
CERN

Introduction to Accelerators

Part 1 of 2 : Introduction & CERN Accelerator Complex

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Topics

- A brief Word on Accelerator History
- The CERN Accelerator Complex
- A Brief Word on Relativity & Units

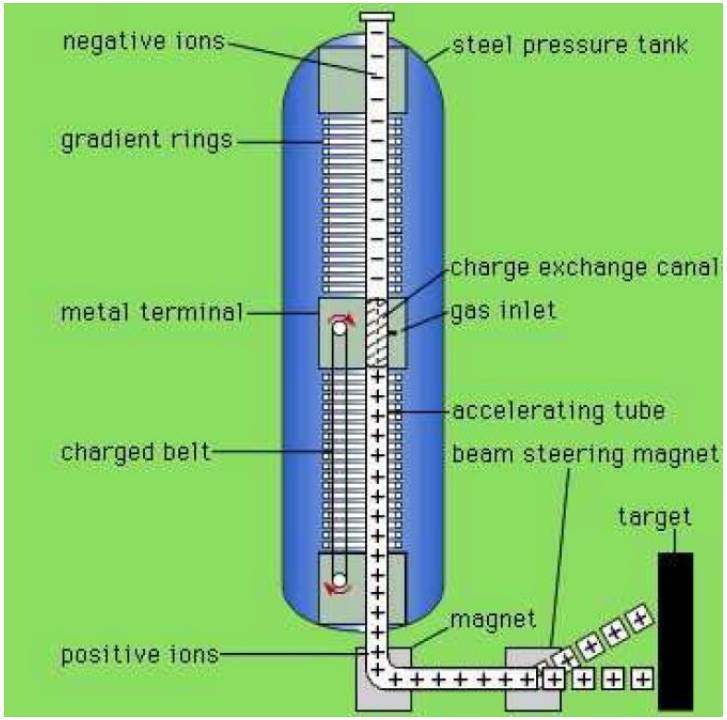
Q1: Accelerators

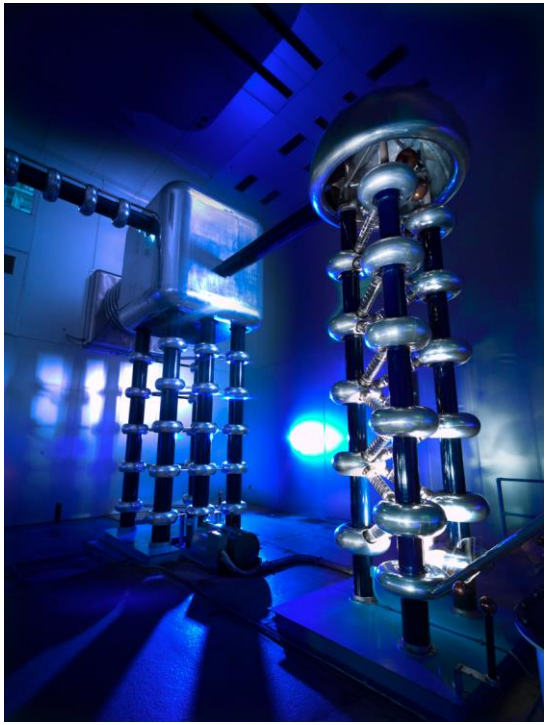
- What do you know about accelerators ?
- Do you have an idea how an accelerator works ?
- What do you think are the main components of an accelerator ?

A brief Word on Accelerator History

Cockroft & Walton / van de Graaff

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

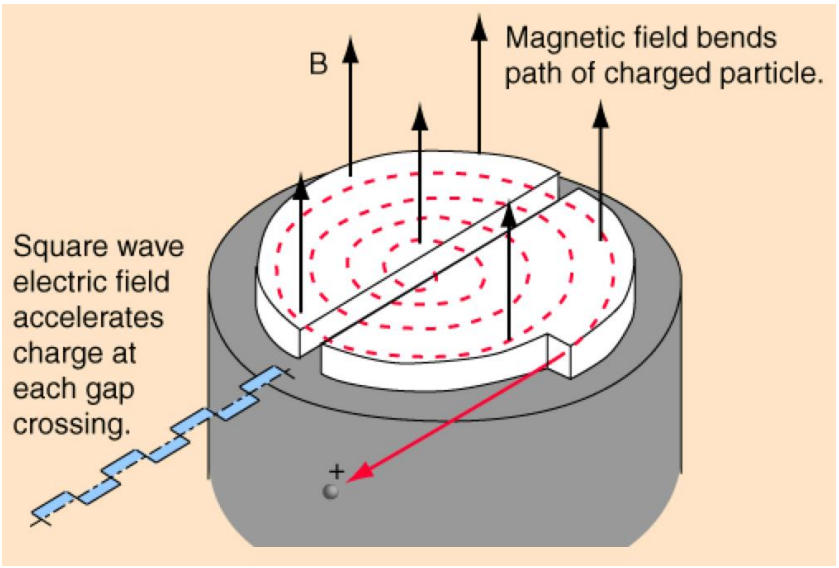




Cyclotron

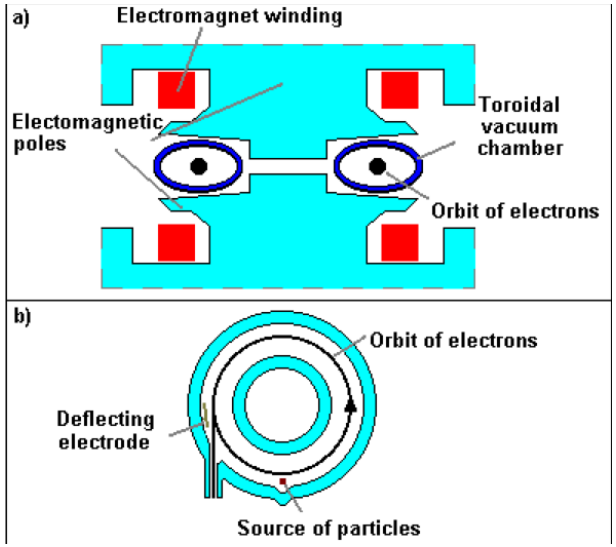
- 1932: 1.2 MeV – 1940: 20 MeV (E.O. Lawrence, M.S. Livingston)
- **Constant magnetic field** resulting in E = 80 keV for 41 turns
- Alternating voltage between the two D's
- **Increasing particle orbit radius**
- Development lead to the synchro-cyclotron to cope with the relativistic effects (Energy ~ 500 MeV)

In 1939 Lawrence received the Noble prize for his work.



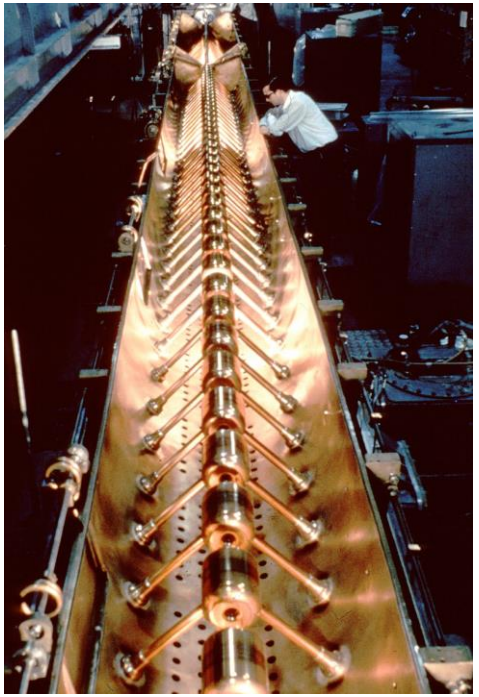
Betatron

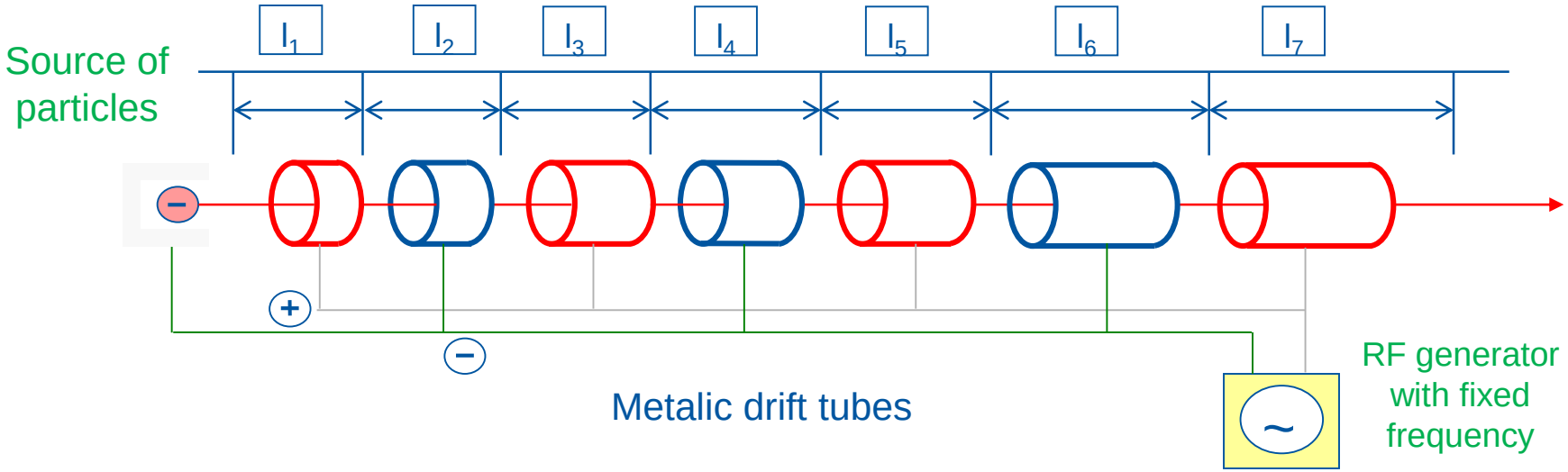
- 1940: Kerst (based on the idea of Widroe) 2.3 MeV and very quickly 300 MeV
- First machine to accelerate electrons to energies higher than from electron guns
- It is actually a transformer with a beam of electrons as secondary winding
- The magnetic field is used to bend the electrons in a circle, but also to accelerate them
- A deflecting electrode is use to deflect the particles for extraction.



Linear Accelerator

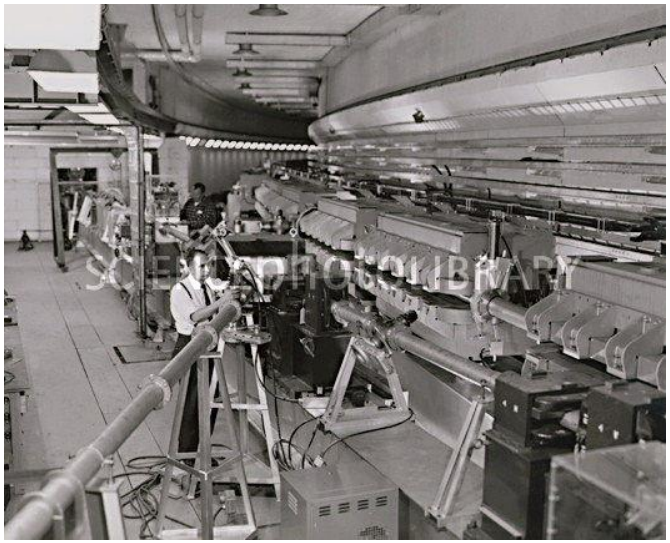
- Many people involved: Wideroe, Sloan, Lawrence, Alvarez,….
- Main development took place between 1931 and 1946.
- Development was also helped by the progress made on high power high frequency power supplies for radar technology.
- Today still the first stage in many accelerator complexes.
- Limited 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
- **Varying magnetic field** and radio frequency give a **fixed particle radius**
- Phase stability
- Important focusing of particle beams (Courant – Snyder)
- Providing beam for fixed target physics
- **Paved the way to colliders**



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

These lectures will mainly concentrate on **Synchrotron** machines
That form the source of particle for the majority of accelerator based experiments

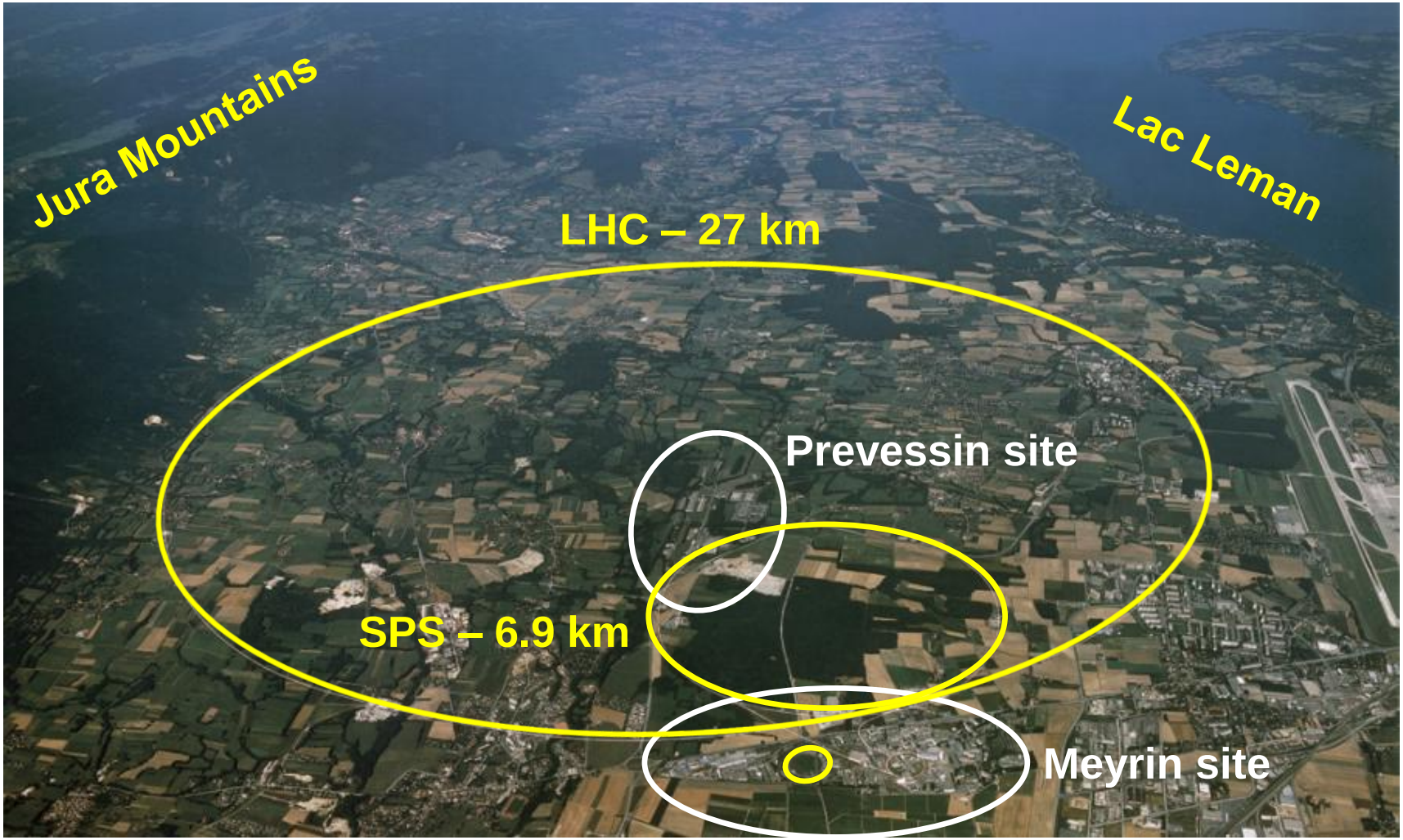
**Source: World Scientific Reviews of Accelerator Science and Technology*
A.W. Chao

Fixed Target vs. Colliders

Fixed Target	Collider
	
$E_{sec} \propto \sqrt{E_{primary}}$	$E = \sqrt{E_{beam1}^2 + E_{beam2}^2}$
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

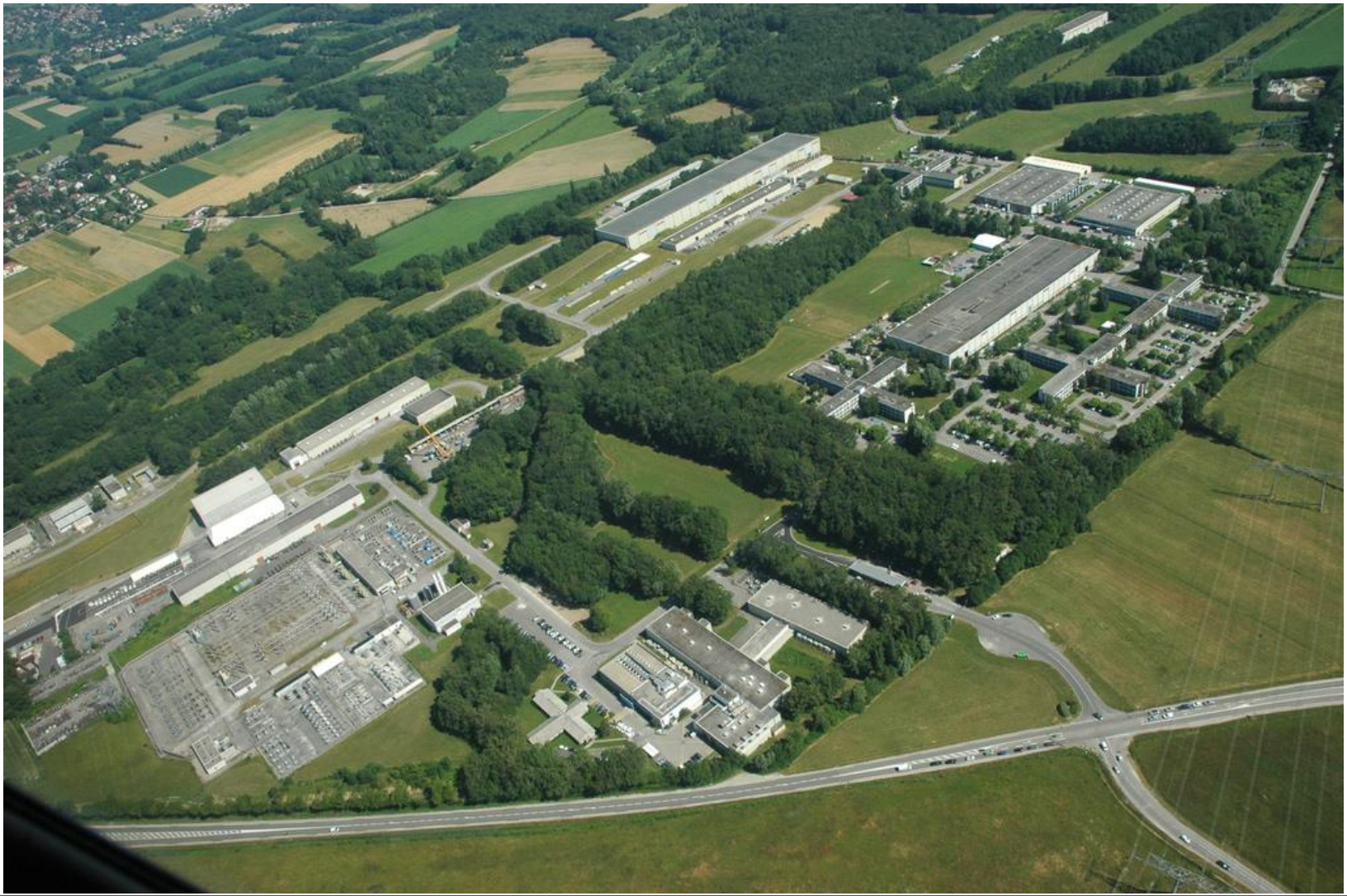
The CERN Accelerator Complex

Aerial View of CERN

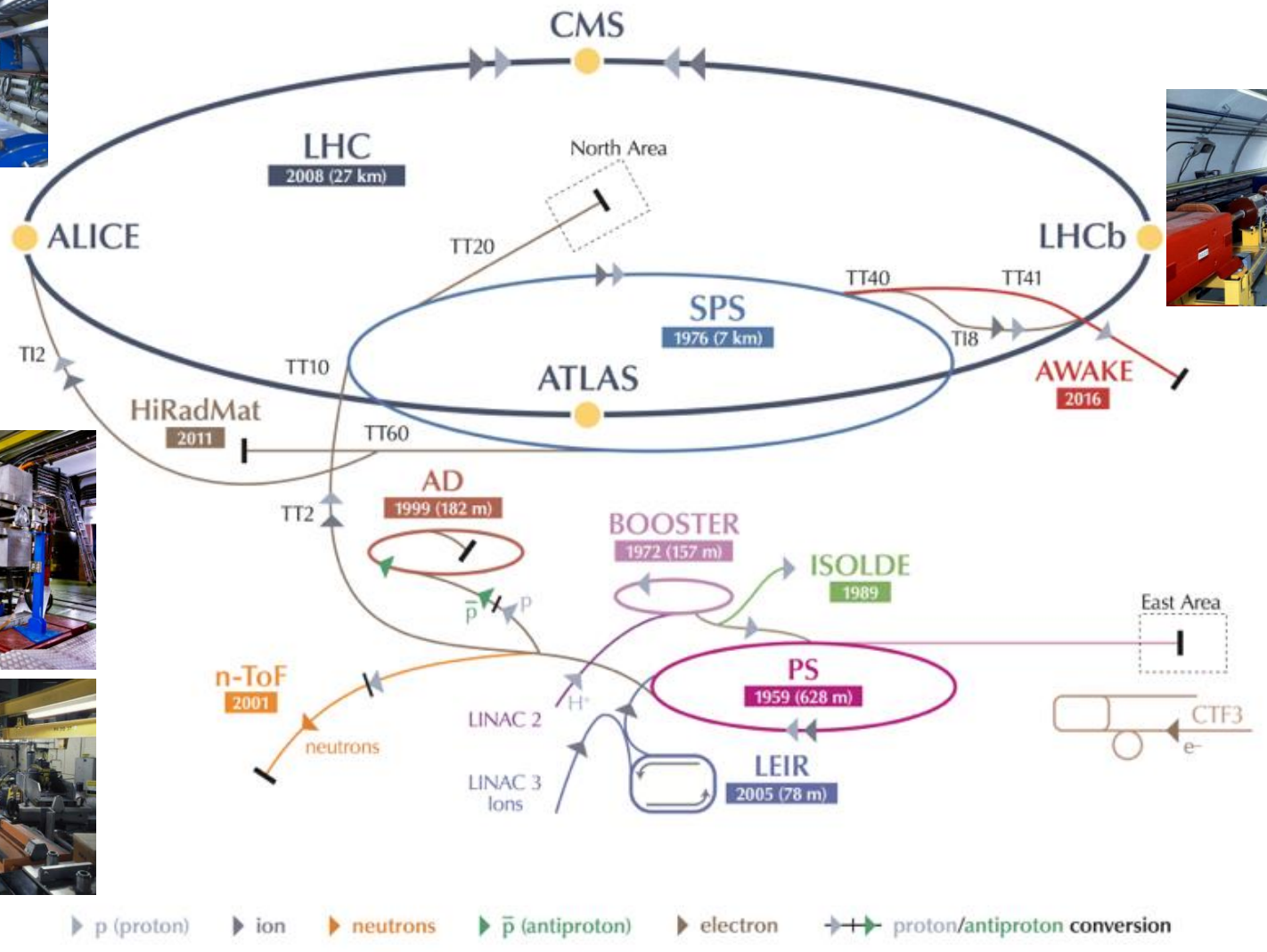


Aerial View of the Meyrin Site

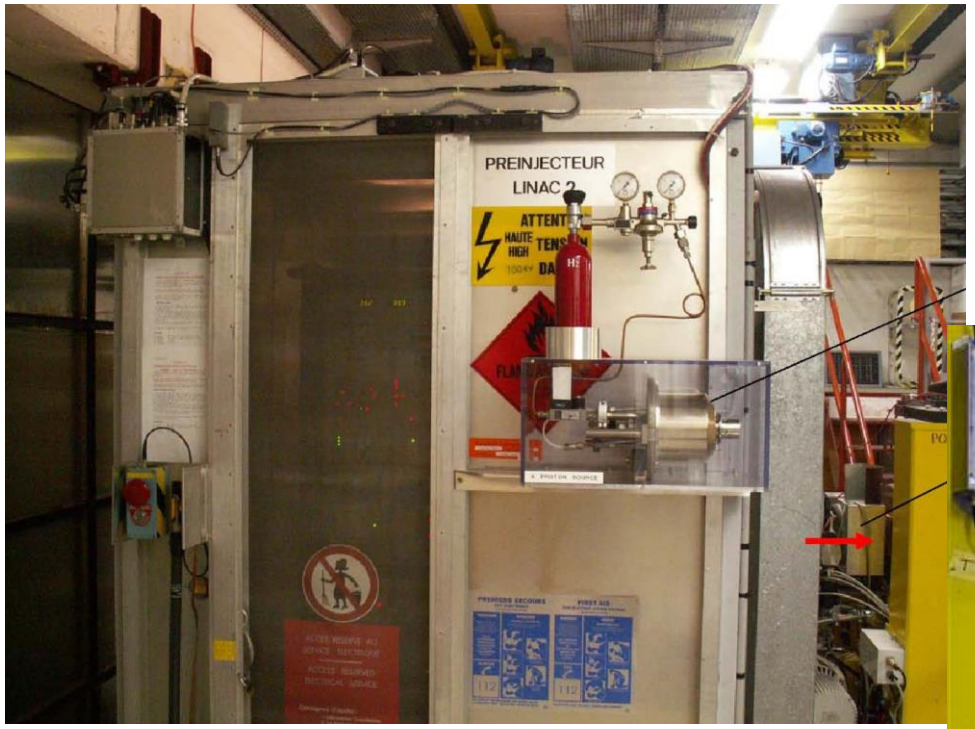
Aerial View of the Prevessin



The CERN Accelerator Complex



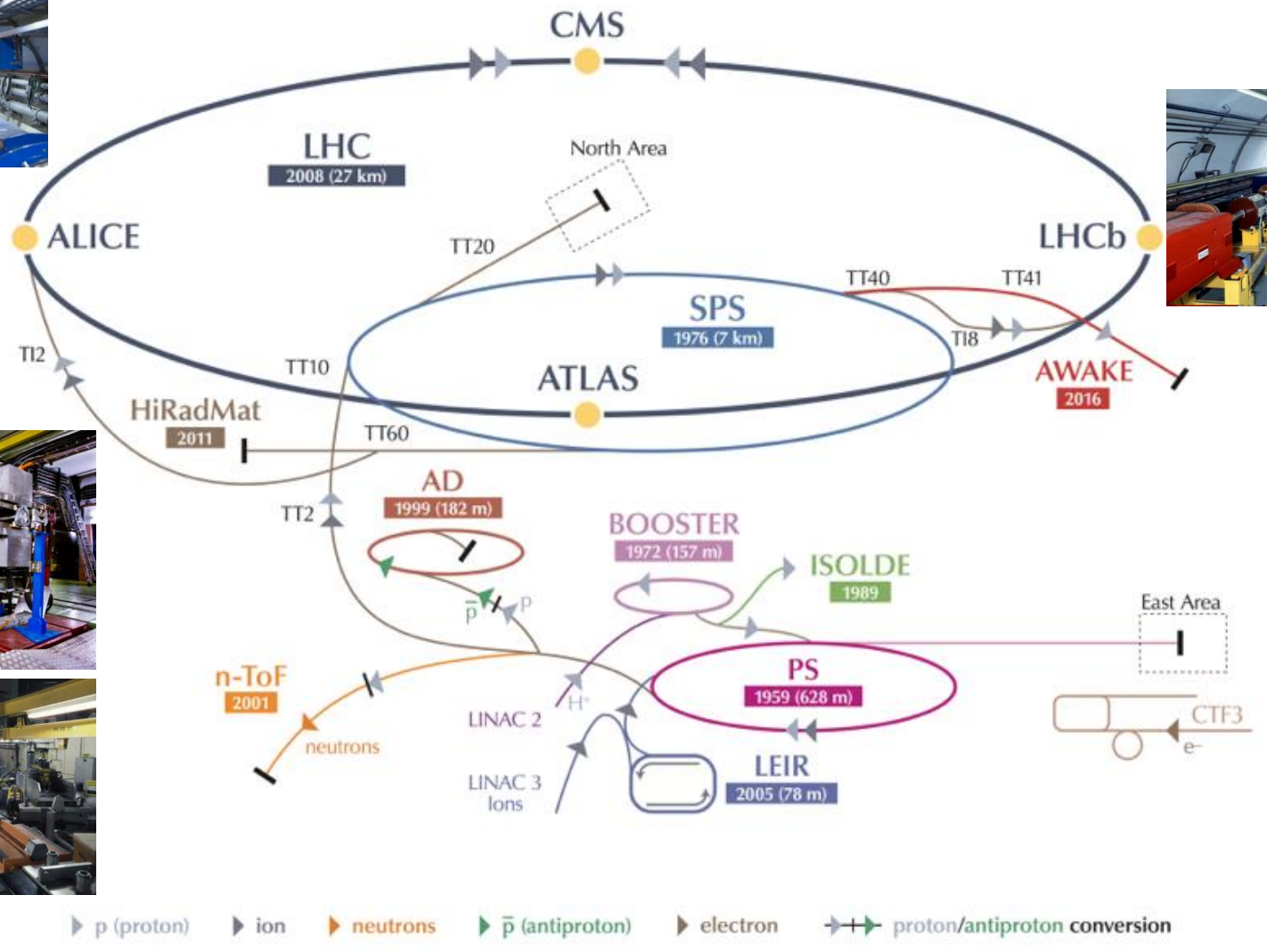
LINAC 2



- Duoplasmatron proton source
- Extract protons at 90 keV from H_2

- Accelerates beam up to 50 MeV over a length of 33m, using Alvarez structures
- Provides a beam pulse every 1.2s

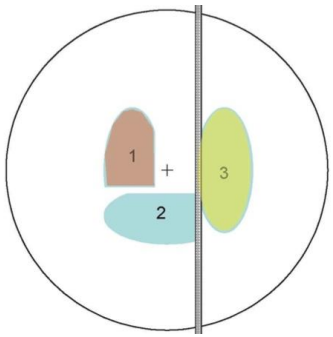
The CERN Accelerator Complex



PS Booster

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

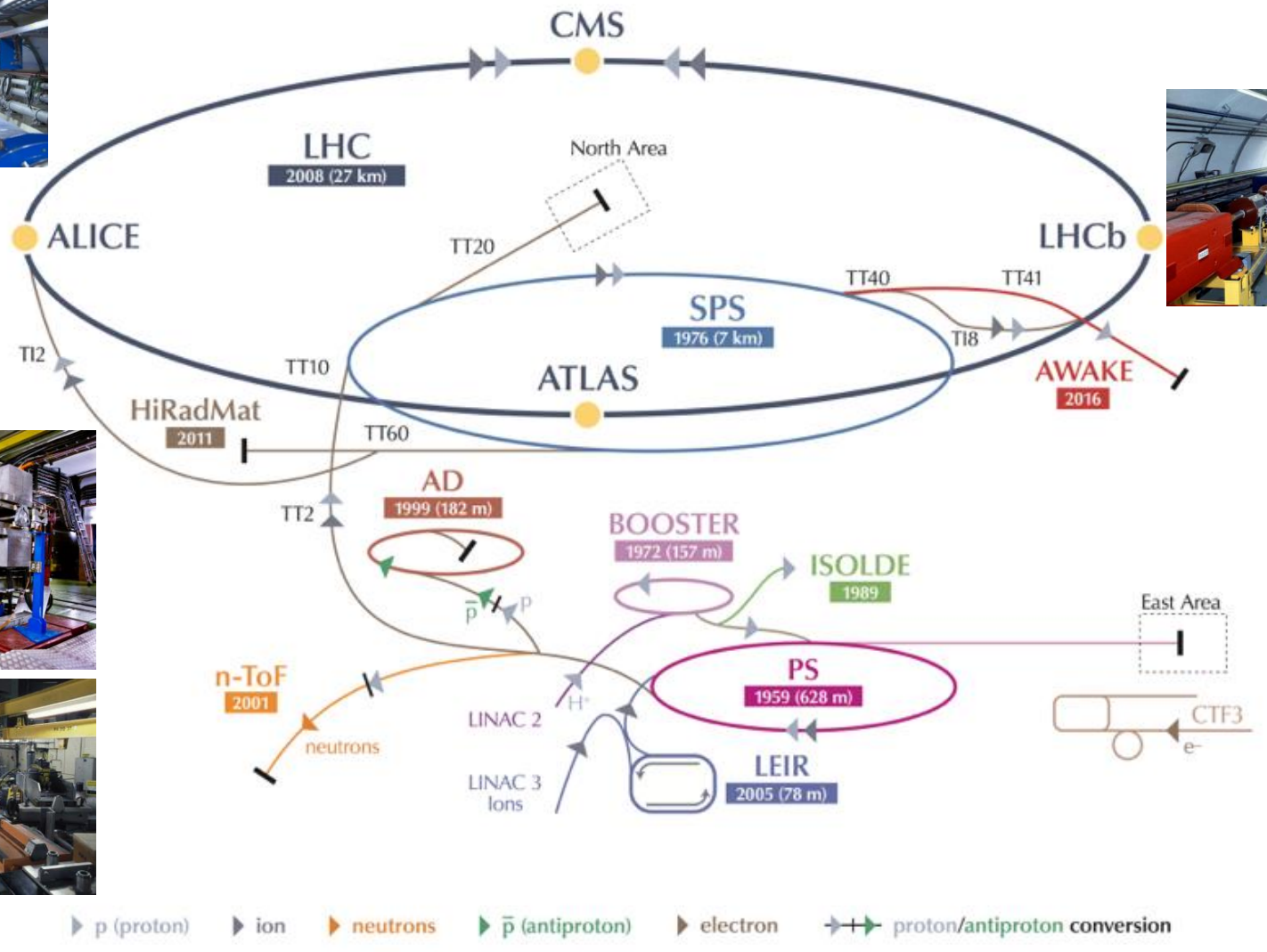
- The LINAC2 pulse is distributed over the four rings, using kicker magnets
- Each ring will inject over multiple turns, accumulating beam in the horizontal phase space



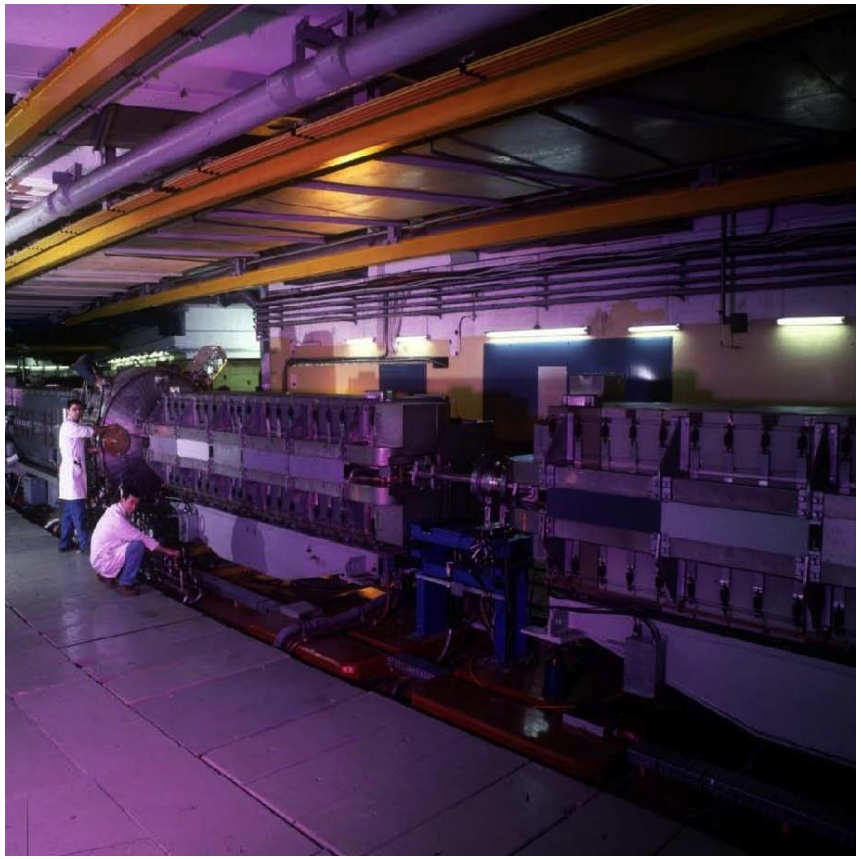
- This means that the beam size (transverse emittance) increases when the intensity increases → ~ constant density

The PS Booster determines the transverse Brightness of the LHC beam

The CERN Accelerator Complex



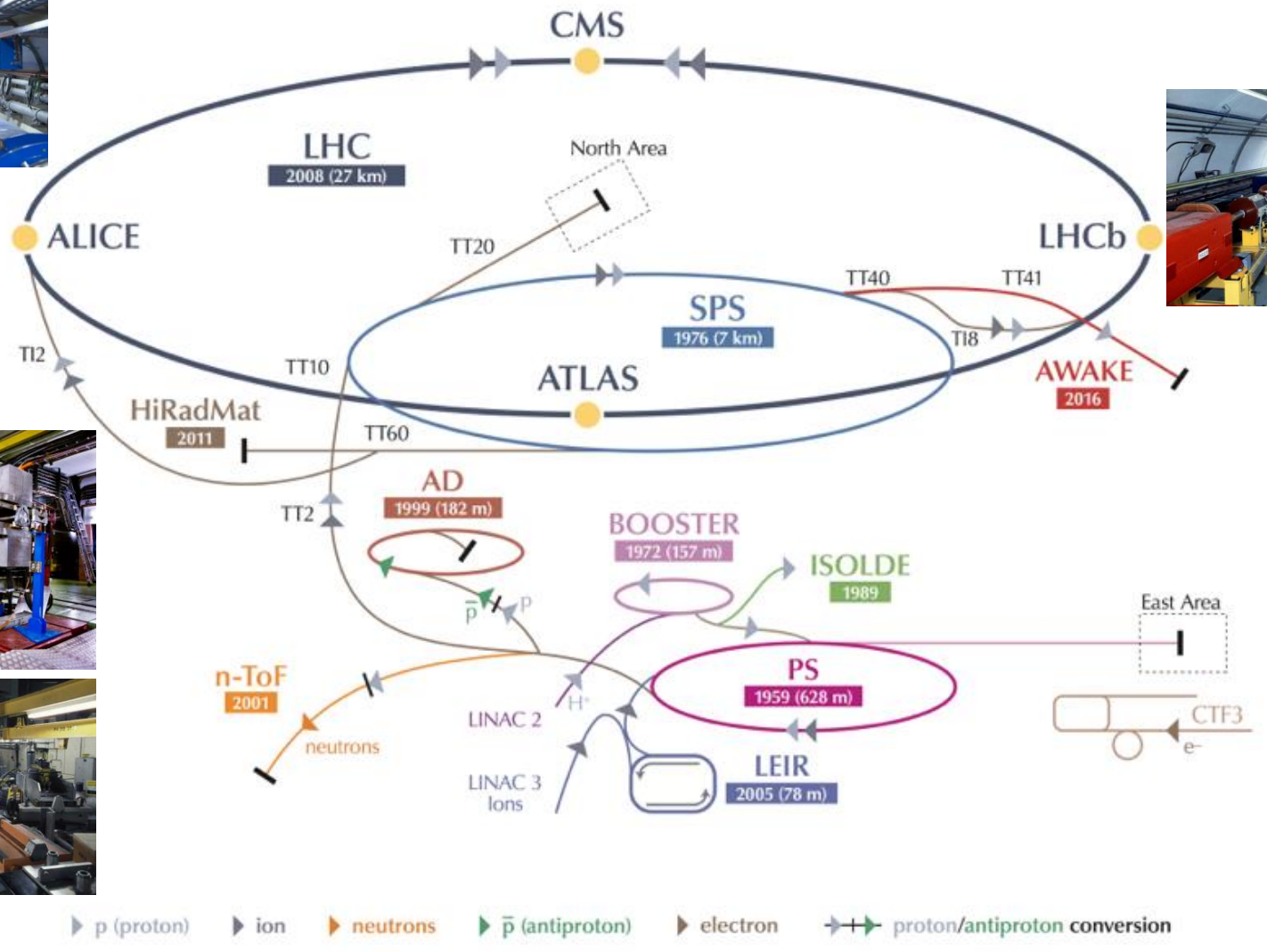
PS



- 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

- The many different RF systems allow for complex RF gymnastics:
  - 10 MHz, 13/20 MHz, 40 MHz, 80 MHz, 200 MHz
- Various types of extractions:
  - Fast extraction
  - Multi-turn extraction (MTE)
  - Slow extraction

The CERN Accelerator Complex

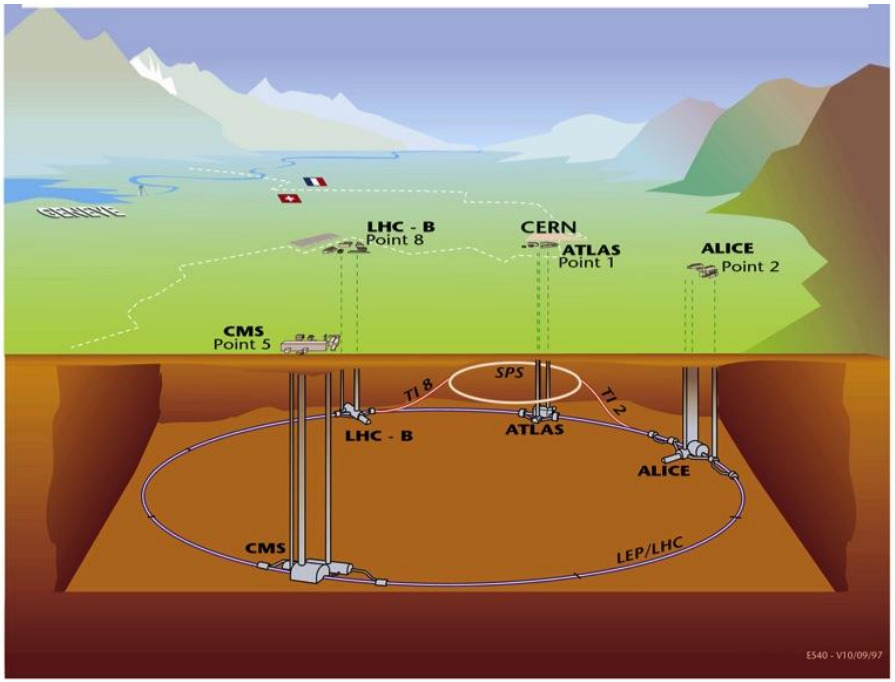


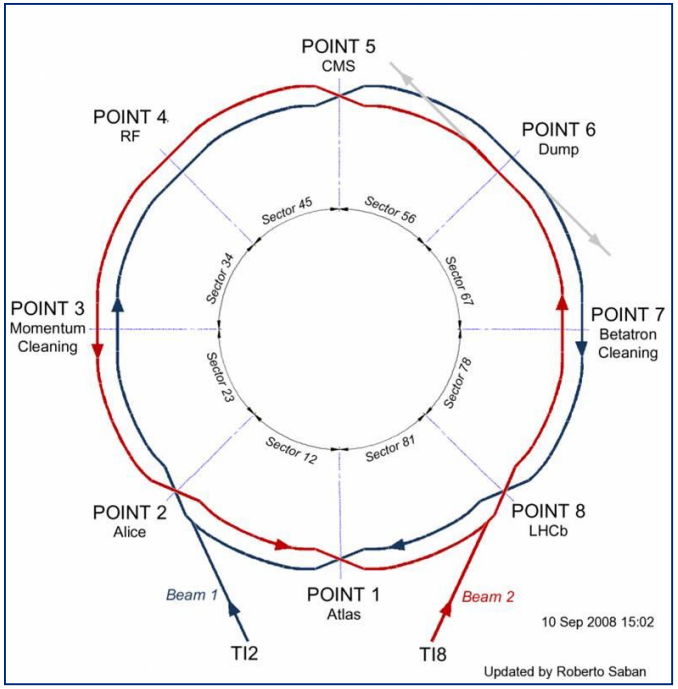
SPS

- 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

- Provides slow extracted beam to the North Area
- Provides fast extracted beam to LHC, AWAKE and HiRadMat

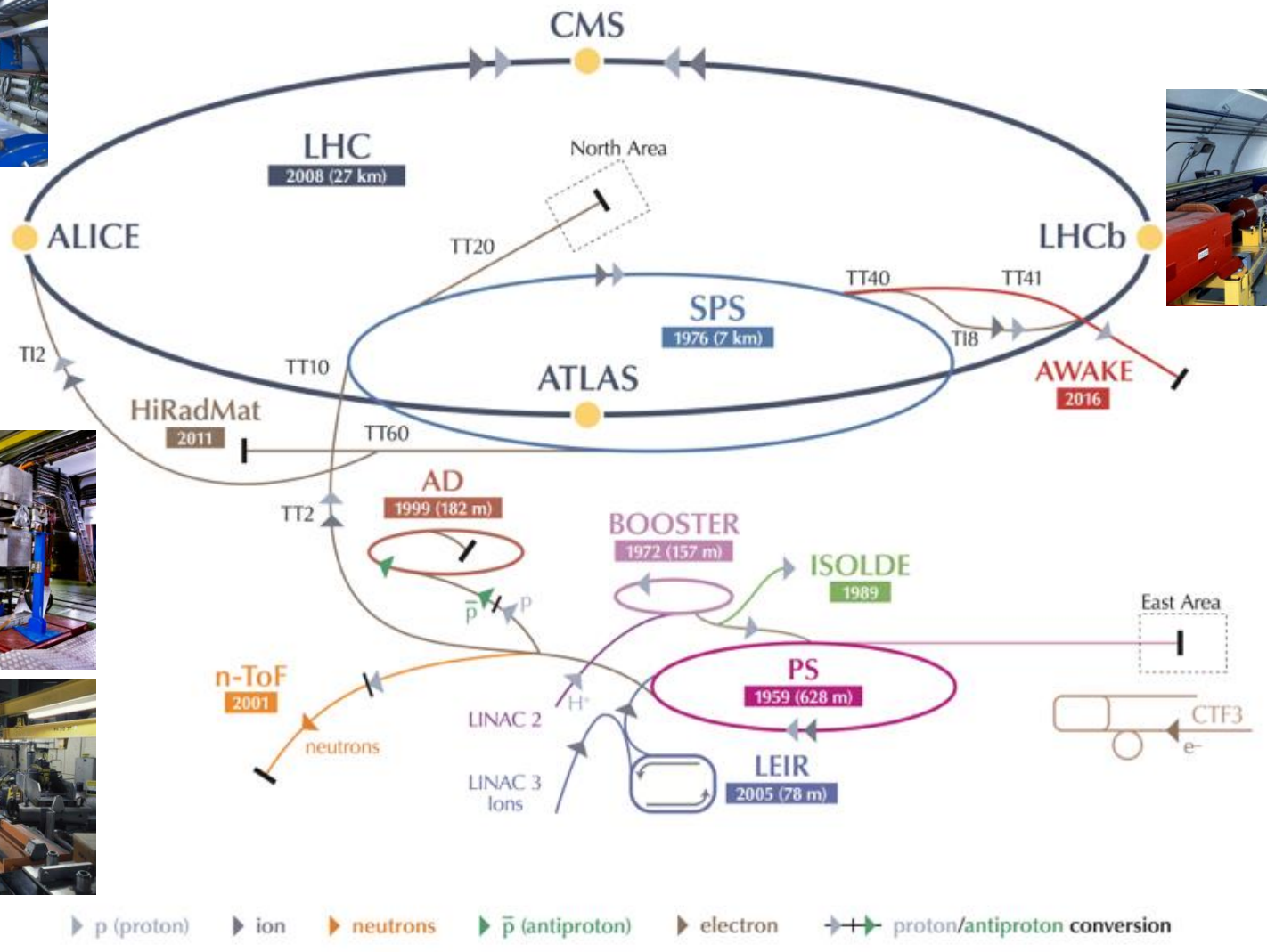
LHC



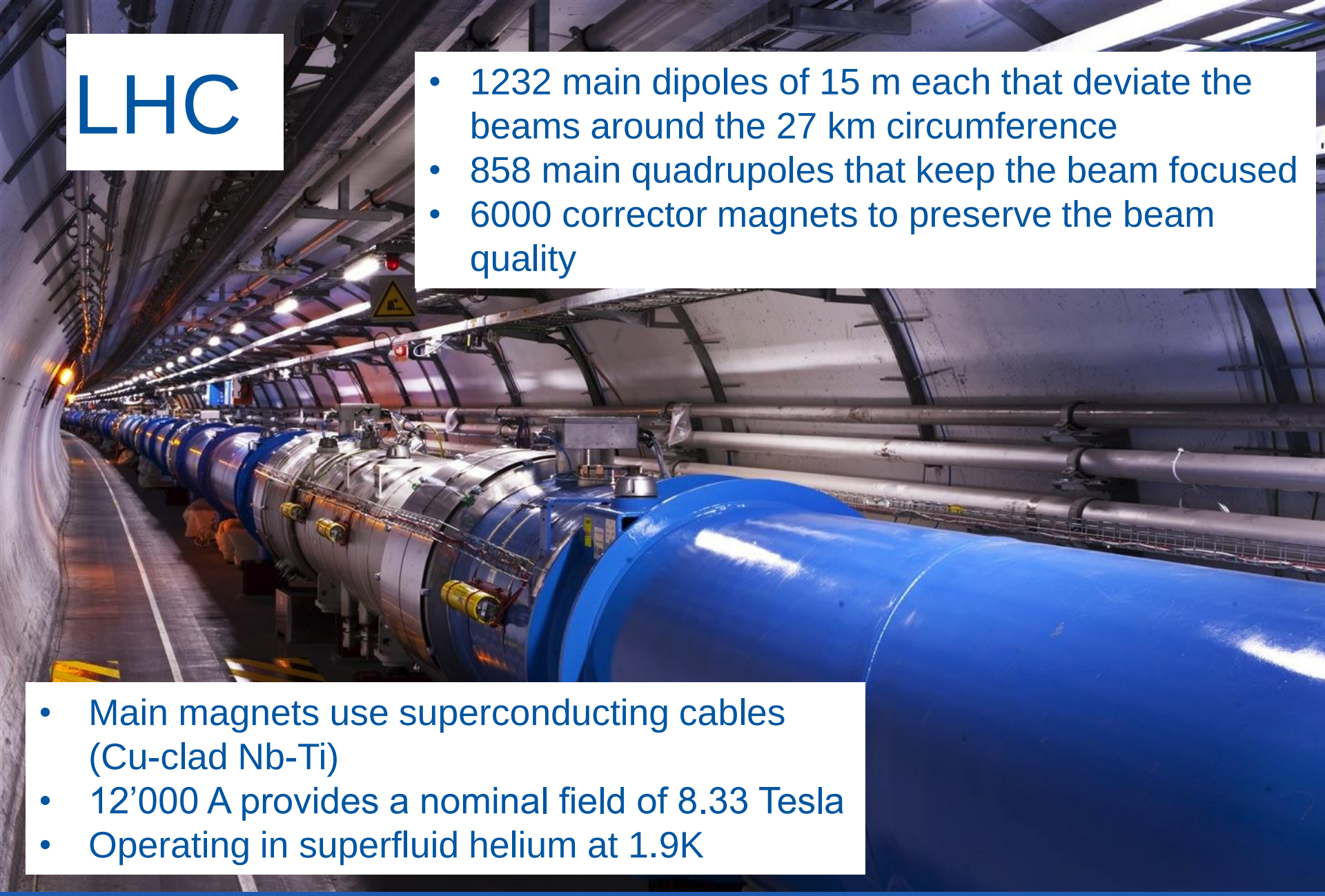


- Situated on average ~100 m under ground
- Four major experiments (ATLAS, CMS, ALICE, LHCb)
- Circumference 26.7 km
- Two separate beam pipes going through the same cold mass 19.4 cm apart
- 150 tonnes of liquid helium to keep the magnets cold and superconducting

The CERN Accelerator Complex



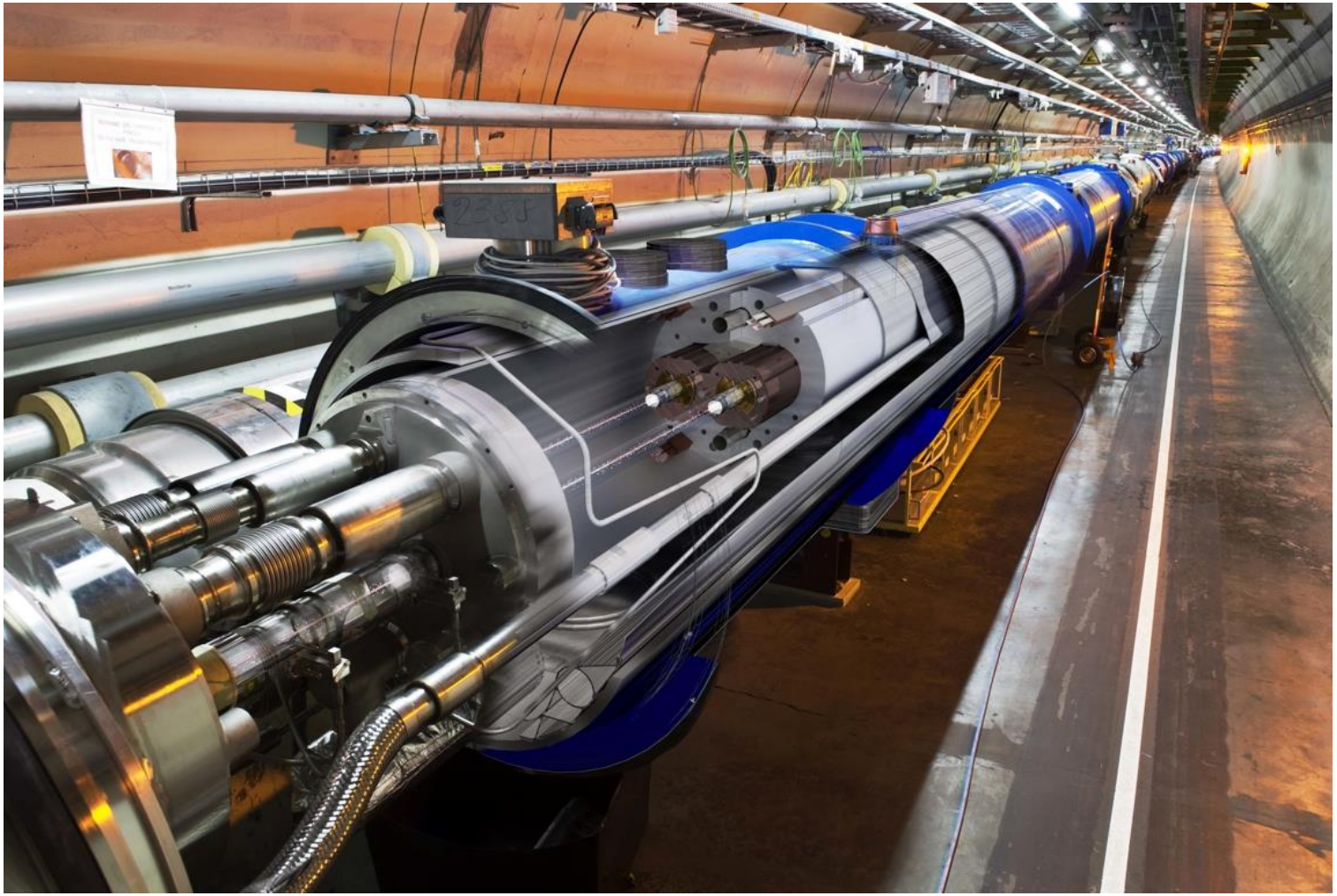
LHC



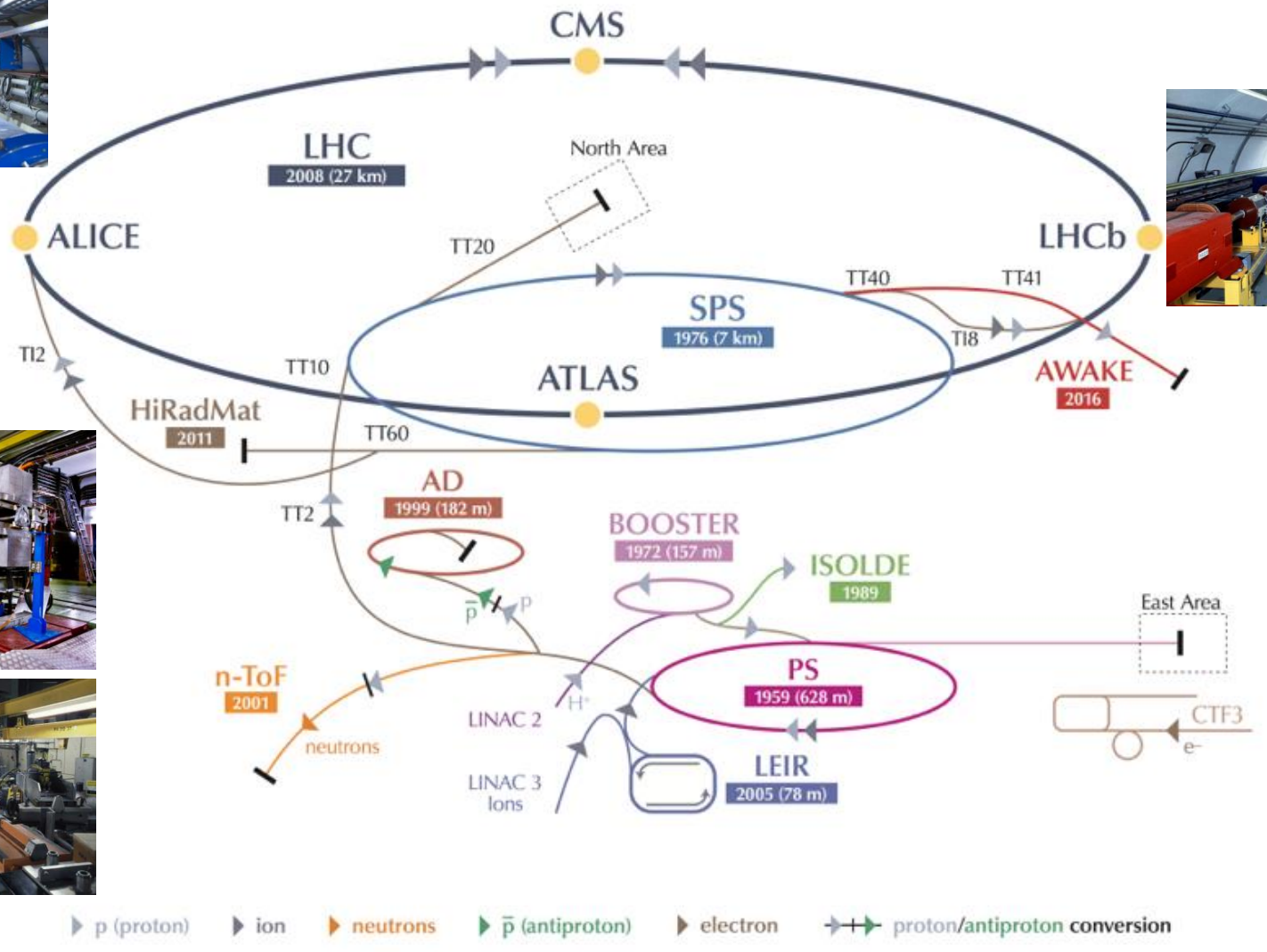
- 1232 main dipoles of 15 m each that deviate the beams around the 27 km circumference
- 858 main quadrupoles that keep the beam focused
- 6000 corrector magnets to preserve the beam quality

- 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

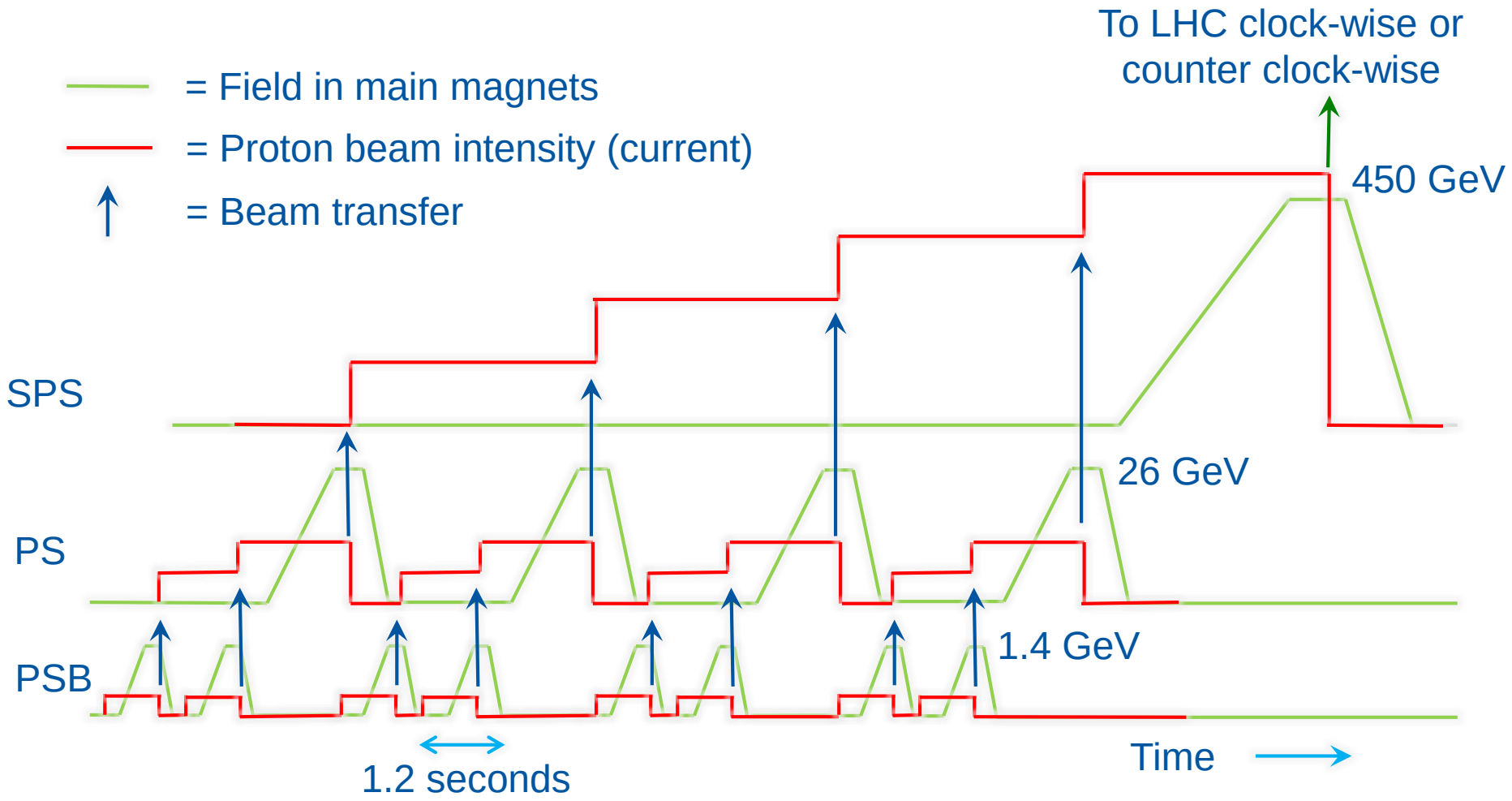
The LHC Magnet



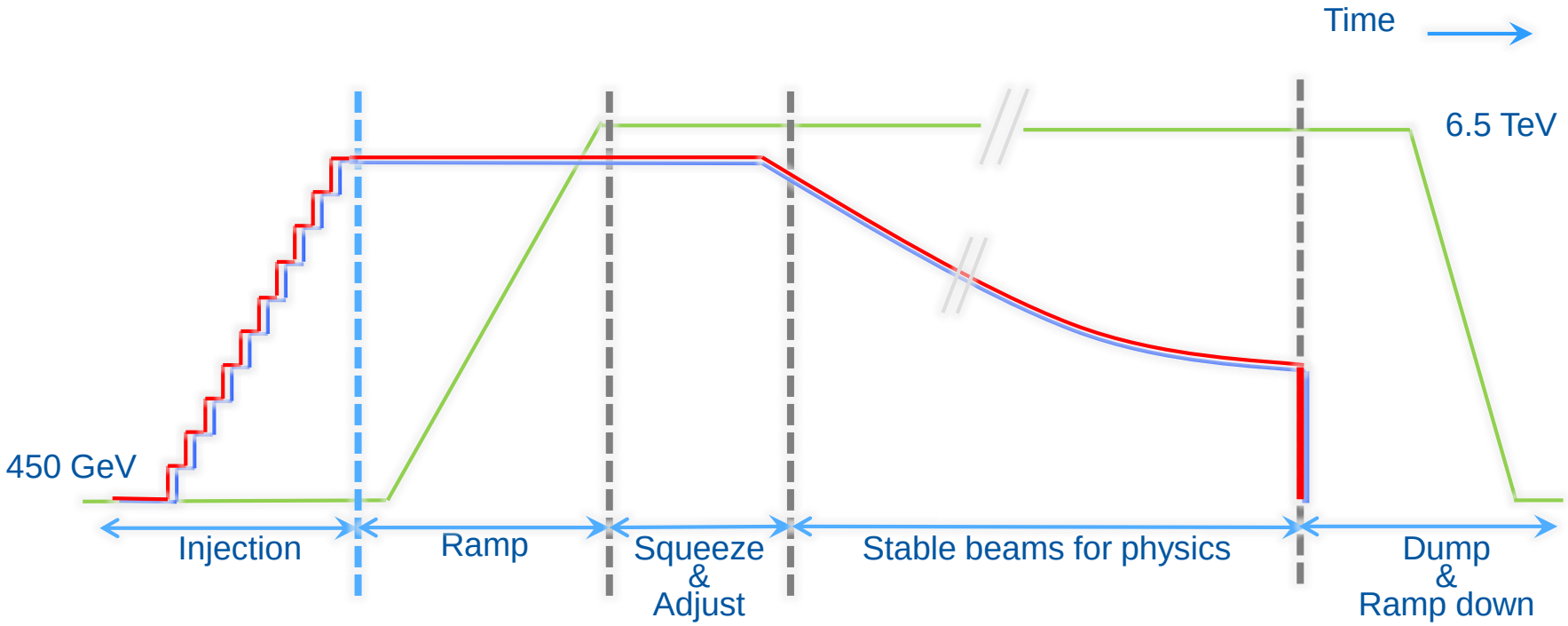
The CERN Accelerator Complex



Filling the LHC and Satisfying Fixed Target users



How does the LHC fit in this ?



= Field in main magnets

= Beam 1 intensity (current)

= Beam 2 intensity (current)

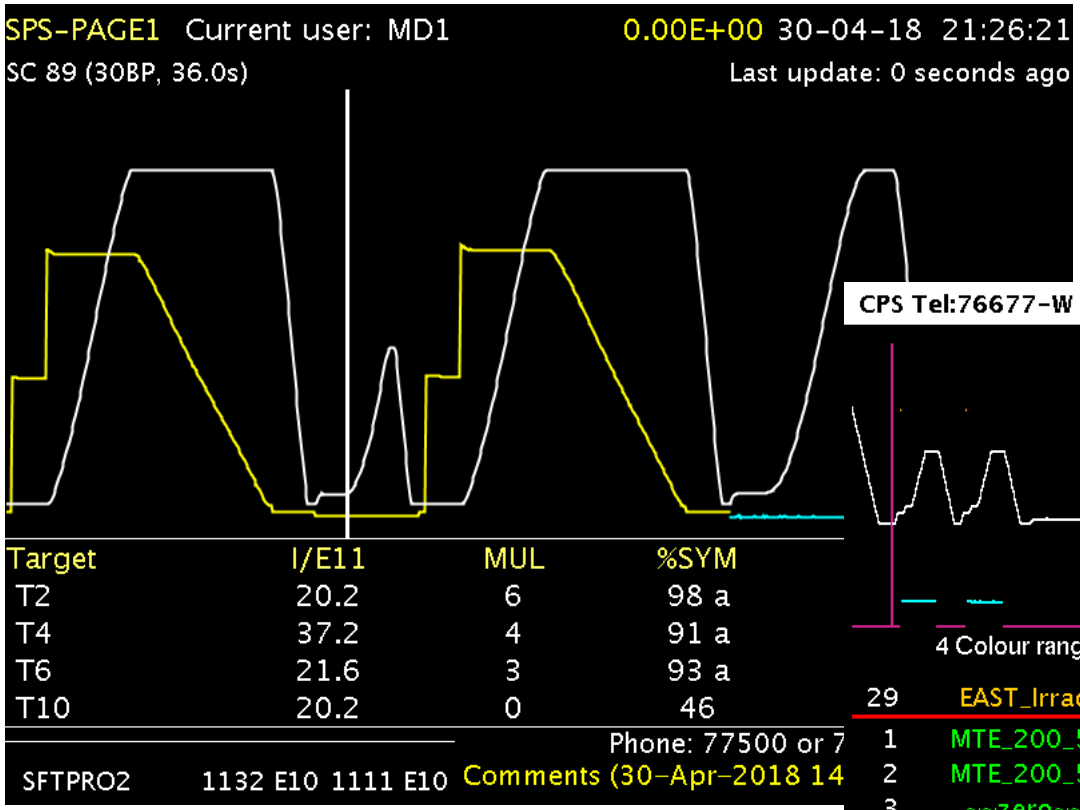
The LHC is built to collide protons at 7 TeV per beam, which is **14 TeV centre of Mass**

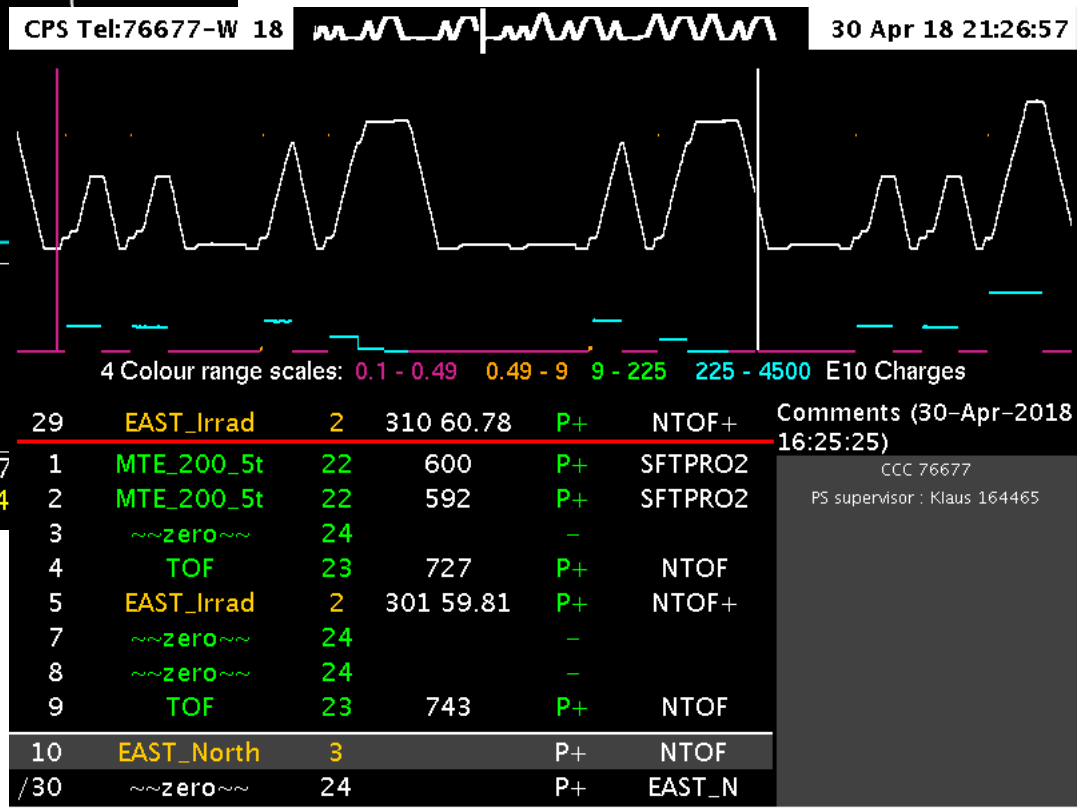
In 2012 it ran at 4 TeV per beam, 8 TeV c.o.m.

Since 2015 it runs at 6.5 TeV per beam, 13 TeV c.o.m

URL: https://op-webtools.web.cern.ch/vistar/vistars.php?usr=LHC1

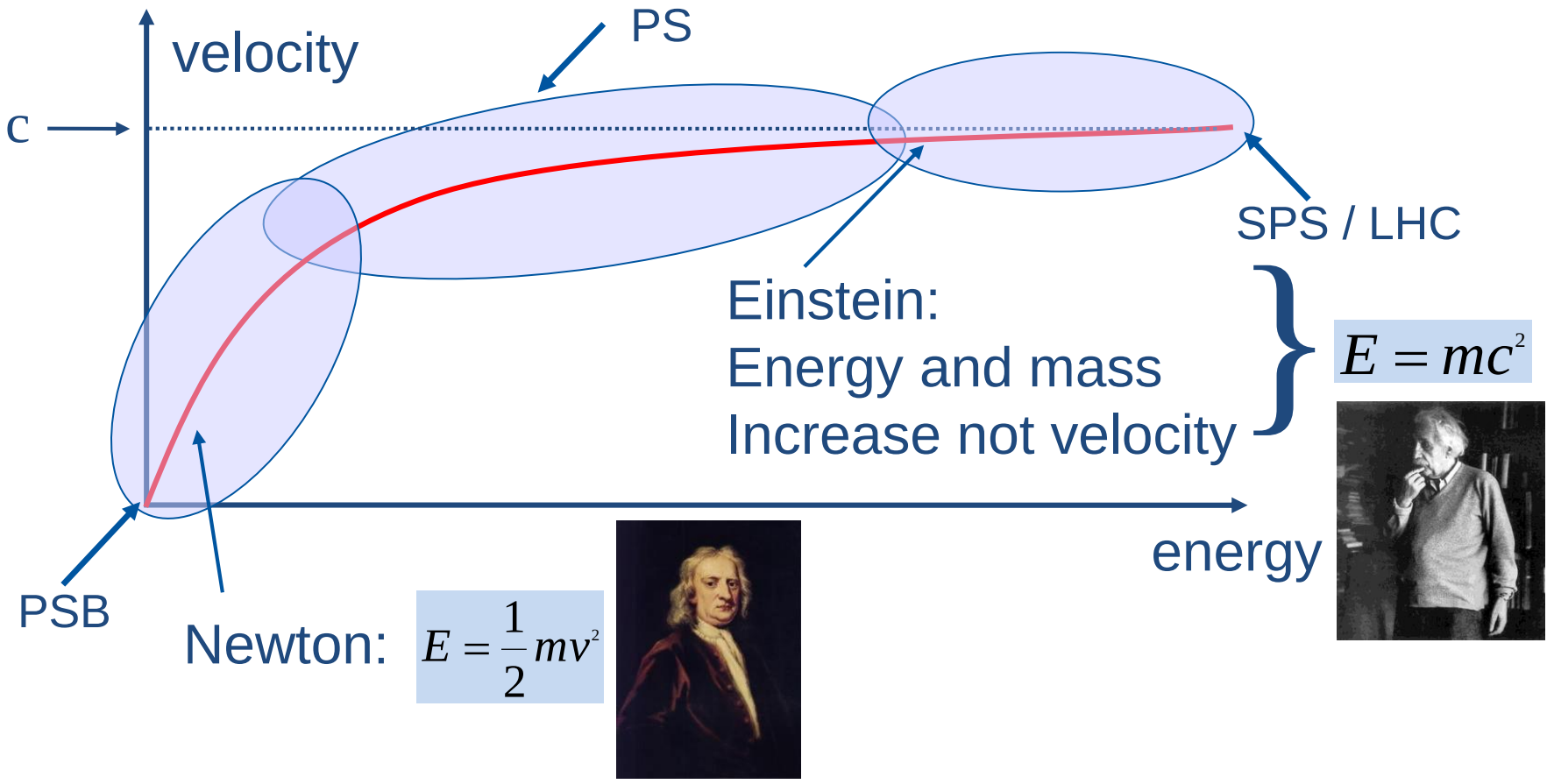
The PS & SPS Super Cycles





A Brief Word on Relativity & Units

Towards Relativity



Basic Relativity

Einstein's formula:

$E = mc^2$ which for a mass at rest is: $E_0 = m_0 c^2$

The ratio between the real velocity and the velocity of light is the **relative velocity**

$$\boldsymbol{\beta = \frac{v}{c}}$$

The ratio between the total energy and the rest energy is the **Lorentz factor**

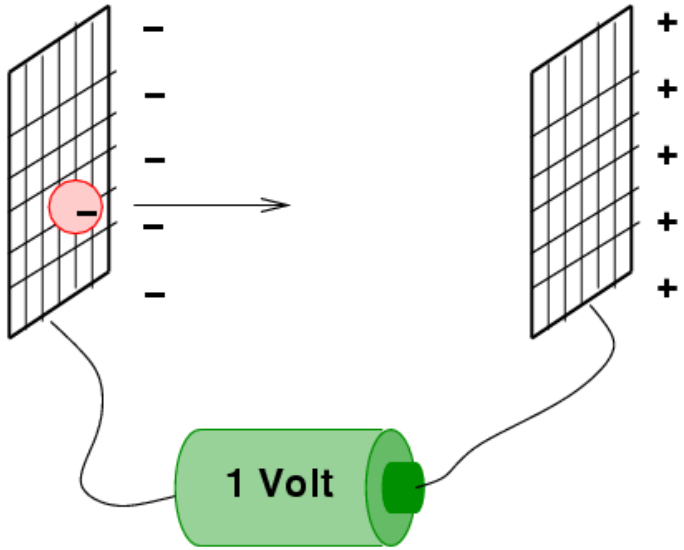
$$\boldsymbol{\gamma = \frac{E}{E_0} = \frac{1}{\sqrt{1-\beta^2}}}$$

We can write: $\beta = \frac{mvc}{mc^2}$

Momentum is: $p = mv$

$$\boldsymbol{\beta = \frac{pc}{E}} \quad \Leftrightarrow \quad \boldsymbol{p = \frac{E\beta}{c}}$$

The Units



- The energy acquired by an electron in a potential of 1 Volts is defined as being 1 eV
- Hence 1 eV = 1.6 x 10^{-19} Joules
- Units:
  - Energy: eV
  - Momentum: eV/c
  - Mass: eV/c^2
- The unit eV is too small to be used today, we use:
  - 1 KeV = 10^3, MeV = 10^6, GeV = 10^9, TeV = 10^{12}

$$p = \frac{E\beta}{c}$$

when $\beta = 1$: value for energy [eV] and momentum [eV/c] are equal
when $\beta < 1$: value for energy [eV] and momentum [eV/c] are not equal

Q2: The LHC Beam Stored Energy

- The LHC runs with 2556 bunches per beam
- Each bunch is populated with 1.15×10^{11} protons
- The center of mass energy during collisions is 14 TeV

- What is the total stored energy per beam at the start of collisions?

- Could you come up with a more known example that represents the same stored energy ?

Q2a: The LHC Beam Stored Energy

- The LHC runs with 2556 bunches per beam
- Each bunch is populated with 1.15×10^{11} protons
- The center of mass energy during collisions is 14 TeV
- Both beams have the same $B\rho$

- What is the total stored energy per beam at the start of the squeeze ?

  - The collisions take place on the high energy flat top where the beams are at 14 TeV center of mass, which is 7 TeV per beam.

  - $1\text{eV} = 1.6 \times 10^{-19}$ Joules

  - 2556 bunches of 1.15×10^{11} protons each is 2.94×10^{14} protons per beam

  - $E_{stored} = 2.94 \times 10^{14} \times 1.6 \times 10^{-19} \times 7 \times 10^{12} = 330$ MJoules

Q2b: The LHC Beam Stored Energy

- LHC stored beam energy = 330 MJoules
- Could you come up with a more known example that represents the same stored energy ?
  - TGV train weight = 380000 kg
  - Velocity of 150 km/h corresponds to 41.67 m/s
  - E_{stored} = 380000 x 41.67^2 = 330 Mjoules

…but then concentrated in the size of a needle

LHC: Luminosity

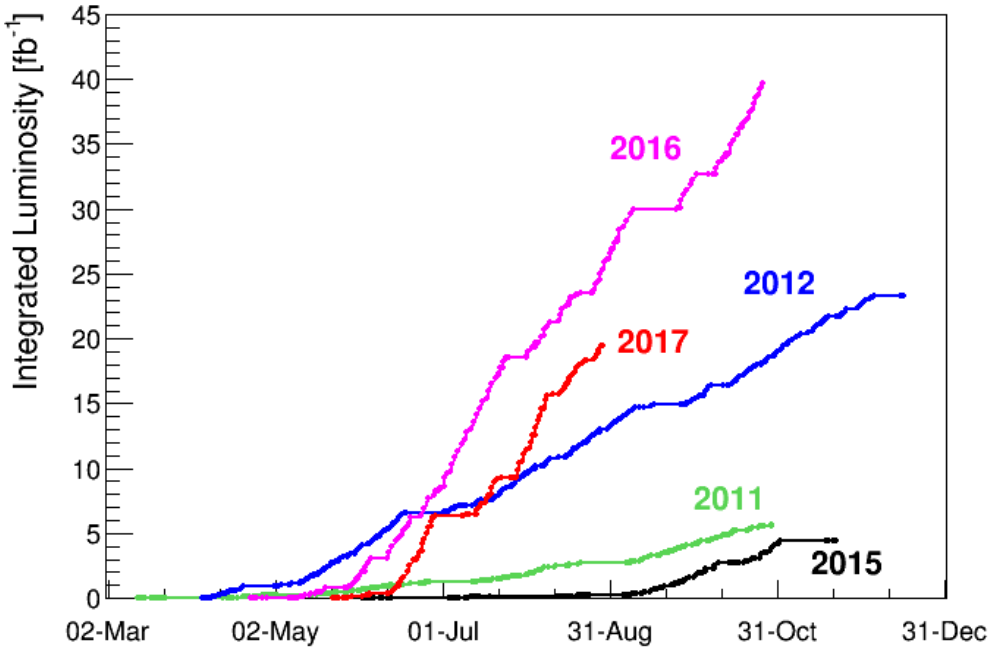
$$LUMINOSITY = \frac{N_{event/sec}}{s_r} = \frac{N_1 N_2 f_{rev} n_b}{4\pi s_x s_y} F$$

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

Questions…..?

www.cern.ch