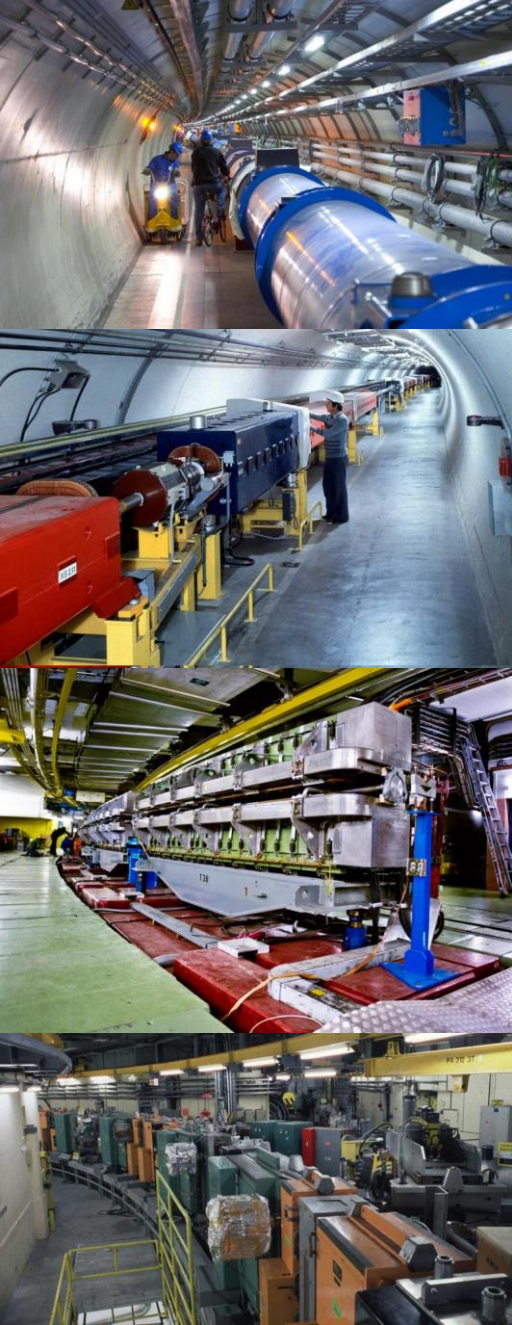




Introduction to Particle Accelerators for the CERN-Solvay Student Camp

Rende Steerenberg – BE/OP

2 October 2023



Content

Why Accelerators & Colliders?

The CERN Accelerator Complex

An Accelerator's Main Ingredients

A Brief Word on the Future



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**What is the first physics
formula that jumps in your
mind?**

$$E = M c^2$$

This is the most famous equation of twentieth- century physics.

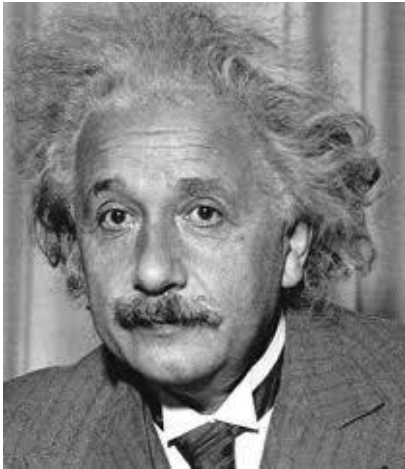
It is a statement that mass and energy are two forms of the same thing, and that one can be converted into the other.

In our accelerator we add **Energy to the particle through our RF systems and observe the **M**ass created in the experiments.**

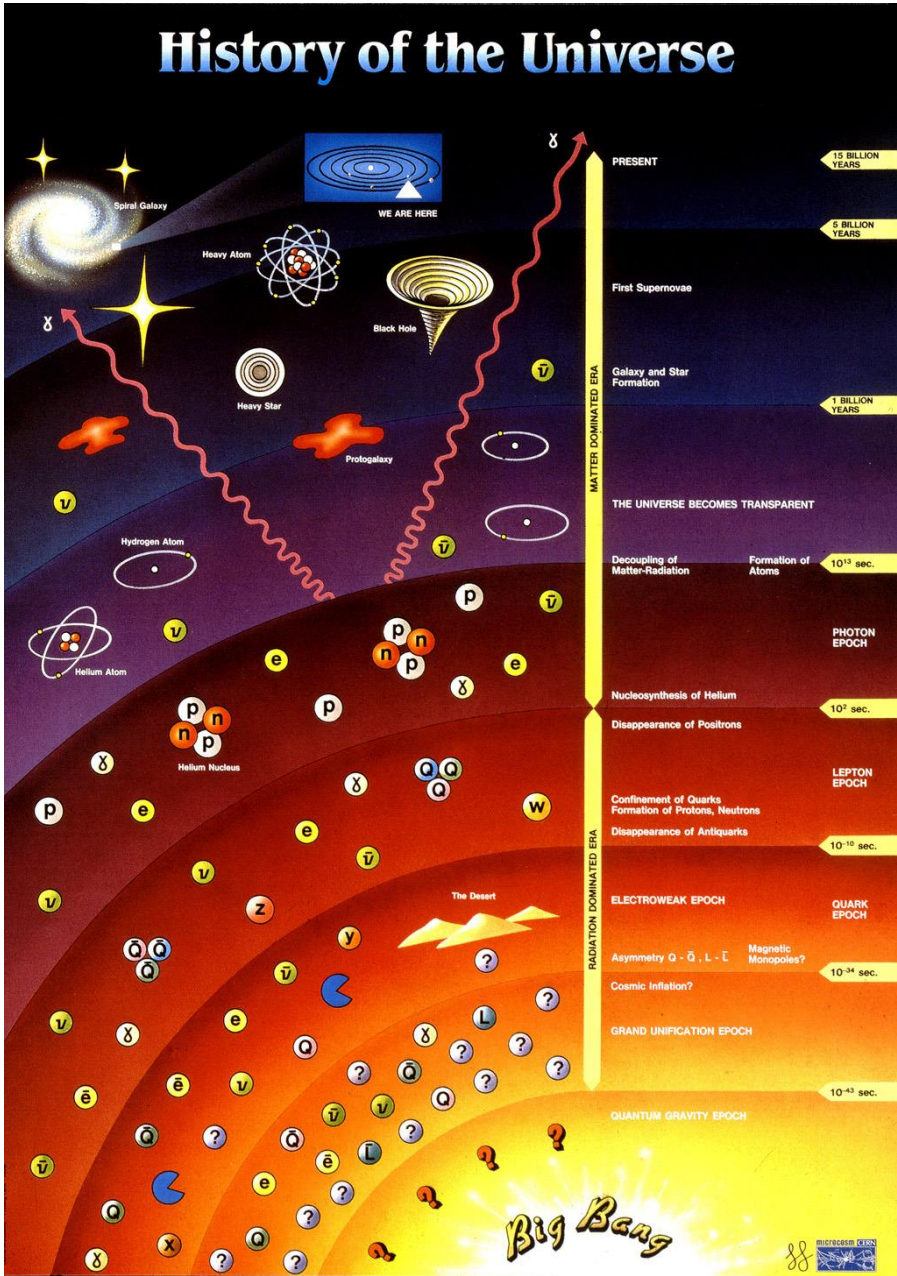
Creating Matter from Energy

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

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

$\lambda = 400 \rightarrow 700 \text{ nm}$



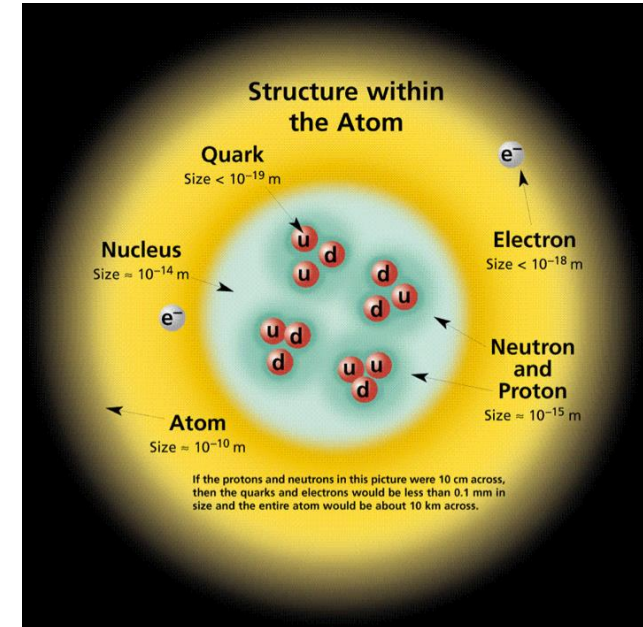
X-ray

$\lambda = 0.01 \rightarrow 10 \text{ nm}$



Particle accelerators

$\lambda < 0.01 \text{ nm}$



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

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

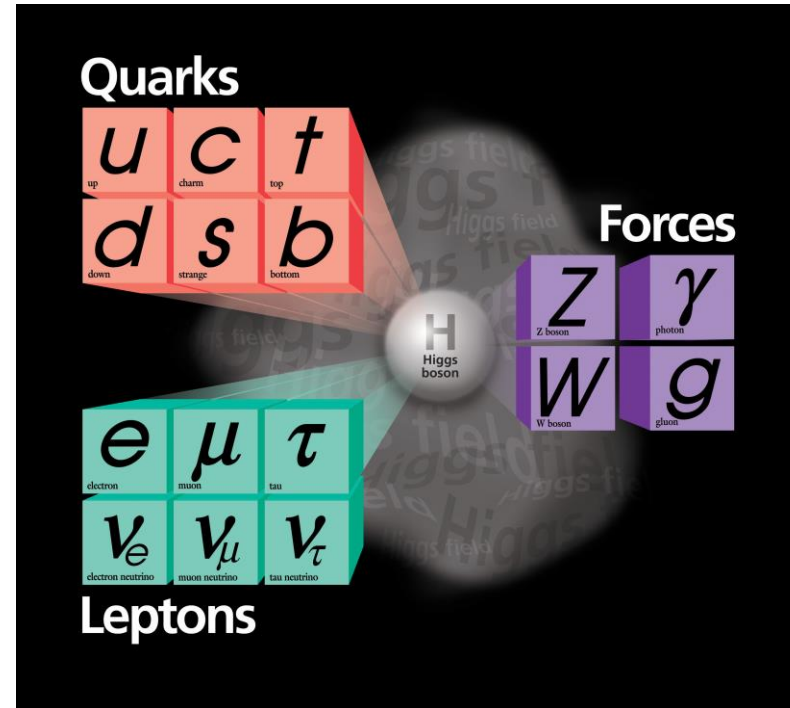


$$E = E_{beam1} + E_{beam2}$$

All energy will be available for particle production

The Aim:

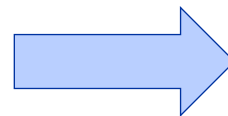
Specific assemblies of quarks
form hadrons.
Protons, Neutrons, pions,..



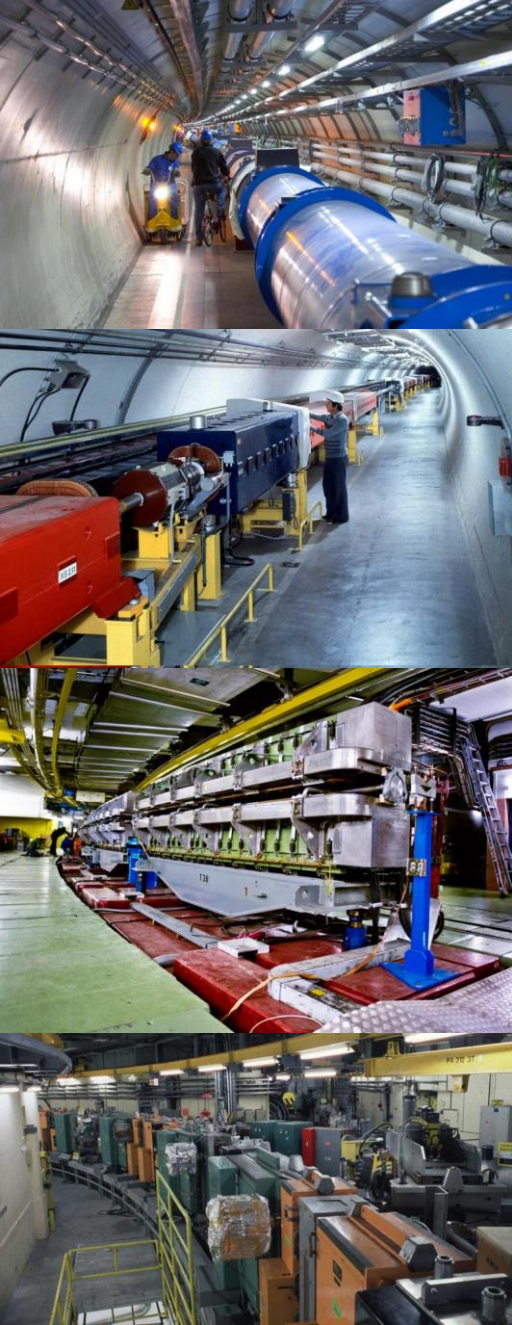
Gravitational force
Electromagnetic force
Strong interacting force
Weak interacting force

For every particle there is a
corresponding anti-particle

Verify the Standard
Model



Search for physics beyond
the Standard Model



Content

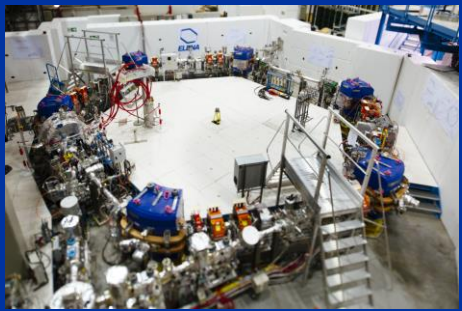
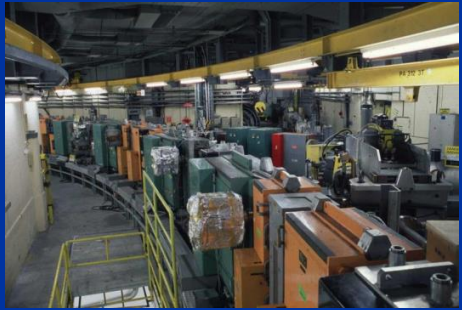
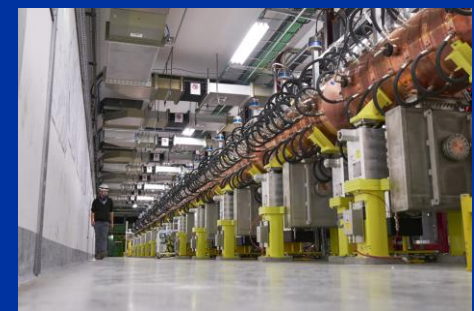
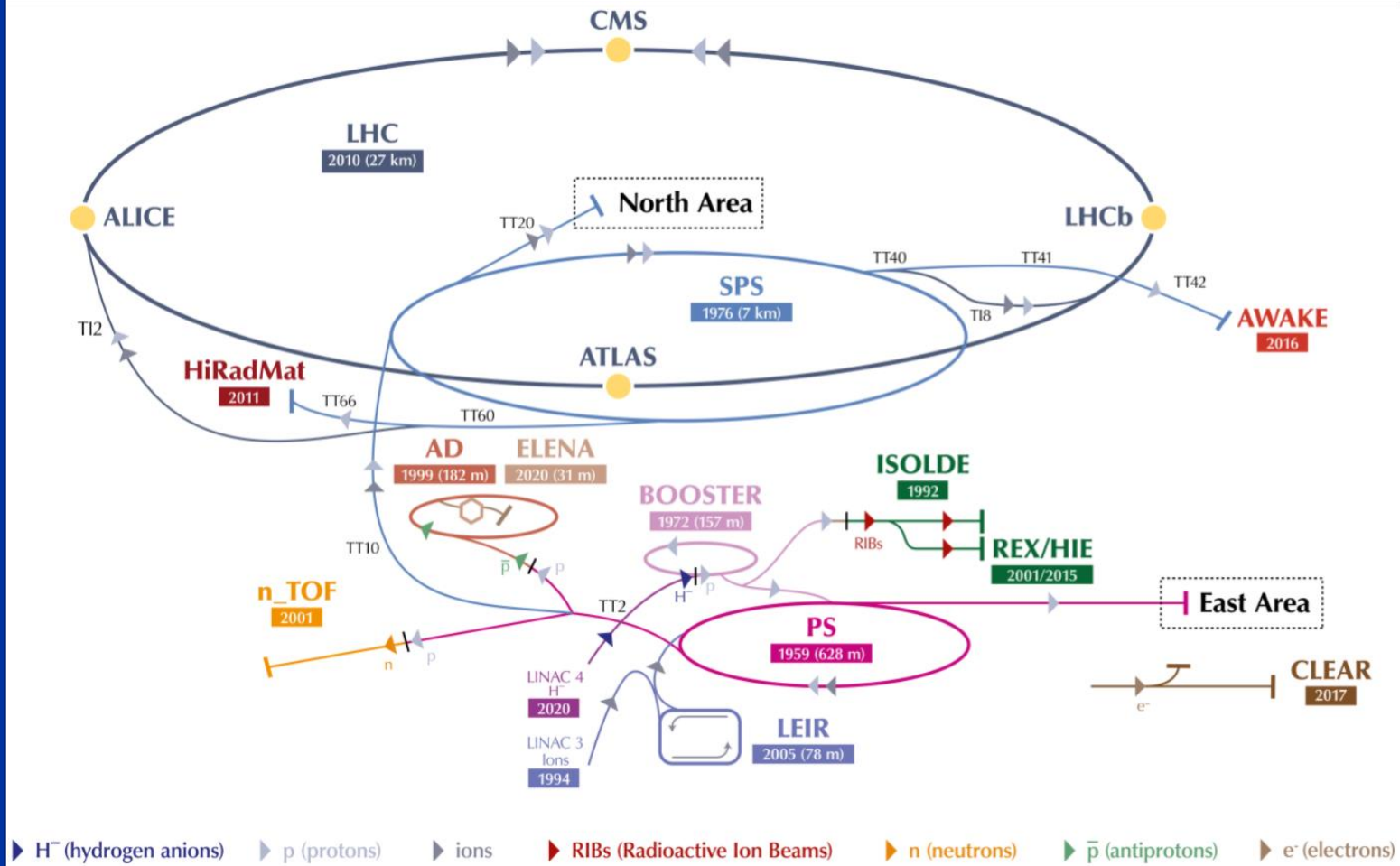
Why Accelerators & Colliders?

The CERN Accelerator Complex

An Accelerator's Main Ingredients

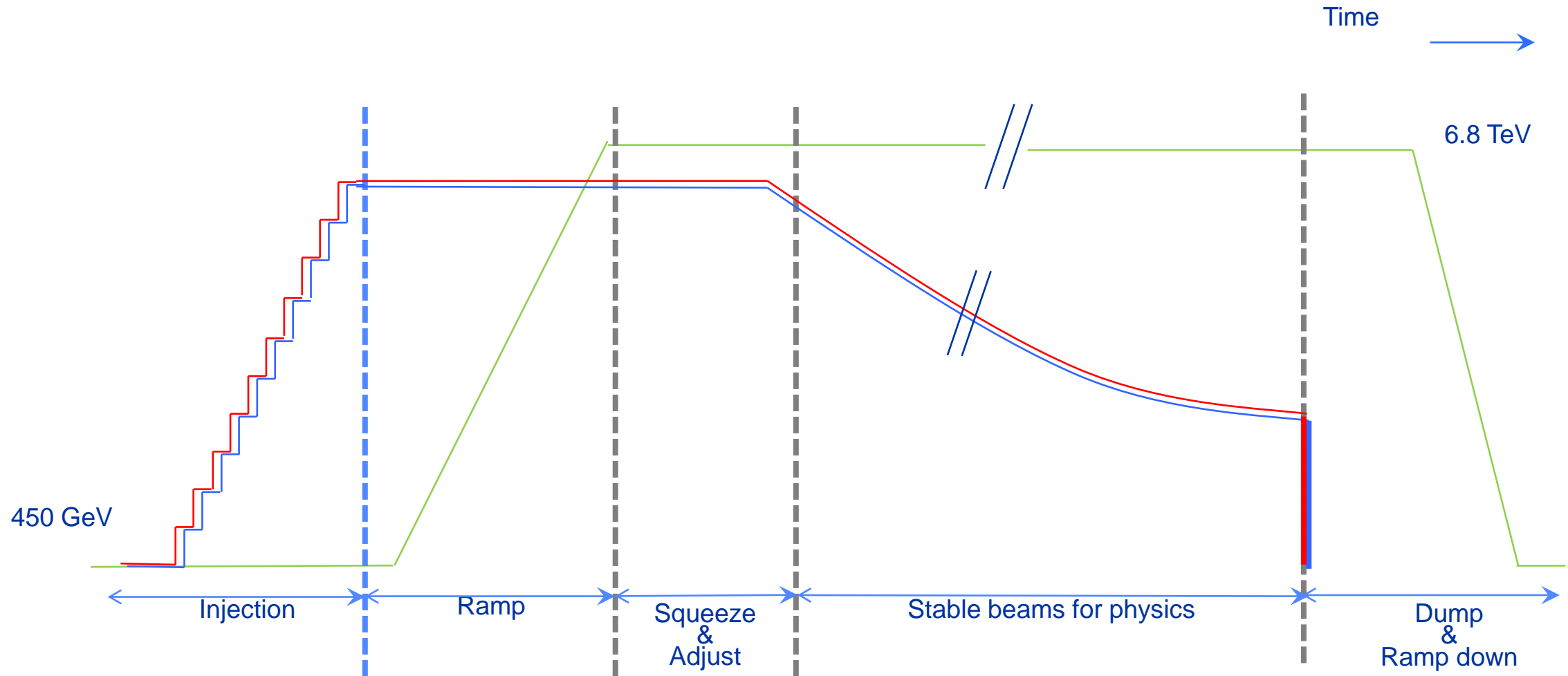
A Brief Word on the Future

The CERN Accelerator Complex

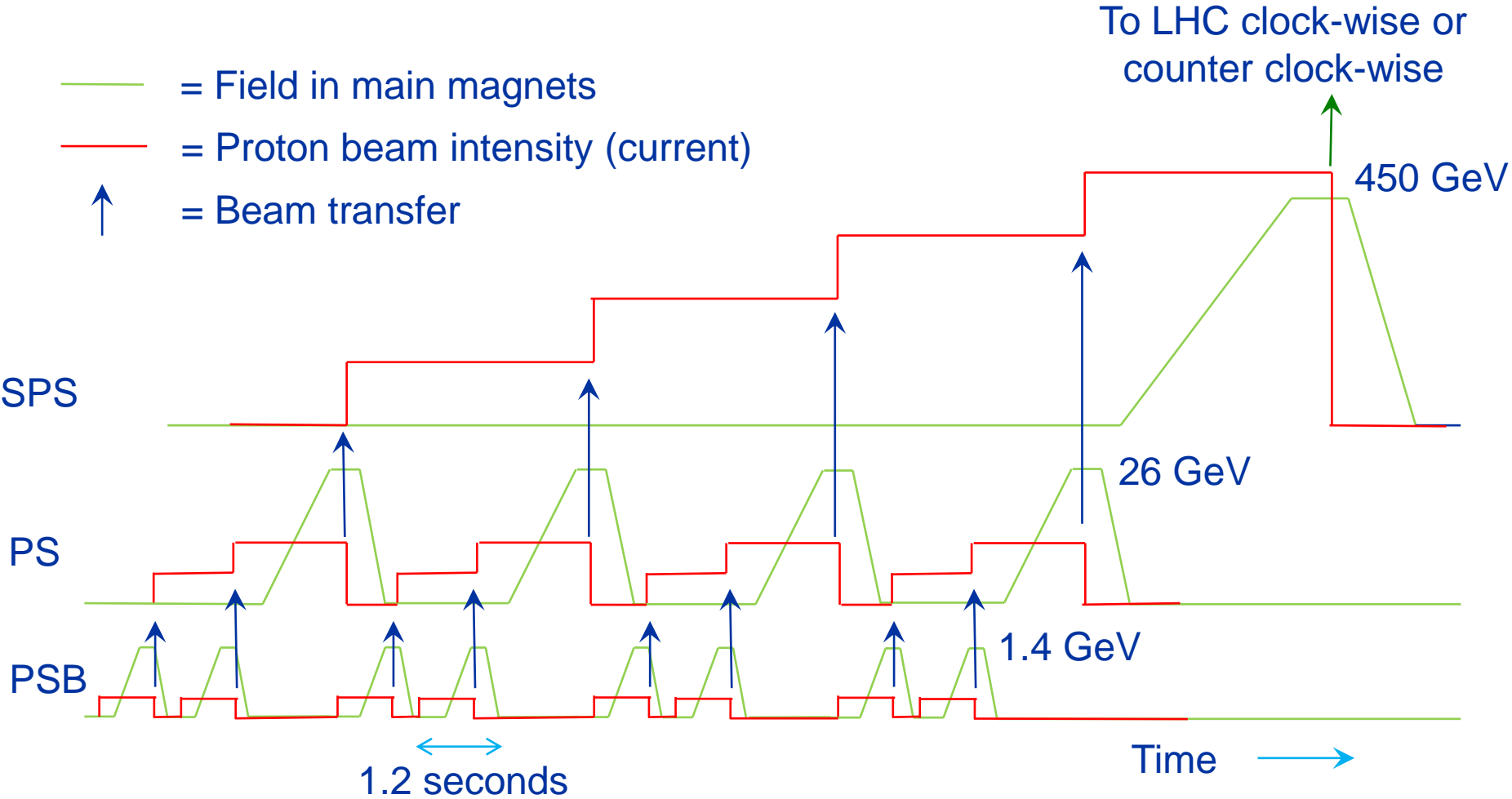


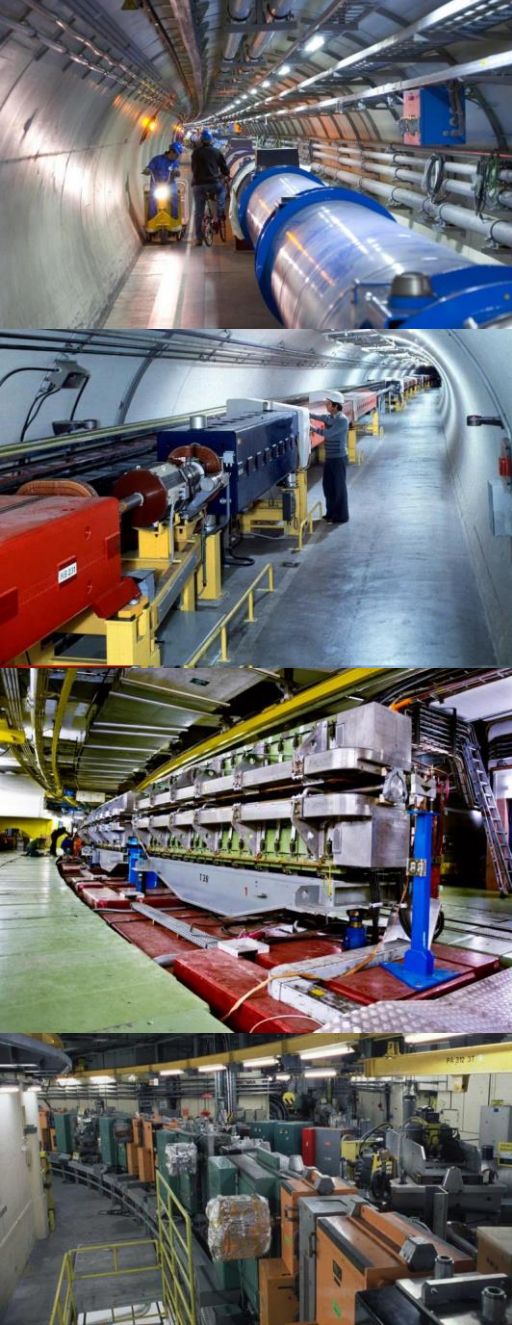
The LHC Cycle

- = Field in main magnets
- = Beam 1 intensity (current)
- = Beam 2 intensity (current)



Filling the LHC & Satisfying Fixed Target users





Content

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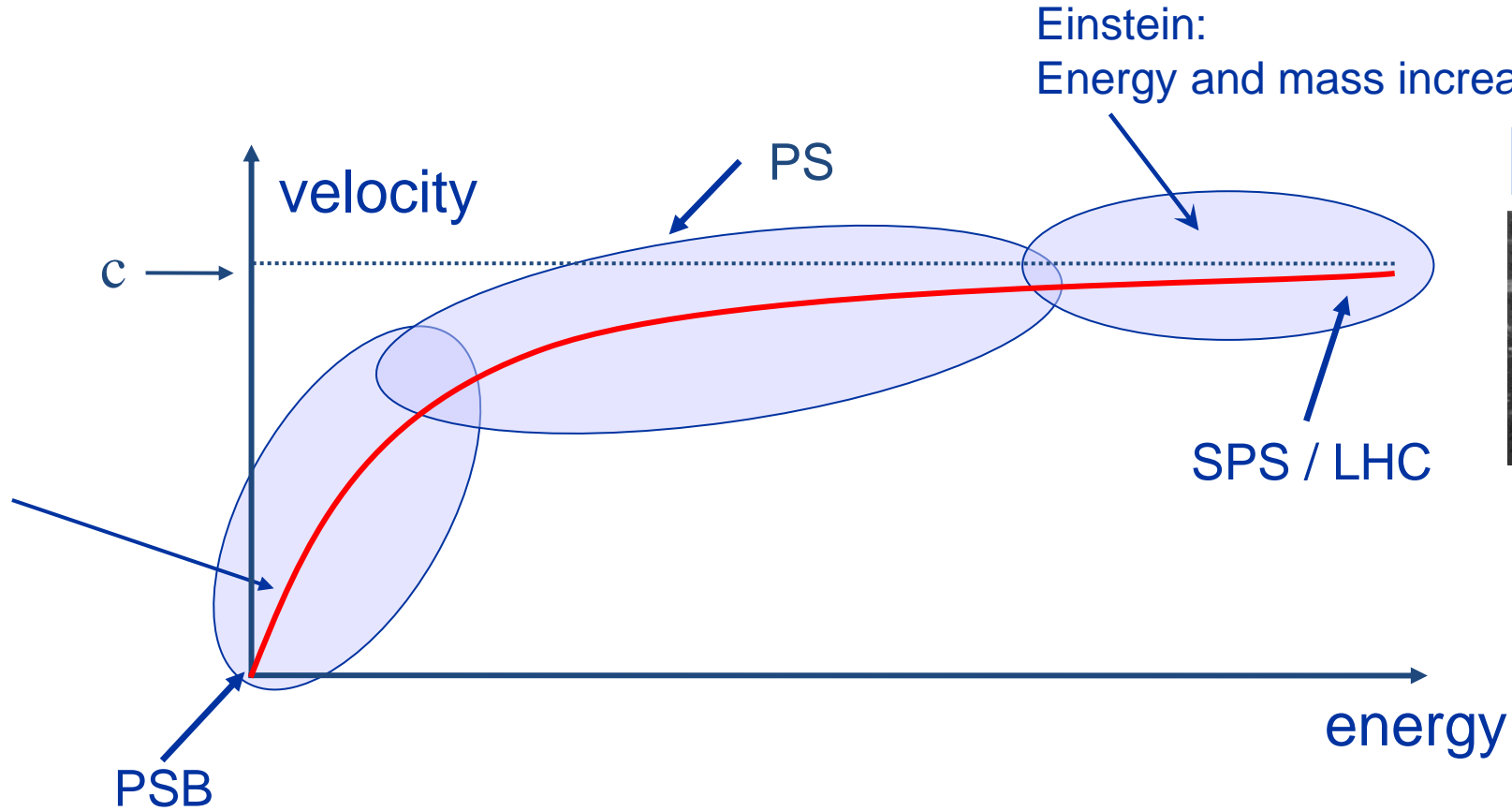
A Brief Word on the Future

What does “Relativity” in an accelerator mean for you?

Towards Relativity...

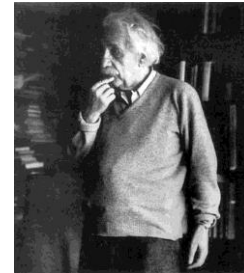
Newton:

$$E = \frac{1}{2}mv^2$$



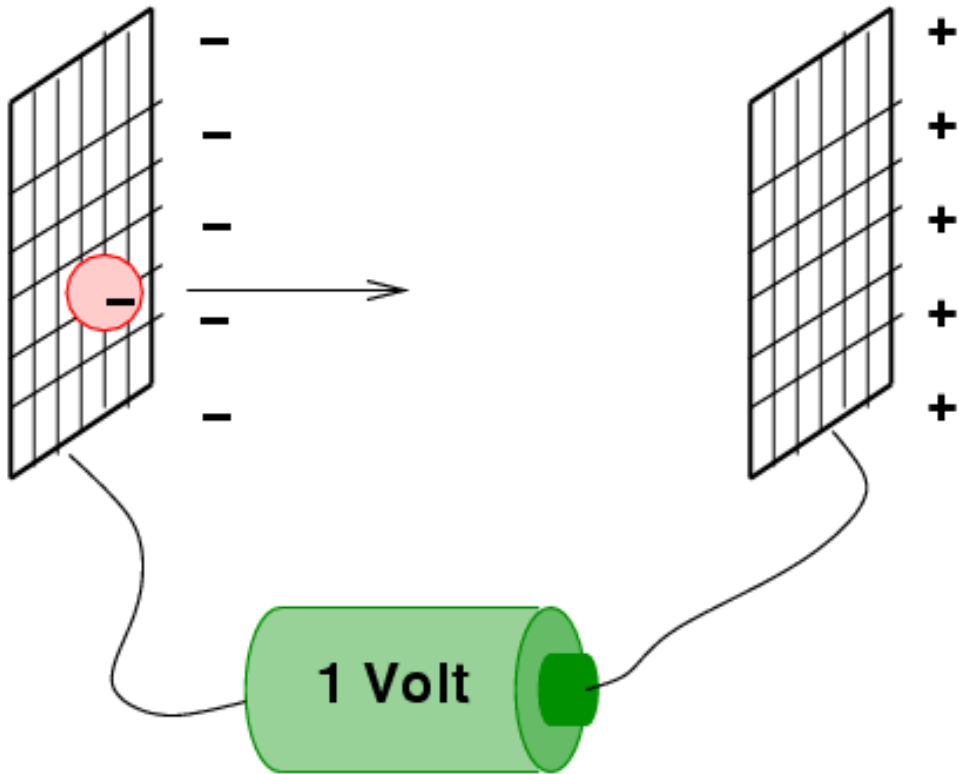
Einstein:
Energy and mass increase not much velocity

$$E = mc^2$$



What units for energy do you know?

The Units we use for Energy in Accelerators



- The energy acquired by an **electron** in a potential of **1 Volts** is defined as being **1 eV**
- Thus **1 eV = 1.6 x 10⁻¹⁹ Joules**
- The unit eV is too small to be used today, we use:
1 KeV = 10³, MeV = 10⁶, GeV = 10⁹, TeV = 10¹²

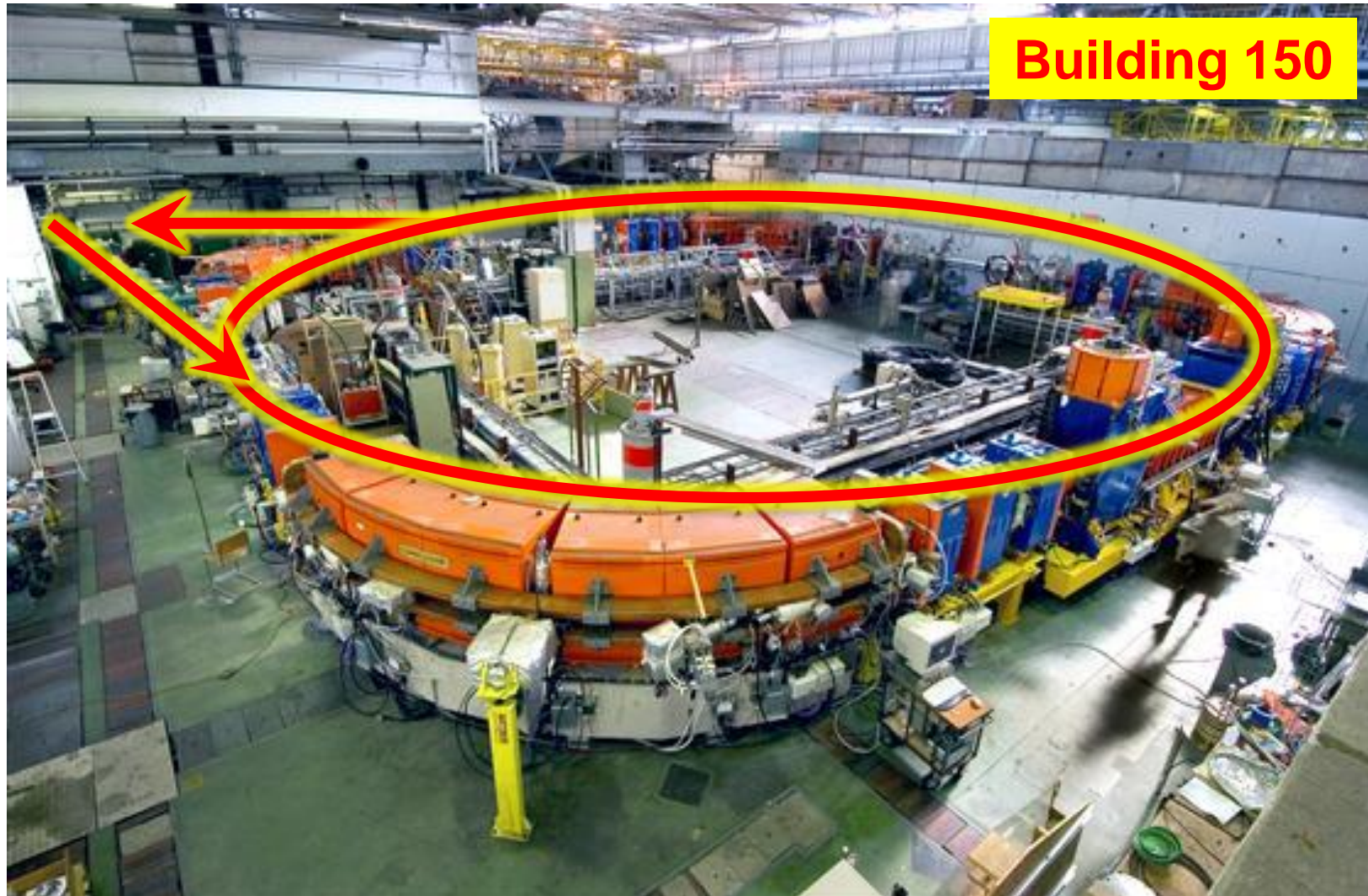
The Energy in the LHC beam

- The energy in one LHC beam at high energy is about 320 Million Joules
- This corresponds to the energy of a TGV train going at 150 km/h



..... but then concentrated in the size of a needle

The LEIR Accelerator as Example



Travelling through nothingness



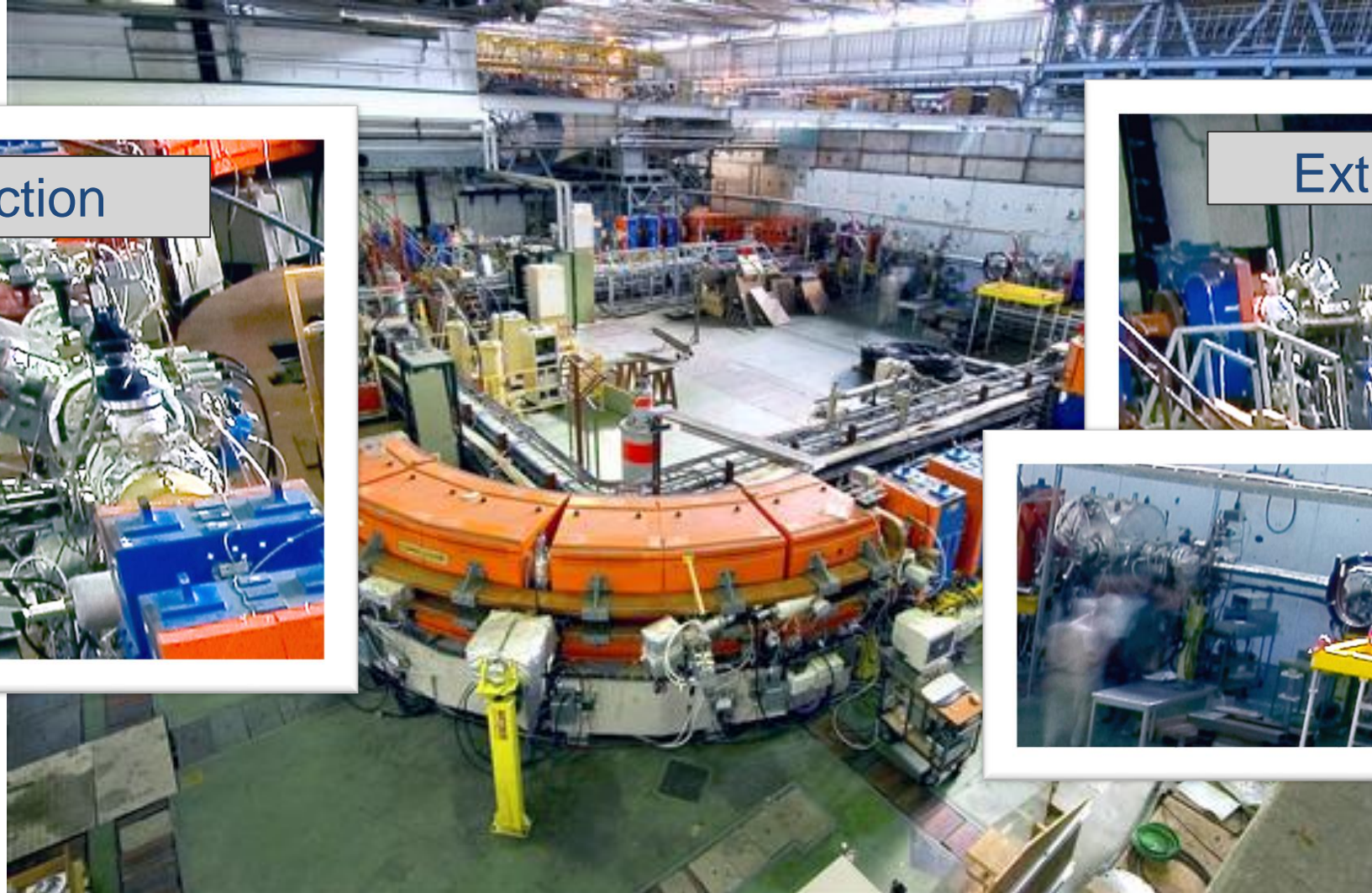
Vacuum in a mostly **stainless steel vacuum chamber** is required to **avoid** the particles to **interact** with the **gas molecules**

Especially important for low energy particles and anti-matter particles, but also for colliders

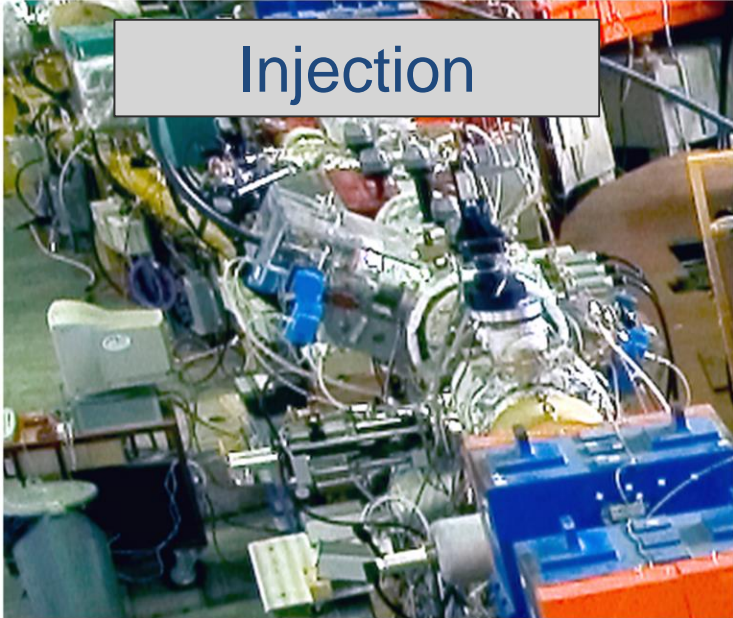


In the LHC vacuum is also used as **thermal insulator**

Injecting & Extracting Particles



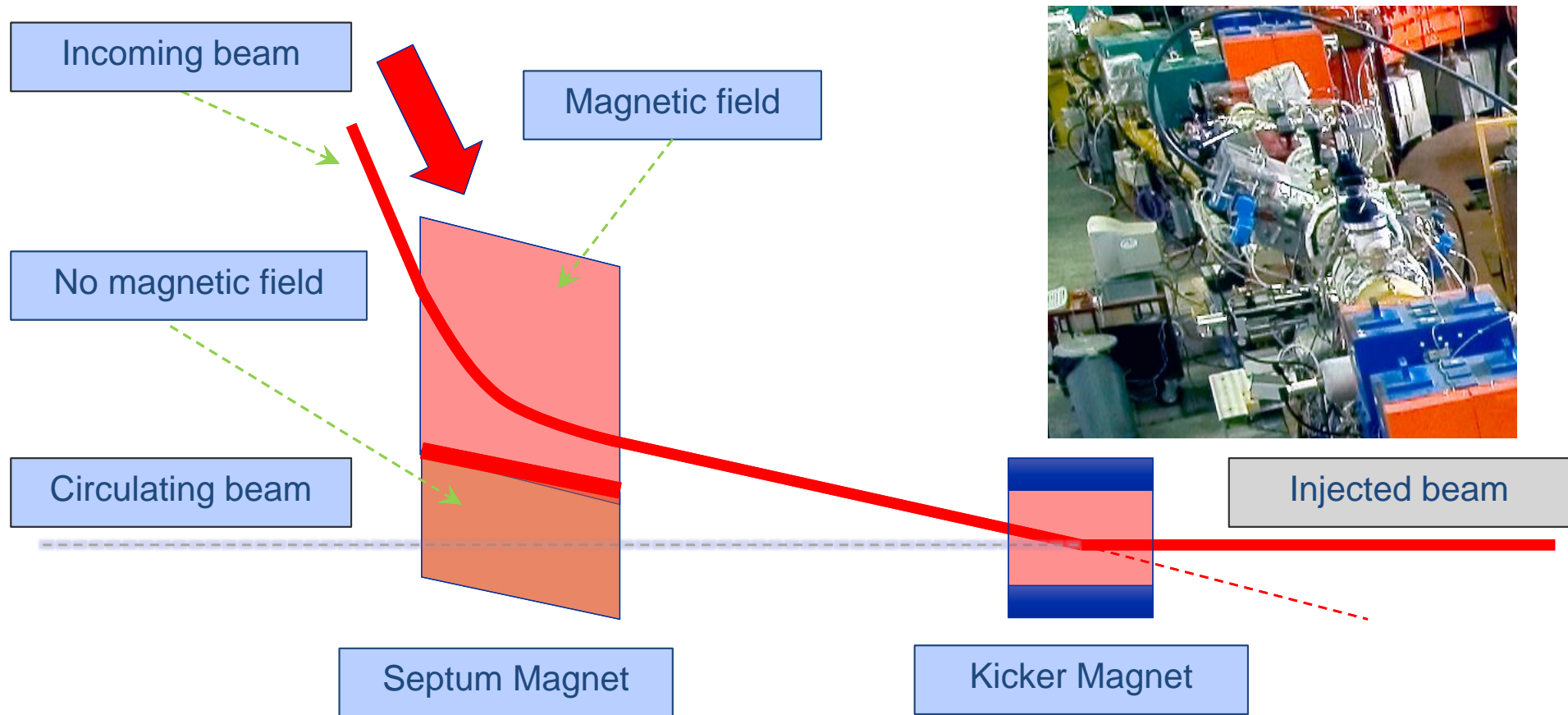
Injection



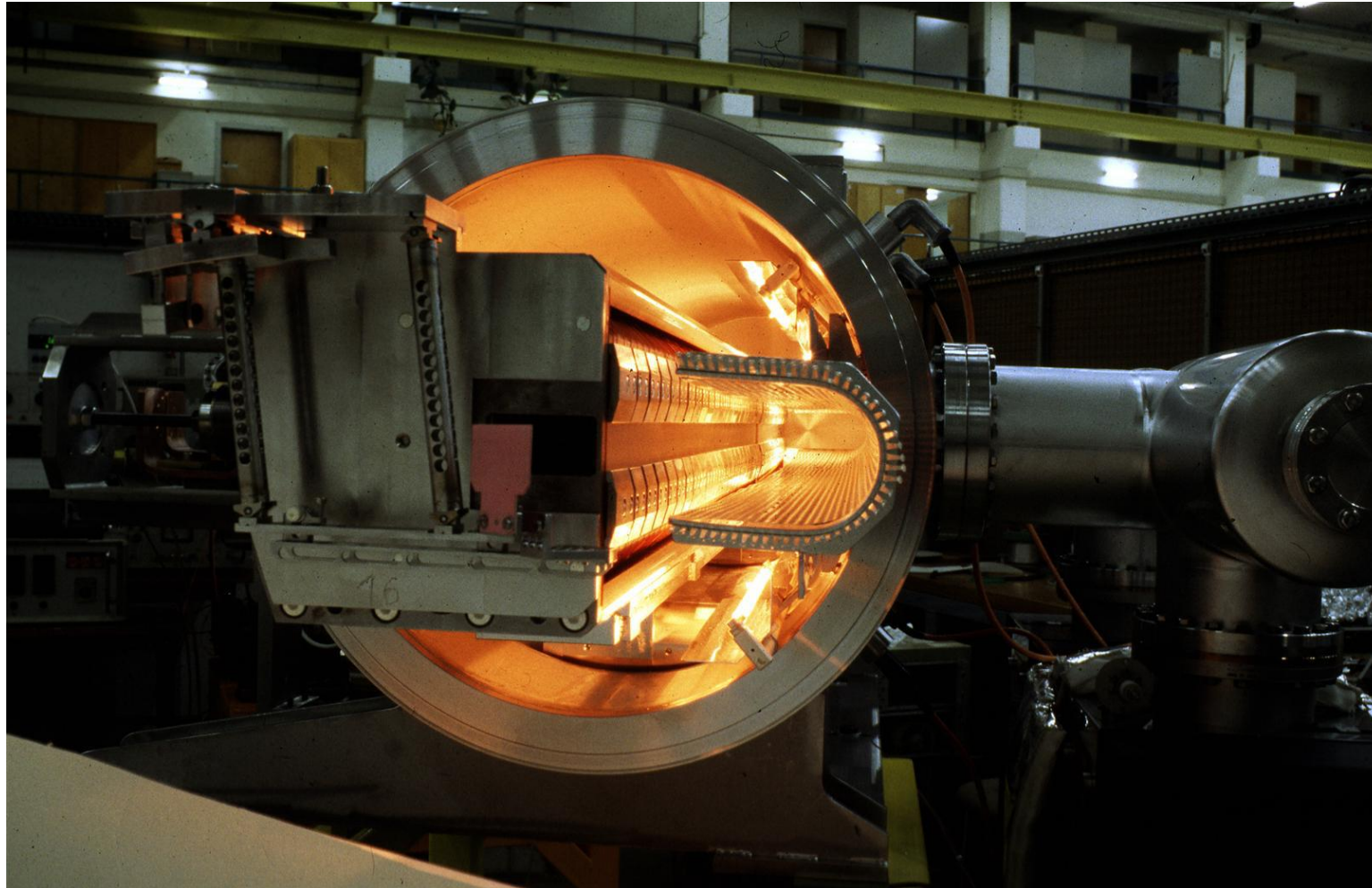
Extraction



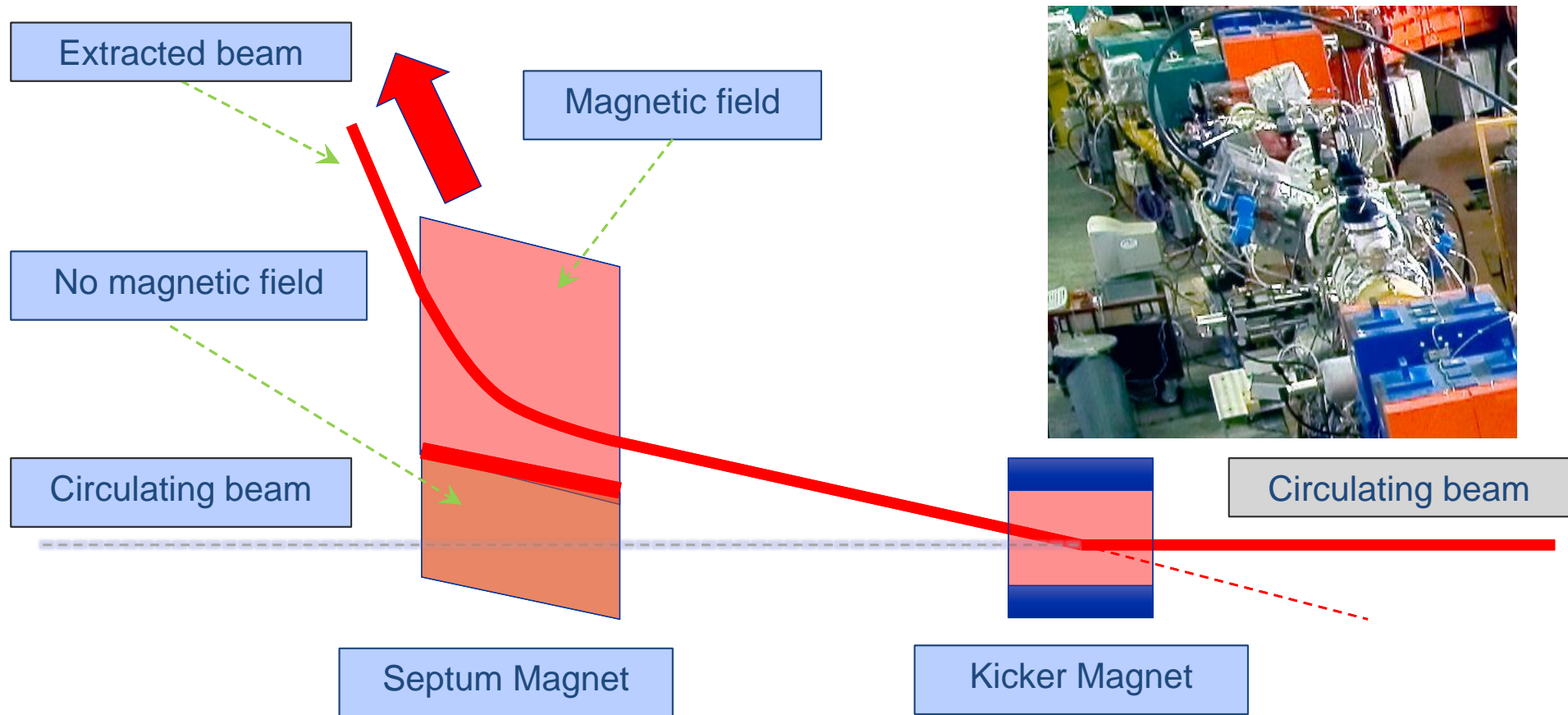
Injecting & Extracting Particles



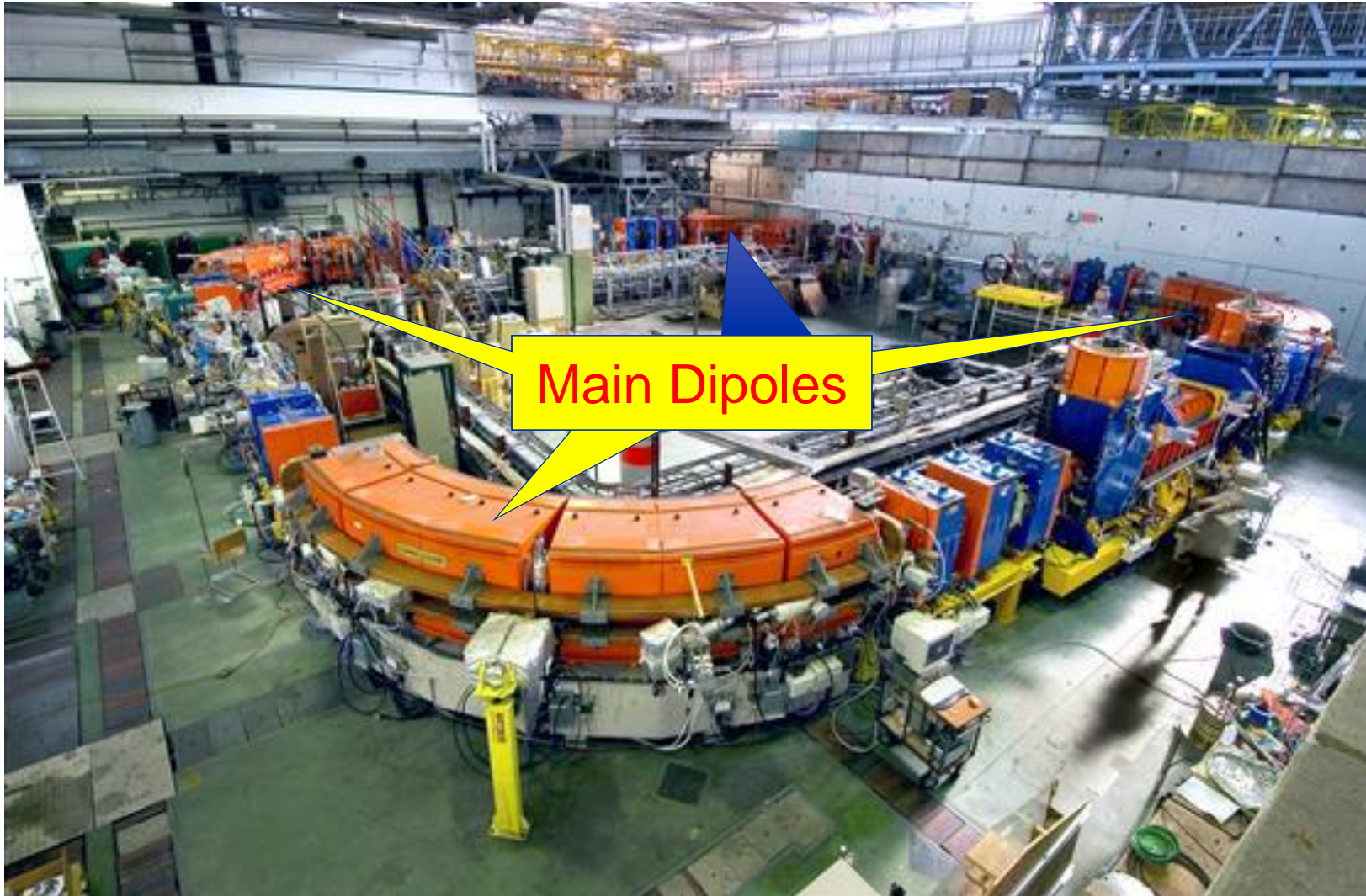
Septum Magnet



Injecting & Extracting Particles

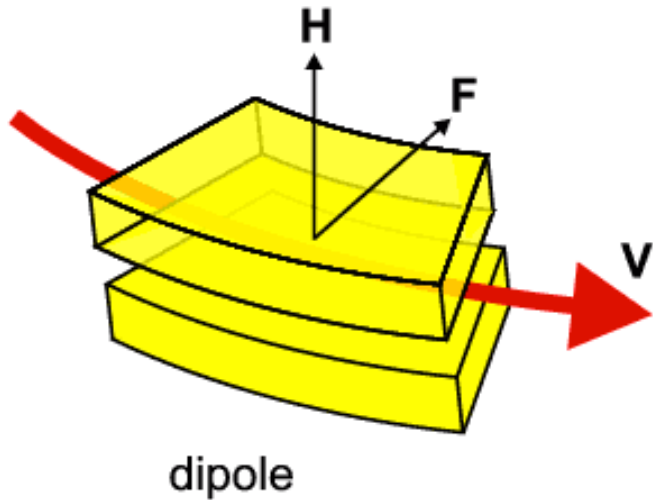


Make Particles Circulate



Deviating Charged Particles

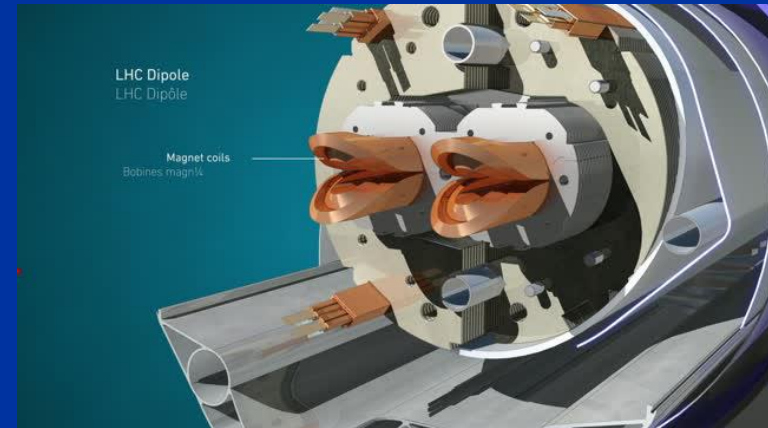
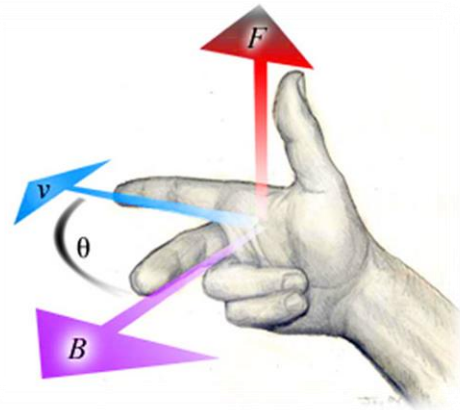
Moving charged particles are deviated in a magnetic field



dipole

Magnetic Lorentz Force:

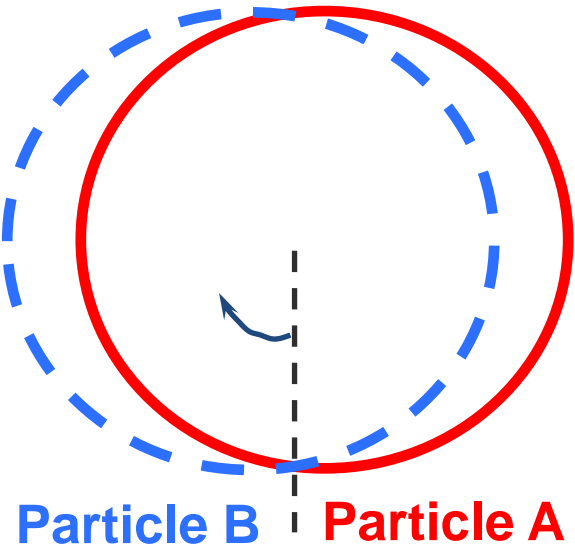
$$F = e(\vec{v} \times \vec{B})$$



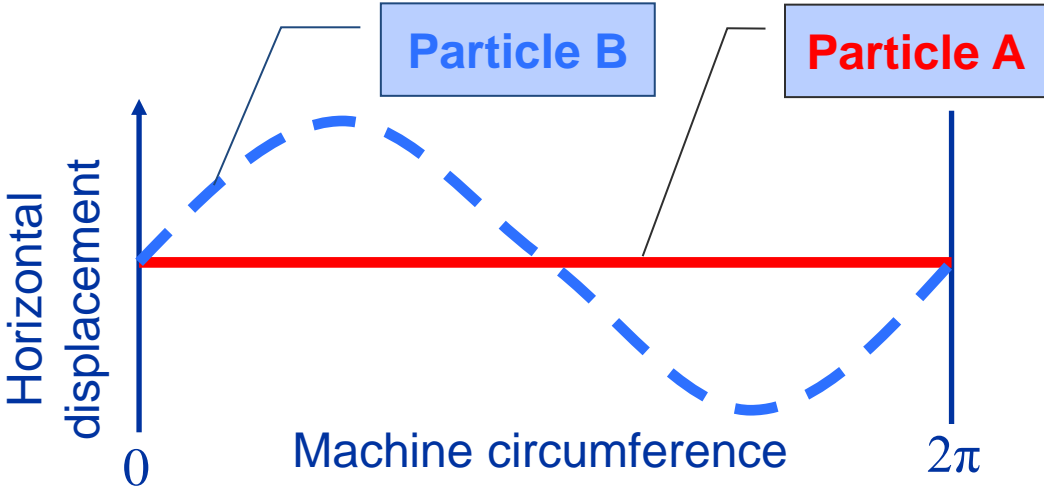
**Any ideas about how strong
magnet fields in dipole magnets
can be?**

Motion in the Horizontal Plane

Two charged Particles in a homogeneous magnetic field



Horizontal motion

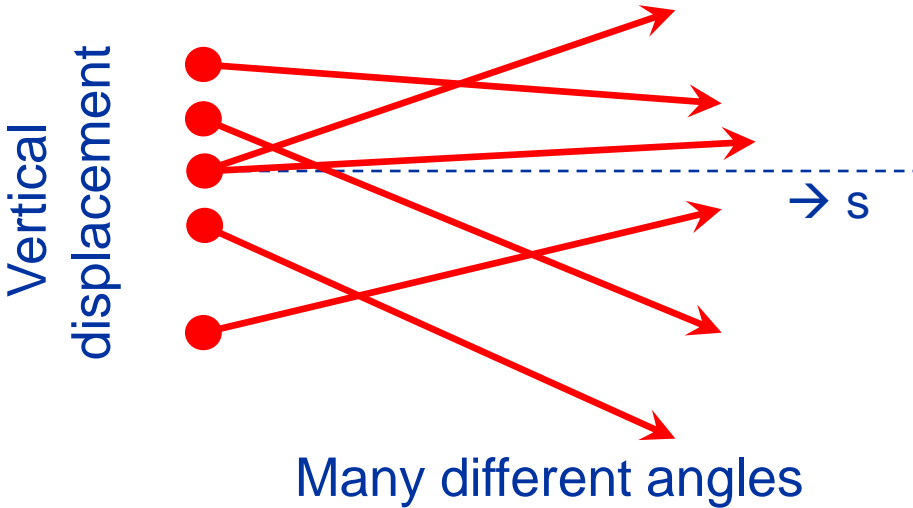


Different particles with different initial conditions in a homogeneous magnetic field will cause oscillatory motion in the horizontal plane → **Betatron Oscillations**

Motion in the Vertical Plane

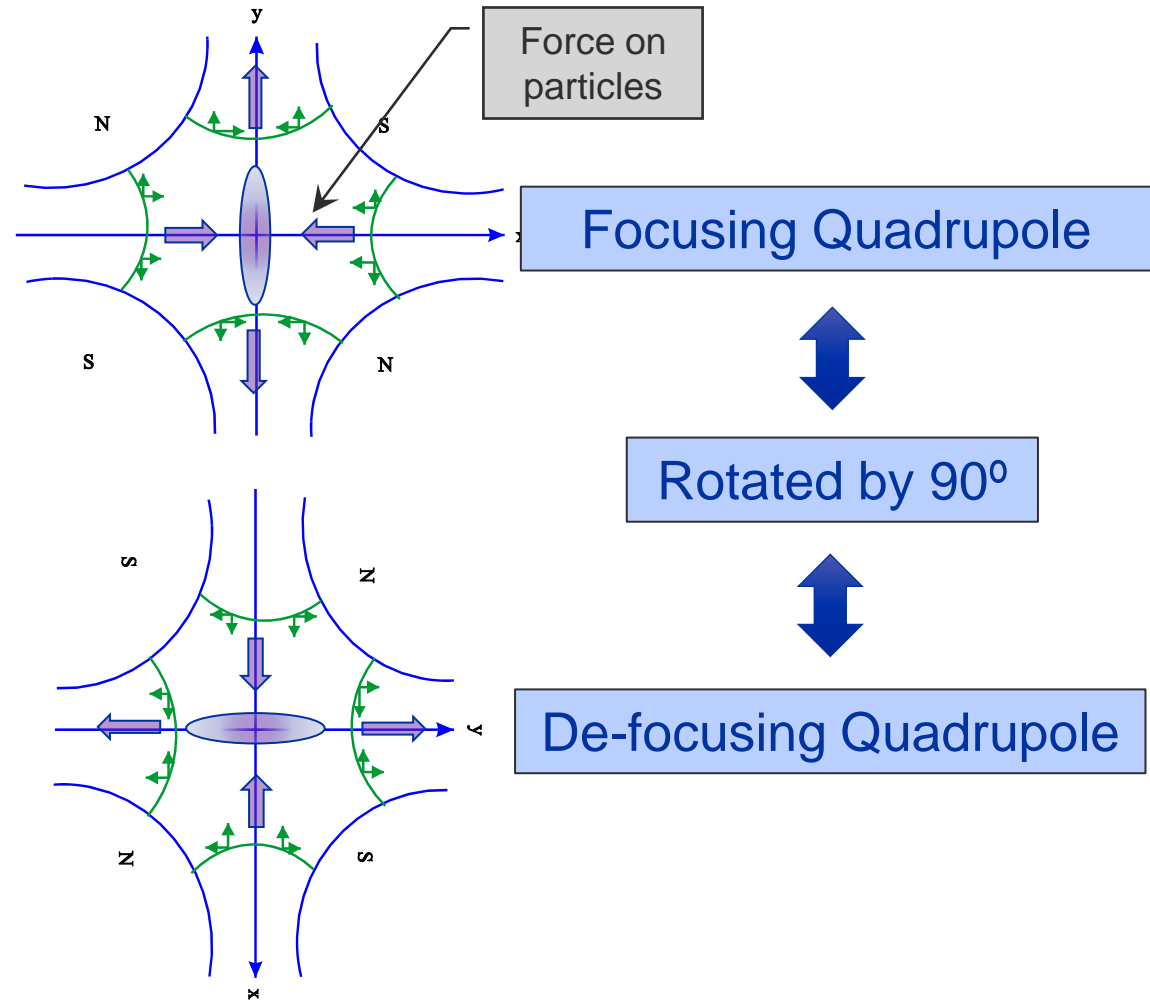
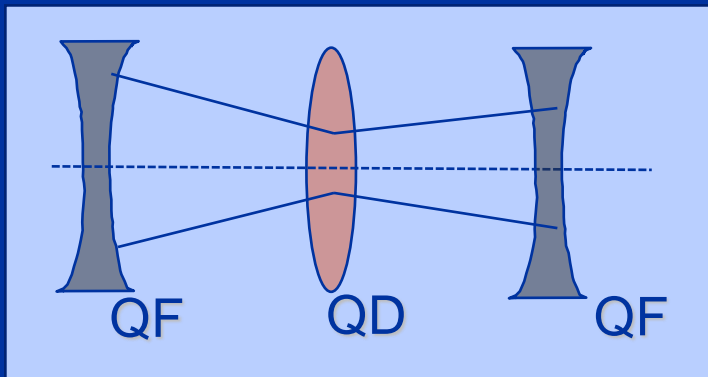
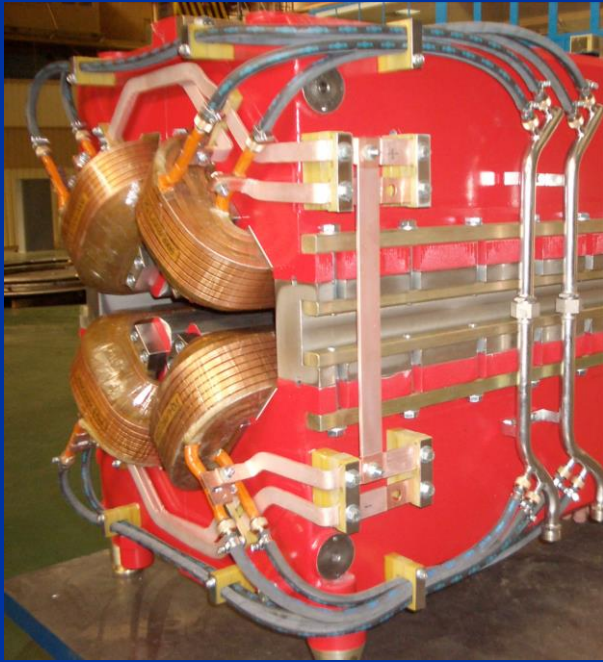
The horizontal motion seems to be “stable”.... What about the vertical plane ?

Many particles many initial conditions

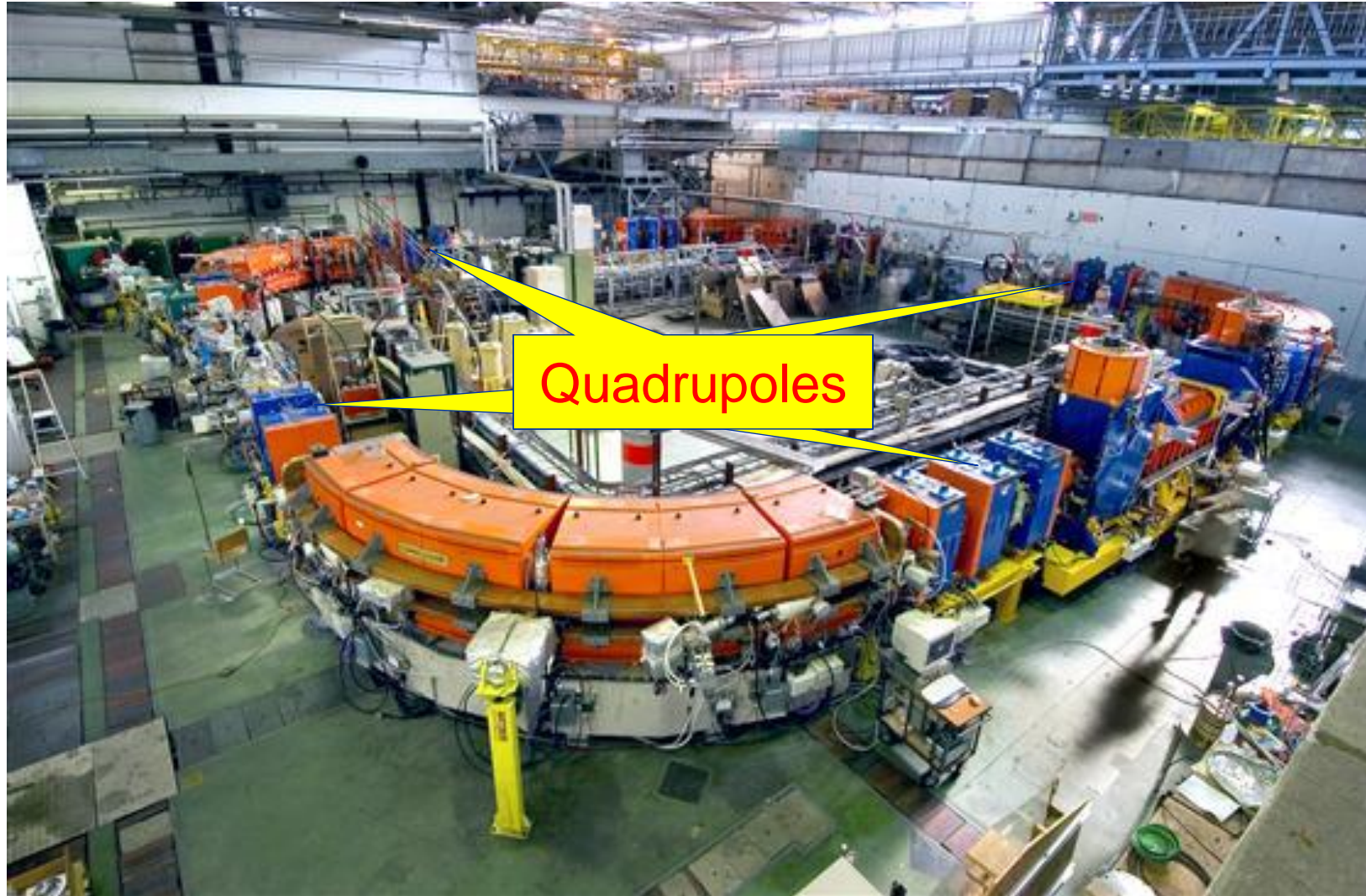


Any ideas on how to solve this issue?

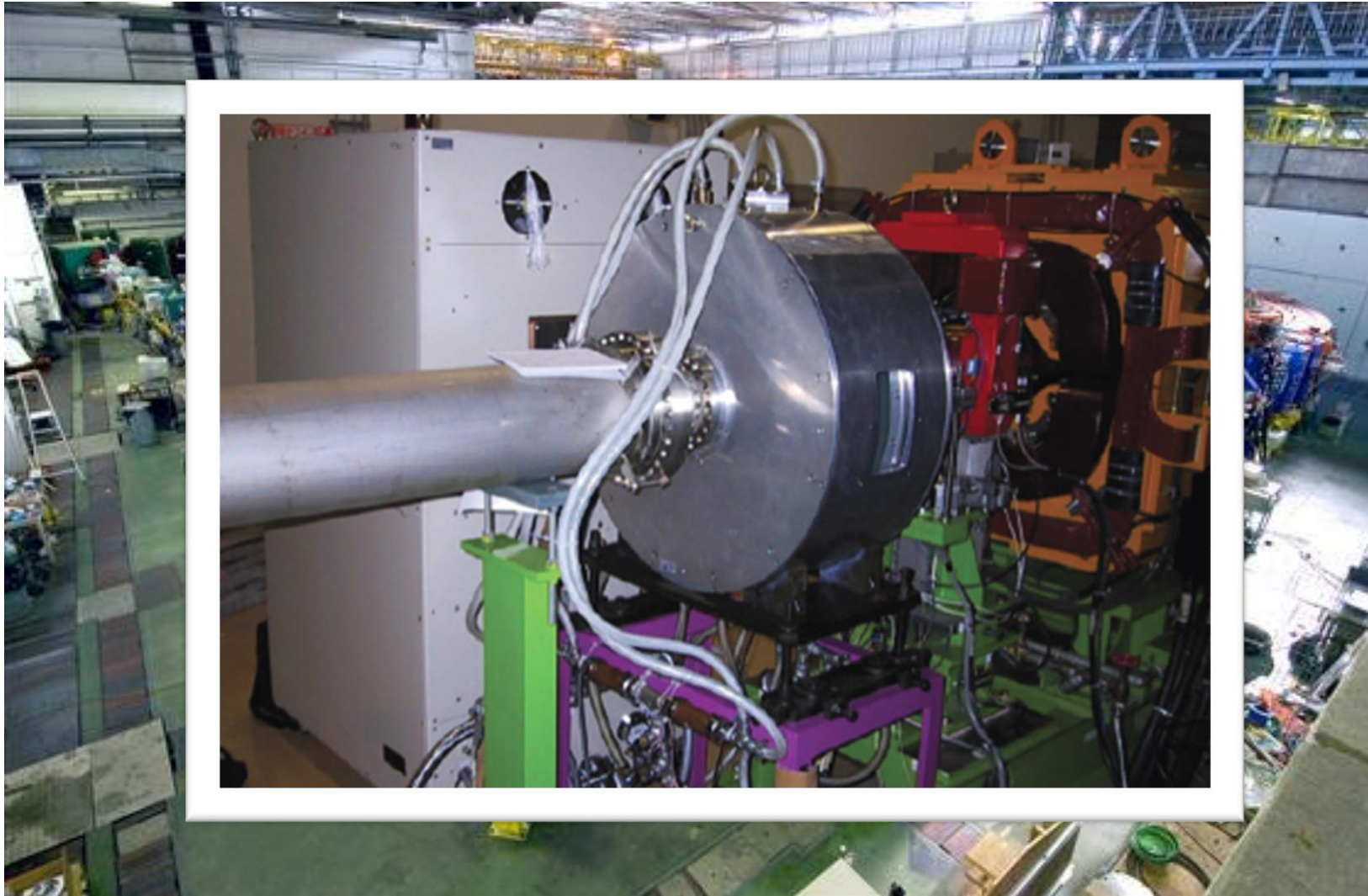
Focusing Particle Beams, a bit like a lens



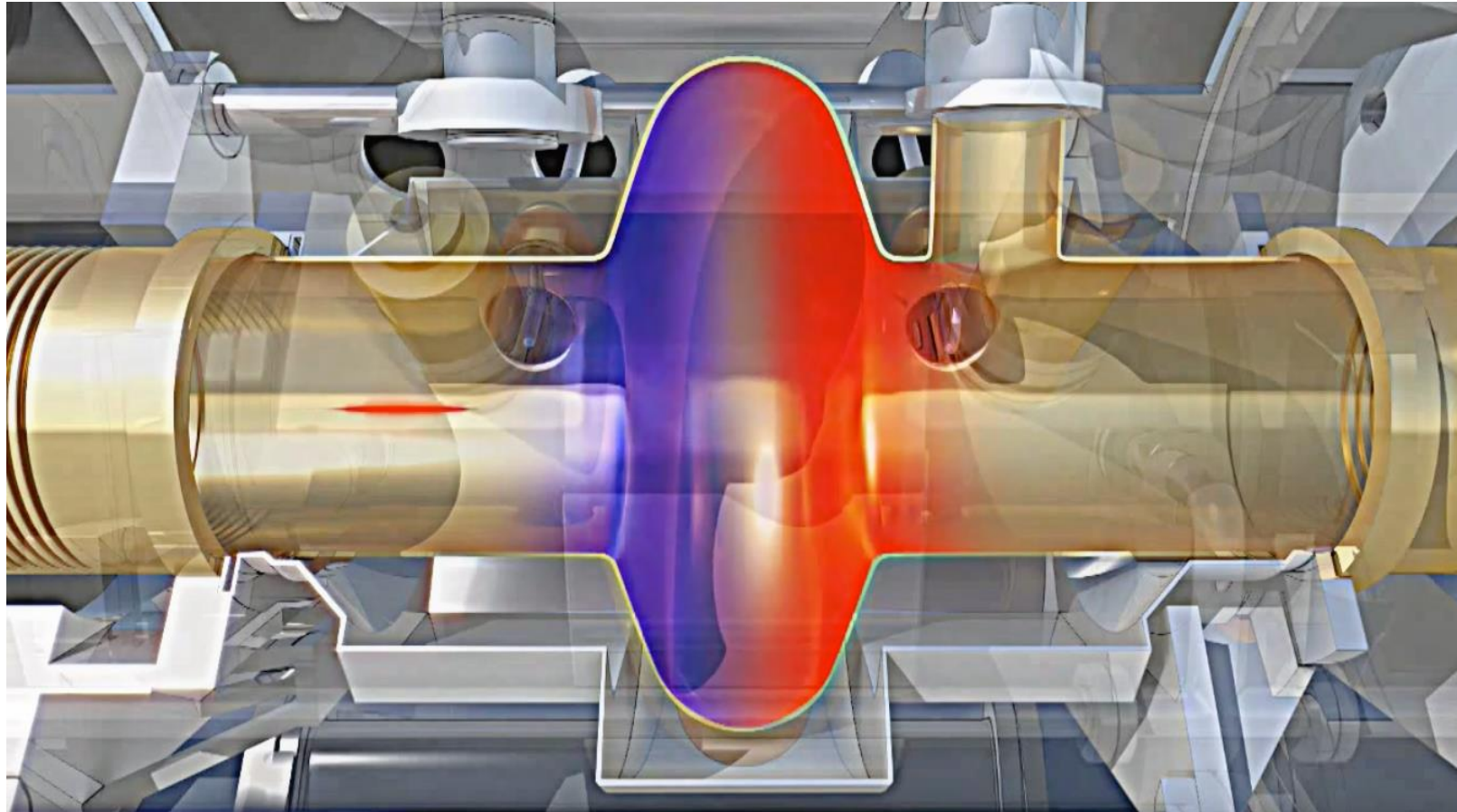
Focusing Particle Beams in LEIR



Accelerating Particles, Using Electrical Fields



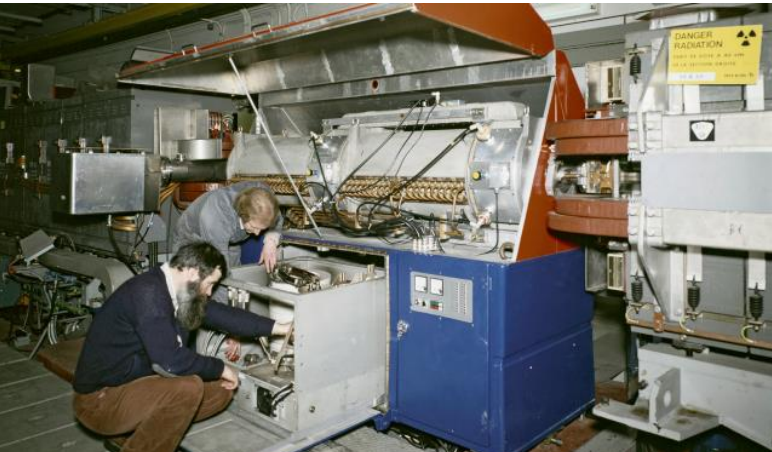
Radio Frequency Cavity



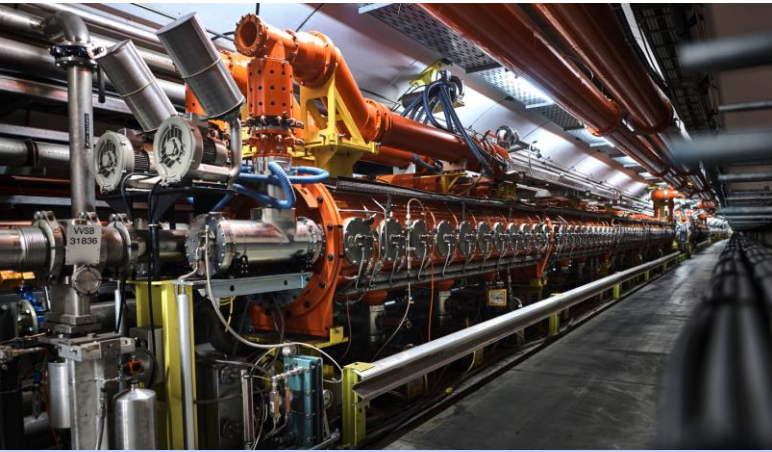
Charged particles are accelerated by a longitudinal electric field

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

RF Cavities

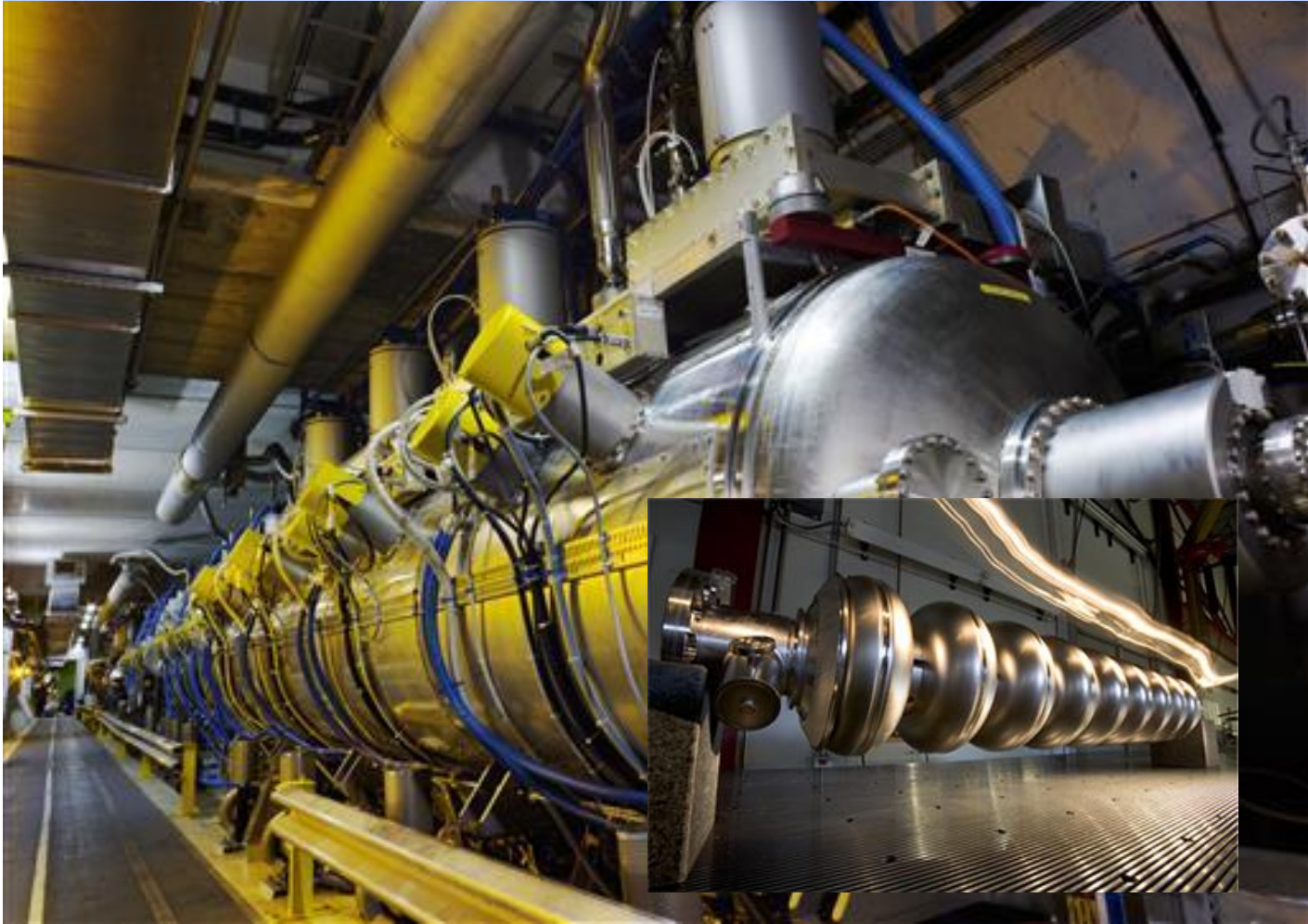


Variable frequency cavity (PS)

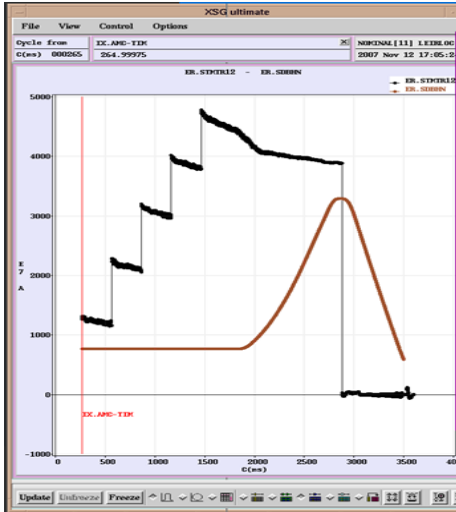


Fixed frequency cavities (SPS)

Super conducting fixed frequency cavities (LHC)

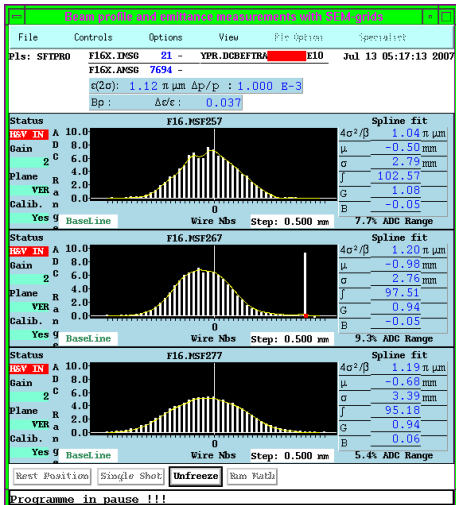
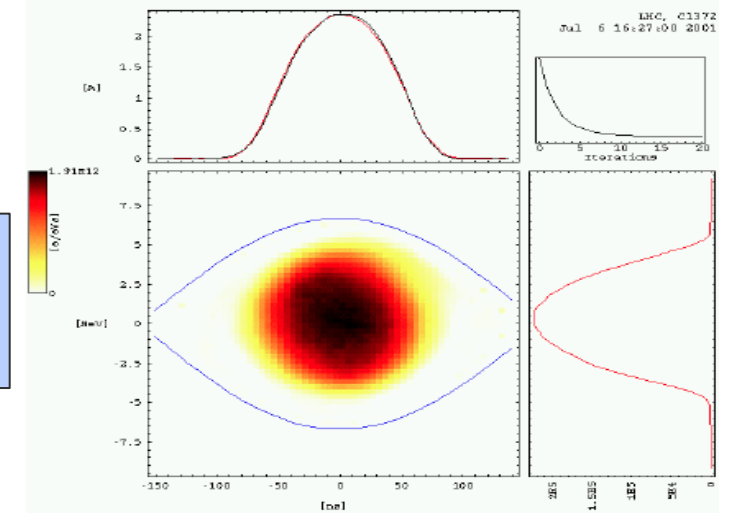


The Eyes of Operations



Beam intensity or current measurement

Longitudinal beam profile measurements



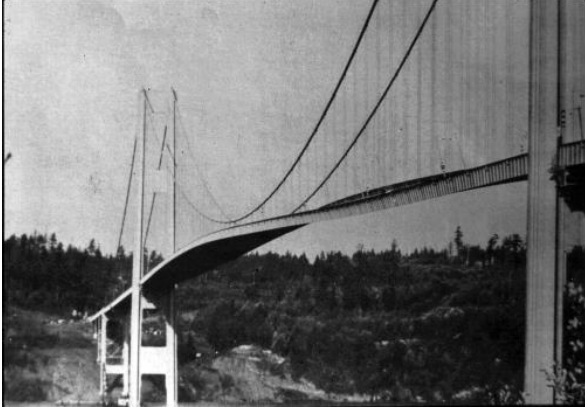
Transverse beam profile measurement

Measure the LHC luminosity, number of events per surface and time unit.

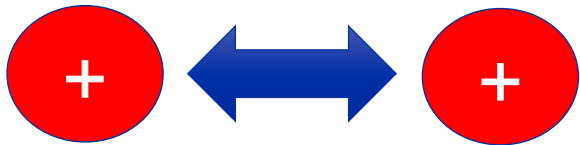
Any many more beam properties.....

Possible Limitations

Machines and elements cannot be built with infinite perfection

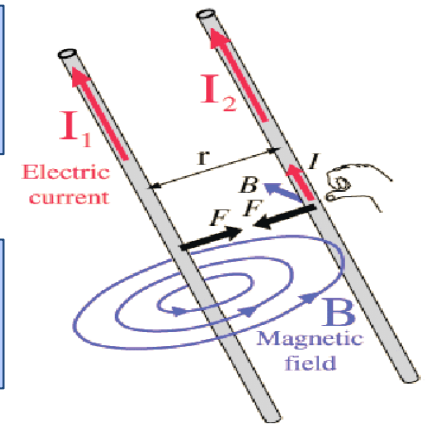


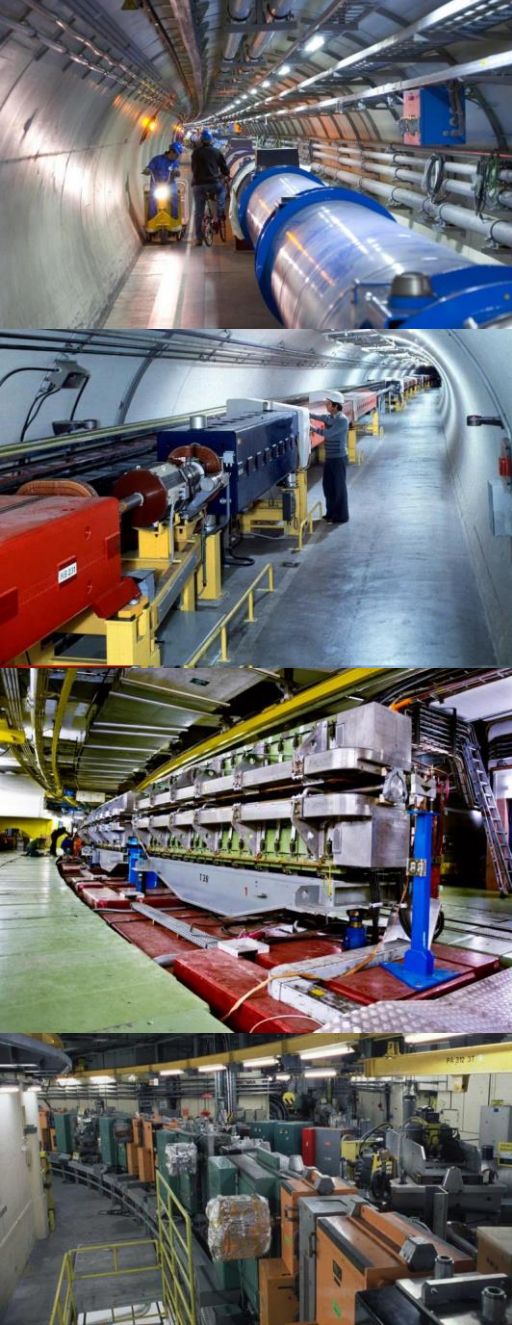
Same phase and frequency for driving force and the system can cause resonances and be destructive



Neighbouring charges with the same polarity experience repelling forces

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





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Luminosity, the Figure of Merit

$$LUMINOSITY = \frac{N_{event}/sec}{S_r} = \frac{N_1 N_2 f_{rev} n_b F}{4\rho s_x s_y}$$

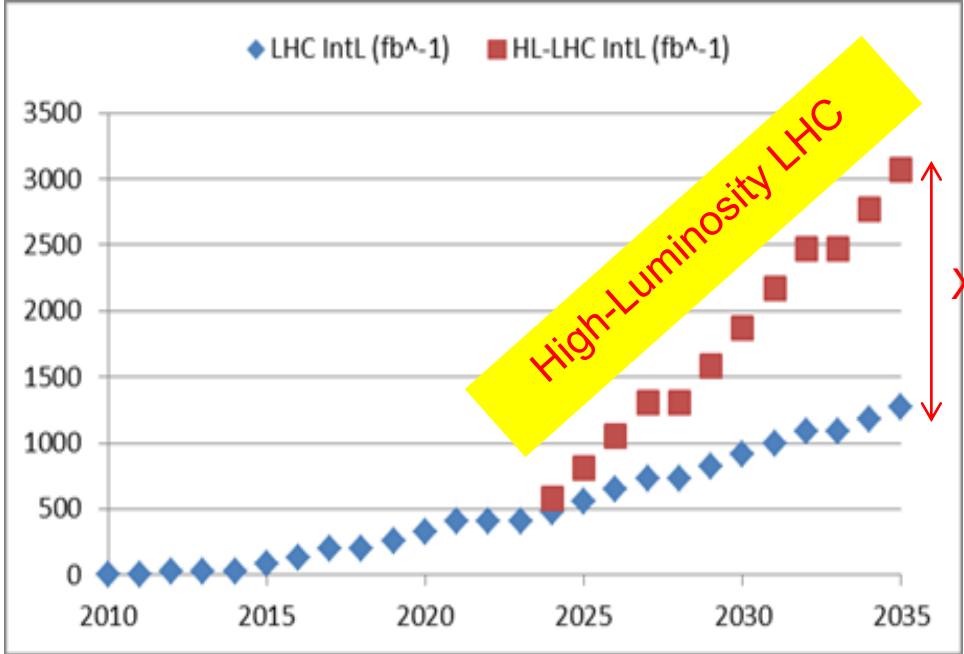
Intensity per bunch

Number of bunches

Geometrical Correction factors

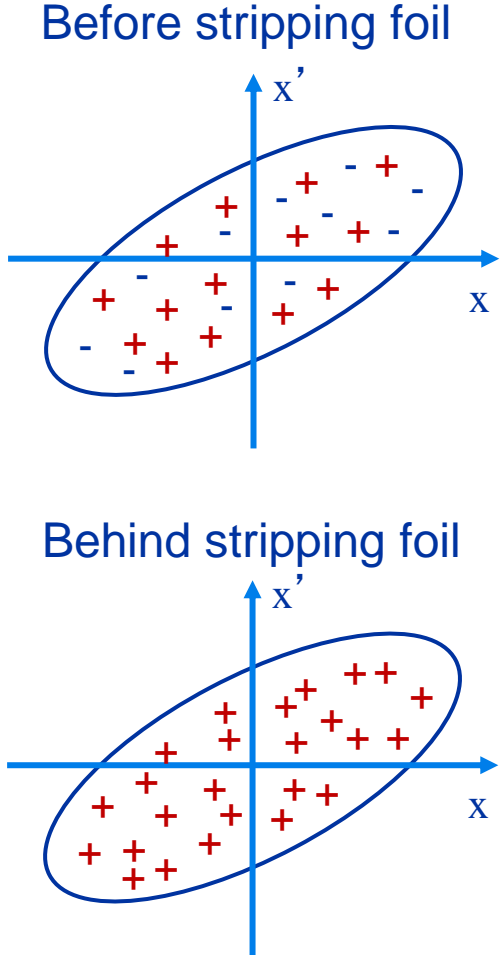
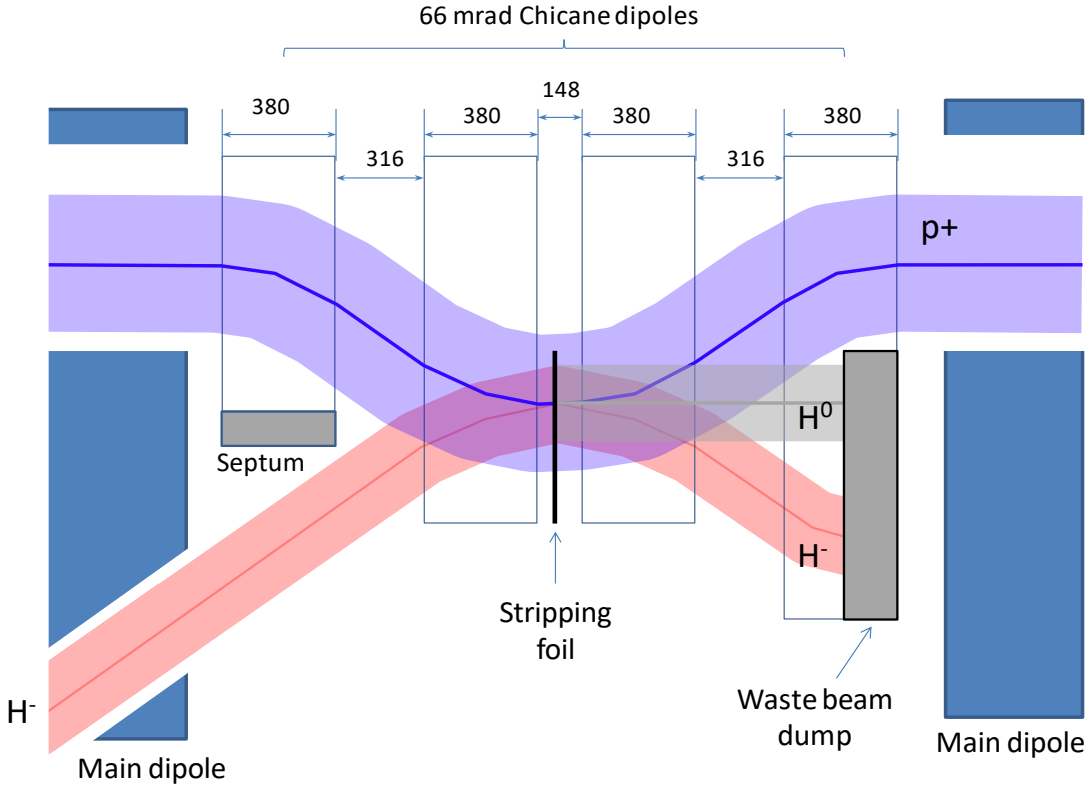
Beam dimensions

- ### Maximise Luminosity:
- Bunch intensity
 - Transverse beam size
 - Beam size at collision points
 - Crossing angle
 - Machine availability



H- injection, a Key LIU Ingredient

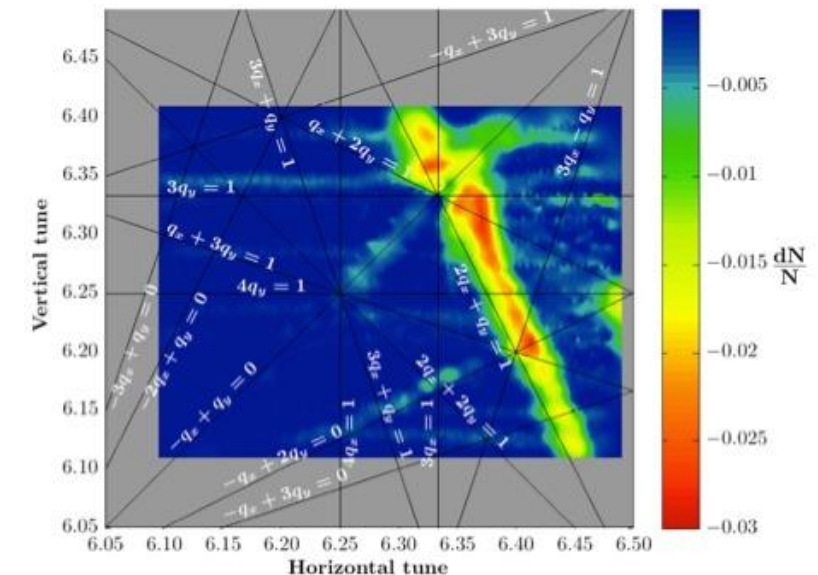
- Charge exchange injection with H⁻



Phase Space Painting is possible (various particle distributions)

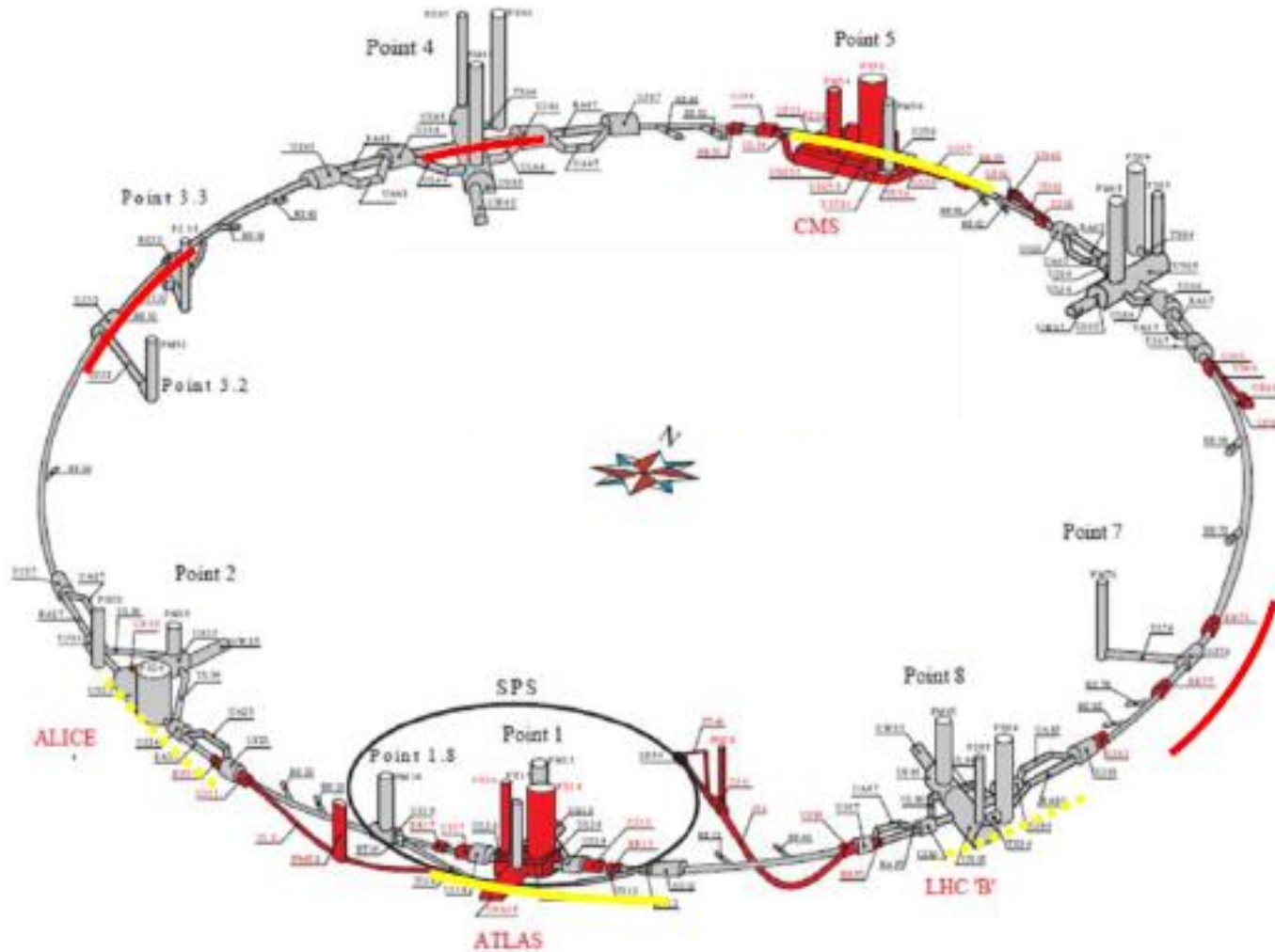
The LHC Injector Upgrade Project is Completed

- LINAC4 – PS Booster:
 - New LINAC 4 with H^- injection
 - Higher injection energy
 - New Finemet® RF cavity system
 - Increase of extraction energy
- PS:
 - Injection energy increase from 1.4 GeV to 2 GeV
 - New Finemet® RF Longitudinal feedback system
 - New RF beam manipulation scheme to increase beam brightness
- SPS
 - Machine Impedance reduction (instabilities)
 - New 200 MHz RF system
 - Vacuum chamber coating against e-cloud



These are only the main modifications and this list is not exhaustive

The High Luminosity LHC Project



- New IR-quads (inner triplets)
- New 11T short dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- ...

Possible Future Accelerators

Compact Linear Collider (CLIC)

- Linear e^+e^- collider up to 3 TeV

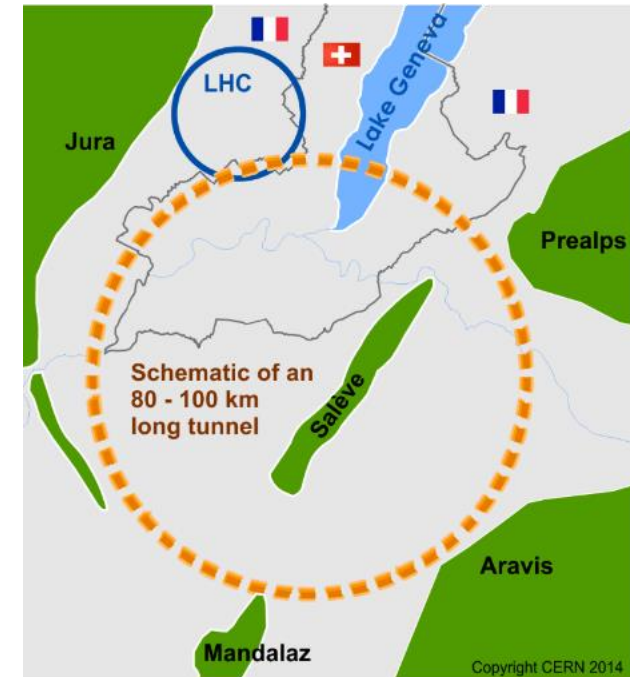
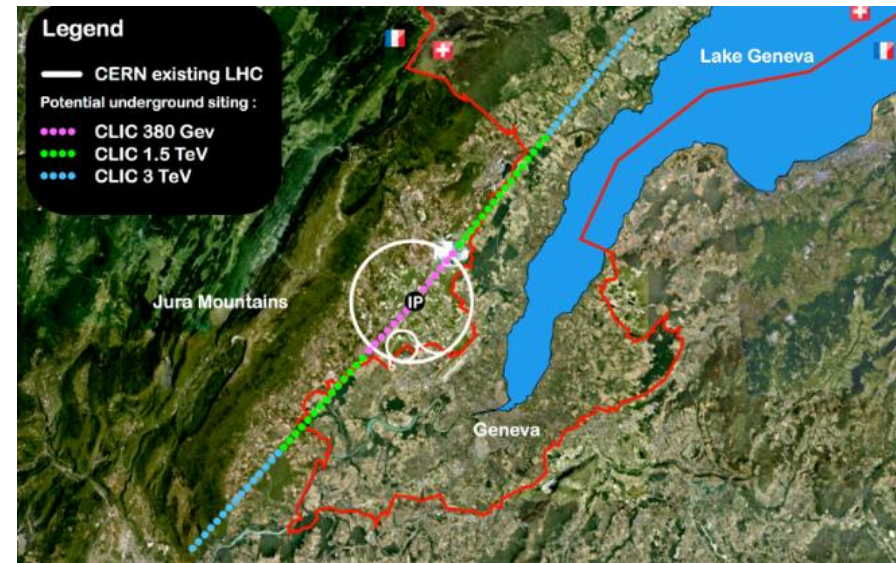
Future Circular Collider (FCC)

- 100 TeV pp collisions in 100km ring
- Requires new magnet technology
- e^+e^- collider (FCC-ee) as 1st step

High Energy LHC in the present LHC tunnel

- ~ 30 TeV with FCC magnet technology

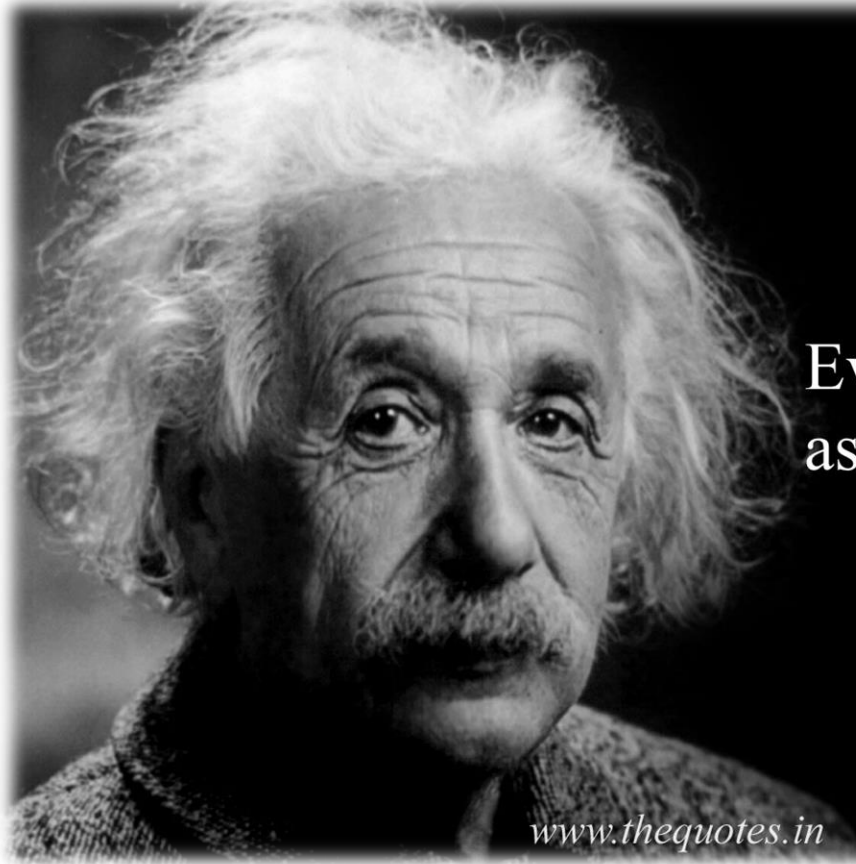
European Strategy for Particle Physics



Follow us...

<https://op-webtools.web.cern.ch/Vistar/vistars.php>





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

Albert Einstein

www.thequotes.in