The CERN Accelerator complex with focus on LHC

French High-School Student Internship Programme 2017

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Acknowledgments: R. Steerenberg

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- Accelerators and Colliders
- The Main Ingredients of an Accelerator
- The Large Hadron Collider

- **Accelerators and Colliders**
- The Main Ingredients of an Accelerator
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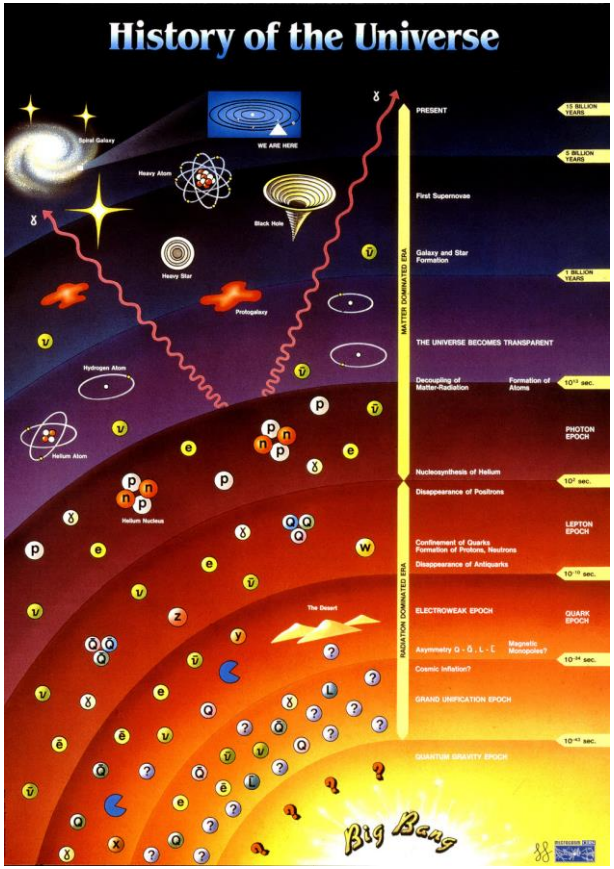
From energy and to matter

During the Big Bang energy was transformed in matter

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

Eventually those particles are made to collide with nuclei (in a target) or with other particles (collider).

In the detectors the particles that are created are observed and analysed, most of them are unstable and decay immediately.

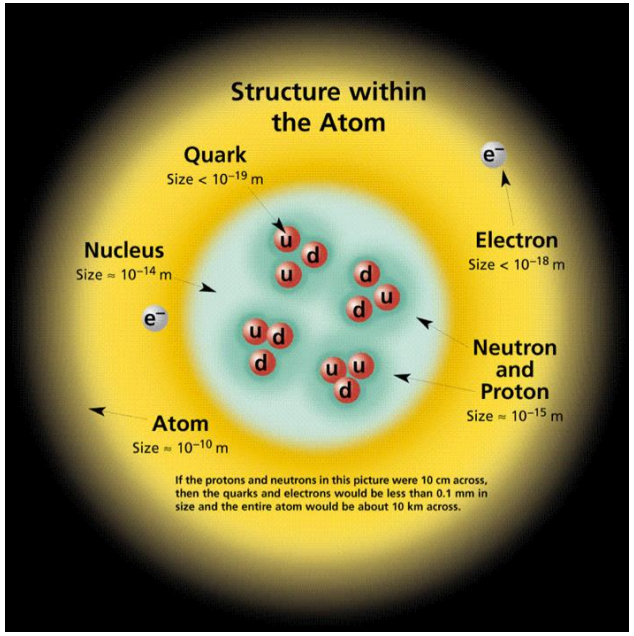


Looking to smaller dimensions

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 reduces the wavelength and provides a probe for smaller dimensions

Fixed target and colliders

Fixed Target

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

A lot of energy is lost in the target and in translation, only part of the energy is available to produce particles

Collider

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

All energy is available for particle production

Which particles?

The classical particles used in most accelerators are **protons** (Hydrogen nuclei), **electrons** and **heavy stable nuclei**.

At CERN the main accelerator chain leading to the LHC is operated with **protons** or stable **nuclei** (lead, argon, xenon) – also called '**hadrons**' (LHC = Large **Hadron** Collider).

A CERN test facility operates with **electrons**.

But some accelerators also operate with **positrons** (anti-electrons), **anti-protons** or with secondary beams of **unstable particles or nuclei**.

- Such particles must first be produced in a target through interactions, selected and then post-accelerated (or just transported).
- It takes roughly 1 million protons to obtain 1 usable anti-proton !

Energy scales and units

The standard unit for energy is the **Joule**, which is however an impractical unit for the particles inside an accelerators.

For accelerators the **Electron-Volt** (**eV** = 1.6×10^{-19} J) is used as standard unit, it is the energy gained by one electron when passing through a potential of 1 V (~battery).

- The **eV** corresponds to the energy scale of **chemical reaction**,
- The **Mega-eV** (MeV = 10^9 eV) corresponds to the scale of **nuclear reactions**.

The energy of the most energetic protons at CERN (in the LHC) reaches **6.5 Tera-eV** (**TeV** = 10^{12} eV), ~6500 times its rest mass.

- The rest mass of a proton is ~ 1 Giga-eV (GeV = 10^9 eV).

The most energetic cosmic particles have energies of ~ 10^8 TeV.

Accelerator zoo

Today: ~ **30'000 accelerators** are 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 (electrons)
- Lin. & Circ. accelerators/colliders

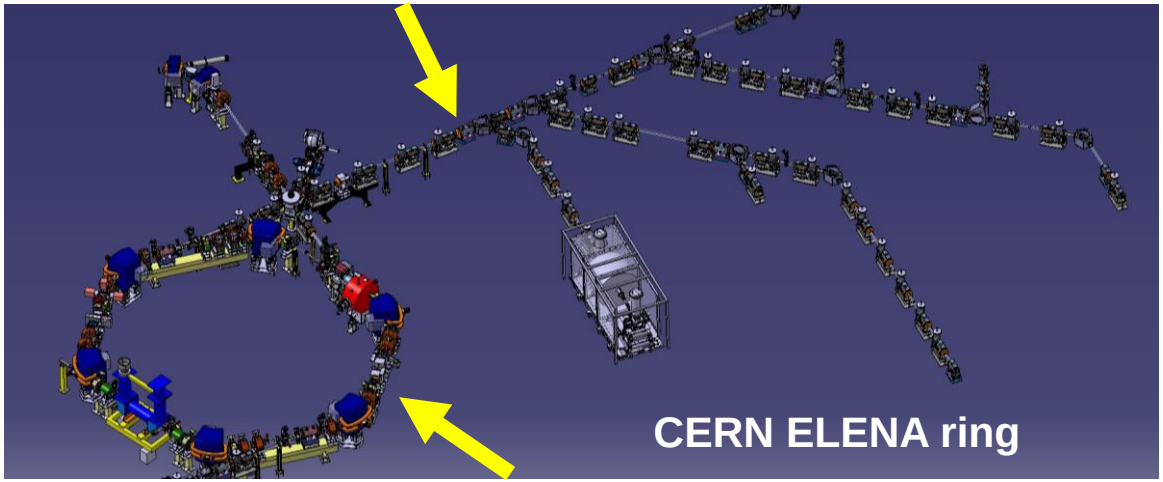
This lecture will concentrate on the CERN accelerators of which the large majority are **Synchrotrons**

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

- Accelerators and Colliders
- **The Main Ingredients of an Accelerator**
- The Large Hadron Collider

Two accelerator ‘categories’

Linear accelerators (or transfer lines)
- The elements are arranged along a ‘line’ (can be curved !).
- Particles enter on one end, exit on the other end : ‘Single pass’.



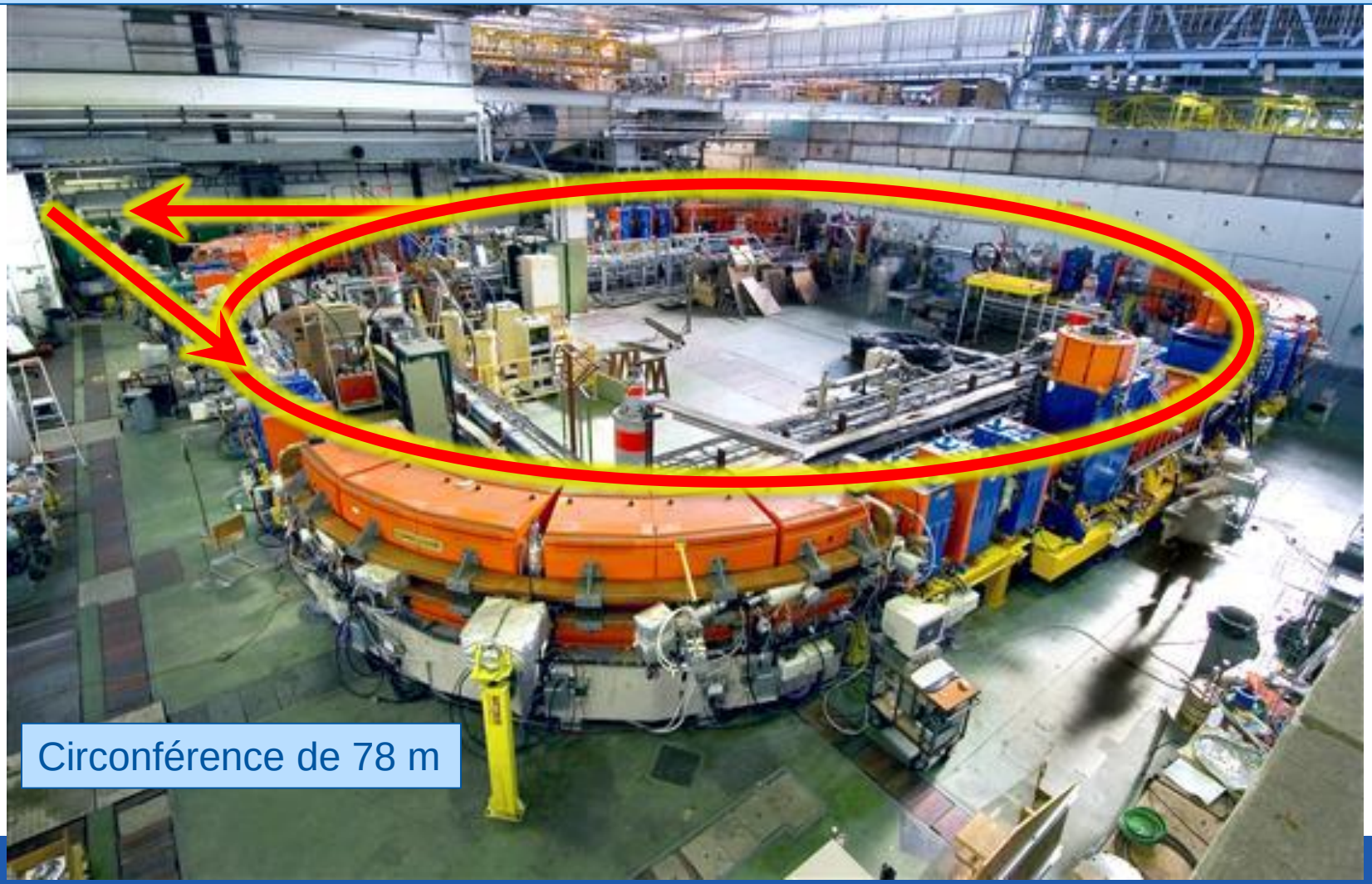
Circular accelerators
- The elements are arranged along a semi-circular shape.
- Particles can circulate in principle ‘forever’ : ‘Multi pass’.
  - But they need an entrance and often also an exit door !

The CERN Accelerator Complex

More than 50 km of beam lines !

LEIR as an example

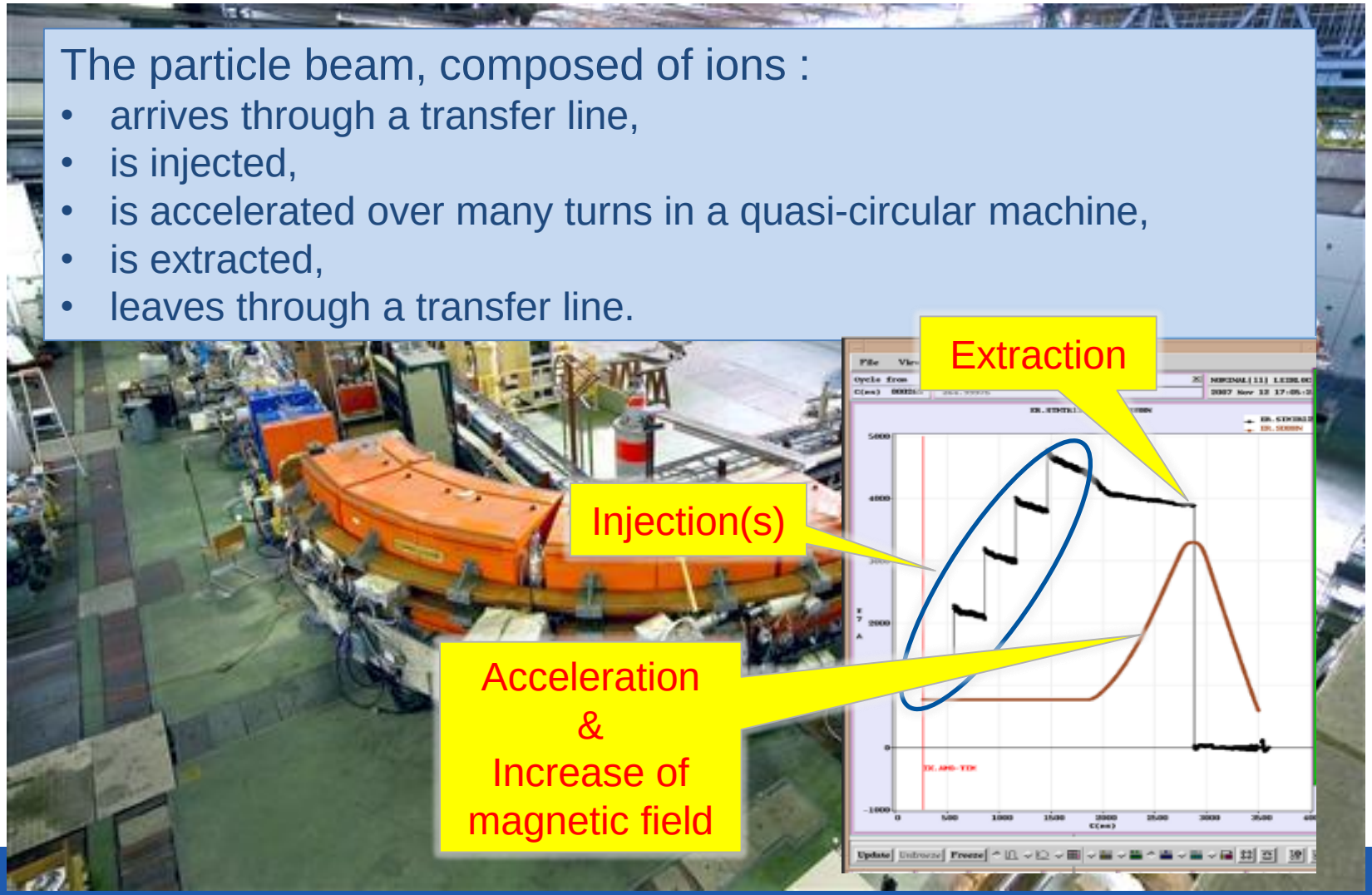
LEIR = Low Energy Ion Ring : sert à accélérer des ions (Plomb, Argon, Xenon)



LEIR as an example

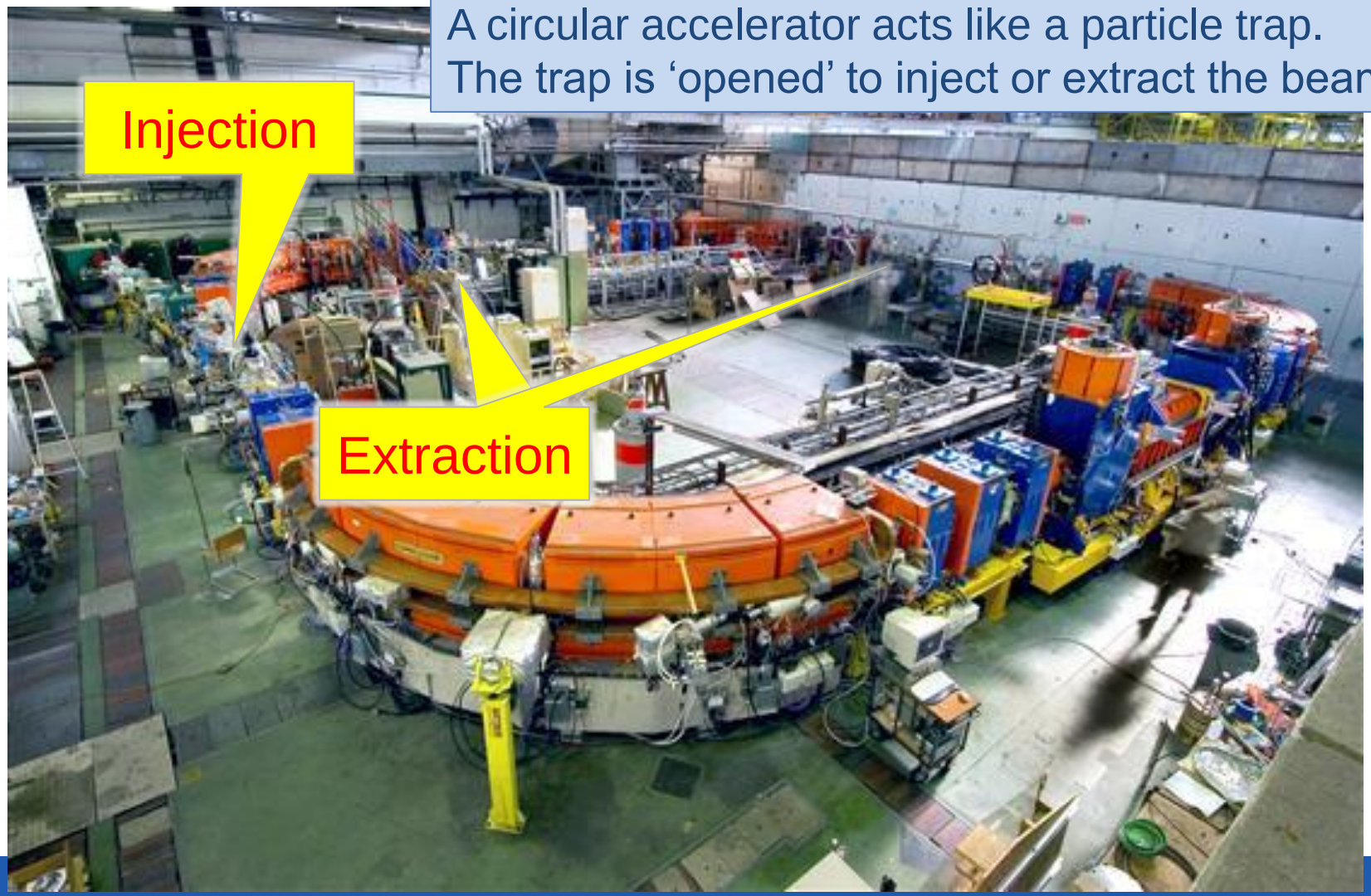
The particle beam, composed of ions :

- arrives through a transfer line,
- is injected,
- is accelerated over many turns in a quasi-circular machine,
- is extracted,
- leaves through a transfer line.

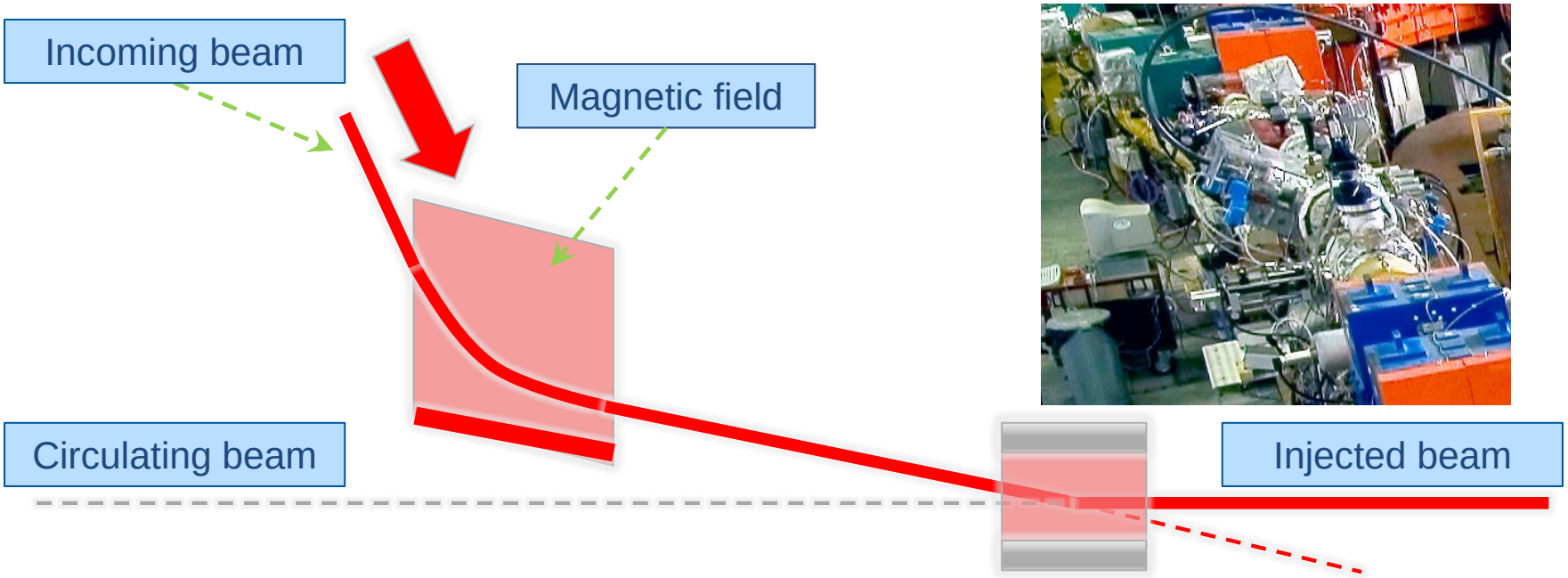


Injecting & extracting particles

A circular accelerator acts like a particle trap.
The trap is ‘opened’ to inject or extract the beam.



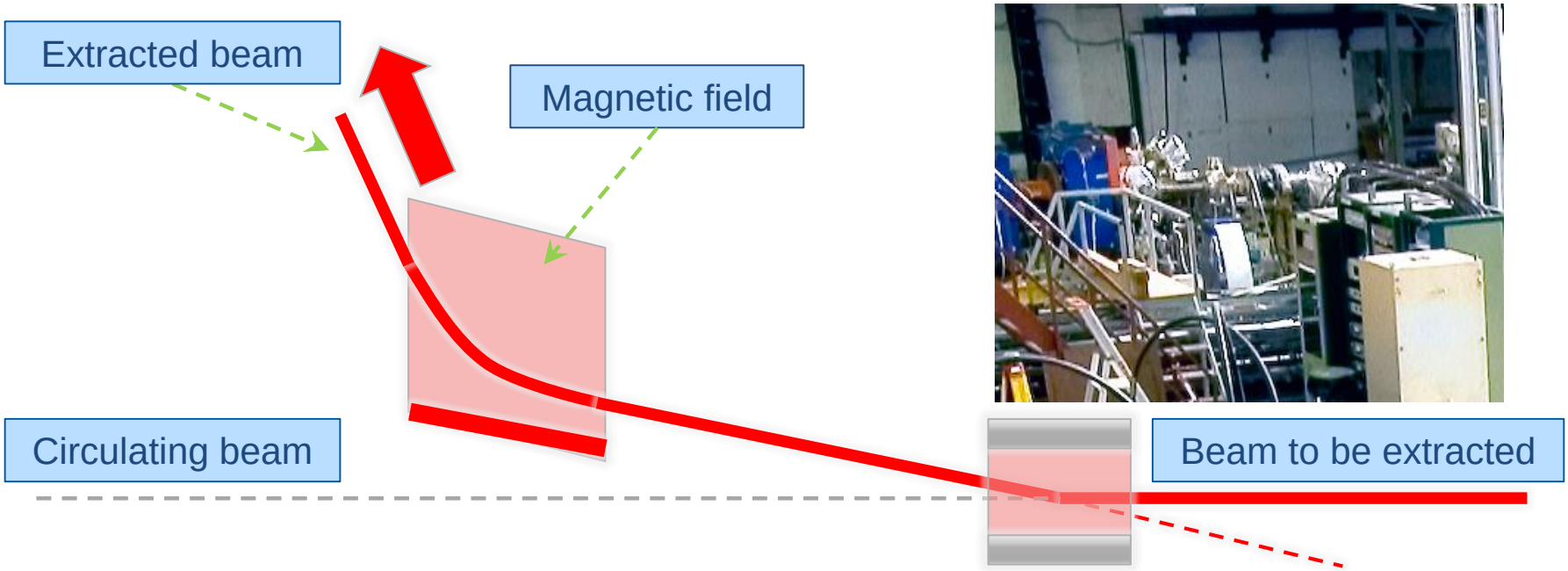
Injecting & extracting particles



Open the trap to let the beam enter, then close the trap again !

Kicker Magnet: very short magnetic field pulse

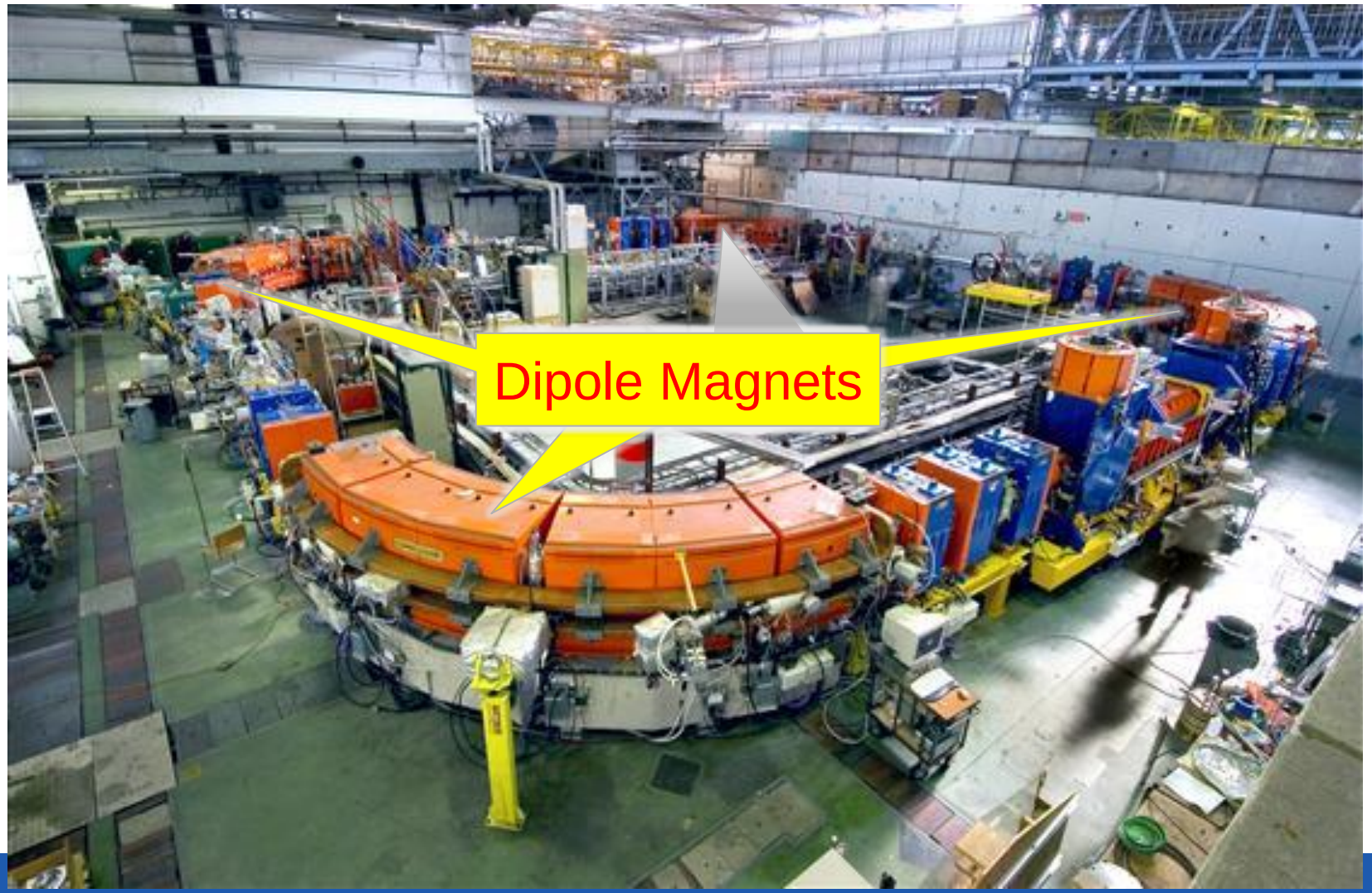
Injecting & **extracting** particles



Open the trap to let the beam exit, then close the trap again !

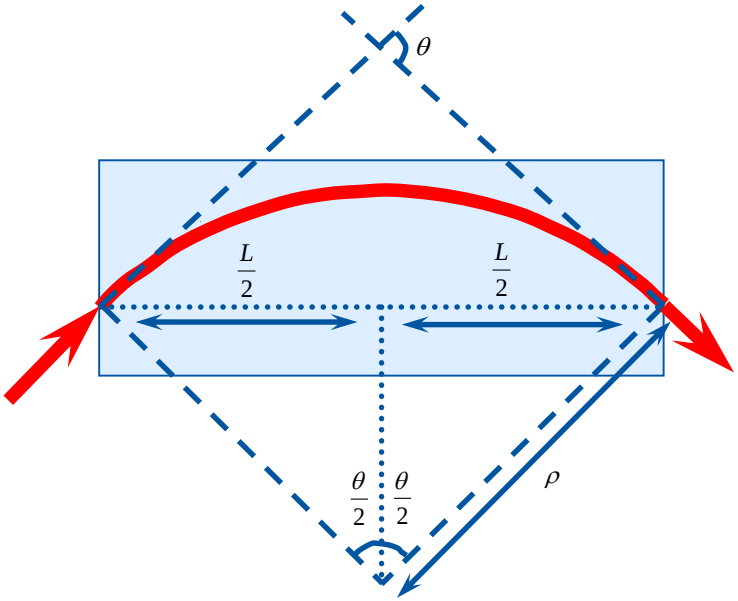
Kicker Magnet: very short magnetic field pulse

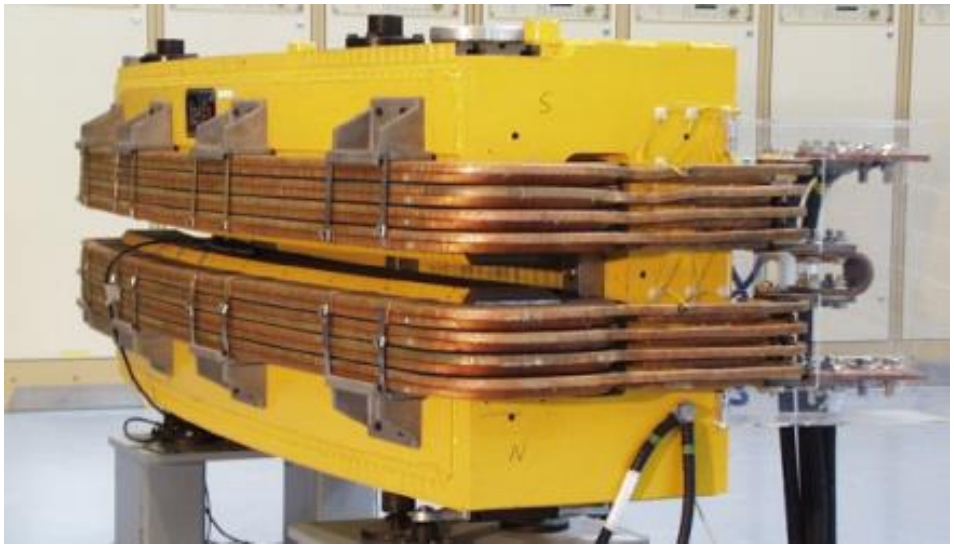
Bending the trajectory



Bending charged particles

Charged Particles are deviated in magnetic fields, dipolar magnets are used for bending



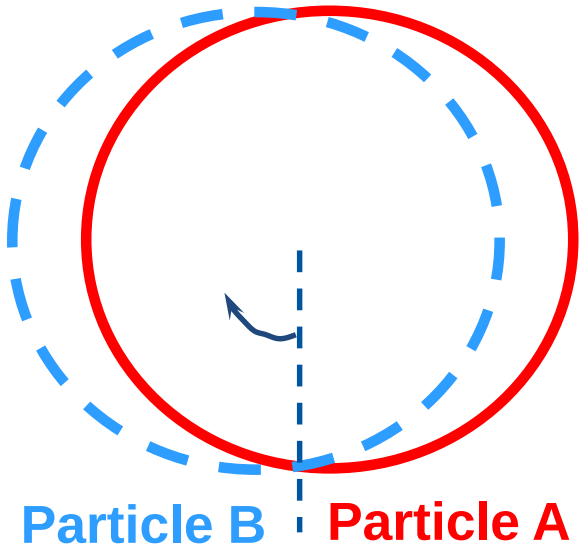


Lorentz force: $F = e\,v \times B$

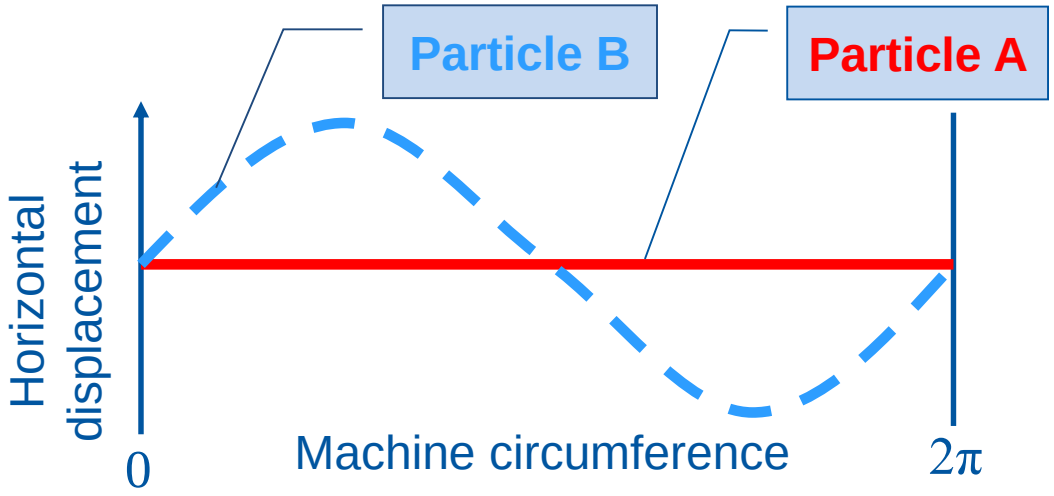
Electric fields are rarely used to deflect particles in accelerators as they are not practical (too high electric fields required).

Oscillatory motion of particles

Two charged Particles in a homogeneous magnetic field



Horizontal motion

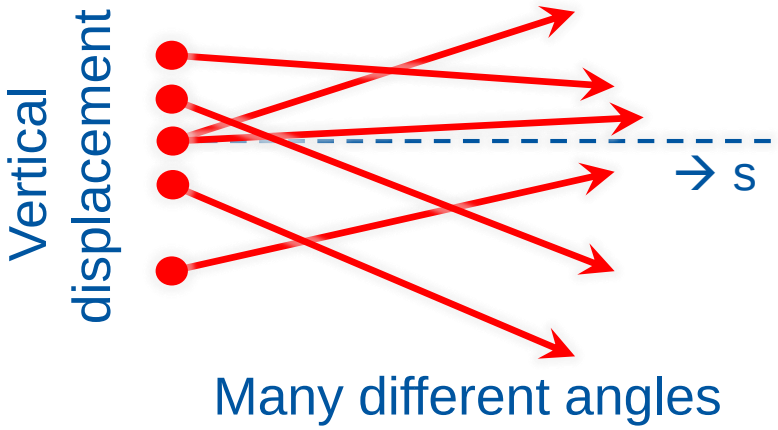


Particles with different initial conditions in a homogeneous magnetic field will cause oscillatory motion in the horizontal plane
→ **Betatron Oscillations**

Oscillatory motion of particles

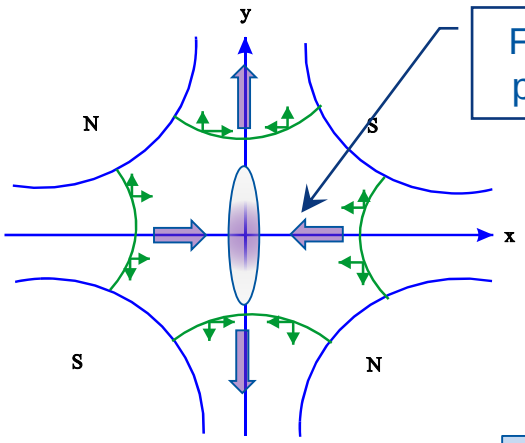
The horizontal motion seems to be “stable”….
What about the vertical plane ?

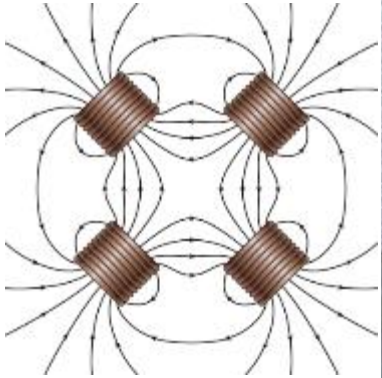
Many particles = many initial conditions



Focusing particle beams

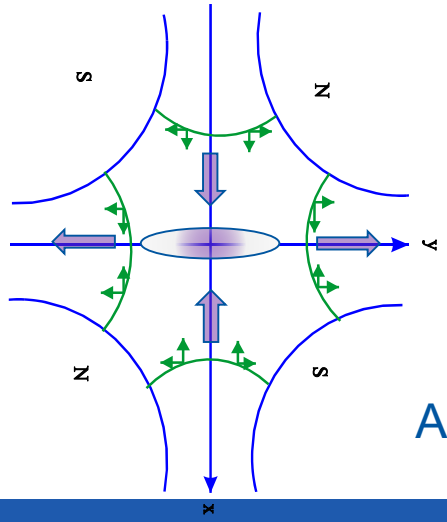
Focusing particles is **similar to light optics** (lenses)



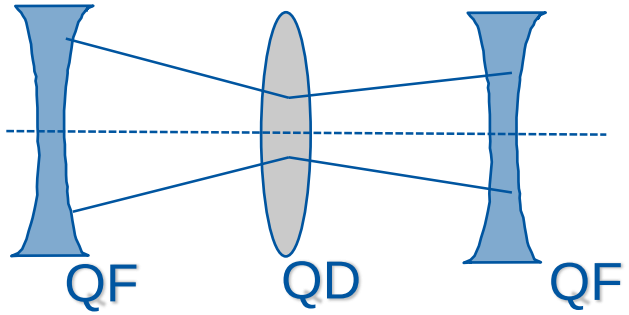


Focusing Quadrupole (QF)

Rotated by 90º

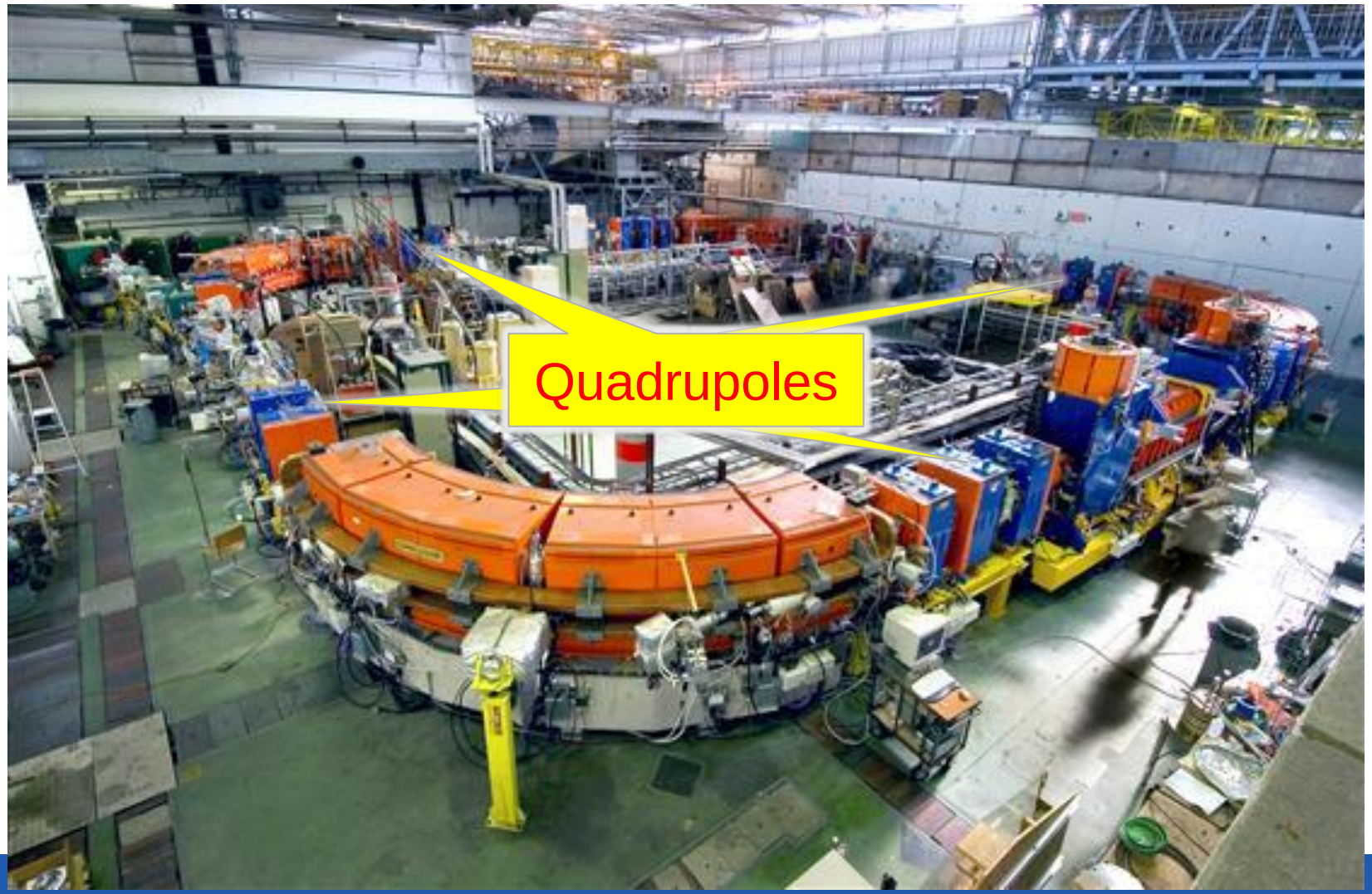


De-focusing Quadrupole (QD)



An alternating ‘lattice’ of QF and QD provides overall focussing !

Focusing the particle beam

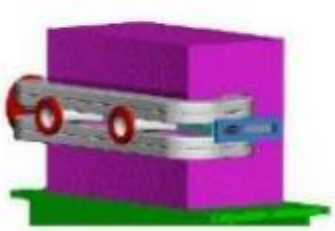


Magnetic multipoles

To operate efficiently accelerators make use of a wide range of magnet multipoles (up to 10 poles at LHC)

Multipole Magnets

Dipole



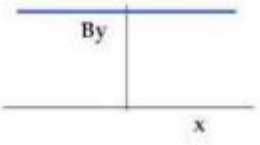


Image: Wikimedia commons

Quadrupole

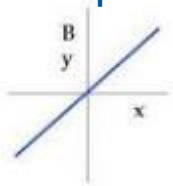


Image: STFC

Sextupole

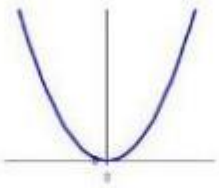
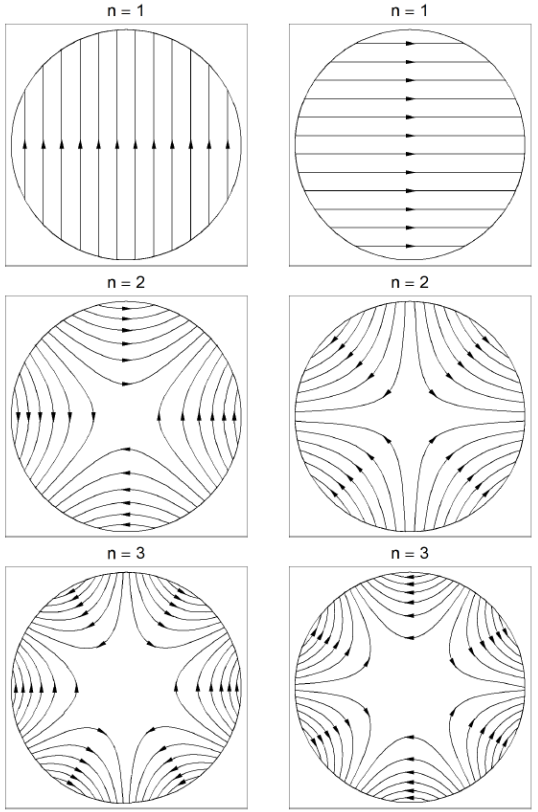


Image: Danfysik

Images: Ted Wilson, JAI Course 2012 20

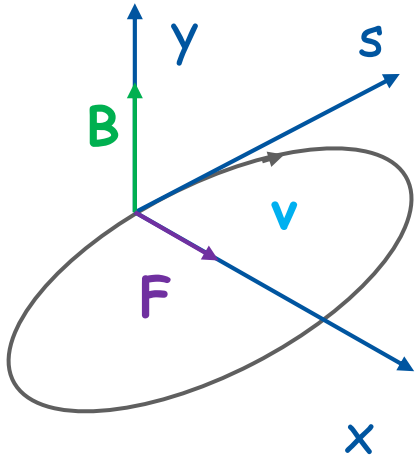
Magnetic field lines



Energy range of a synchrotron

For a circular accelerator with **dipole field B** and **radius R**, the **energy E** is proportional to the product:

$$E \propto B\,R$$



To increase the energy one can increase B or R (or both).

In a synchrotron, for a given R, the **highest energy E_{max}** is defined by the maximum magnetic field – for iron magnets B_{max} = 2 T – while the **lowest energy E_{min}** is defined by a number of factors, one of them is the minimal practical magnetic field.

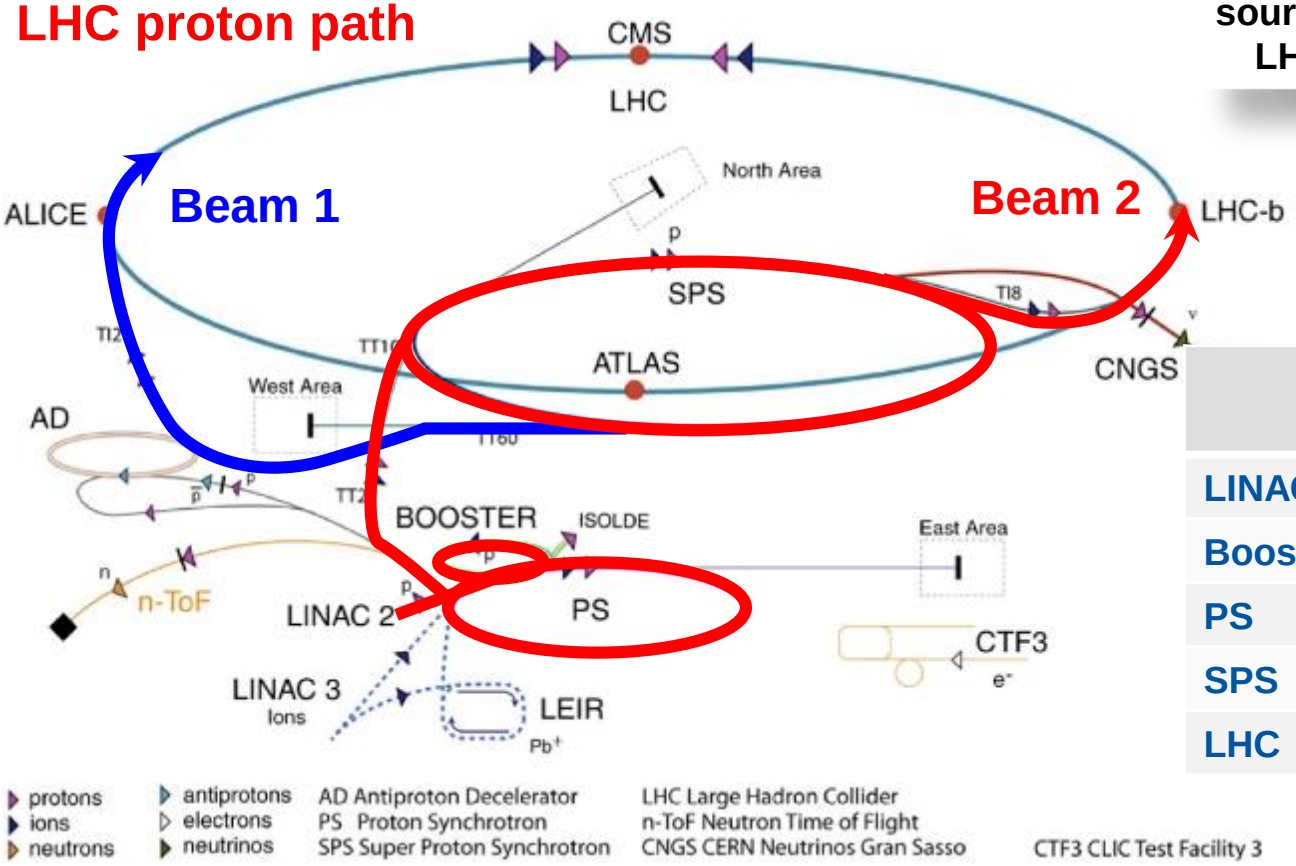
In general: $$\frac{E_{\max}}{E_{\min}} \leq 20$$

LHC /CERN accelerator chain

Like the **gears of a car**, a chain of accelerators is used to boost the energy of the beam in stages.

The proton journey from the source until injection into the LHC lasts ~7-24 seconds

LHC proton path



	Max. P (GeV/c)	Length / Circ. (m)
LINAC2	0.050	30
Booster	1.4	157
PS	26	628
SPS	450	6’911
LHC	6’500	26’657

Accelerating particles

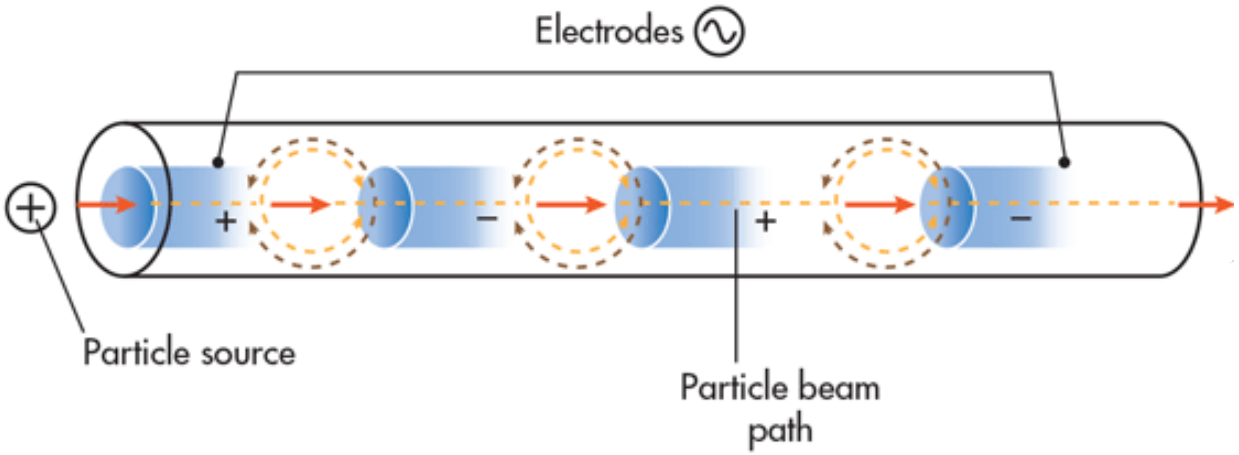
Accelerating particles

Particle acceleration is performed in special devices called **Radio-Frequency (RF) cavities**.

Such (metallic) devices are filled with an electromagnetic field oscillating typically between 1 MHz and 500 MHz (‘microwaves’).

The oscillation of the field is tuned to be in phase with the arrival of the beam particles.

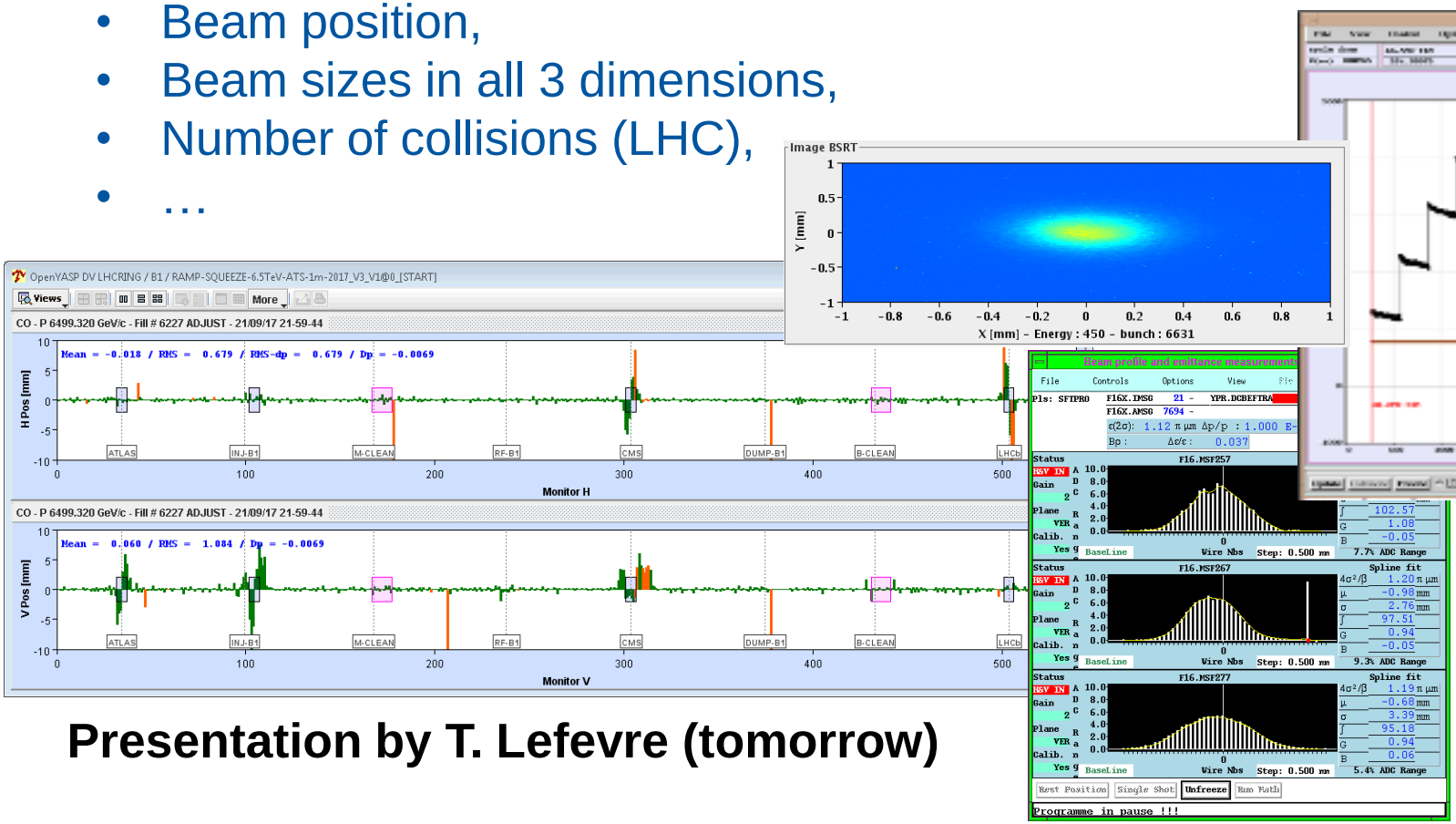
Typical accelerating fields are in the range of **1 – 30 MV/m**.



Eyes of acceleration operation

A diverse set of instruments is available to measure beam parameters:

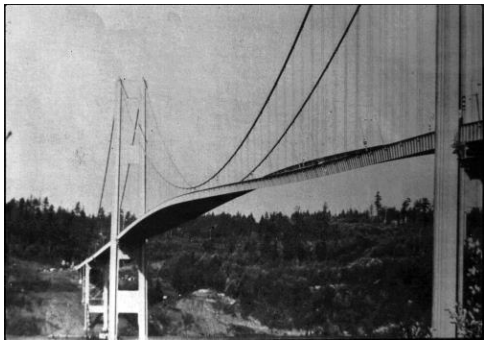
- Beam intensity (number of charges),
- Beam position,
- Beam sizes in all 3 dimensions,
- Number of collisions (LHC),
- …



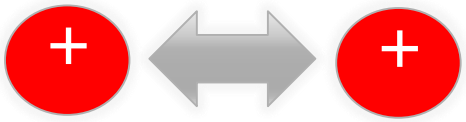
Presentation by T. Lefevre (tomorrow)

What limits acceleration performances?

Machines and elements cannot be built with infinite perfection

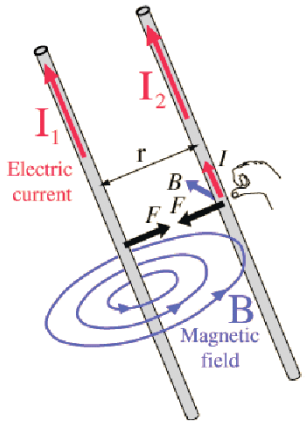


Same phase and frequency for driving force and the system can cause resonances and be destructive – applies also to beams



Neighbouring charges inside the beam with the same polarity experience repelling forces

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

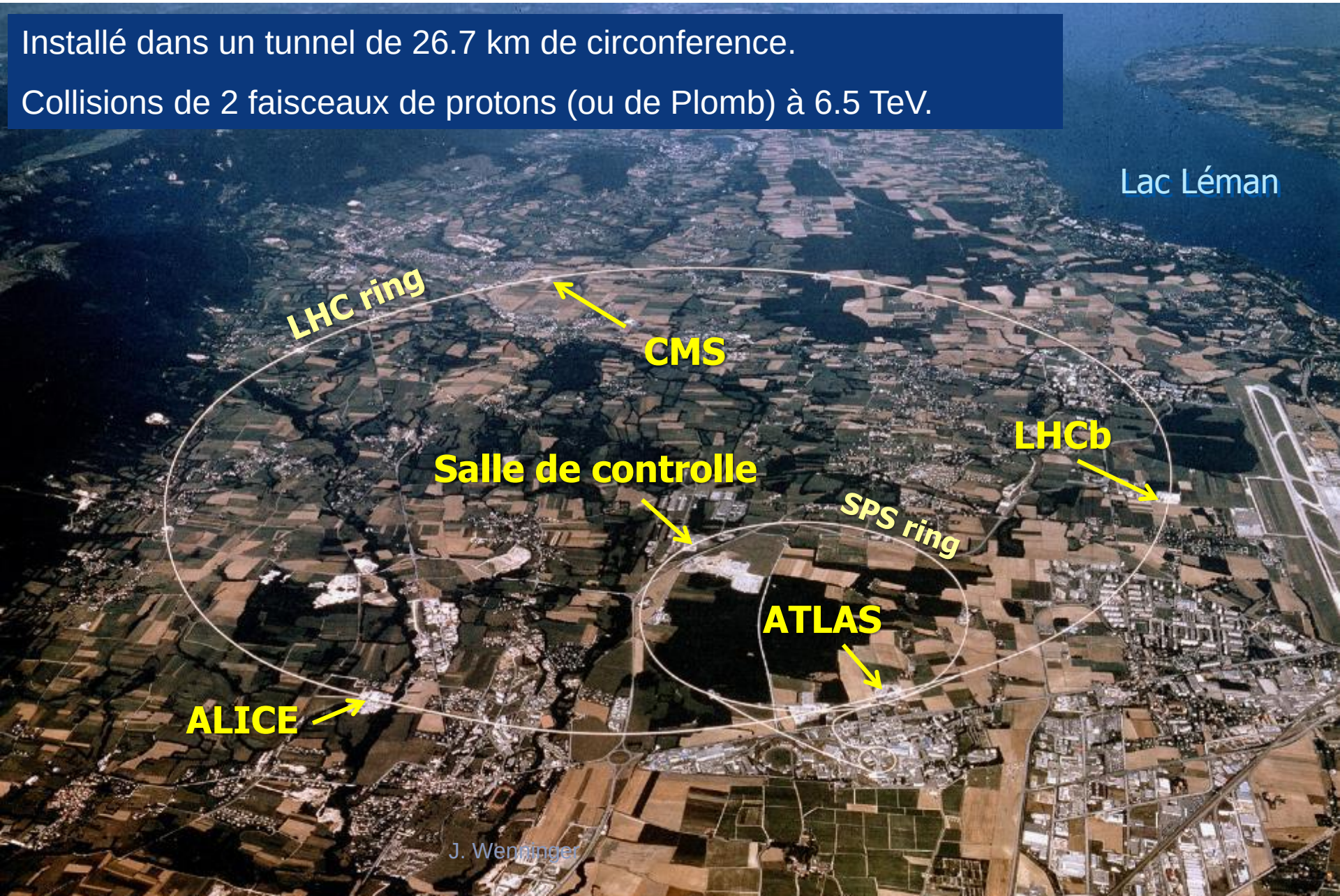


- Accelerators and Colliders
- The Main Ingredients of an Accelerator
- **The Large Hadron Collider**

Le Grand Collisionneur à Hadrons - LHC

Installé dans un tunnel de 26.7 km de circonference.

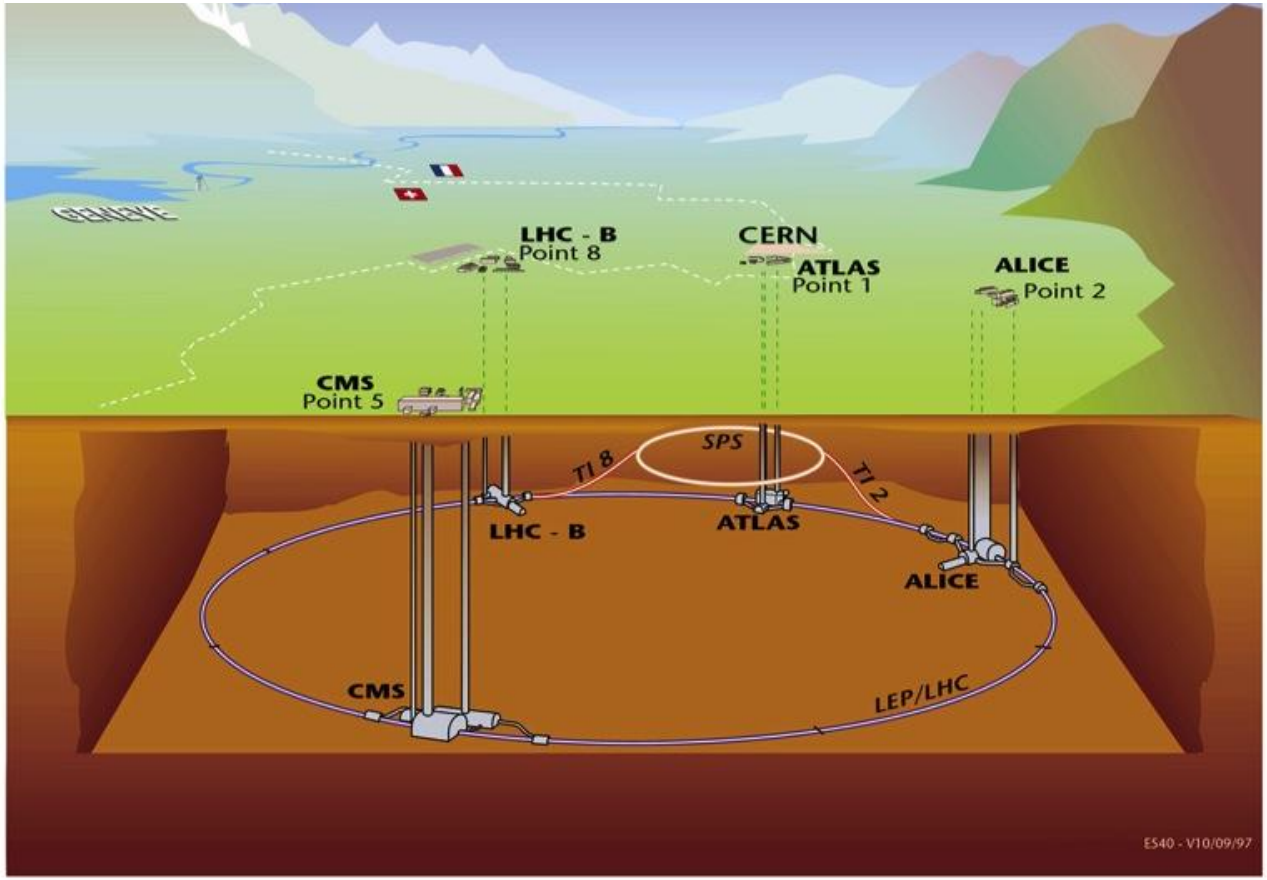
Collisions de 2 faisceaux de protons (ou de Plomb) à 6.5 TeV.

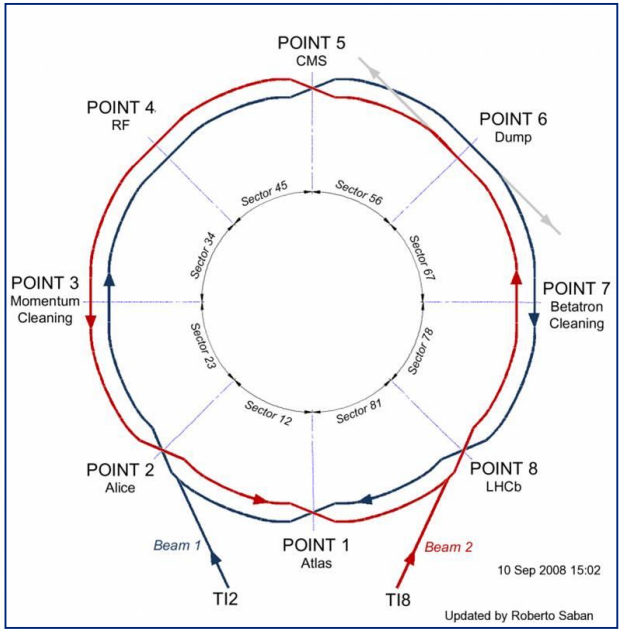


LHC layout

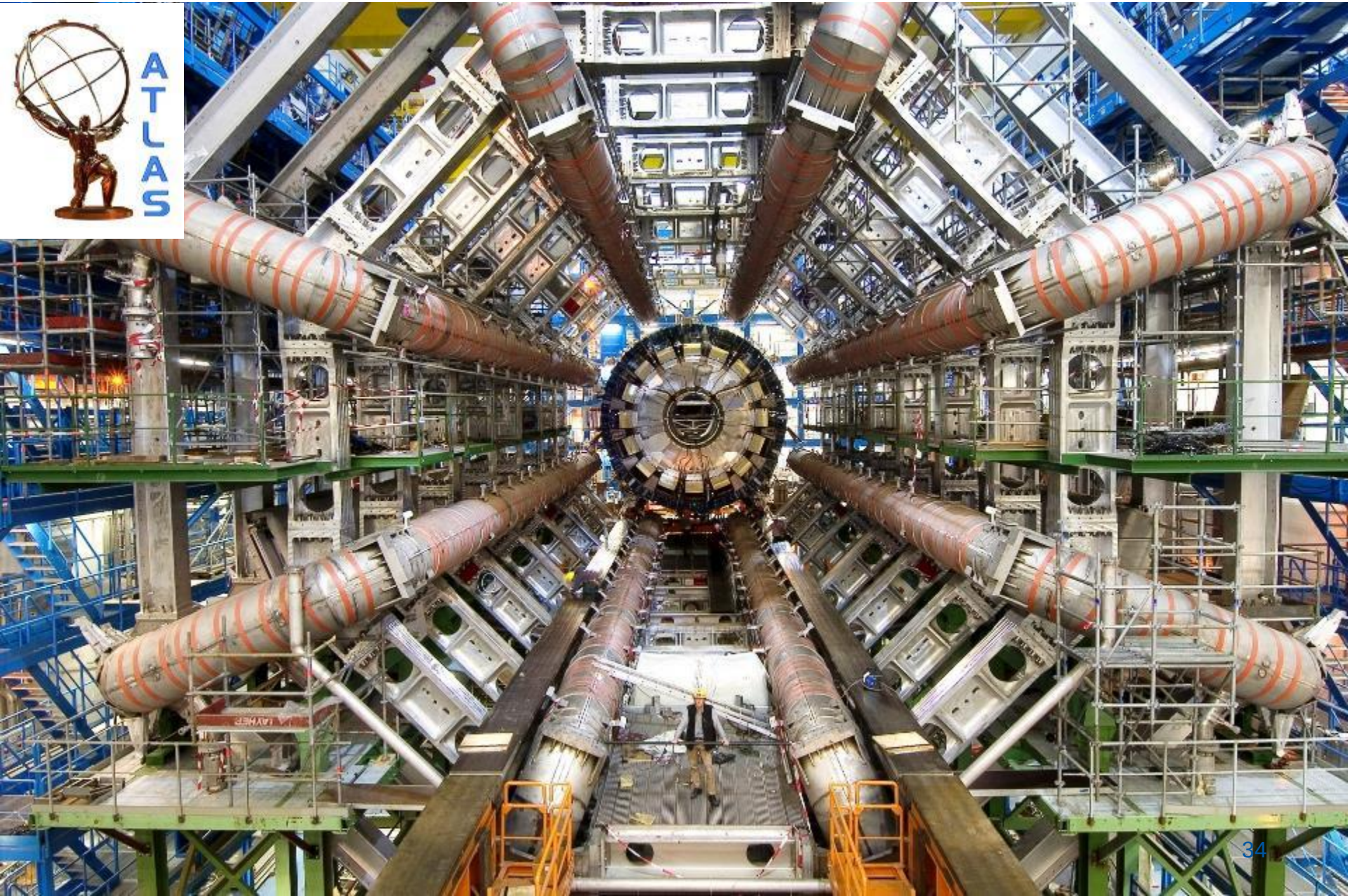
Four large experiments installed permanently around the LHC ring.

When the LHC is running, the 4 experiments operate and take data in parallel.

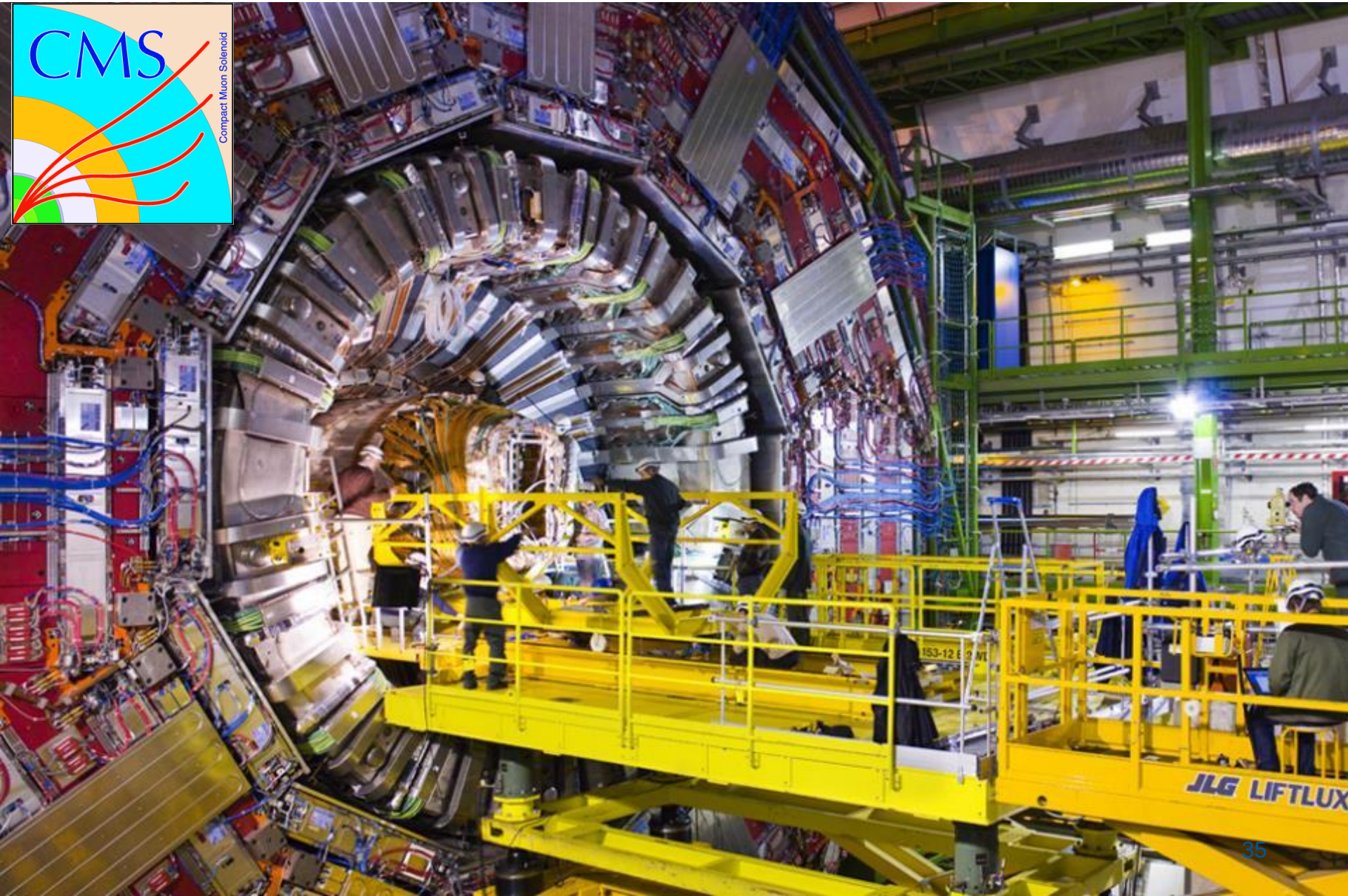




ATLAS

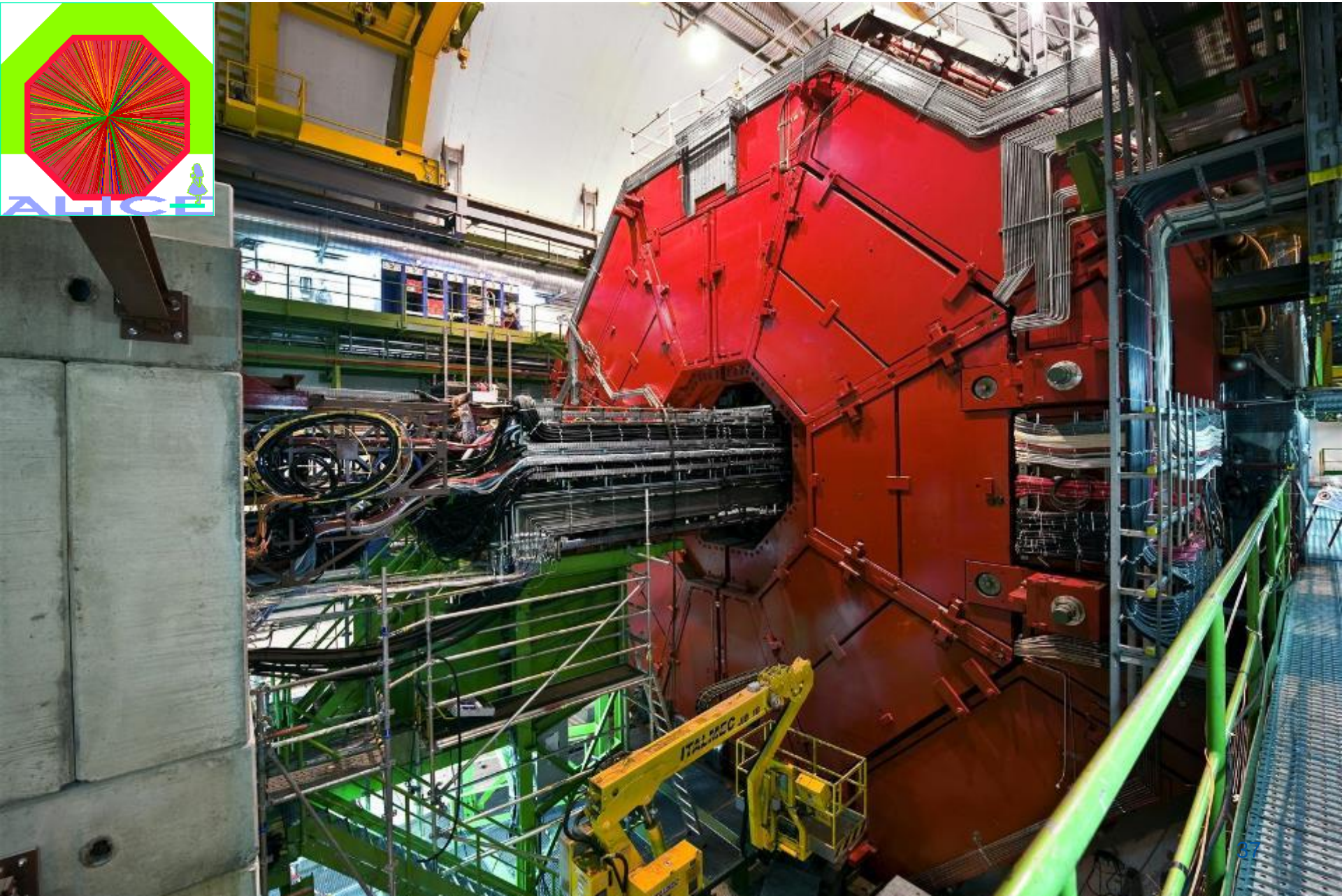


CMS



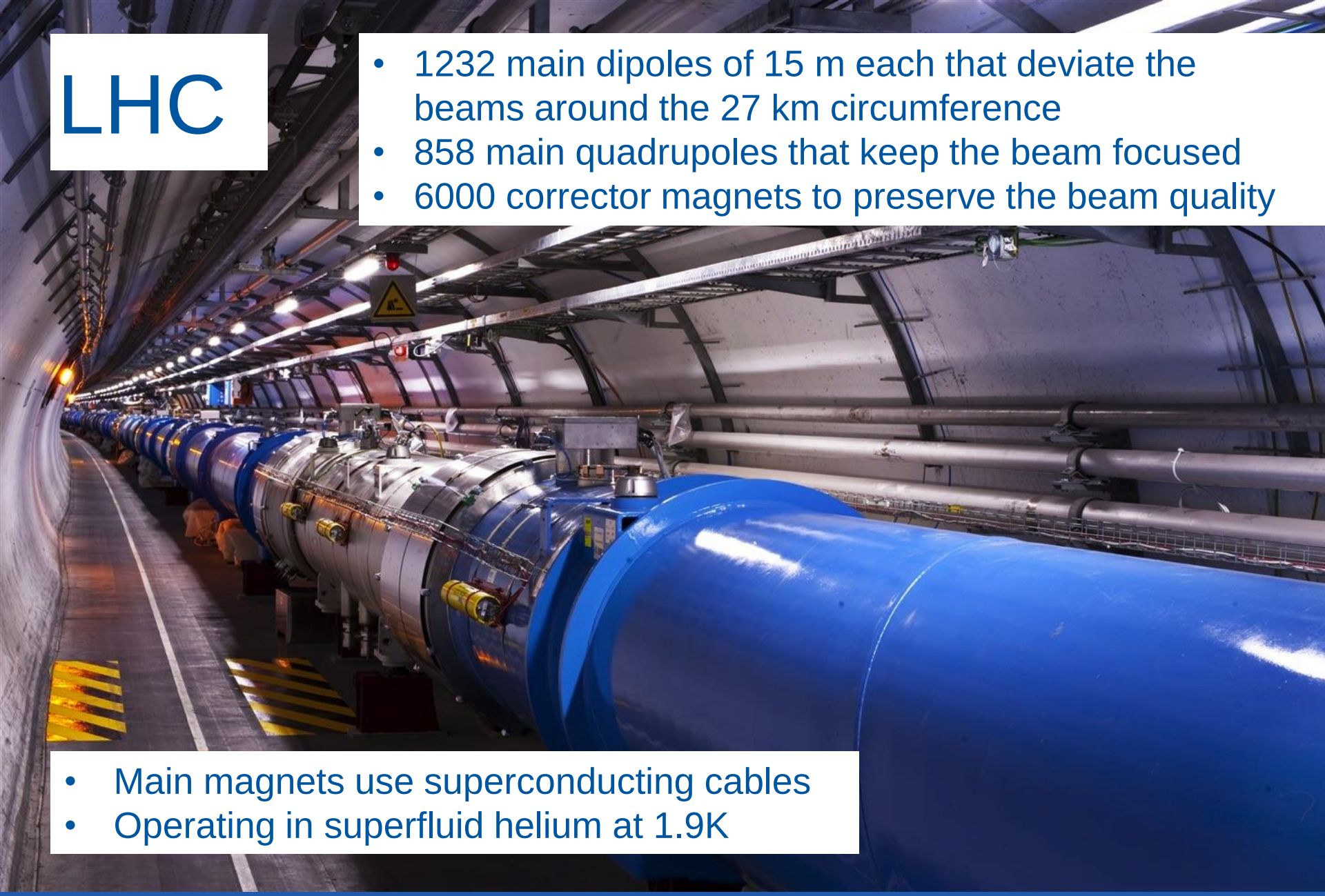
LHCb

ALICE



LHC

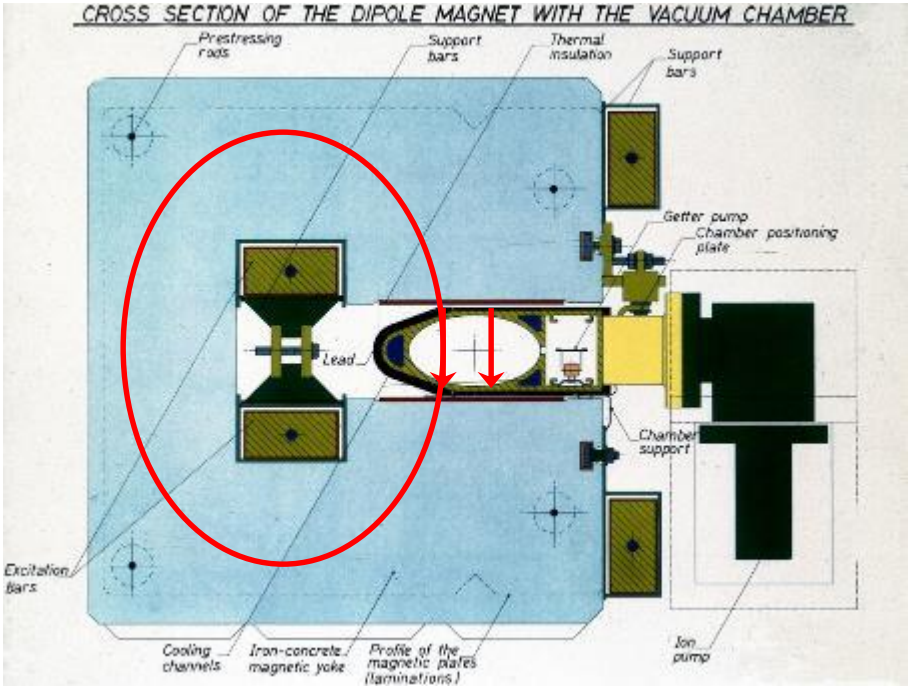
- 1232 main dipoles of 15 m each that deviate the beams around the 27 km circumference
- 858 main quadrupoles that keep the beam focused
- 6000 corrector magnets to preserve the beam quality



- Main magnets use superconducting cables
- Operating in superfluid helium at 1.9K

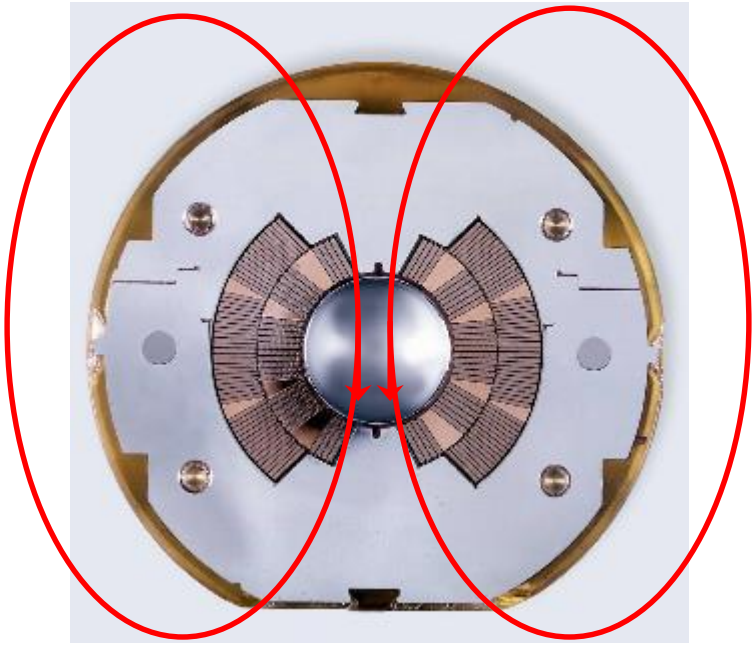
Les aimants dipolaires

Aimant fer



Champ magnétique limité à 2 Tesla

Aimant supraconducteur



Champ magnétique typique 4-5 Tesla,
Le LHC atteint 8.3 Tesla,
Bientôt 11 Tesla (2021?),
Limité par la technologie.

Supraconductivité

Pour atteindre des champs de 8.3 Tesla il faut utiliser des aimants supraconducteurs.

Pas de résistance électrique dans le câble,

Pas de perte d'énergie dans le câble.

Le matériau choisi détermine:

Tc la température critique → température de fonctionnement.

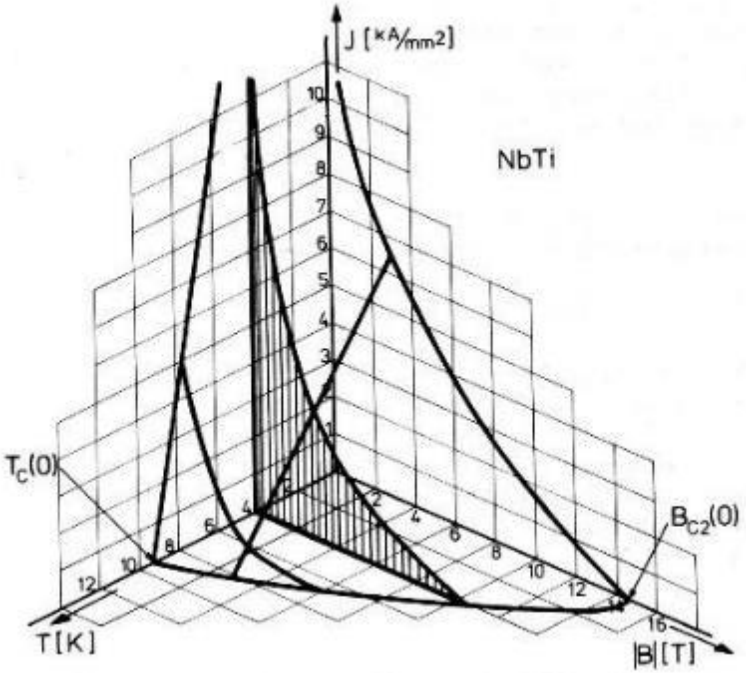
Bc le champ critique.

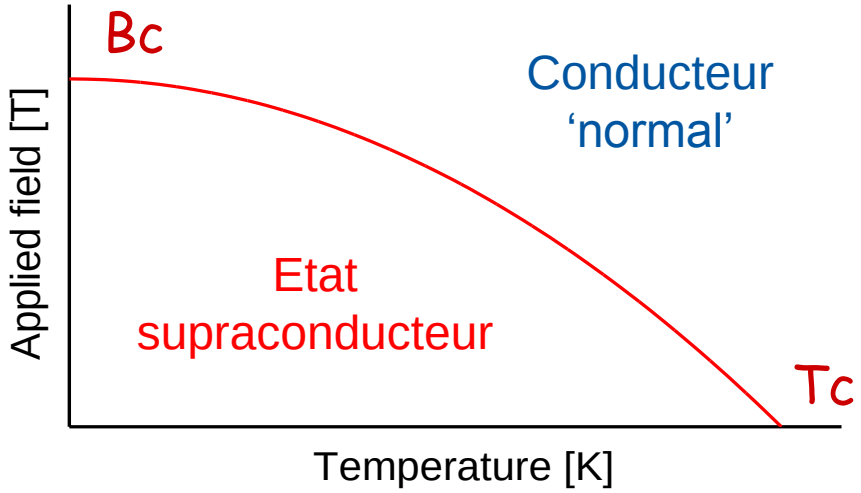
Plus la température est basse, plus haut est le champ atteignable.

Les densités de courants sont énormes, pour l'alliage NbTi @ 4.2 K (Niobium-Titane):

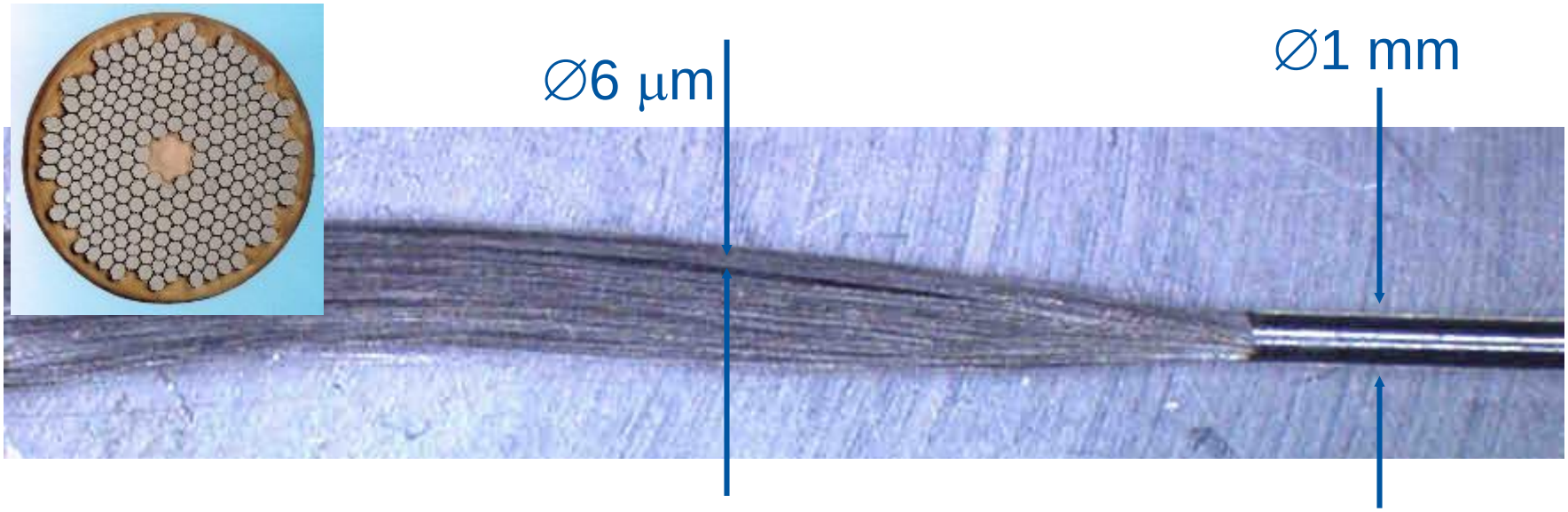
2000 A/mm^2 @ avec un champ de 6 T

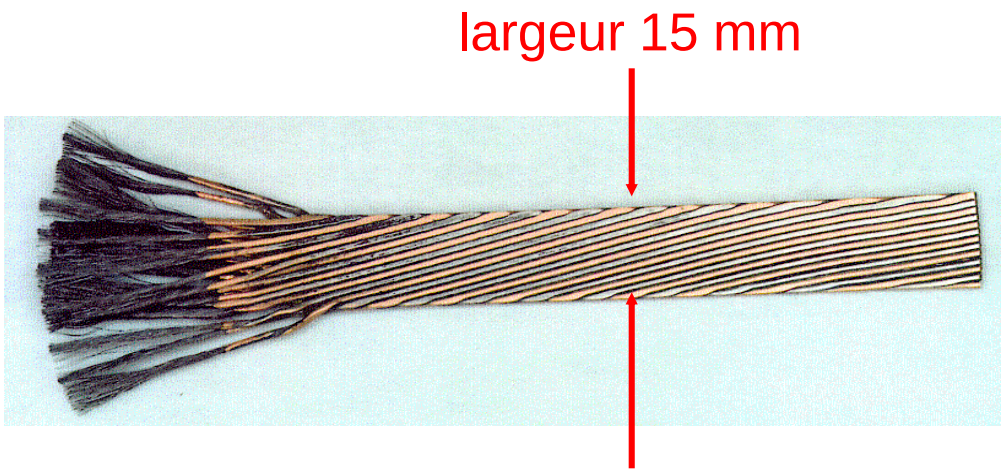
La majorité des aimants LHC fonctionnent à 1.9 K (−271,25 °C).





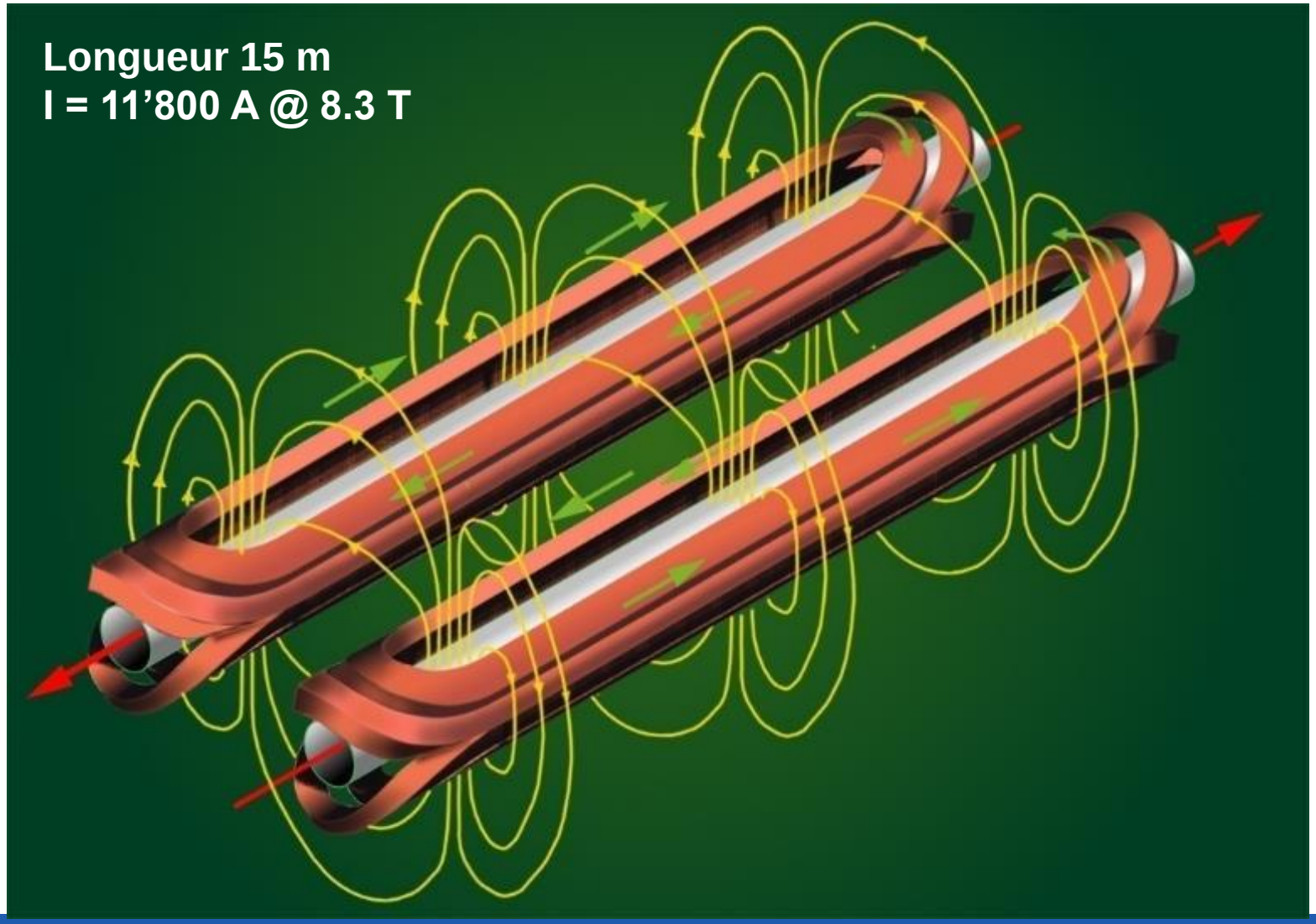
Le câble supraconducteur



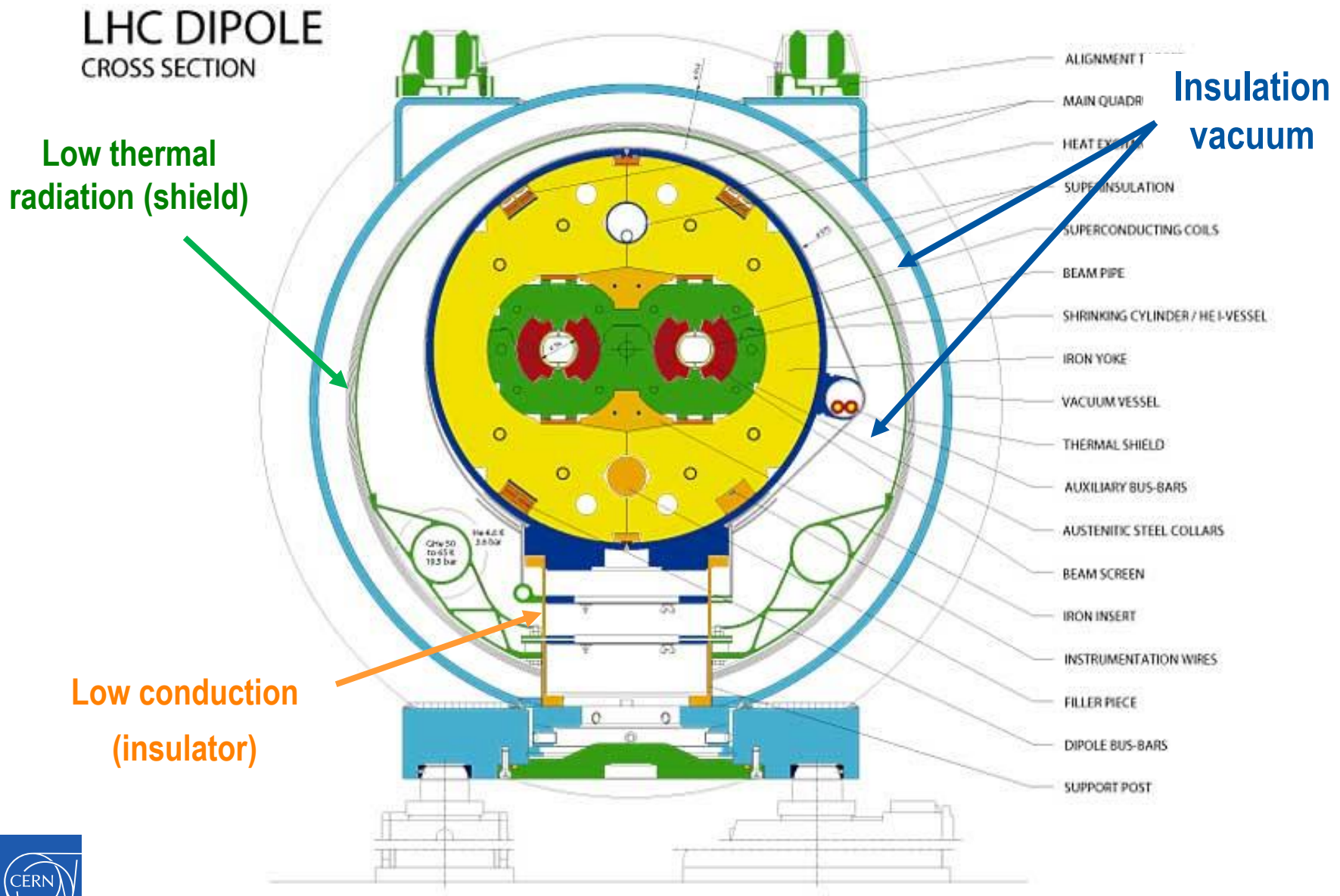


Le supraconducteur pour le LHC est un alliage de Niobium et de Titane (NbTi). Il est inséré dans une matrice de cuivre afin d'obtenir une meilleure conduction de chaleur. Les fils sont ensuite 'tressés' en câbles plats (par exemple).

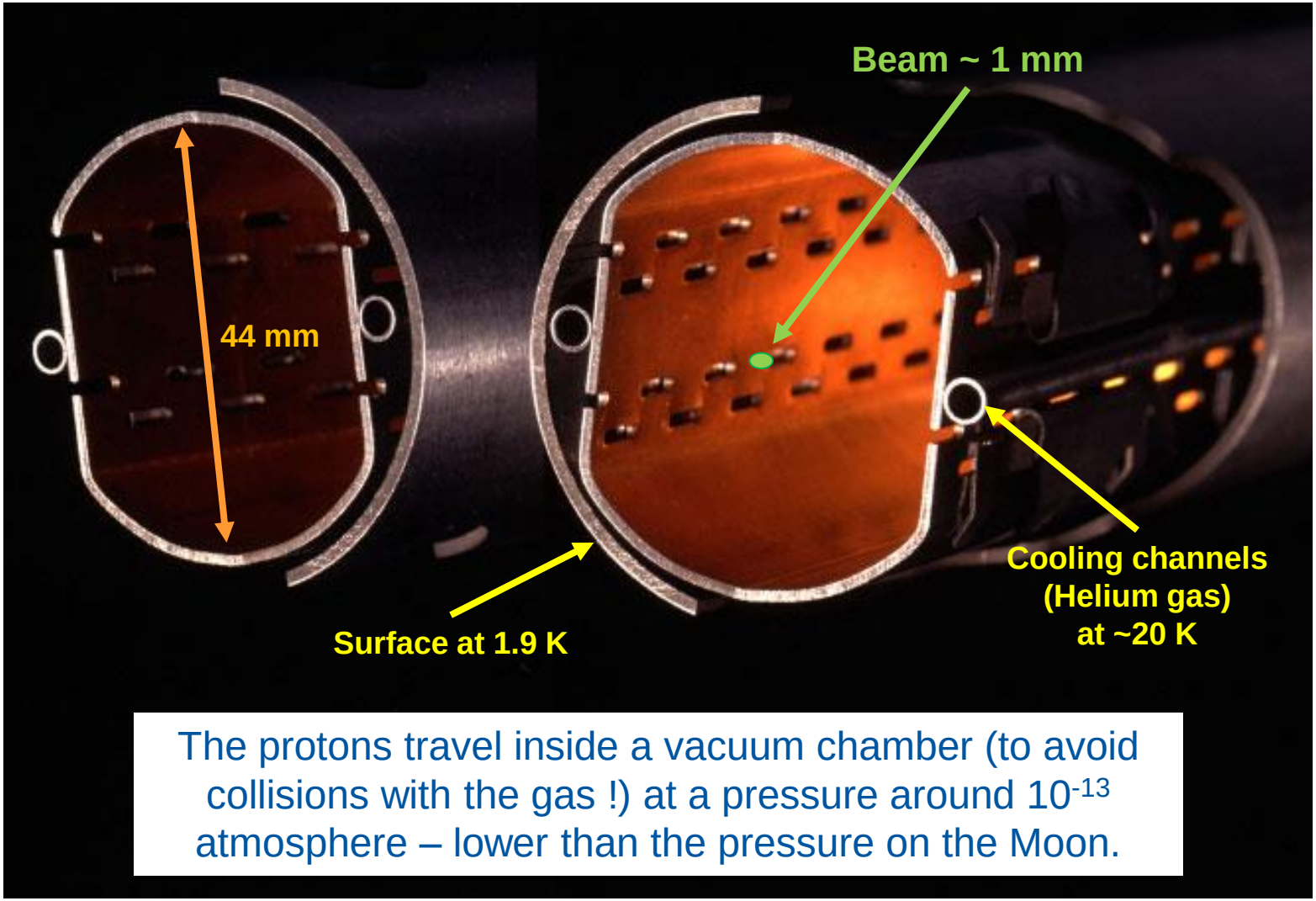
Du câble à la bobine



LHC dipole cryostat

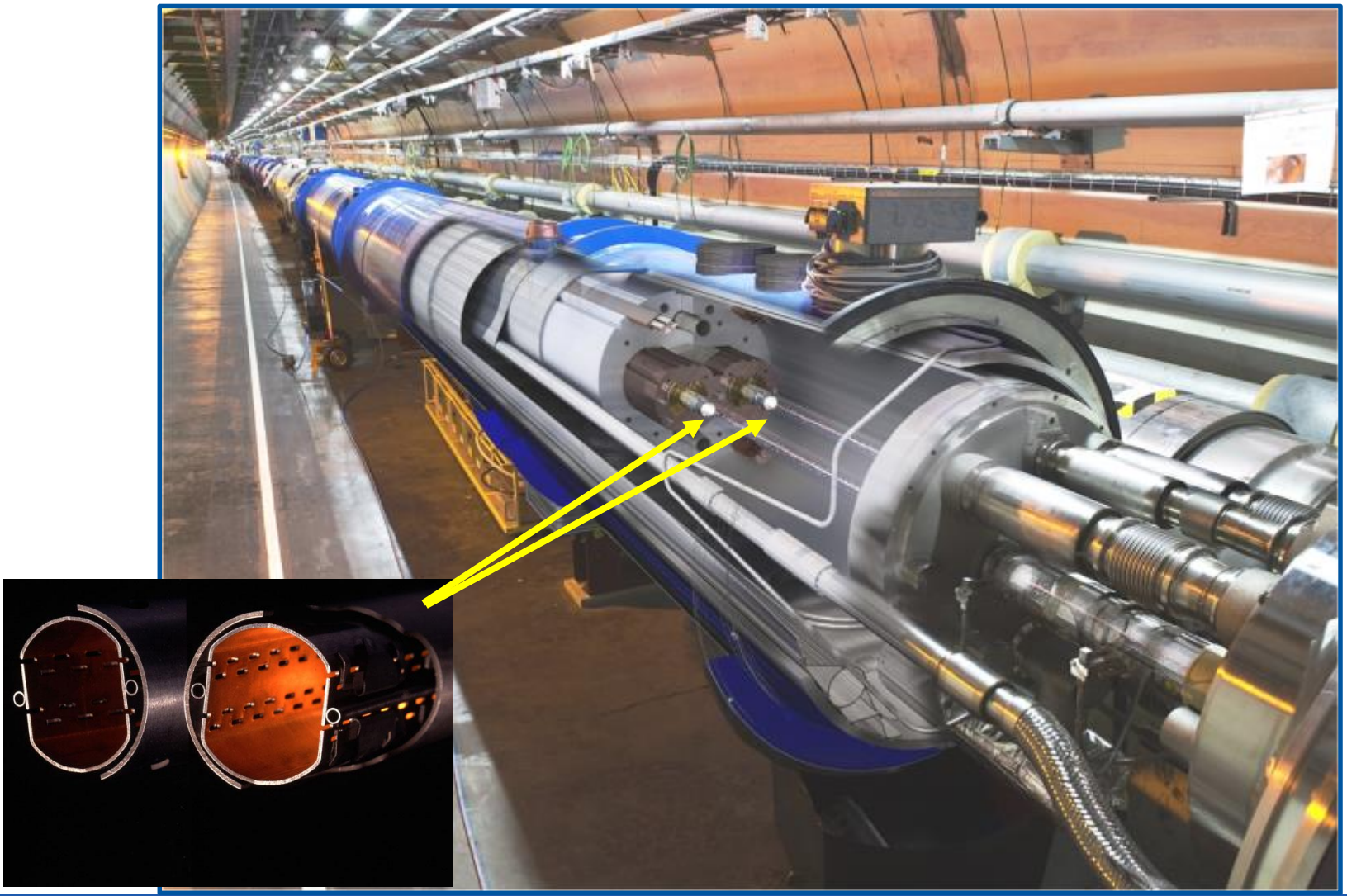


A cold and dark place



The protons travel inside a vacuum chamber (to avoid collisions with the gas !) at a pressure around 10^{-13} atmosphere – lower than the pressure on the Moon.

Where is the vacuum chamber?



Transport et installation

Chaque aimant est testé en surface et descendu dans le tunnel par un unique puit d'accès.

Le premier aimant a été descendu en Mars 2005, le dernier au printemps 2007.

Installation

Le transport dans le tunnel se fait à l'aide d'un véhicule à guidage optique.

Environ 1600 assemblages d'aimants ont été transportés sur une distance allant jusqu'à 20 km à une vitesse de 3 km/heure.

LHC beams

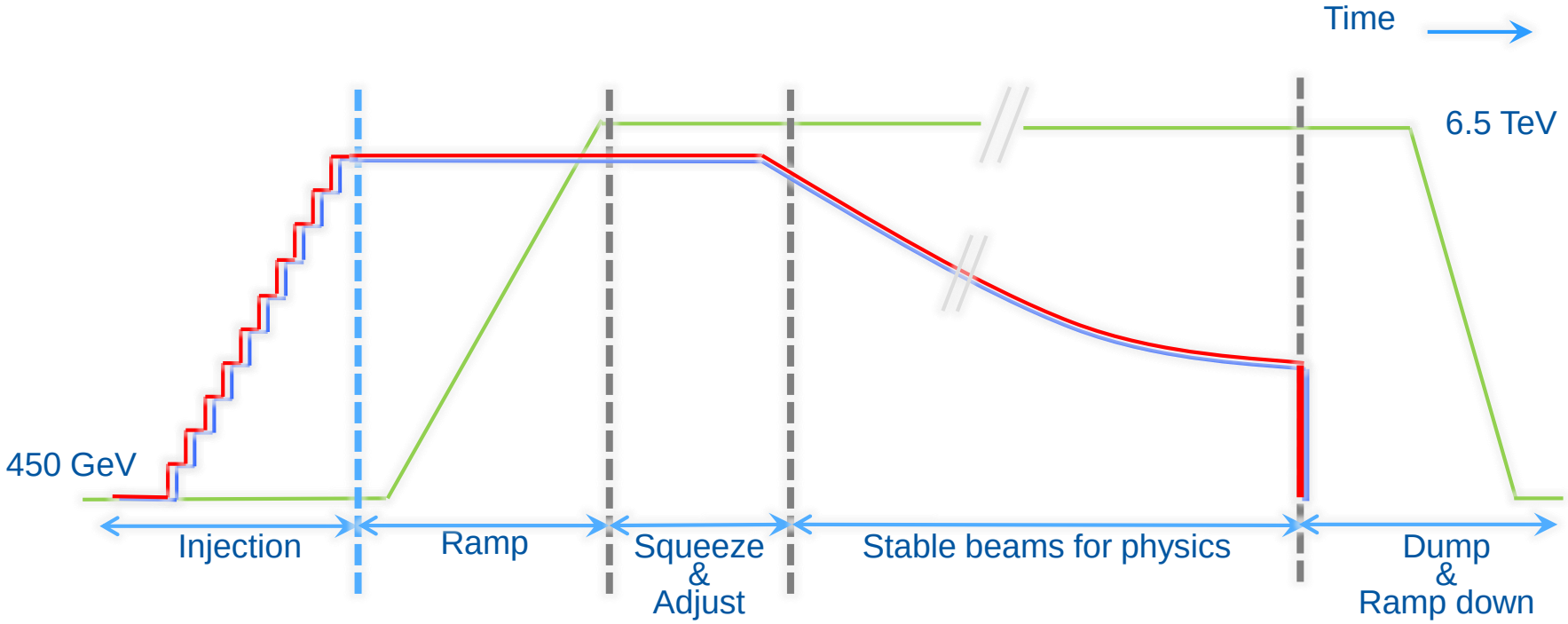
The LHC operates with 2 beams of particles that travel in opposite directions.

The protons are grouped in small packets called *'bunches*'. We operate typically with around ***2000*** bunches separated by ***7.5 m***.

Each bunch:

- is ~ *30 cm* long,
- contains up to around *140 billion* protons,
- has its width squeezed to the *size of a thin human hair* (12 micrometers) at the points where it collides with other bunches inside the experiments.

The LHC Cycle



= Field in main magnets

= Beam 1 intensity (current)

= Beam 2 intensity (current)

The LHC is built to collide protons at 7 TeV per beam.

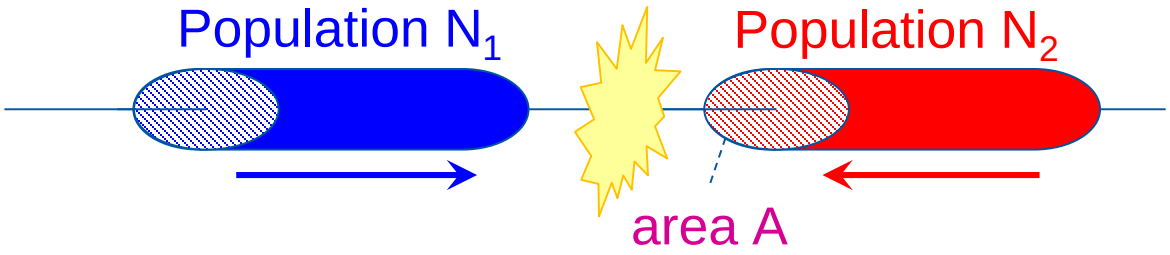
Since 2015 it operates at 6.5 TeV per beam.

Luminosity

A key parameter for the LHC experiments is the rate of events dN/dt. For a physics process with *cross-section* σ it is proprotional to the collider **Luminosity *L***:

$$dN/dt = L\sigma$$

unit of L :
1/(surface × time)



$$\text{Collision rate} \propto \sigma \times \underbrace{\frac{N1 \times N2}{A}}_{\textit{Luminosity}} \times \text{encounters/second}$$

To maximize L we are trying to squeeze as many particles as possible into the smallest possible volume !

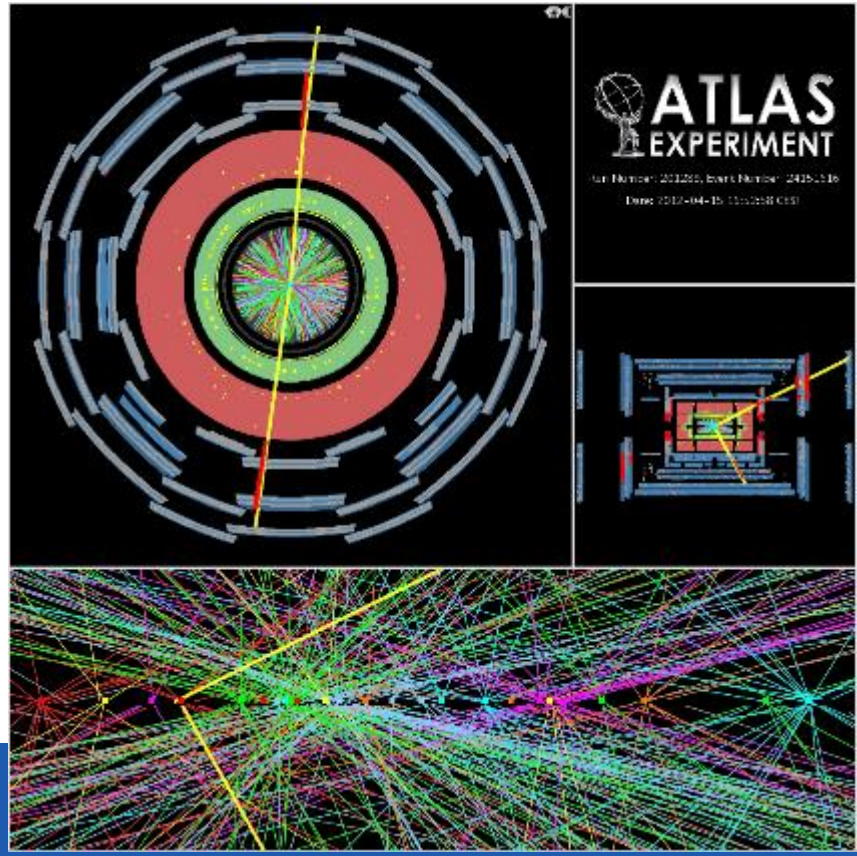
Luminosity and collision rates

At its current performance the LHC produces **1.2 billion** (**1.2×10^9**) proton-proton (pp) collisions **per second** in the ATLAS and CMS experiments.

The bunches of protons cross each other **~ 21 million times per second**.

Every time 2 bunches cross there are ~50-60 individual pp collisions happening at the same time.

The experiments have to filter in real time this huge data stream for interesting physics. They can only store ~1000 out of the 21 million collisions.

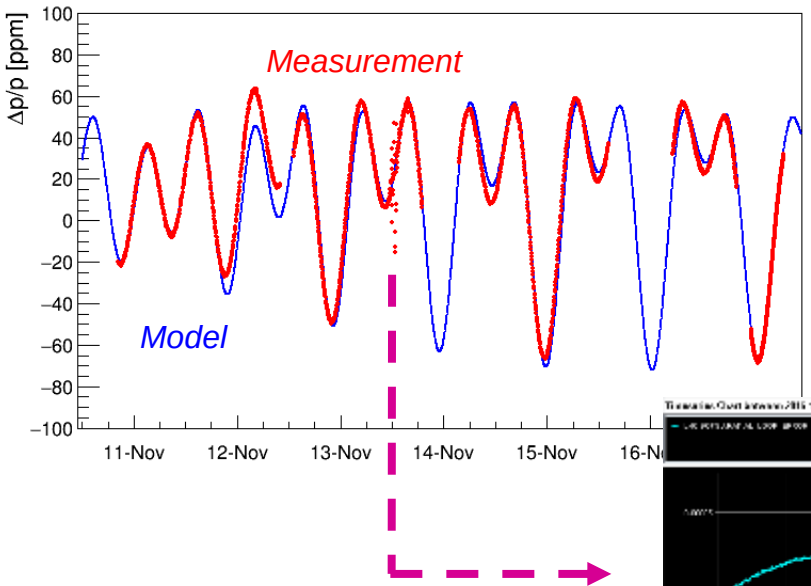


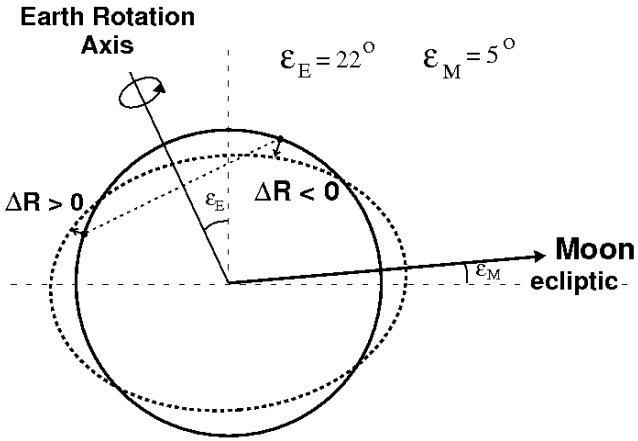
Gravity matters !

The **tide** bulge due to Moon & Sun induces LHC circumference changes of **~1 mm**.

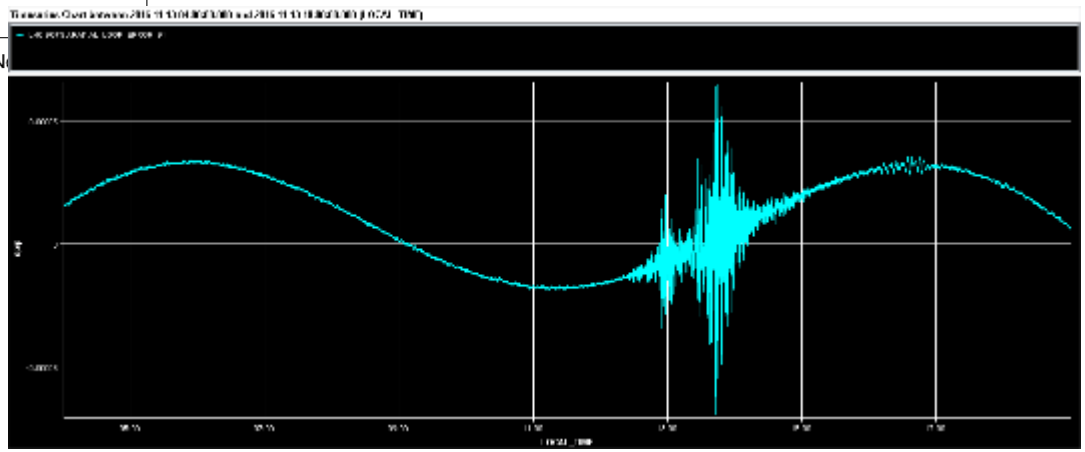
$$\Delta R \propto \frac{M}{2d^3}(3\cos^2\theta - 1)$$

Tide observations at the LHC





Earthquake in New Zealand

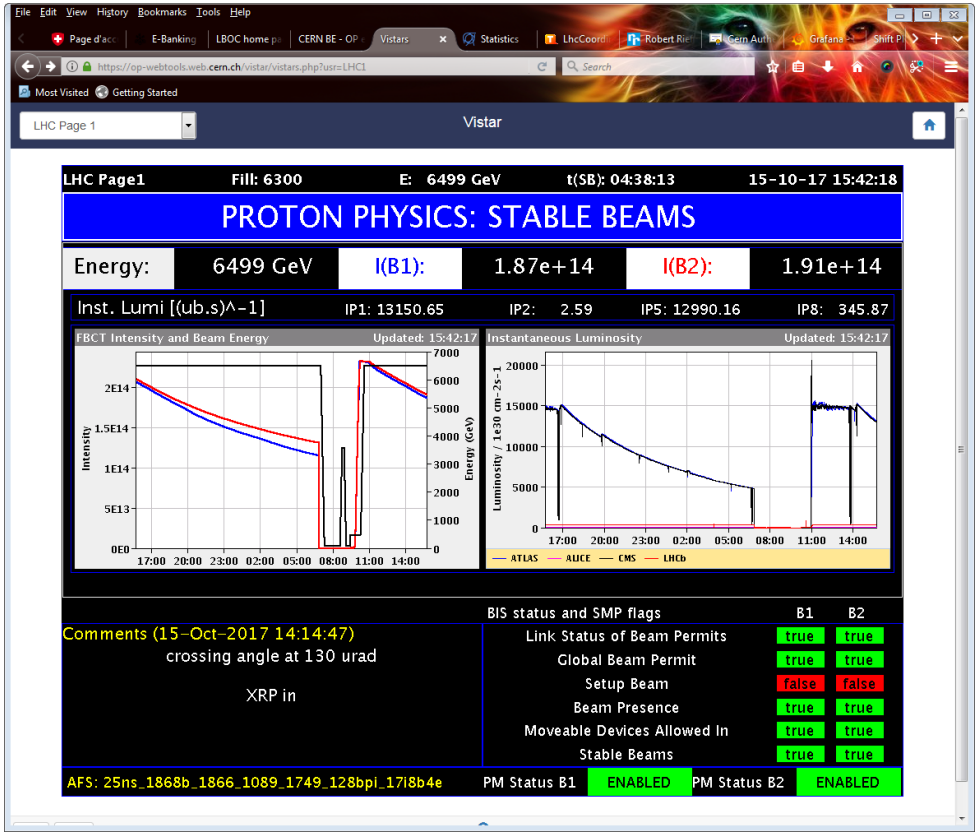


The pressure waves induce a modulation of the LHC circumference

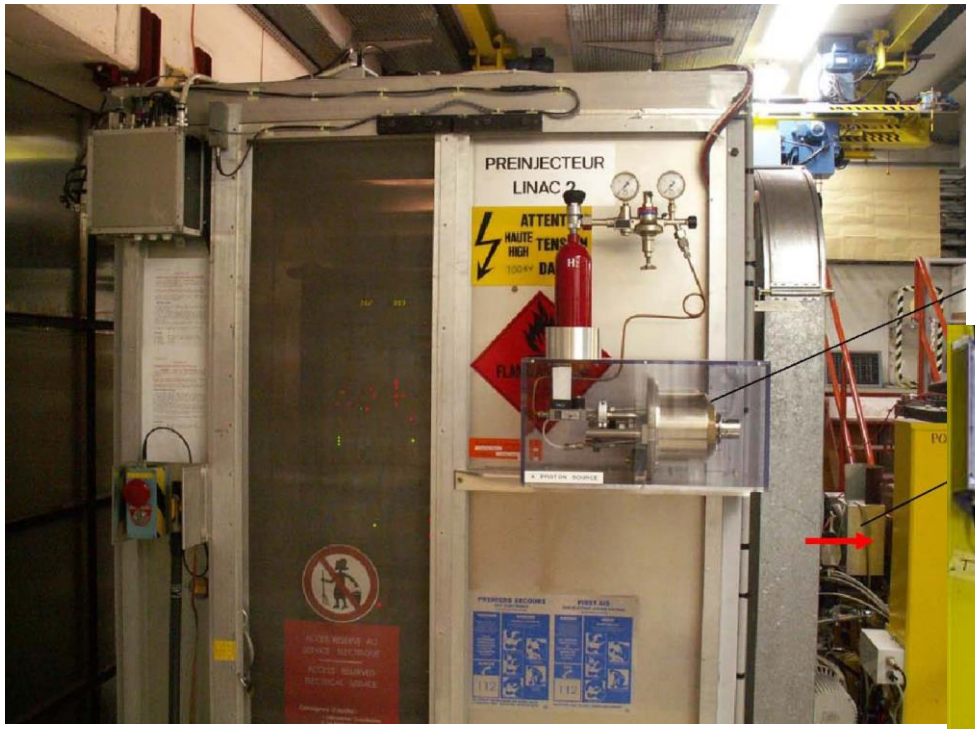
Follow us

At the link: https://op-webtools.web.cern.ch/vistar/

You can follow the status and performance of the entire CERN accelerator chain, for the LHC : **LHC Page1**



LINAC 2



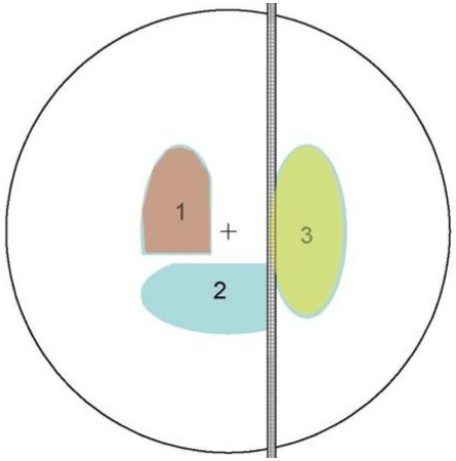
- Source extracts protons at 90 keV from H_2

- Accelerates beam up to 50 MeV over a length of 33m.
- Provides a beam pulse every 1.2s

PS Booster

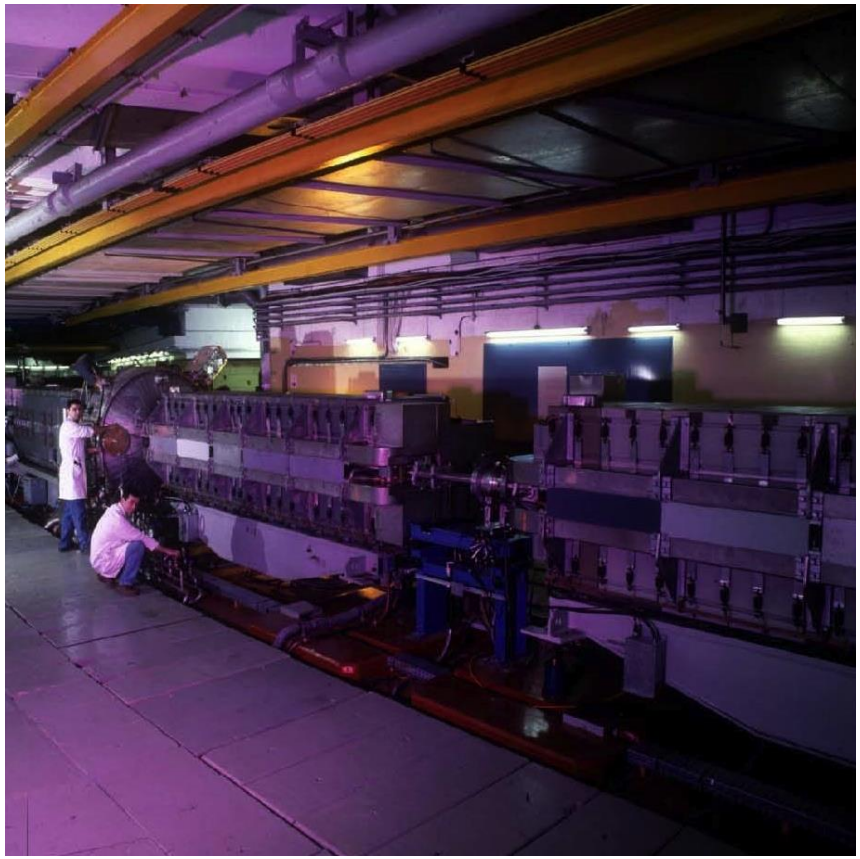
- 1st Synchrotron in the chain with 4 superposed rings
- Circumference of 157m
- Increases proton energy from 50 MeV to 1.4 GeV in 1.2s

- The LINAC2 beam pulse is distributed over the four rings, using fast kicker magnets
- Each ring will inject over multiple turns, accumulating beam

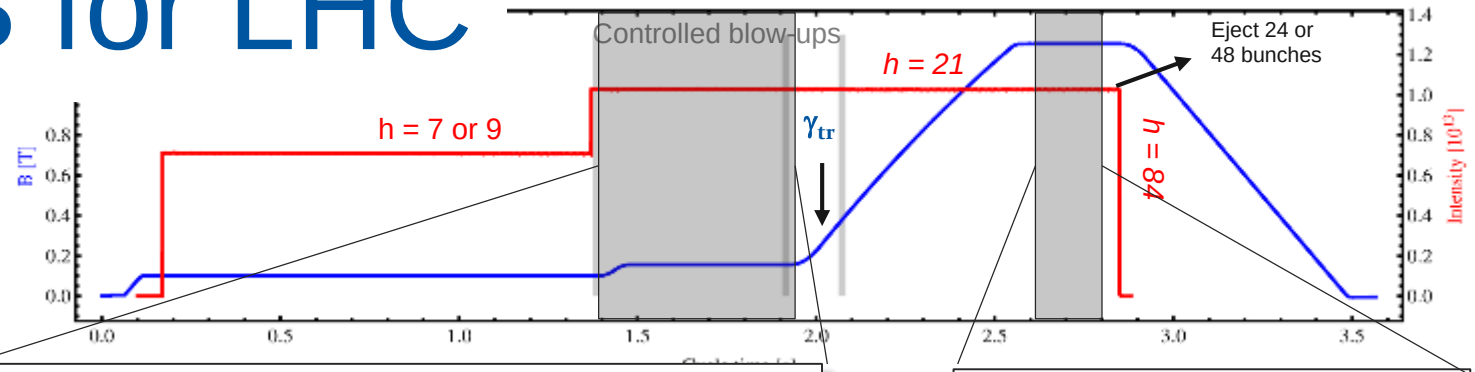


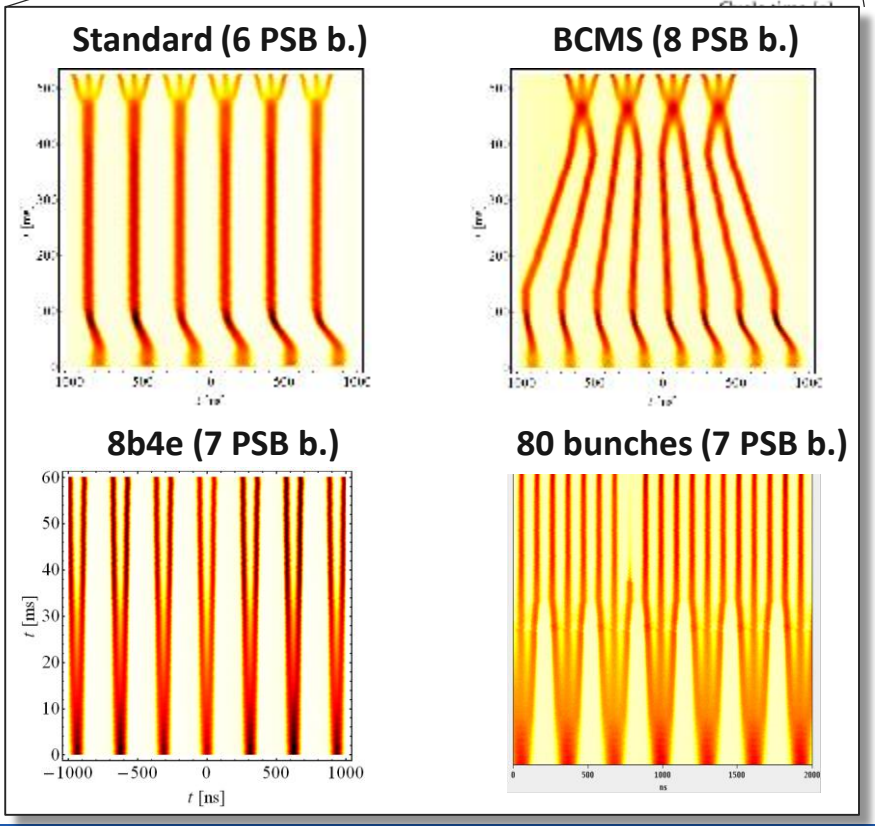
PS

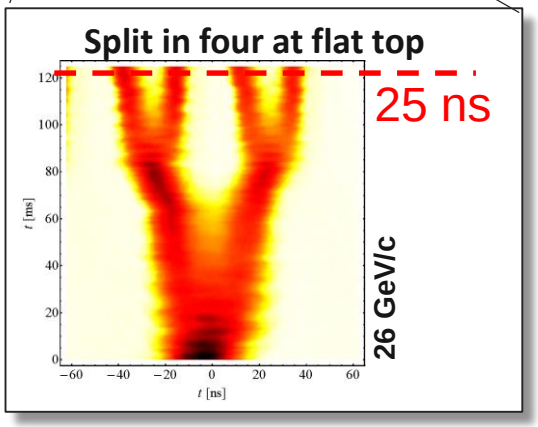
- The oldest operating synchrotron at CERN
- Circumference of 628m
  - 4 x PSB circumference
- Increases proton energy from 1.4 GeV to a range of energies up to 26 GeV
- Cycle length varies depending on the final energy, but ranges from 1.2s to 3.6s



PS for LHC







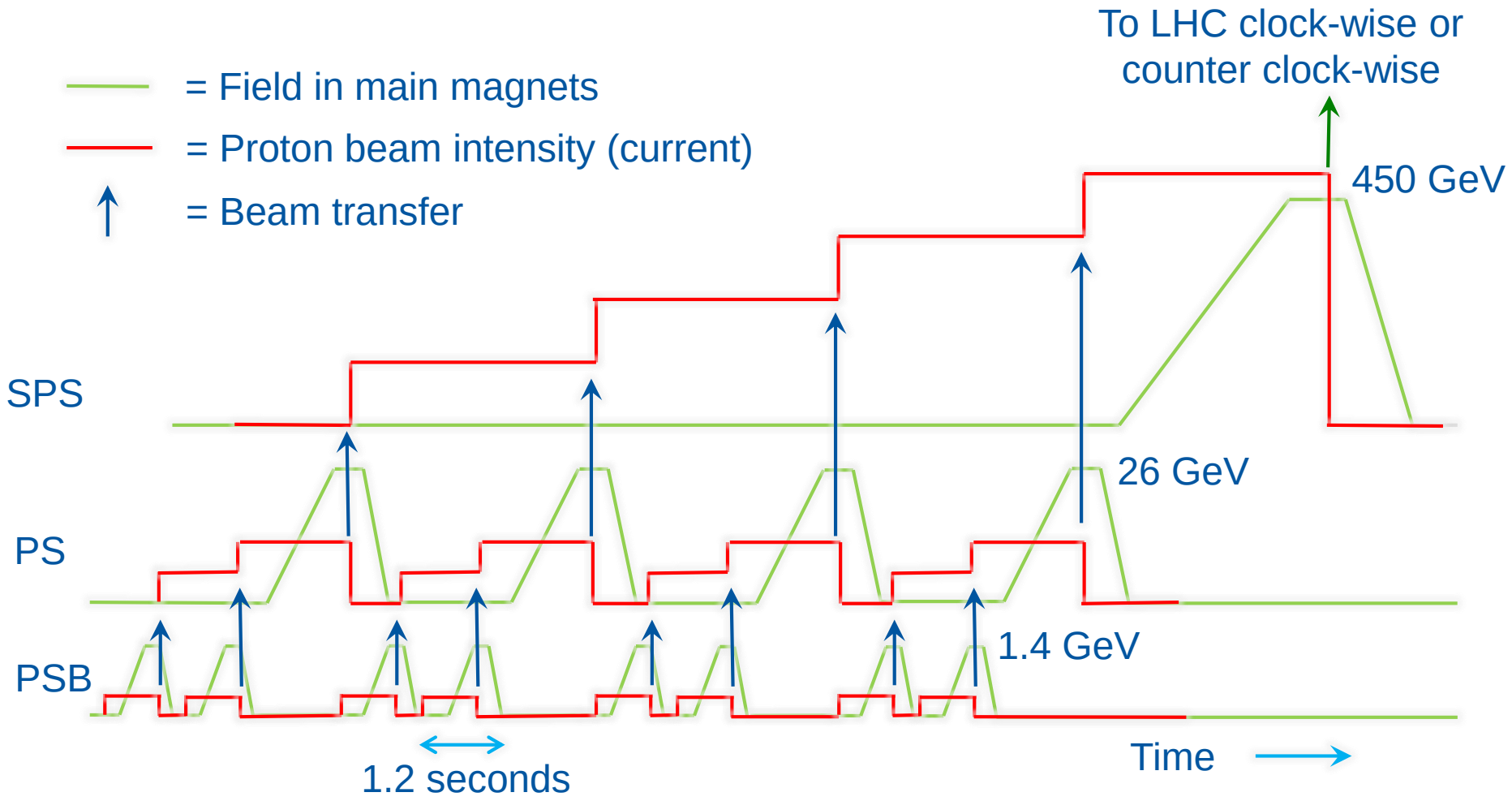
Standard: 72 bunches @ 25 ns
BCMS: 48 bunches @ 25 ns

The PS defines the longitudinal beam characteristics

SPS

- The first synchrotron in the chain at about 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

Filling the LHC and Satisfying Fixed Target users



Very large colliders