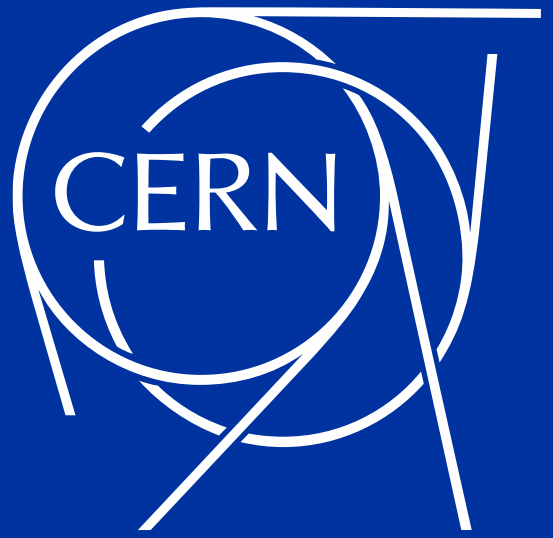
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Accelerators for Beginners and the CERN Complex

Rende Steerenberg – CERN BE/OP

9 May 2022

Content

- **Why Accelerators and Colliders ?**
- **The CERN Accelerator Complex**
- **Cycling the Accelerators & Satisfying Users**
- **The Main Ingredients of an Accelerator**

Content

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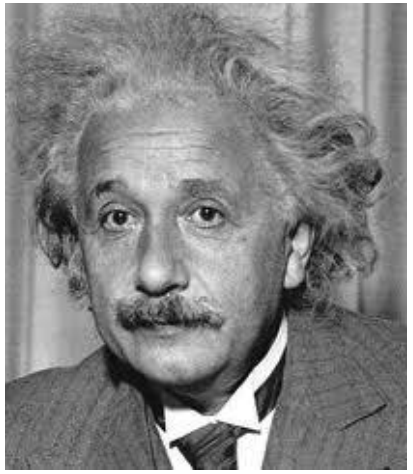
Creating Matter from Energy

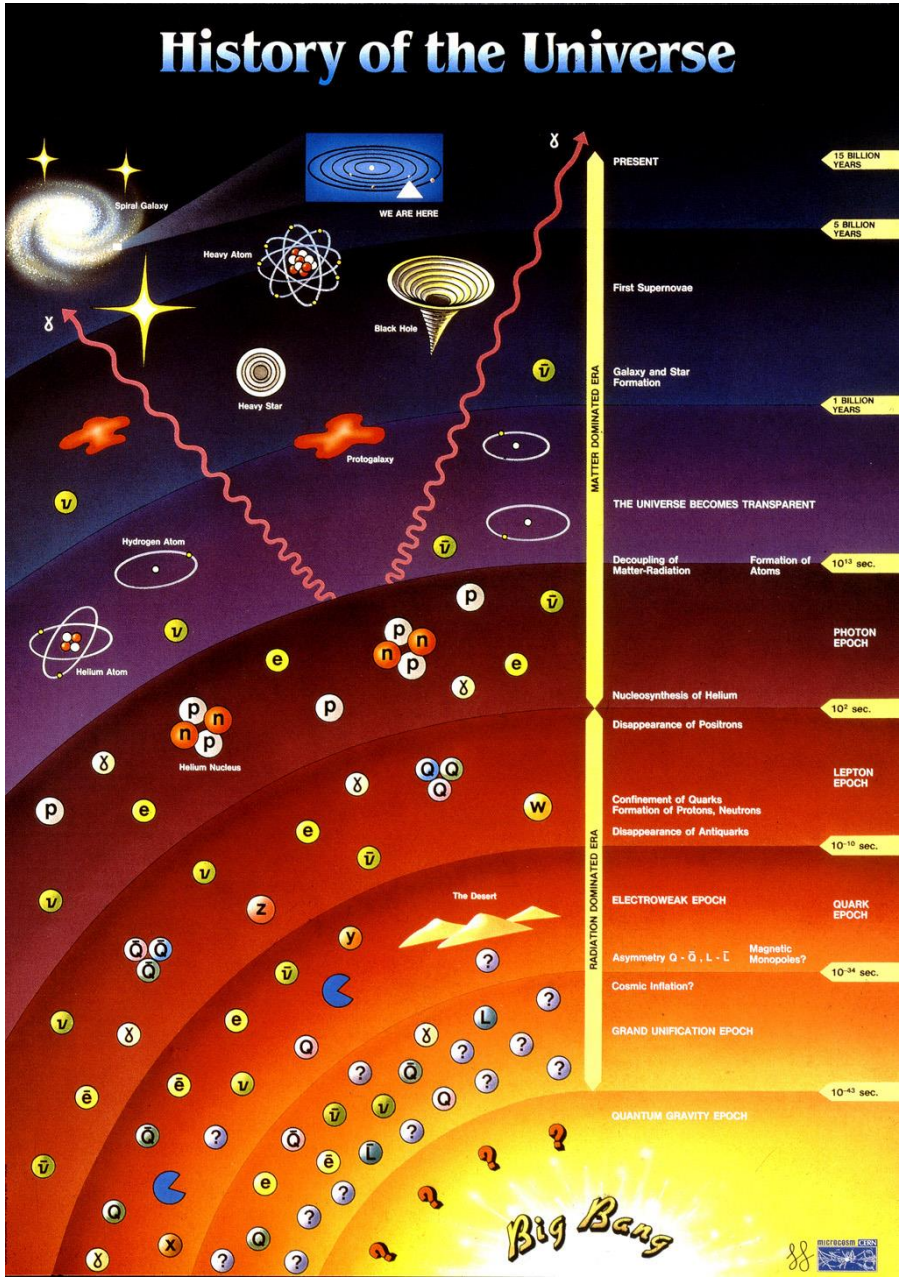
$E = m \cdot c^2$

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

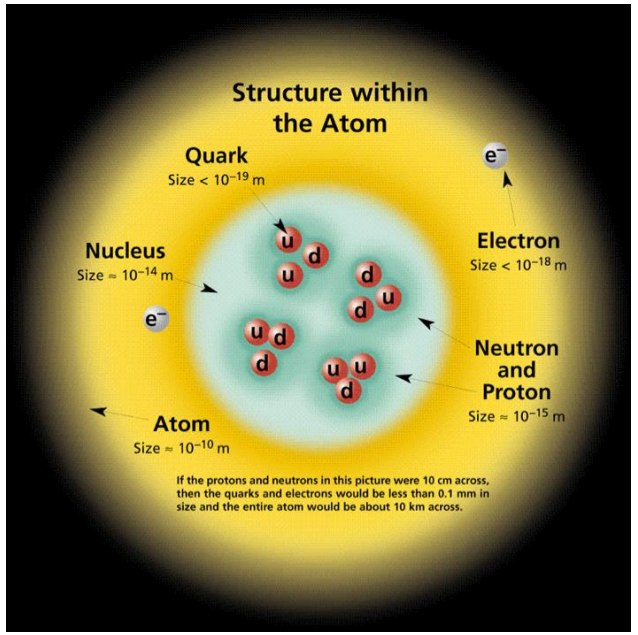


Looking to smaller dimensions

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

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

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

Accelerators and Their Use

Today: ~ **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*

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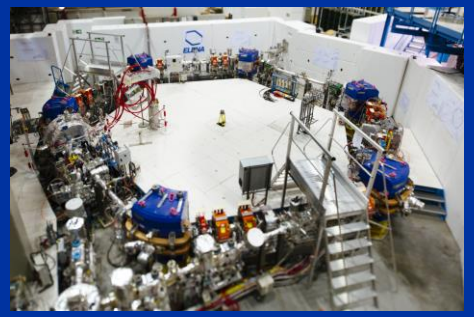
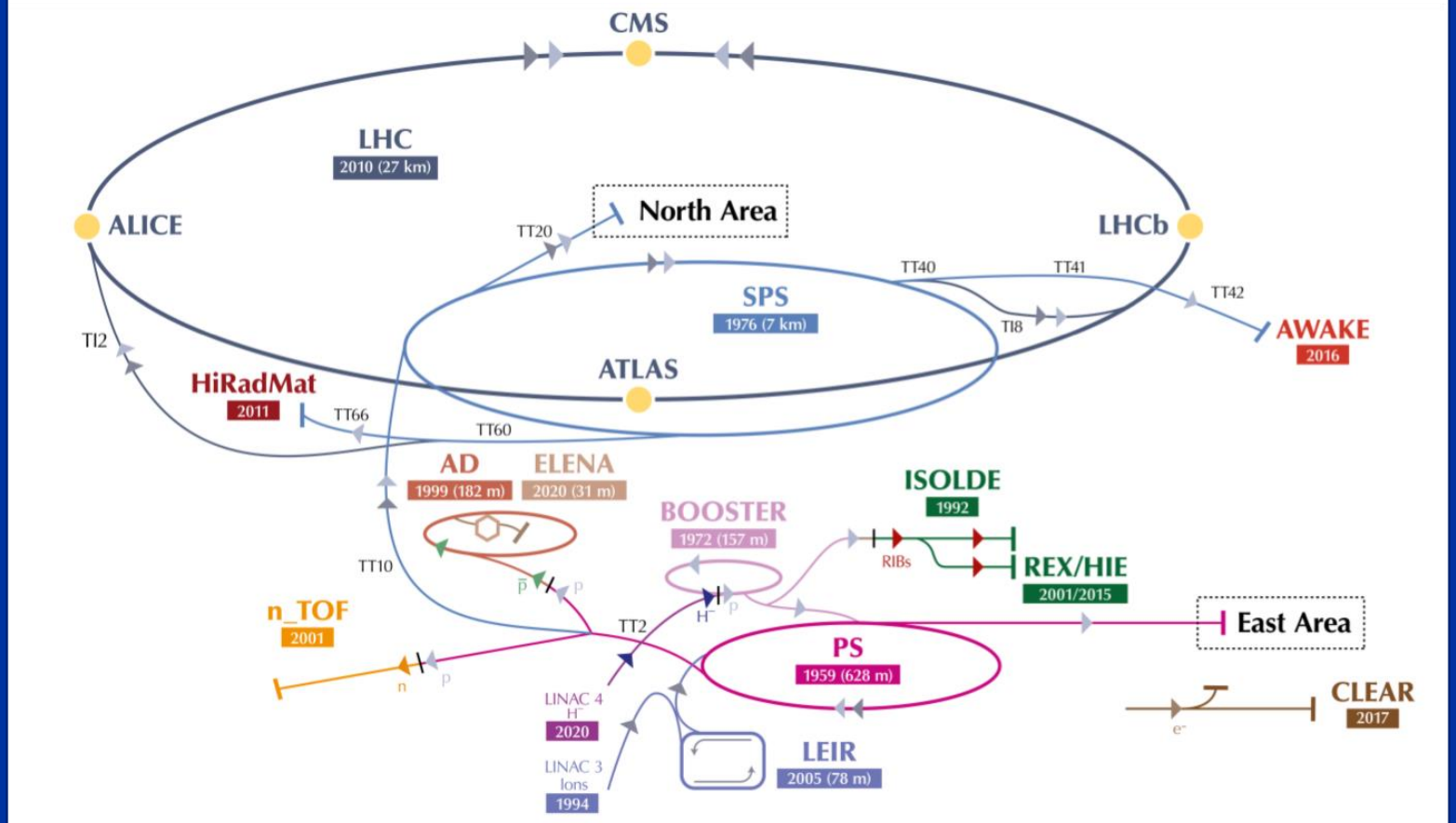
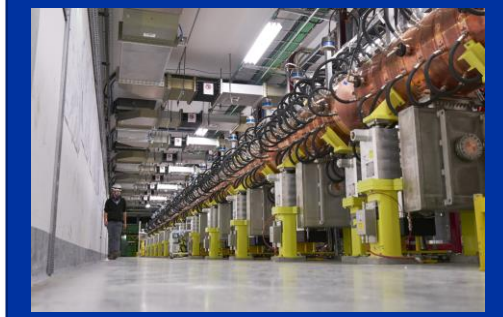
The CERN Accelerator Complex

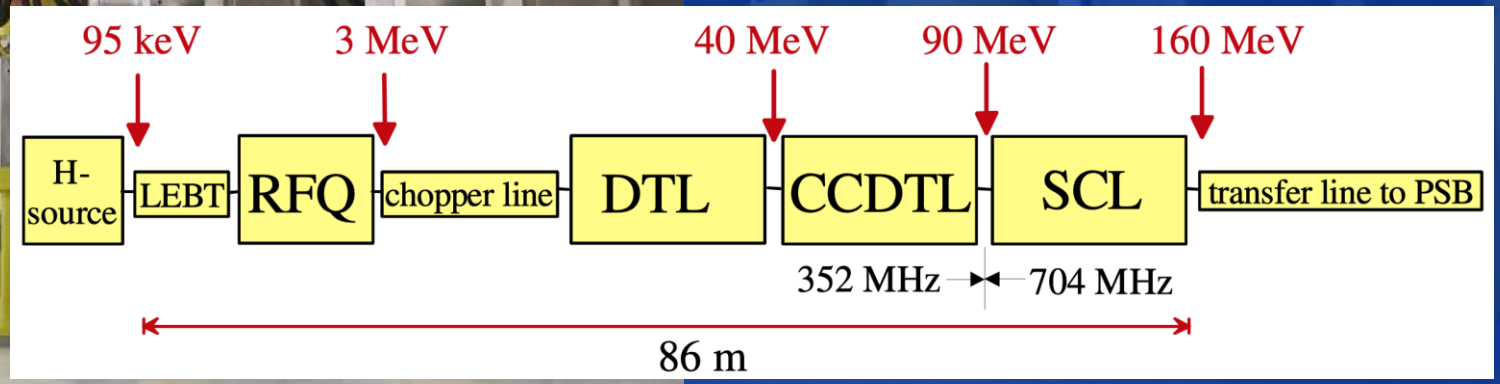






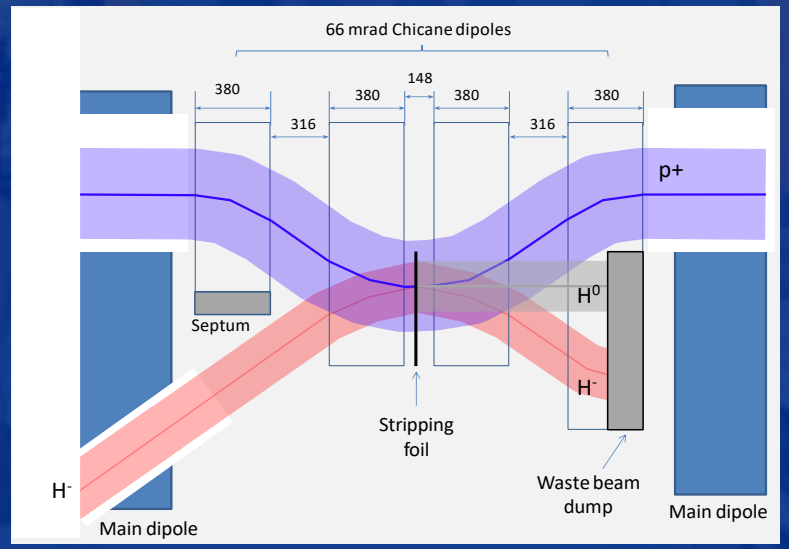
Linac 4

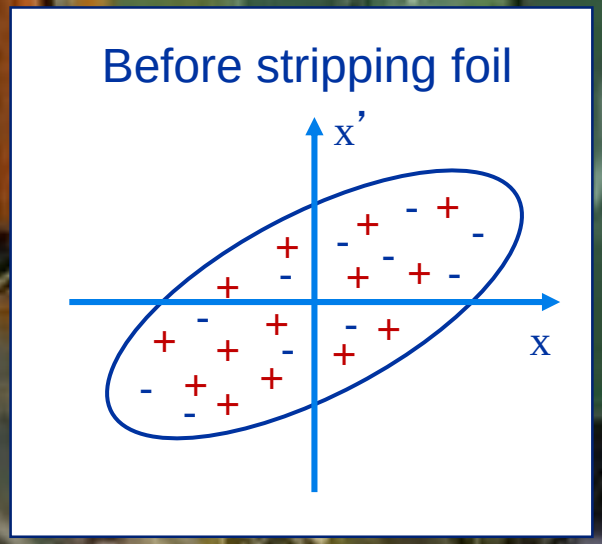
- H^- ion source at 95 keV
- Accelerates beam up to 160 MeV
- The chopping scheme allows removing some of the Linac bunches to make the beam fit into the PS Booster RF buckets
- Pulse rate 1.2 s

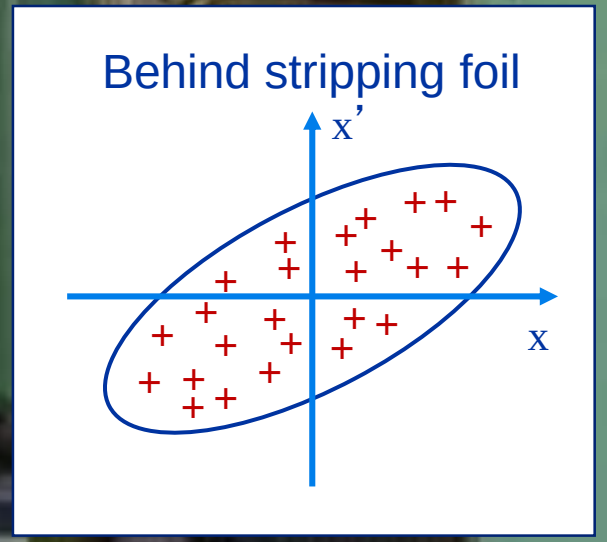


PS Booster

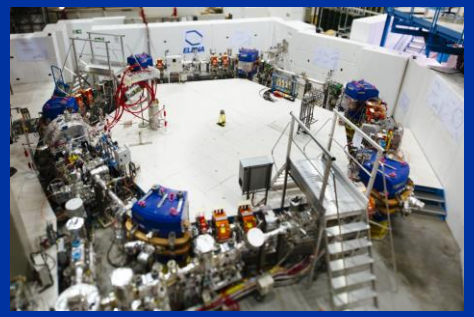
- 1st Synchrotron with 4 superposed rings
- Circumference of 157 m
- Proton energy from 160 MeV to 2 GeV
- Can cycle every 1.2 s
- Each ring will inject over multi-turns, using charge exchange injection

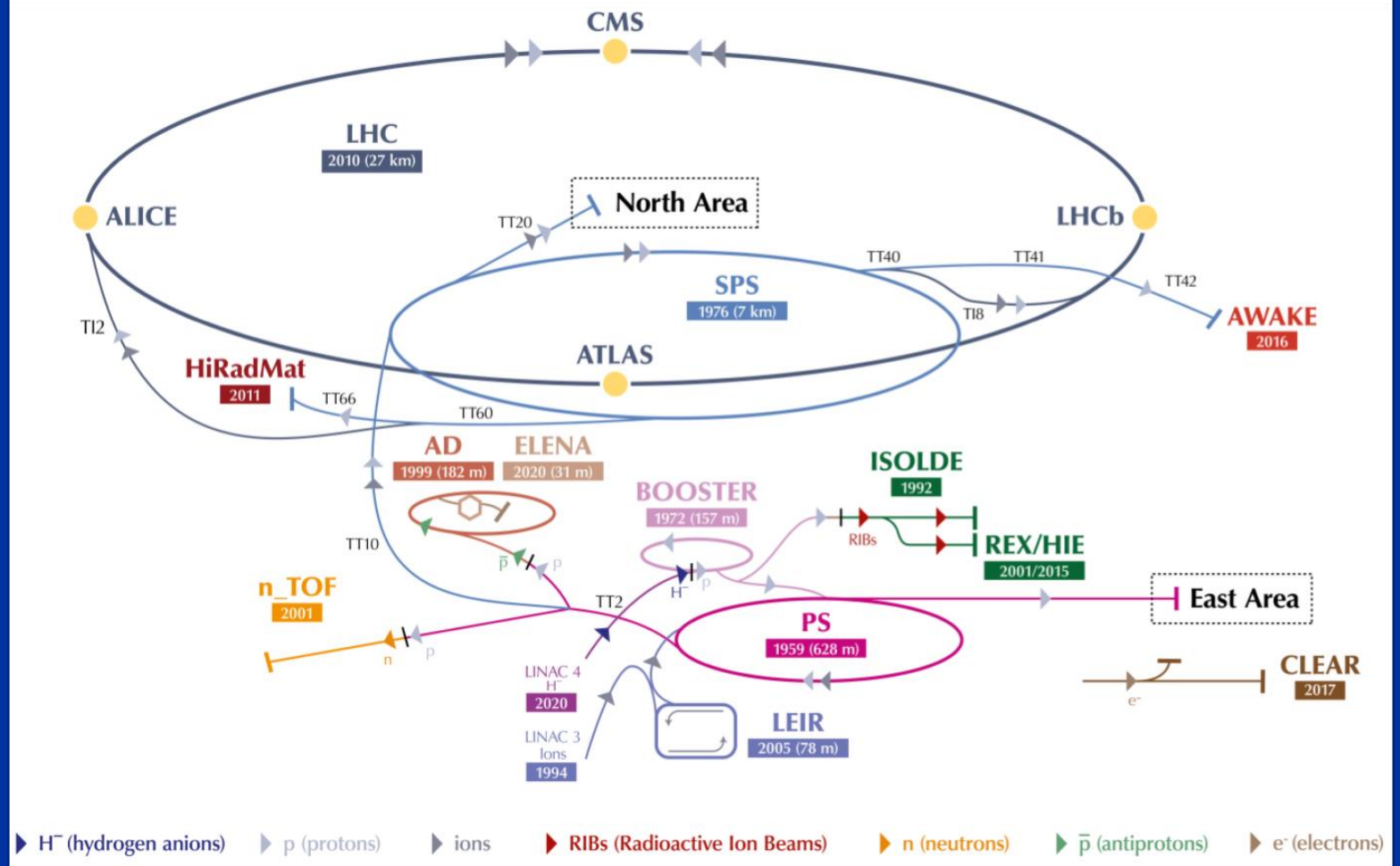


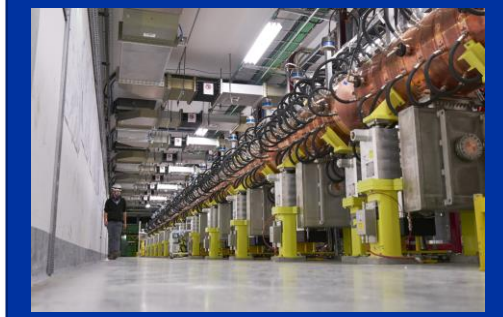




The CERN Accelerator Complex

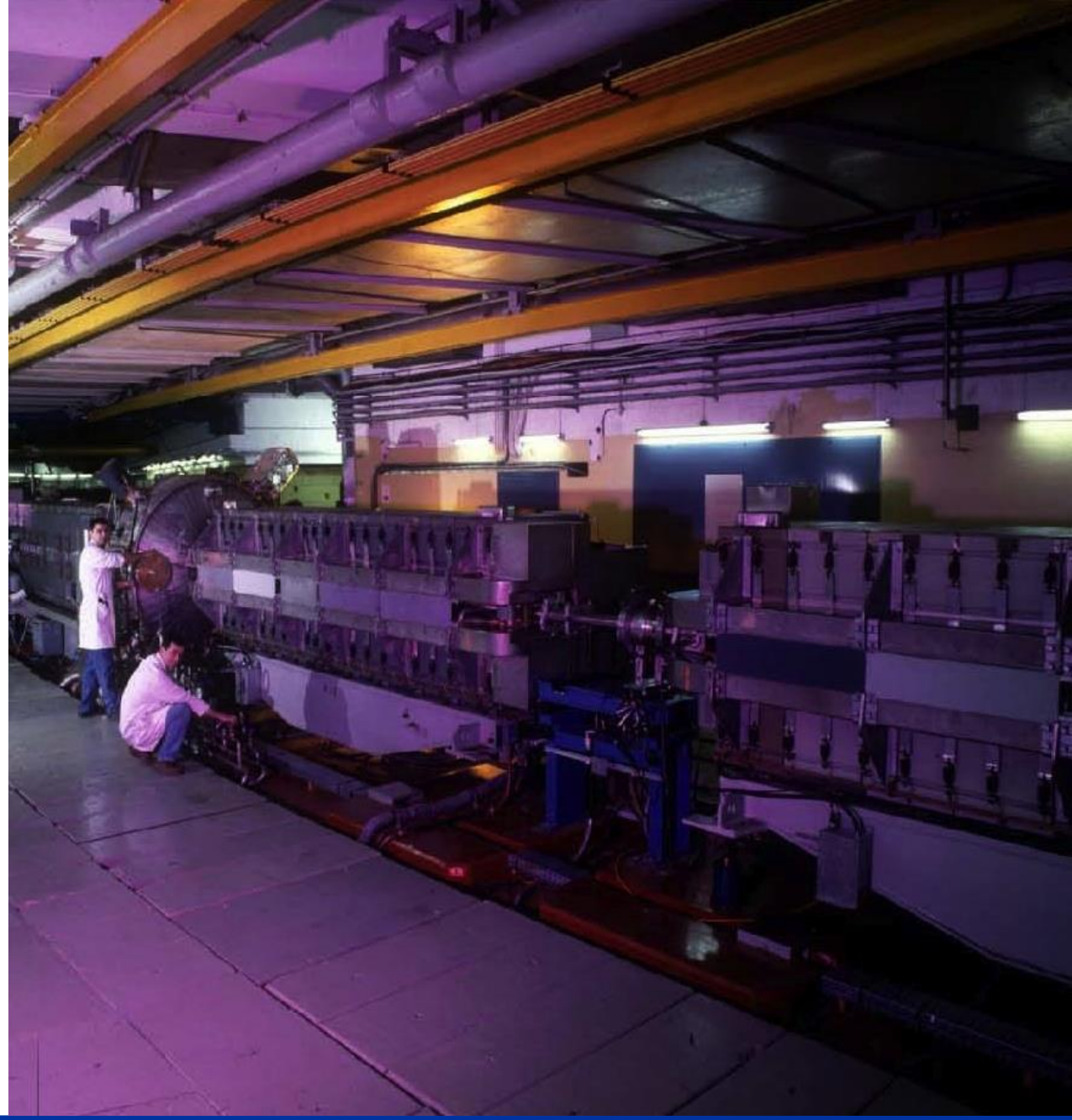






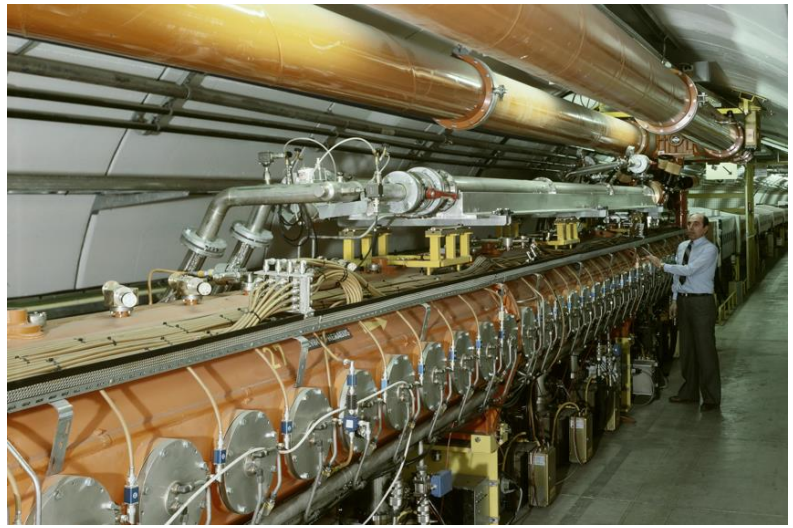
PS

- **The oldest operating synchrotron at CERN**
- **Circumference of 628m**
  - 4 x PSB circumference
- **Increases proton energy from 2 GeV to max. 26 GeV**
- **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

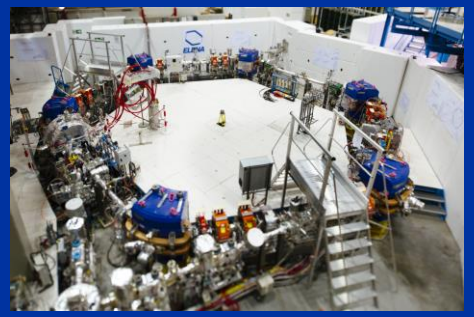


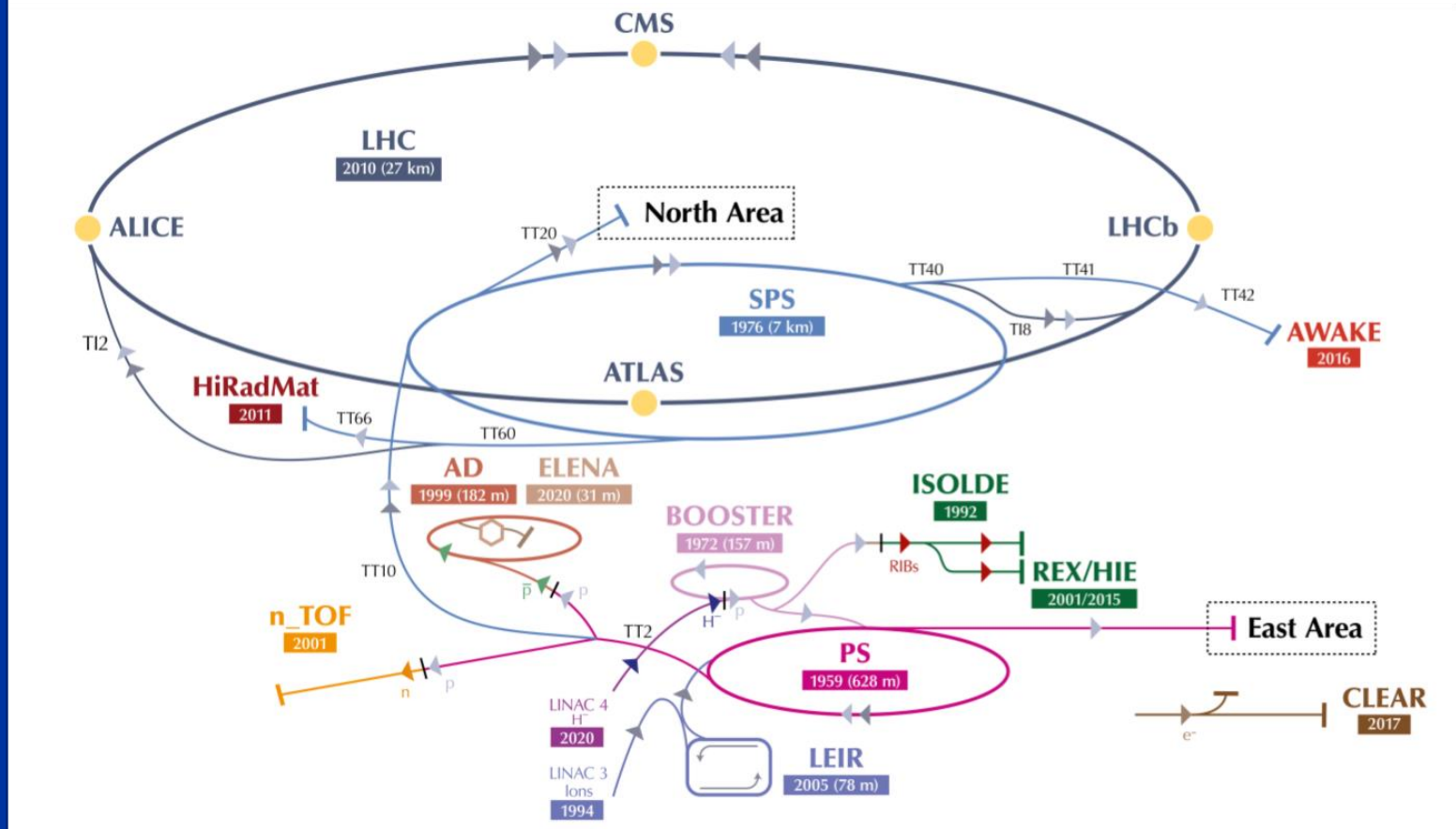
SPS

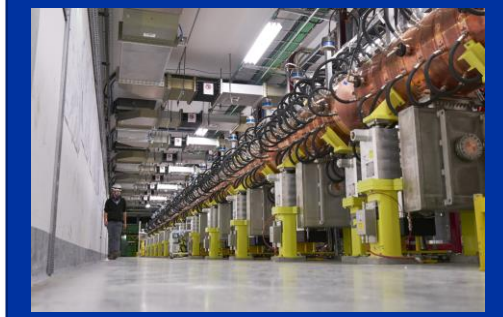
- **The first synchrotron in the chain at ~30m under ground**
- **Circumference of 6.9 km**
  - 11 x PS circumference
- **Increases proton beam energy up to 450 GeV with up to ~5x10^{13} protons per cycle**
- **Provides slow extracted beam to the North Area**
- **Provides fast extracted beam to LHC, AWAKE and HiRadMat**



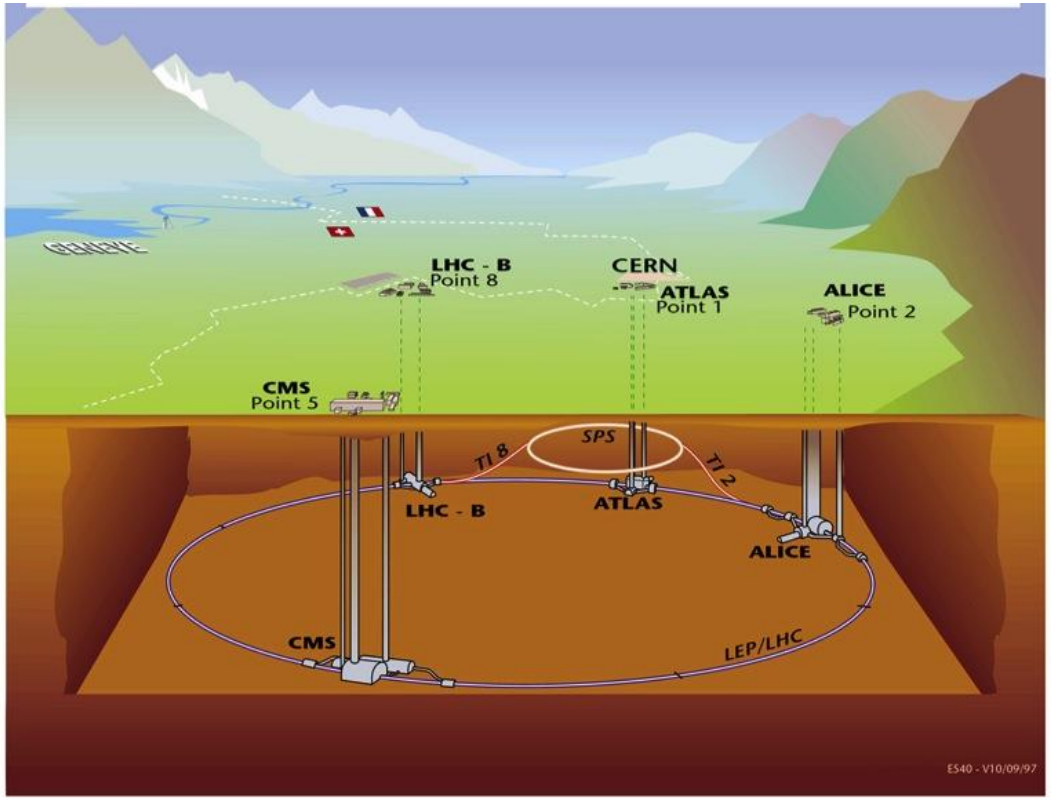
The CERN Accelerator Complex

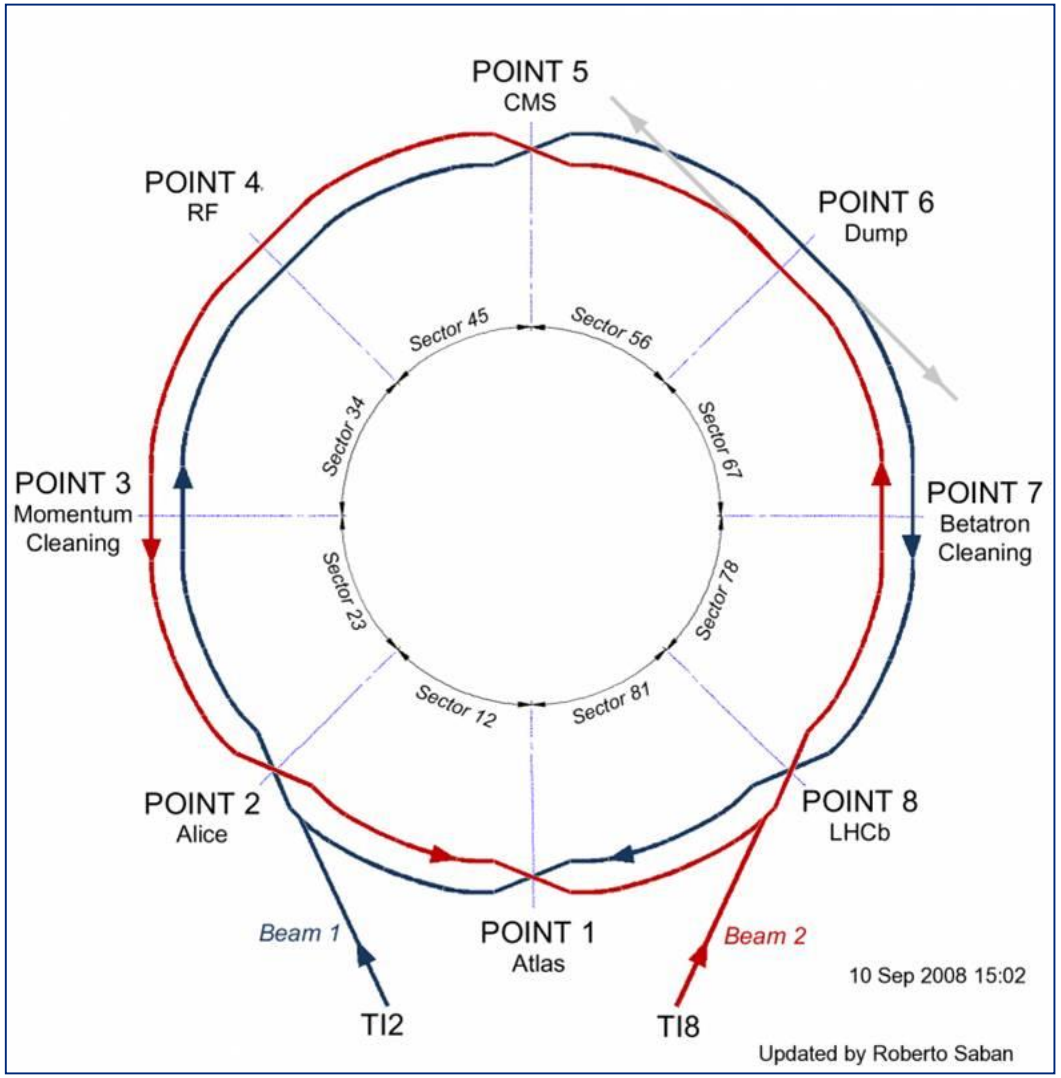




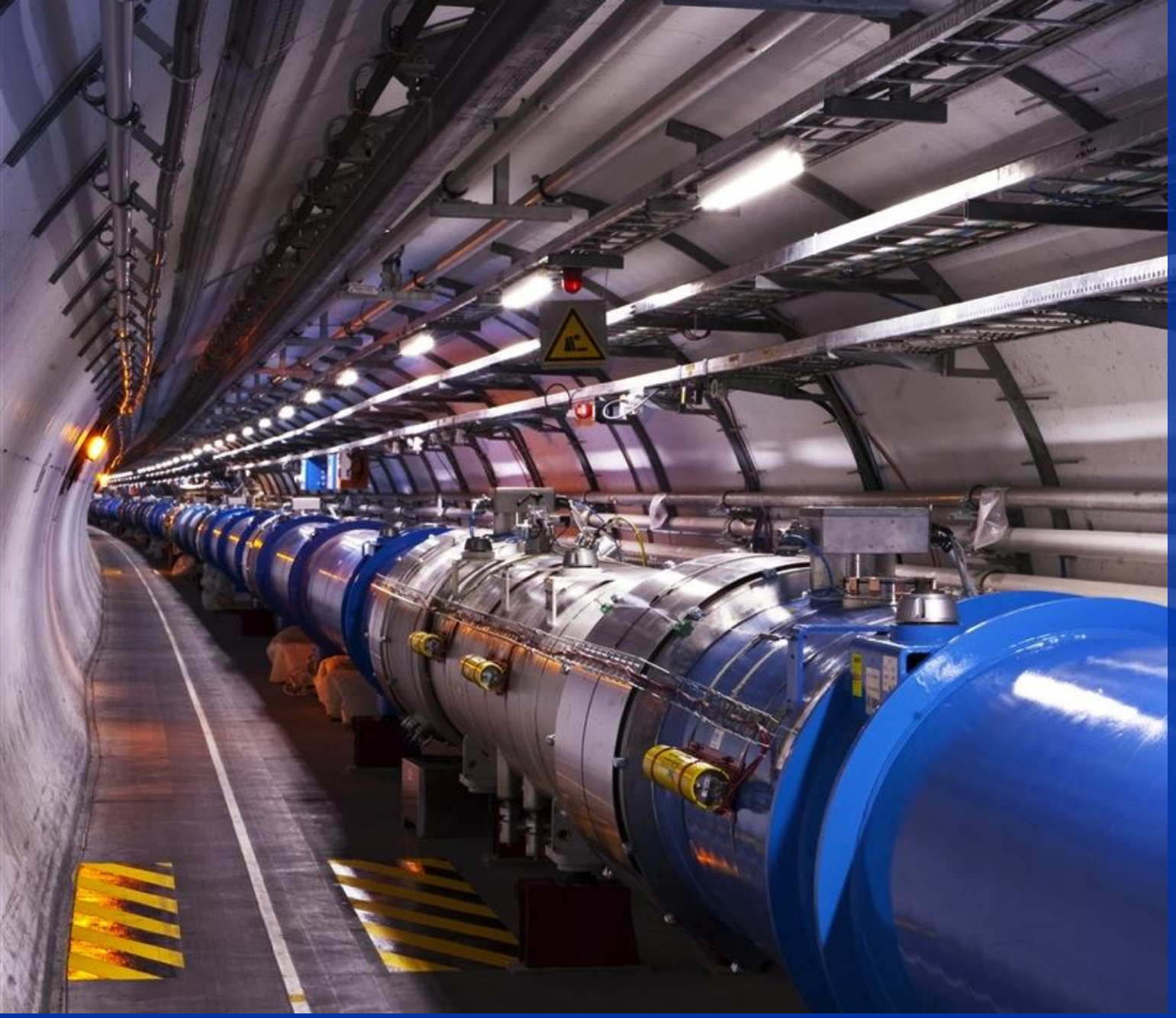


LHC





- **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

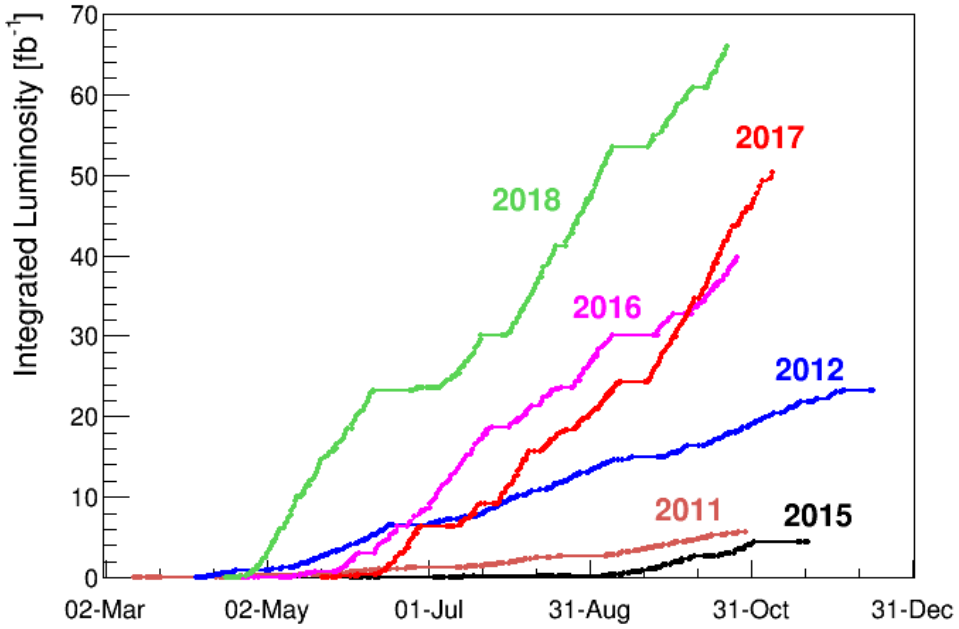
$$LUMINOSITY = \frac{N_{event/sec}}{s_r} = \frac{N_1 N_2 f_{rev} n_b}{4\pi s_x s_y} F$$

Intensity per bunch

Number of bunches

Geometrical Correction factors

Beam dimensions



Maximise Luminosity:

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

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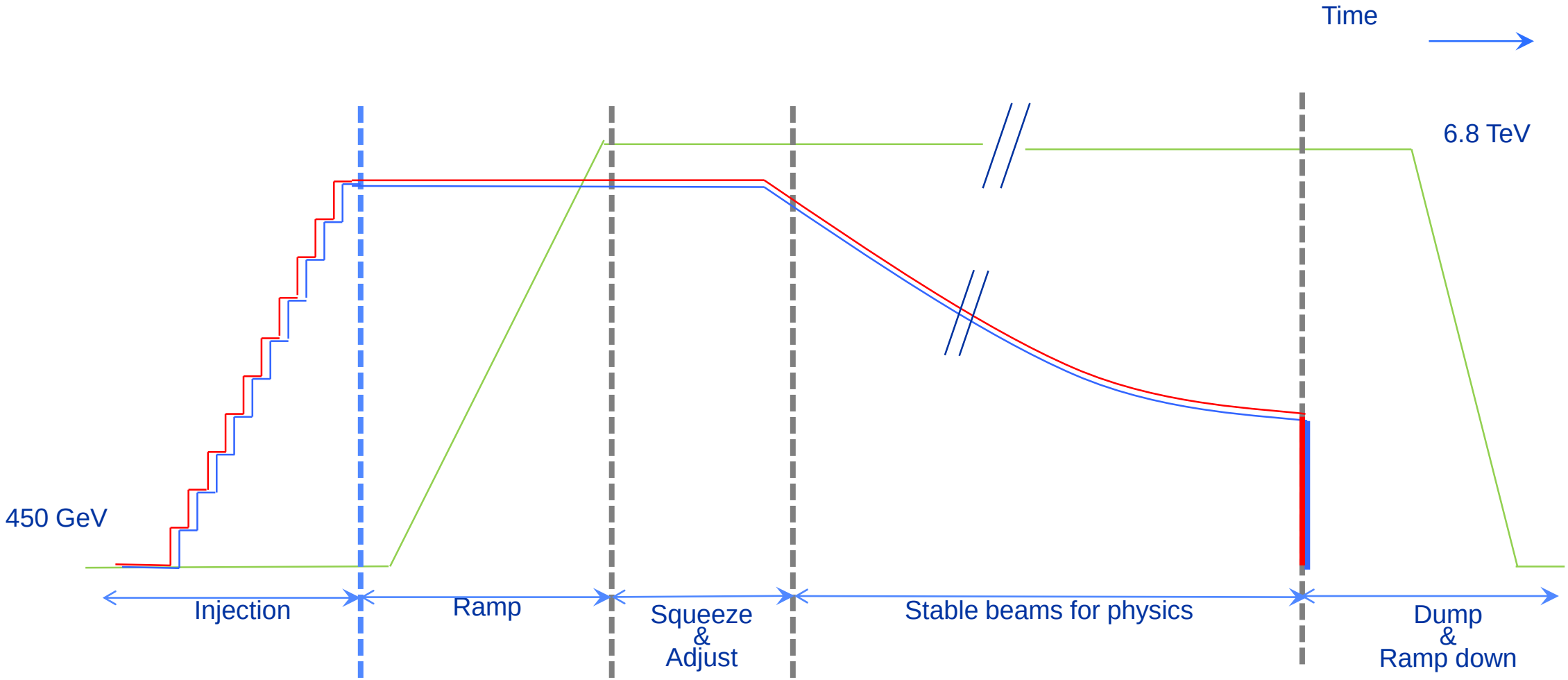
The LHC Cycle

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

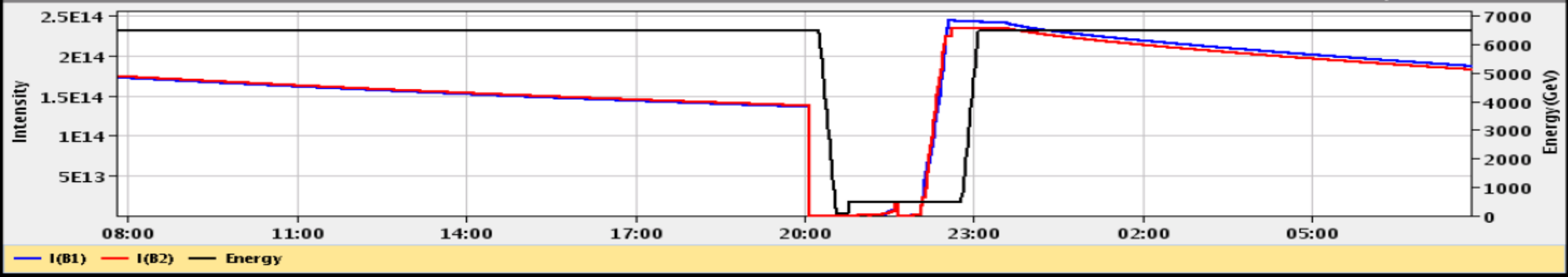


16-Oct-2016 07:48:46 | Fill #: 5418 | Energy: 6499 GeV | I(B1): 1.87e+14 | I(B2): 1.83e+14

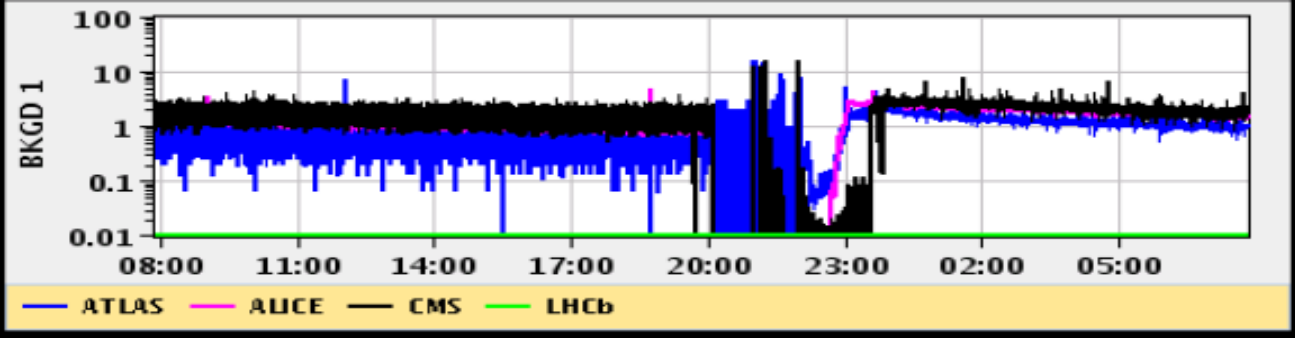
	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Lumi [(ub.s)^-1]	7346.231	1.672	7730.174	355.048
BRAN Luminosity [(ub.s)^-1]	7462.0	1.8	6917.8	181.2
Fill Luminosity (nb)^-1	265785.063	49.302	293245.594	10312.992
Beam 1 BKGD	0.927	1.401	1.645	0.000
Beam 2 BKGD	4.488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

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

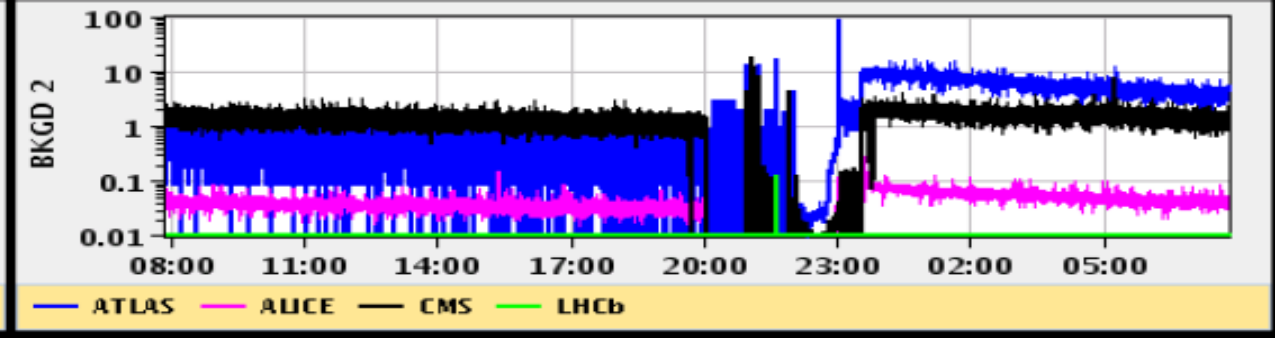
Performance over the last 24 Hrs — Updated: 07:48:42



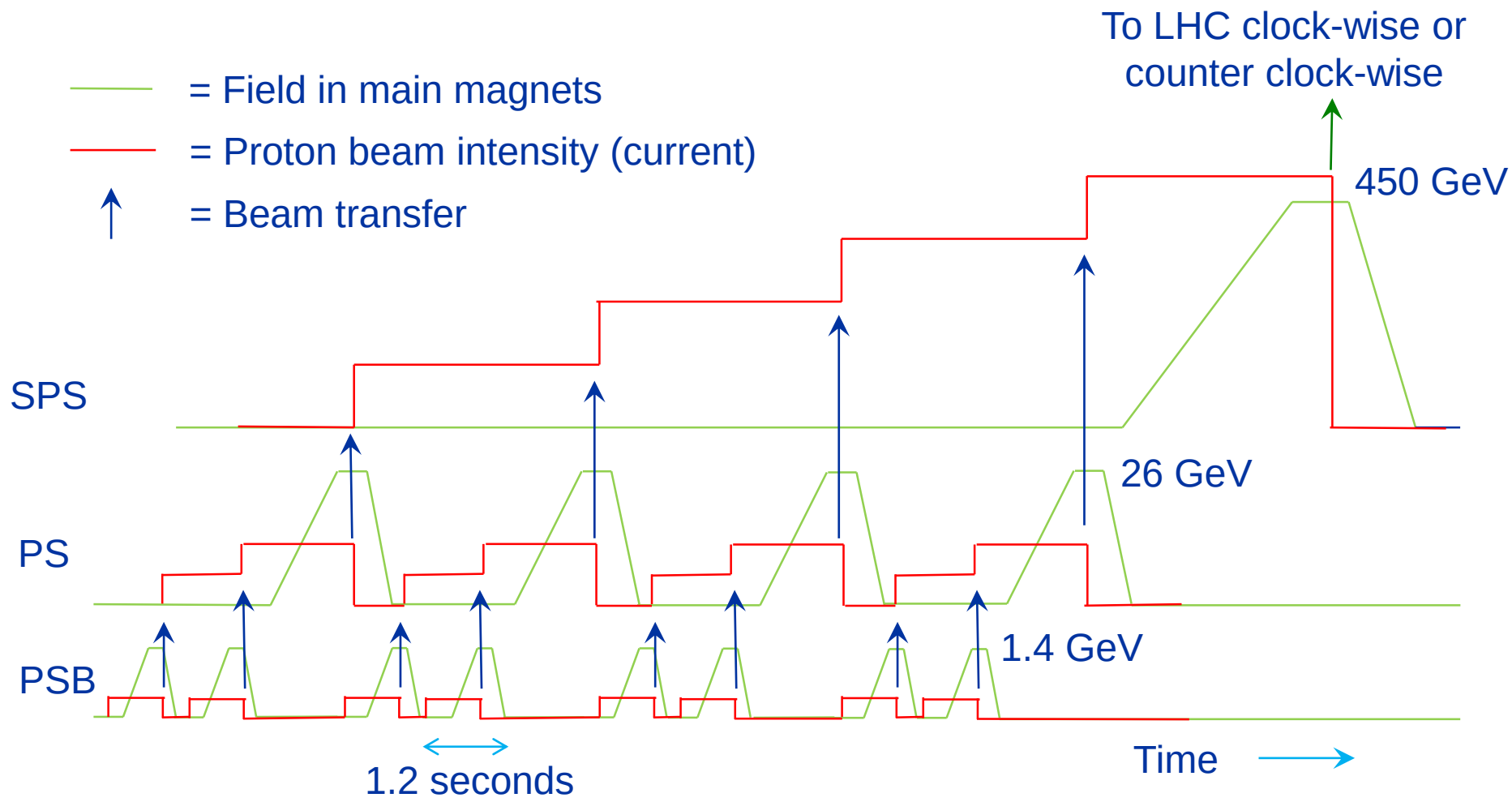
Beam 1 BKGD — Updated: 07:48:41



Beam 2 BKGD — Updated: 07:48:41



Filling the LHC & Satisfying Fixed Target users



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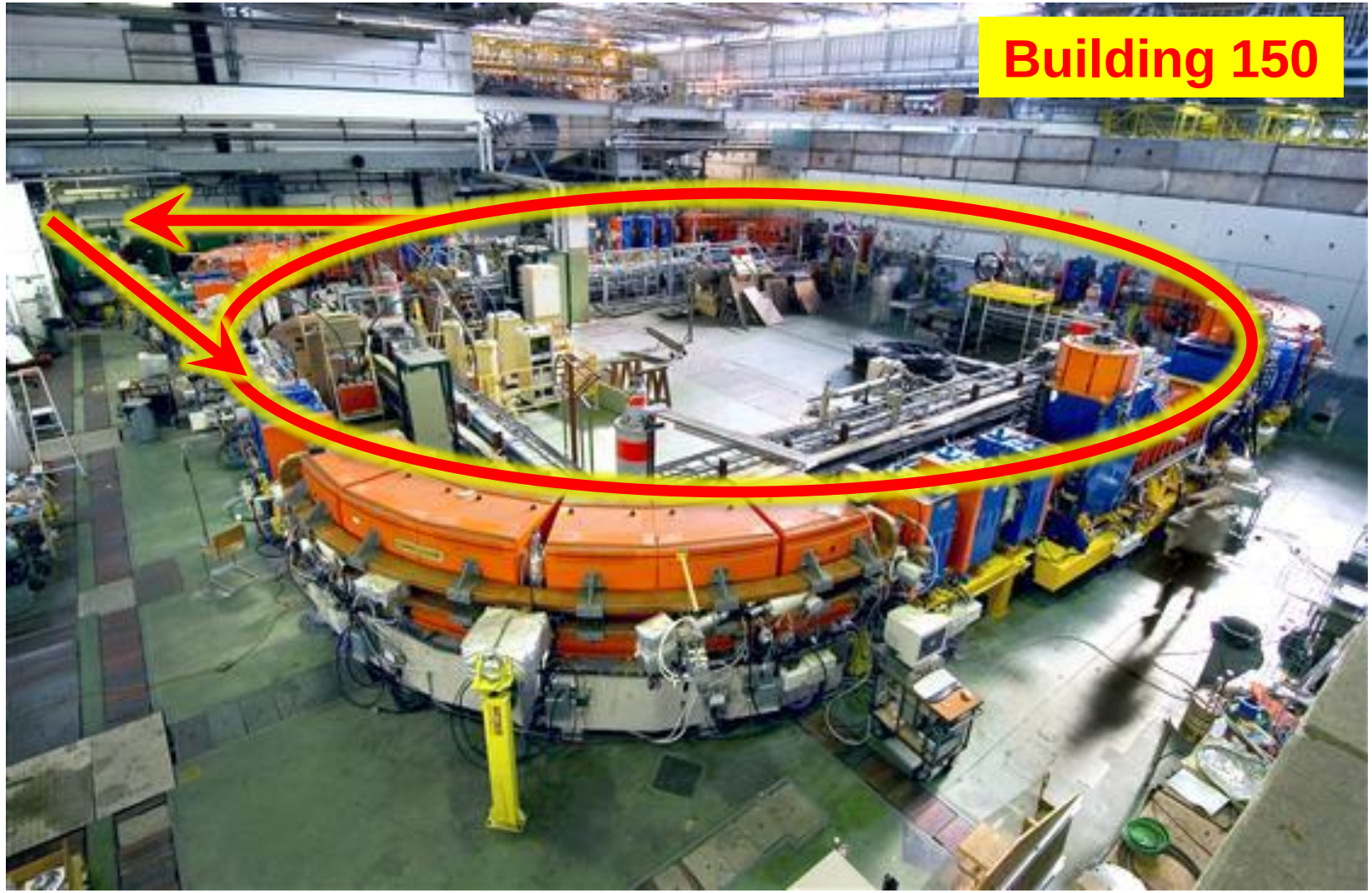
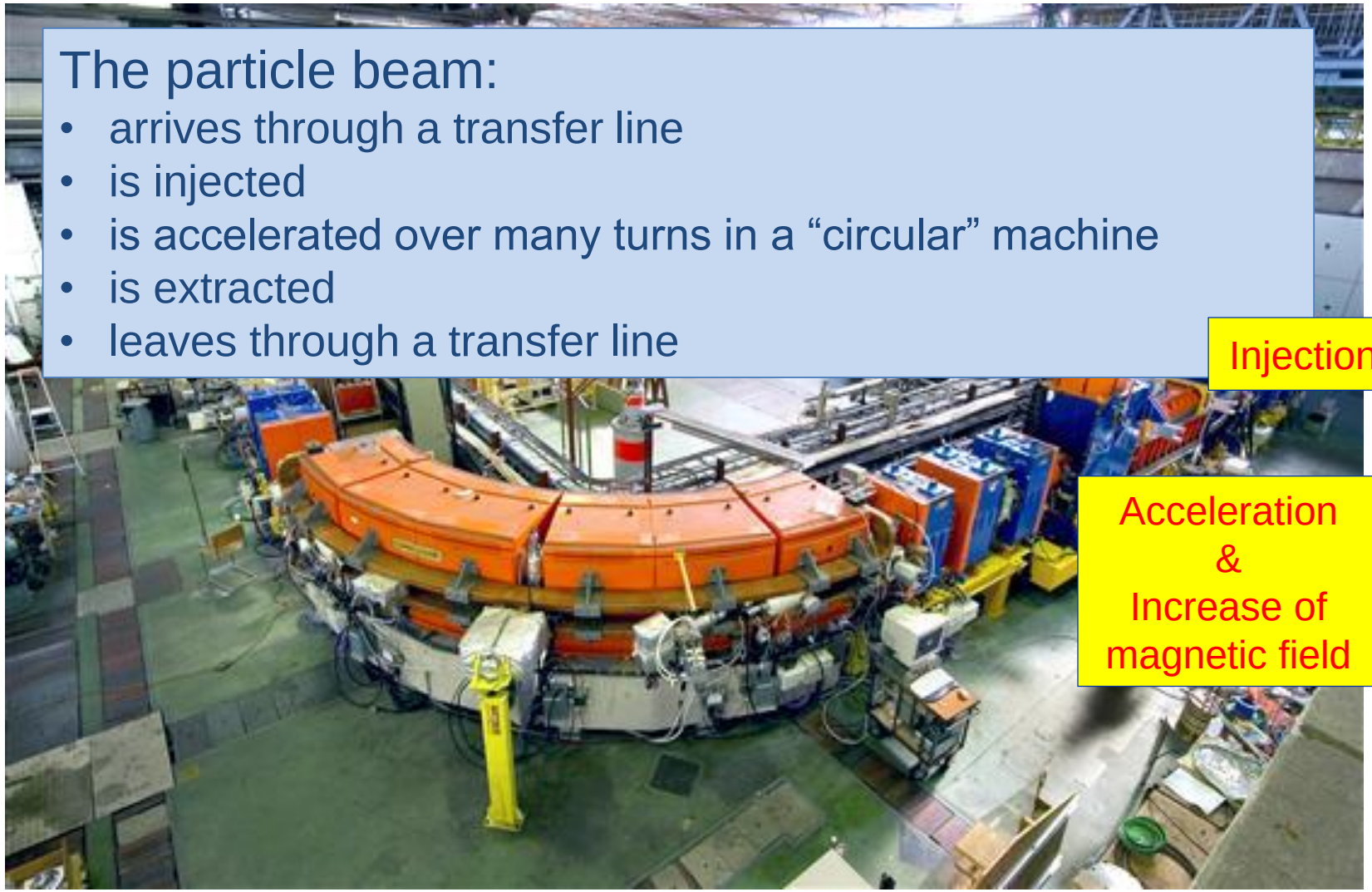
The LEIR Accelerator as Example

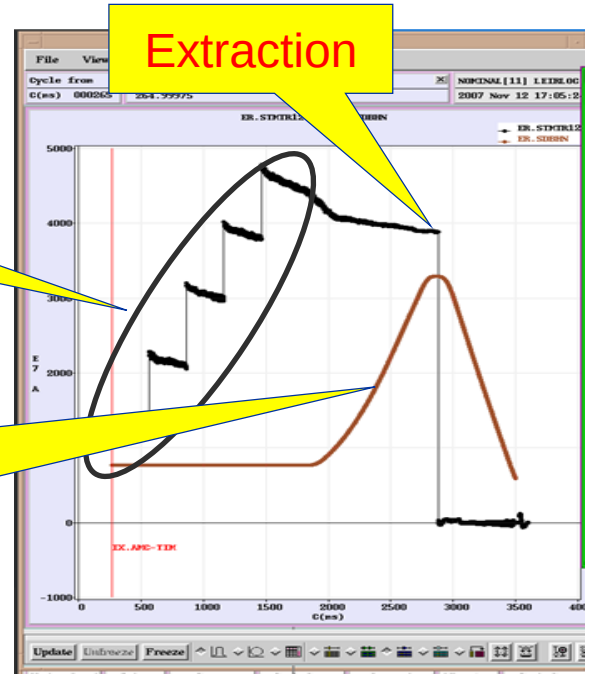


Vacuum Chamber

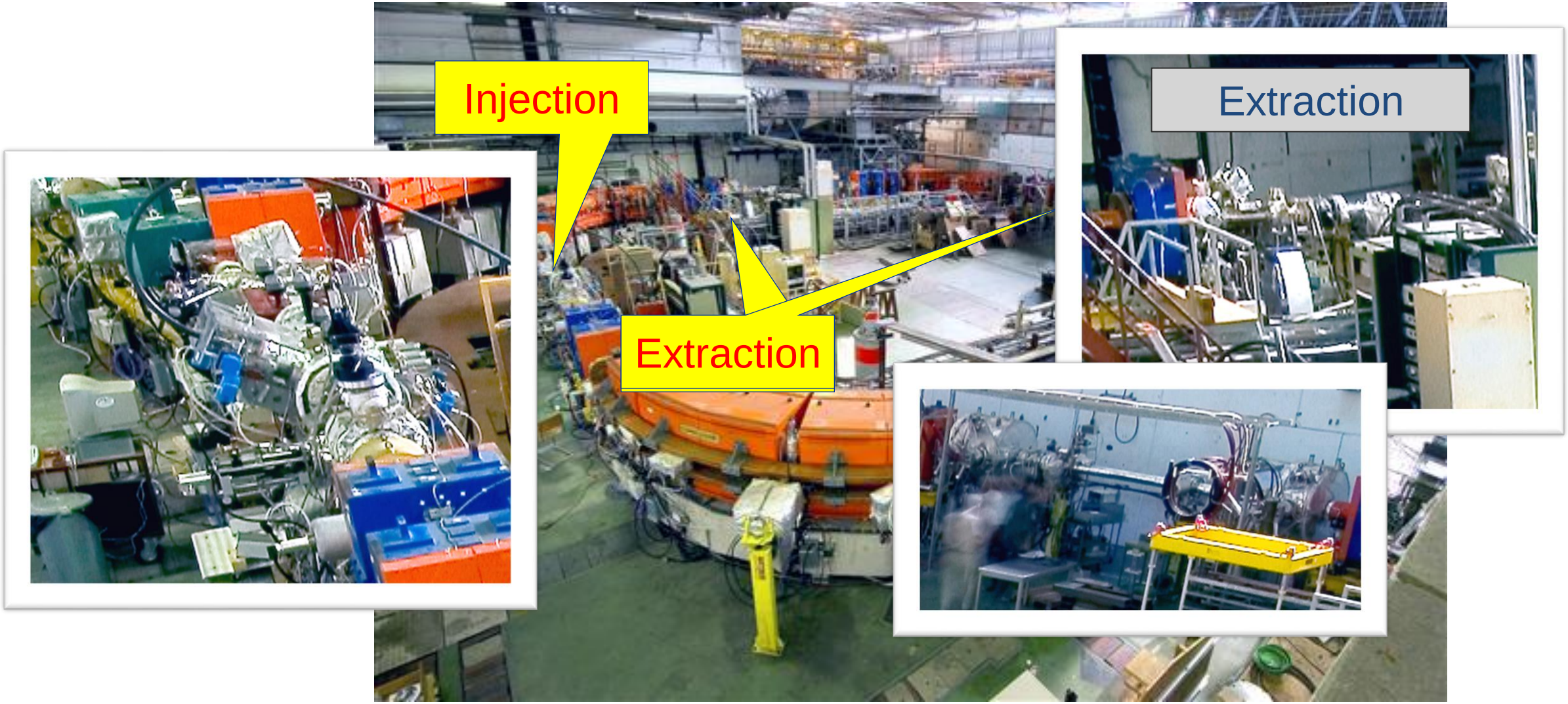
The particle beam:

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

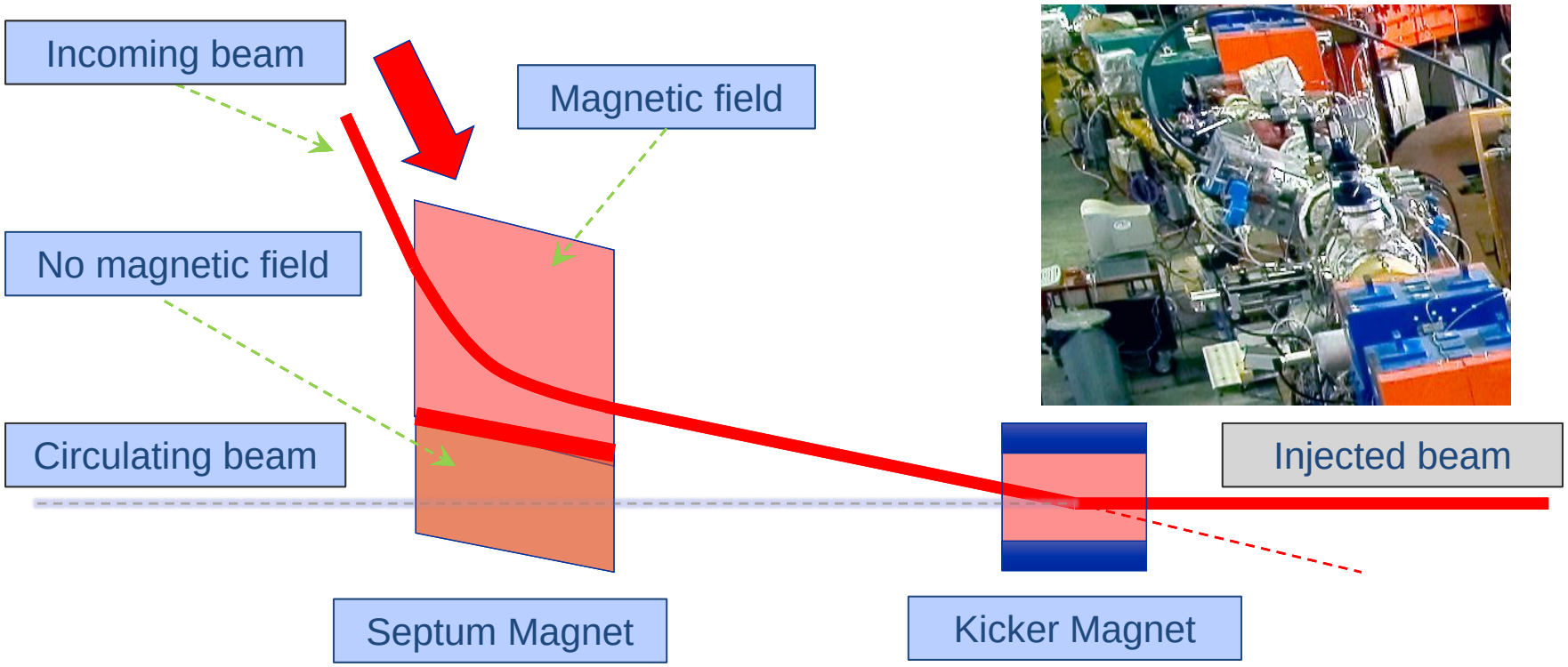




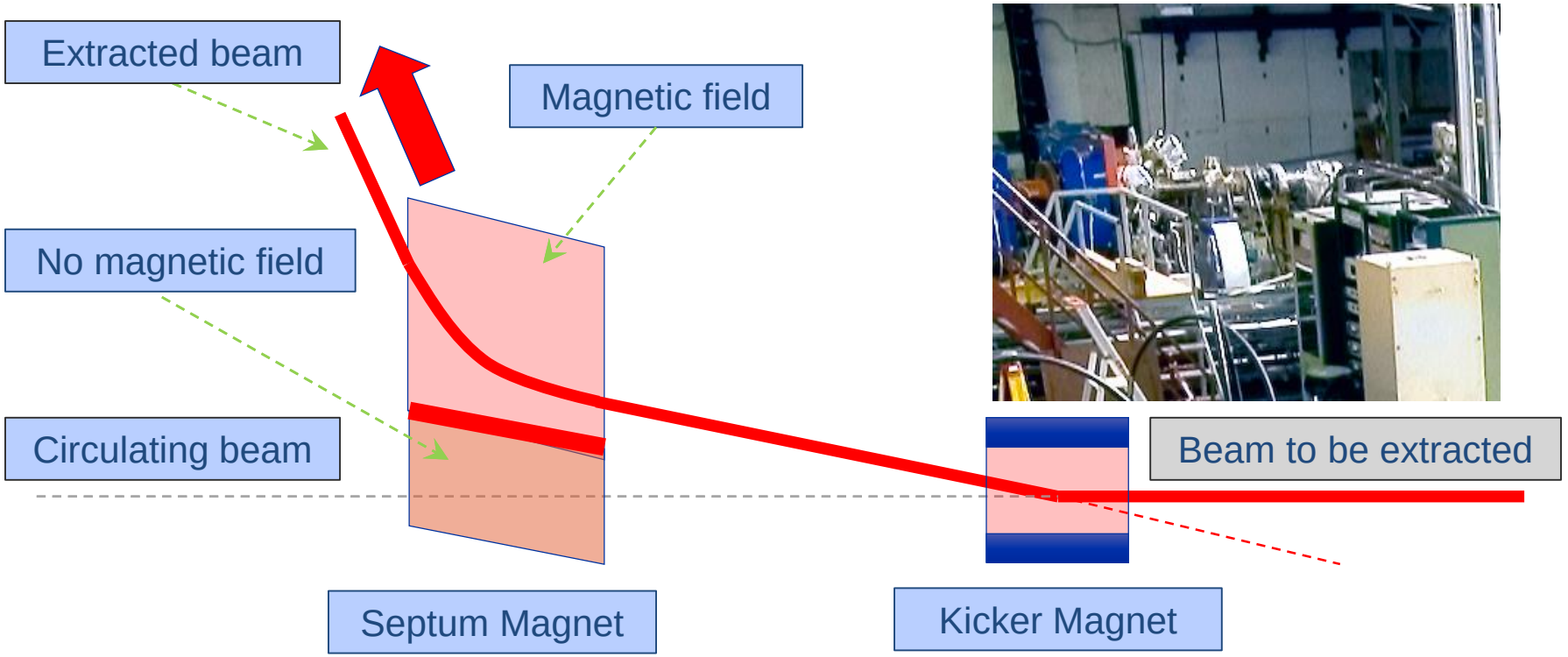
Injecting & Extracting Particles



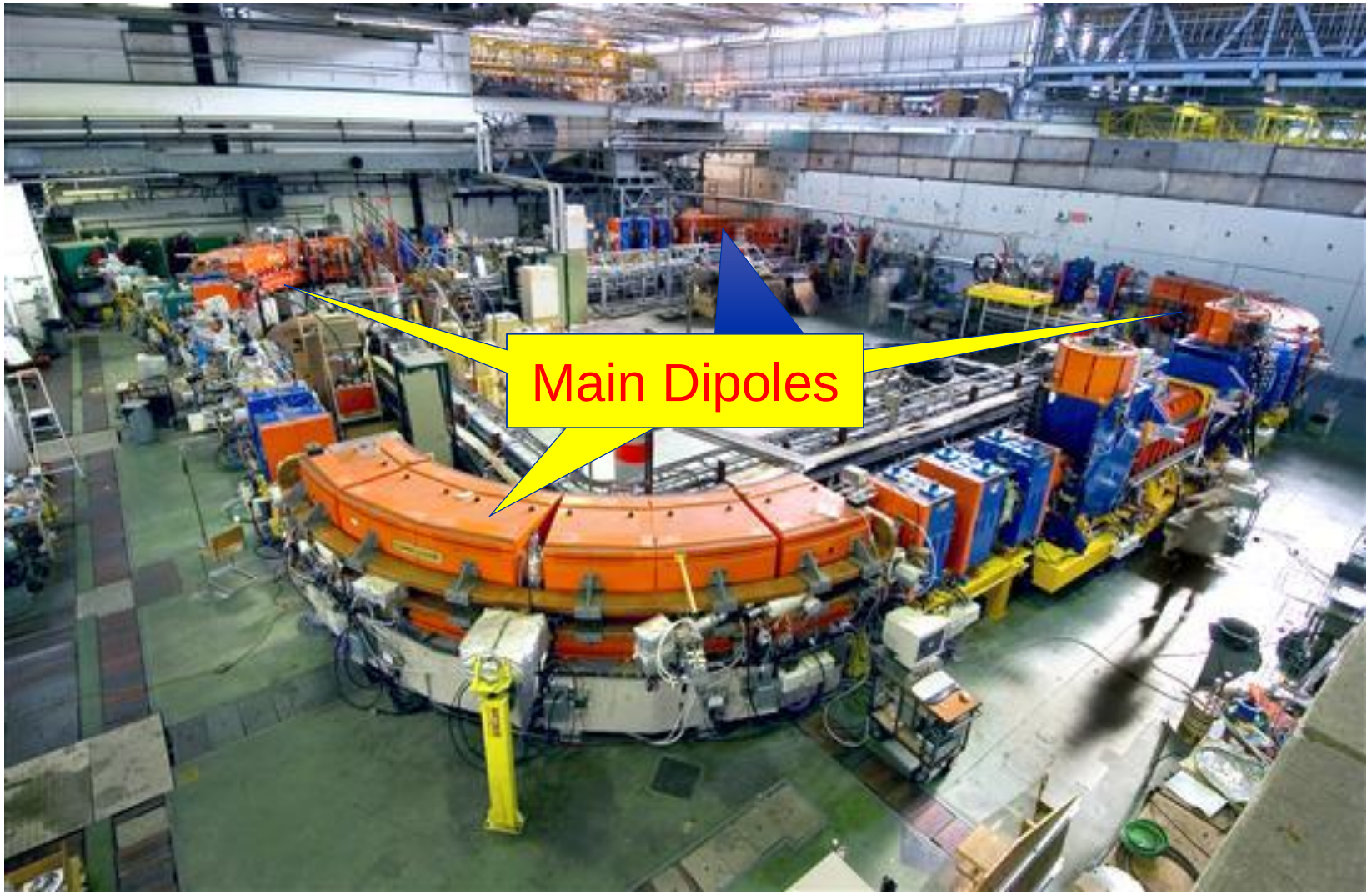
Injecting & Extracting Particles



Injecting & Extracting Particles

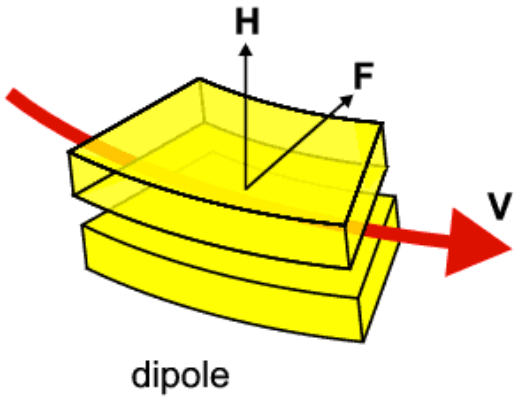


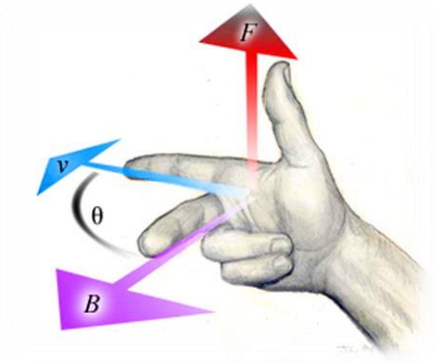
Make Particles Circulate



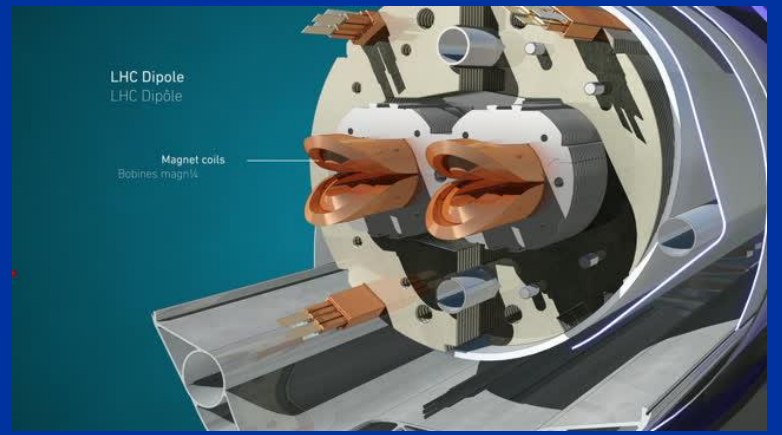
Deviating Charged Particles

Moving charged particles are deviated in a magnetic field



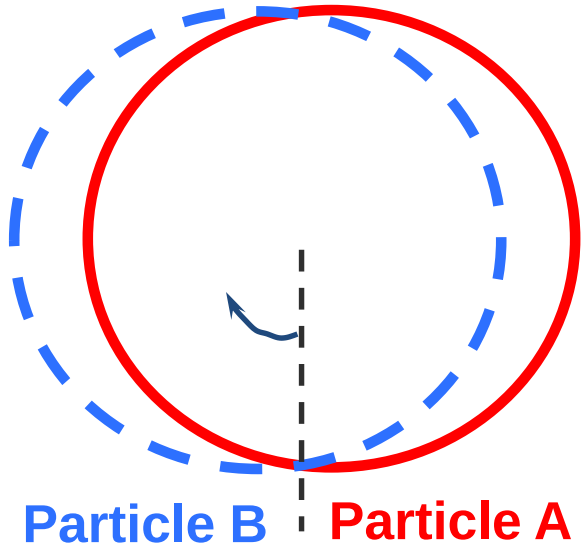


Magnetic Lorentz Force: $F = e(\vec{v} \times \vec{B})$

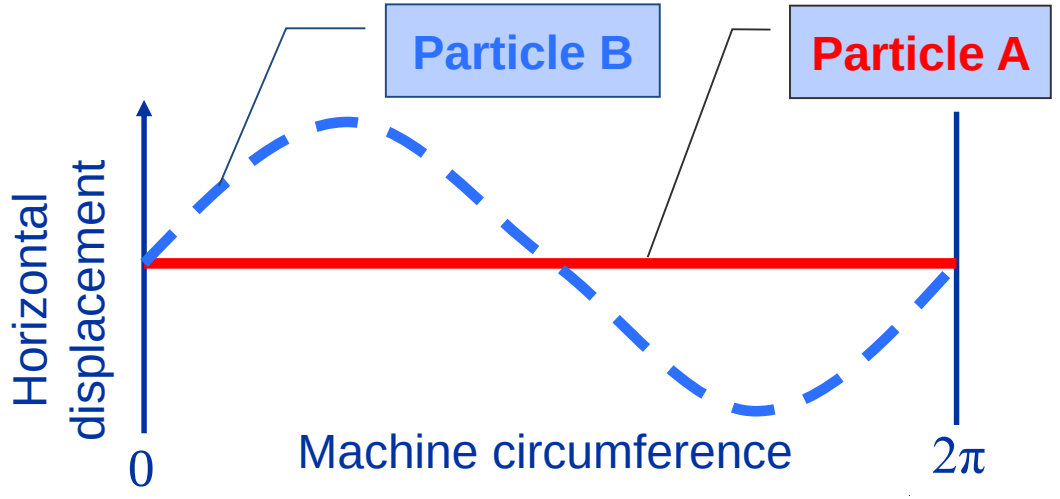


Oscillatory Motion in the Horizontal Plane

Two charged Particles in a homogeneous magnetic field



Horizontal motion

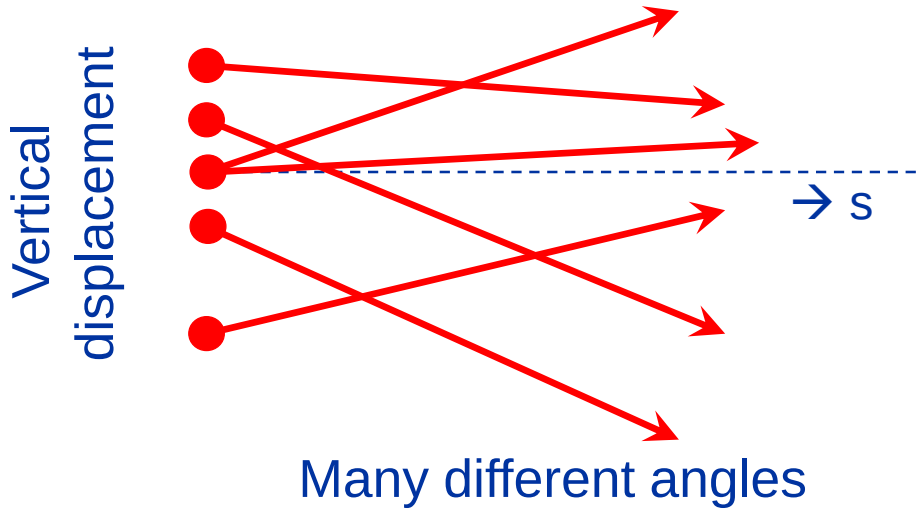


Different particles with different initial conditions in a homogeneous magnetic field will cause oscillatory motion in the horizontal plane → **Betatron Oscillations**

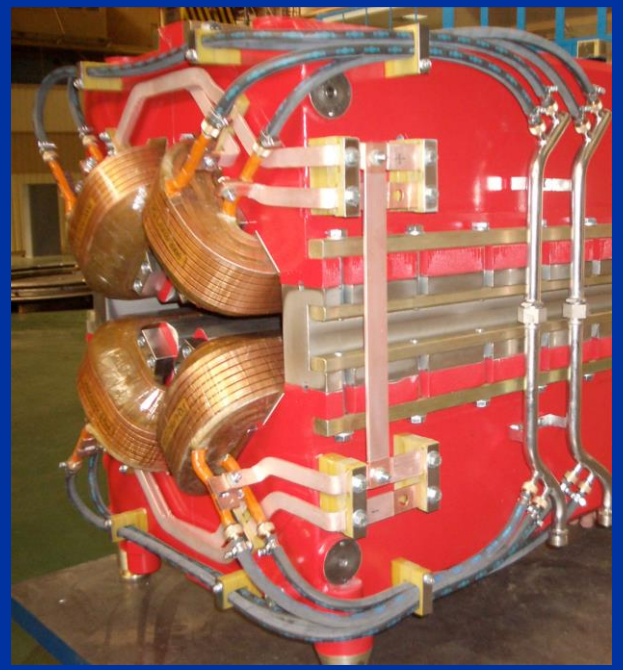
Oscillatory Motion in the Vertical Plane

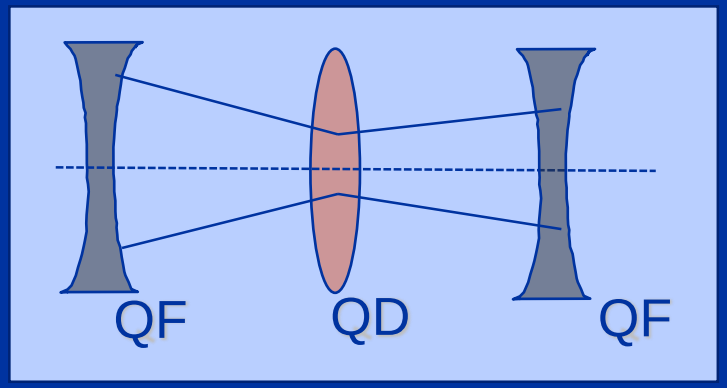
The horizontal motion seems to be “stable”…. What about the vertical plane ?

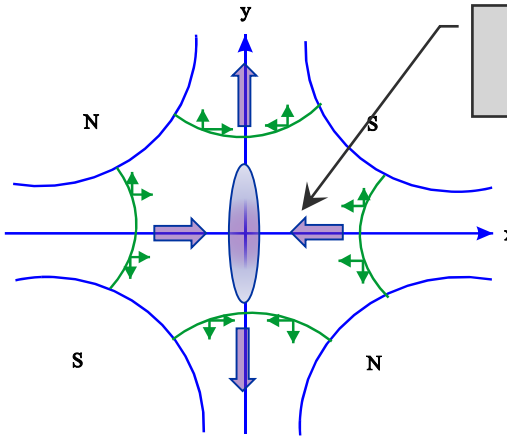
Many particles many initial conditions



Focusing Particle Beams, a bit like a lens



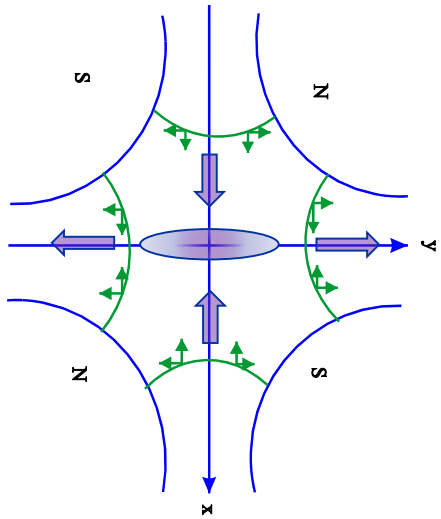




Force on particles

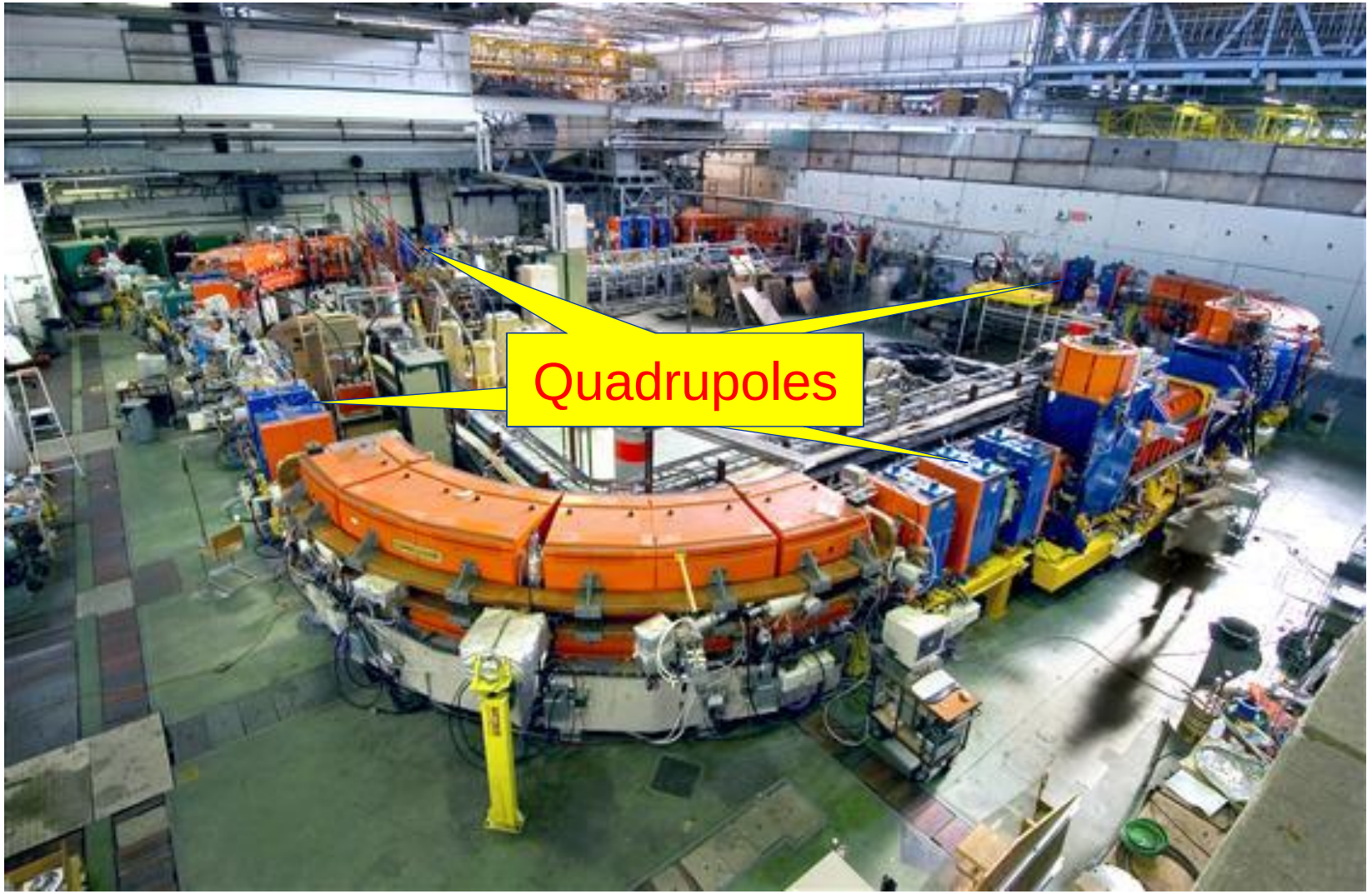
Focusing Quadrupole

Rotated by 90º



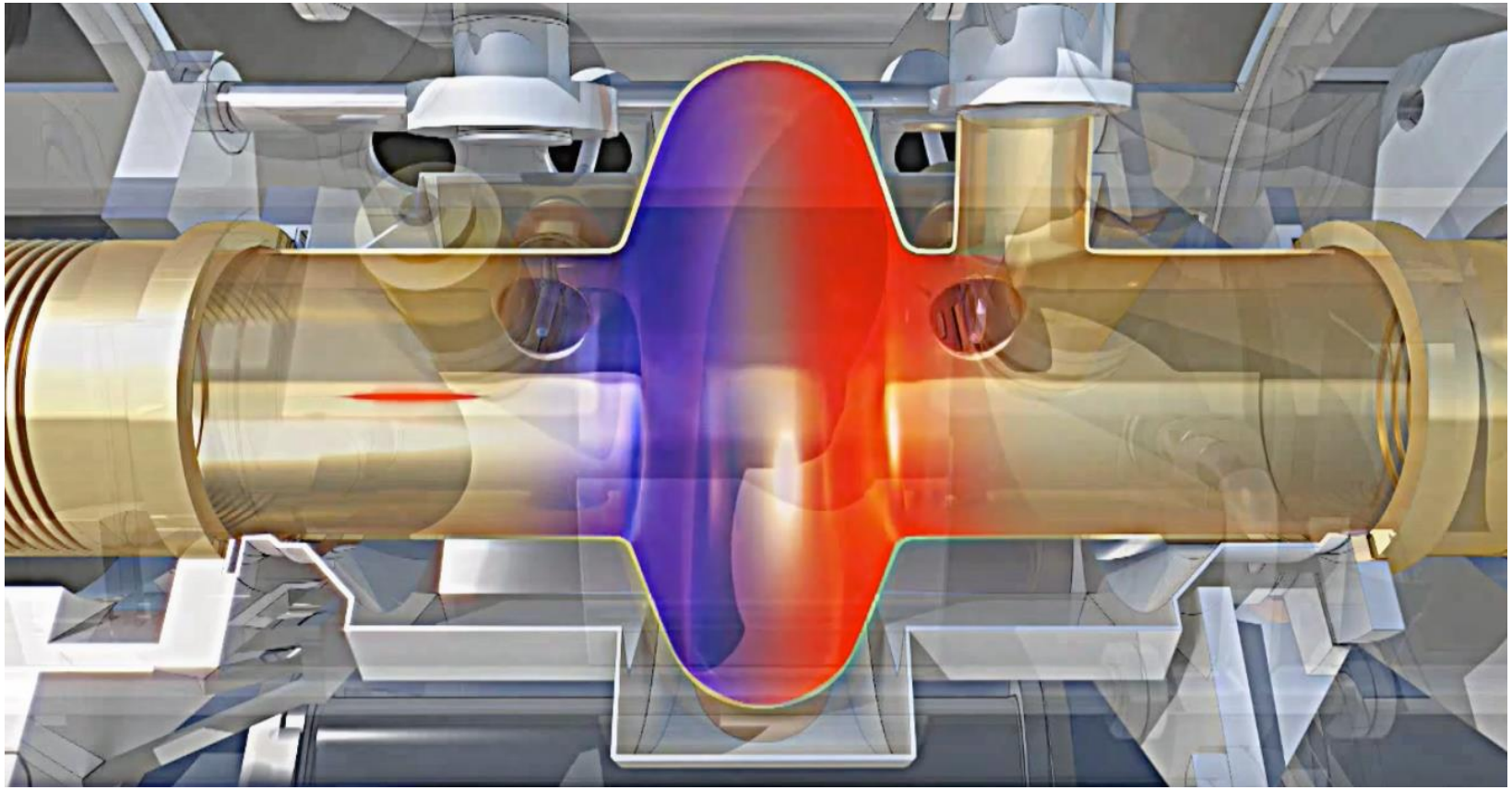
De-focusing Quadrupole

Focusing Particle Beams in LEIR



Accelerating Particles, Using Electrical Fields

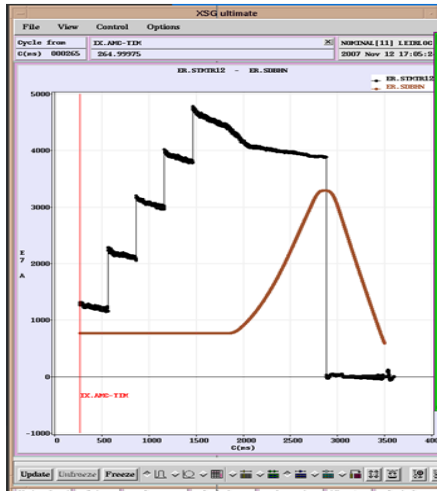
Radio Frequency Cavity



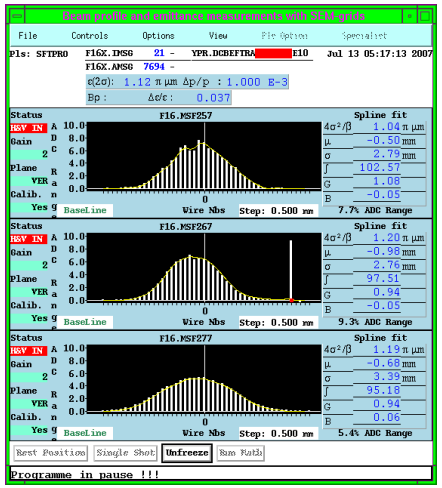
Charged particles are accelerated by a longitudinal electric field

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

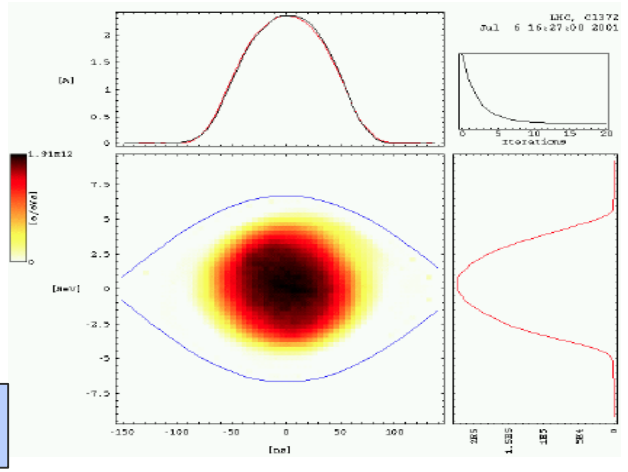
The Eyes of Operations



Beam intensity or current measurement



Transverse beam profile/size measurement



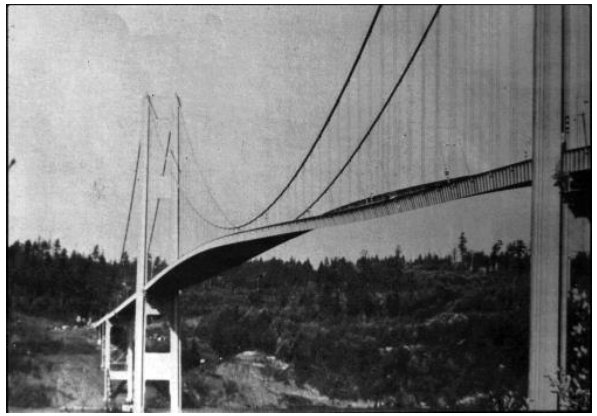
Longitudinal beam profile measurements

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

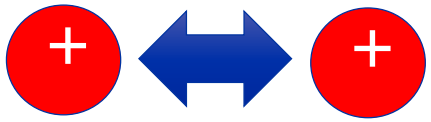
Any many more beam properties…..

Possible Limitations

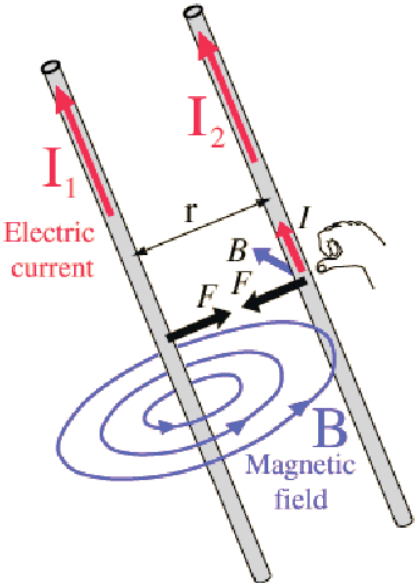
Machines and elements cannot be built with infinite perfection



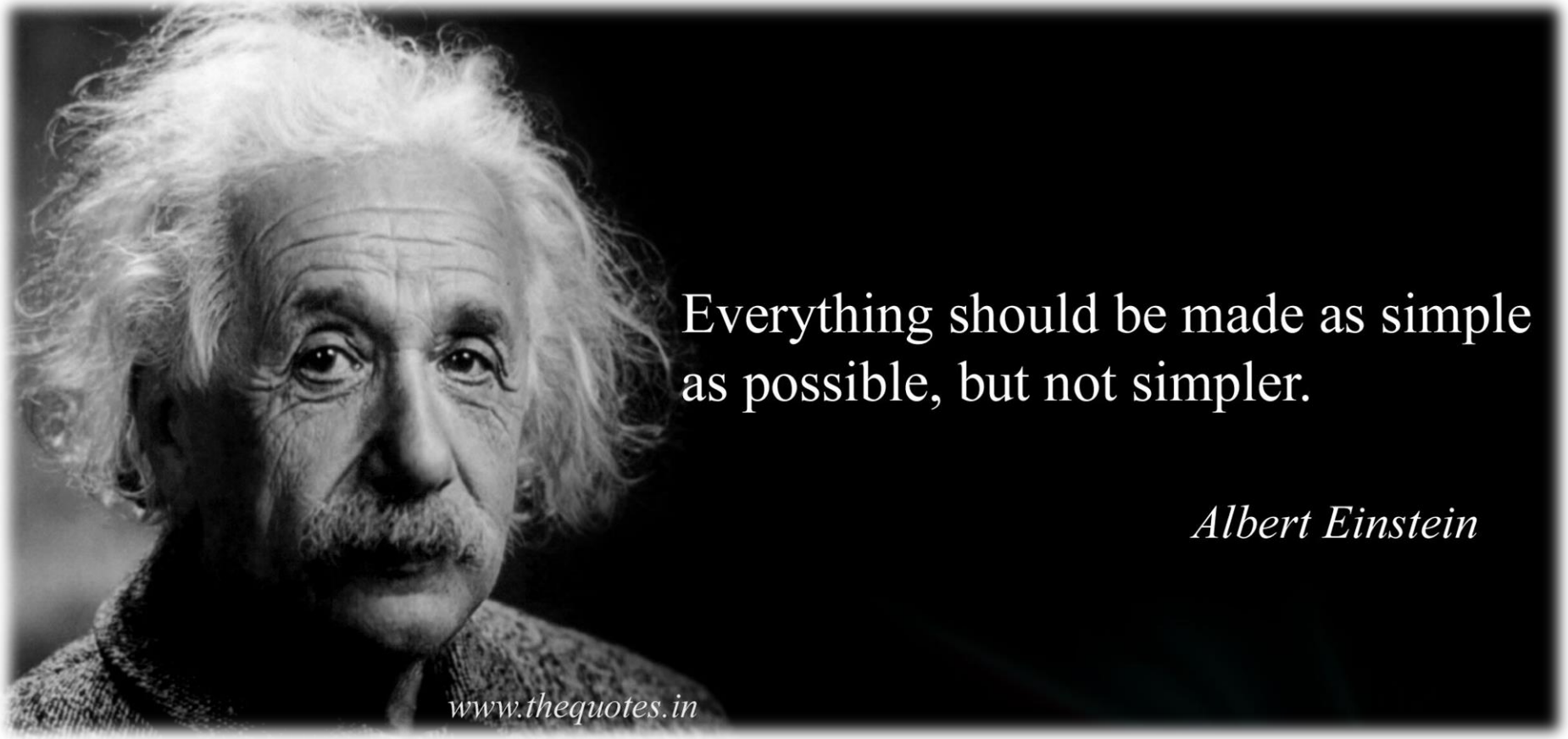
Same phase and frequency for driving force and the system can cause resonances and be destructive



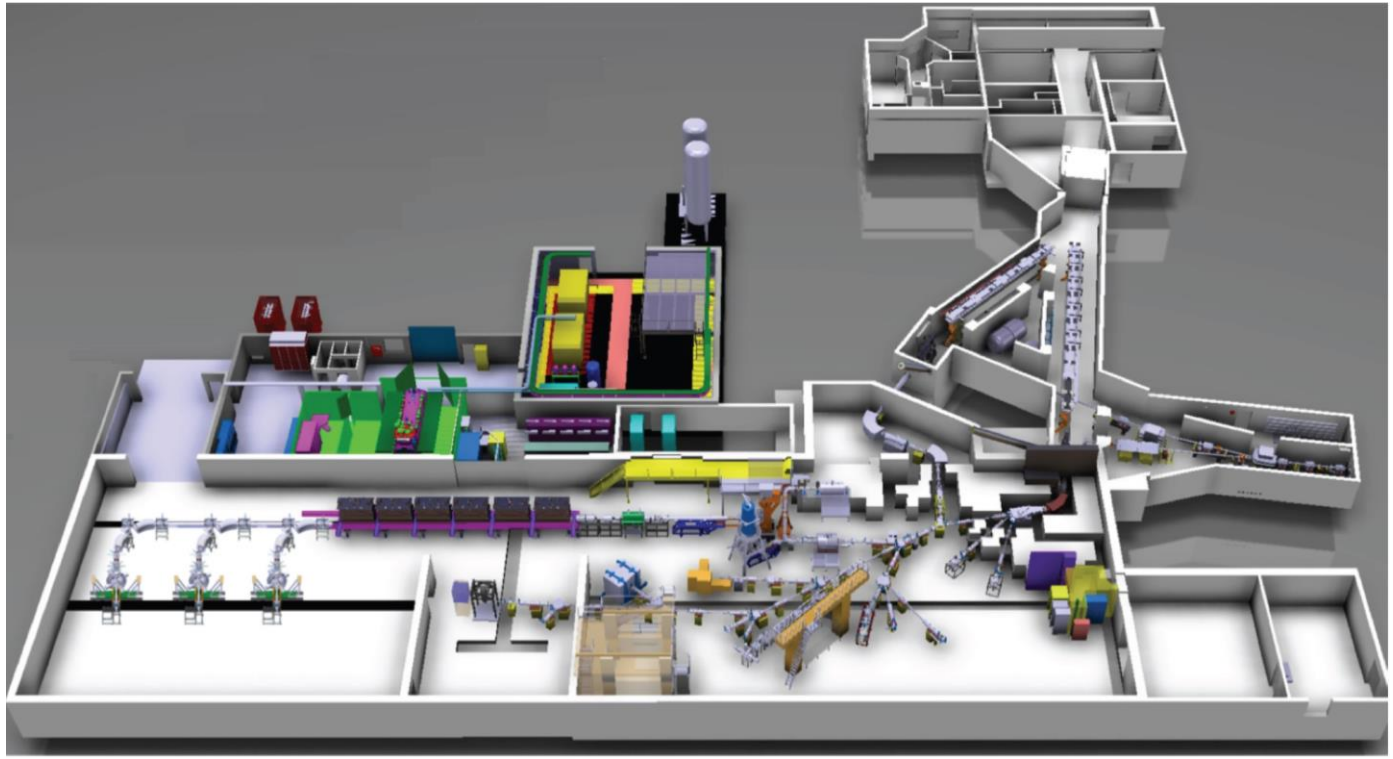
Neighbouring charges with the same polarity experience repelling forces



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


Everything should be made as simple as possible, but not simpler.
Albert Einstein
www.thequotes.in

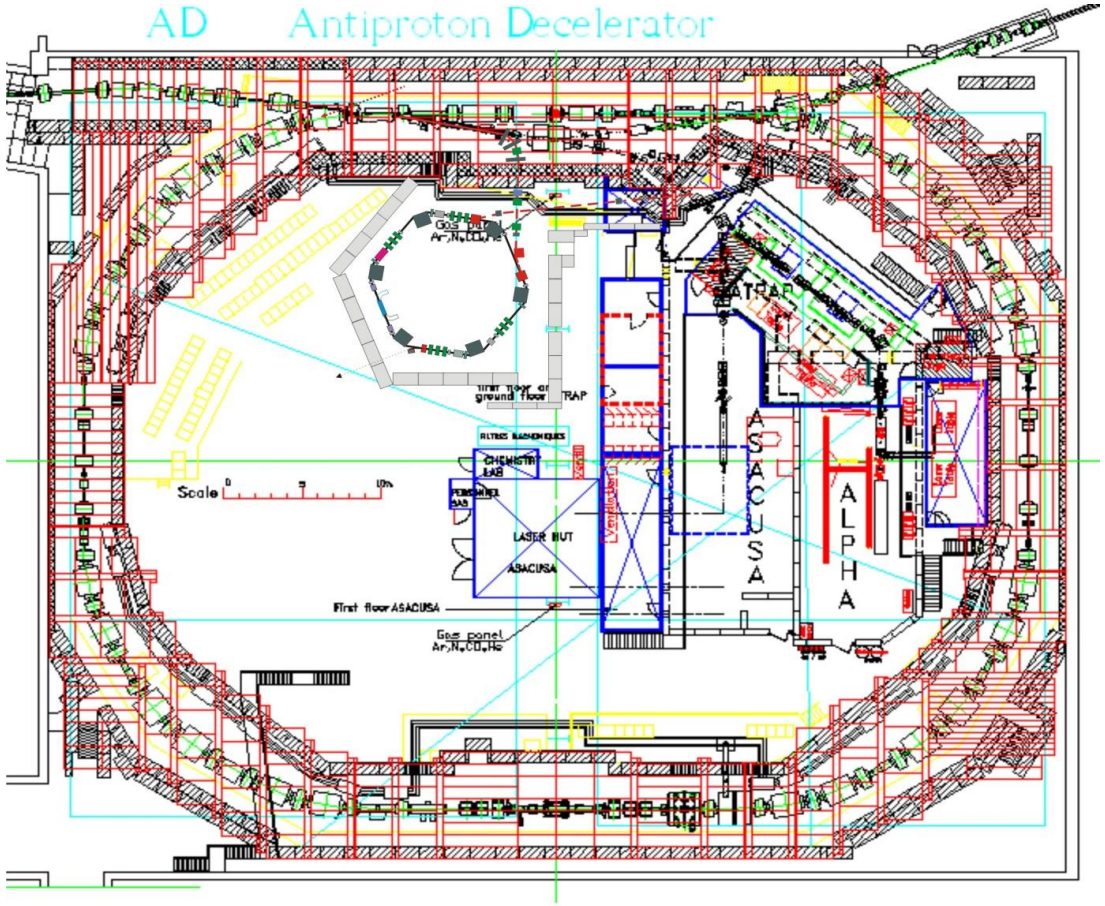
ISOLDE / HIE-ISOLDE



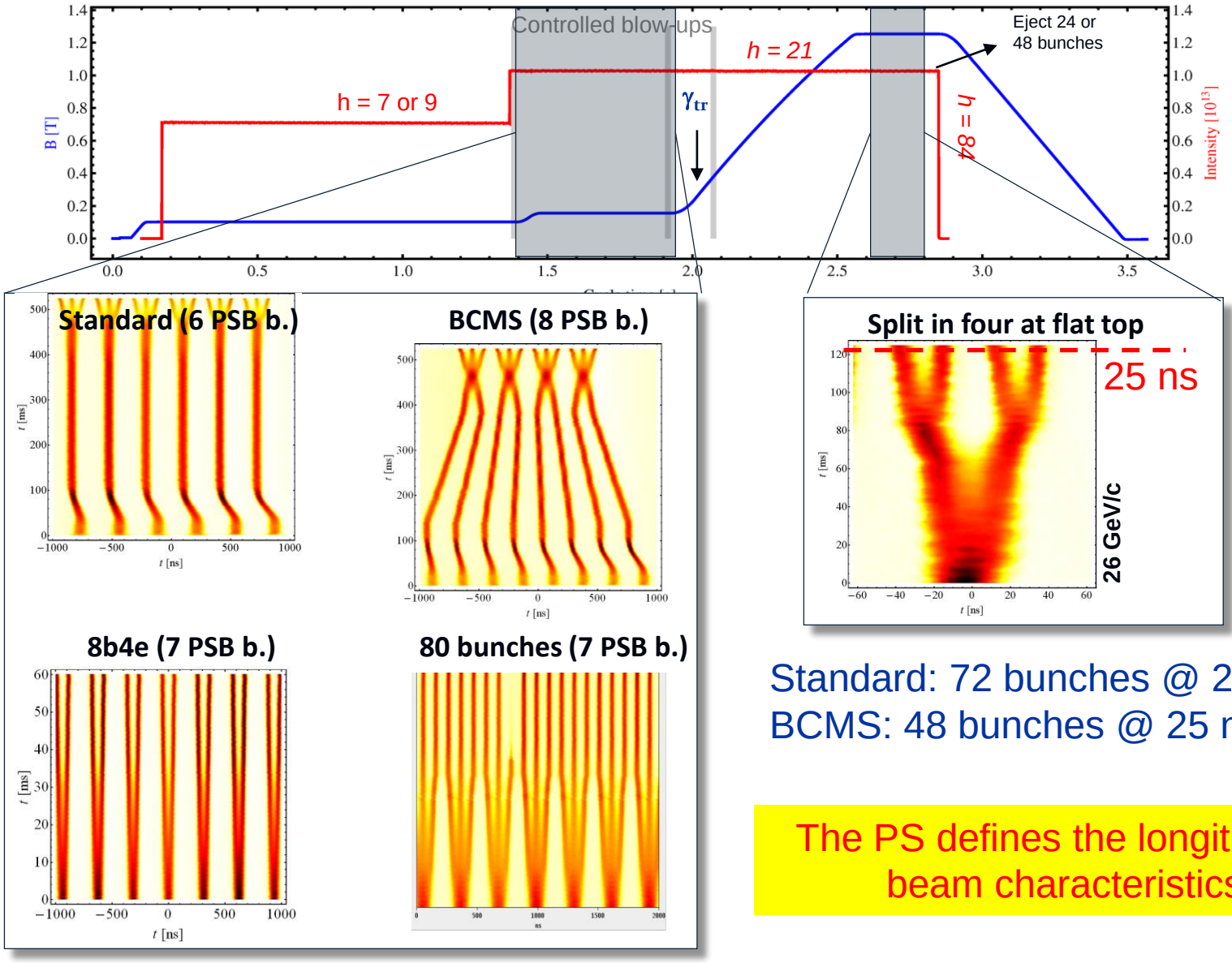
- **The PSB proton beam impinges on a target producing a range of isotopes**
- **Two mass separators (GPS & HRS) allow selection of isotopes**
- **The post acceleration of isotopes is being extended**
  - REX, normal conducting accelerating structures
  - HIE-ISOLDE, super conducting LINAC

AD-ELENA

- **Receives fast extracted proton beam from PS at 26 GeV/c on a target**
- **Every million protons yields about one usable antiproton at 3.5 GeV/c.**
- **AD decelerates beam in stages down to 5.3 MeV**
- **ELENA will further decelerate down to 100 keV**
- **Experiments:**
  - ASACUSA, ALPHA, AEGIS, BASE, GBAR



PS for LHC

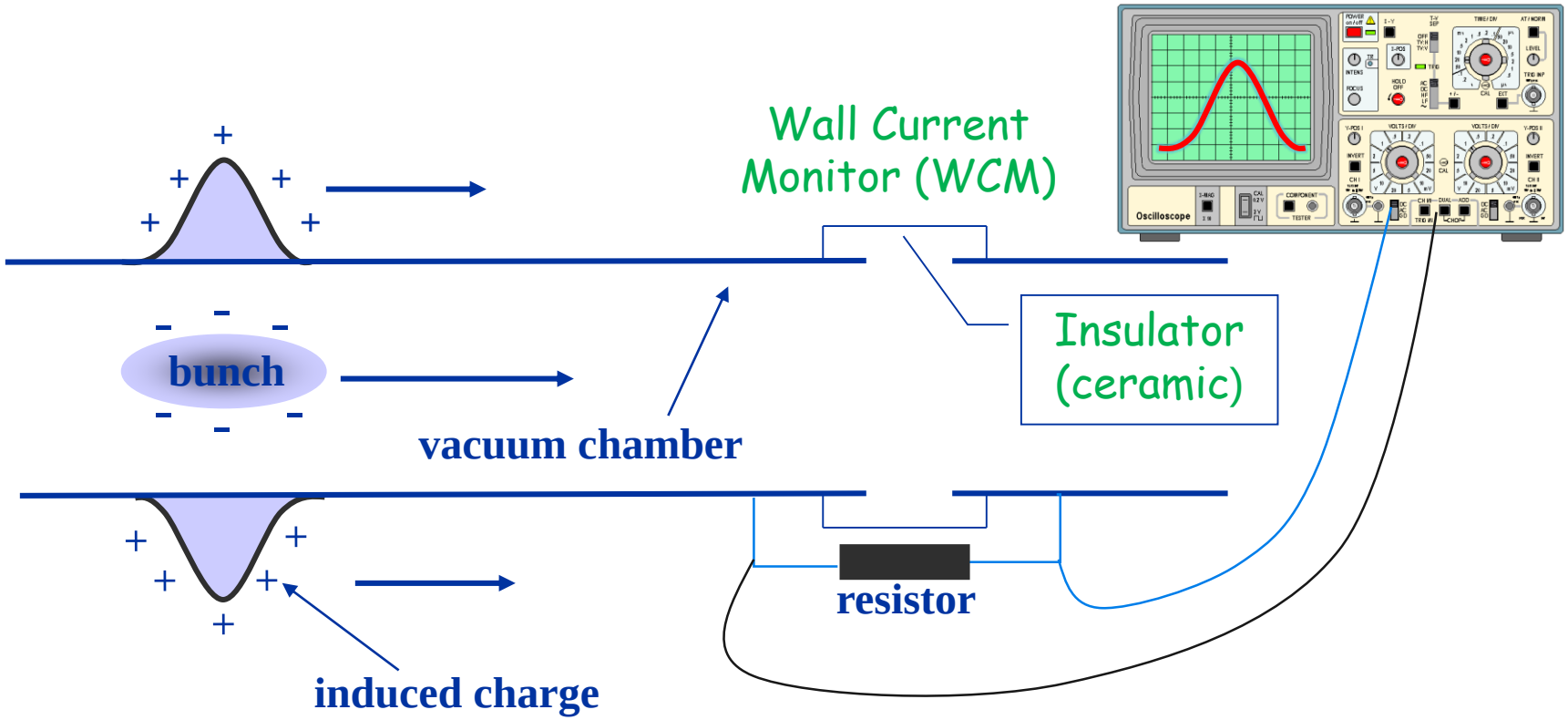


Standard: 72 bunches @ 25 ns
BCMS: 48 bunches @ 25 ns

The PS defines the longitudinal beam characteristics

Example: Wall Current Monitor

A circulating bunch creates an image current in vacuum chamber.



The induced image current is the same size but has the opposite sign to the bunch current.