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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Accelerators and Their Use

Today: over **30'000 accelerators** operational world-wide*

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

- Industrial applications: ~ 20'000*
- Medical applications: ~ 10'000*

Les 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 world-wide*

Linear or circular

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

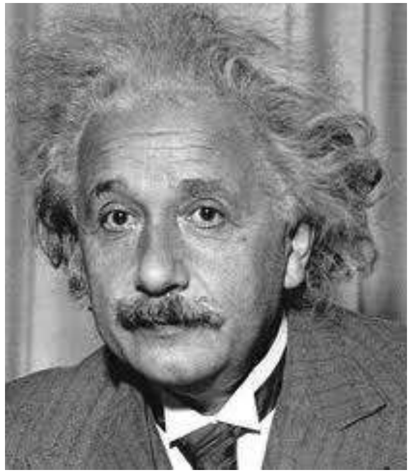
operated in continuous or pulsed modes

- 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

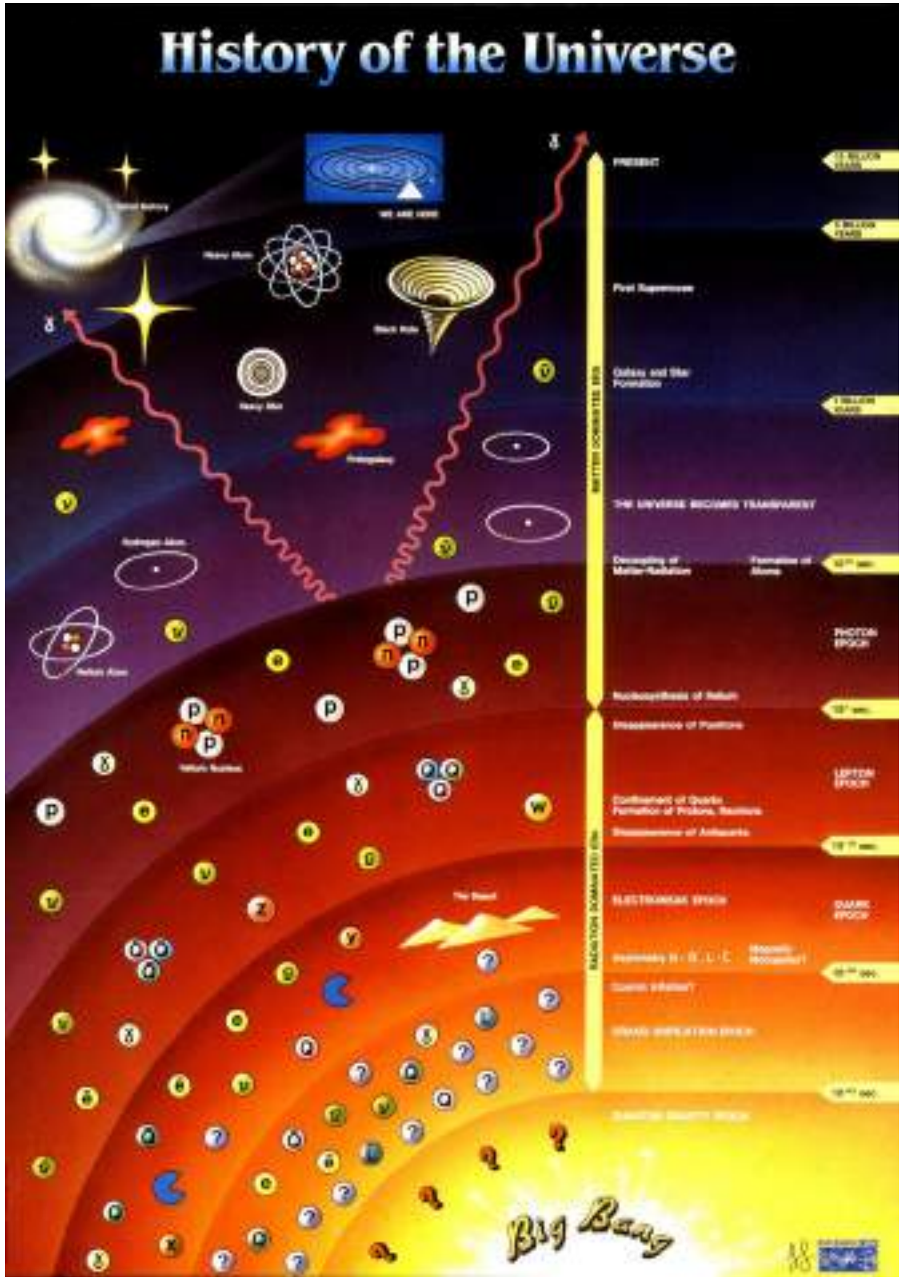
$E = m \cdot c^2$

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

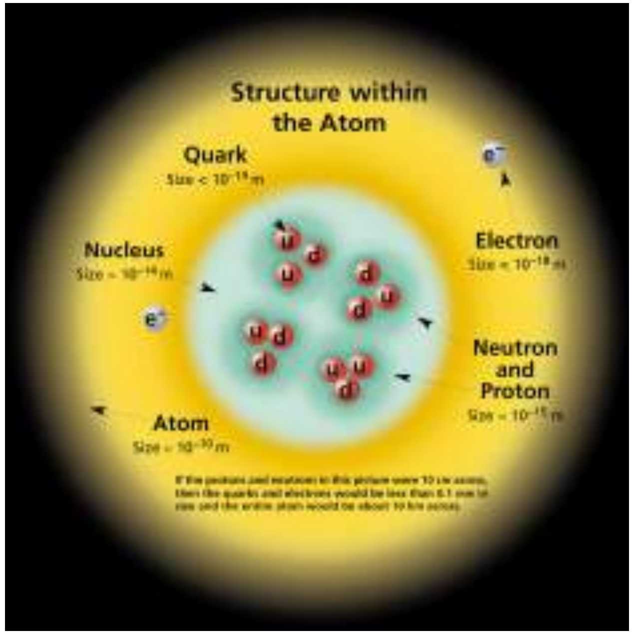


Looking to smaller dimensions

Visible light
λ = 400 – 700 nm

X-ray
λ = 0.01 – 10 nm

Particle accelerators
λ < 0.01 nm



$$\lambda = \frac{h\,c}{E}$$

Increasing the energy will reduce the wavelength

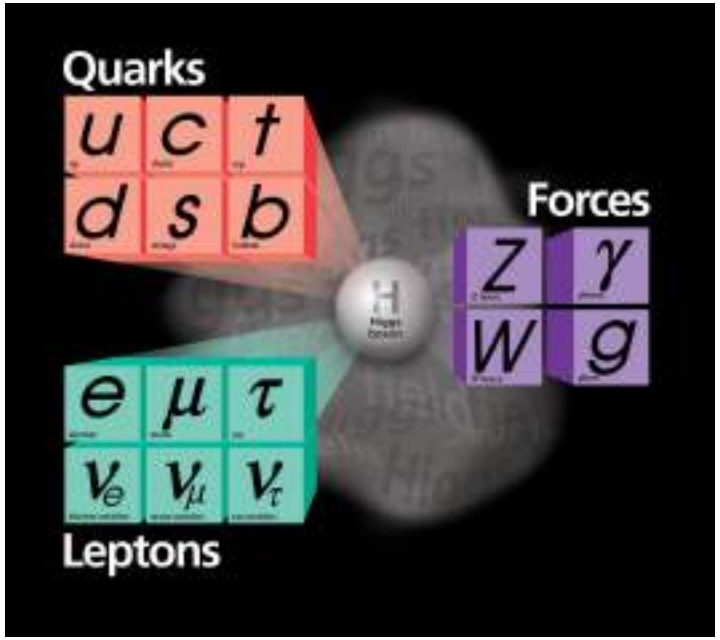
Fixed Target vs. Colliders

Fixed Target	Collider
	
$E \propto \sqrt{E_{beam}}$	$E = E_{beam1} + E_{beam2}$
Much of the energy is lost in the target and only part is used to produce secondary particles	All energy will be available for particle production


Oxford Sparks
A quick look
around the LHC
www.oxfordsparks.net

The Aim

Verify and improve the Standard Model



Discover the **Higgs** boson

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.

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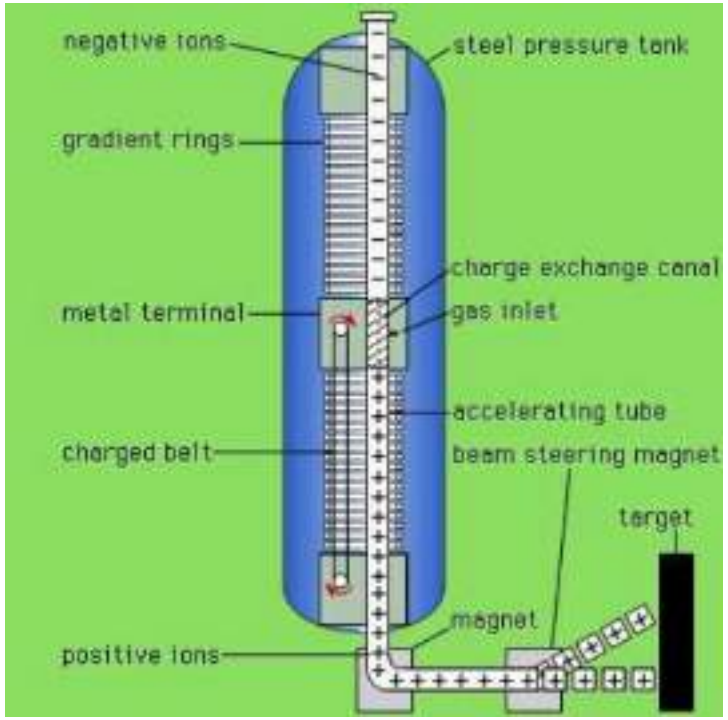
Cockroft & Walton / van de Graaff

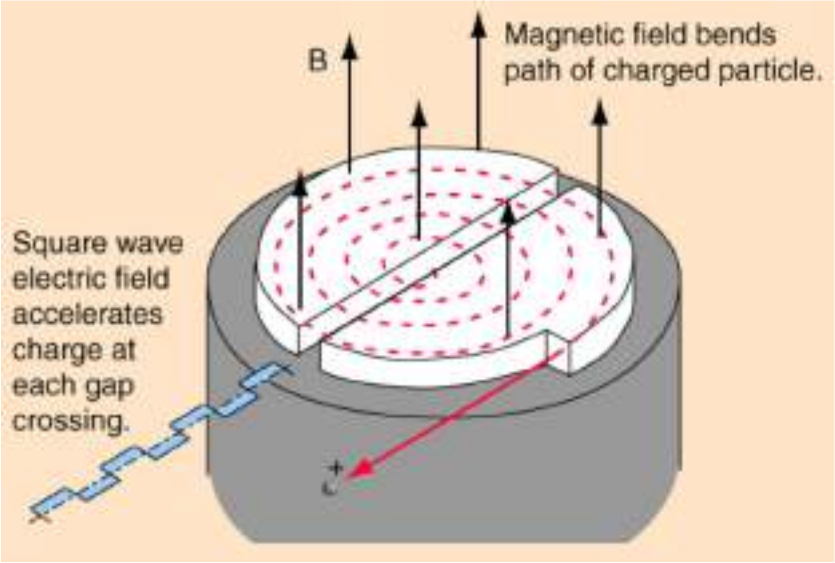
- 1932: First accelerator – single passage 160 - 700 keV
- Static voltage accelerator
- Limited by the high voltage needed



Cyclotron

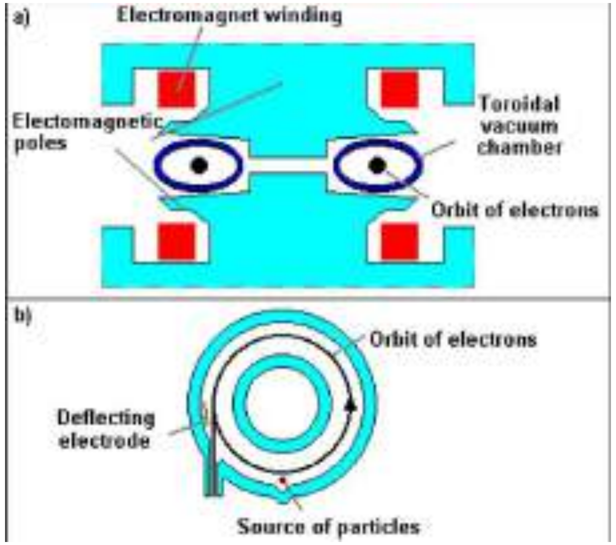
- 1932: 1.2 MeV – 1940: 20 MeV (E.O. Lawrence, M.S. Livingston)
- Constant magnetic field
- Alternating voltage between the two D's
- Increasing particle orbit radius
- Development lead to the synchrocyclotron to cope with the relativistic effects.

In 1939 Lawrence received the Noble prize for his work.

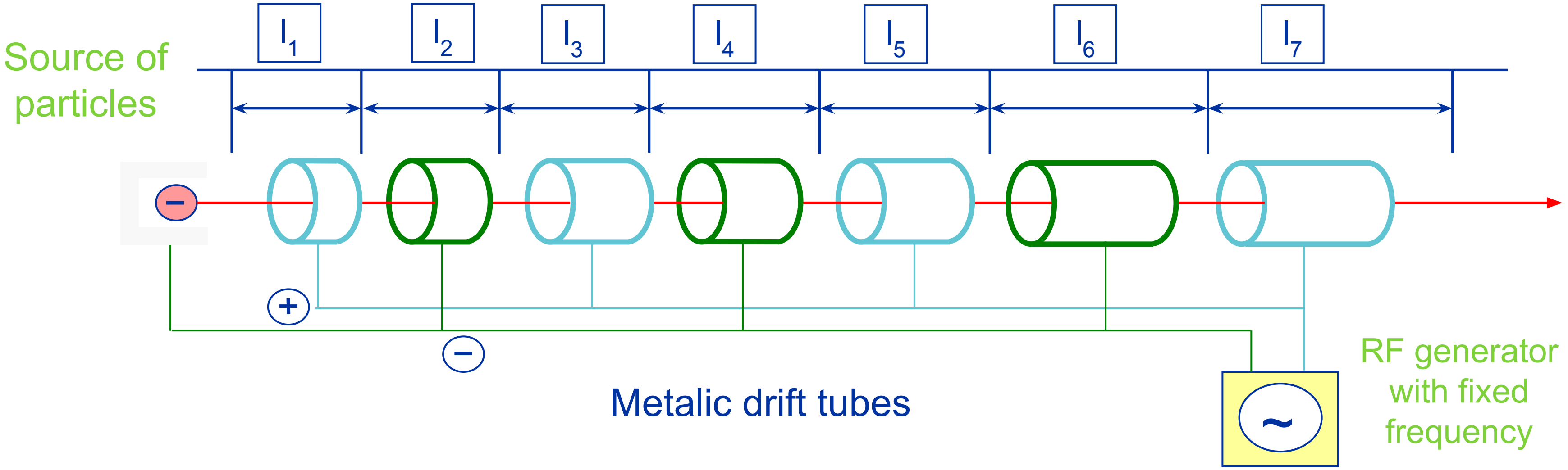


Betatron

- 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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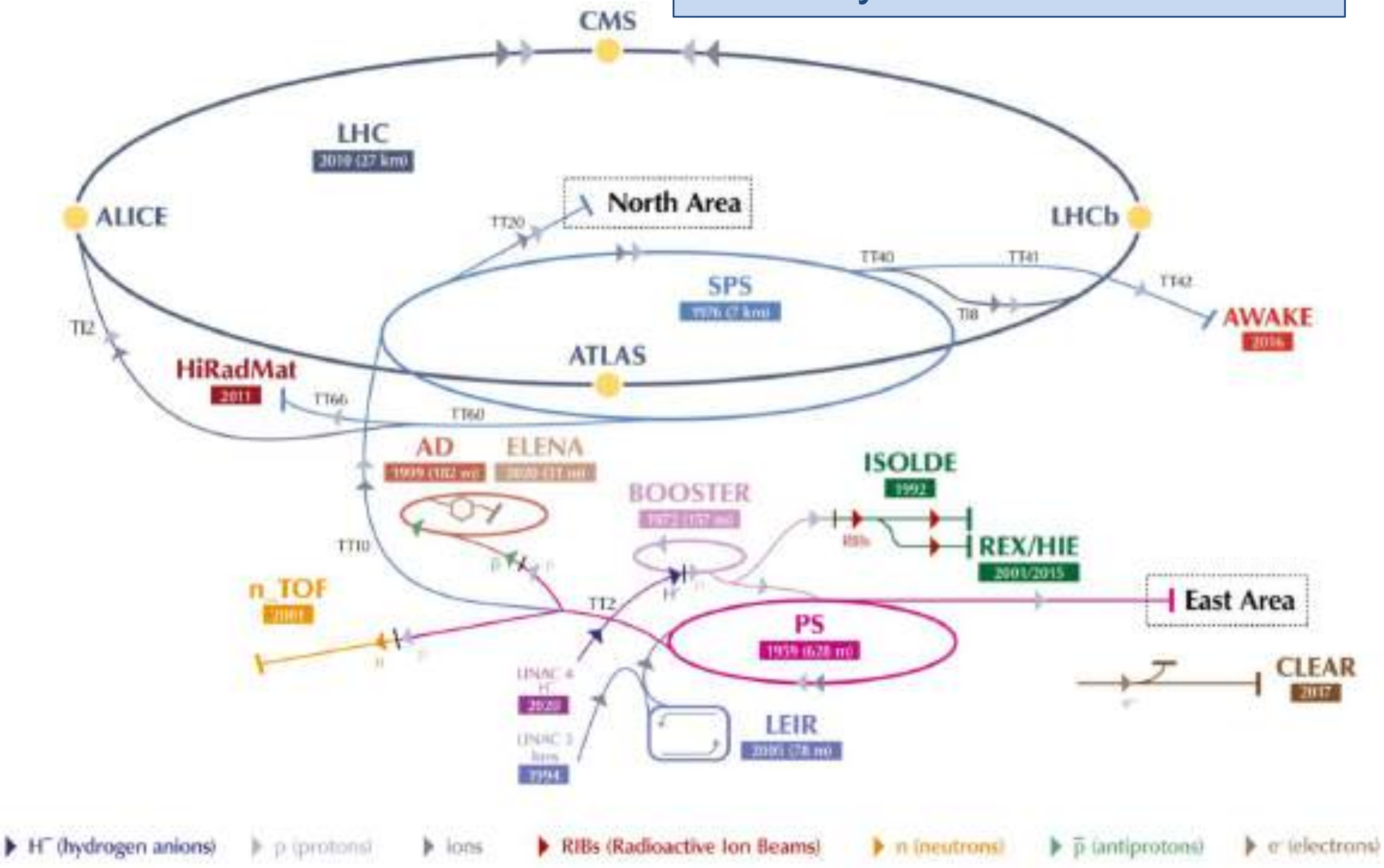
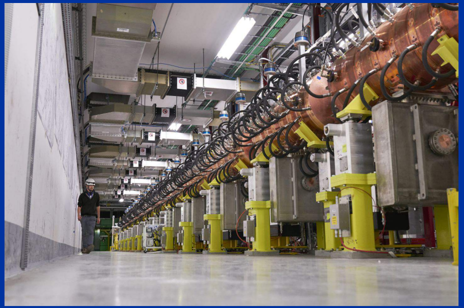
The CERN Accelerator Complex

Mostly Circular Machines

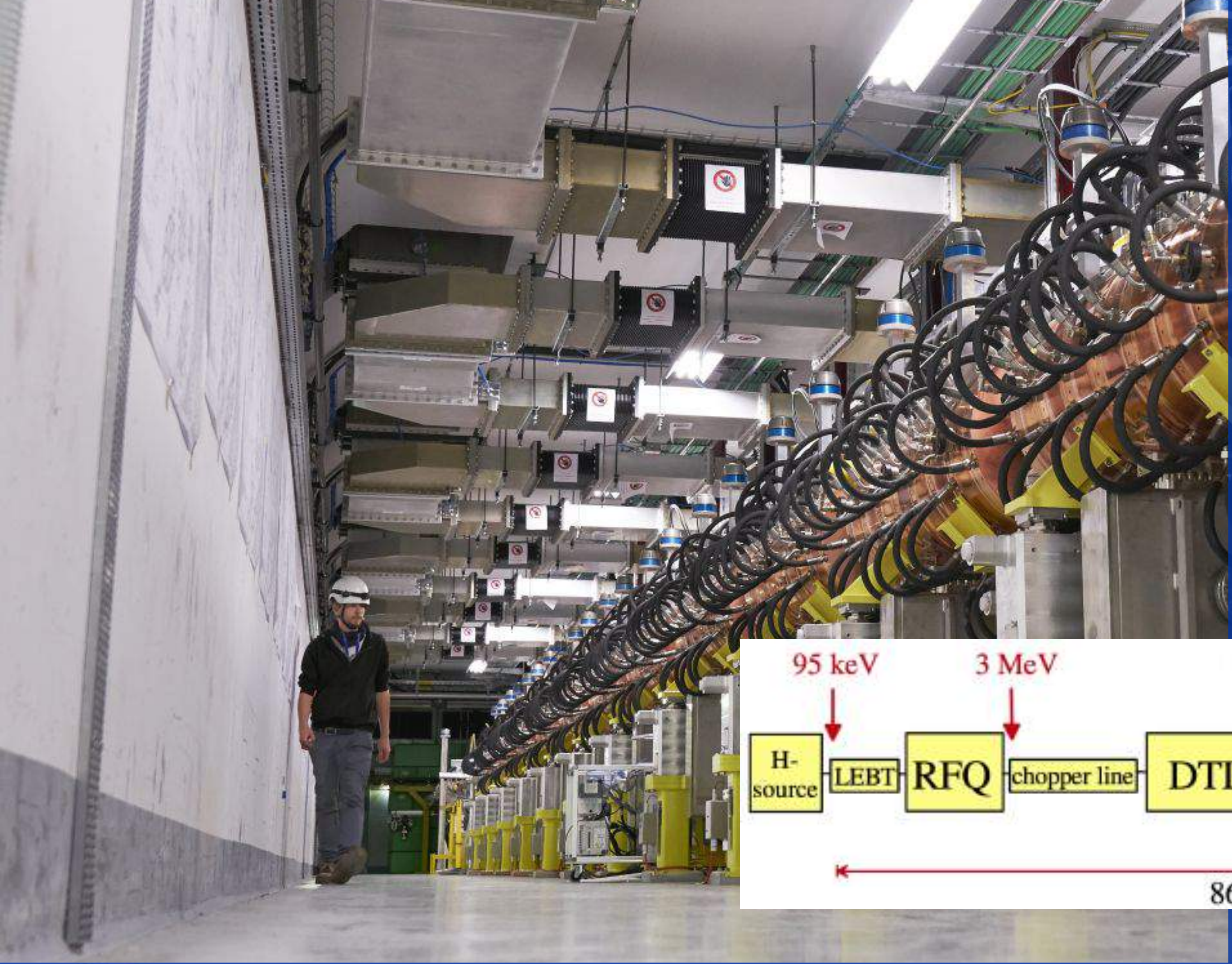


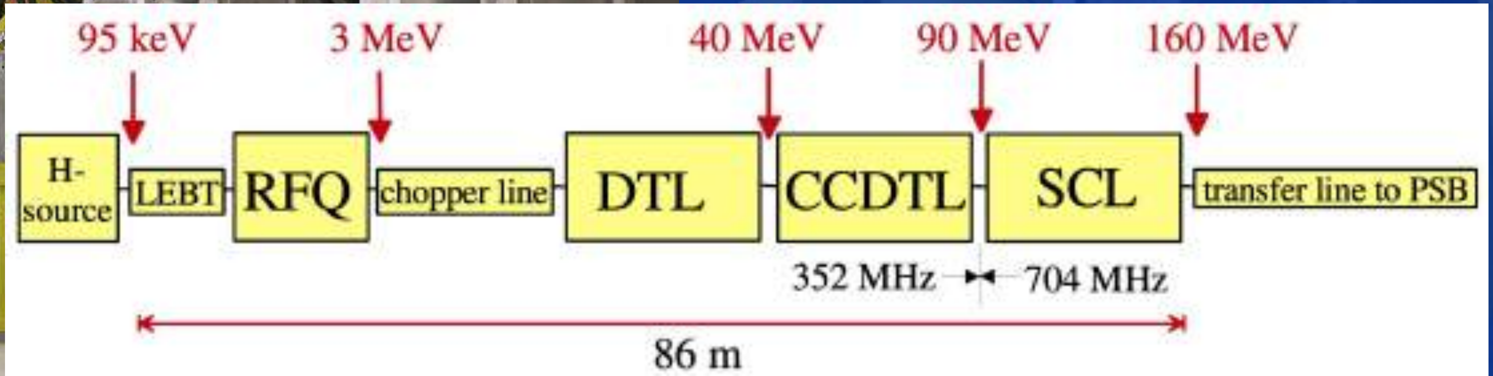





Linac 4

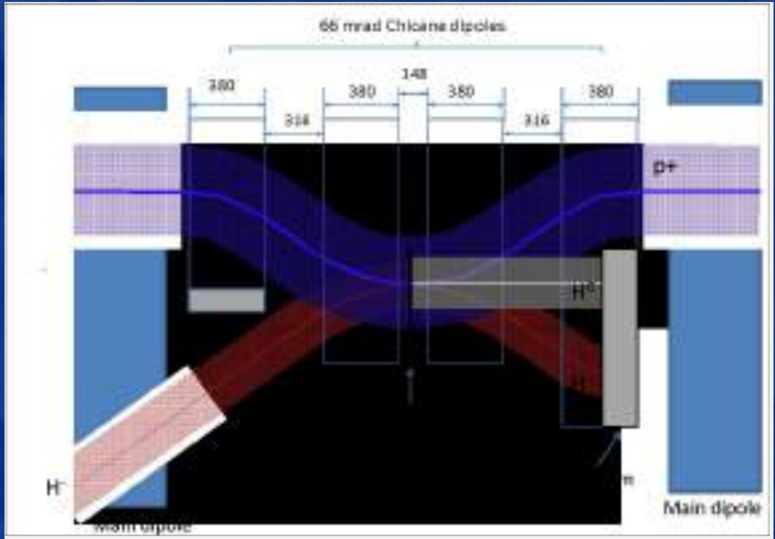


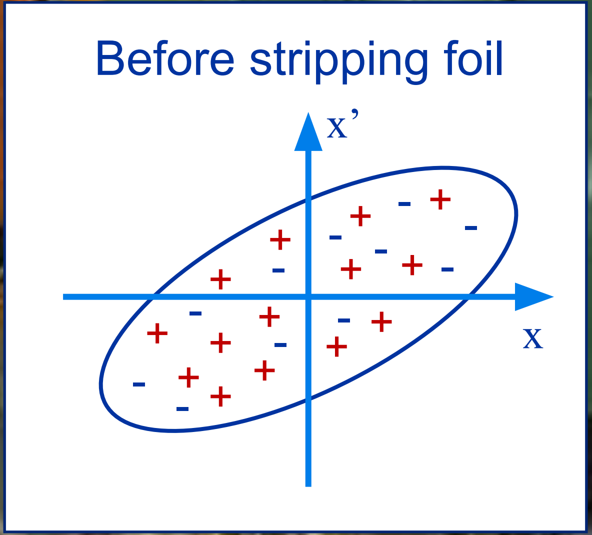
- H^- ion source at 95 keV
- Accelerates beam up to 160 MeV
- The chopping scheme allows removing some of the Linac bunches to make the beam fit into the PS Booster RF buckets
- Pulse rate 1.2 s

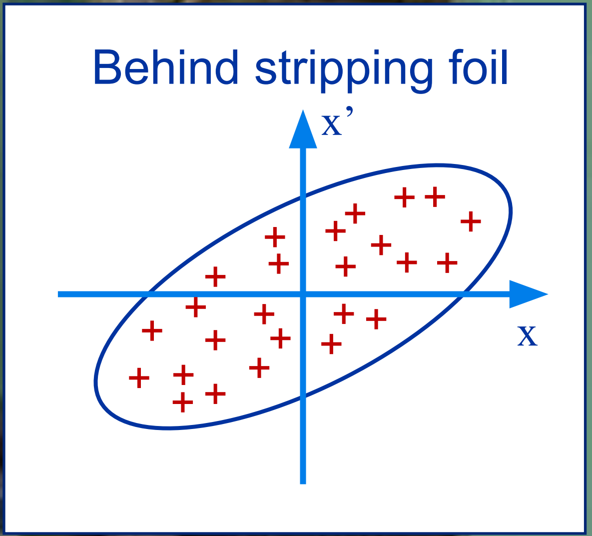


PS Booster

- 1st 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



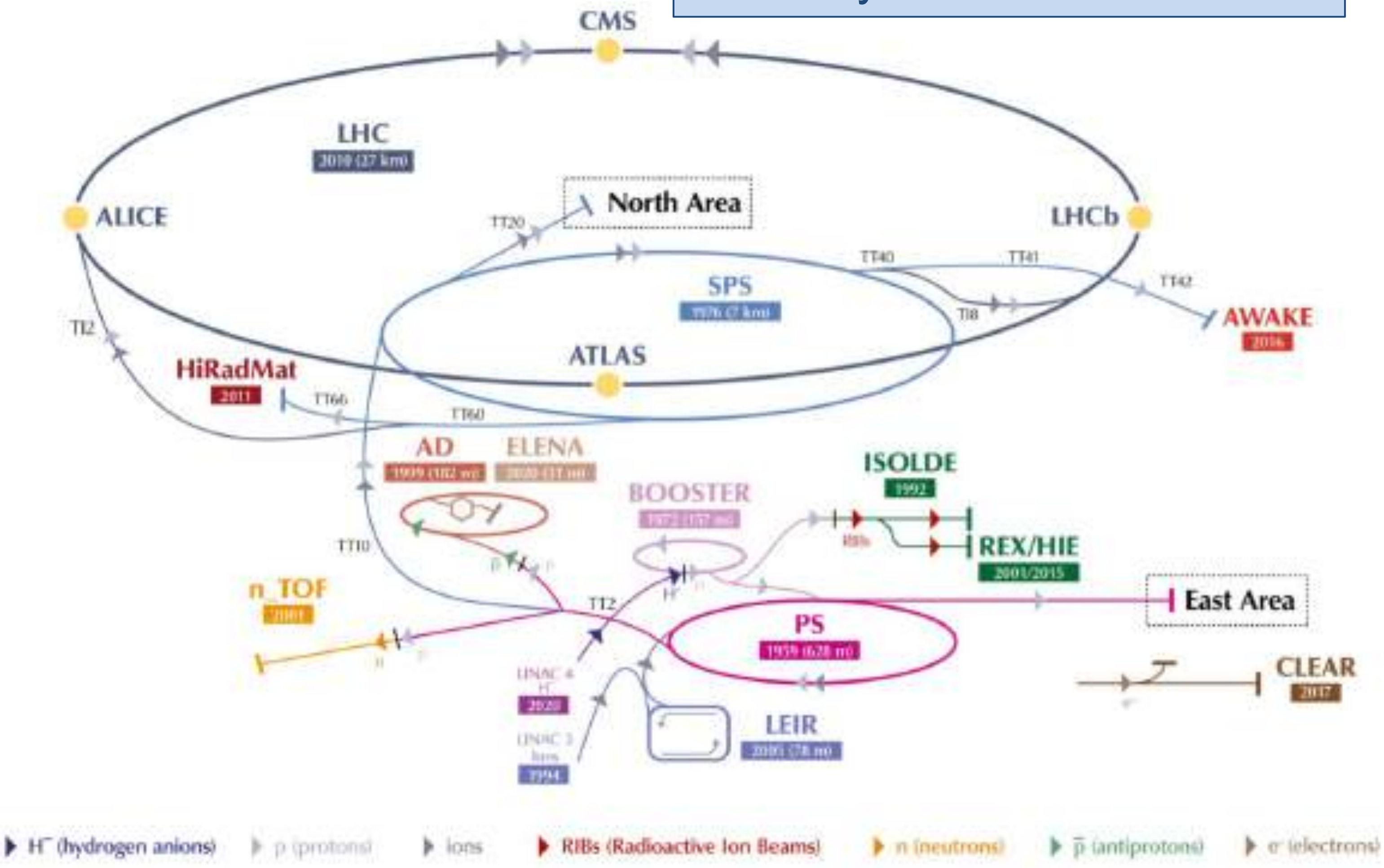







The CERN Accelerator Complex

Mostly Circular Machines






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

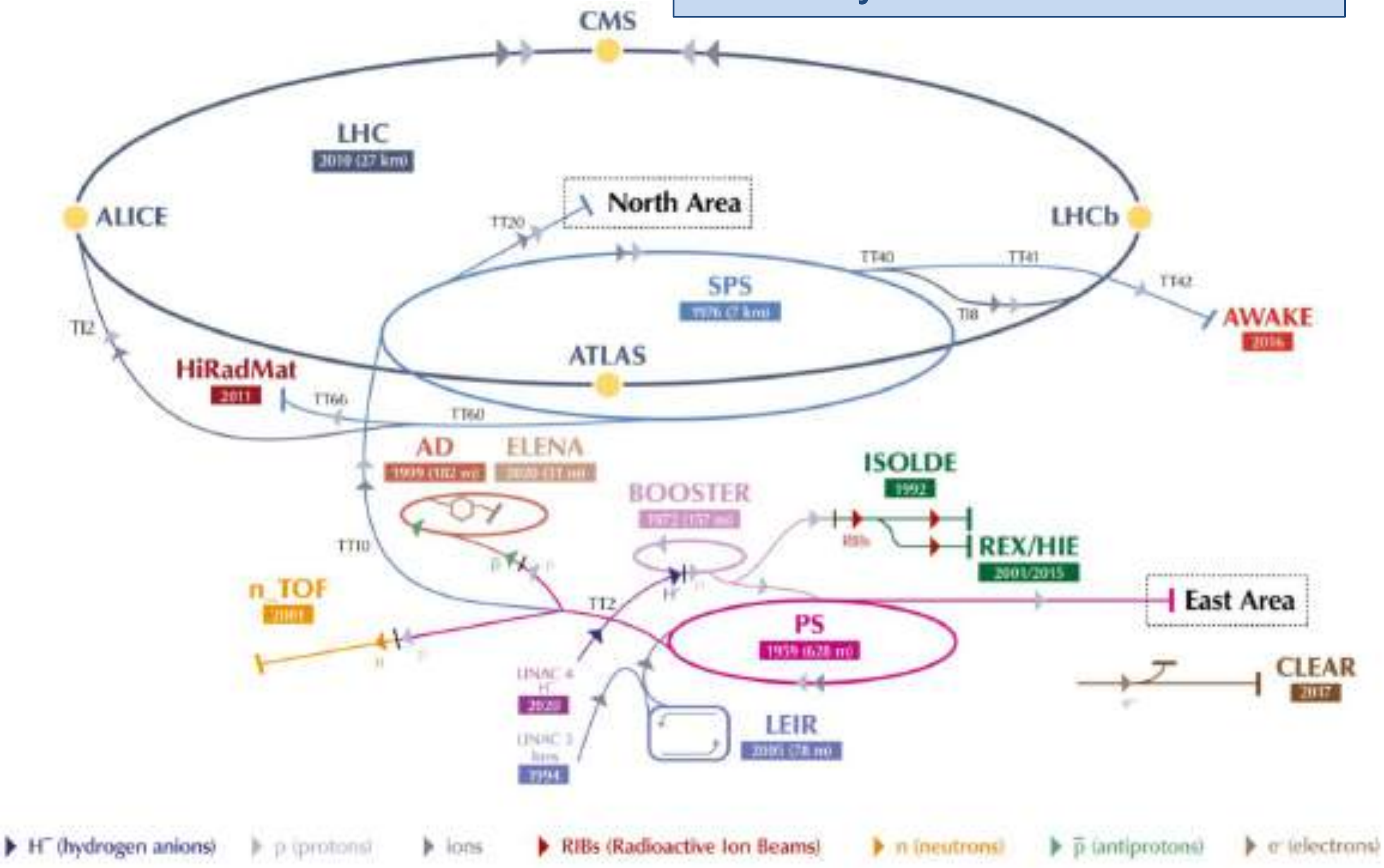
SPS

- **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 ~5x10^{13} protons per cycle**
- **Provides slow extracted beam to the North Area**
- **Provides fast extracted beam to LHC, AWAKE and HiRadMat**

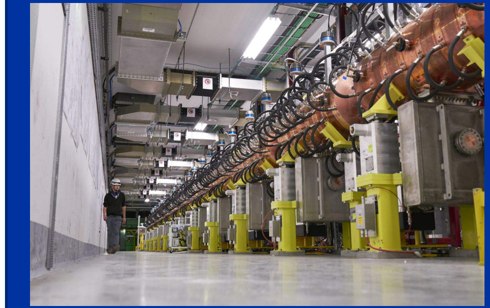
The CERN Accelerator Complex

Mostly Circular Machines

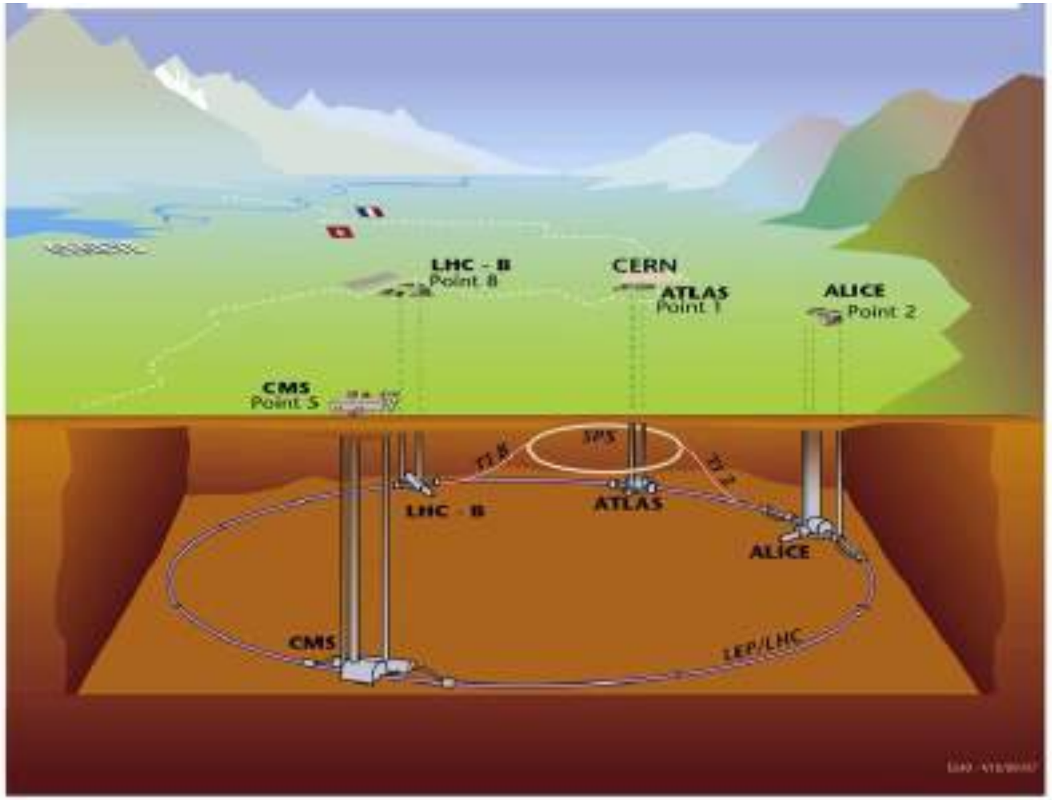


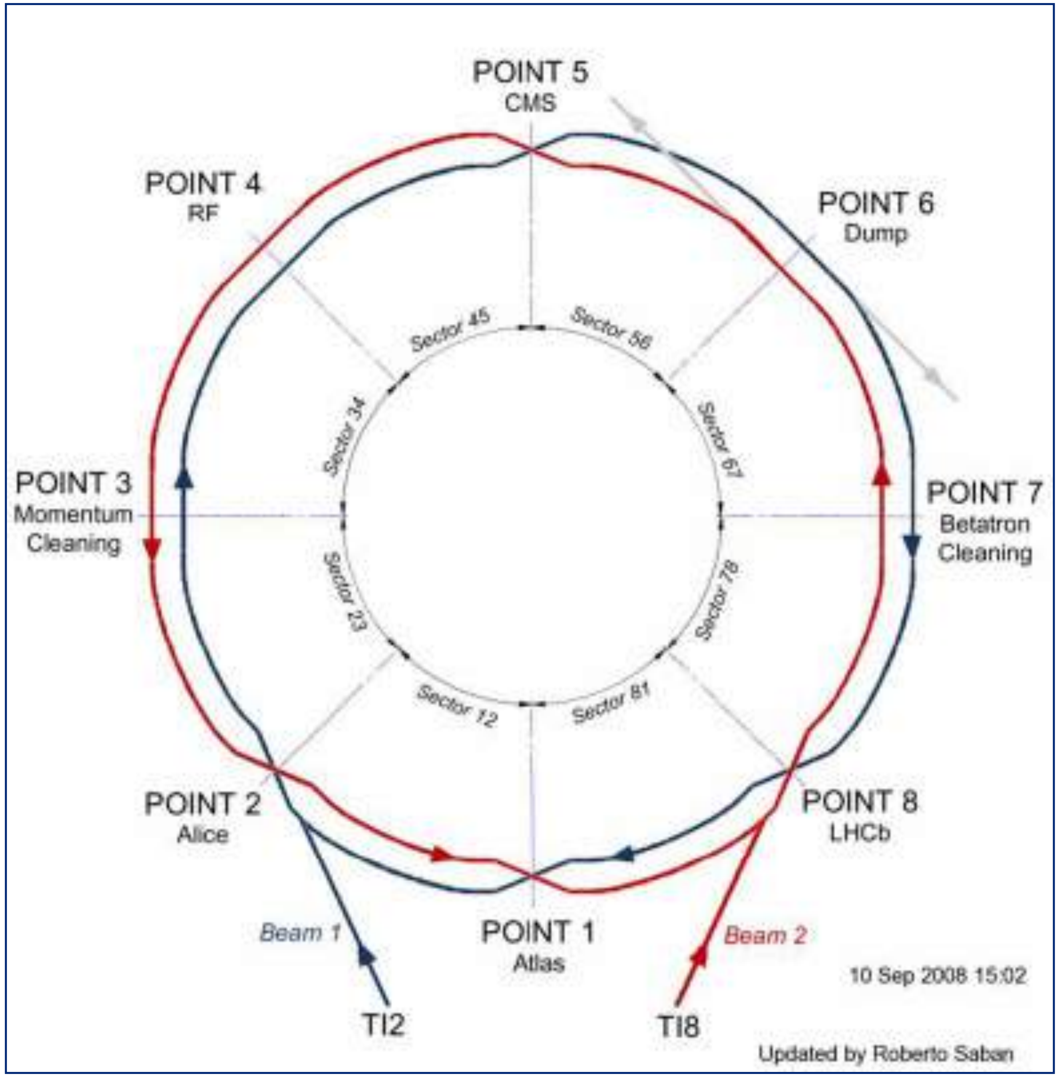





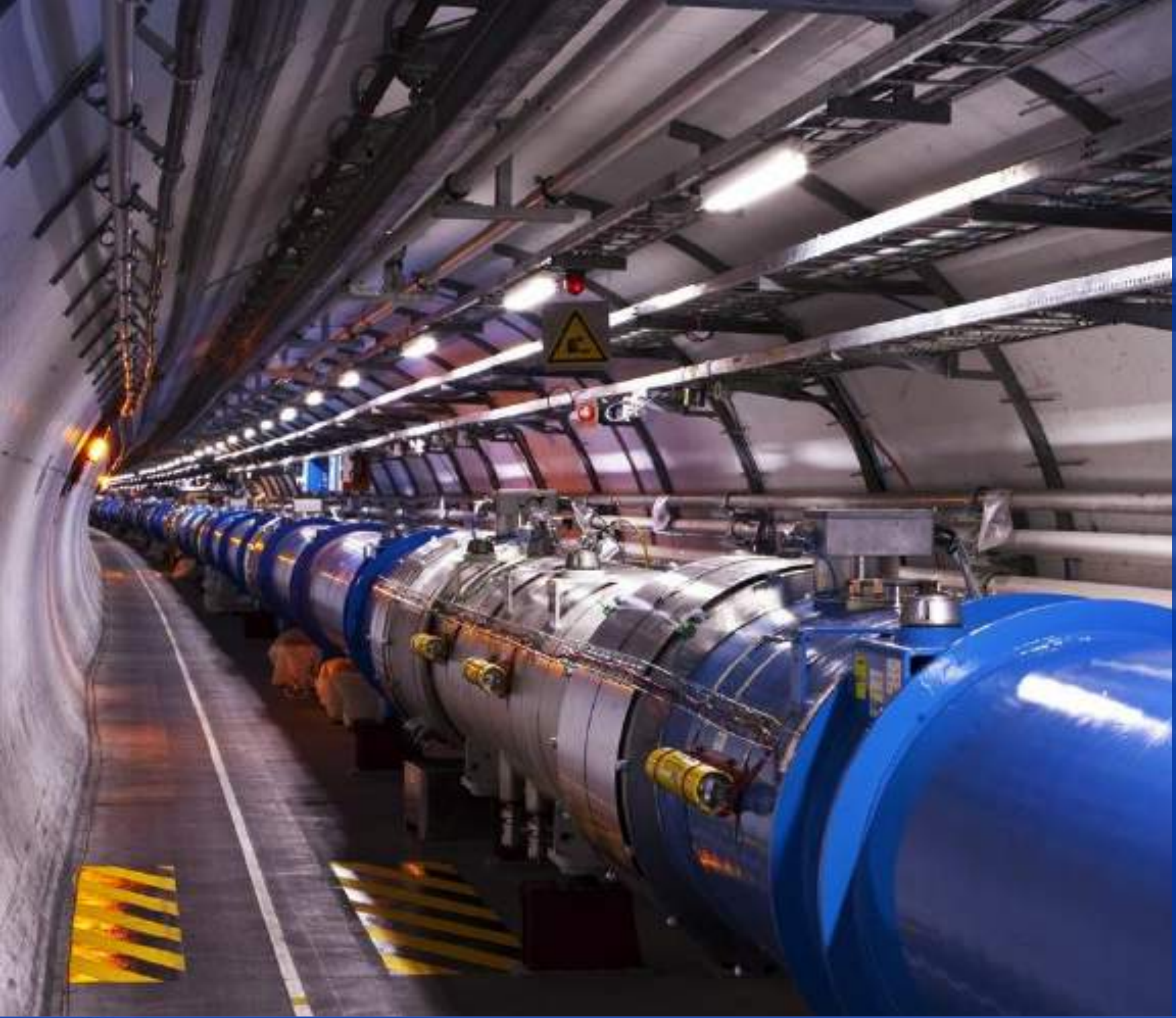



LHC





- 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

Intensity per bunch

Number of bunches

Geometrical Correction factors

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

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 [$cm^{-2}s^{-1}$]
- Integrating this over time results in the integrated luminosity.

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

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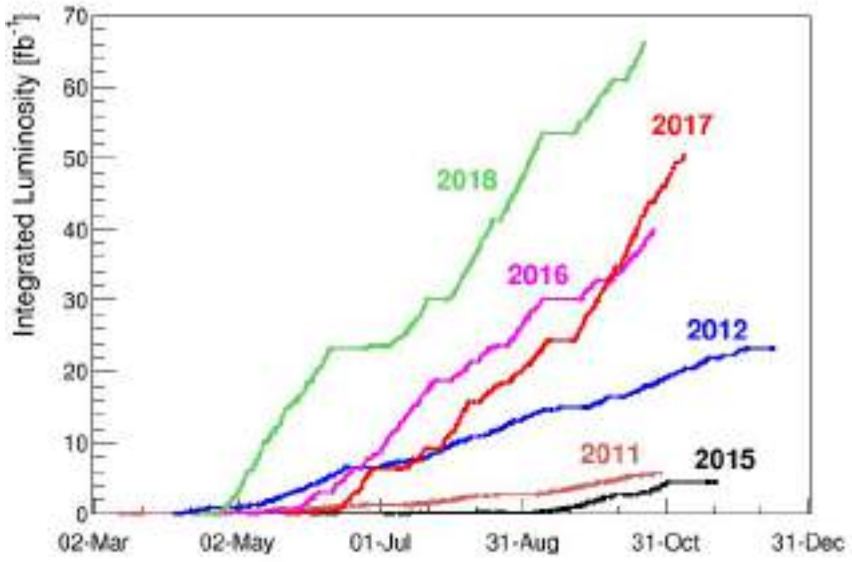


Maximise Luminosity:

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

Ways to Increase Luminosity

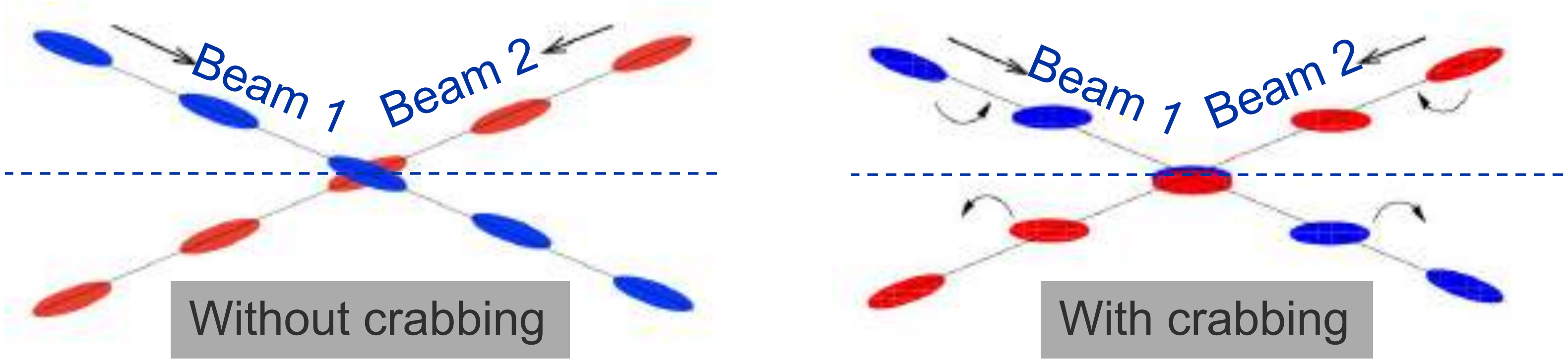
Increase the beam brightness from the injectors (N and σ)
- More particle in smaller beams (increase brightness)

Increase number of bunches
- Higher harmonic RF systems

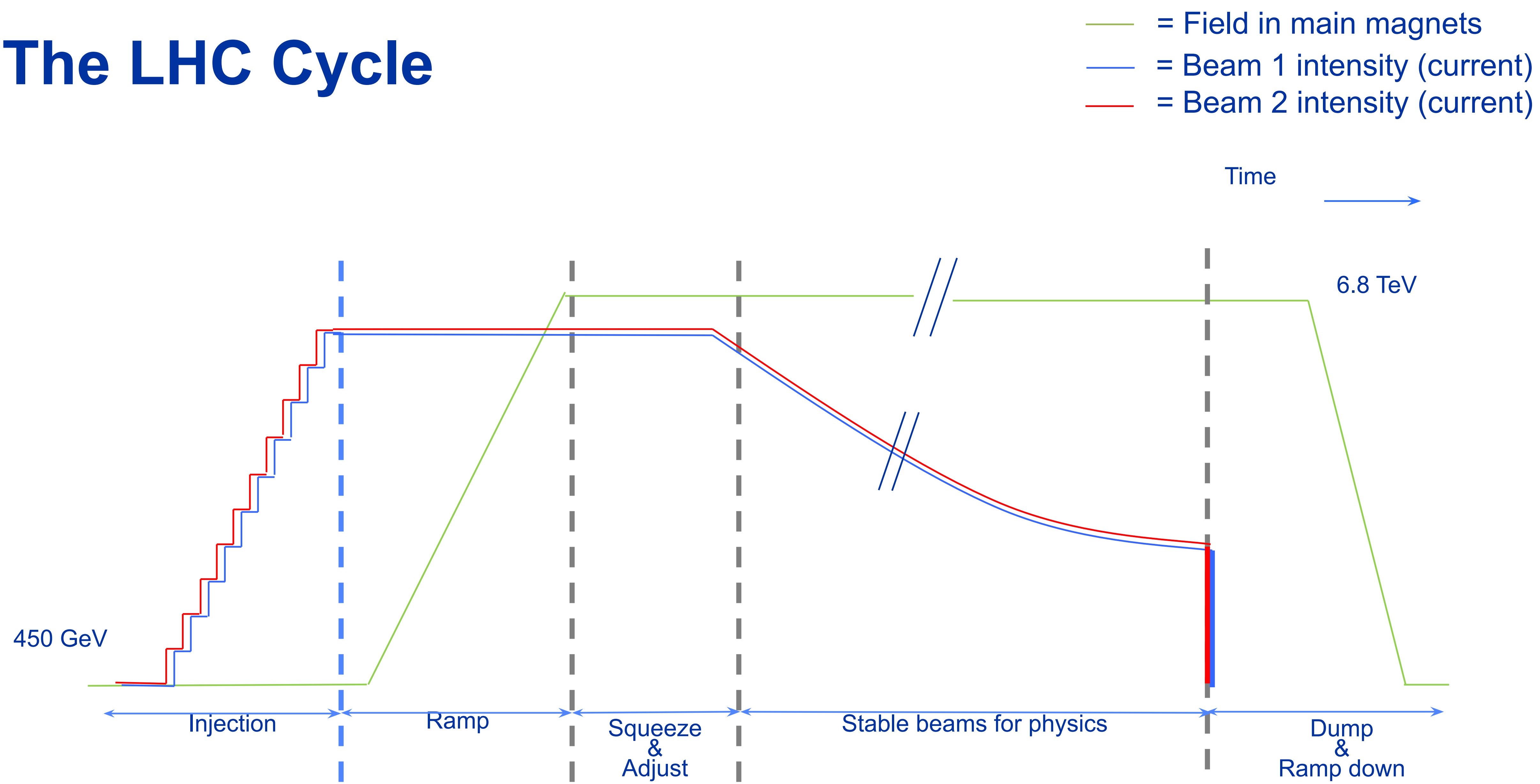
Reduce the β* (σ)
- Stronger focusing around the interaction points

Use crab cavities to reduce the crossing angle effect (s)
- Tilt the bunches to have more head-on collision effect

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



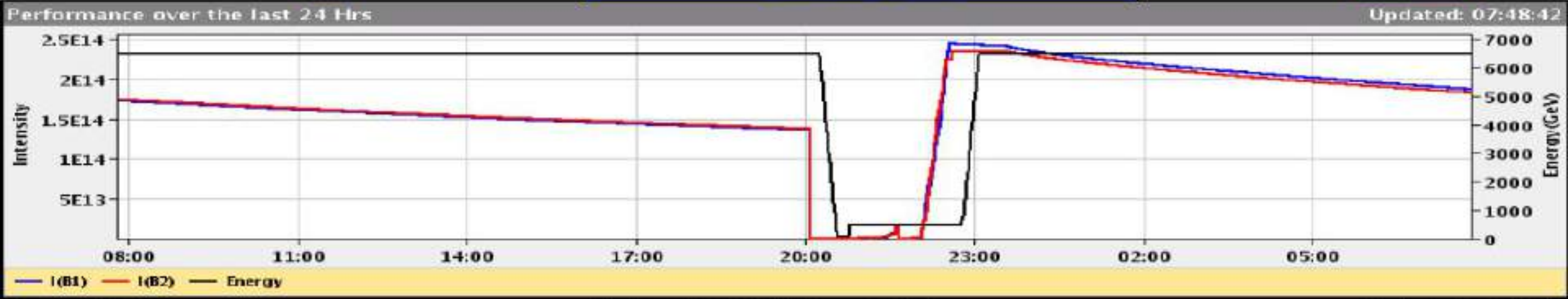
The LHC Cycle

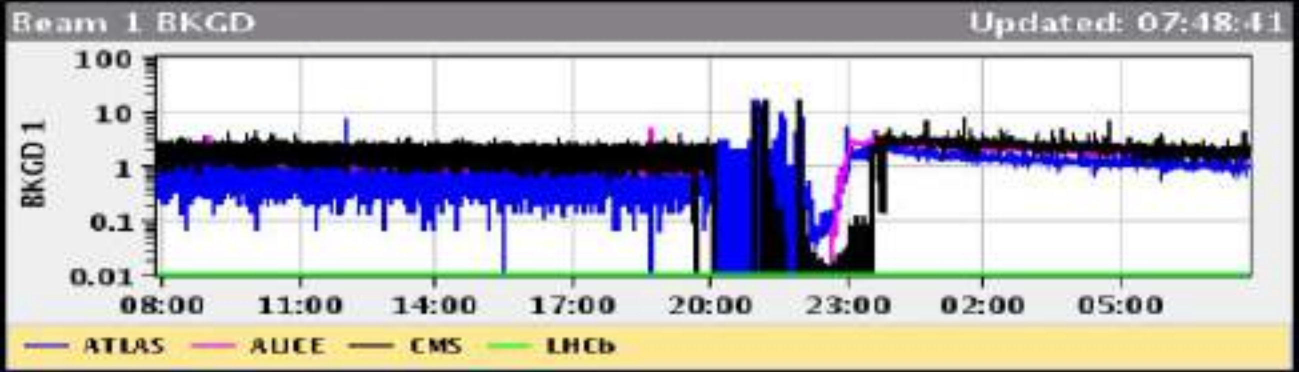


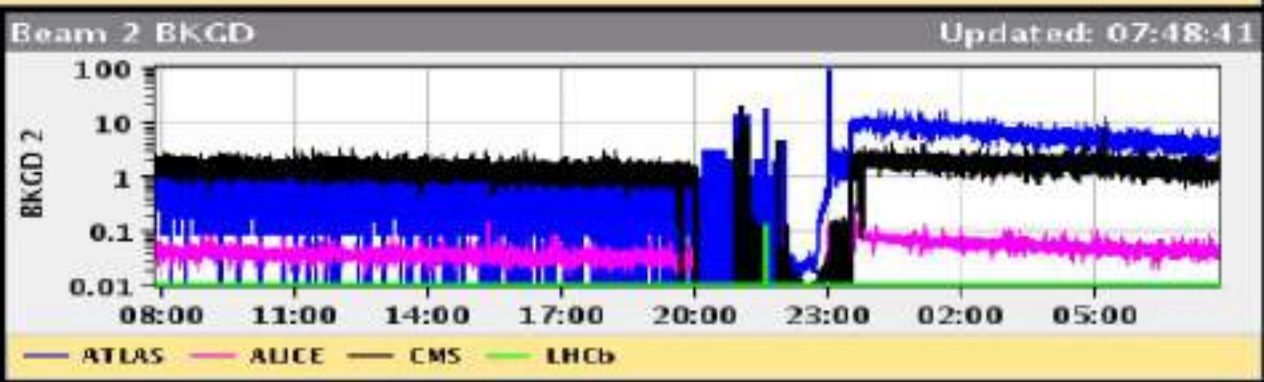
16-Oct-2016 07:48:46 | Fill #: 5418 | Energy: 6499 GeV | I(B1): 1.87e+14 | I(B2): 1.83e+14

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Lumi [(ub.s)^-1]	7346.231	1.672	7730.174	355.048
BRAN Luminosity [(ub.s)^-1]	7462.0	1.8	6917.8	181.2
Fill Luminosity (nb)^-1	265785.063	49.302	293245.594	10312.992
Beam 1 BKGD	0.927	1.401	1.645	0.000
Beam 2 BKGD	4.488	0.042	1.143	0.001

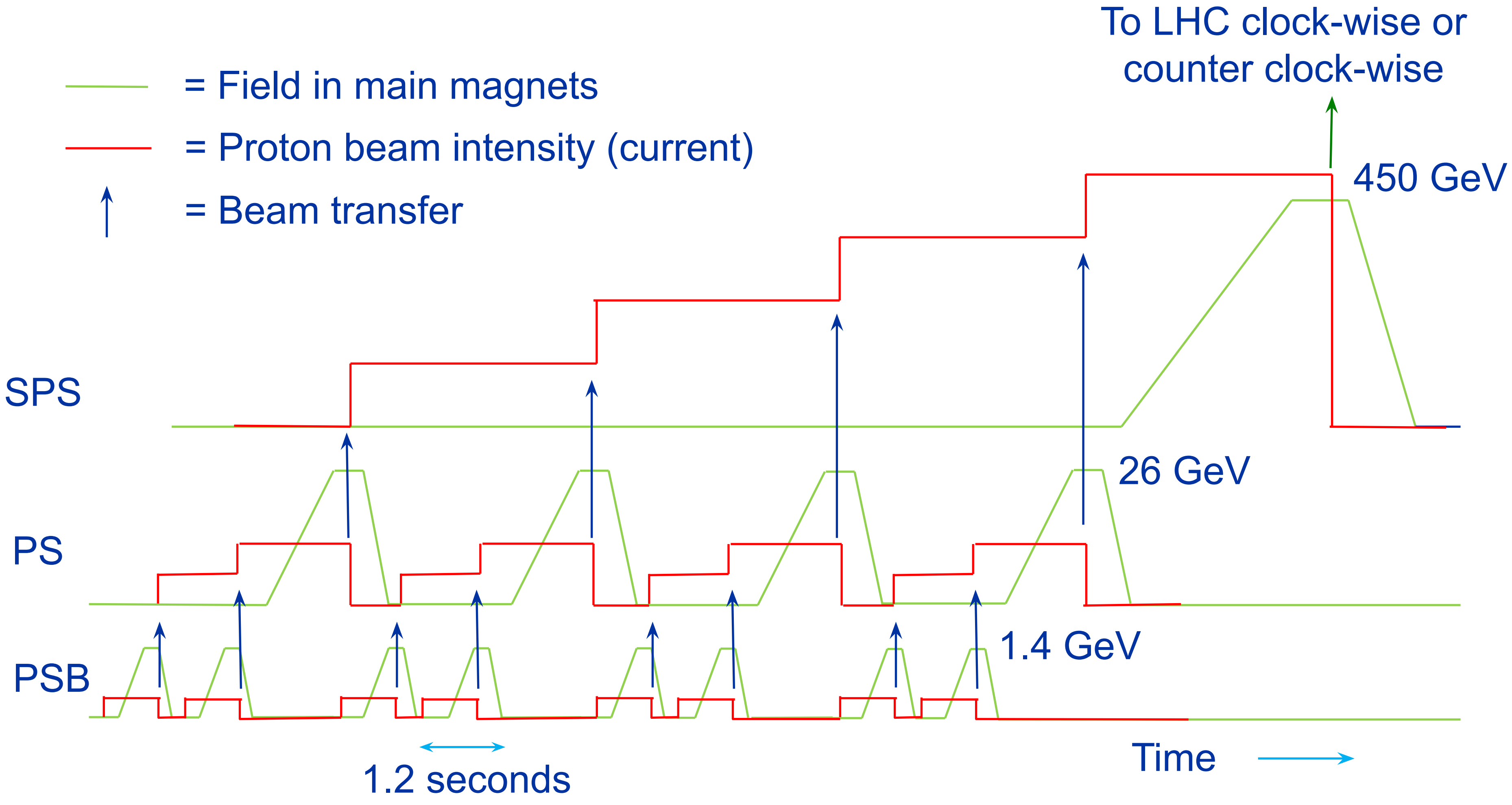
LHCb VELO Position IN Gap: -0.0 mm | STABLE BEAMS | TOTEM: PHYSICS







Filling the LHC & Satisfying Fixed Target users



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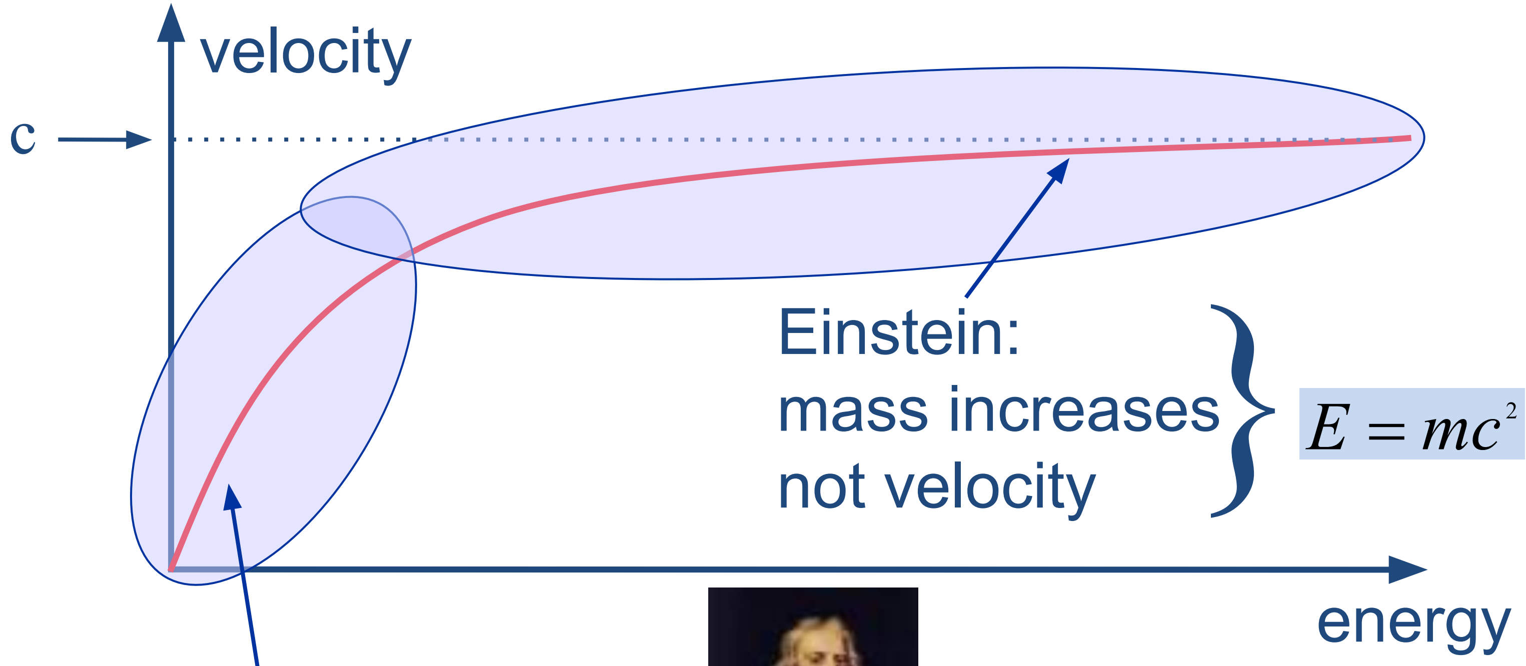
Towards Relativity



$$E = mc^2$$

Newton: $E = \frac{1}{2} m v^2$

A Guided Tour

Lets have a look at a synchrotron:

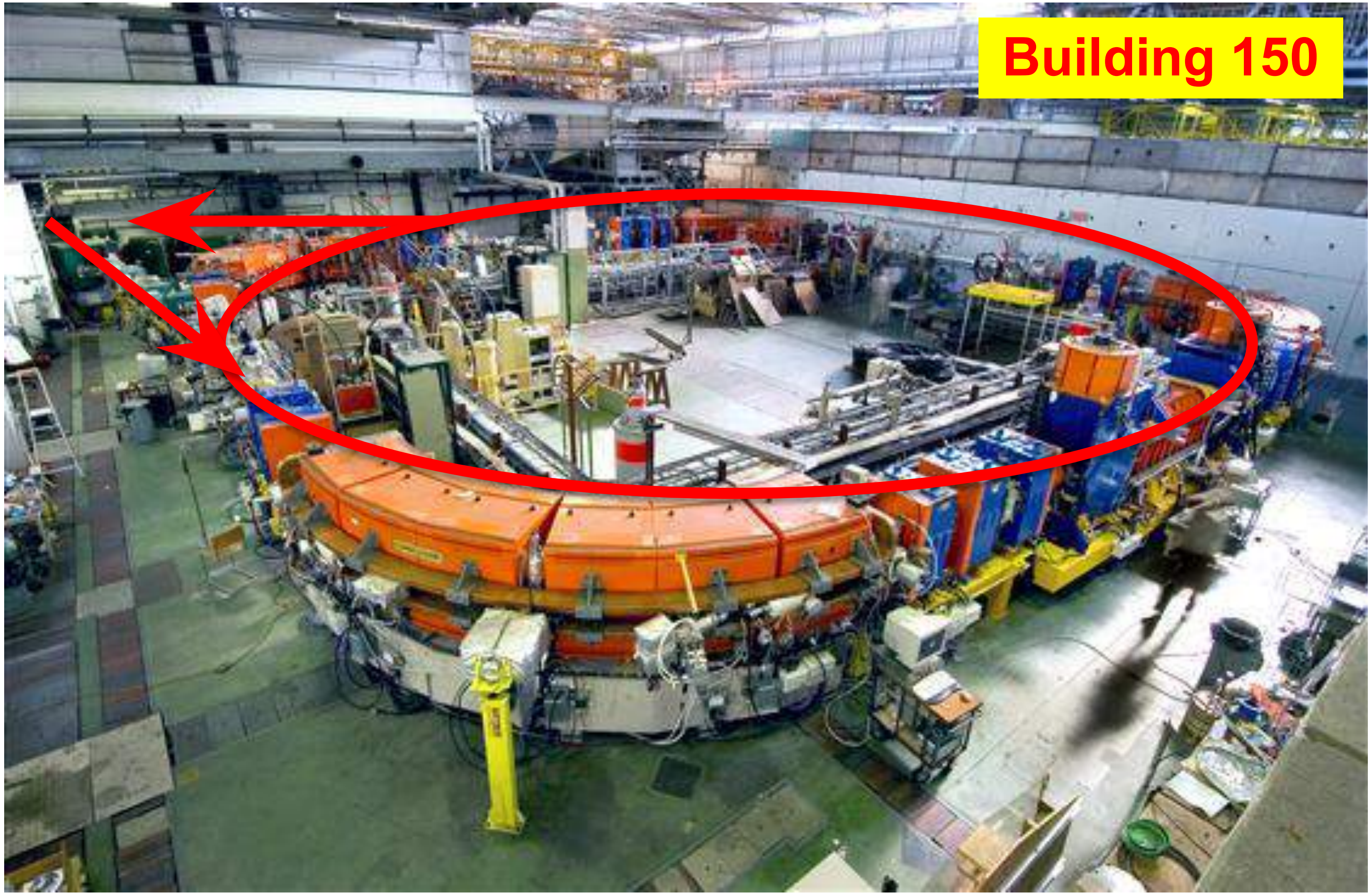
- Identify the main components and processes
- Briefly address their function

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

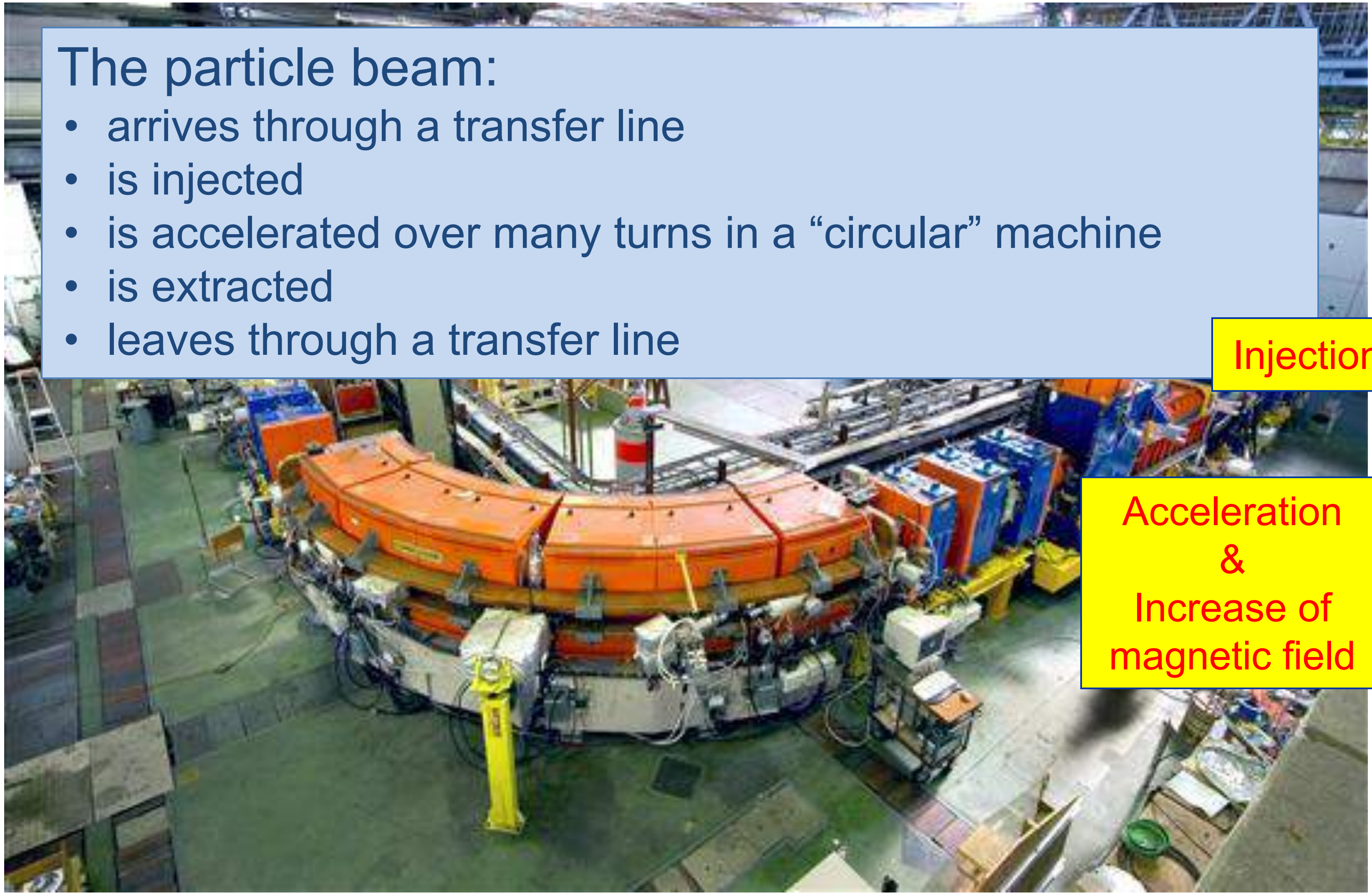
LEIR

Low **E**nergy **I**on **R**ing

LEIR as an Example

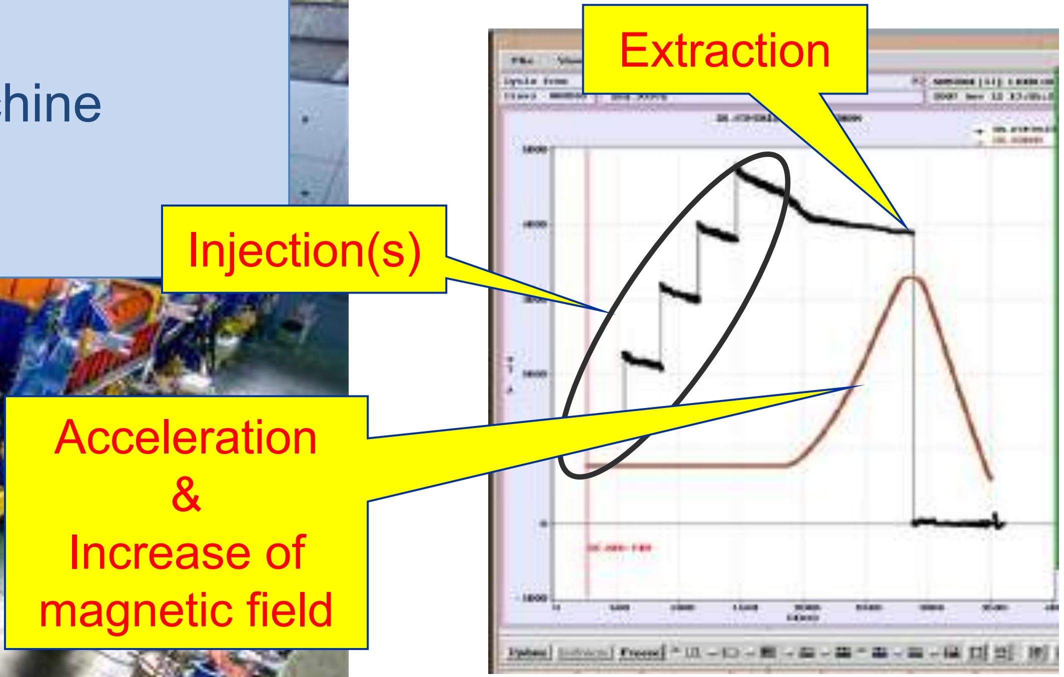


Vacuum Chamber



The particle beam:

- arrives through a transfer line
- is injected
- is accelerated over many turns in a “circular” machine
- is extracted
- leaves through a transfer line



LINAC 3, injector of LEIR

The CERN LINAC 3 provides different ion species

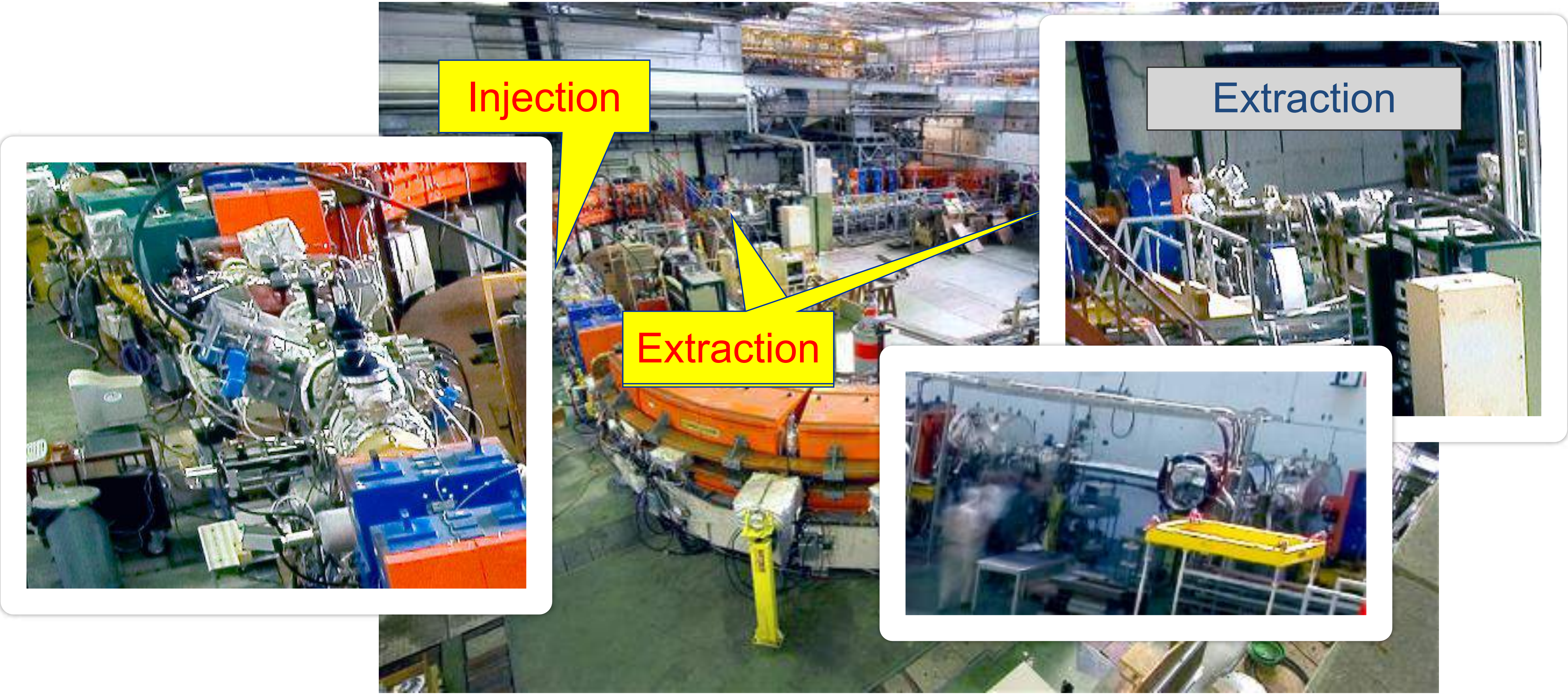
The ion source in the blue cage with the spectrometer in the front, follow by the LINAC behind

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

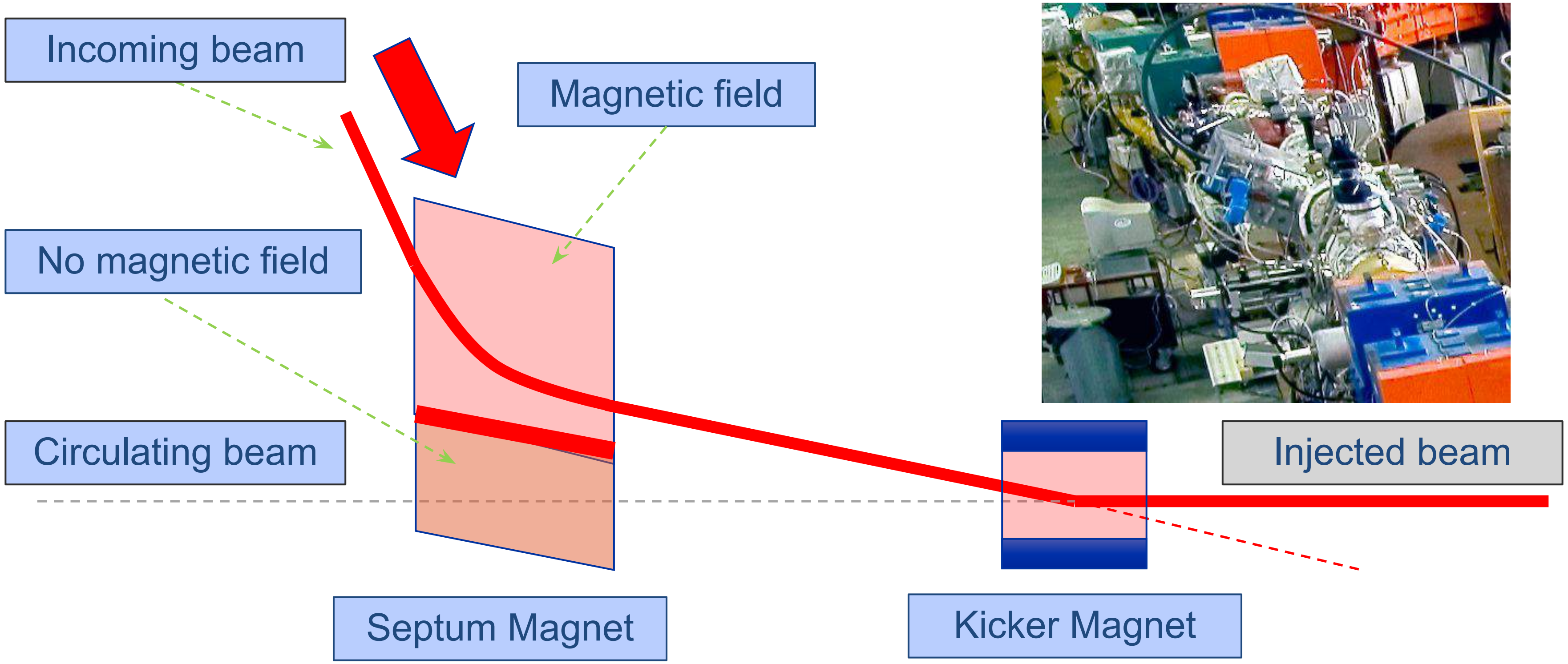
LINAC Accelerating Structure

The CERN LINAC 4 drift tube

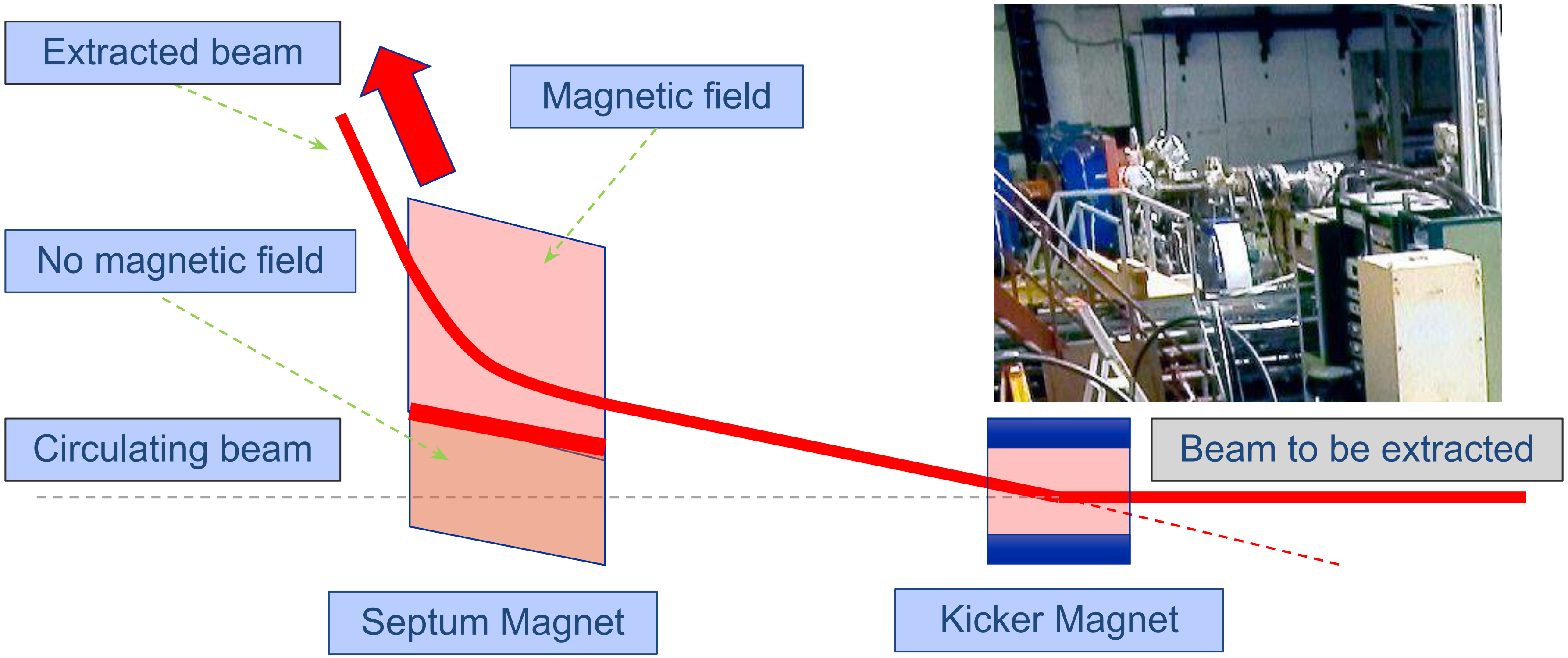
Injecting & Extracting Particles



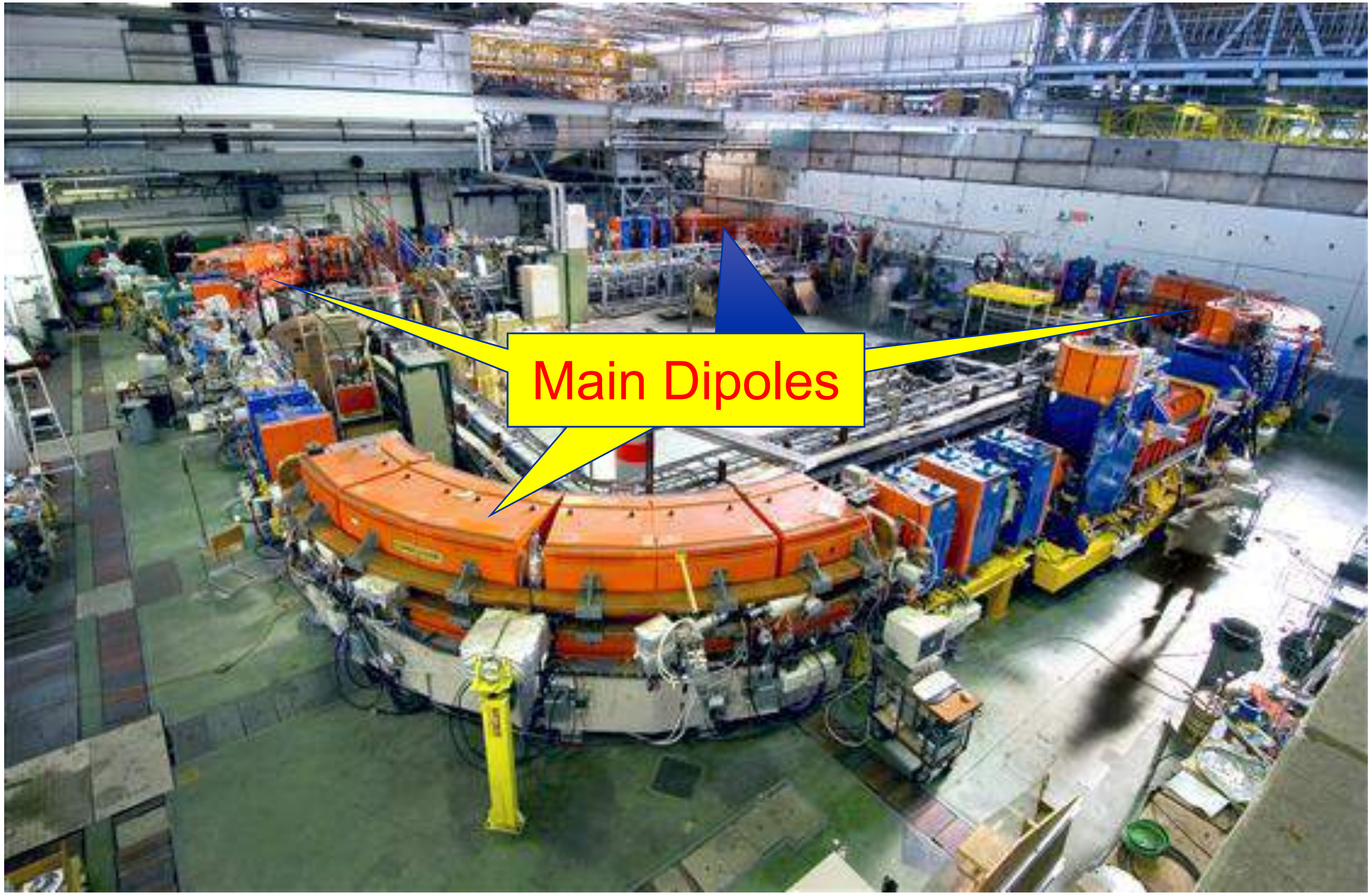
Injecting & Extracting Particles



Injecting & Extracting Particles

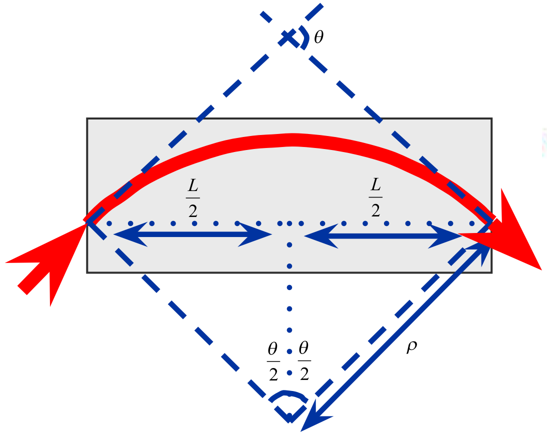


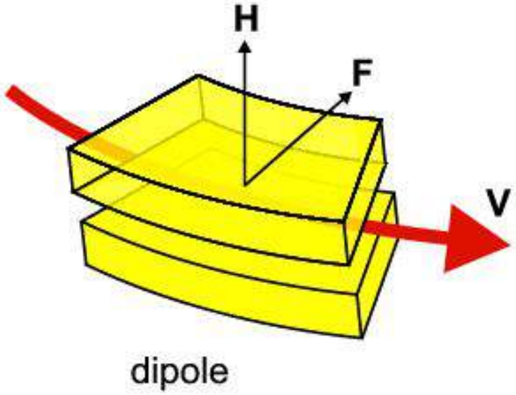
Make Particles Circulate

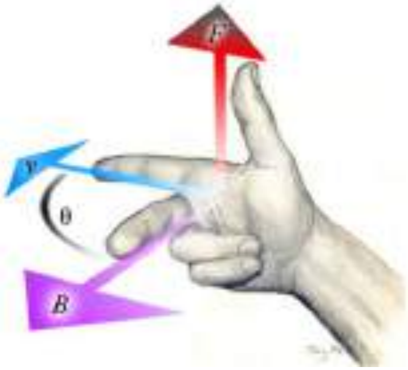


Deviating Charged Particles

Moving charged particles are deviated in a magnetic field





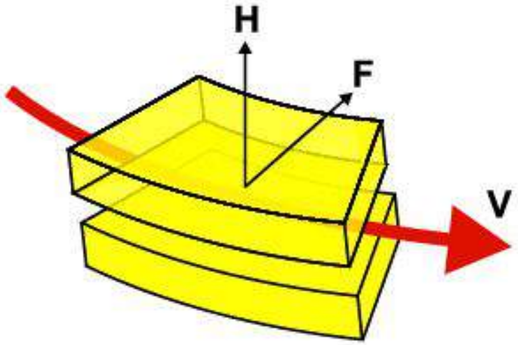


Magnetic Lorentz Force:

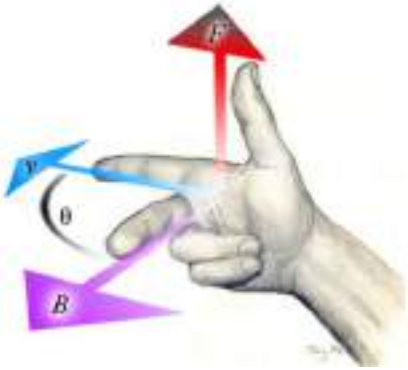
$$F = e(\vec{v} \times \vec{B})$$

Deviating Charged Particles

Moving charged particles are deviated in a magnetic field



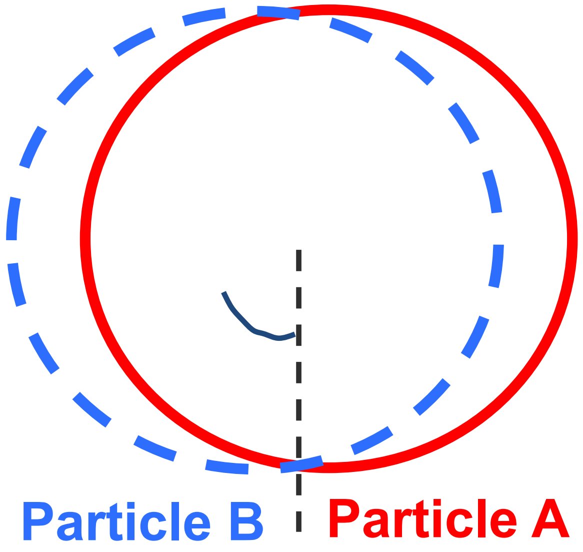
dipole



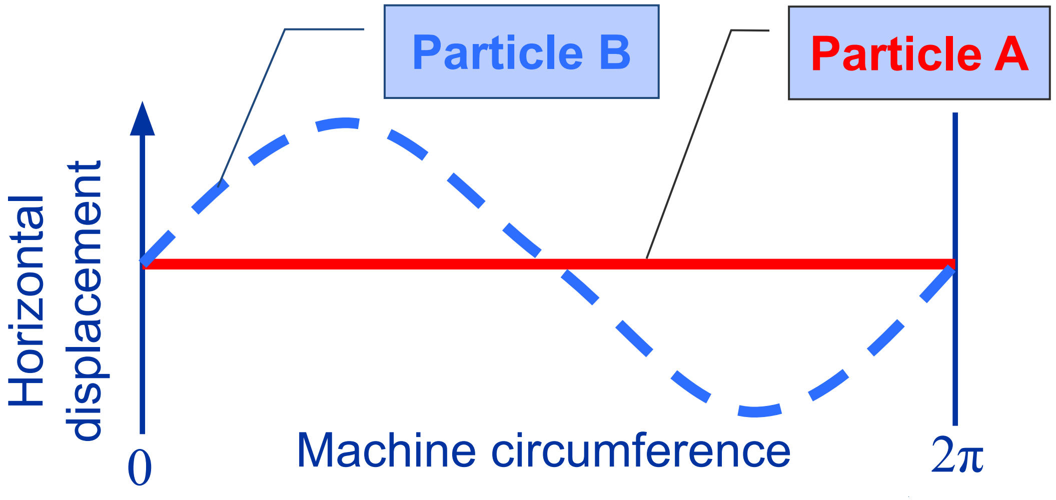
Magnetic Lorentz Force: $$F = e(\vec{v} \times \vec{B})$$

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**

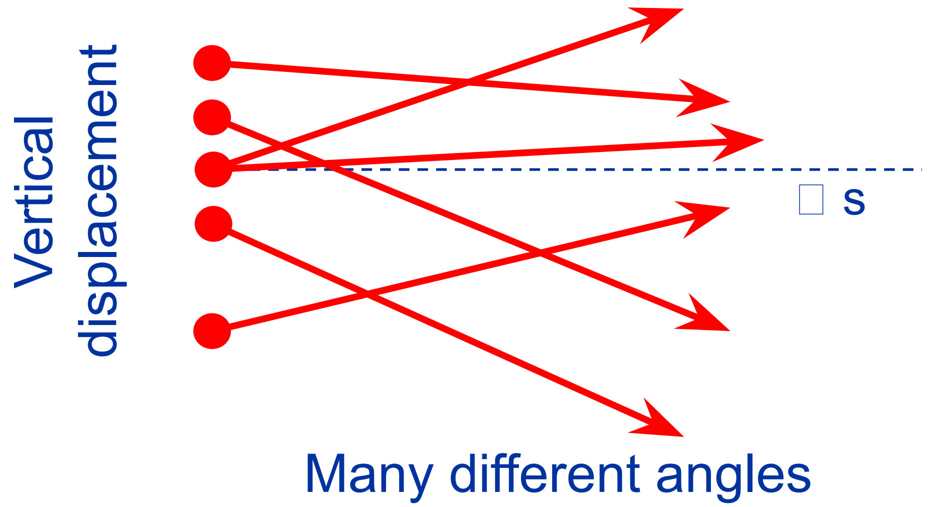
Oscillatory Motion of Particles

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

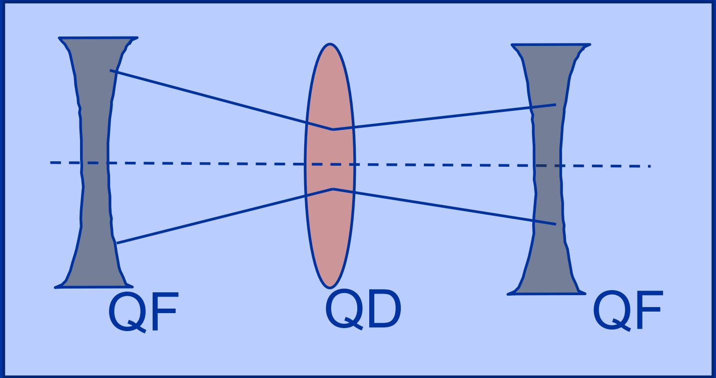
Oscillatory Motion in the Vertical Plane

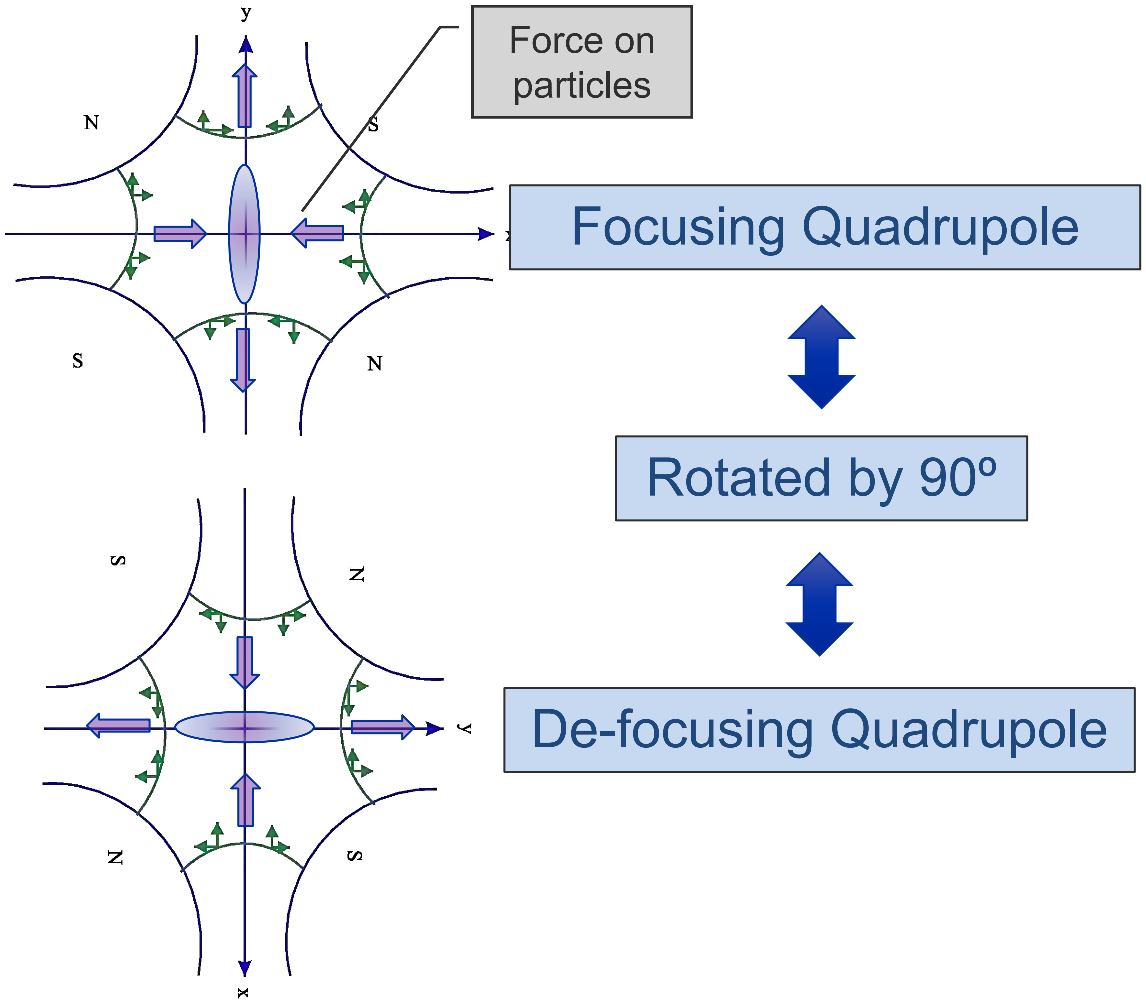
The horizontal motion seems to be "stable"…. What about the vertical plane ?

Many particles many initial conditions

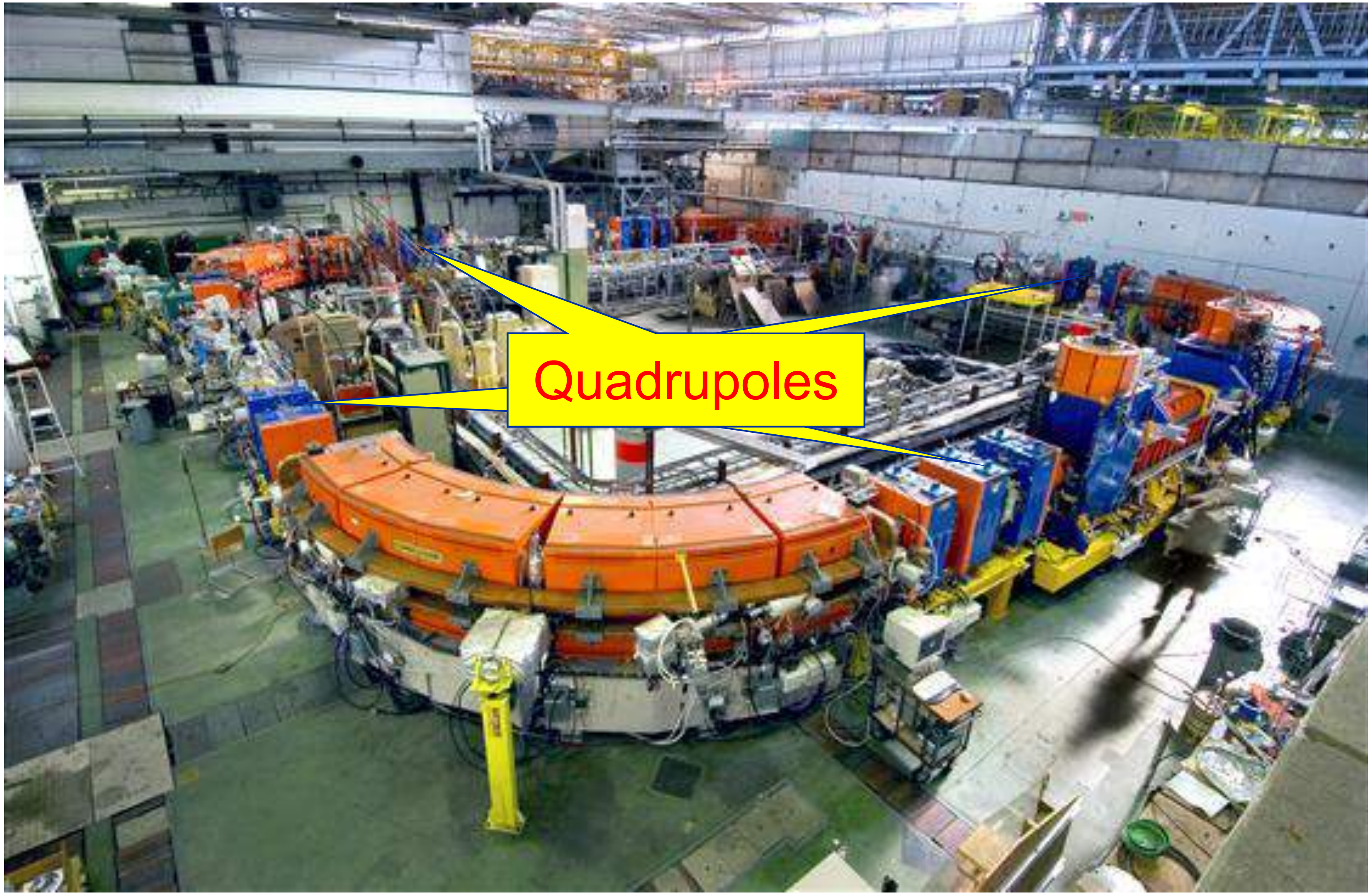


Focusing Particle Beams, a bit like a lens

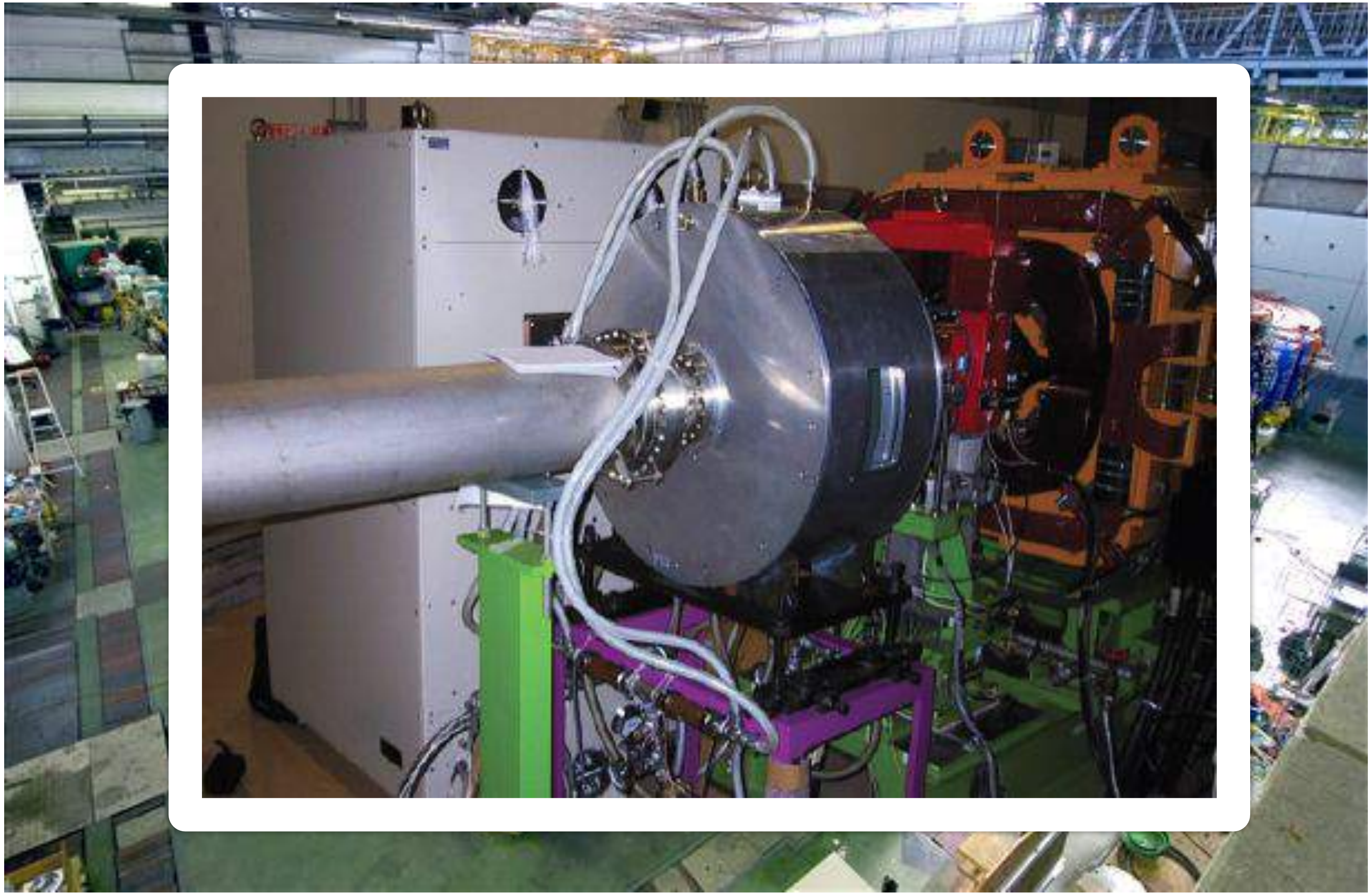




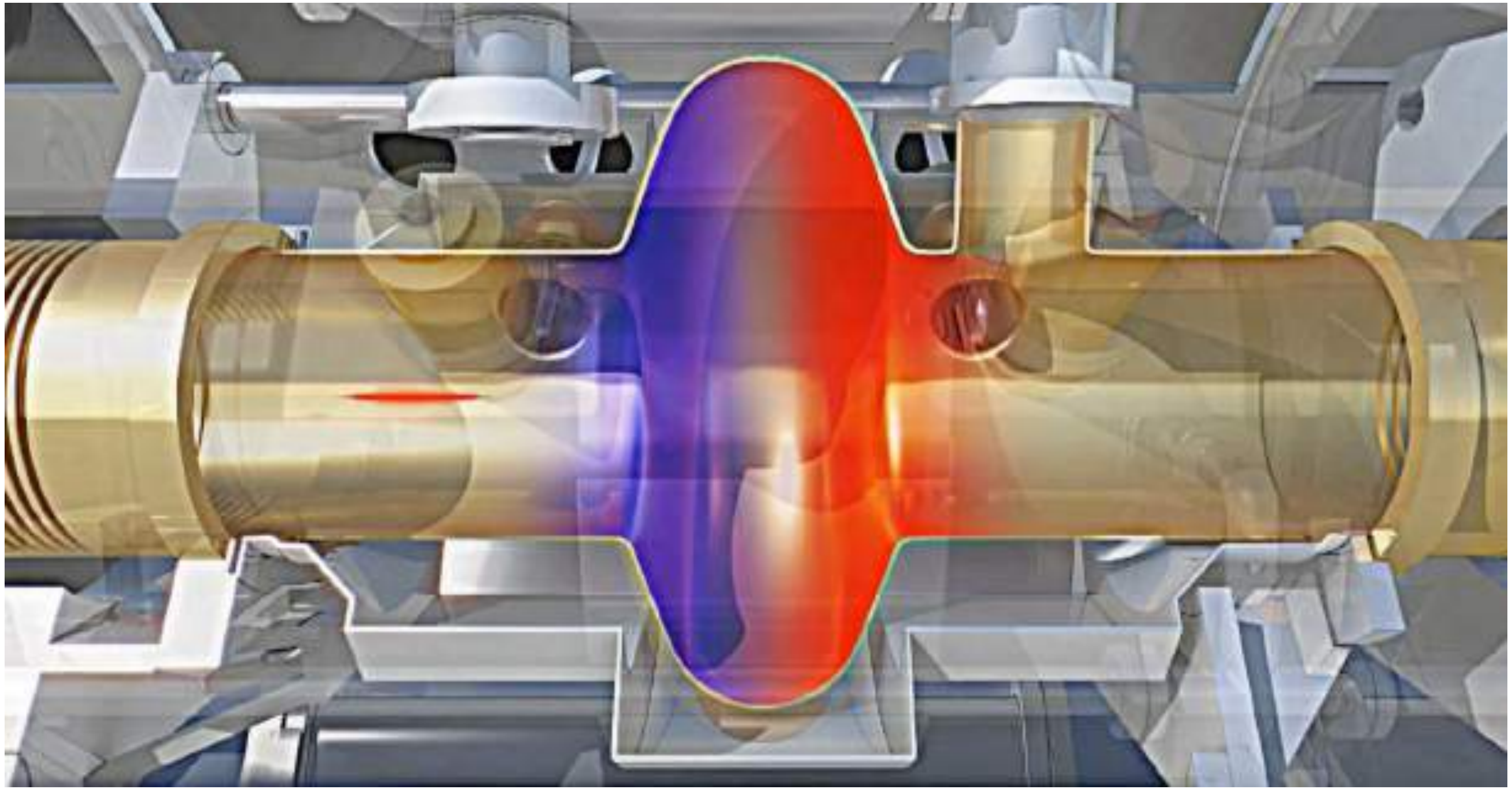
Focusing Particle Beams in LEIR



Accelerating Particles, Using Electrical Fields



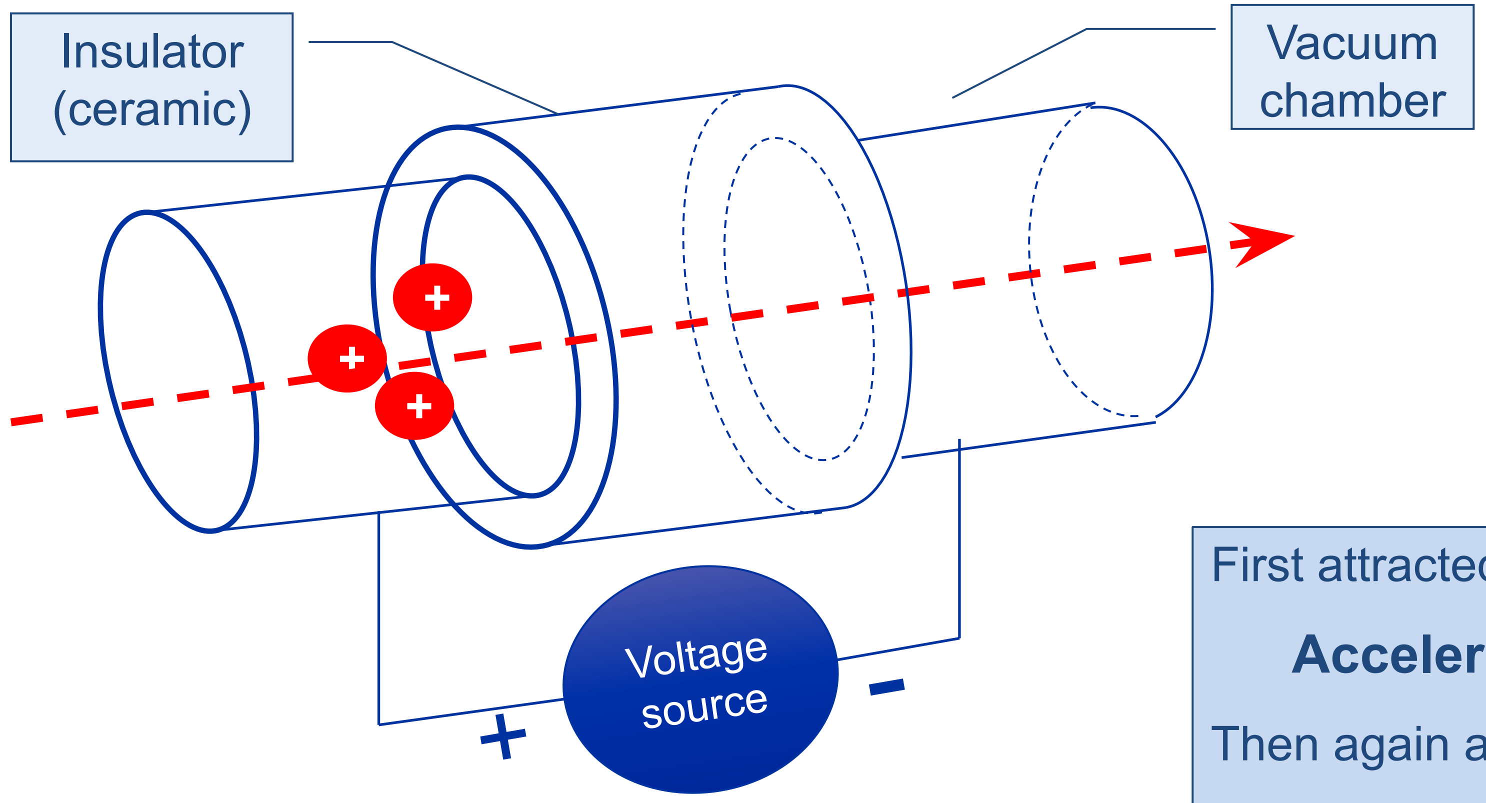
Radio Frequency Cavity



- Charged particles are accelerated by a longitudinal electric field

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

Accelerating Beams



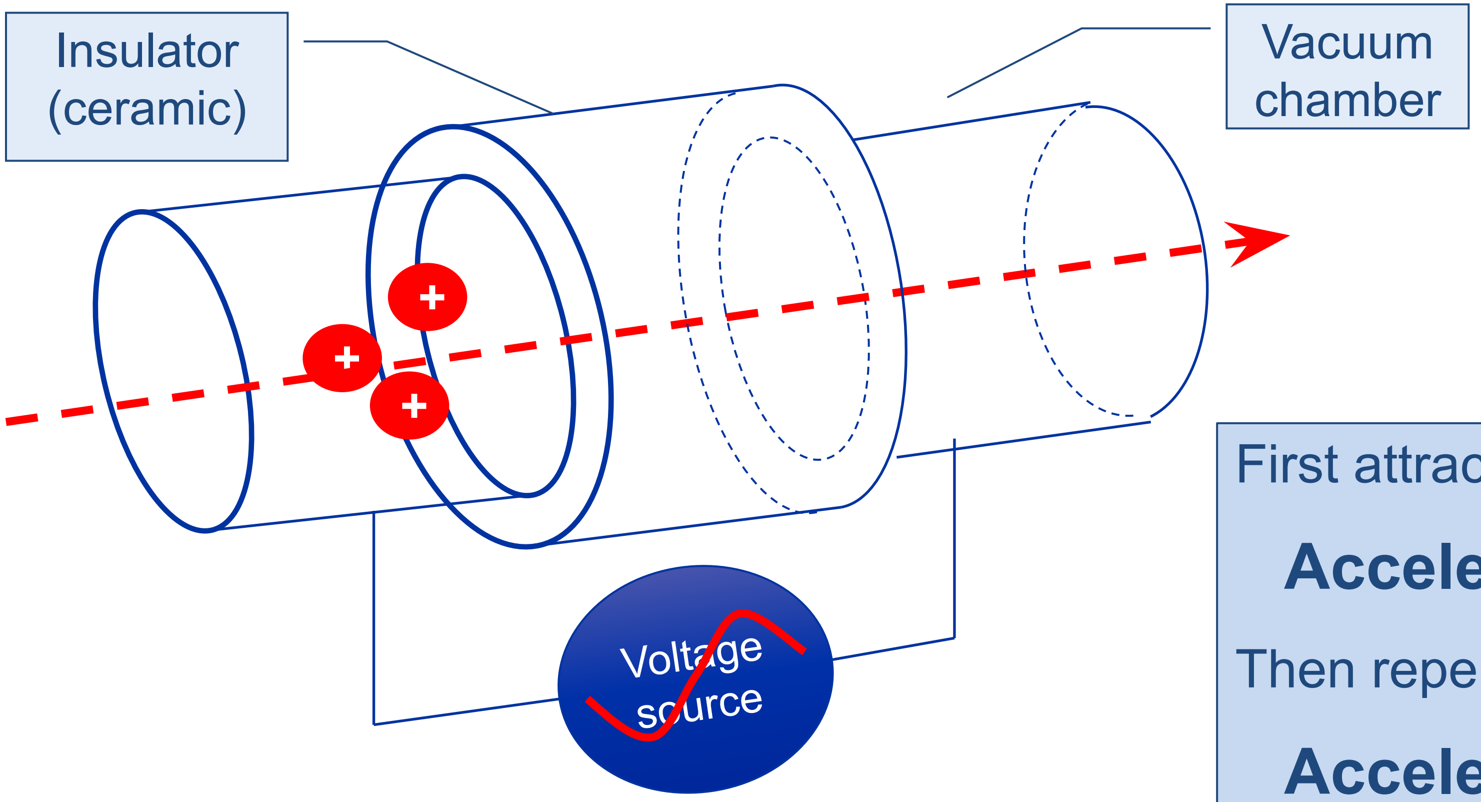
First attracted

Acceleration

Then again attracted

Deceleration

Accelerating Beams



First attracted

Acceleration

Then repelled

Acceleration

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:

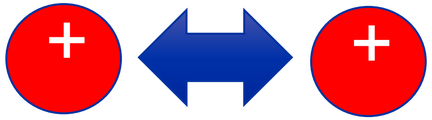
- Longitudinal emittance
- Number of bunches
- Bunch spacing, shaping, etc.

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

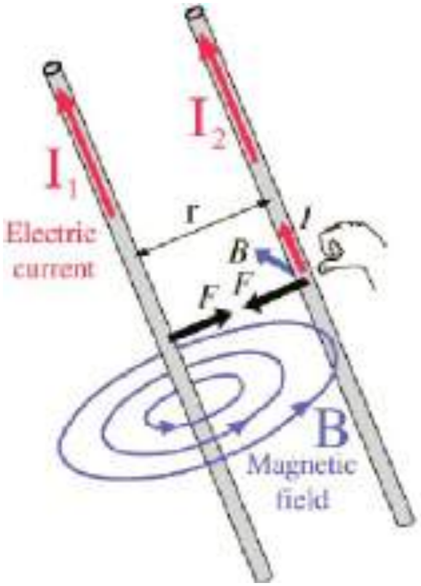
Possible Limitations

Machines and elements cannot be built with infinite perfection

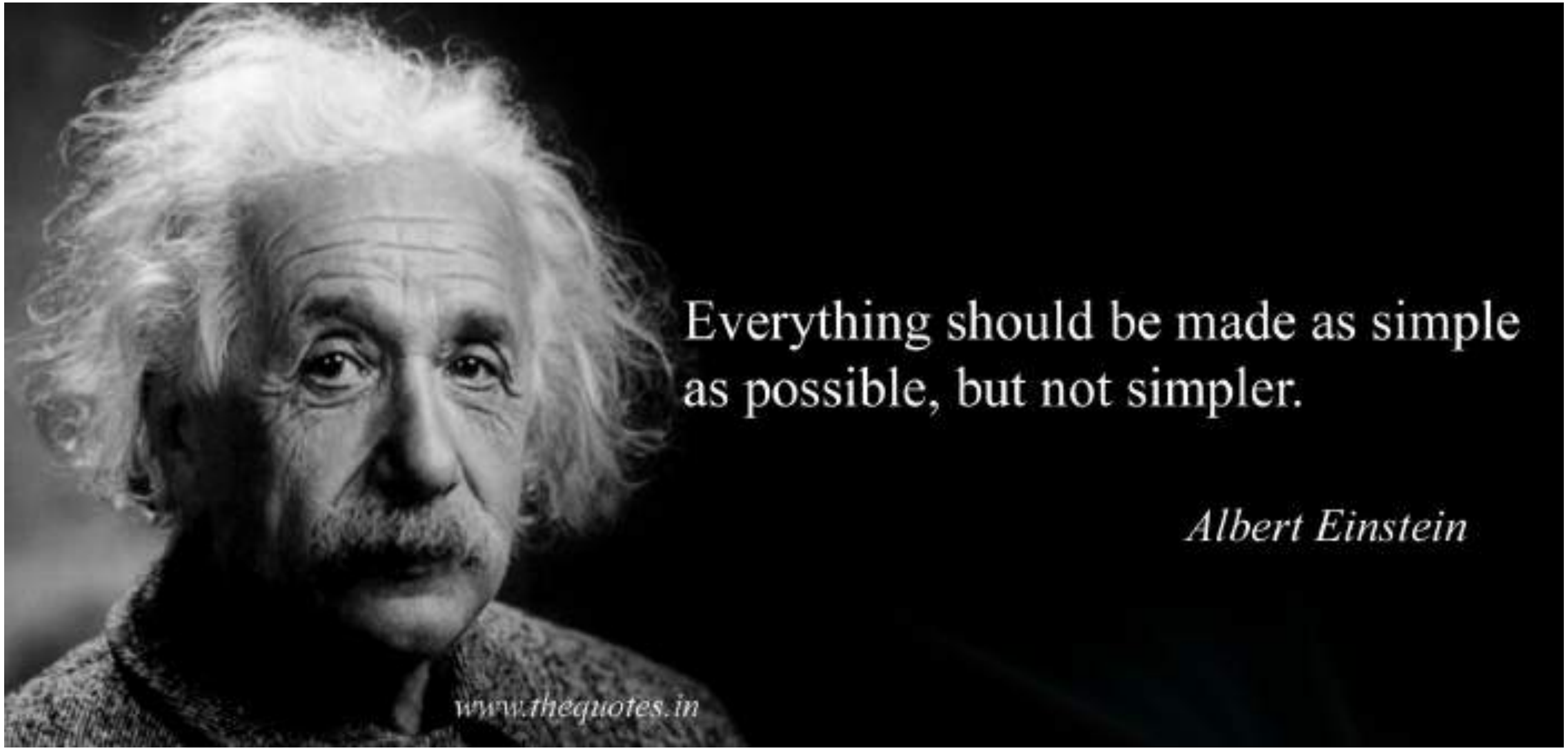
Same phase and frequency for driving force and the system can cause resonances and be destructive



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

What are we going to talk about?

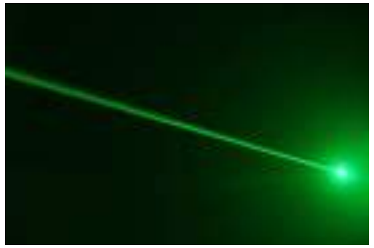
- Why Accelerators and Colliders ?
- A very Brief Historic Overview
- The CERN Accelerator Complex
- The Main Ingredients of an Accelerator
- **Some ways of using Accelerators**

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:

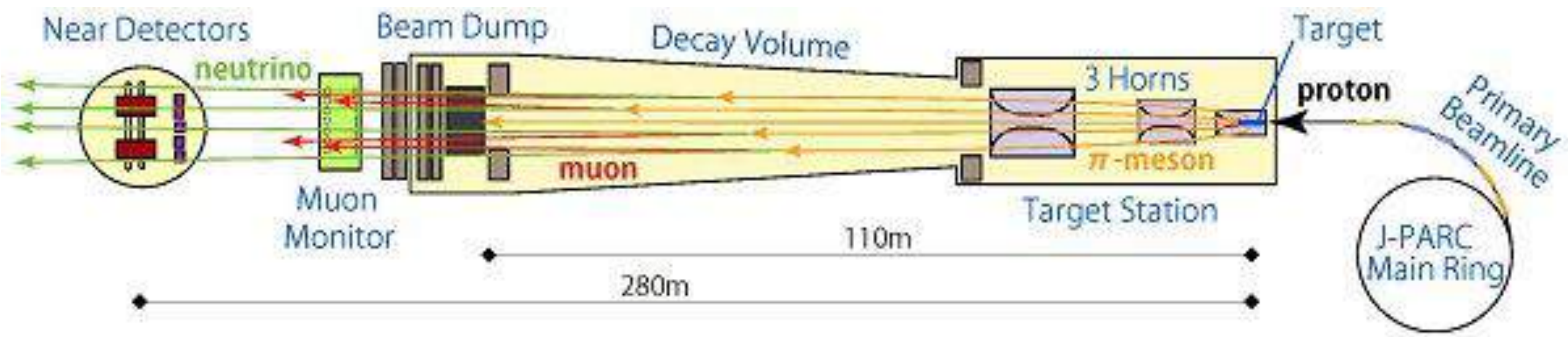
Light Sources:



Collider Physics:

Fixed Target Physics

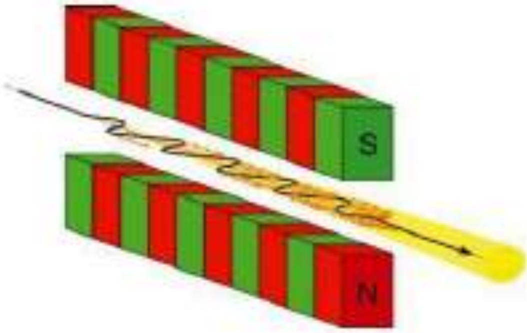
Just a few examples among many:

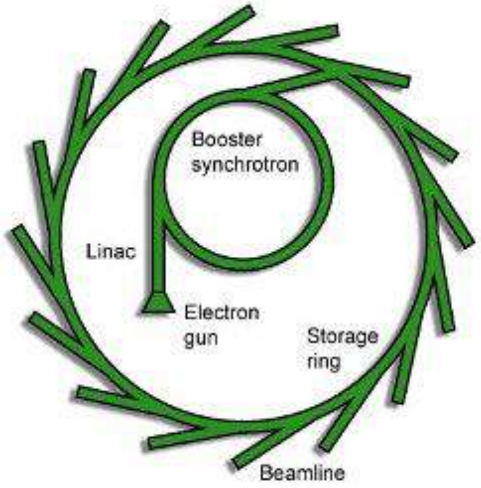


- Neutrino physics and Spallation sources: high beam power
  - High beam **intensity** with small beam size
  - High beam **energy** and / or high **repetition rate**
- J-PARC – Japan
- FermiLab - USA
- Previously CERN to CNGS – Europe
- Spallation Neutron Source (SNS) Oak Ridge - USA

Synchrotron Light Sources

Just a few examples among many:





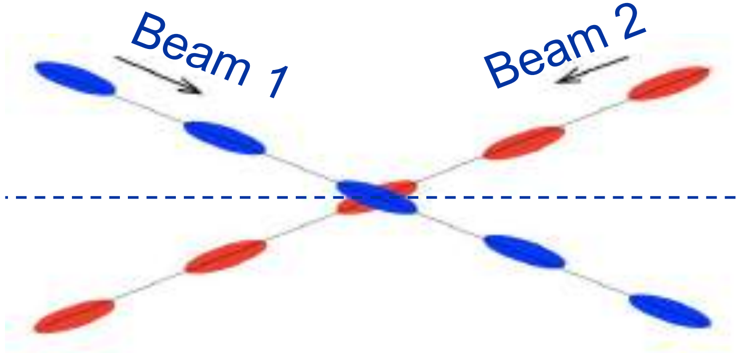
- Photon beam from stored (highly relativistic) electron beam
  - High electron beam intensity (Accelerator & Storage Ring)
  - Use of **undulators** to enhance photon emission
- Swiss Light Source (SLS) – Europe
- European Synchrotron Radiation Facility (ESRF) – Europe
- National Synchrotron Light Source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

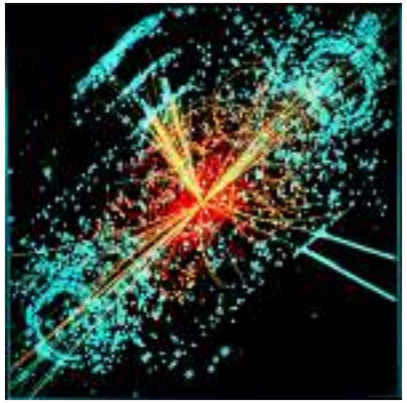
Collider Physics

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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