



# Introduction to Accelerator Physics

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# What are we going to talk about?

- **Why Accelerators and Colliders ?**
- **A very Brief Historic Overview**
- **The CERN Accelerator Complex**
- **The Main Ingredients of an Accelerator**
- **Some ways of using Accelerators**



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# Why Accelerators and Colliders ?



<https://www.menti.com>

Code: 8724 9311

# Accelerators and Their Use

Today: over **30'000 accelerators** operational worldwide\*



The **large majority** is used in  
**industry and medicine**

→ Industrial applications: ~ 20'000\*

→ Medical applications: ~ 10'000\*

**Less than a fraction of a percent** is used  
for **research** and discovery science

→ Cyclotrons

→ Synchrotron light sources ( $e^-$ )

→ Lin. & Circ. accelerators/Colliders

This lecture will concentrate on the CERN type machines of which the majority are  
**Synchrotrons**

\*Source: *World Scientific Reviews of Accelerator Science and Technology*  
A.W. Chao

# Accelerators and Their Use

Today: over **30'000 accelerators** operational worldwide\*

Linear or circular

small enough to sit on a table or tens of kilometres long

operated in continuous or pulsed modes

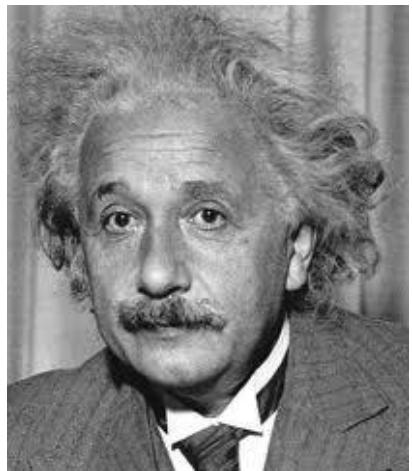


- Processing semiconductors
- Vulcanizing rubber and modifying polymer properties
- Medical imaging and cancer treatment
- Sterilization of medical equipment and food products
- Cleaning industrial flue gases (for instance, combustion exhaust gas produced at power plants) and purifying water
- Mineral and oil prospecting
- Cargo screening
- Radioisotope production
- Radiocarbon and other radiometric dating

# Creating Matter from Energy

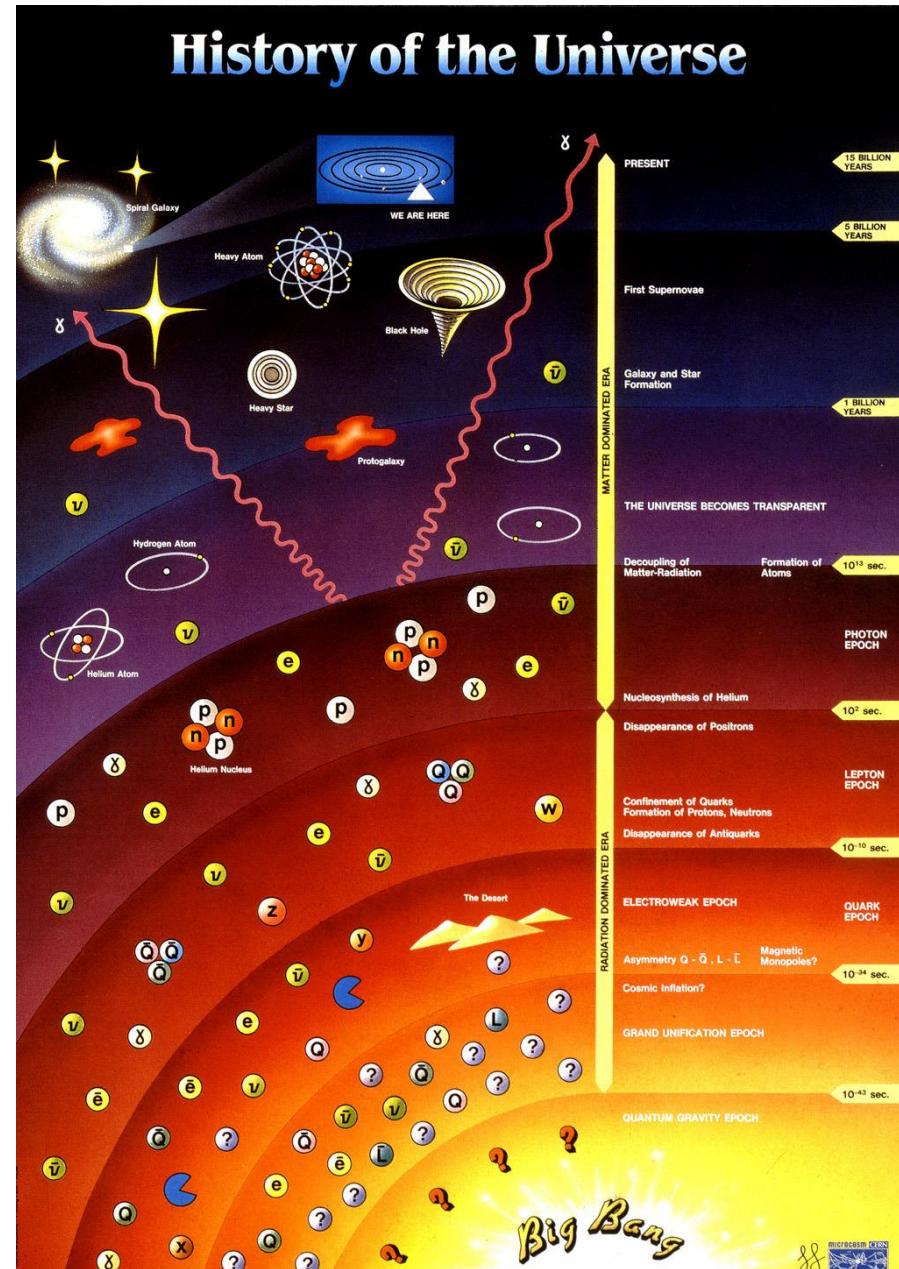
$$E = m \cdot c^2$$

During the Big Bang Energy was transformed in matter



In our accelerators we provide energy to the particles we accelerate.

In the detectors we observe the matter created



# Looking to smaller dimensions

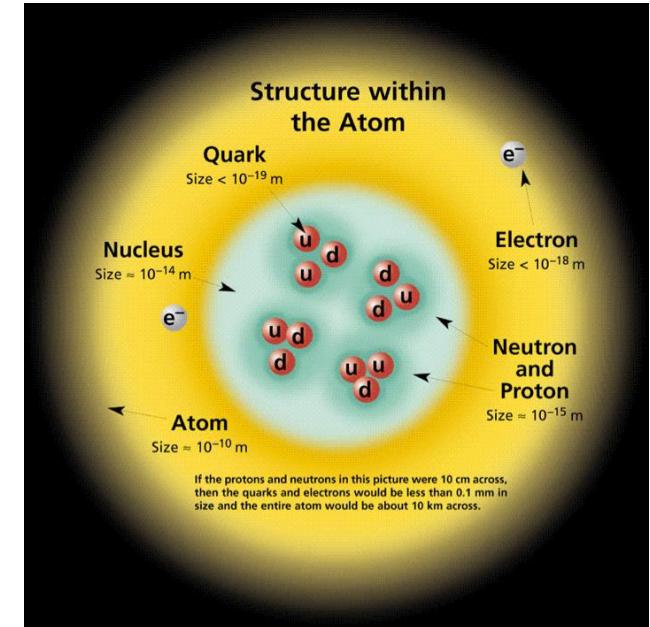
**Visible light**  
 $\lambda = 400 \rightarrow 700 \text{ nm}$



**X-ray**  
 $\lambda = 0.01 \rightarrow 10 \text{ nm}$



**Particle accelerators**  
 $\lambda < 0.01 \text{ nm}$



$$\lambda = \frac{hc}{E}$$

Increasing the energy will reduce the wavelength

# Fixed Target vs. Colliders

## Fixed Target



$$E \propto \sqrt{E_{beam}}$$

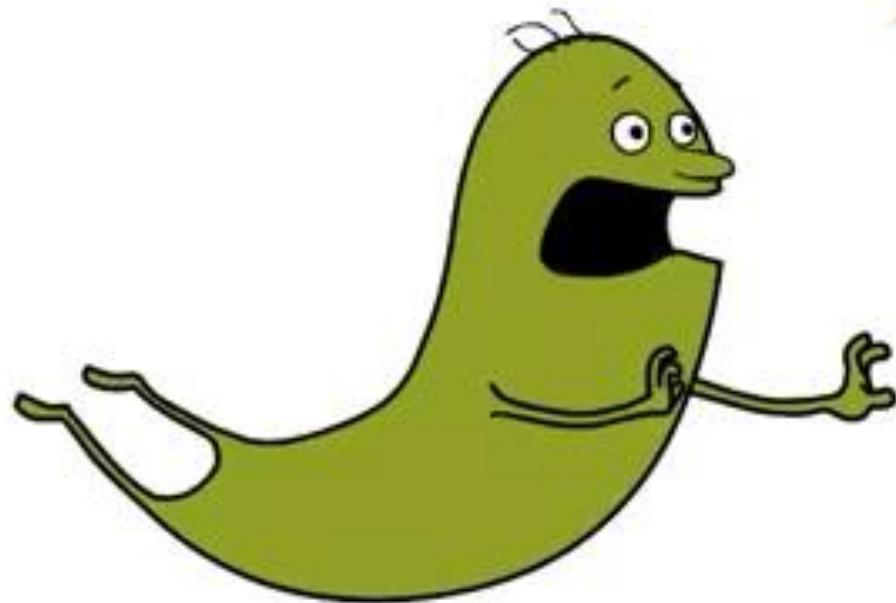
Much of the energy is lost in the target and only part is used to produce secondary particles

## Collider



$$E = E_{beam1} + E_{beam2}$$

All energy will be available for particle production

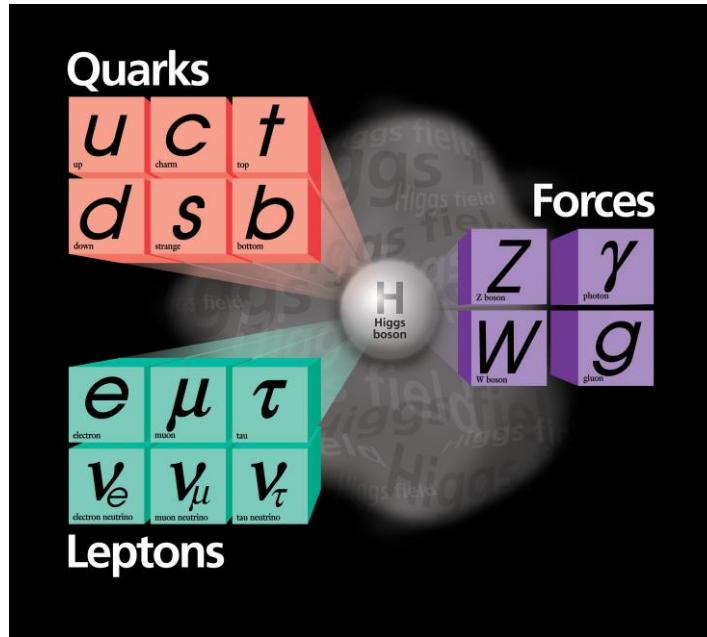


**A quick look  
around the LHC**

[www.oxfordsparks.net](http://www.oxfordsparks.net)

# The Aim

Verify and  
improve the  
Standard  
Model



Search for physics beyond the Standard Model  
Such as dark matter and dark energy

# Phenomena not explained in SM

## Gravity:

The standard model does not explain gravity. The approach of simply adding a graviton to the Standard Model does not recreate what is observed experimentally without other modifications, as yet undiscovered, to the Standard Model.

## Dark matter and dark energy:

Cosmological observations tell us the standard model explains about 5% of the energy present in the universe.

## Neutrino masses:

According to the standard model, neutrinos are massless particles.

## Matter–antimatter asymmetry:

The universe is made out of mostly matter. However, the SM predicts that matter and antimatter should have been created in (almost) equal amounts if the initial conditions of the universe did not involve disproportionate matter relative to antimatter.



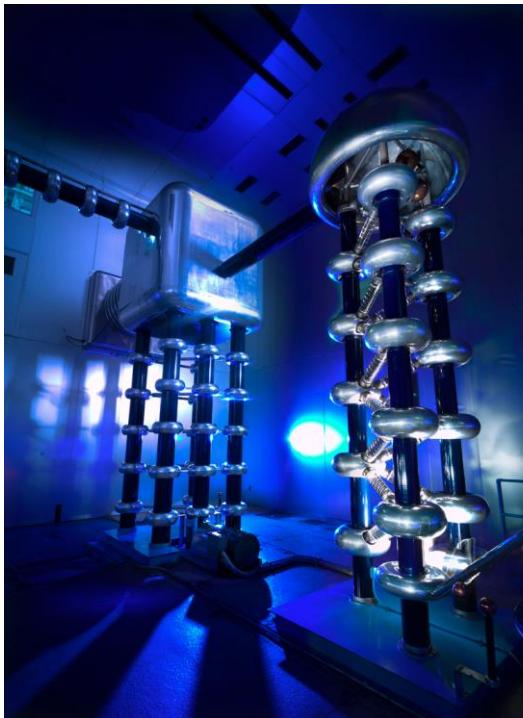
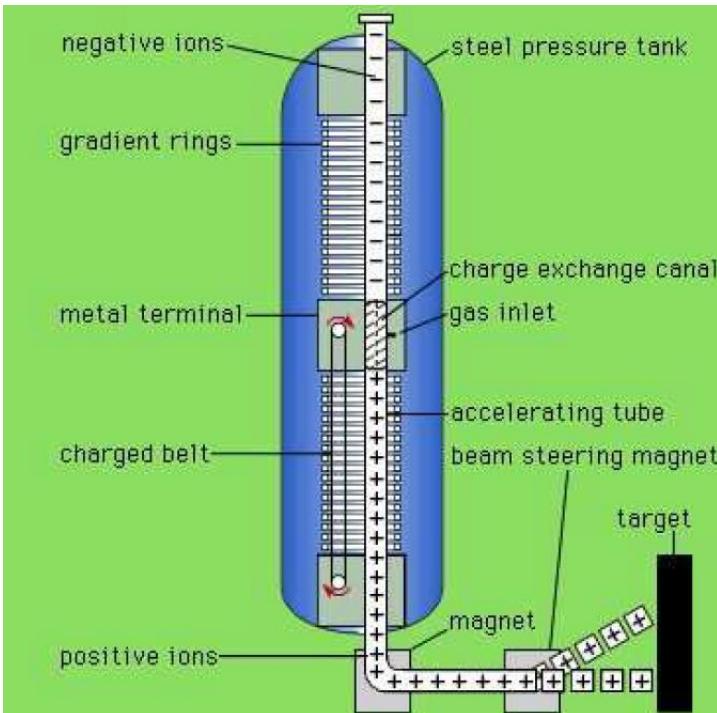


# What are we going to talk about?

- Why Accelerators and Colliders ?
- A very Brief Historic Overview
- The CERN Accelerator Complex
- The Main Ingredients of an Accelerator
- Some ways of using Accelerators

# Cockroft & Walton / van de Graaff

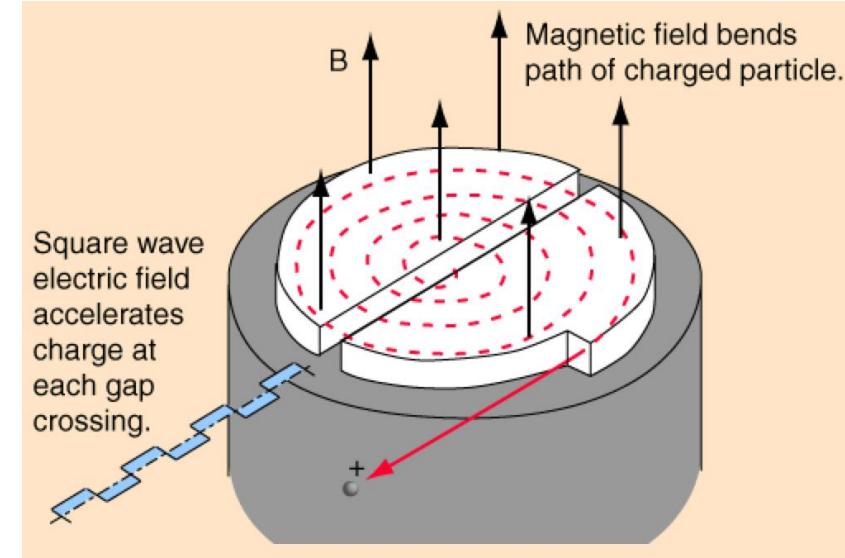
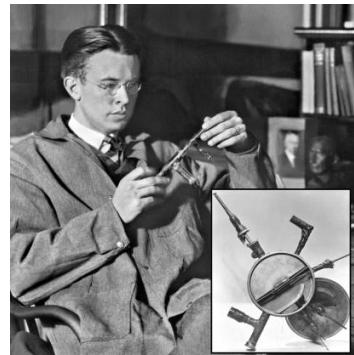
- 1932: First accelerator – single passage 160 - 700 keV
- Static voltage accelerator
- Limited by the high voltage needed



# Cyclotron

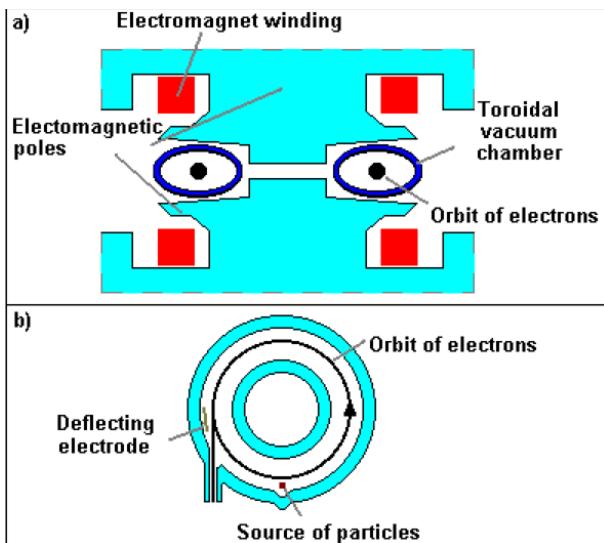
- 1932: 1.2 MeV – 1940: 20 MeV (E.O. Lawrence, M.S. Livingston)
- Constant magnetic field
- Alternating voltage between the two D's
- Increasing particle orbit radius
- Development lead to the synrocyclotron to cope with the relativistic effects.

In 1939 Lawrence received the Noble prize for his work.

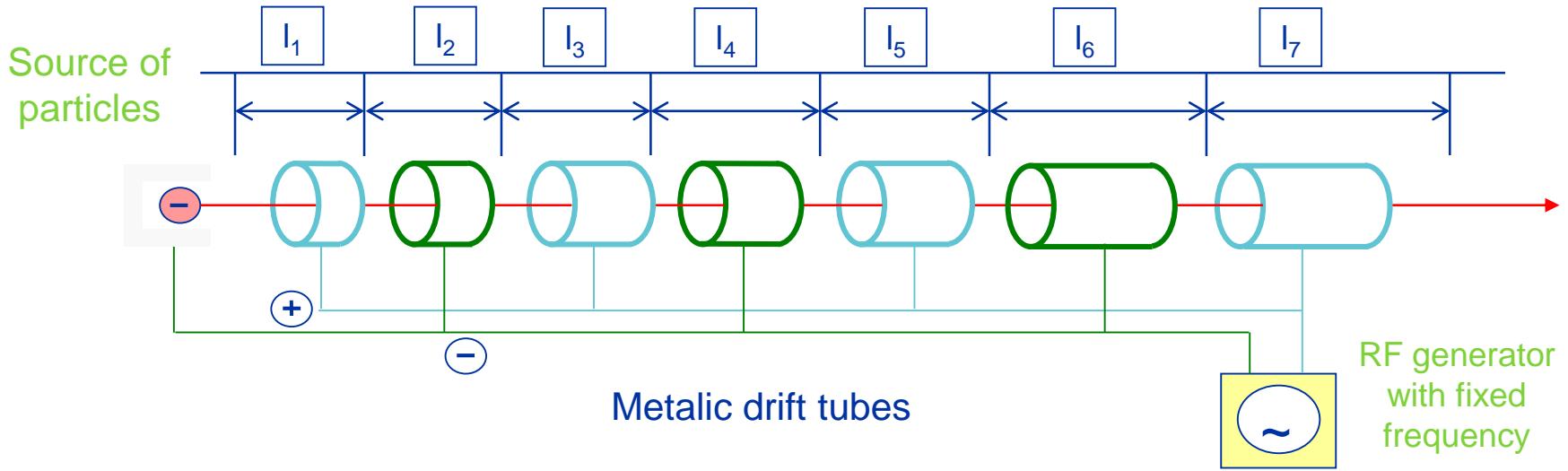


# Betatron

- 1940: Kerst 2.3 MeV and very quickly 300 MeV
- It is actually a transformer with a beam of electrons as secondary winding.
- The magnetic field is used to bend the electrons in a circle, but also to accelerate them.
- A deflecting electrode is use to deflect the particle for extraction.



# Linear Accelerator



- Many people involved: Wideroe, Sloan, Lawrence, Alvarez,....
- Main development took place between 1931 and 1946.
- Development was also helped by the progress made on high power high frequency power supplies for radar technology.
- Today still the first stage in many accelerator complexes.
- Limited by energy due to length and single pass.

# Synchrotrons

- 1943: M. Oliphant described his synchrotron invention in a memo to the UK Atomic Energy directorate
- 1959: CERN-PS and BNL-AGS
- Fixed radius for particle orbit
- Varying magnetic field and radio frequency
- Phase stability
- Important focusing of particle beams (Courant – Snyder)
- Providing beam for fixed target physics
- Paved the way to colliders



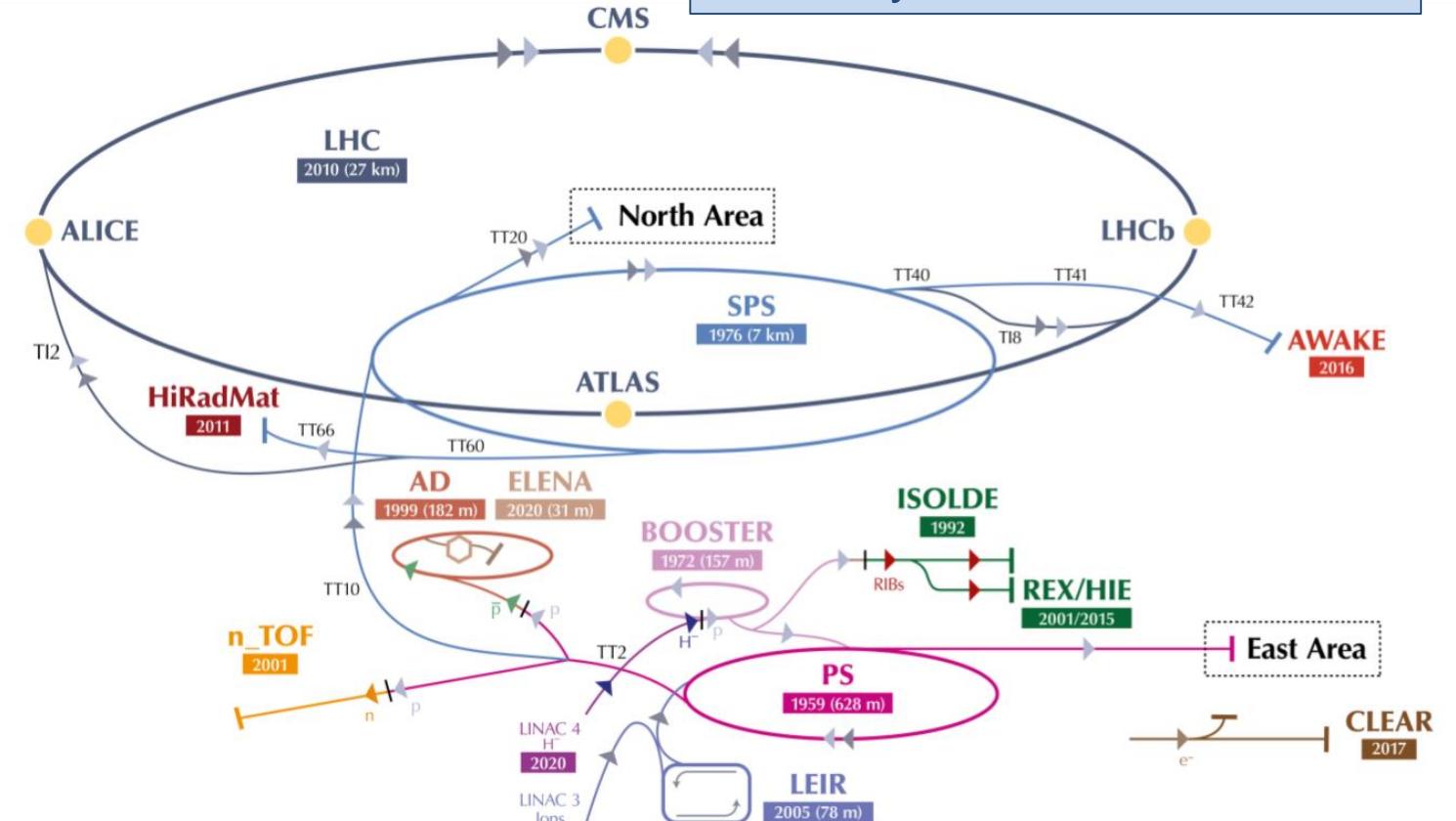


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# The CERN Accelerator Complex

Mostly Circular Machines



►  $H^-$  (hydrogen anions)   ►  $p$  (protons)   ► ions   ► RIBs (Radioactive Ion Beams)   ►  $n$  (neutrons)   ►  $\bar{p}$  (antiprotons)   ►  $e^-$  (electrons)



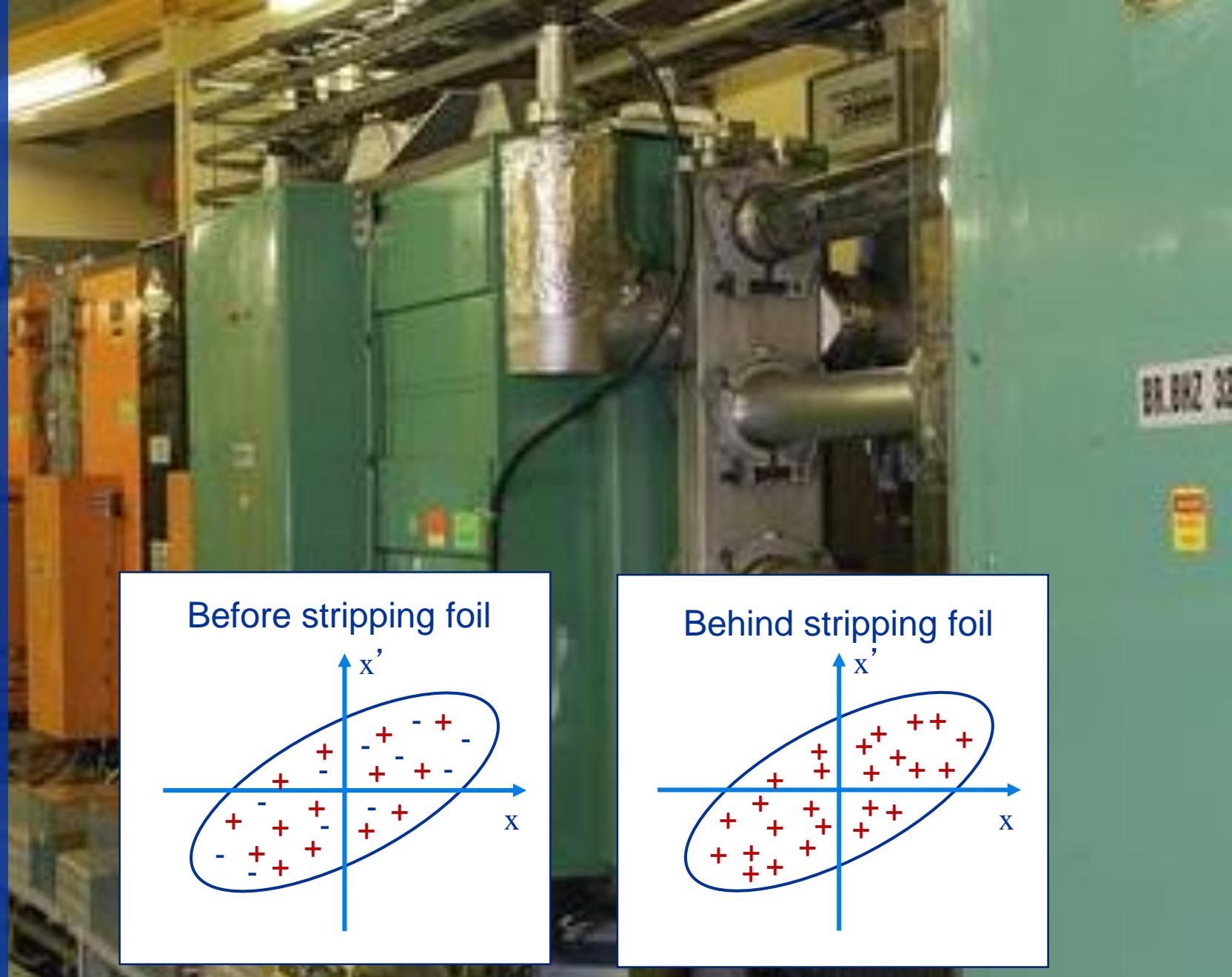
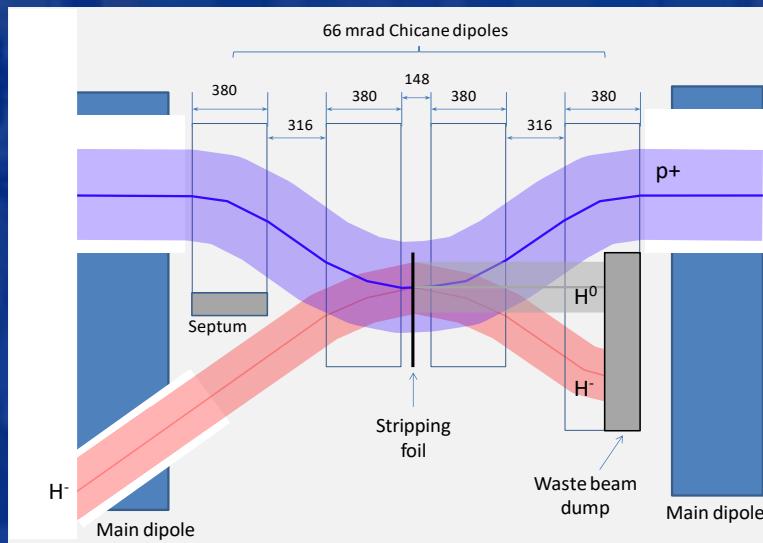
# Linac 4

- H<sup>-</sup> ion source at 95 keV
- Accelerates beam up to 160 MeV



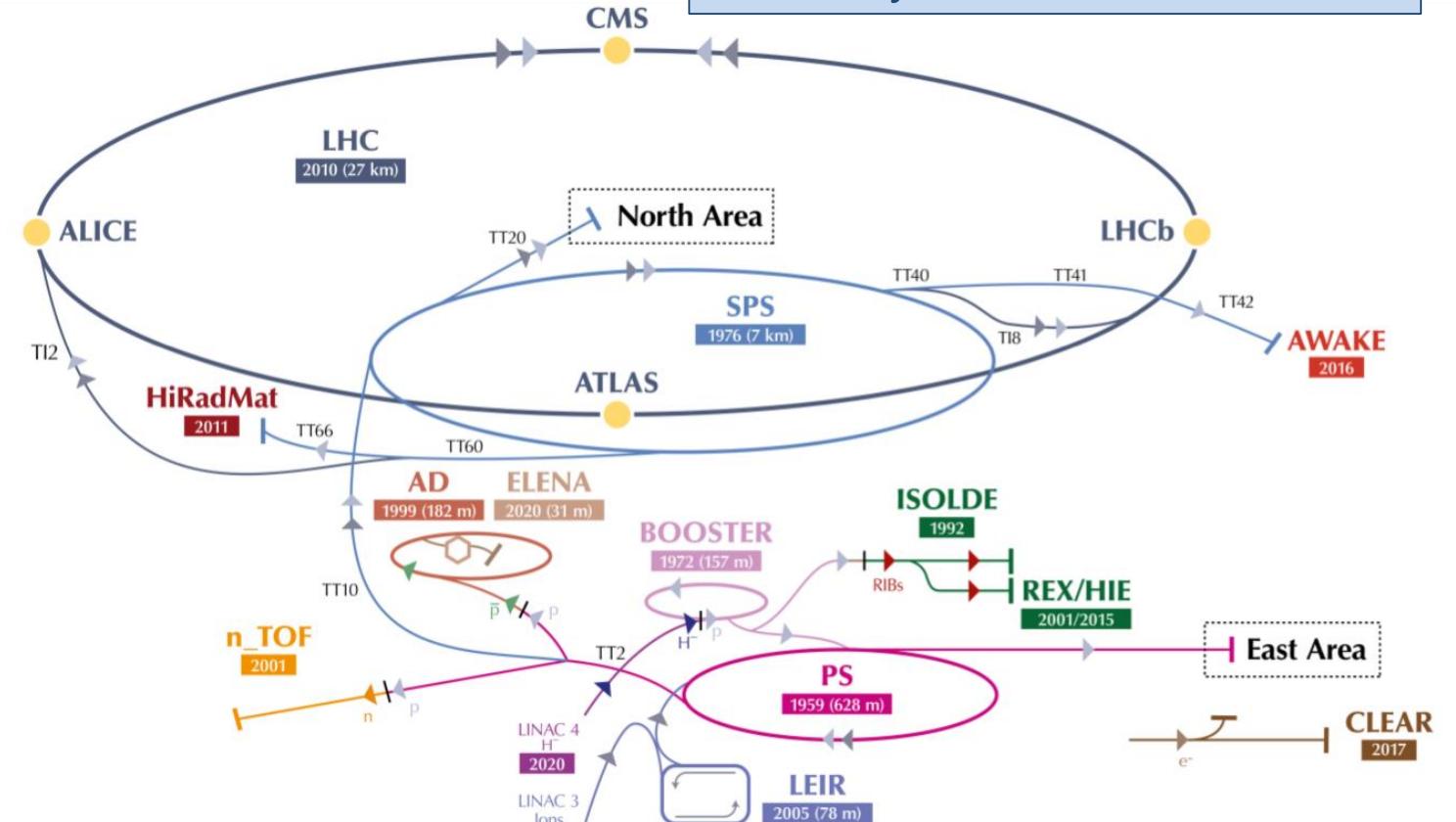
# PS Booster

- 1<sup>st</sup> Synchrotron with 4 superposed rings
- Circumference of 157 m
- Proton energy from 160 MeV to 2 GeV
- Can cycle every 1.2 s
- Each ring will inject over multi-turns, using charge exchange injection

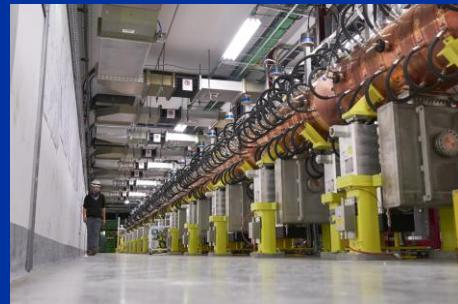


# The CERN Accelerator Complex

Mostly Circular Machines



►  $H^-$  (hydrogen anions)   ► p (protons)   ► ions   ► RIBs (Radioactive Ion Beams)   ► n (neutrons)   ►  $\bar{p}$  (antiprotons)   ►  $e^-$  (electrons)



# PS

- The **oldest** operating synchrotron at CERN
- Circumference of **628m**
  - 4 x PSB circumference
- Increases proton energy from 2 GeV to max. 26 GeV
- Acceleration cycle length ranges from 1.2s to 3.6s
- Many RF systems allow for complex RF gymnastics
- Various types of extractions:
  - Fast extraction
  - Multi-turn extraction (MTE)
  - Slow extraction



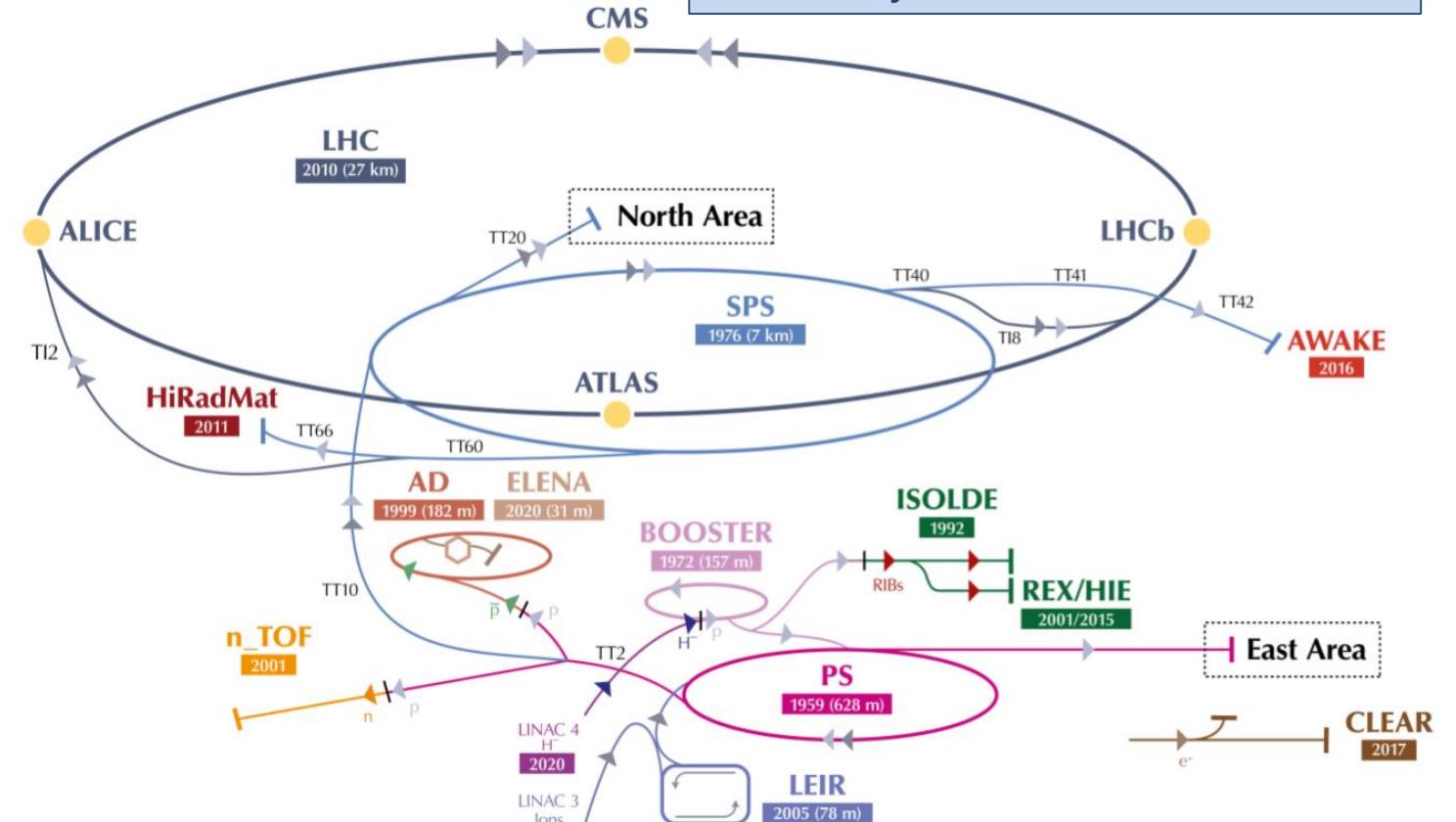
# SPS

- The first synchrotron in the chain at ~30m under ground
- Circumference of 6.9 km
  - 11 x PS circumference
- Increases proton beam energy up to 450 GeV with up to  $\sim 5 \times 10^{13}$  protons per cycle
- Provides slow extracted beam to the North Area
- Provides fast extracted beam to LHC, AWAKE and HiRadMat

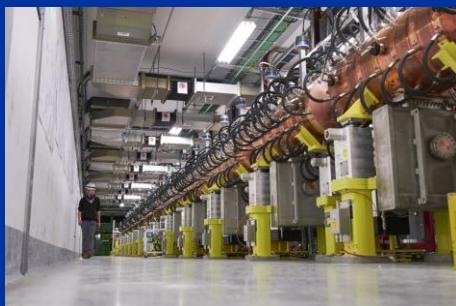


# The CERN Accelerator Complex

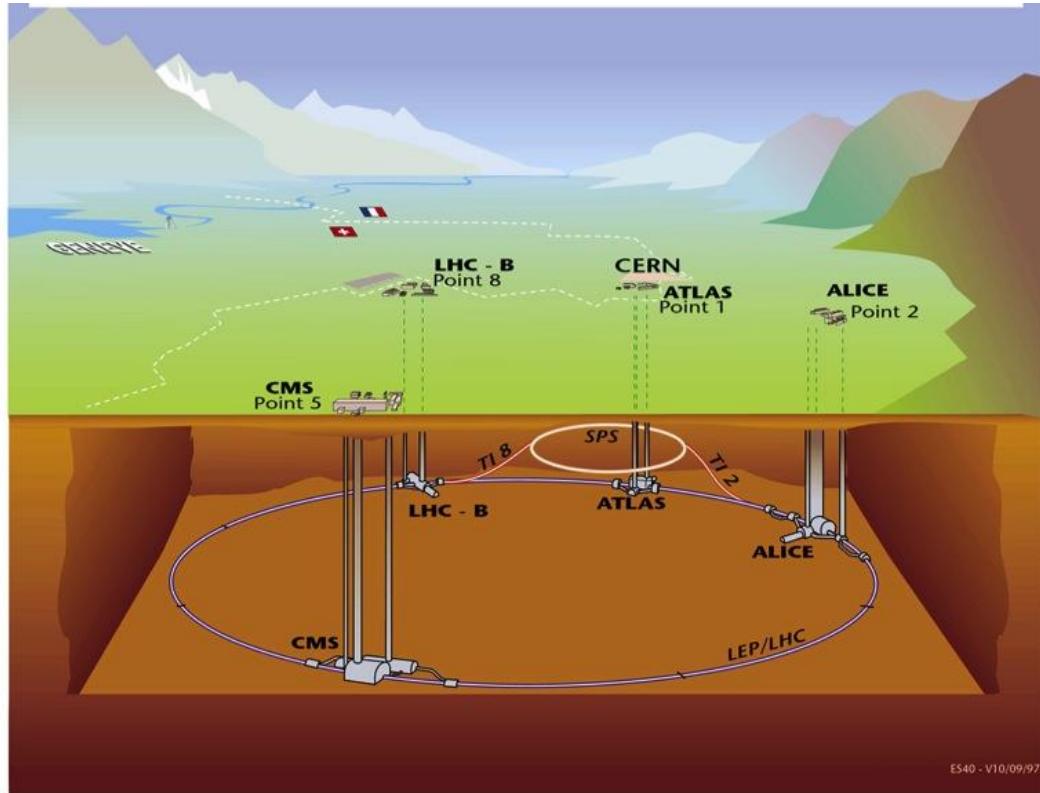
Mostly Circular Machines



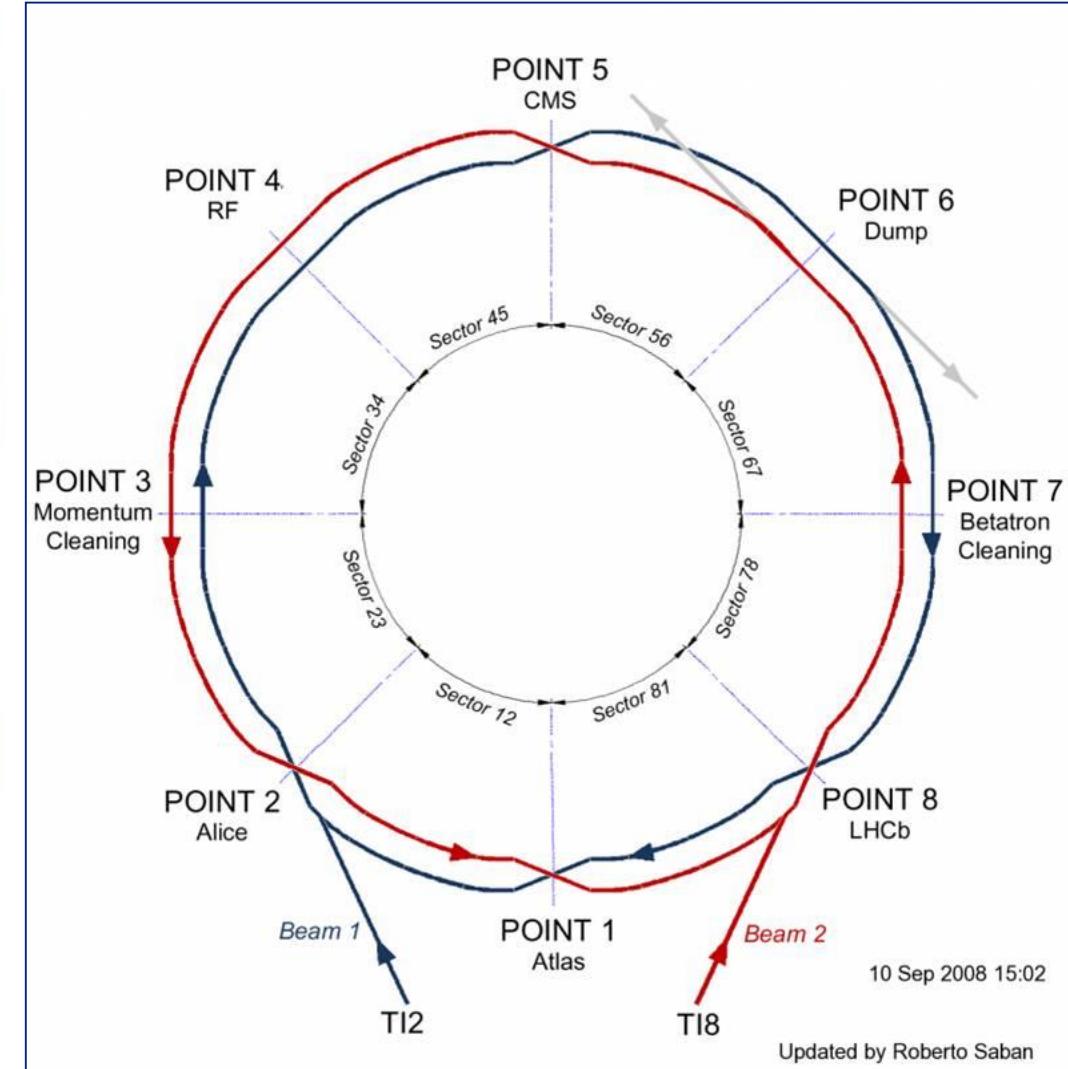
►  $H^-$  (hydrogen anions)   ► p (protons)   ► ions   ► RIBs (Radioactive Ion Beams)   ► n (neutrons)   ►  $\bar{p}$  (antiprotons)   ►  $e^-$  (electrons)



# LHC

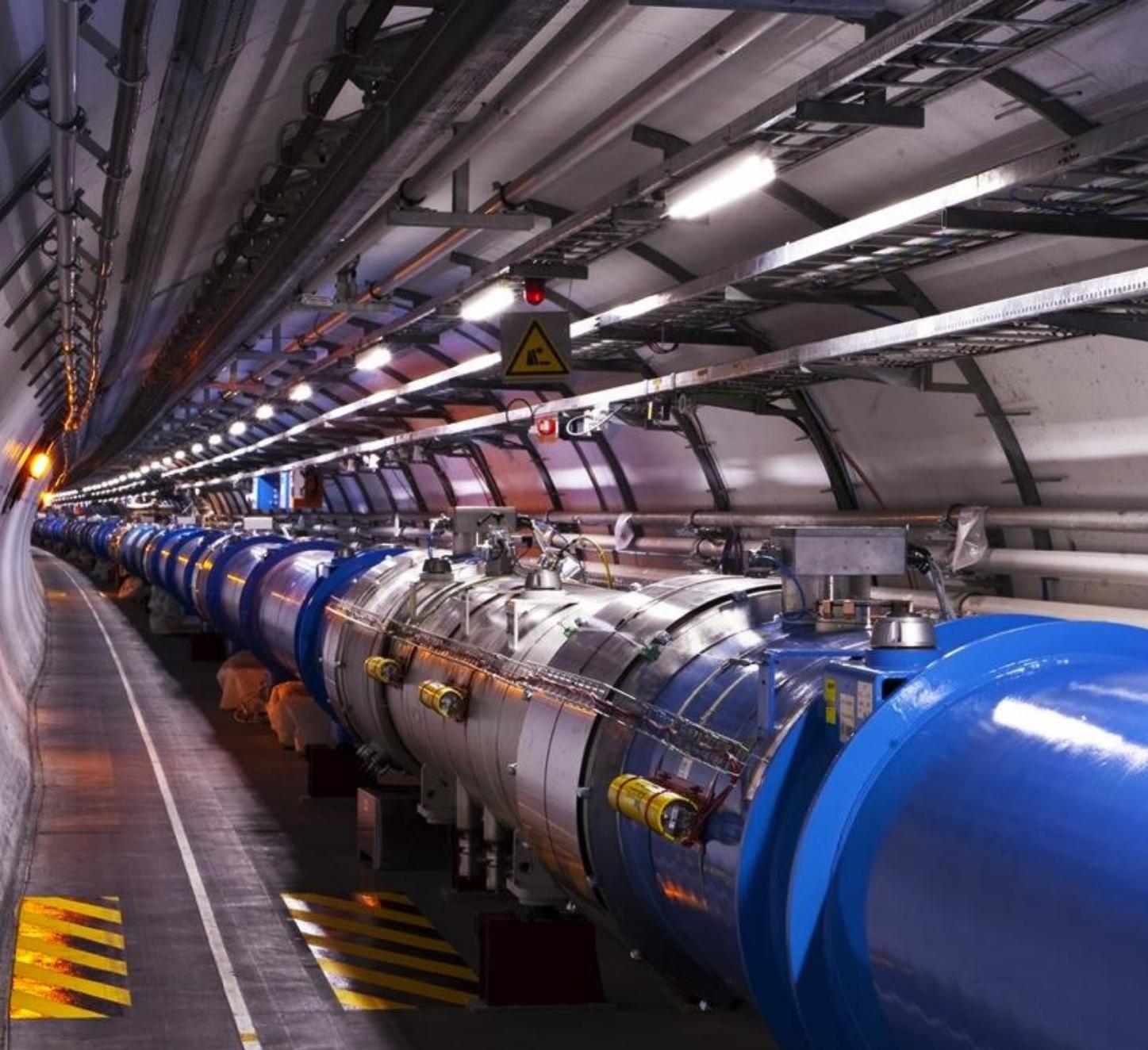


- Situated on average ~100 m under ground
- Four major experiments
- Circumference 26.7 km
- Two separate beam pipes going through the same cold mass 19.4 cm apart
- 150 tons of liquid helium to keep the magnets cold and superconducting



# LHC

- 1232 main dipoles of 15 m each that deviate the beams around the 27 km circumference
- 858 main quadrupoles that keep the beam focused
- 6000 corrector magnets to preserve the beam quality
- Main magnets use superconducting cables (Cu-clad Nb-Ti)
- 12'000 A provides a nominal field of 8.33 Tesla
- Operating in superfluid helium at 1.9K



# LHC: Luminosity the Figure of Merit

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi \sigma_x \sigma_y} \cdot W \cdot e^{\frac{B^2}{A}} \cdot S$$

Annotations:

- Intensity per bunch
- Number of bunches
- Geometrical Correction factors
- Beam dimensions

$$\sigma_{x,y} = \sqrt{\epsilon \cdot \beta_{x,y}^*}$$

- The instantaneous luminosity is the amount of events per unit of surface per second  $[\text{cm}^{-2}\text{s}^{-1}]$
- Integrating this over time results in the integrated luminosity.

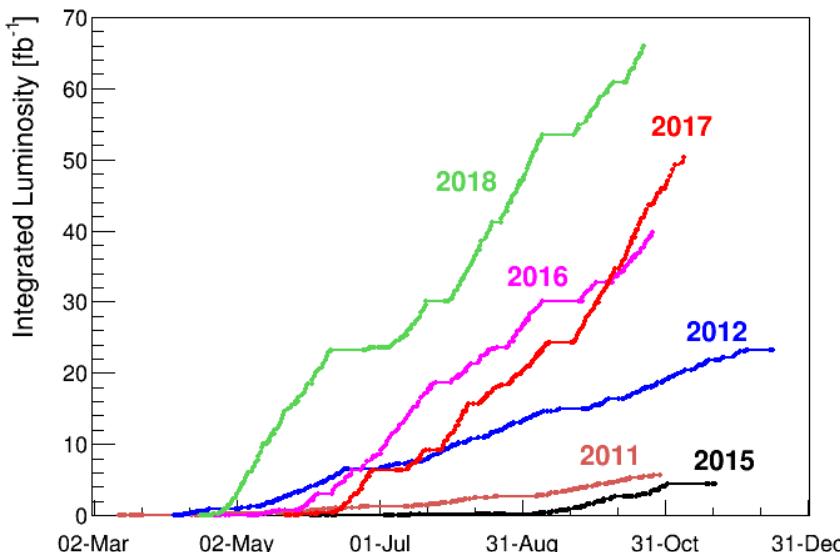
*Note: Cross section is expressed in units of barns (1 barn =  $10^{-28}\text{m}^2$ )*

# LHC: Luminosity the Figure of Merit

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$$\sigma_{x,y} = \sqrt{\epsilon \cdot \beta_{x,y}^*}$$

Maximise Luminosity:

- Bunch intensity
- Transverse beam size
- Beam size at collision points (optics functions)
- Crossing angle
- Machine availability

# Ways to Increase Luminosity

Increase the beam brightness from the injectors (N and  $\sigma$ )

- More particle in smaller beams (increase brightness)

Increase number of bunches

- Higher harmonic RF systems

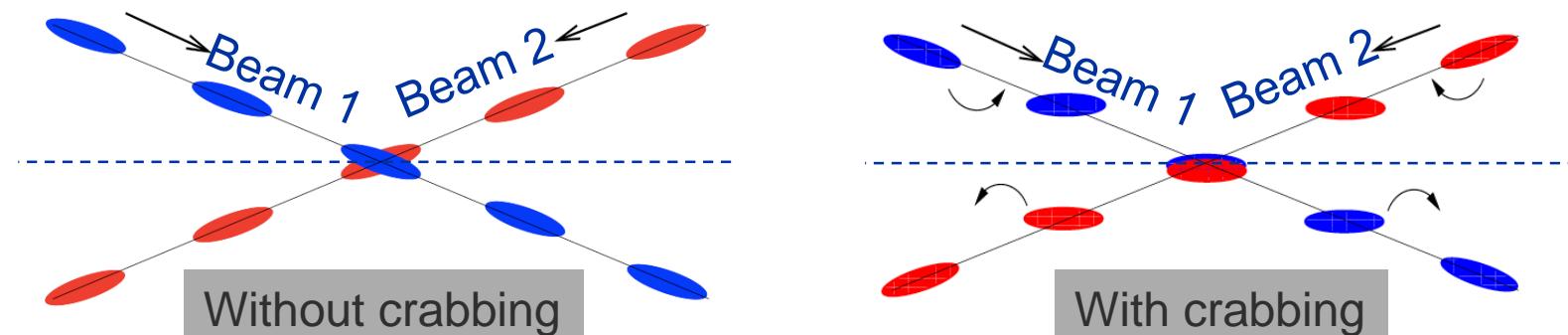
Reduce the  $\beta^*$  ( $\sigma$ )

- Stronger focusing around the interaction points

Use crab cavities to reduce the crossing angle effect (s)

- Tilt the bunches to have more head-on collision effect

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y} \cdot W \cdot e^{\frac{B^2}{A}} \cdot S$$

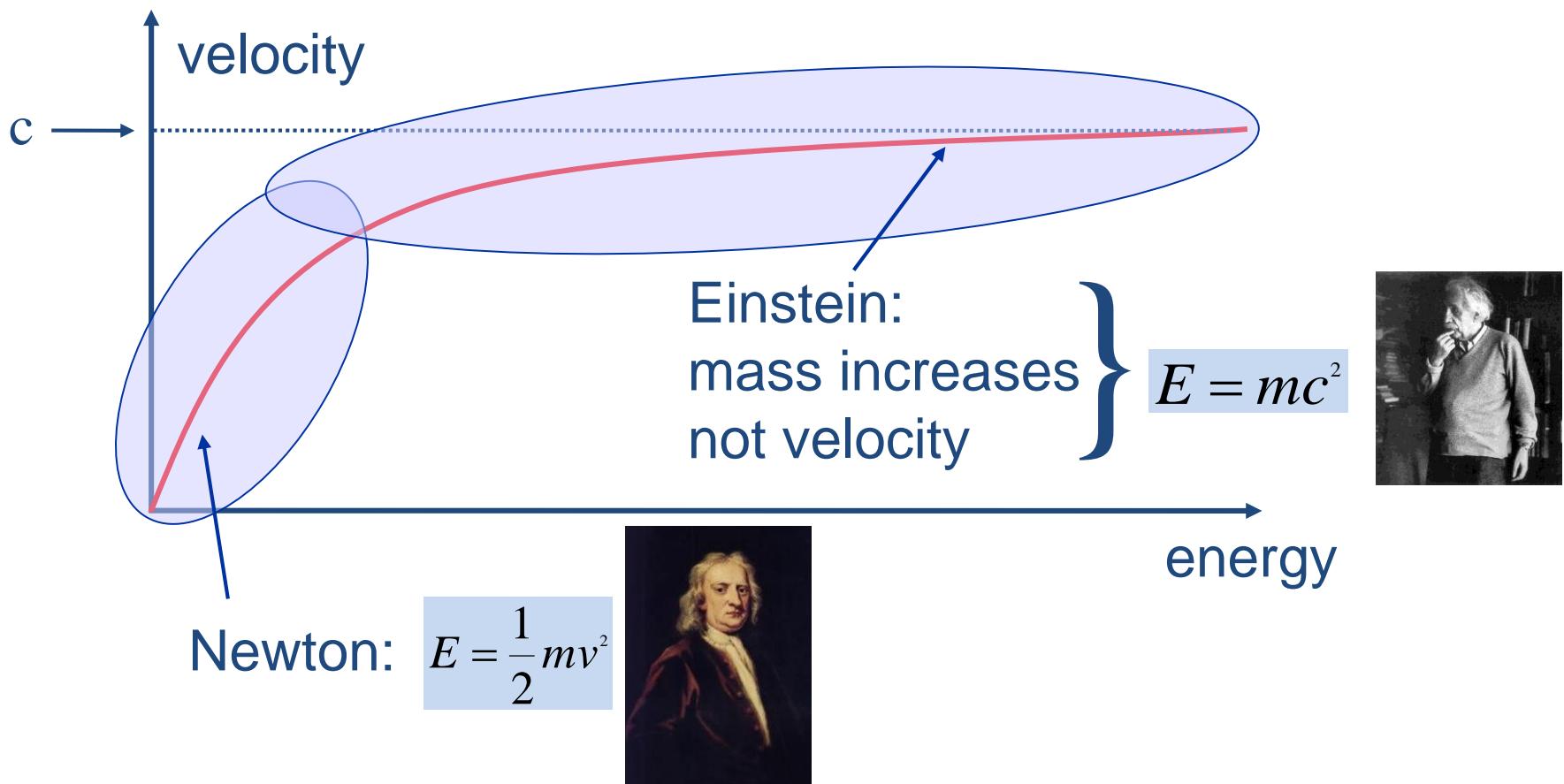




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# Towards Relativity



# A Guided Tour

Lets have a look at a synchrotron:

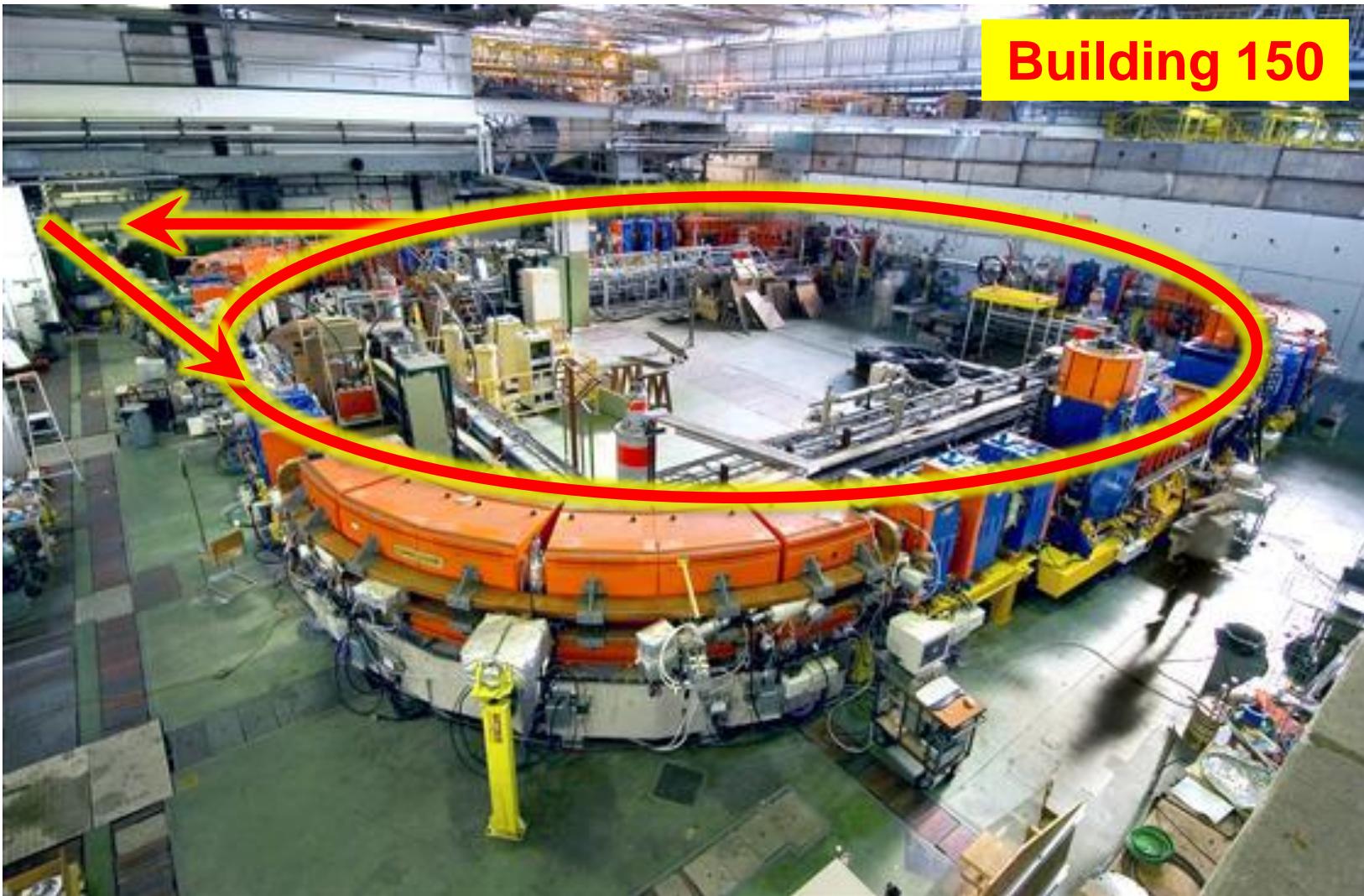
- Identify the main components and processes
- Briefly address their function

As an example I took a machine at CERN that can be seen from the top, even when it is running.

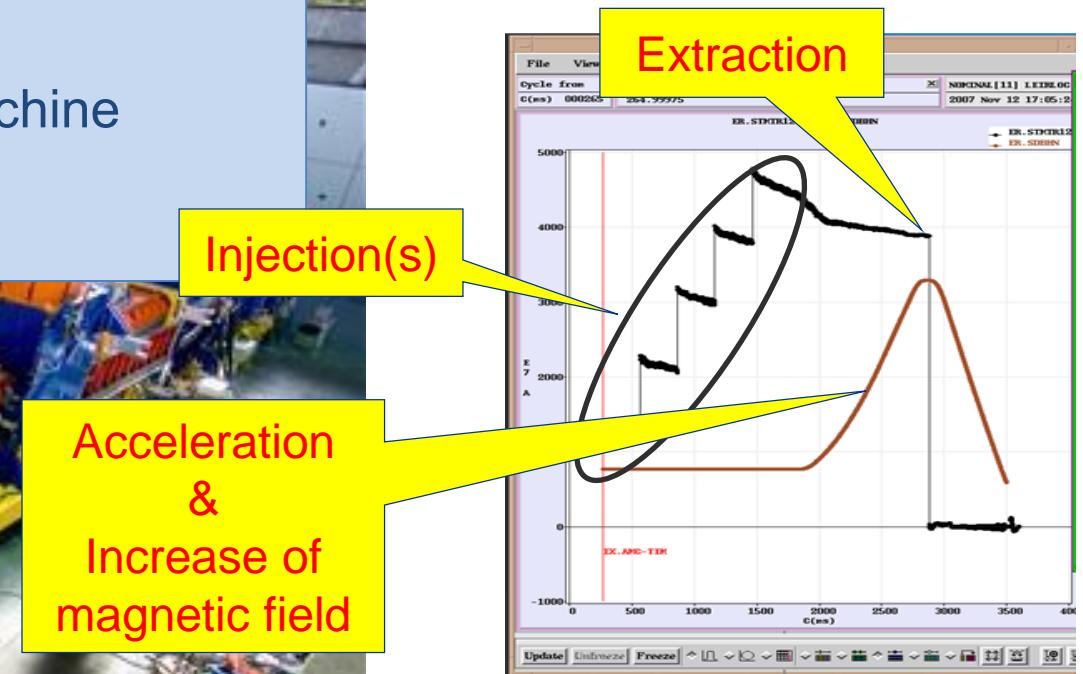
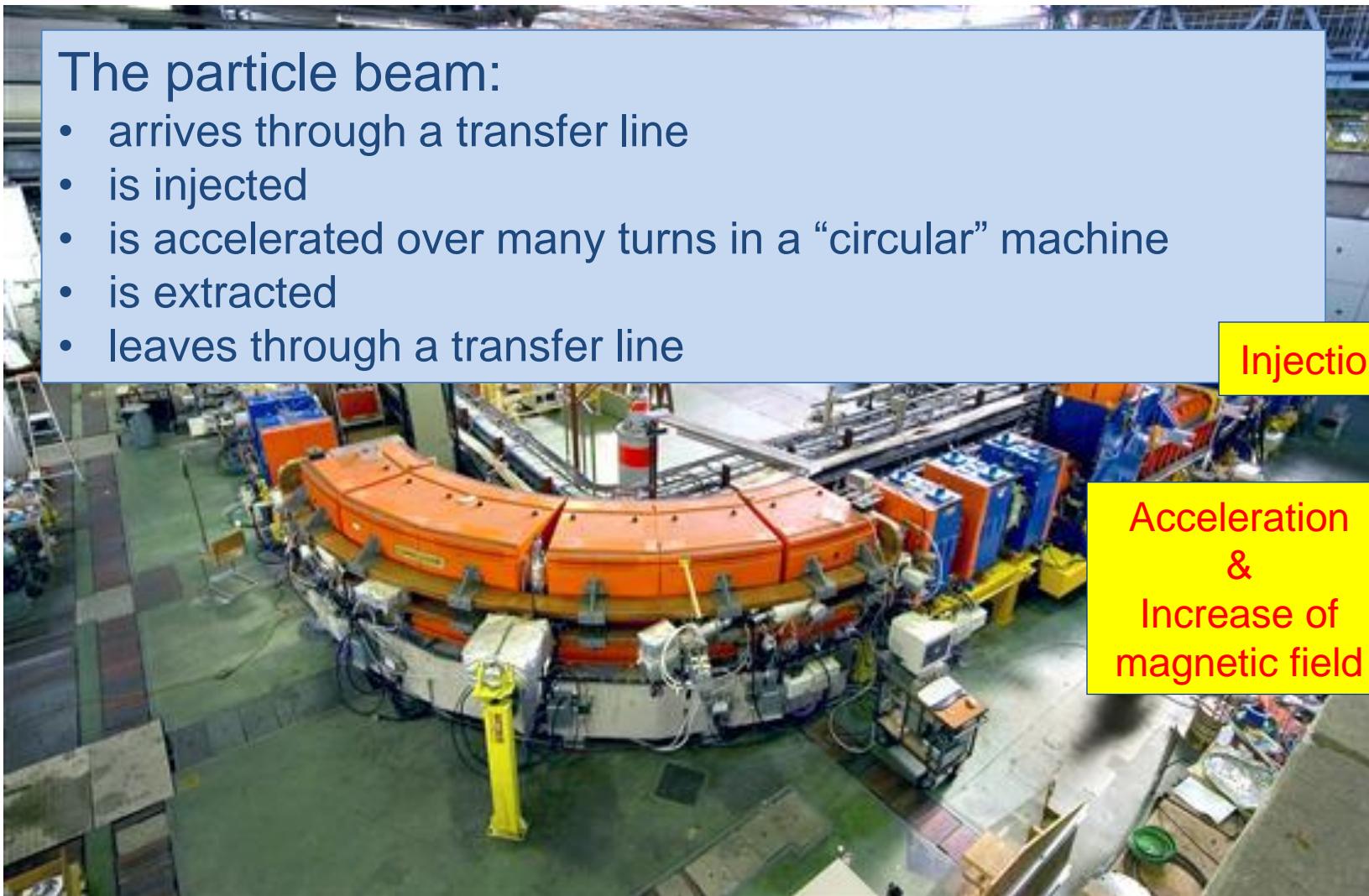
**LEIR**  
**Low Energy Ion Ring**



# LEIR as an Example

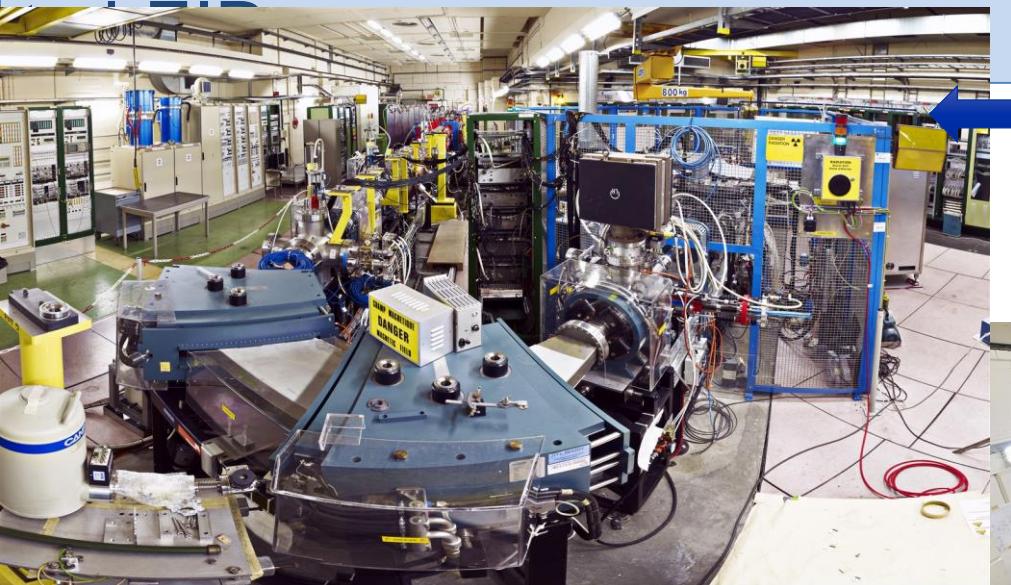


# Vacuum Chamber



# LINAC 3, injector of LEIR

The CERN LINAC 3 provides different ion species

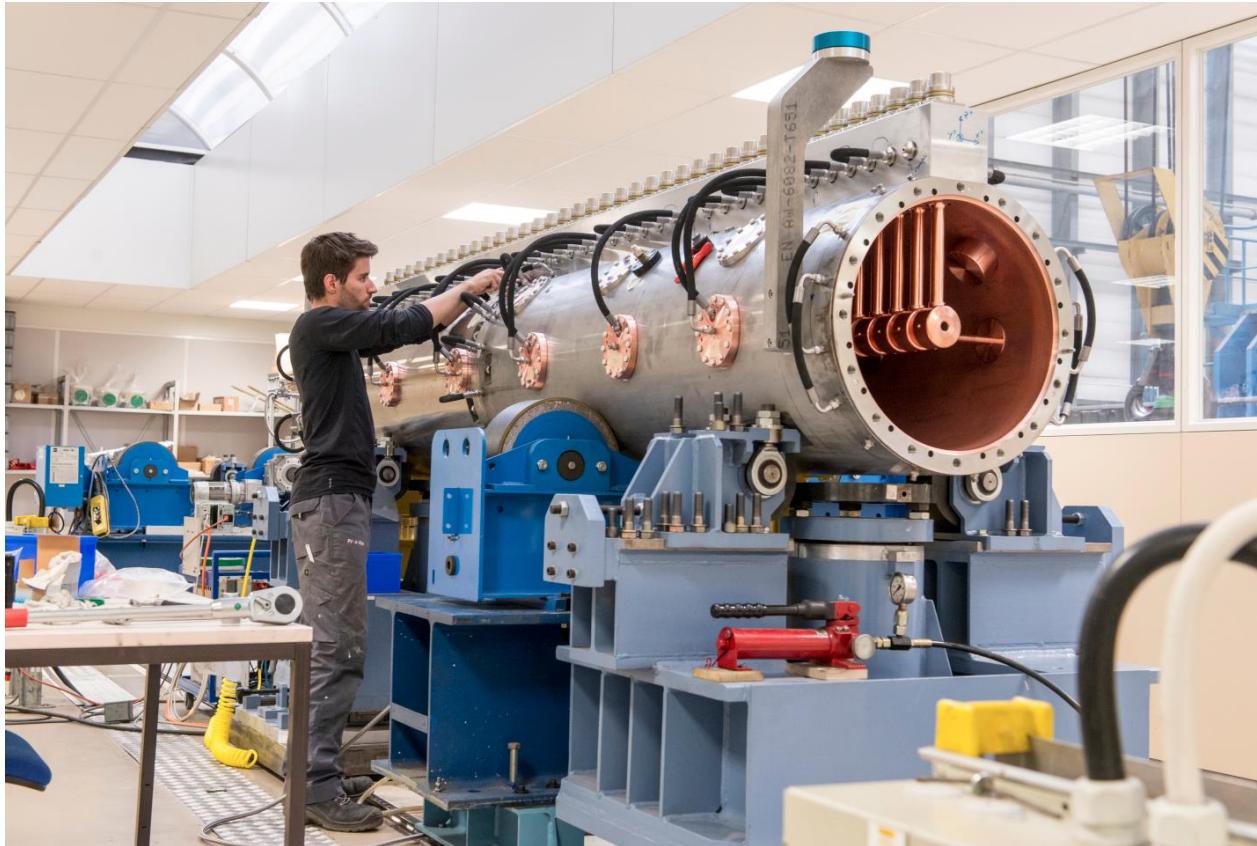


The ion source in the blue cage with the spectrometer in the front, follow by the LINAC behind



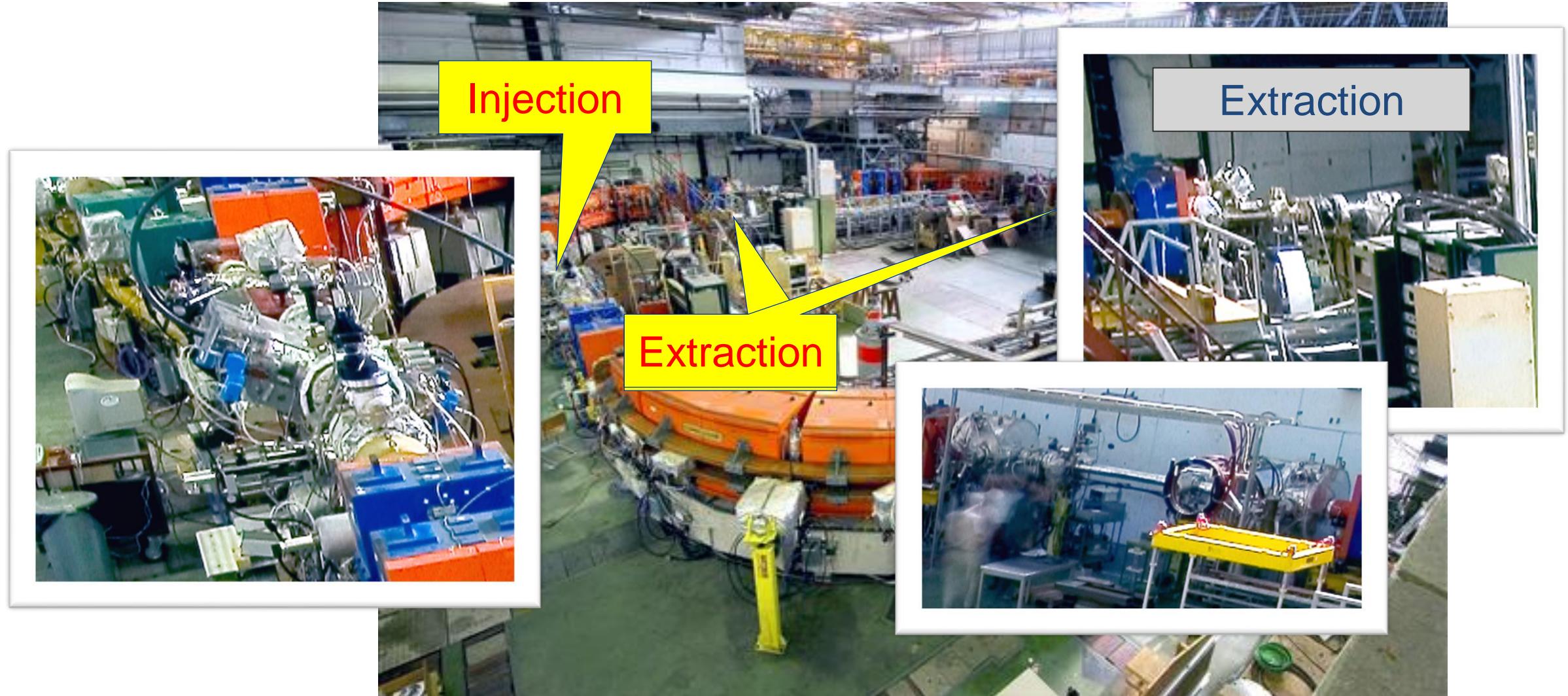
The downstream part of the LINAC with the accelerating structures (Alvarez) in the back of the image and transfer and measurement lines in the front

# LINAC Accelerating Structure

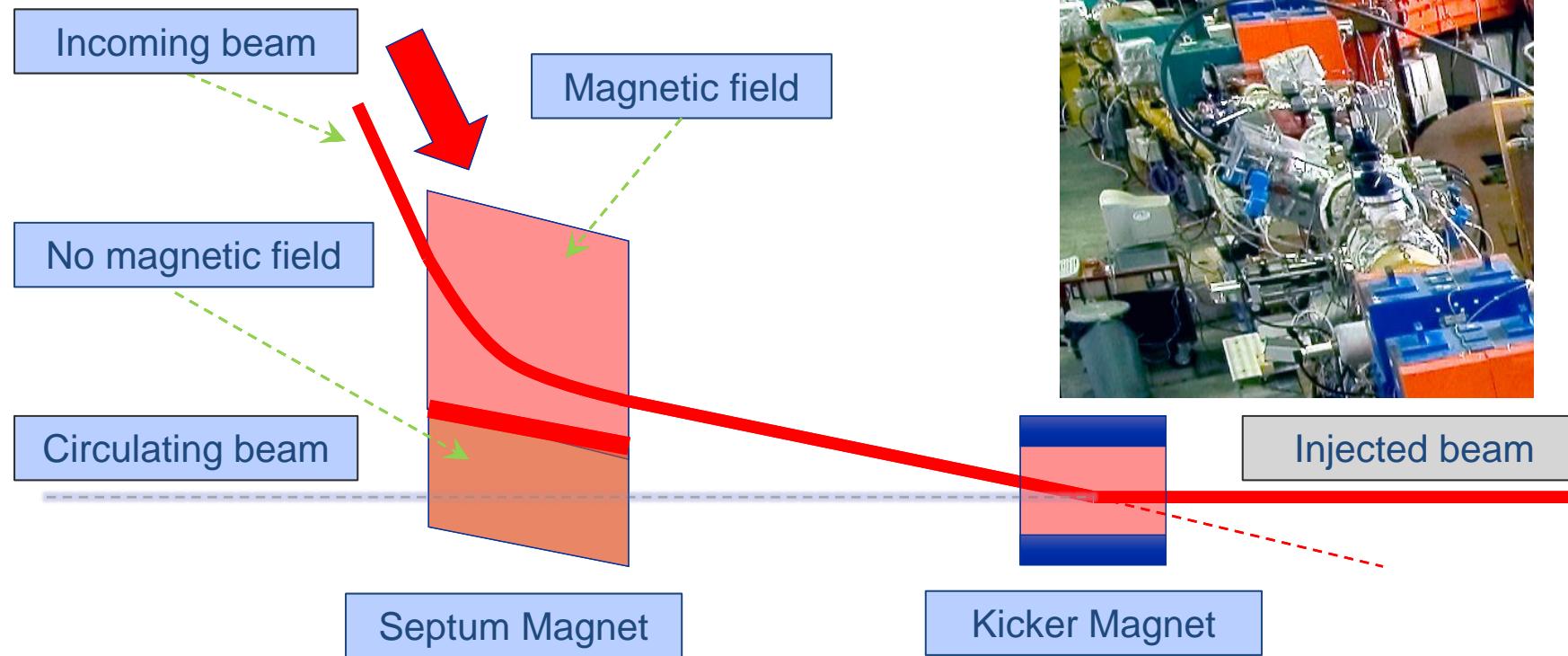


The CERN LINAC 4 drift tube

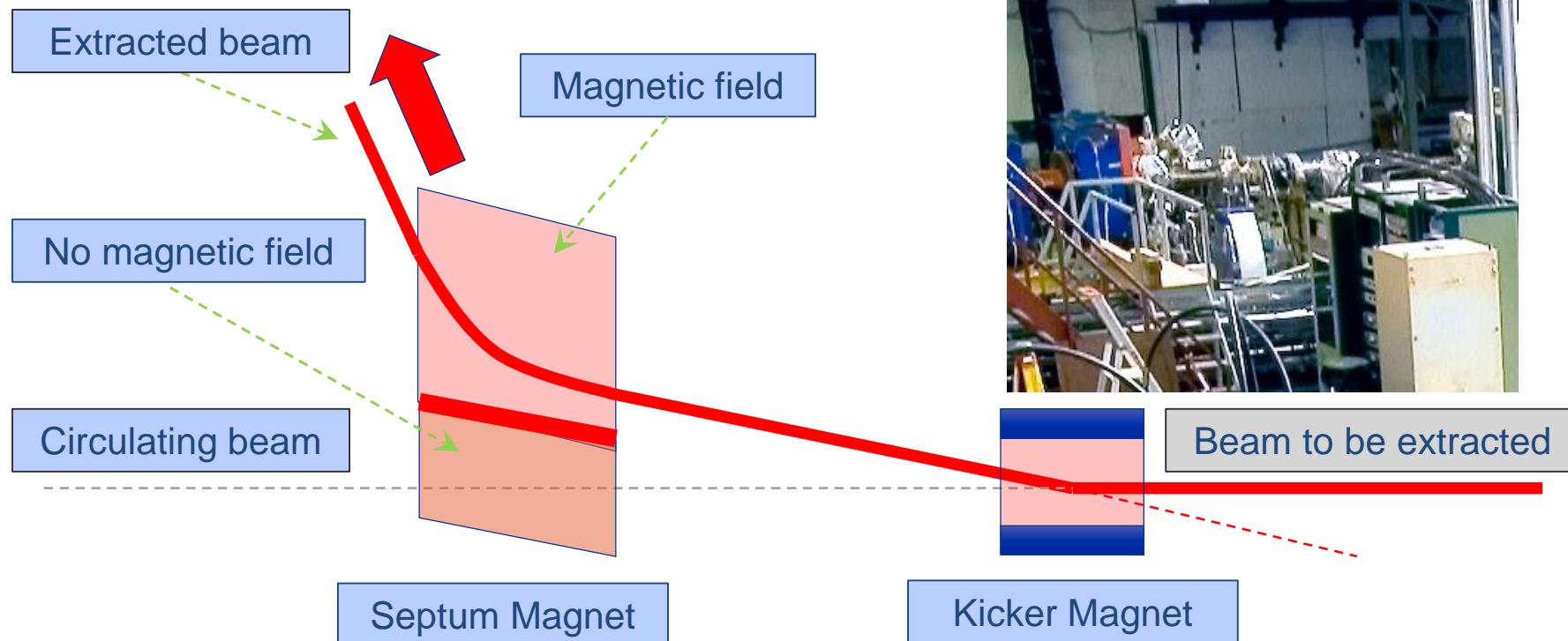
# Injecting & Extracting Particles



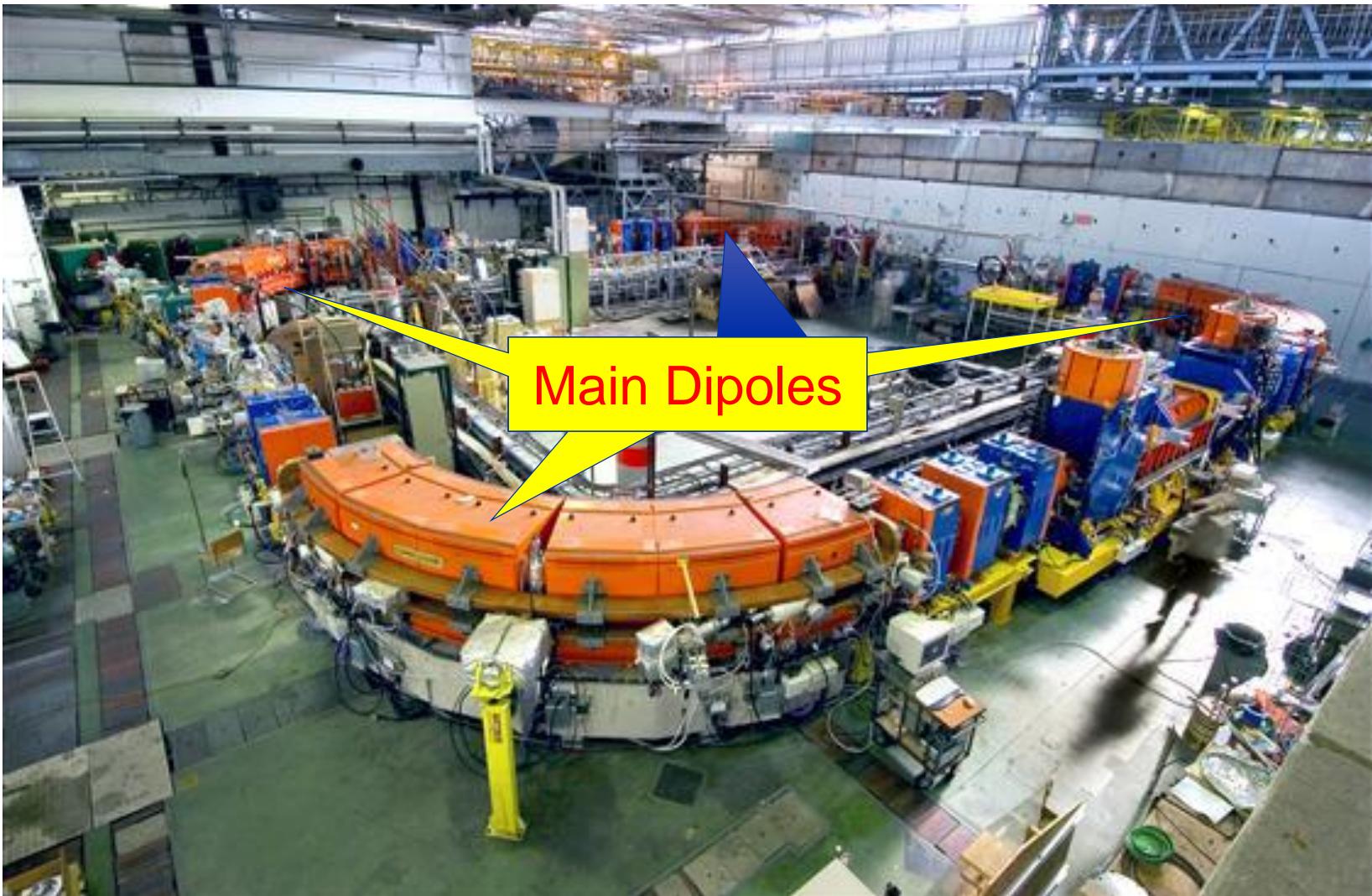
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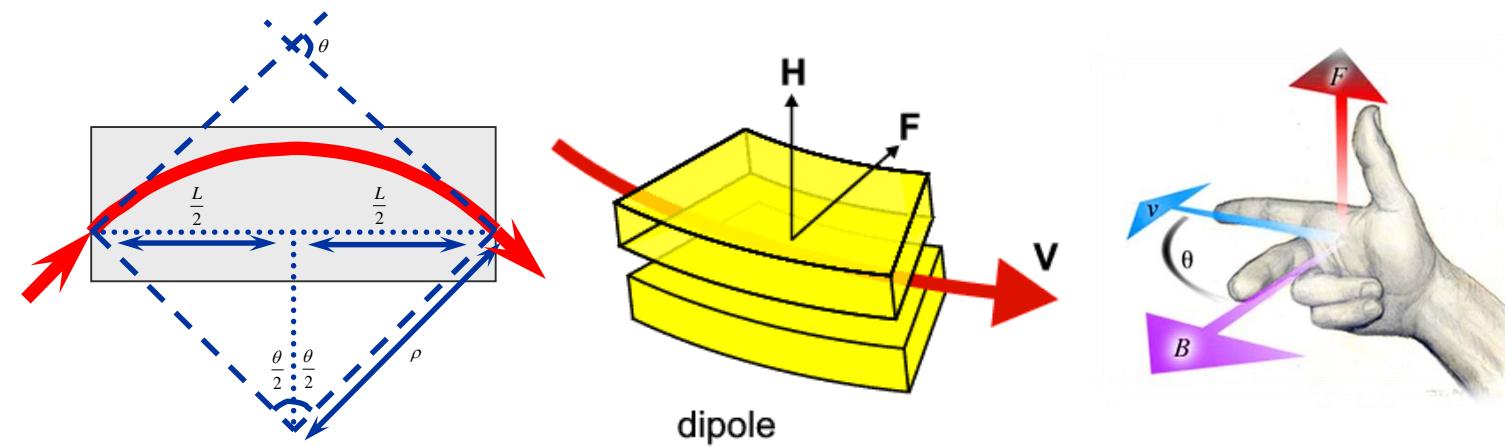


# Make Particles Circulate



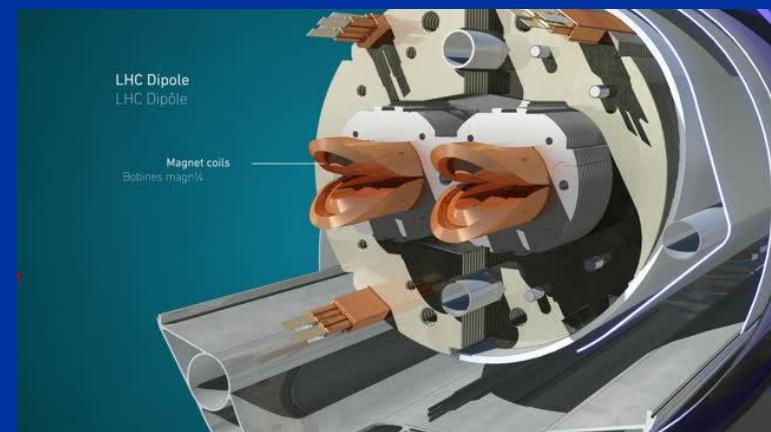
# Deviating Charged Particles

Moving charged particles are deviated in a magnetic field



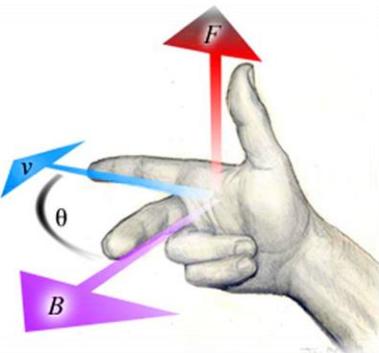
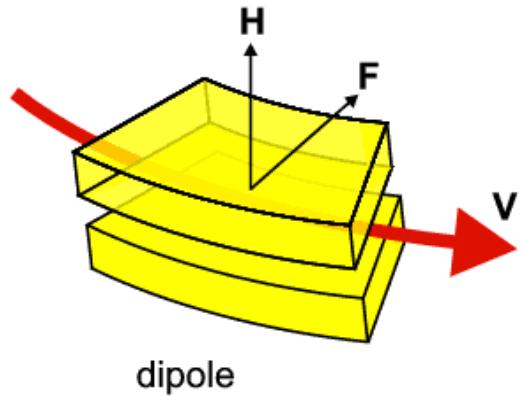
Magnetic Lorentz Force:

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



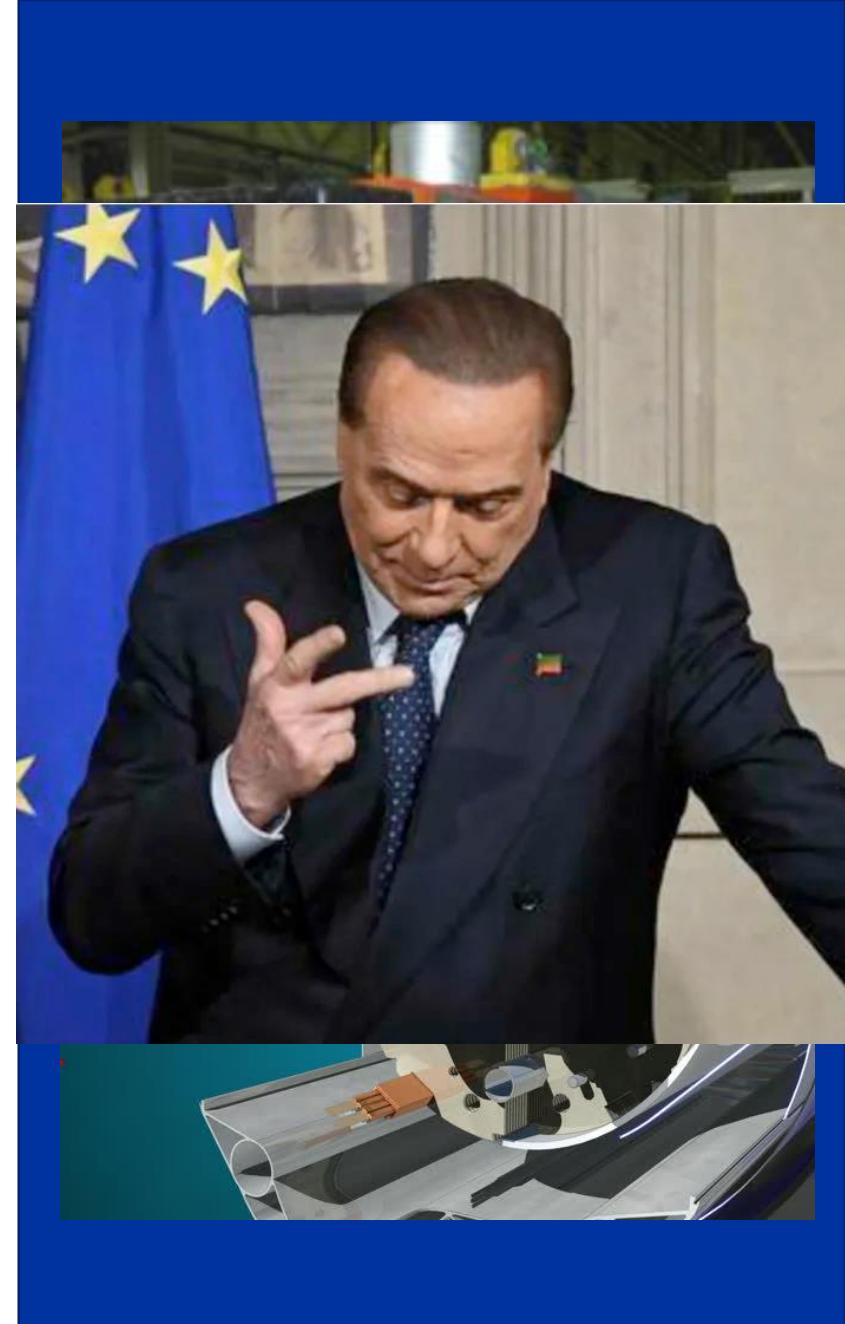
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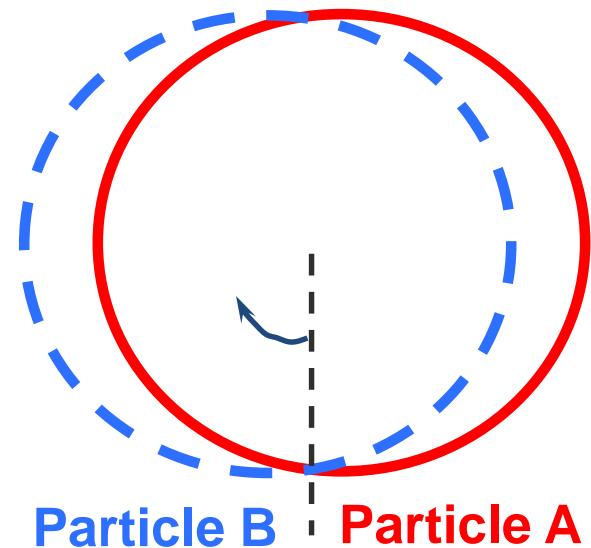
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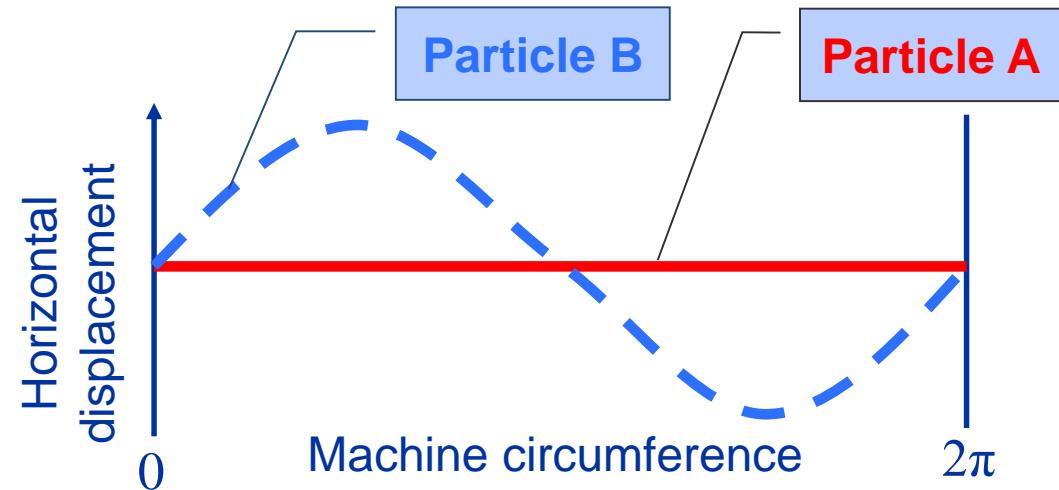


# Oscillatory Motion in the Horizontal Plane

Two charged Particles in a homogeneous magnetic field



Horizontal motion



Different particles with different initial conditions in a homogeneous magnetic field will cause oscillatory motion in the horizontal plane → **Betatron Oscillations**

# Oscillatory Motion of Particles

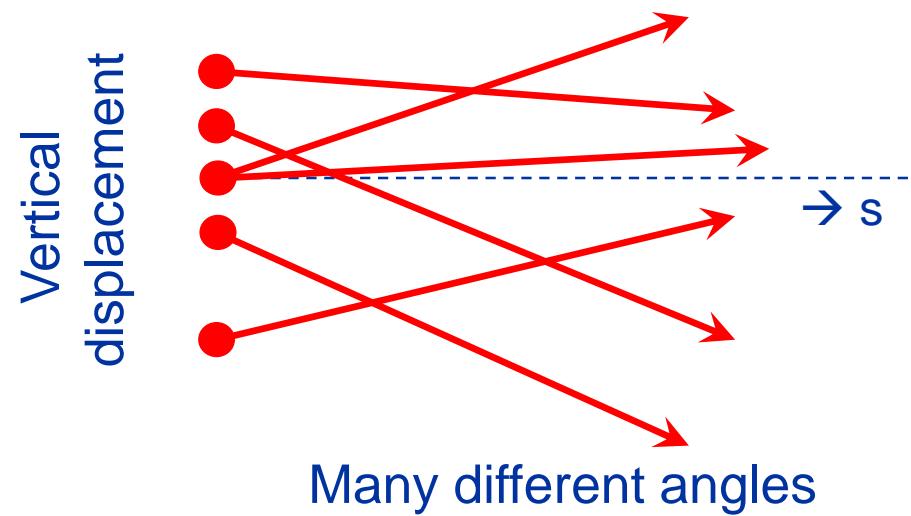
The horizontal motion seems to be “stable”.... What about the vertical plane ?



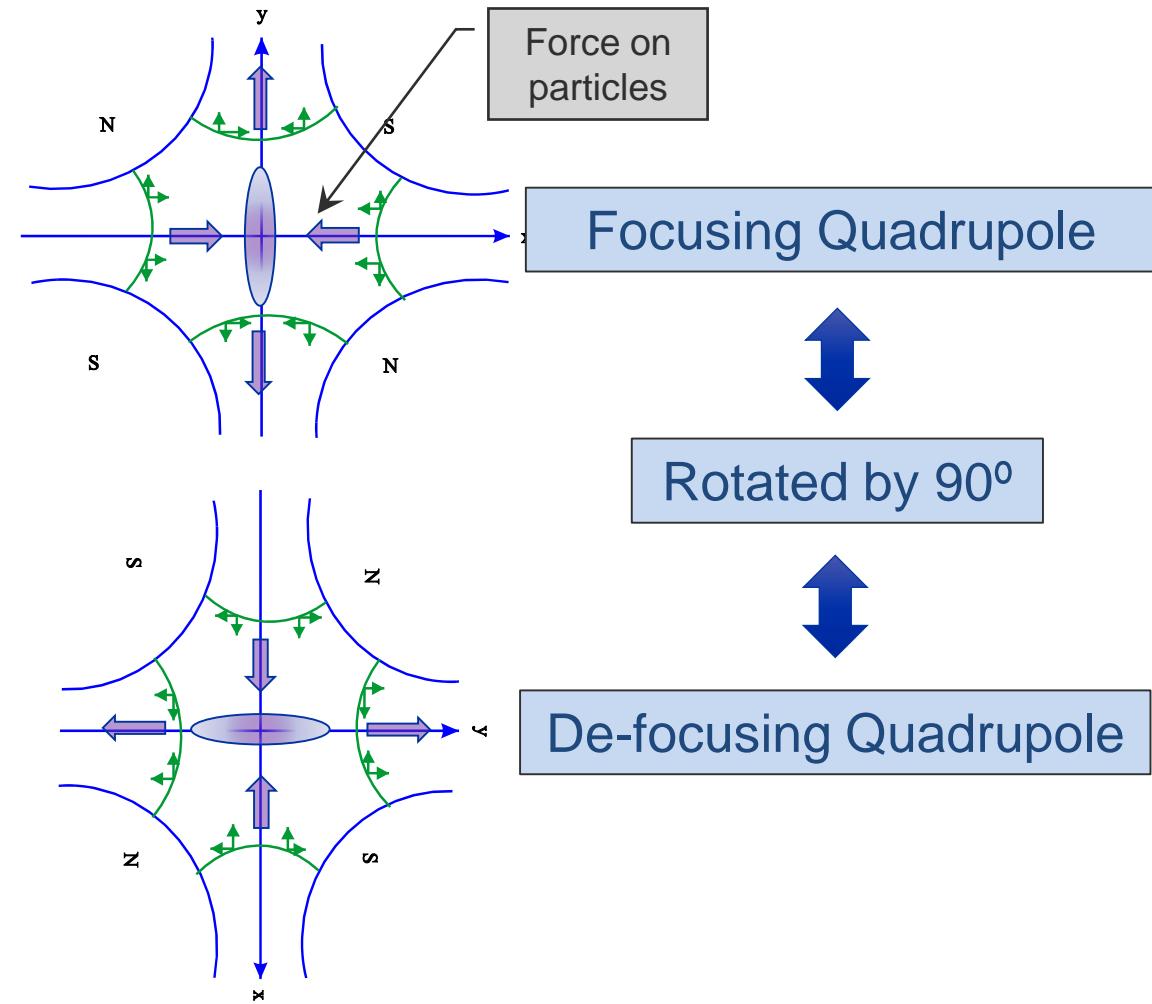
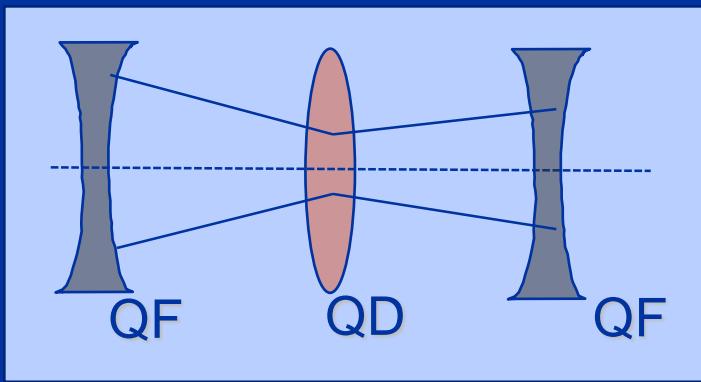
# Oscillatory Motion in the Vertical Plane

The horizontal motion seems to be “stable”.... What about the vertical plane ?

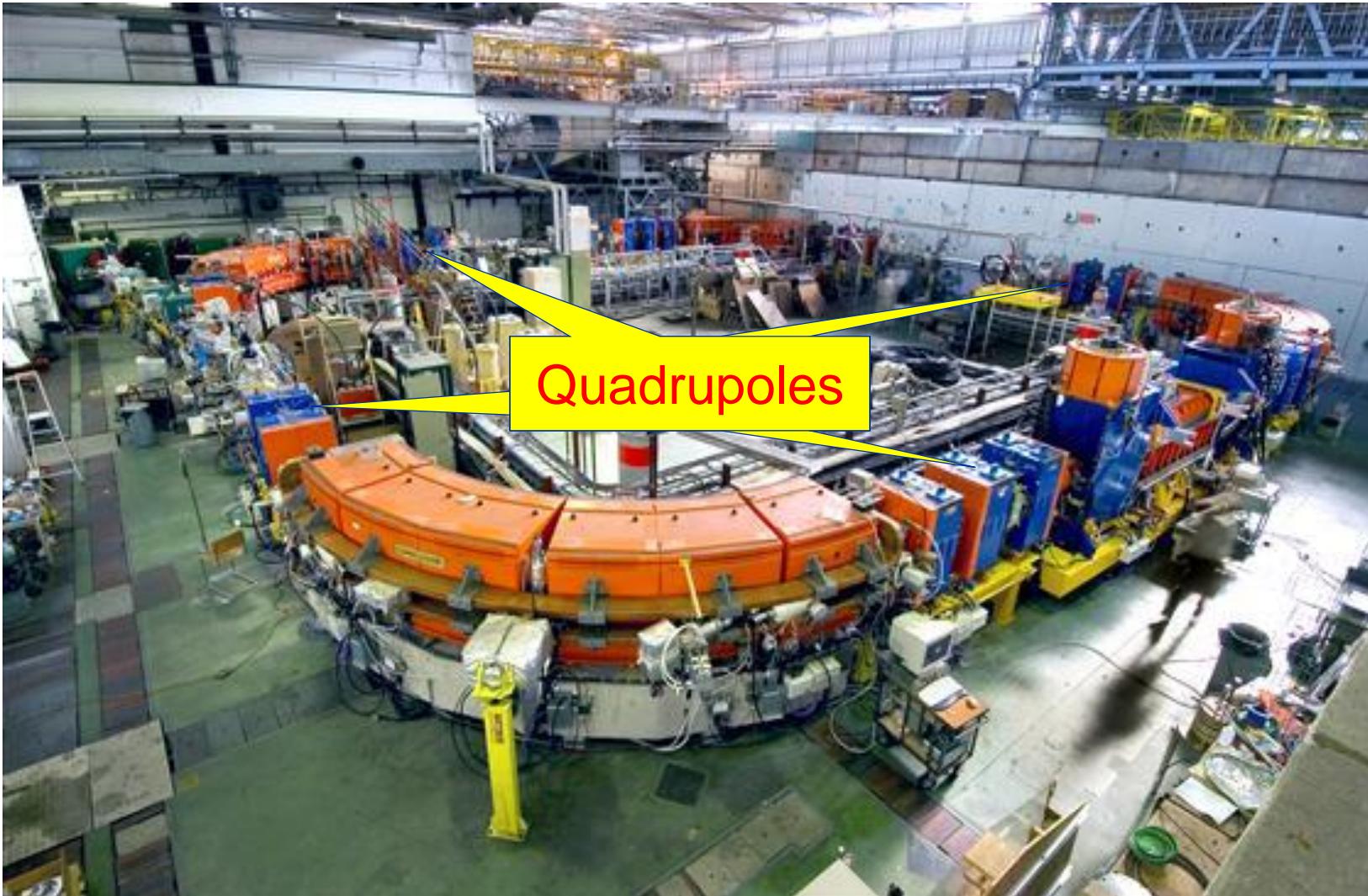
Many particles many initial conditions



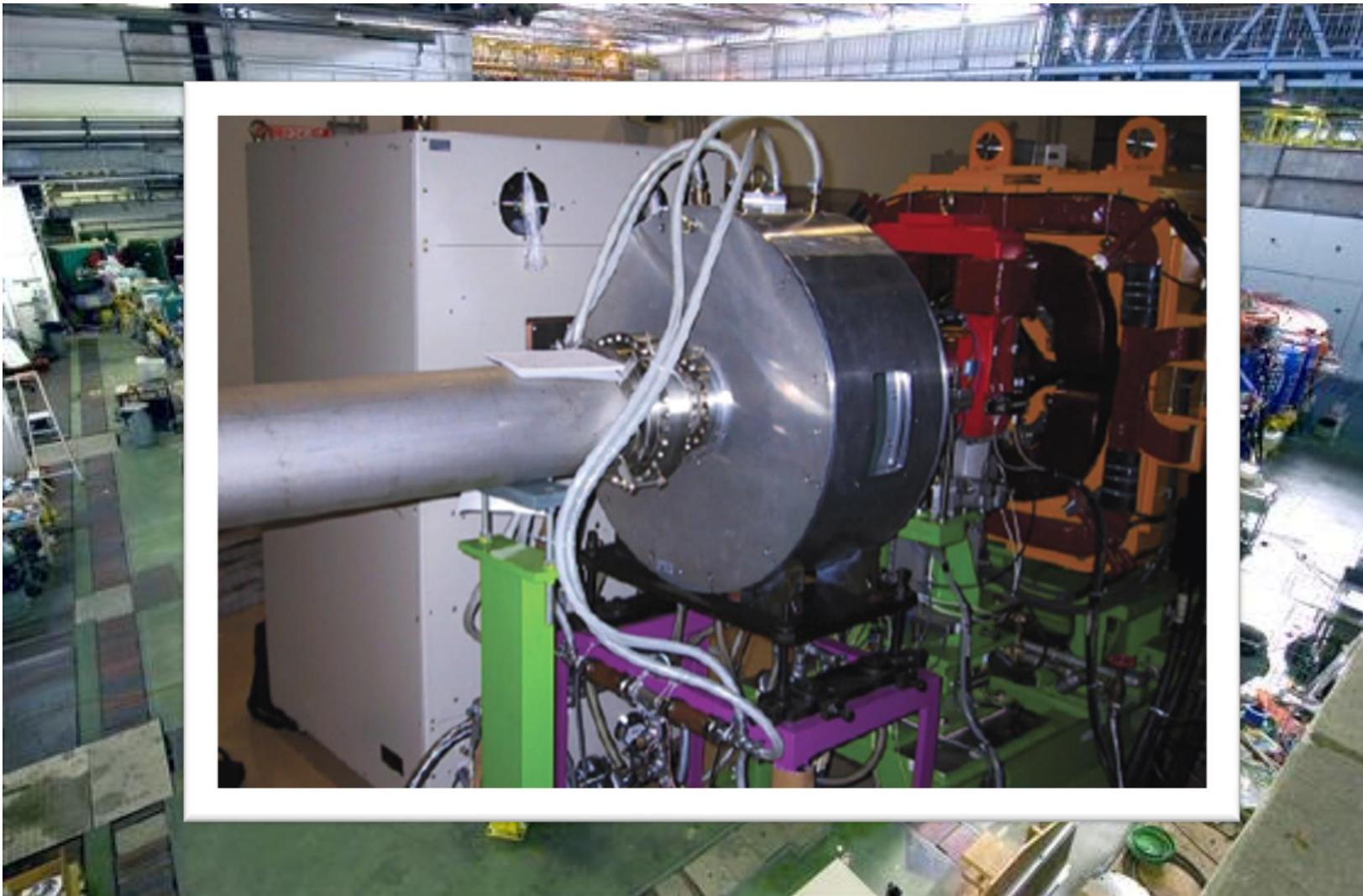
# Focusing Particle Beams, a bit like a lens



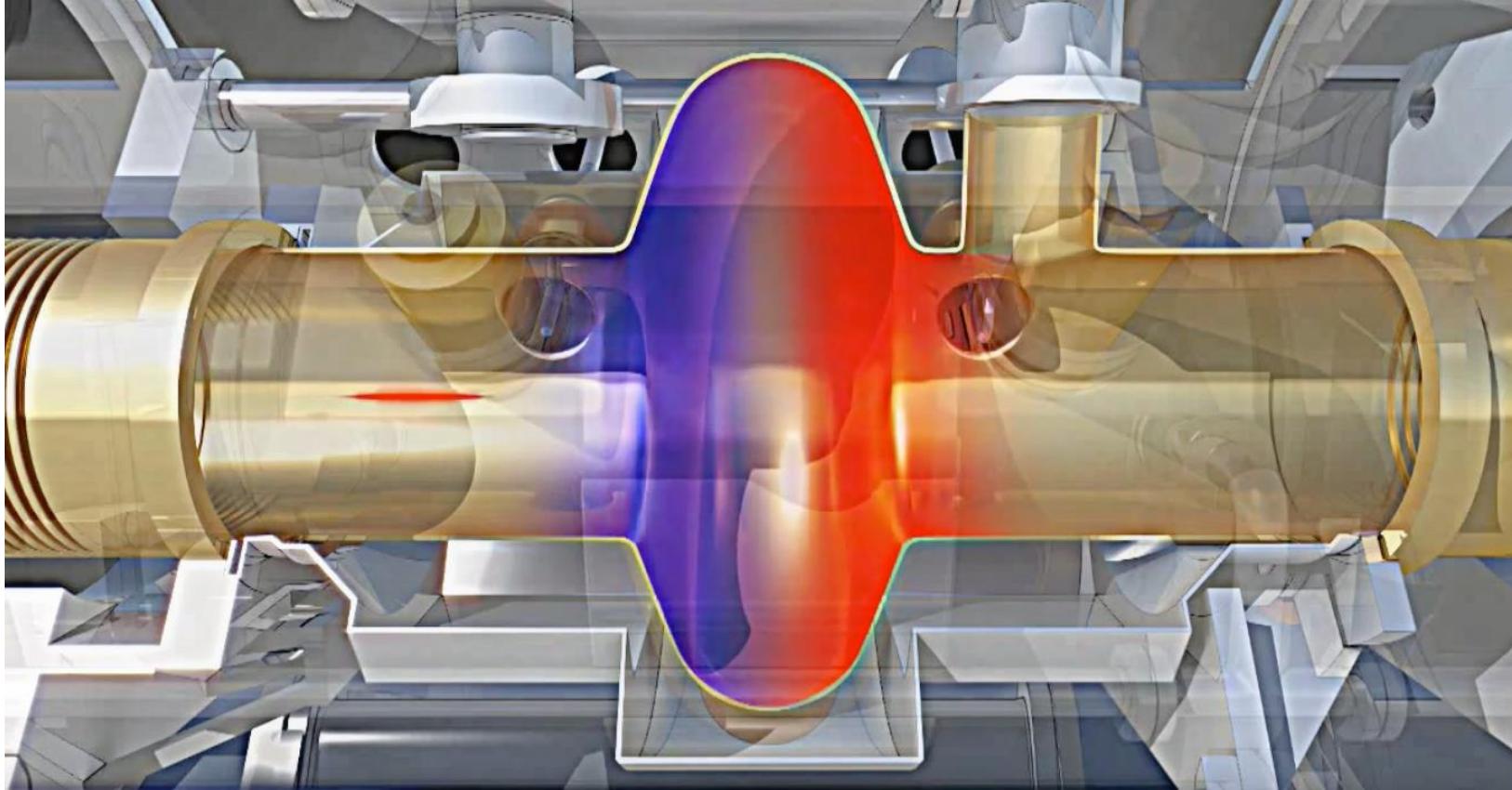
# Focusing Particle Beams in LEIR



# Accelerating Particles, Using Electrical Fields



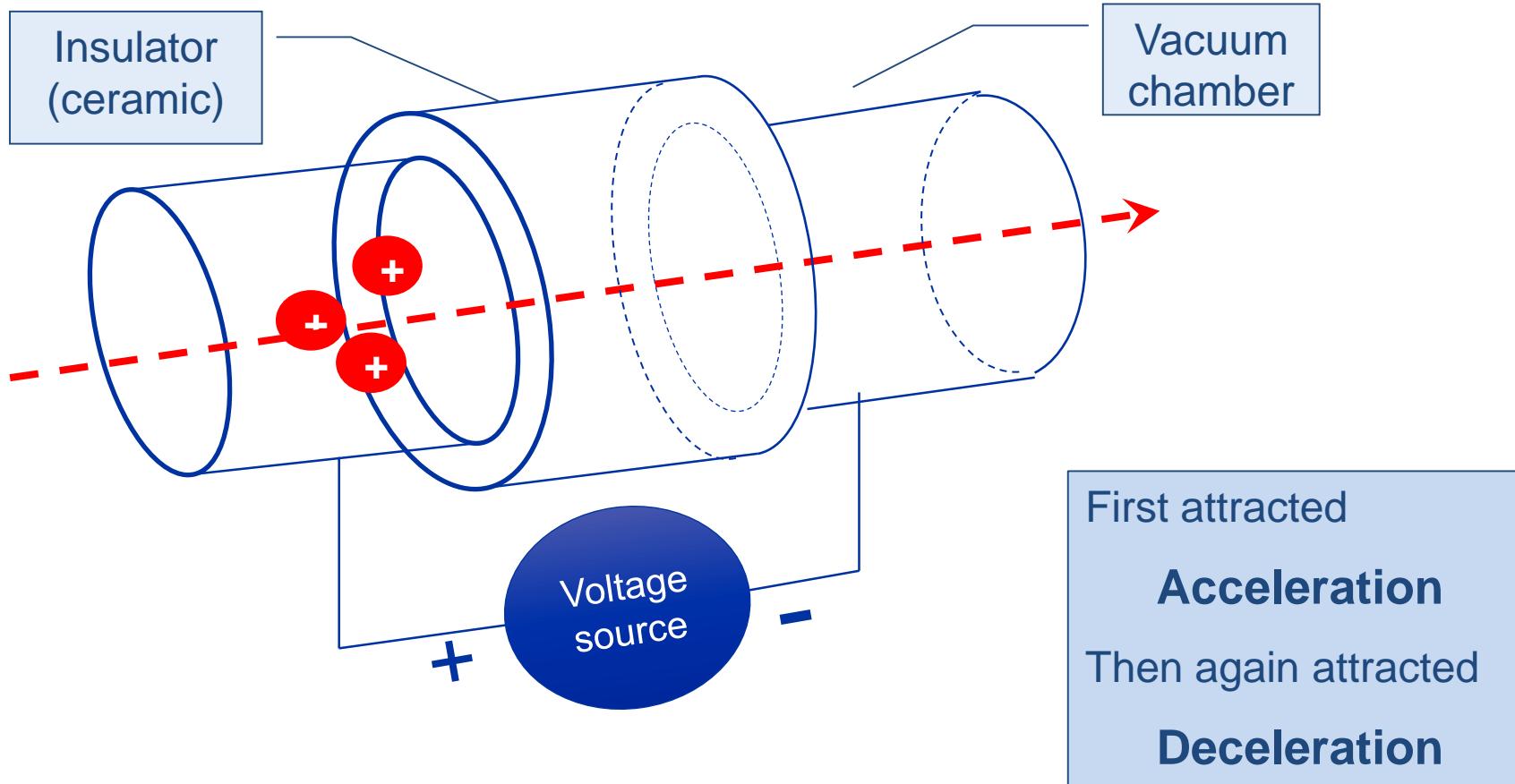
# Radio Frequency Cavity



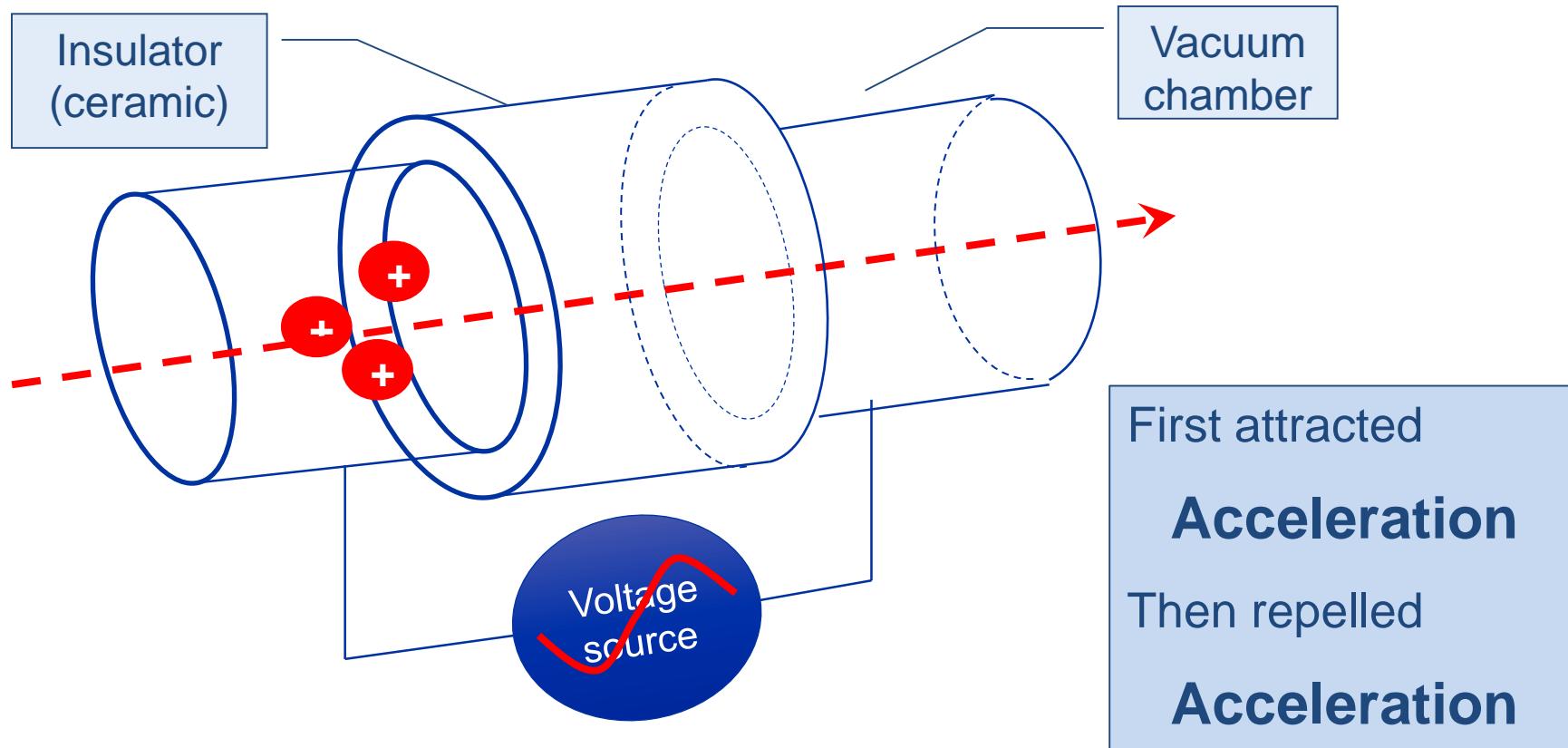
**Charged particles are accelerated by a longitudinal electric field**

**The electric field needs to alternate with a harmonic of the revolution frequency**

# Accelerating Beams



# Accelerating Beams



# Some RF Cavities and feedbacks

Fixed frequency cavities  
(Superconducting) in the LHC



Variable frequency cavities (normal conducting) in the CERN PS



RF cavities are not only used to accelerate beams, but also to shape the beam:

- Longitudinal emittance
- Number of bunches
- Bunch spacing, shaping, etc.

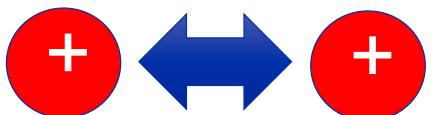
They also make up for lost energy in case of lepton machines.

# Possible Limitations

Machines and elements cannot be built with infinite perfection

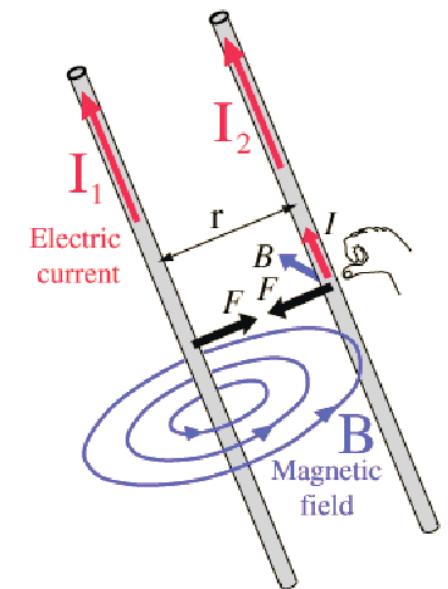


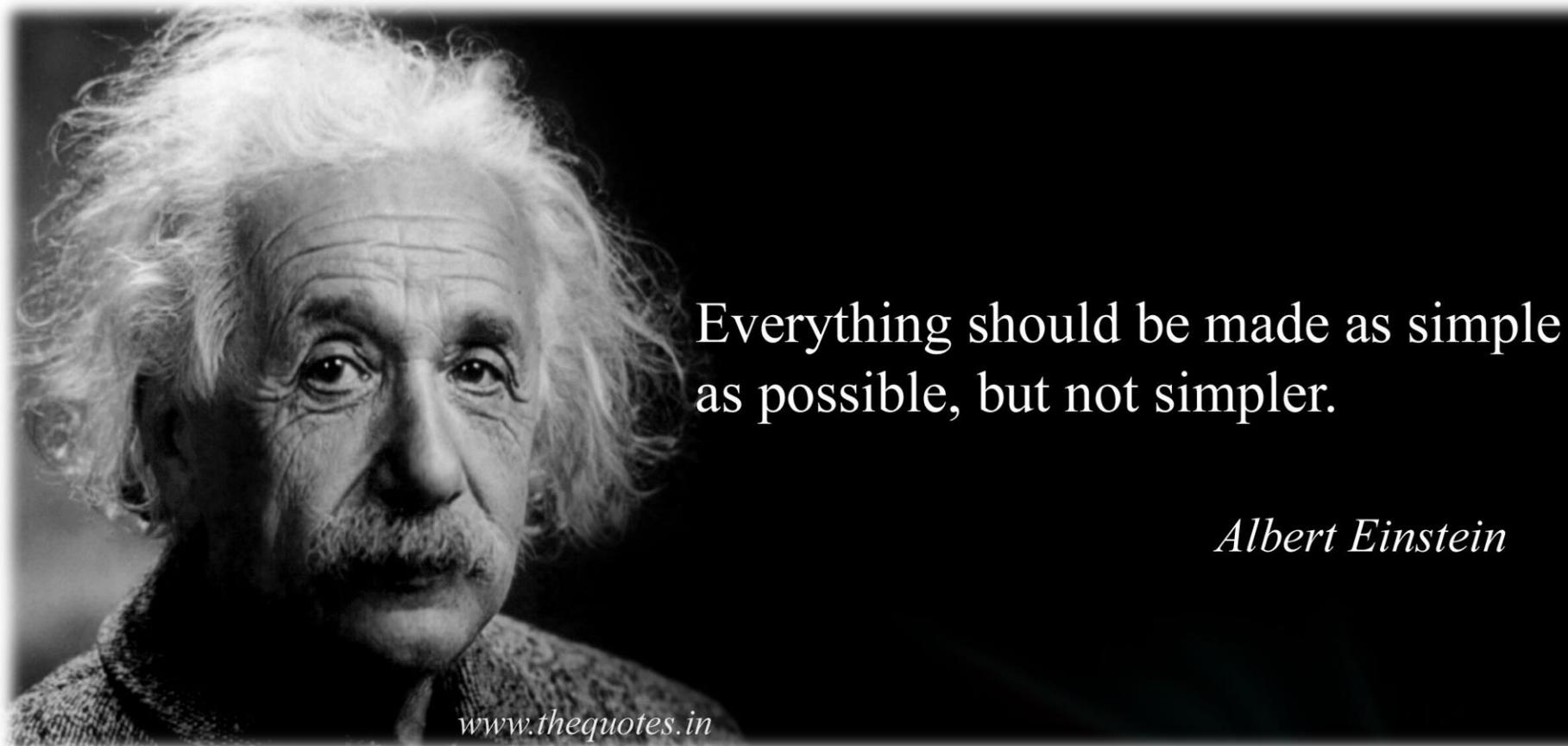
Same phase and frequency for driving force and the system can cause resonances and be destructive



Neighbouring charges with the same polarity experience repelling forces

Moving particles create currents, These currents result in attracting or repelling magnetic fields





Everything should be made as simple  
as possible, but not simpler.

*Albert Einstein*

*www.thequotes.in*

home.cern



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# Figures of Merit in accelerators

For different accelerators and experiments different beam characteristics are important. However, a major division can be made between:

Fixed Target  
Physics:



Light Sources:

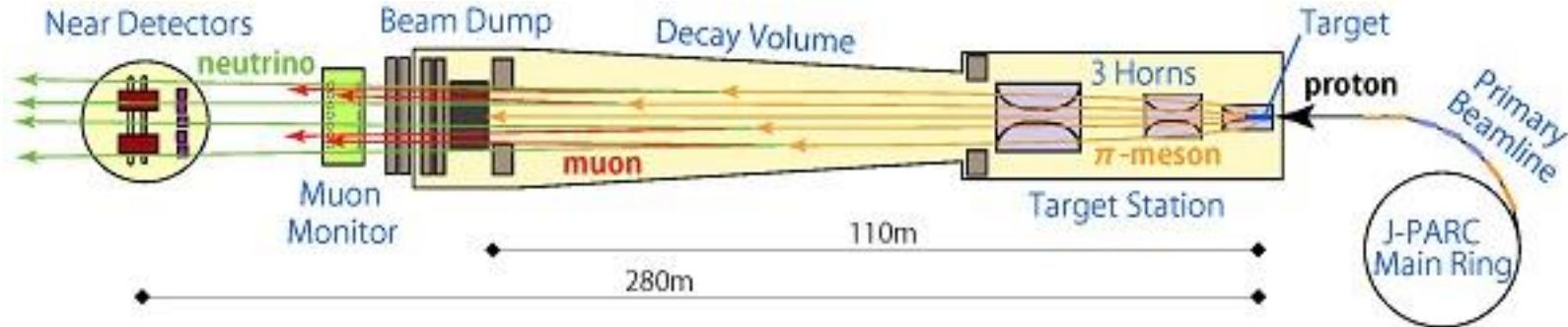


Collider Physics:



# Fixed Target Physics

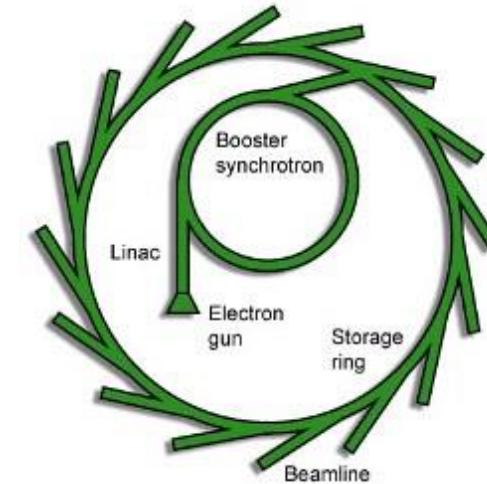
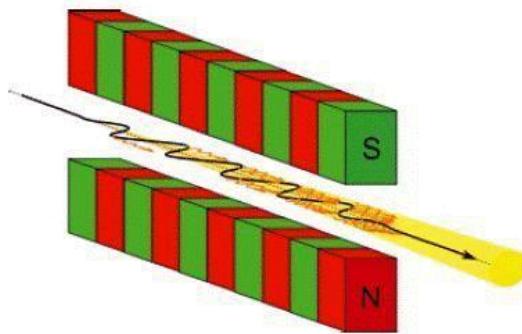
Just a few examples among many:



- Neutrino physics and Spallation sources: high beam power
  - High beam **intensity** with small beam size
  - High beam **energy** and / or high **repetition rate**
- J-PARC – Japan
- FermiLab - USA
- Previously CERN to CNGS – Europe
- Spallation Neutron Source (SNS) Oak Ridge - USA

# Synchrotron Light Sources

Just a few examples among many:



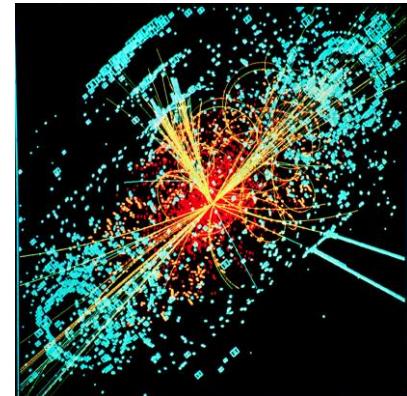
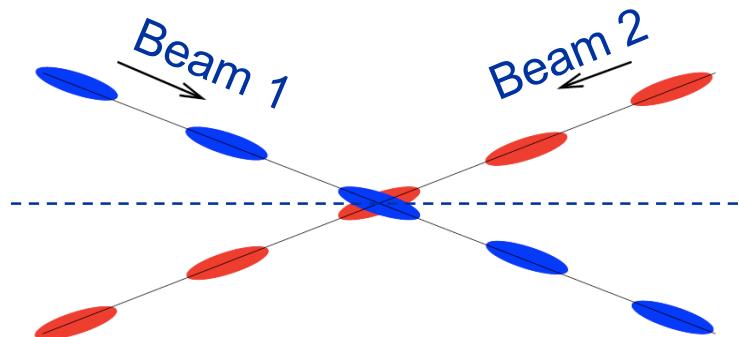
- Photon beam from stored (highly relativistic) electron beam
  - High electron beam intensity (Accelerator & Storage Ring)
  - Use of **undulators** to enhance photon emission
- Swiss Light Source (SLS) – Europe
- European Synchrotron Radiation Facility (ESRF) – Europe
- National Synchrotron Light Source (NSLS II) – USA
- Super Photon Ring (SPRing) – Japan ..... And many more....

# Collider Physics

The aim is to have a high duty cycle of collision, but not too many collisions at the same time in order to allow disentangling of individual events in the detectors (avoid pile-up)

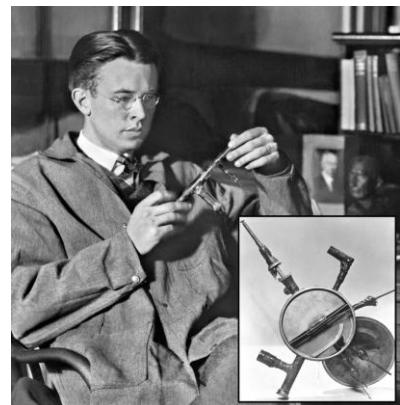
Beams in clockwise and anti-clockwise direction:

- Proton – Proton → 2 separate rings
- Electron – Positron or Proton – Antiproton → single ring

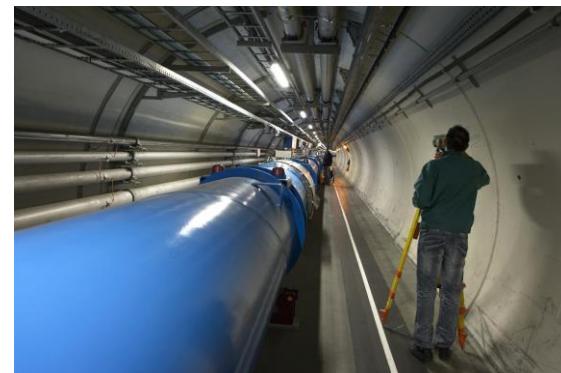


***"We shall have no better conditions in the future if we are satisfied with all those which we have at present."***

*Thomas A. Edison*  
Inventor and businessman, 1874–1931



E. Lawrence who invented the cyclotron in 1929



The LHC Today...

..... much has changed since then....

*Huge thanks to Rende Steerenberg, BE-OP*



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