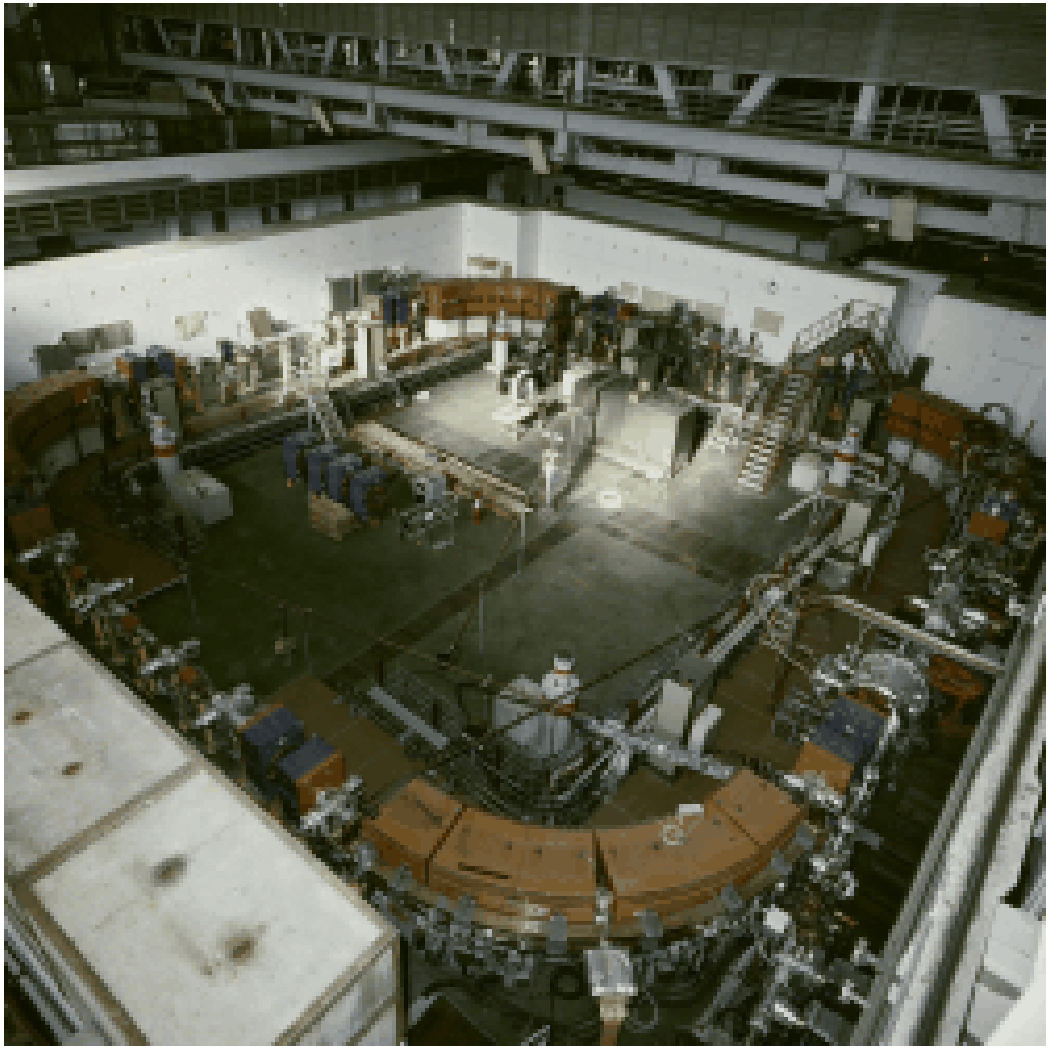
Coldest spot i the universe...

The LHC Dipole in the tunnel

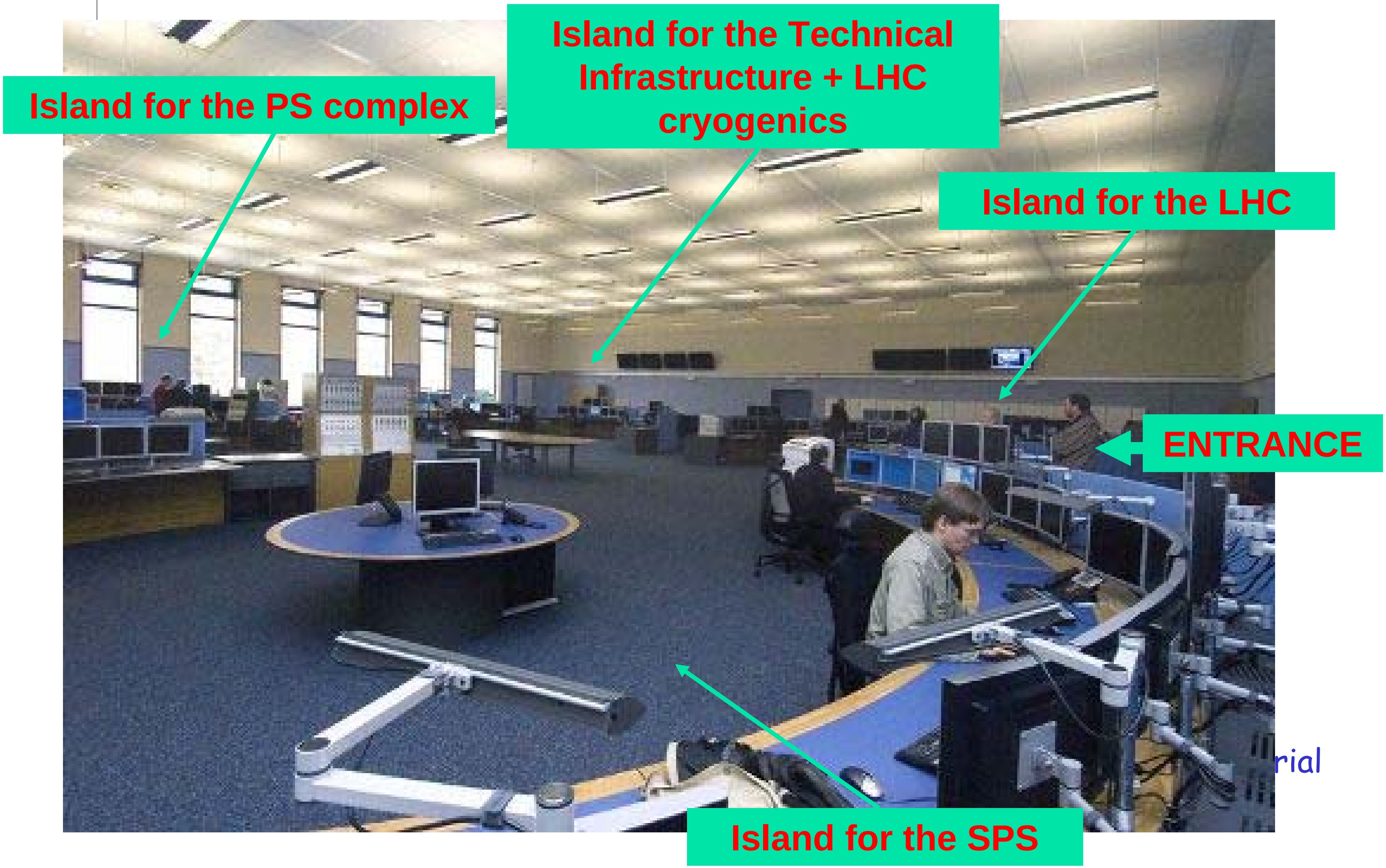


The LHC Magnet interconnection

LEAR



New CERN Control Centre (CCC) ar CERN



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