CERN

The CERN Accelerator School

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Accelerators for Beginners and the CERN Complex

Rende Steerenberg – CERN, BE/OP




Contents

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

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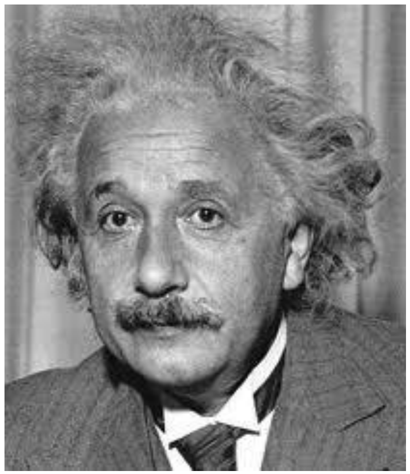
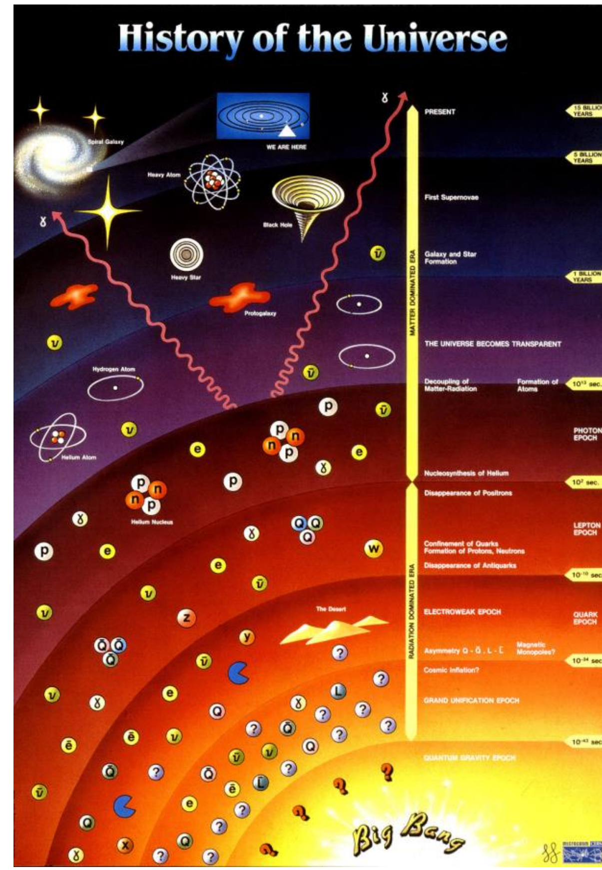
Creating Matter from Energy

$E = m c^2$

During the Big Bang Energy was transformed in matter



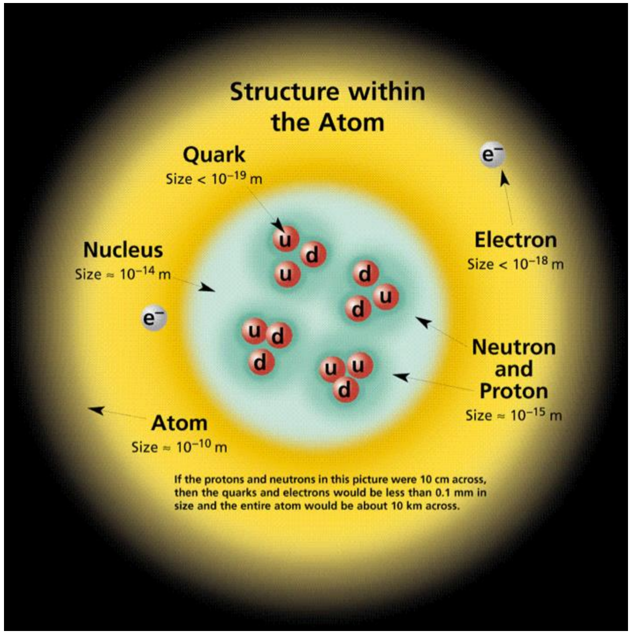


In our accelerators we provide energy to the particles we accelerate.

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**

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

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

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

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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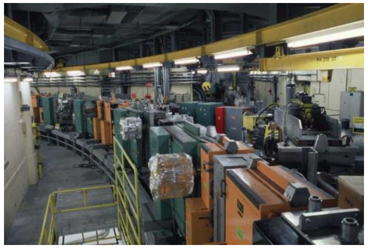
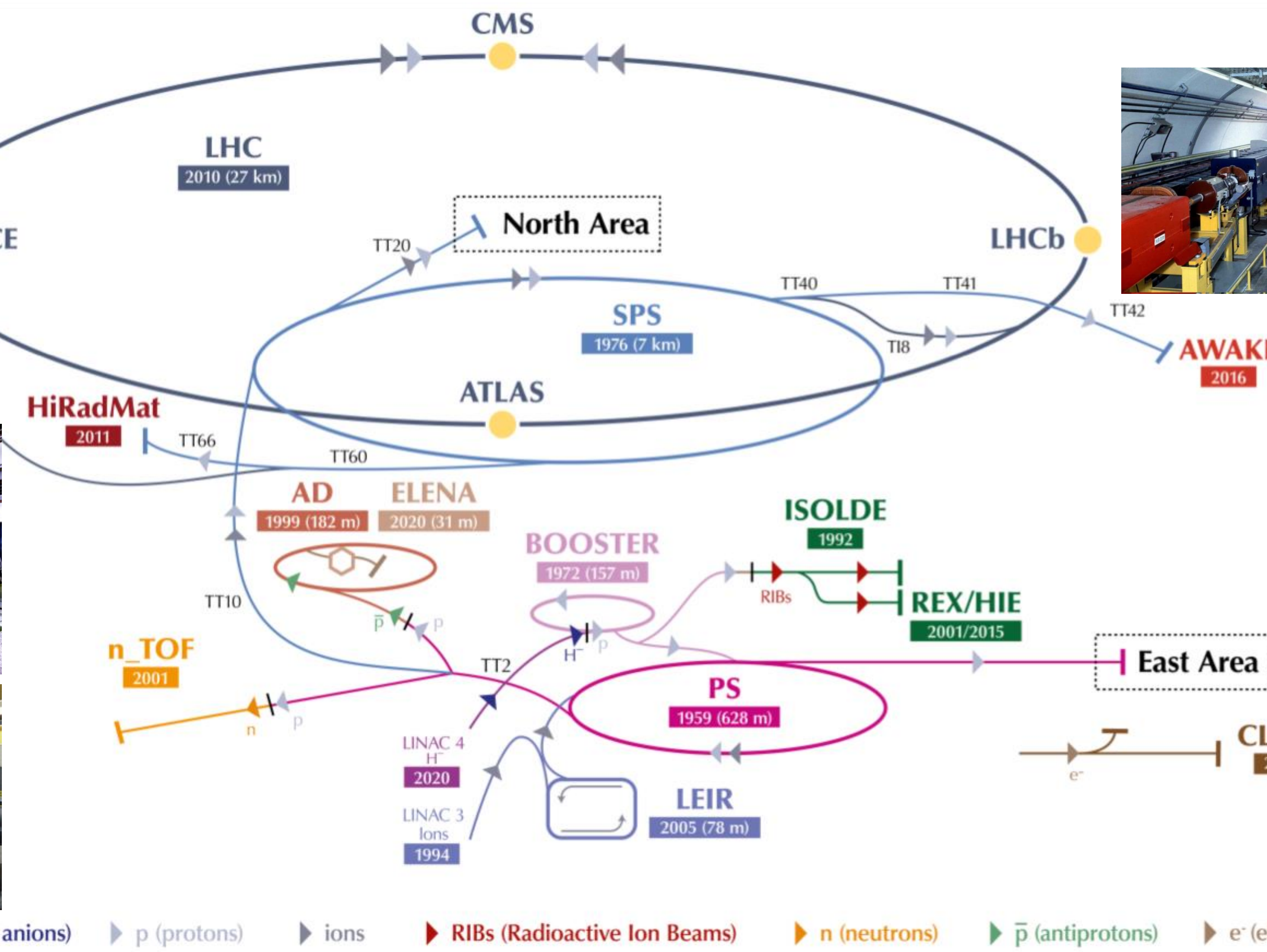
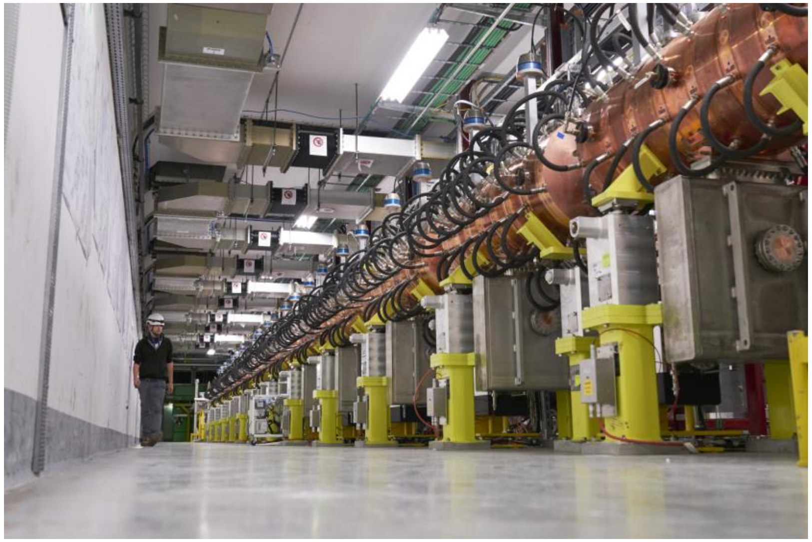
The CERN Accelerator Complex

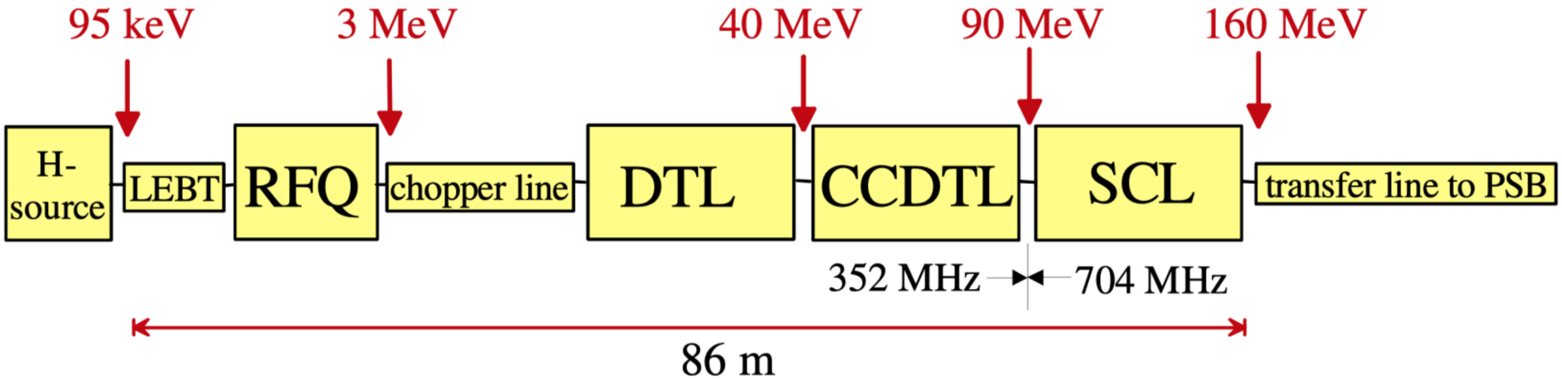




LINAC 4

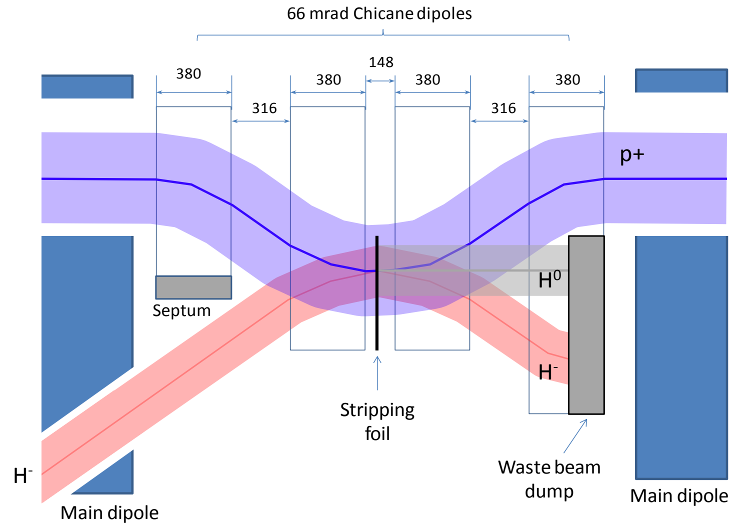
- H^- ion source at 95 keV
- Accelerates beam up to 160 MeV
- The chopping scheme allows removing some of the Linac bunches to make the beam fit into the PS Booster RF buckets
- Four types of accelerating structures:
  - Radio Frequency Quadrupole (RFQ)
  - Drift tube Linac (DTL)
  - Cell-Coupled Drift Tube Linanc (CCDTL)
  - Side Coupled Linac (SCL)
- Pulse rate 1.2 s

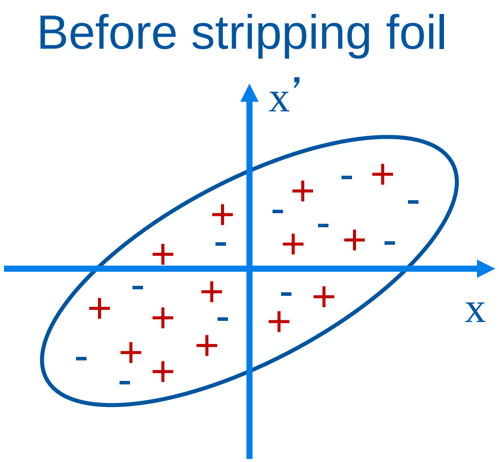


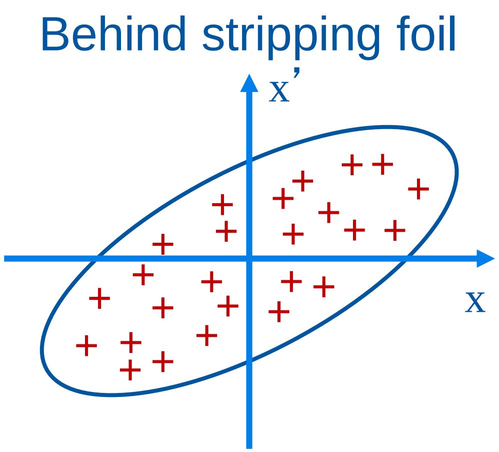


PS Booster

- 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

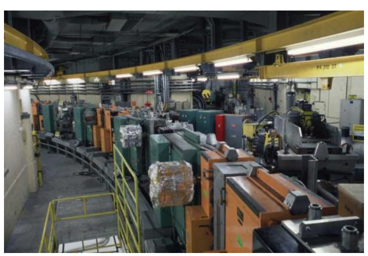


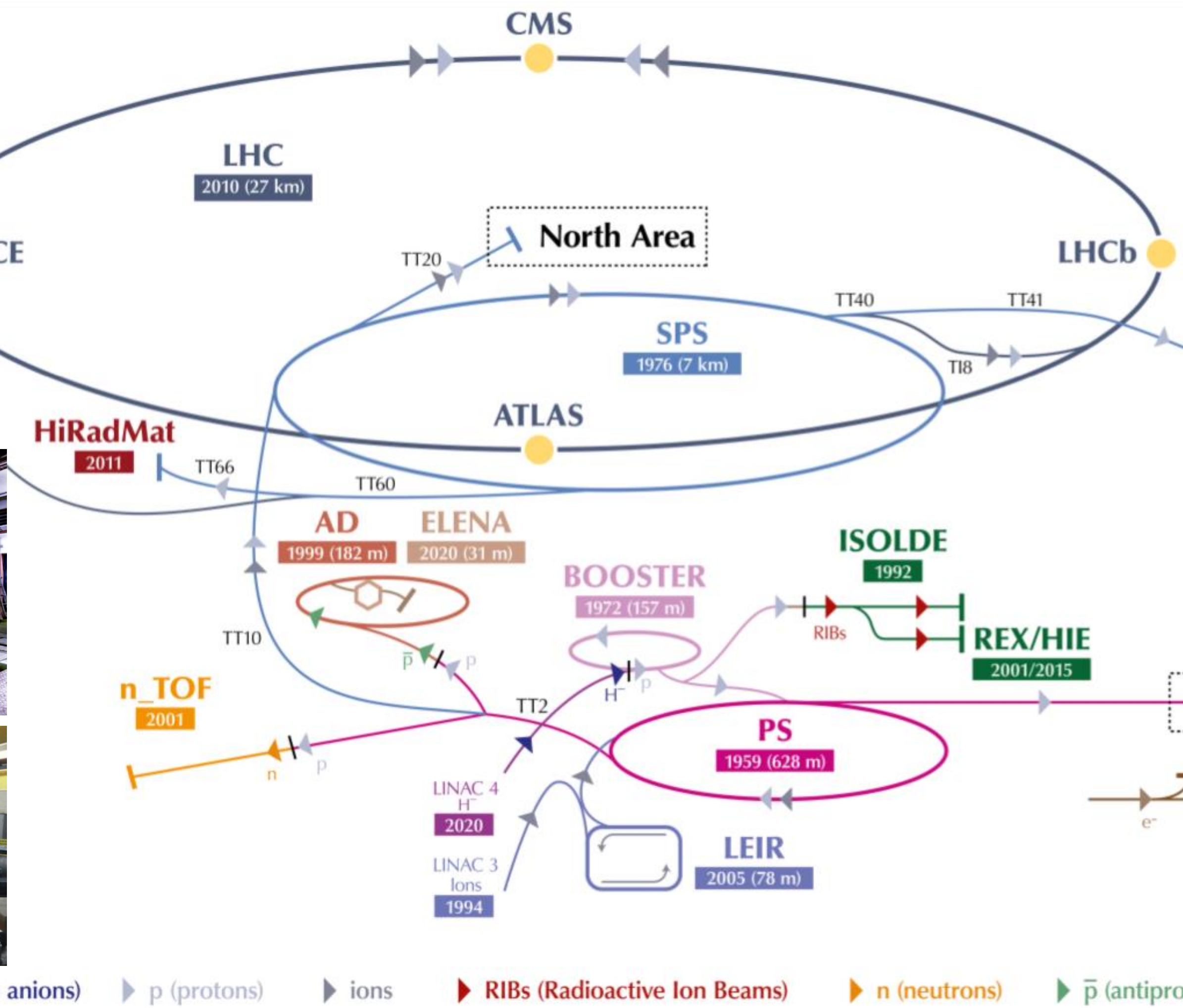




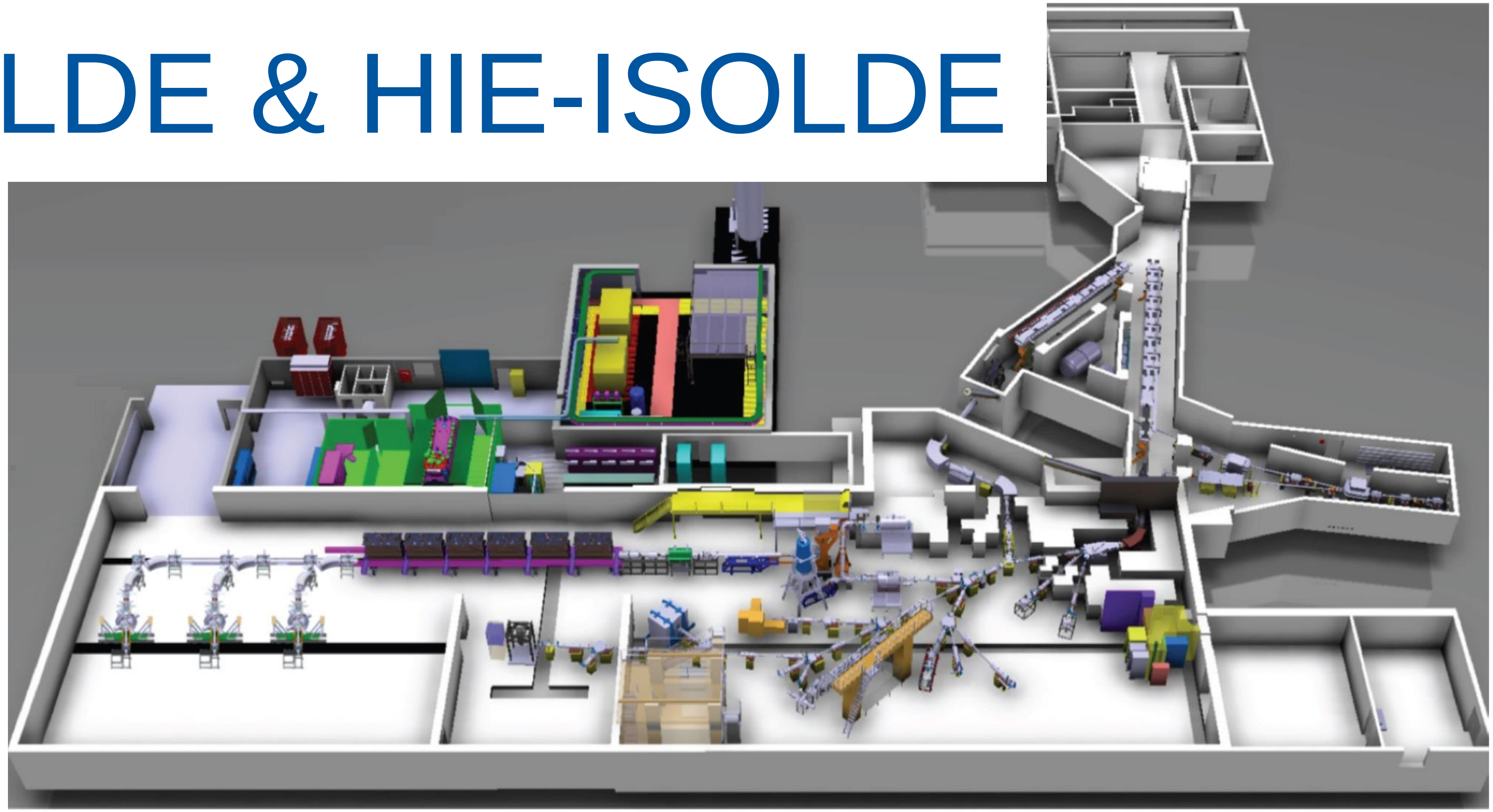
The PS Booster determines the transverse Brightness of the LHC beam

The CERN Accelerator Complex





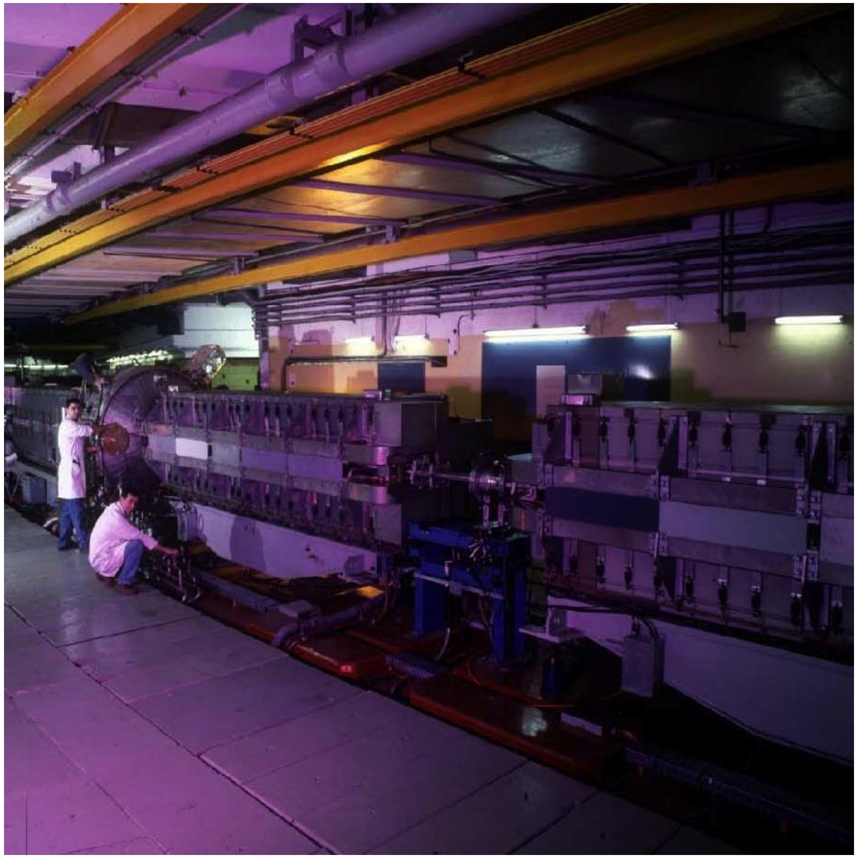
ISOLDE & HIE-ISOLDE



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

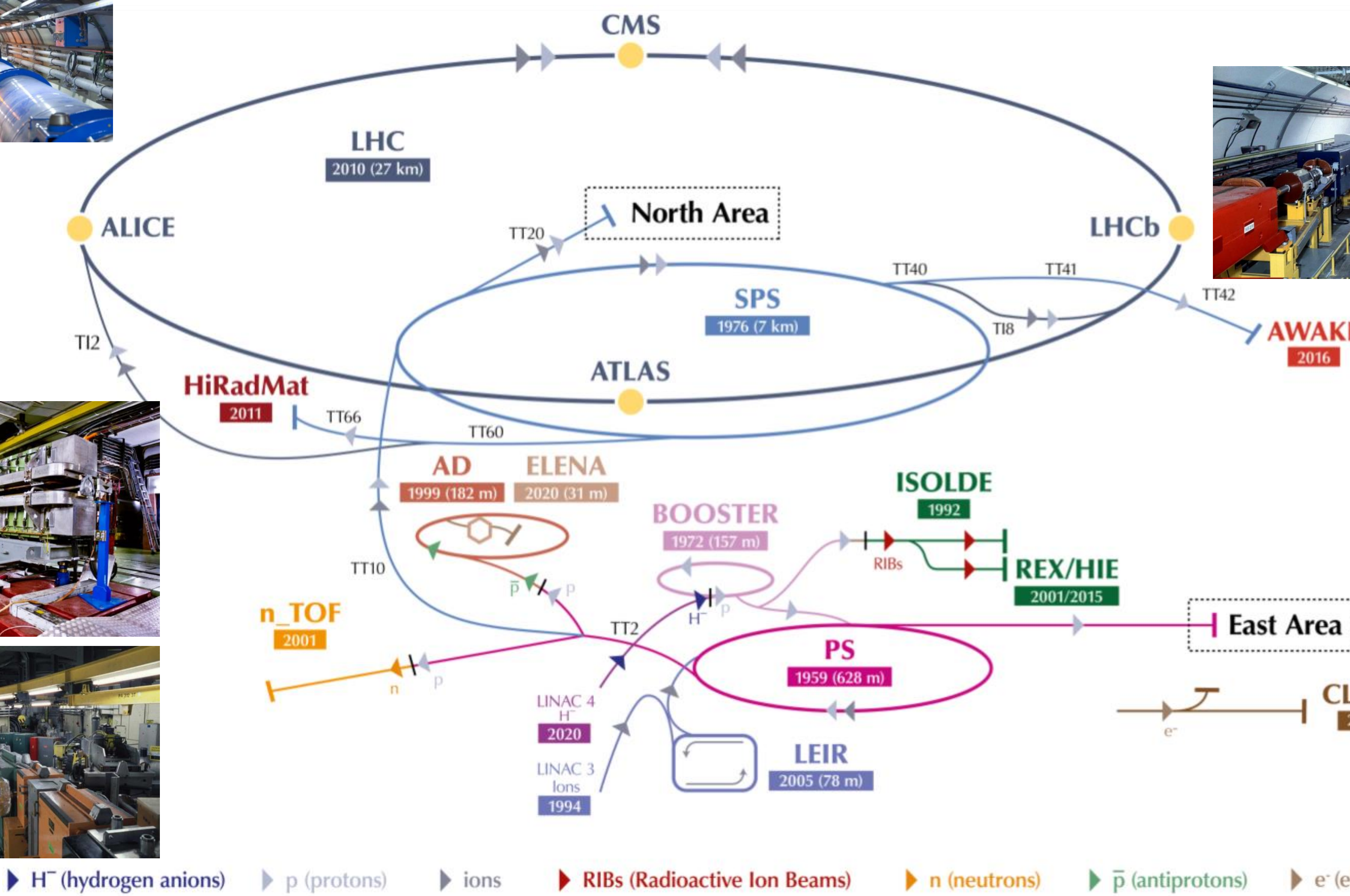
PS

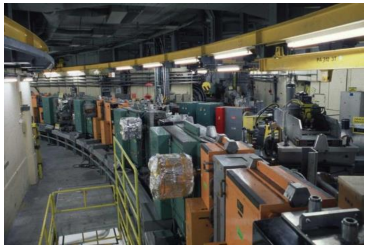
- The oldest operating synchrotron at CERN
- Circumference of 628m
  - 4 x PSB circumference
- Increases proton energy from 2 GeV to a range of energies up to 26 GeV
- Cycle length varies depending on the final energy, but ranges from 1.2s to 3.6s



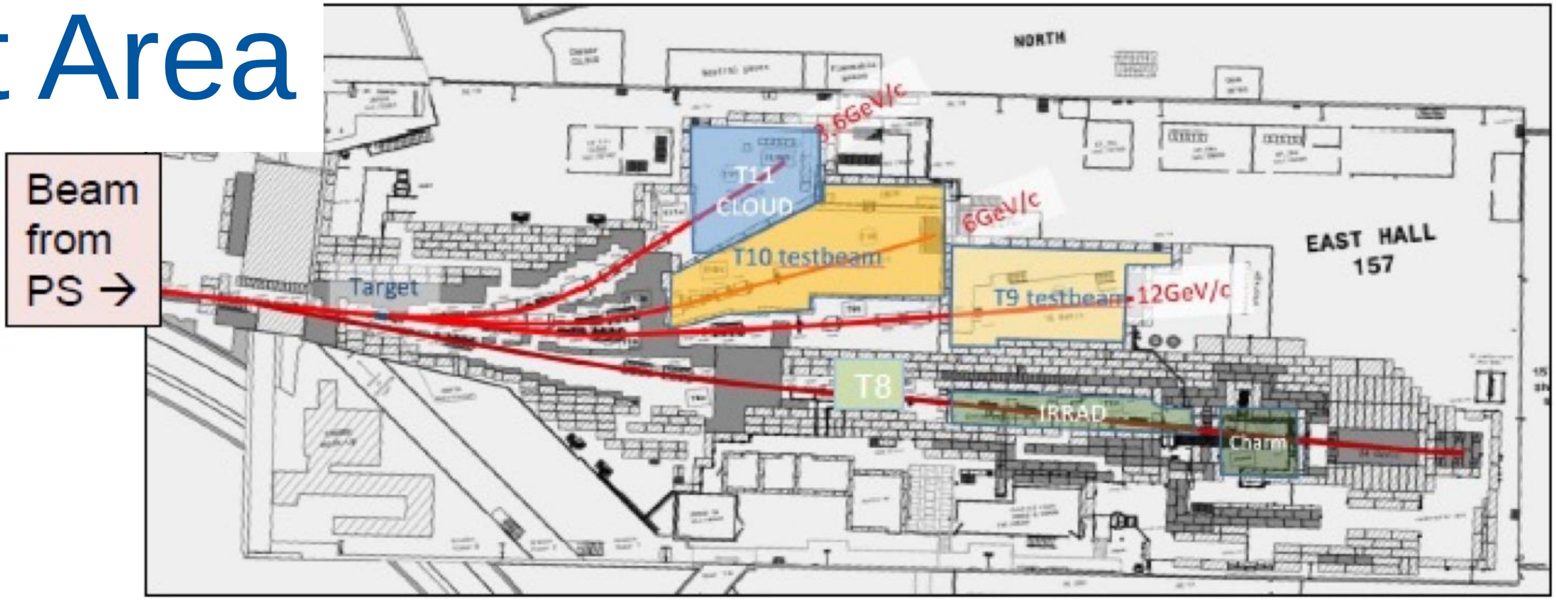
- The many different RF systems allow for complex RF gymnastics:
  - 10 MHz, 13/20 MHz, 40 MHz, 80 MHz, 200 MHz
- Various types of extractions:
  - Fast extraction
  - Multi-turn extraction (MTE)
  - Slow extraction

The CERN Accelerator Complex



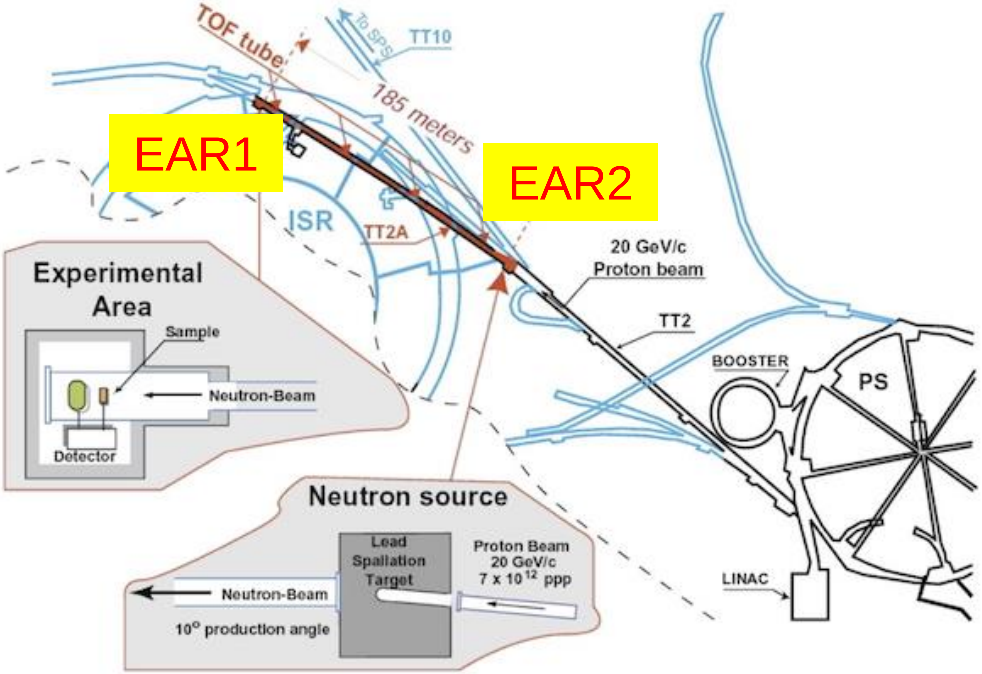


East Area



- Receives slow extracted beam from the PS at 24 GeV/c
  - Beam pulse length ~ 400 ms for a cycle length 2.4s
- Secondary particle beams:
  - From 1 GeV to ~ 15 GeV with ~ 10^6 particles
  - Protons, Electrons, Muons, Pions
- Experiments: CLOUD, previously DIRAC, HARP, ...
- Test beams: LHC, COMPASS, BabyMind, SHiP, AMS, …..
- Irradiation Facilities: IRRAD & CHARM

nTOF



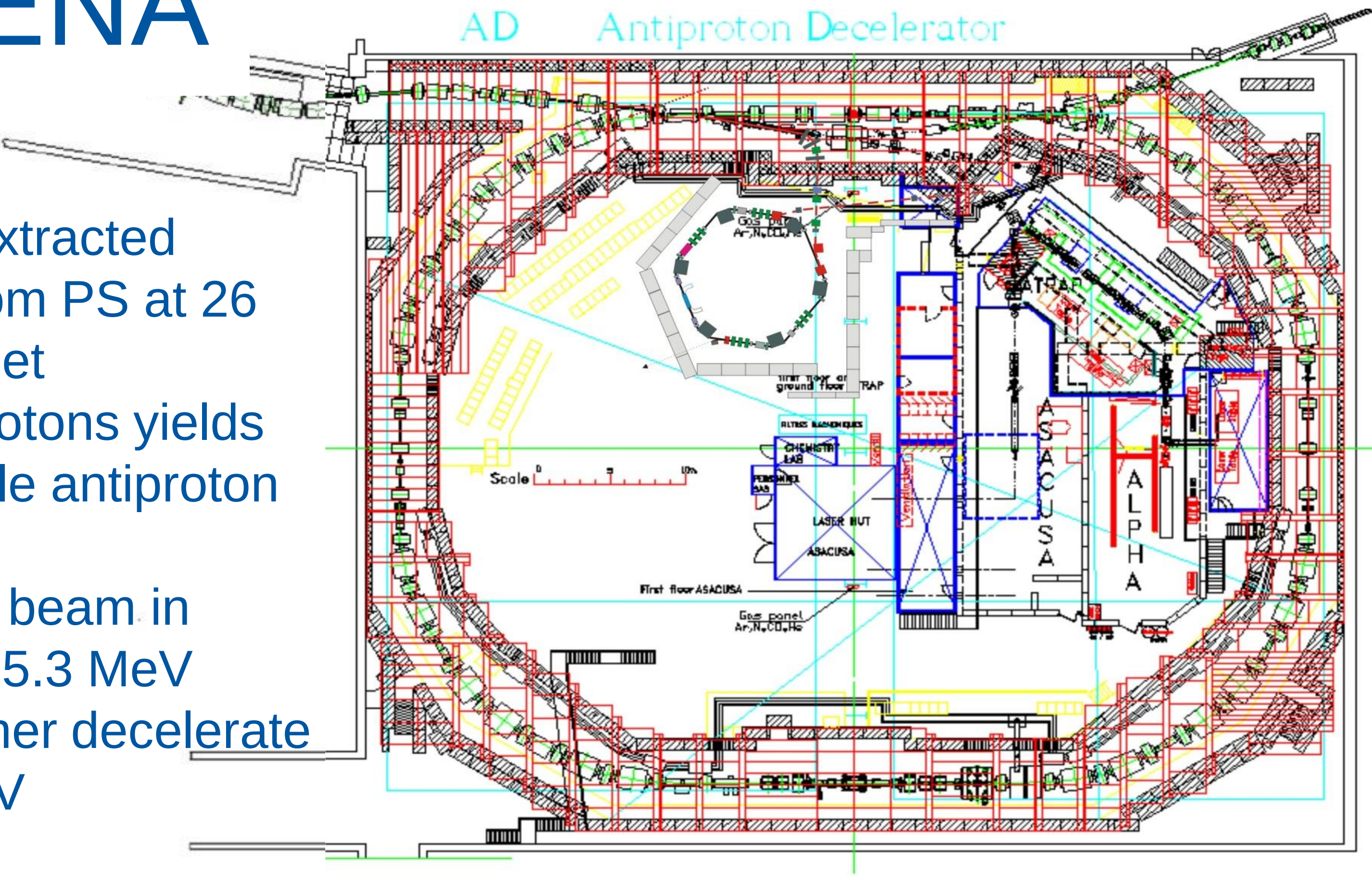
- Receives fast extracted single bunch of protons from PS at 20 GeV/c on a lead spallation target
- Every proton yields about 300 neutrons, spanning an energy range from the MeV region up to the GeV region (slow and fast)

- Experimental area 1 (EAR1):
  - Horizontal beam line with 185 m drift tube
- Experimental area 2:
  - Vertical beam line above the target with 20m drift tube

- Measurement of neutron cross sections relevant for nuclear waste transmutation and for nuclear astrophysics
- Neutrons as probes for fundamental nuclear physics

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

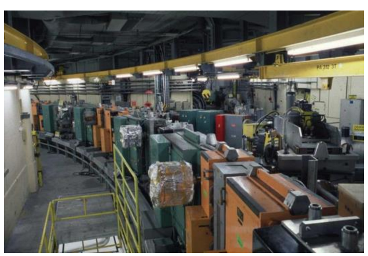


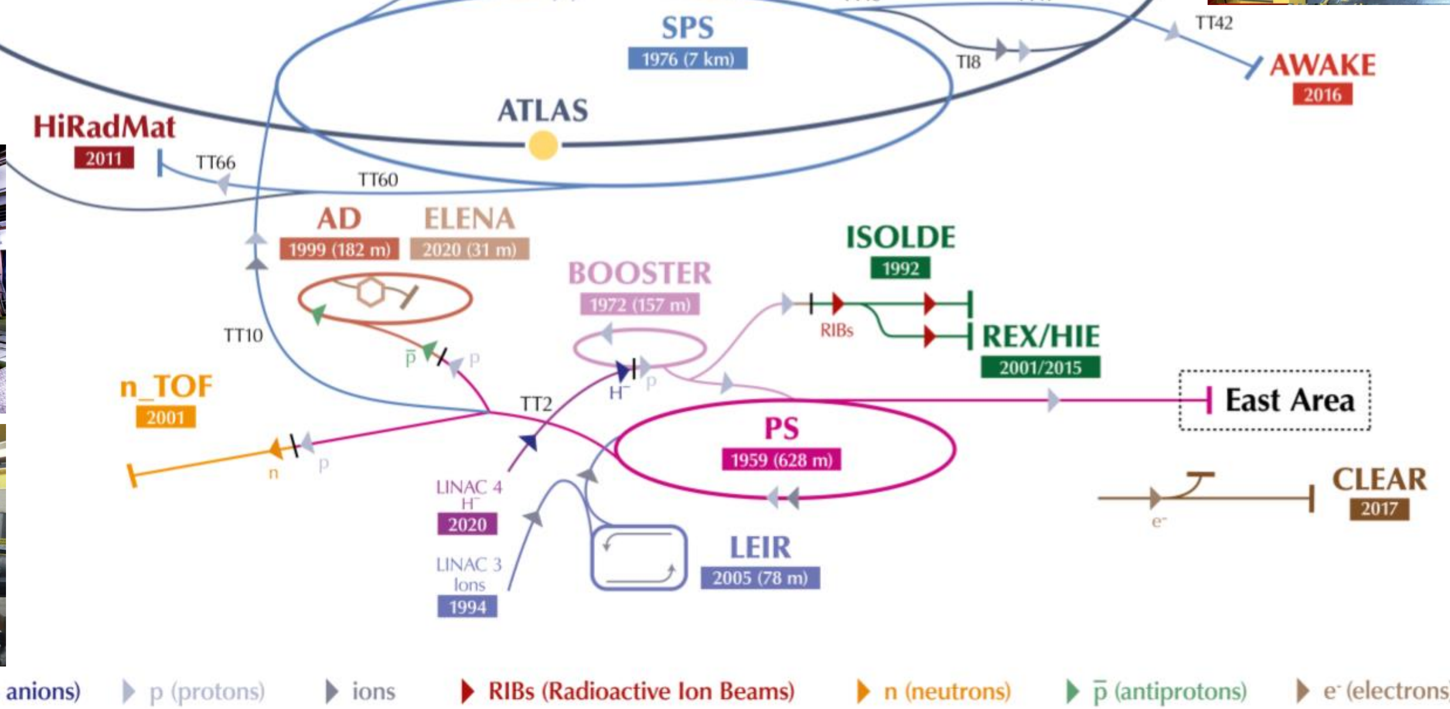
SPS

- 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 ~5×10^{13} protons per cycle

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

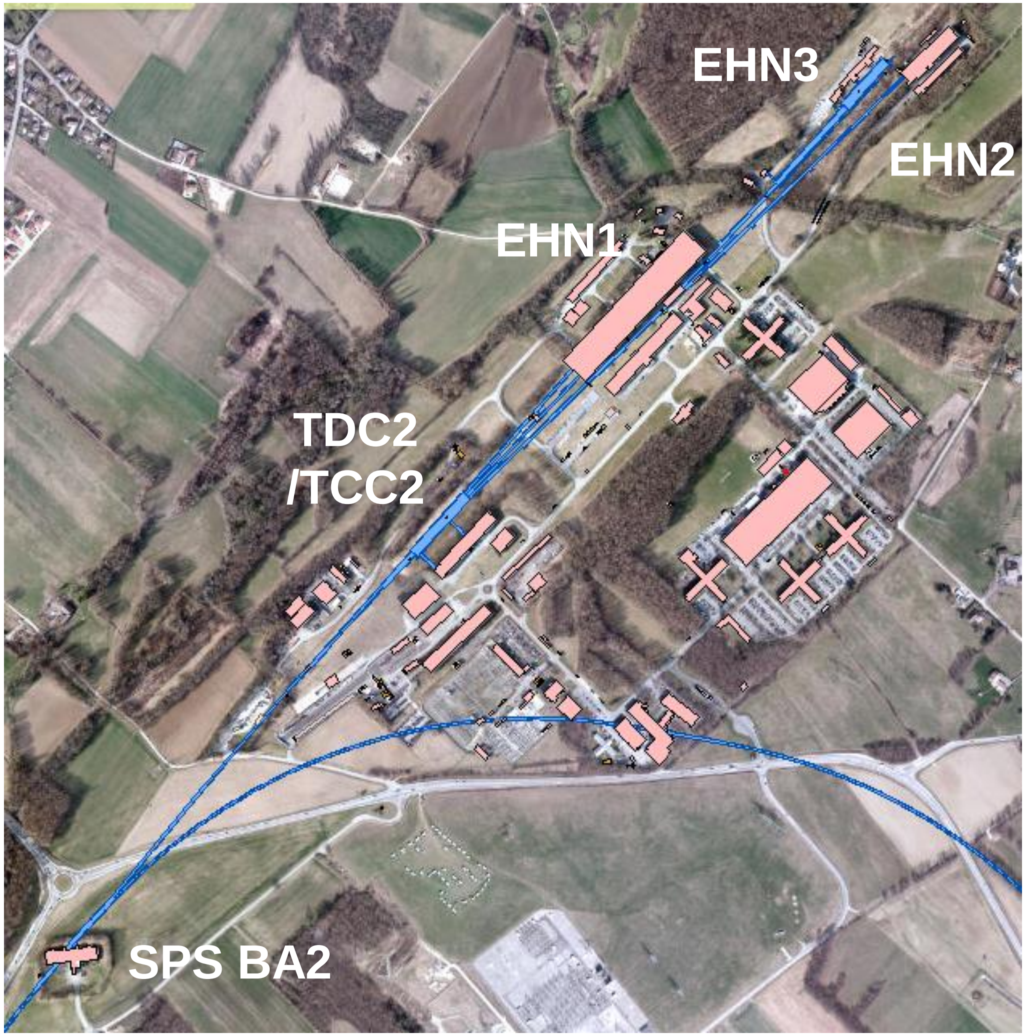
The CERN Accelerator Complex





North Area

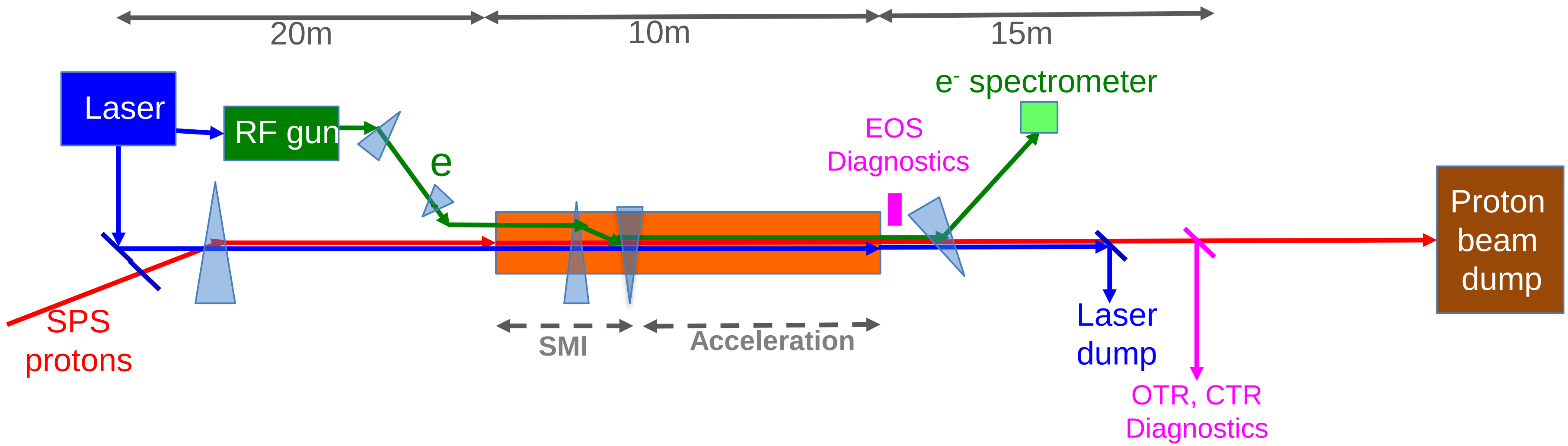
- Receives slow extracted proton beam from the SPS at 400 GeV/c
- Beam spill of ~4.5 s for a cycle length of 10.8s
- Extraction from SPS-BA2
- Beam is sent on various targets
- 7 beam lines with a total length of nearly 6 km
- 3 experimental halls
  - EHN1
  - EHN2
  - EHN3



- Uses nearly every year also ion beams from the SPS for a rich primary and secondary ion physics program

AWAKE

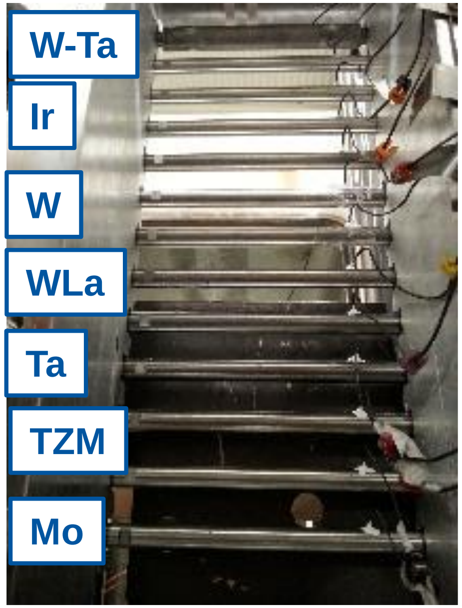
- Proof of principle for **Proton Driven Plasma Wakefield Acceleration**
- Facility situated in previous CNGS target area



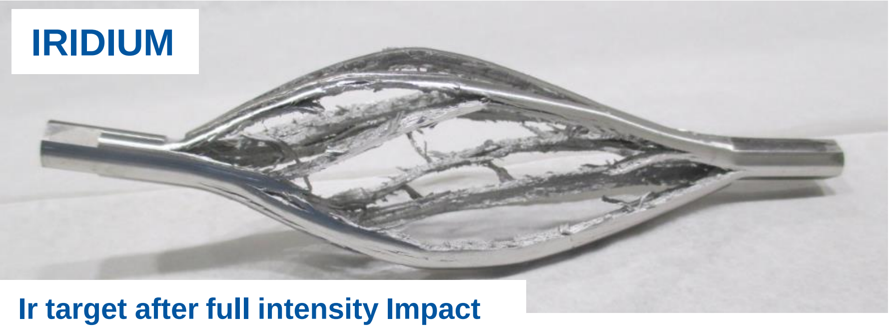
- Proton beam will induce a strong Wakefield in the plasma that is heated using a laser
- 10-20 MeV electron will “surf’ on the waves in the plasma and will be accelerated to multi-GeV range

HiRadMat

- Facility to study the impact of intense pulsed beams on materials
  - Thermal management;
  - Radiation Damage to materials;
  - Thermal shock – beam induced pressure waves.

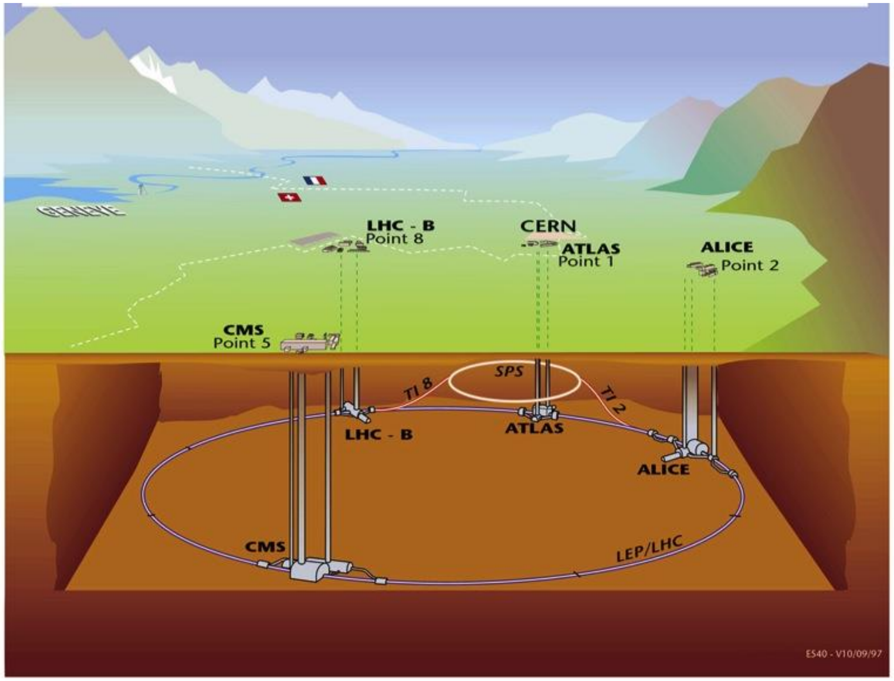


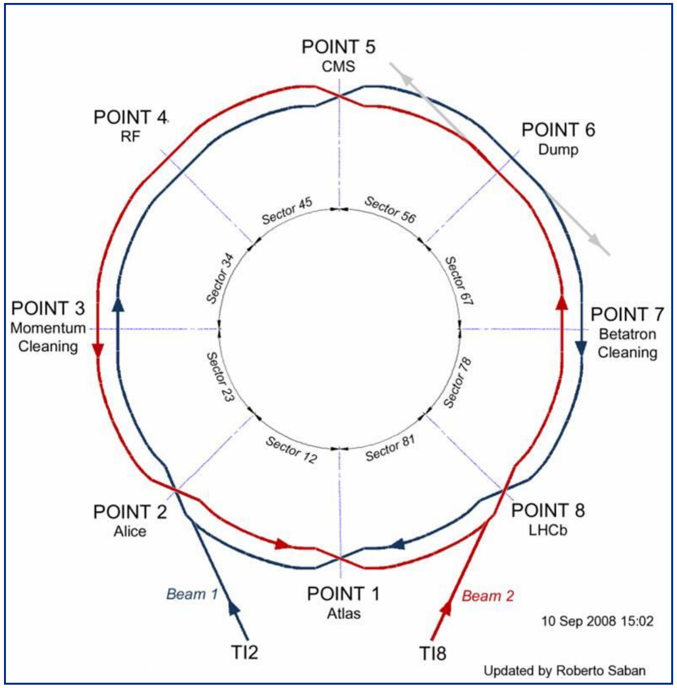
- Built for the LHC Upgrades and target tests
- Makes use of part of the Infrastructure of a previous Neutrino facility
- Uses LHC type beams from the SPS at 450 GeV



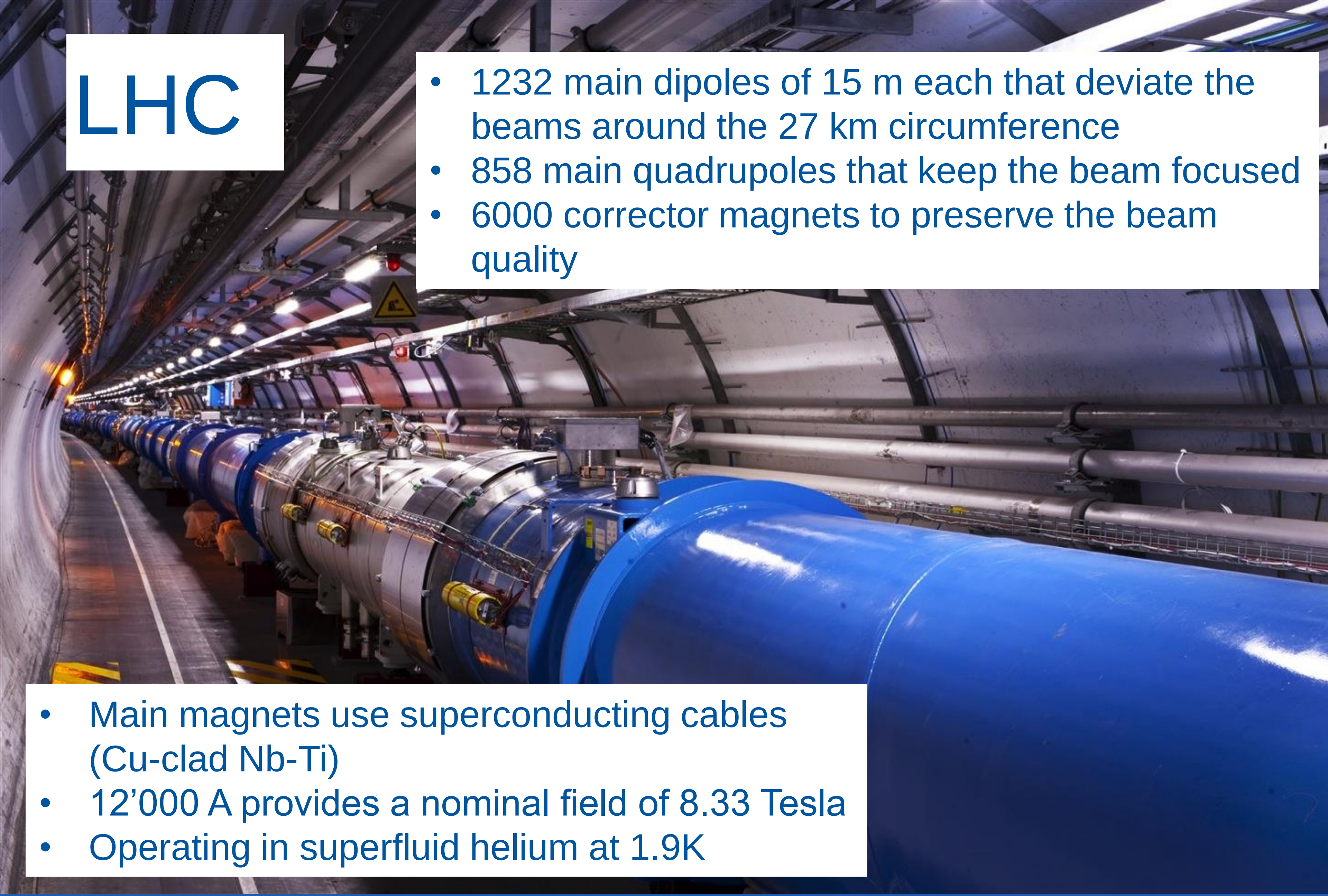
Ir target after full intensity Impact

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

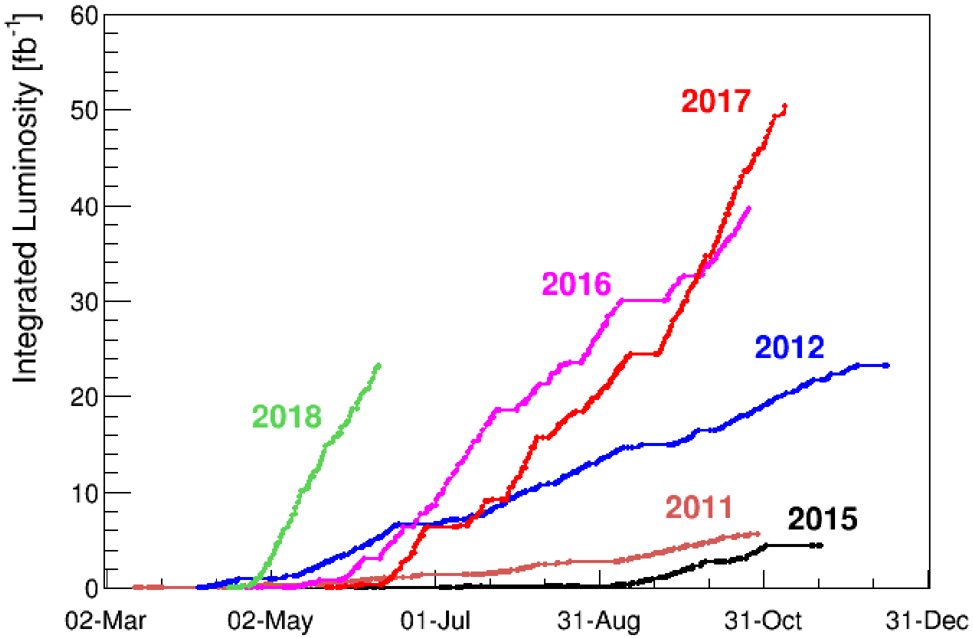
Intensity per bunch

Number of bunches

Geometrical Correction factors

Beam dimensions

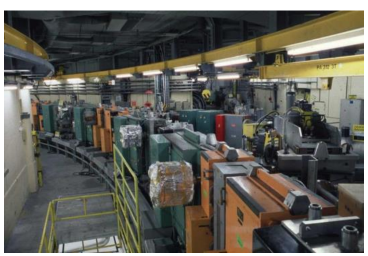
$$LUMINOSITY = \frac{N_{event/\sec}}{s_r} = \frac{N_1 N_2 f_{rev} n_b}{4 p s_x s_y} F$$

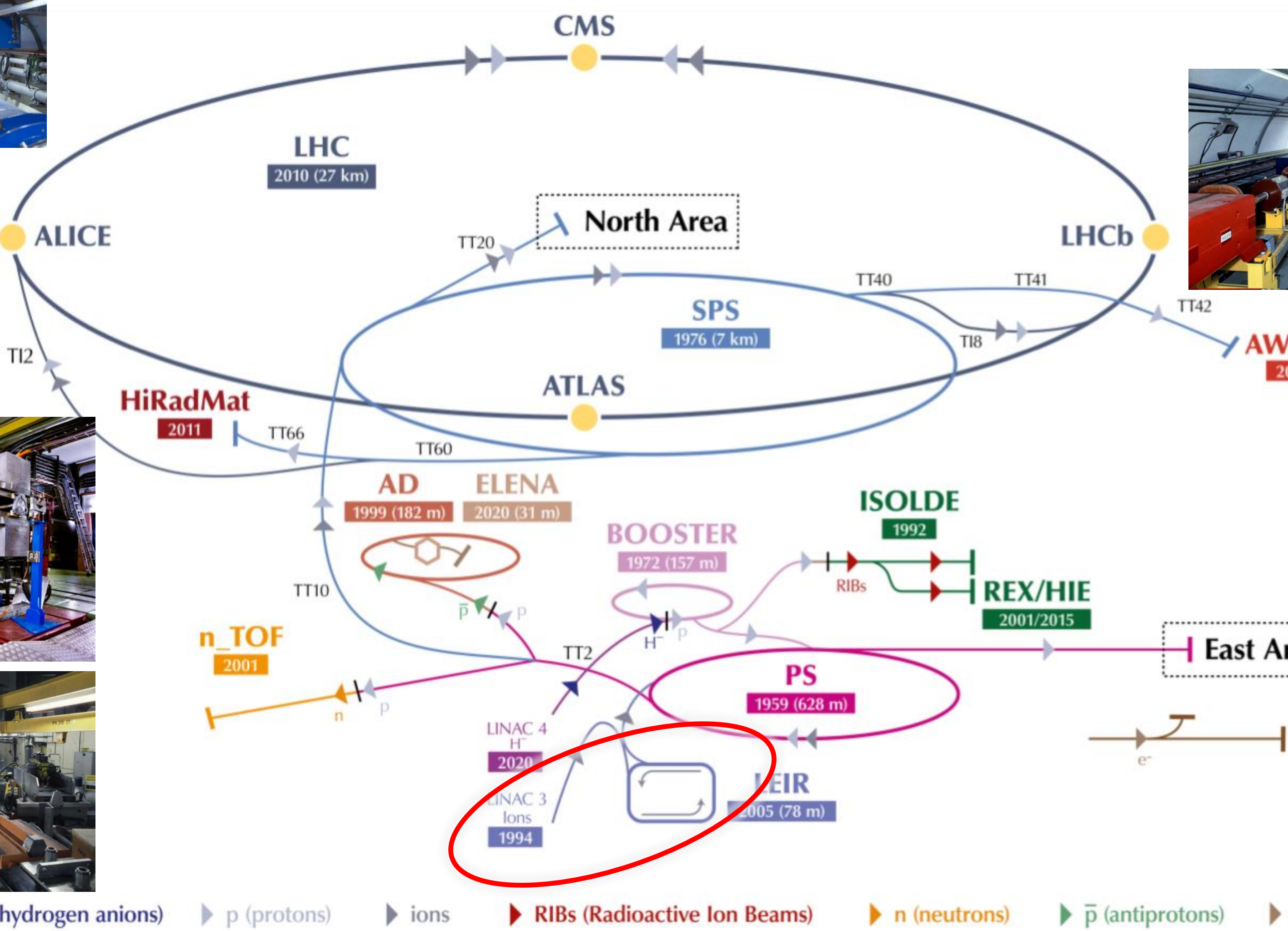


Maximise Luminosity:

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

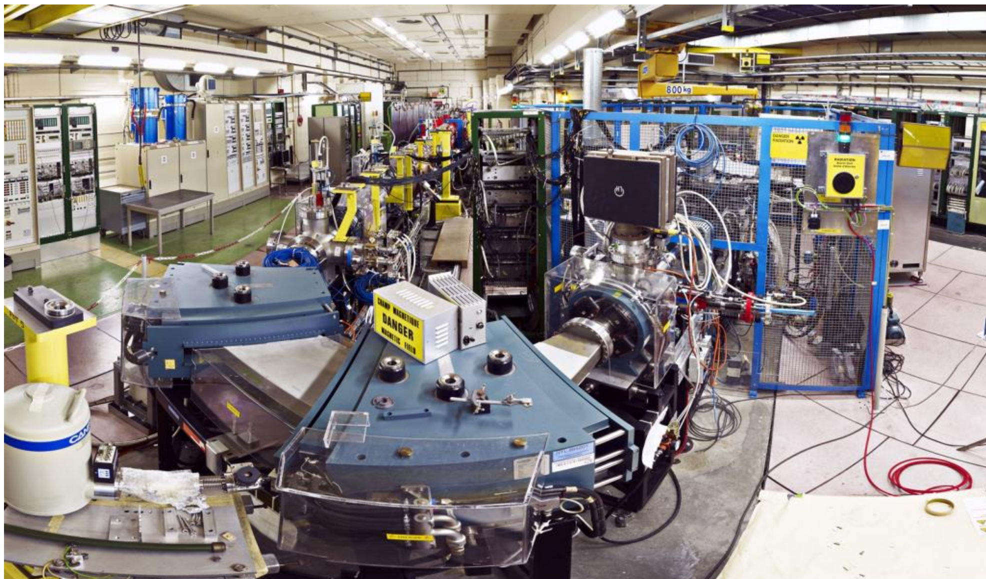
The CERN Accelerator Complex



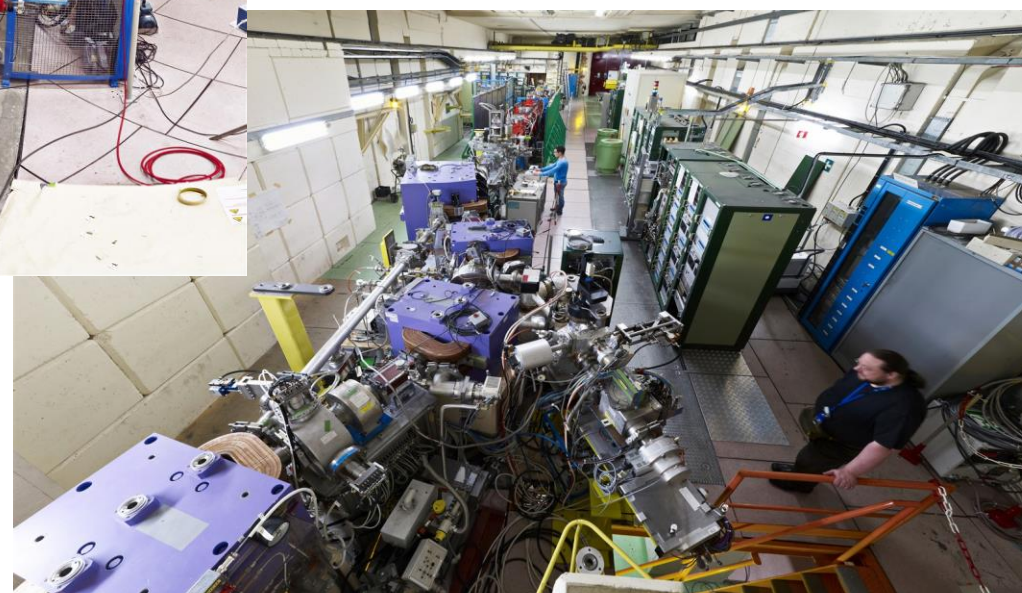


LINAC3

The CERN LINAC 3 provides different ion species to LEIR



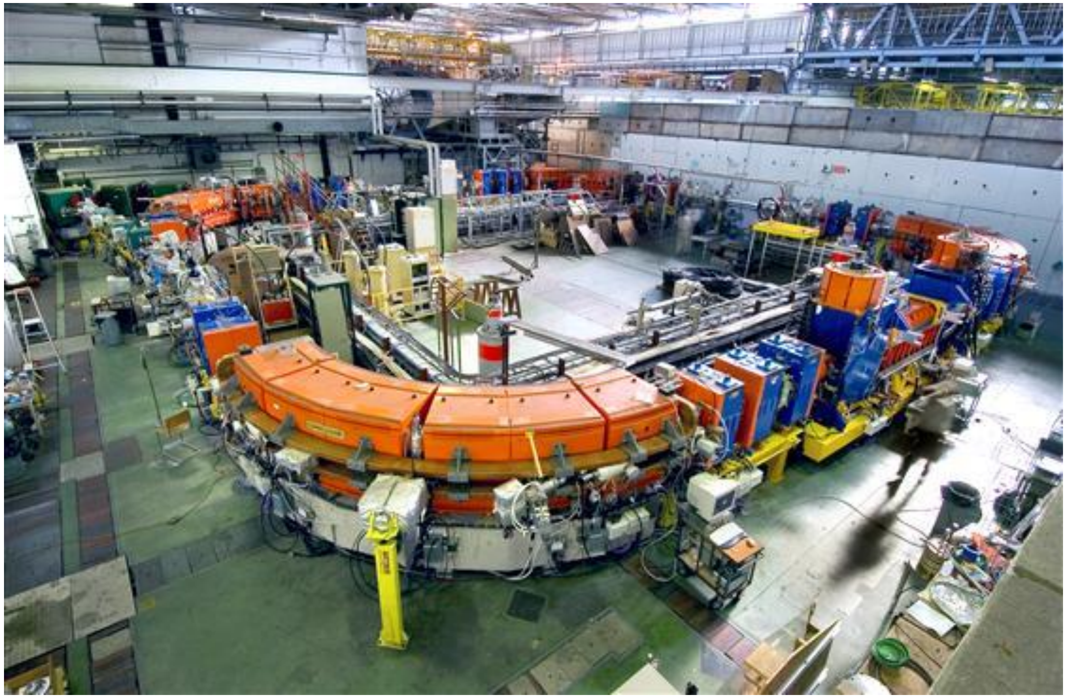
The ion source in the blue cage with the spectrometer in the front, follow by the LINAC behind



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

LEIR

- Receives beam from LINAC3
- Different ion species:
  - Pb (lead)
  - Ar (Argon)
  - Li (Lithium)
  - Xe (Xenon)
  - …
- The LEIR cycle length is 3.6s



- Performs multi-turn injection at a rate of 200 ms
- Uses stochastic and electron cooling to reduces transverse and longitudinal beam dimensions
- Sends the beam to the PS that feeds it in to the SPS for delivery to the LHC and the North Area

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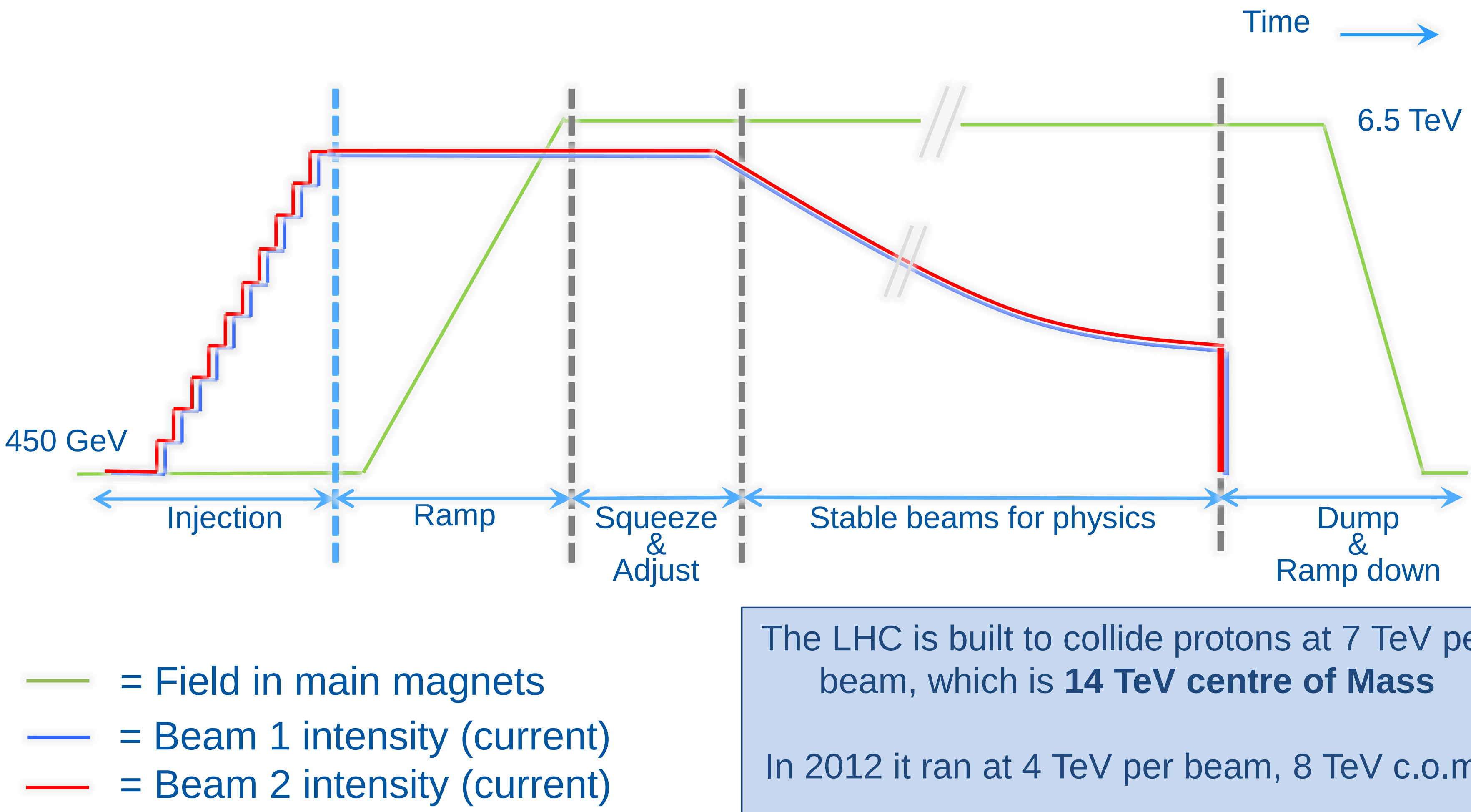
The LHC Cycle



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.

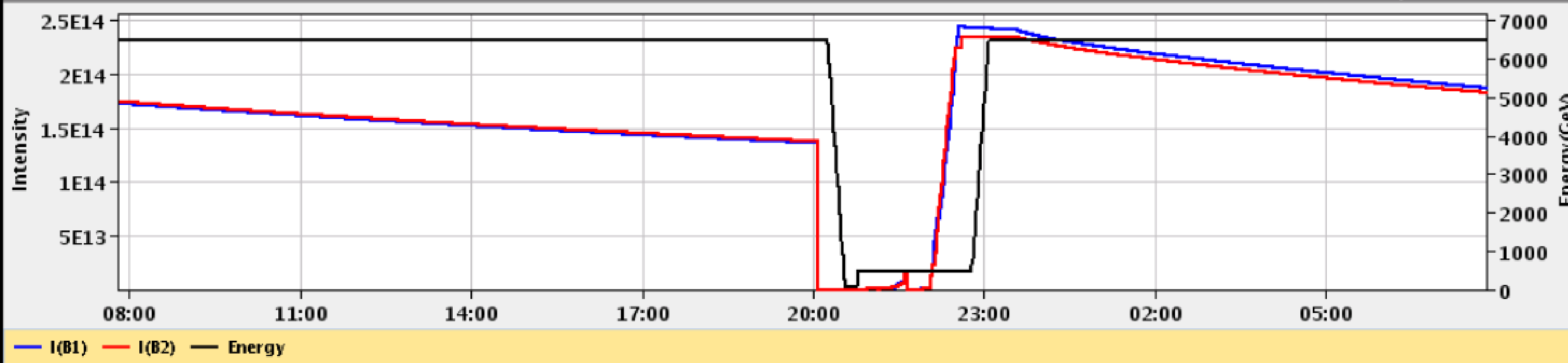
Since 2015 it runs at 6.5 TeV per beam, 13 TeV c.o.m

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

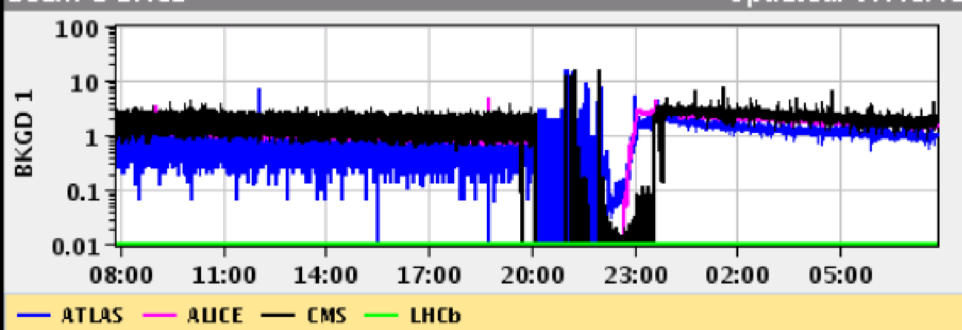
	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Lumi [(ub.s)^-1]	7346.231	1.672	7730.174	355.048
BRAN Luminosity [(ub.s)^-1]	7462.0	1.8	6917.8	181.2
Fill Luminosity (nb)^-1	265785.063	49.302	293245.594	10312.992
Beam 1 BKGD	0.927	1.401	1.645	0.000
Beam 2 BKGD	4.488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

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

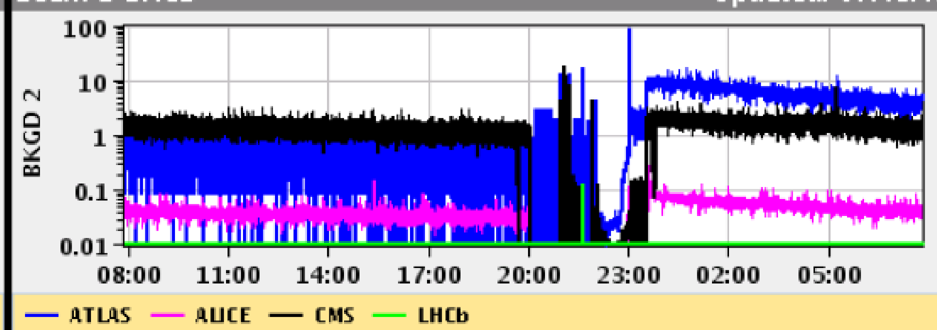
Performance over the last 24 Hrs Updated: 07:48:42



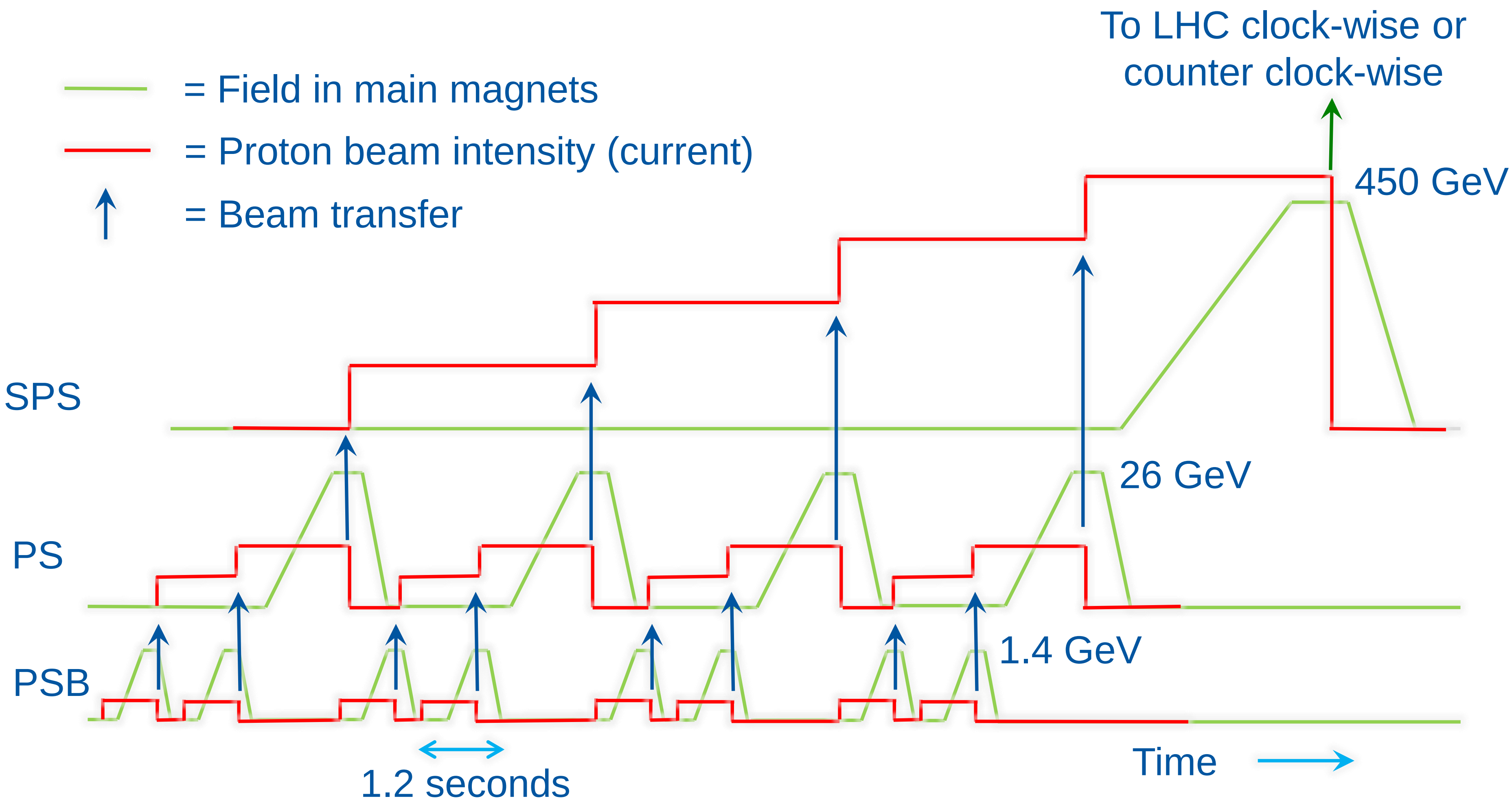
Beam 1 BKGD Updated: 07:48:41



Beam 2 BKGD Updated: 07:48:41



Filling the LHC and Satisfying Fixed Target users



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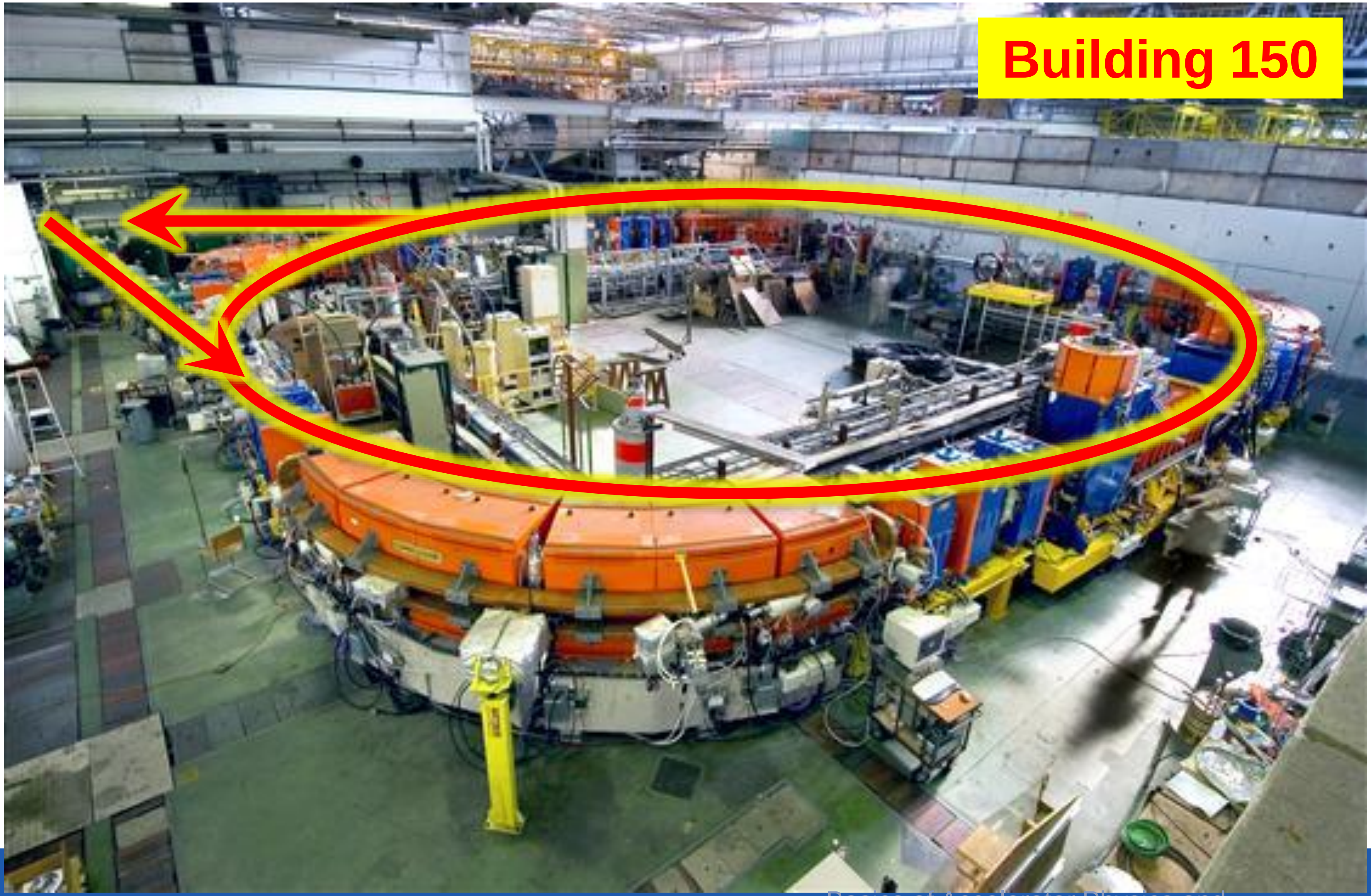
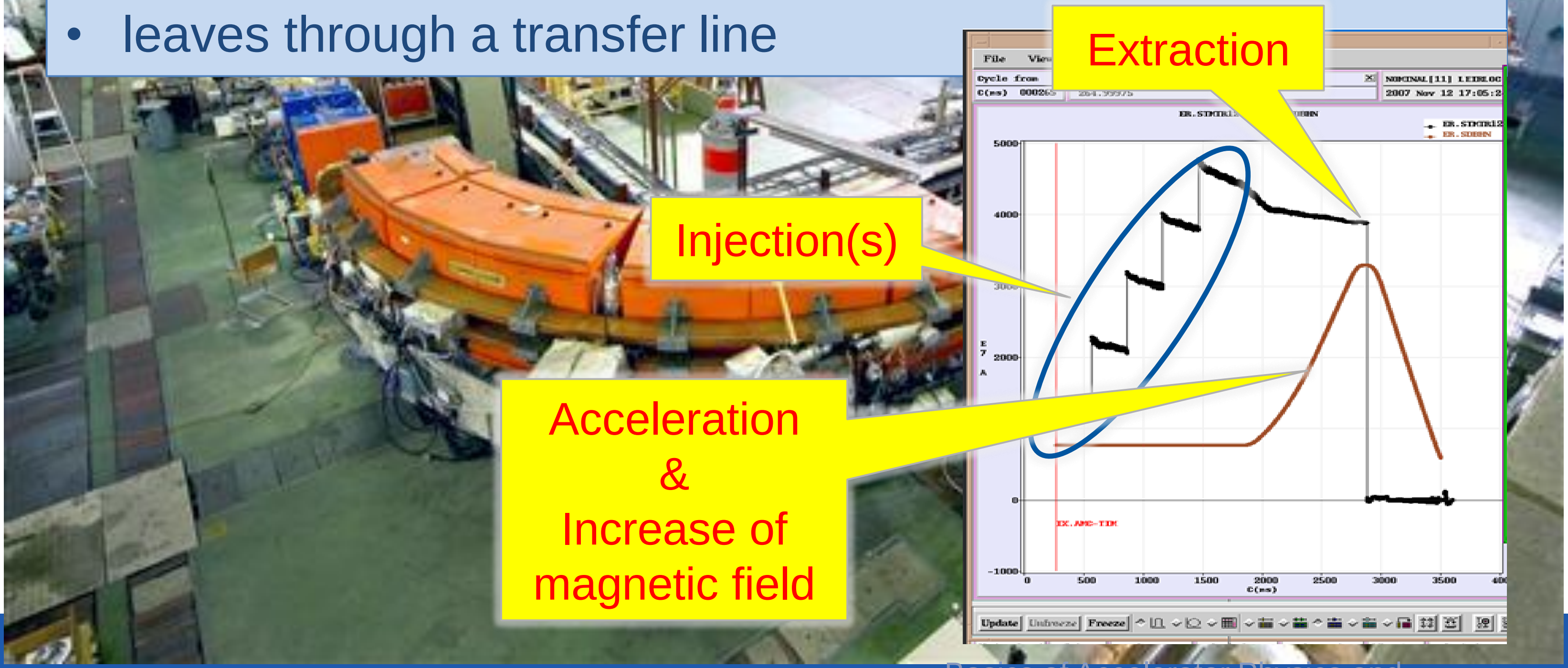
LEIR as an Example



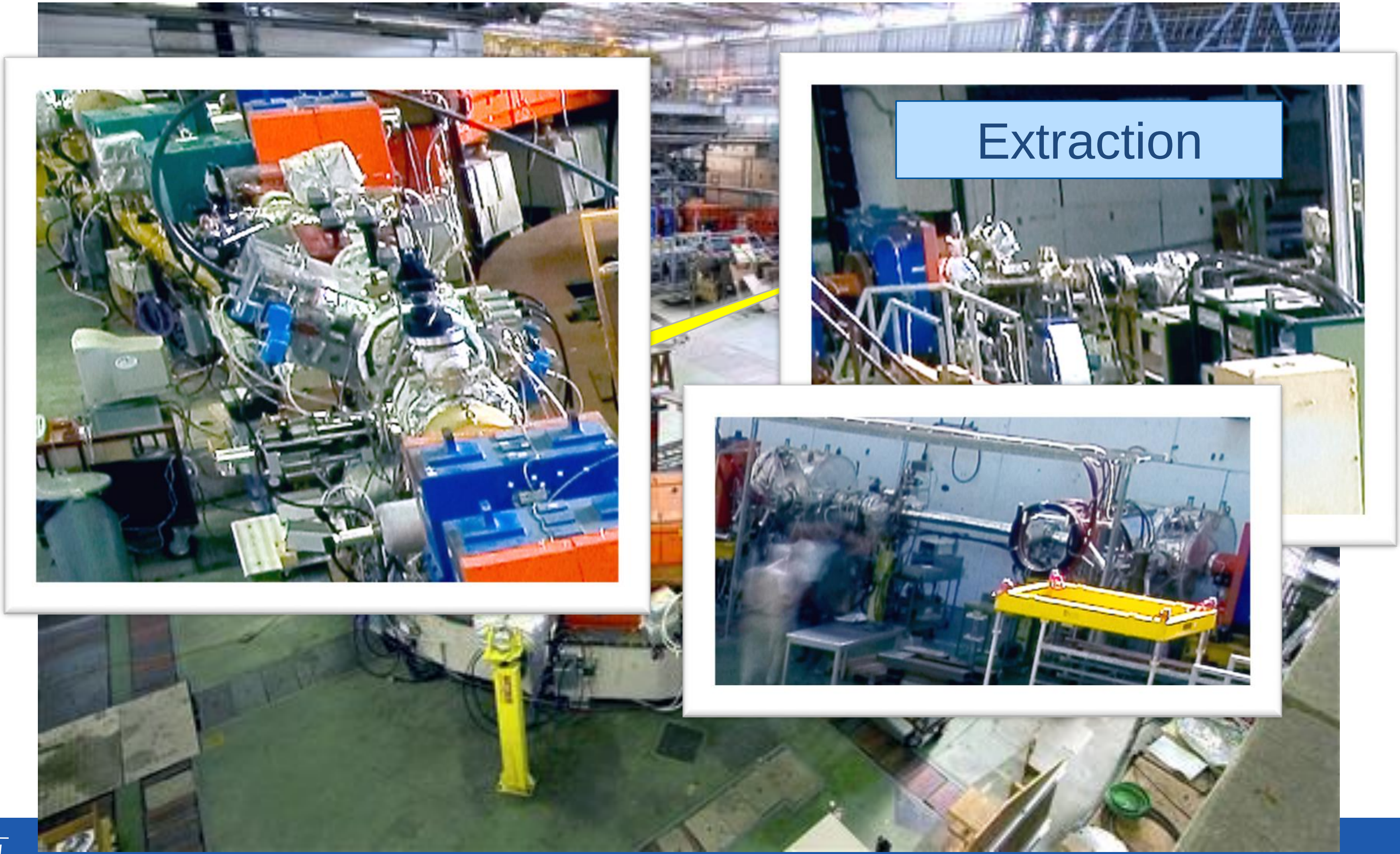
LEIR as an Example

The particle beam:

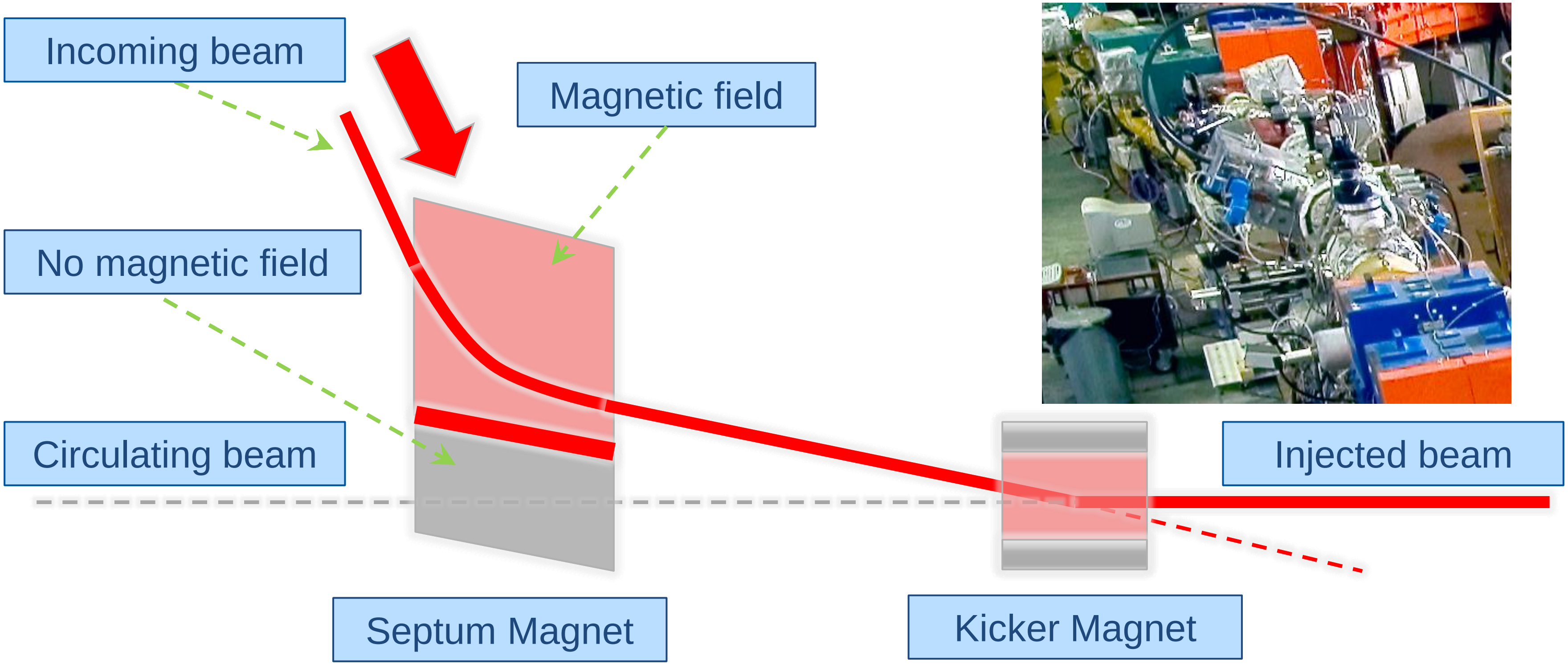
- arrives through a transfer line
- is injected
- is accelerated over many turns in a “circular” machine
- is extracted
- leaves through a transfer line



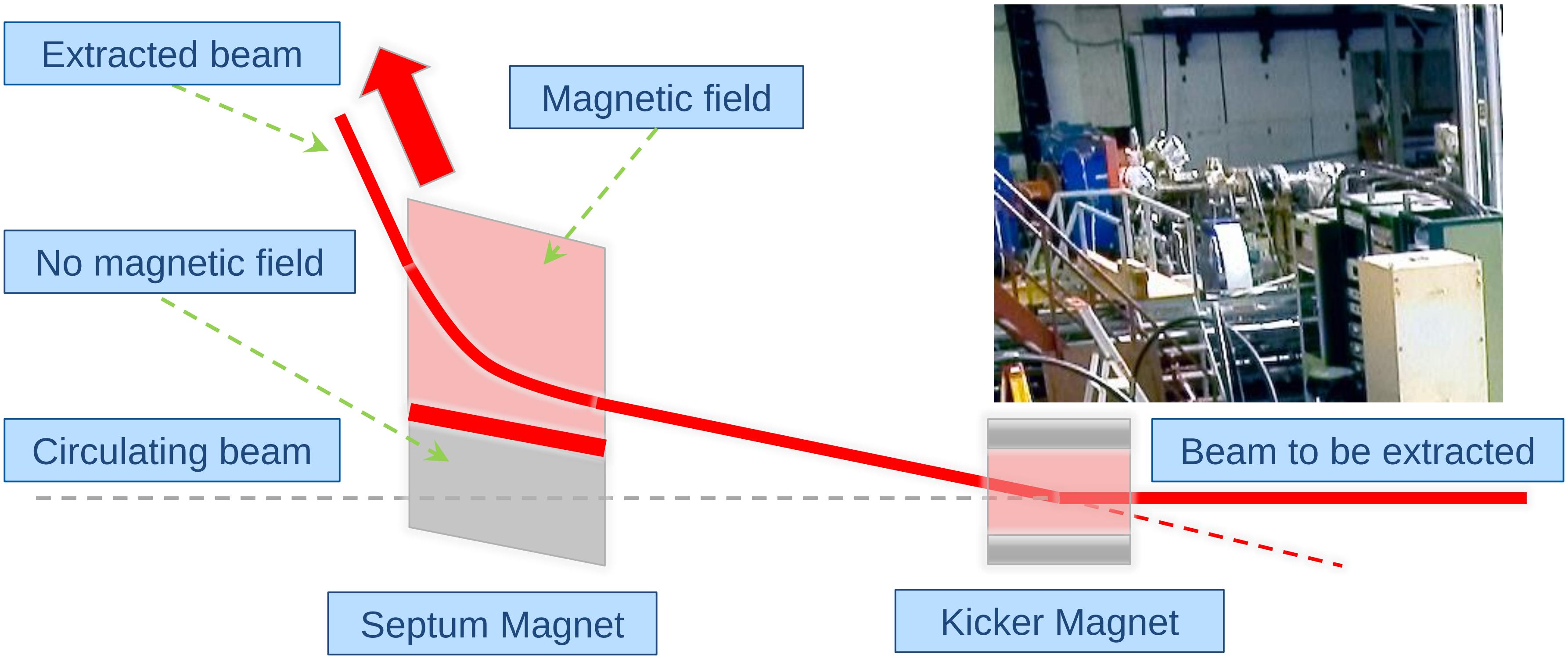
Injecting & Extracting Particles



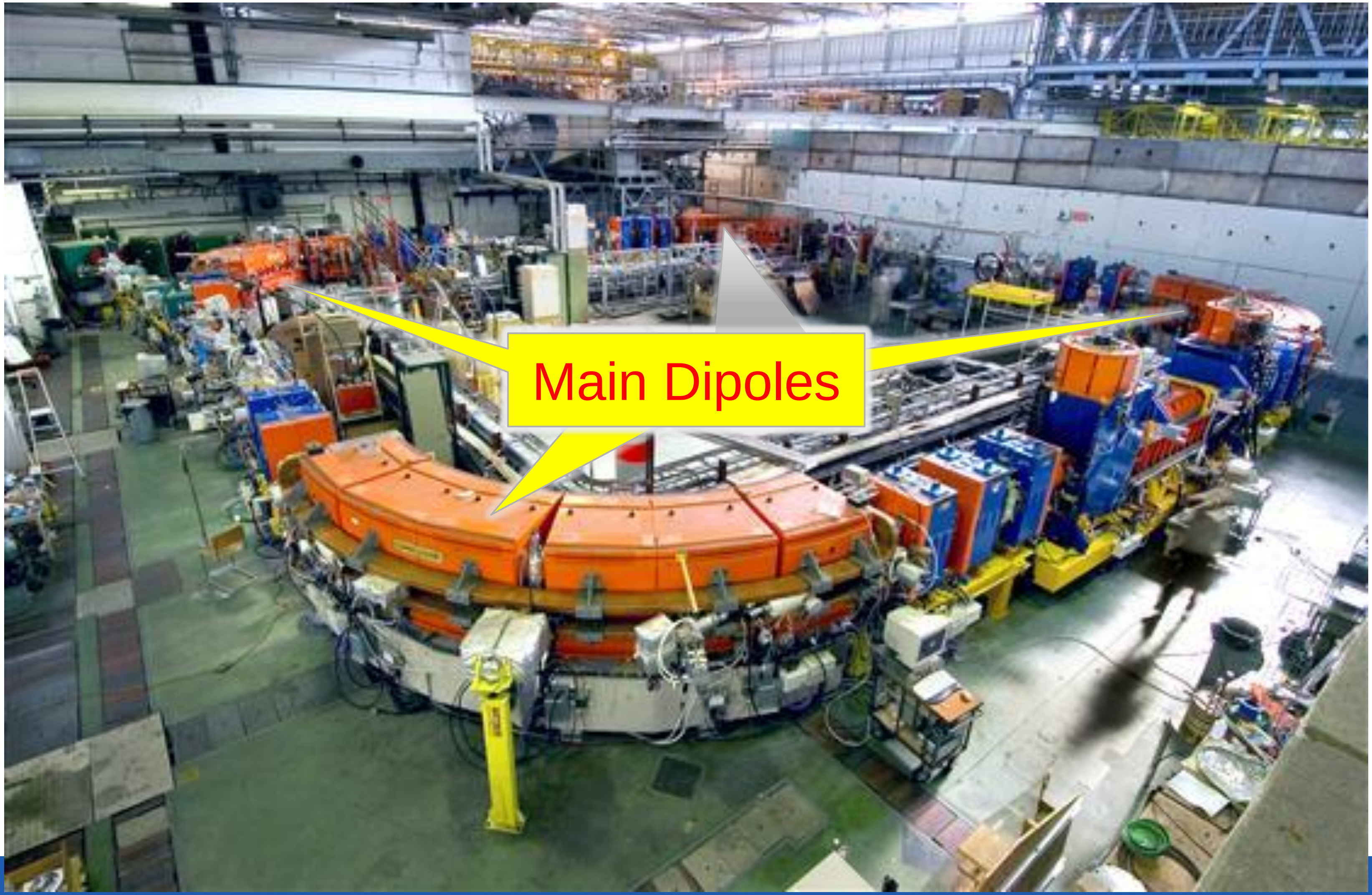
Injecting & Extracting Particles



Injecting & **Extracting** Particles

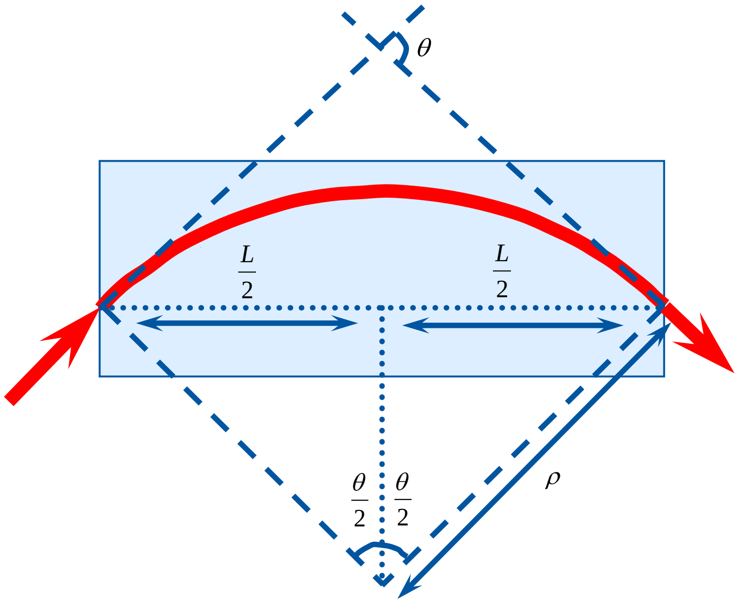


Make Particles Circulate



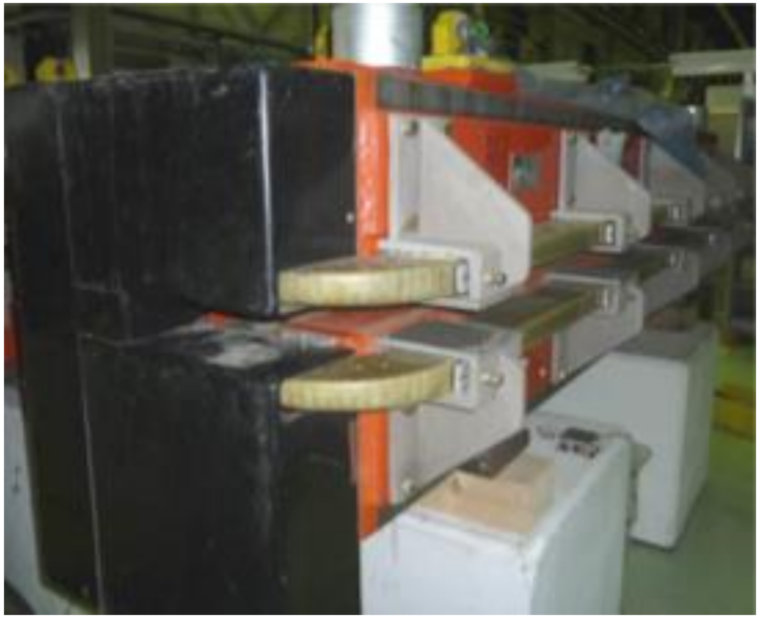
Deviating Charged Particles

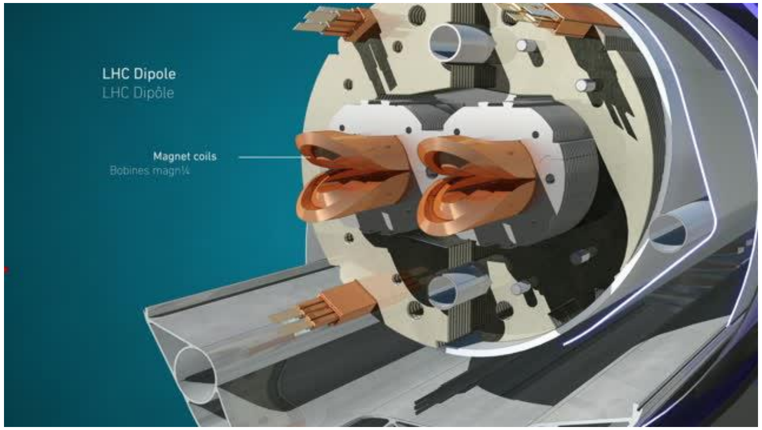
Charged Particles are deviated in magnetic fields



Lorentz force:

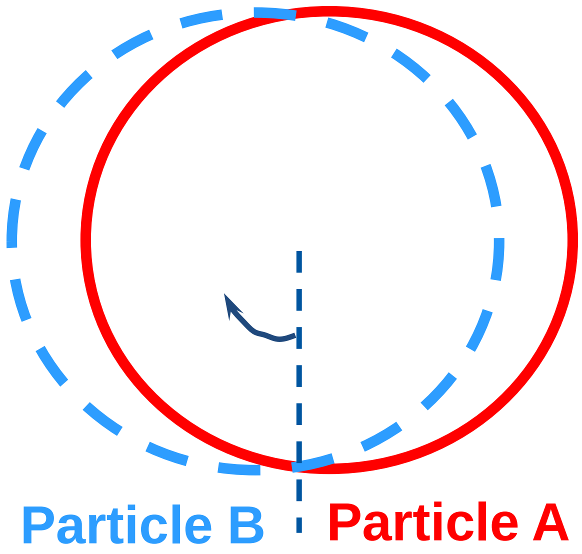
$$F = e\, v \times B$$



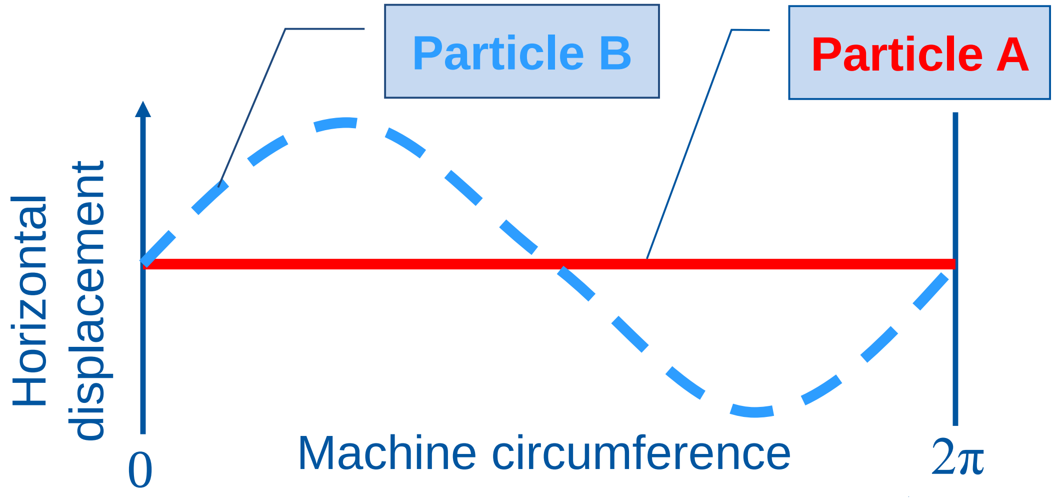


Oscillatory Motion of Particles

Two charged Particles in a homogeneous magnetic field



Horizontal motion

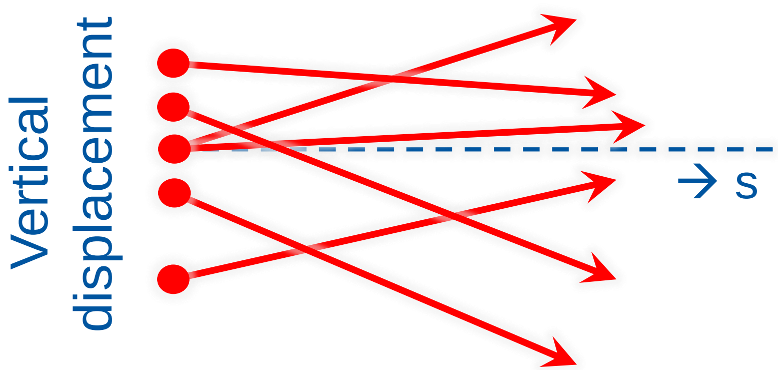


Different particles with different initial conditions in a homogeneous magnetic field will cause oscillatory motion in the horizontal plane → **Betatron Oscillations**

Oscillatory Motion of Particles

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

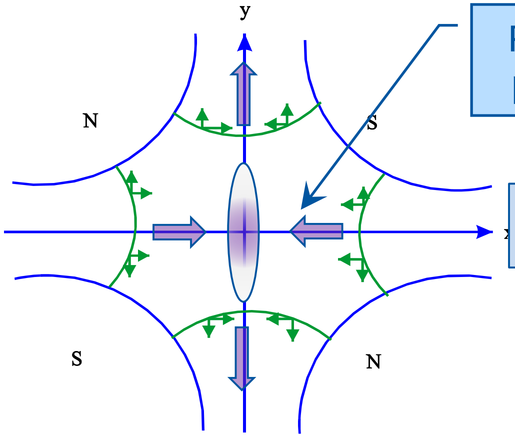
Many particles many initial conditions



Many different angles

Focusing Particle Beams

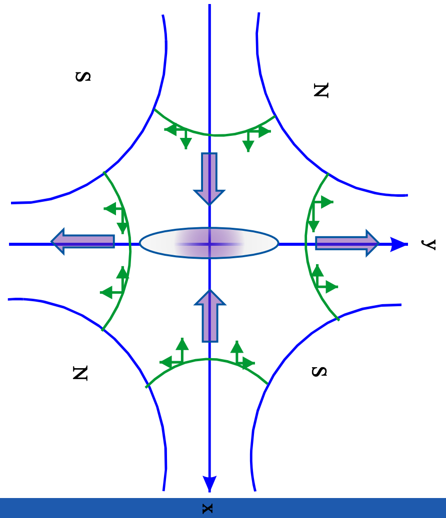
Focusing particles, a bit like light in a lens



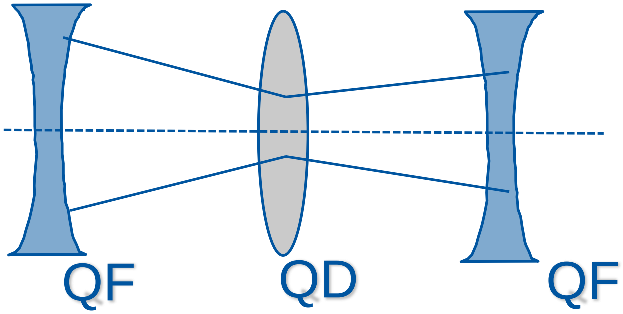
Force on particles

Focusing Quadrupole

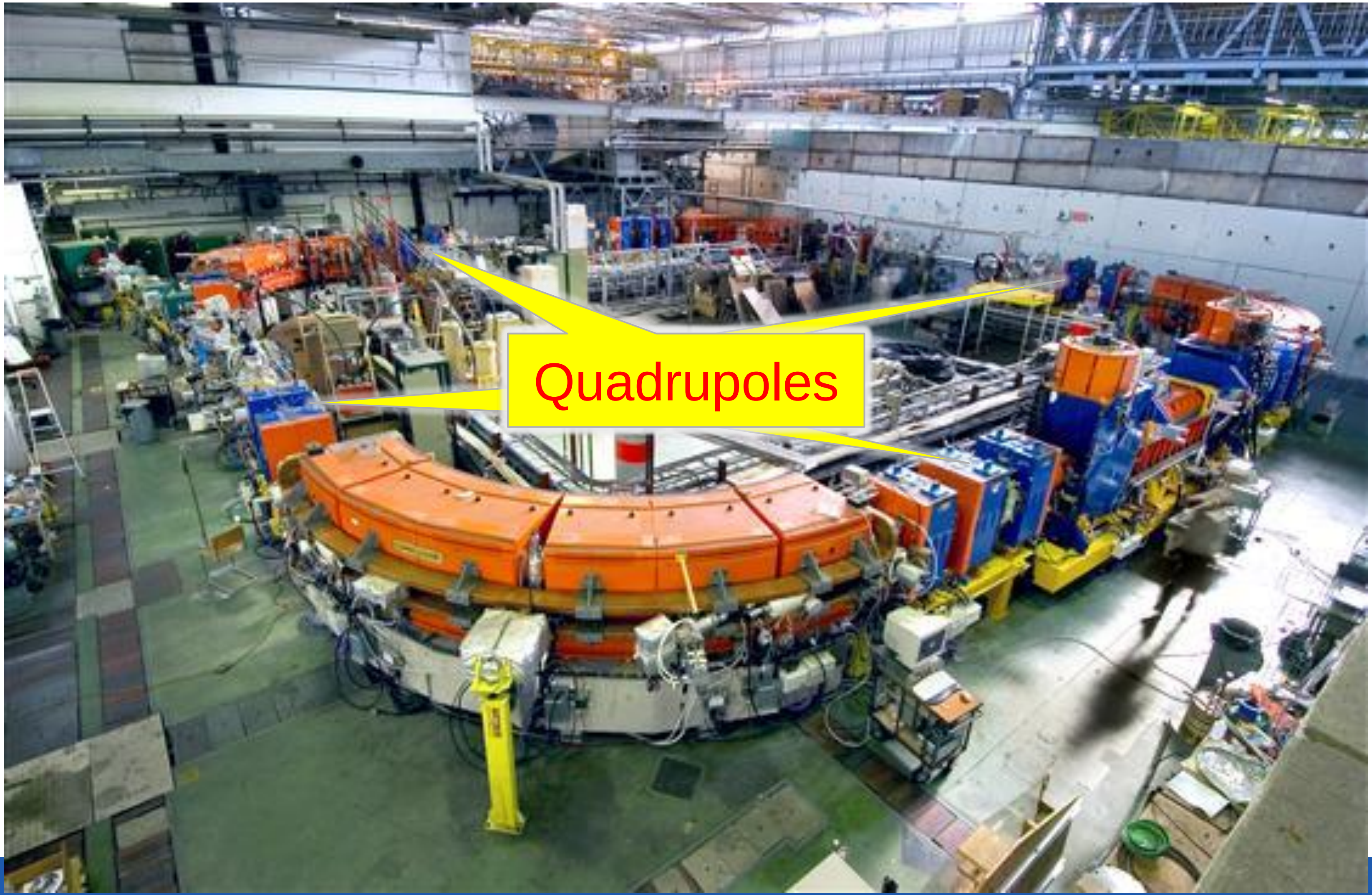
Rotated by 90º



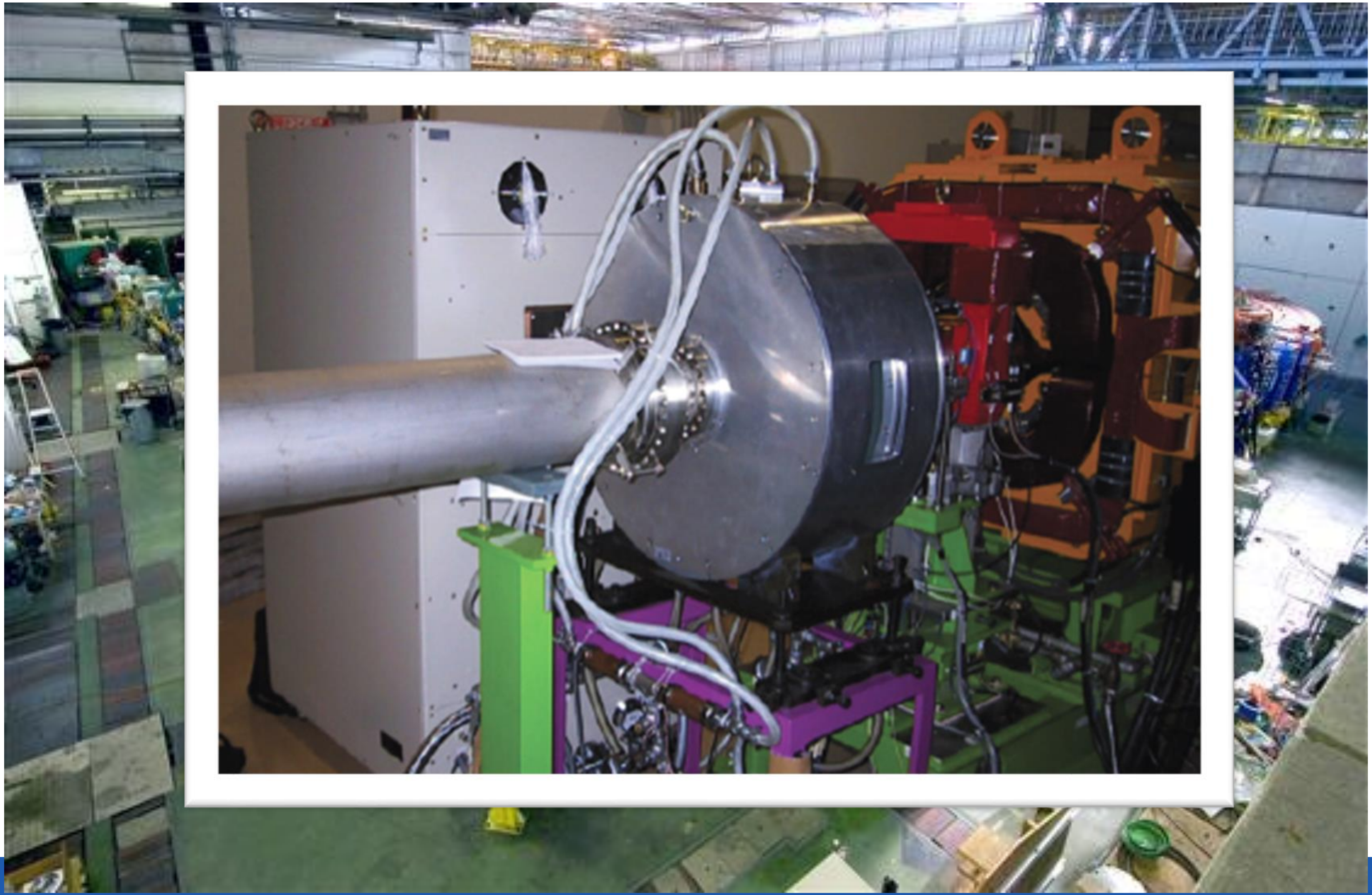
De-focusing Quadrupole



Focusing the Particle Beam

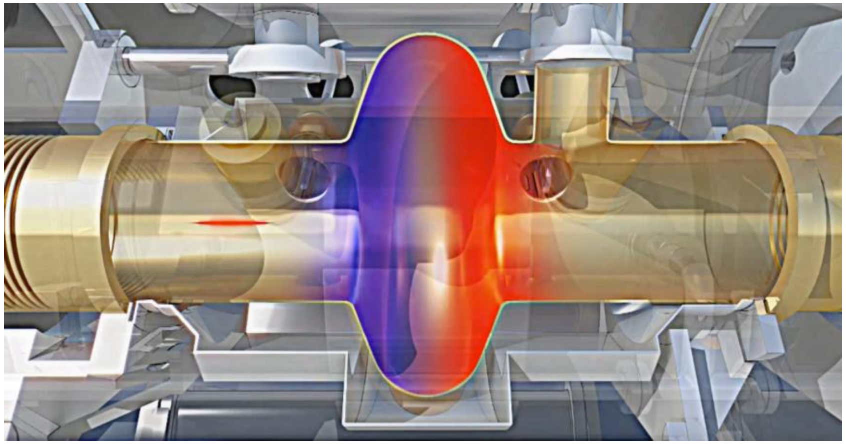


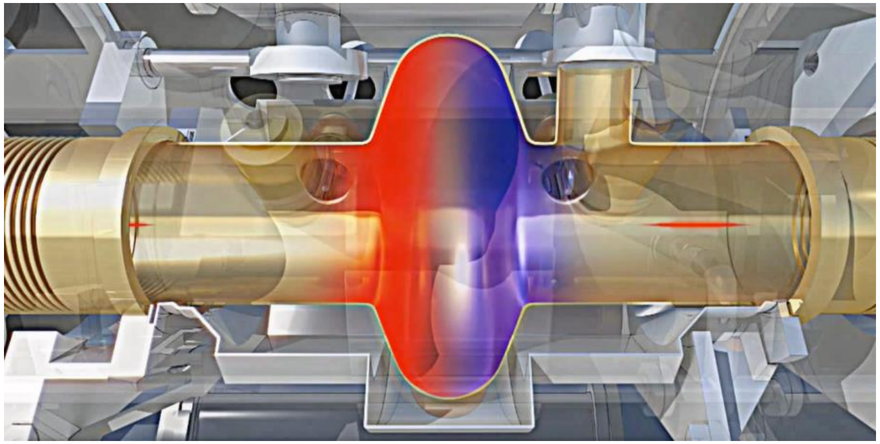
Accelerating Particles



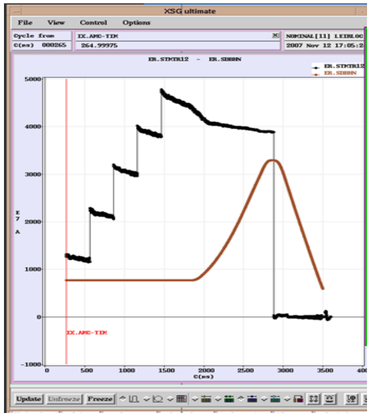
RF Cavity

- Charged particles are accelerated by a longitudinal electric field
- The electric field needs to alternate with a harmonic of the revolution frequency

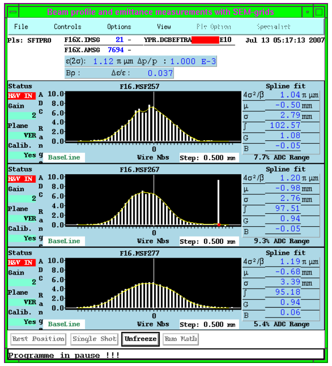




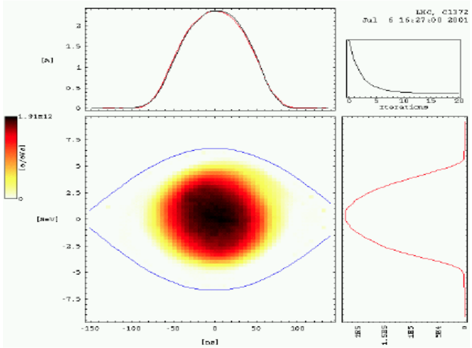
The Eyes of Operations



Beam intensity or current measurement



Transverse beam profile/size measurement



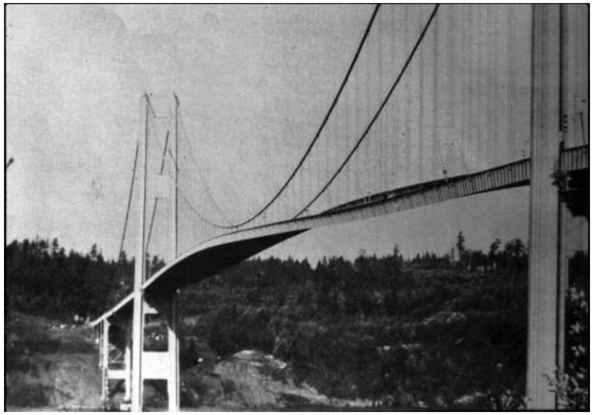
Longitudinal beam profile measurements

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

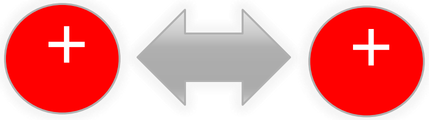
Any many more beam properties…..

Possible Limitations

Machines and elements cannot be built with infinite perfection

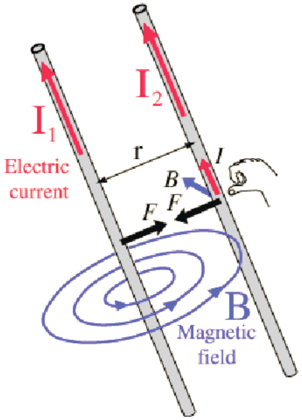


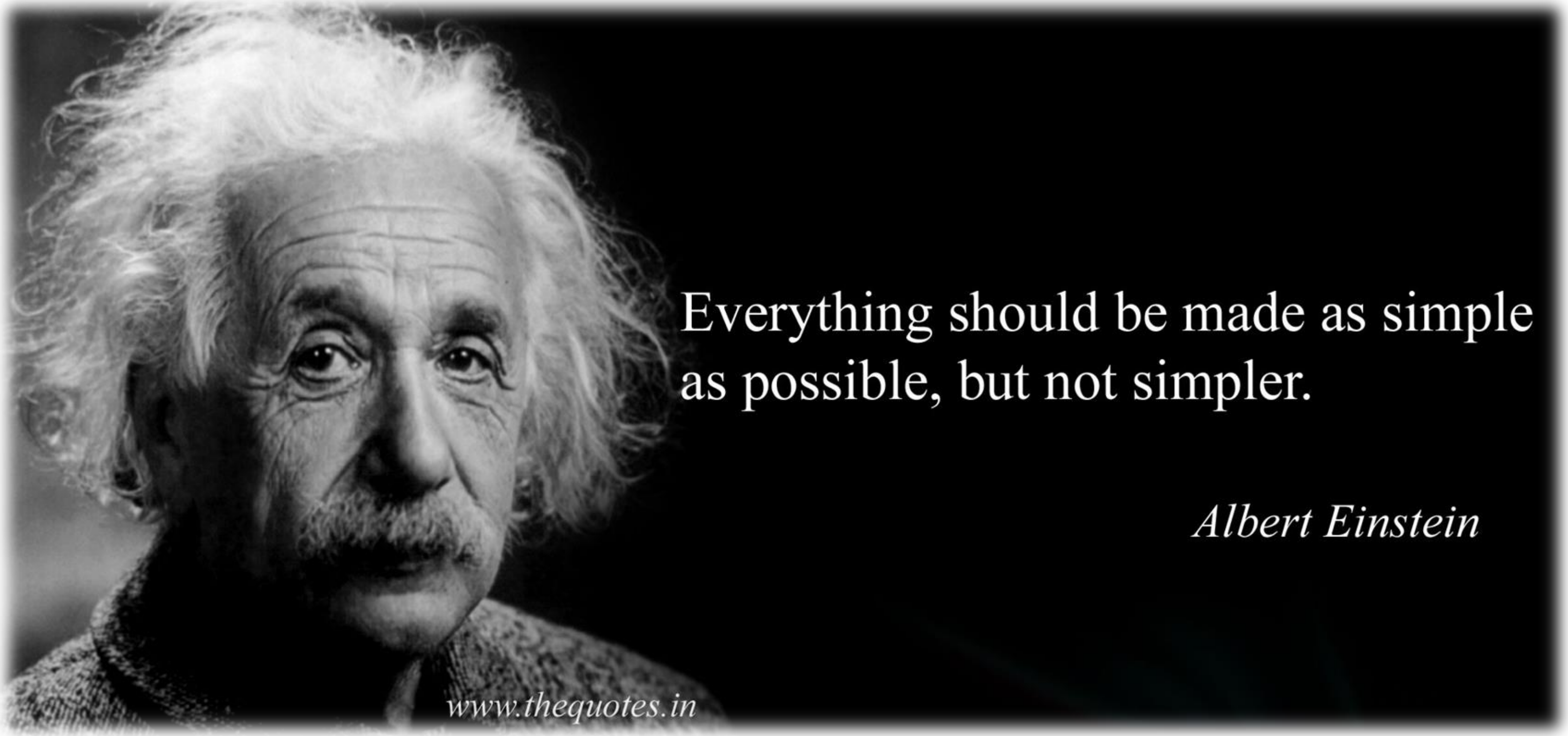
Same phase and frequency for driving force and the system can cause resonances and be destructive



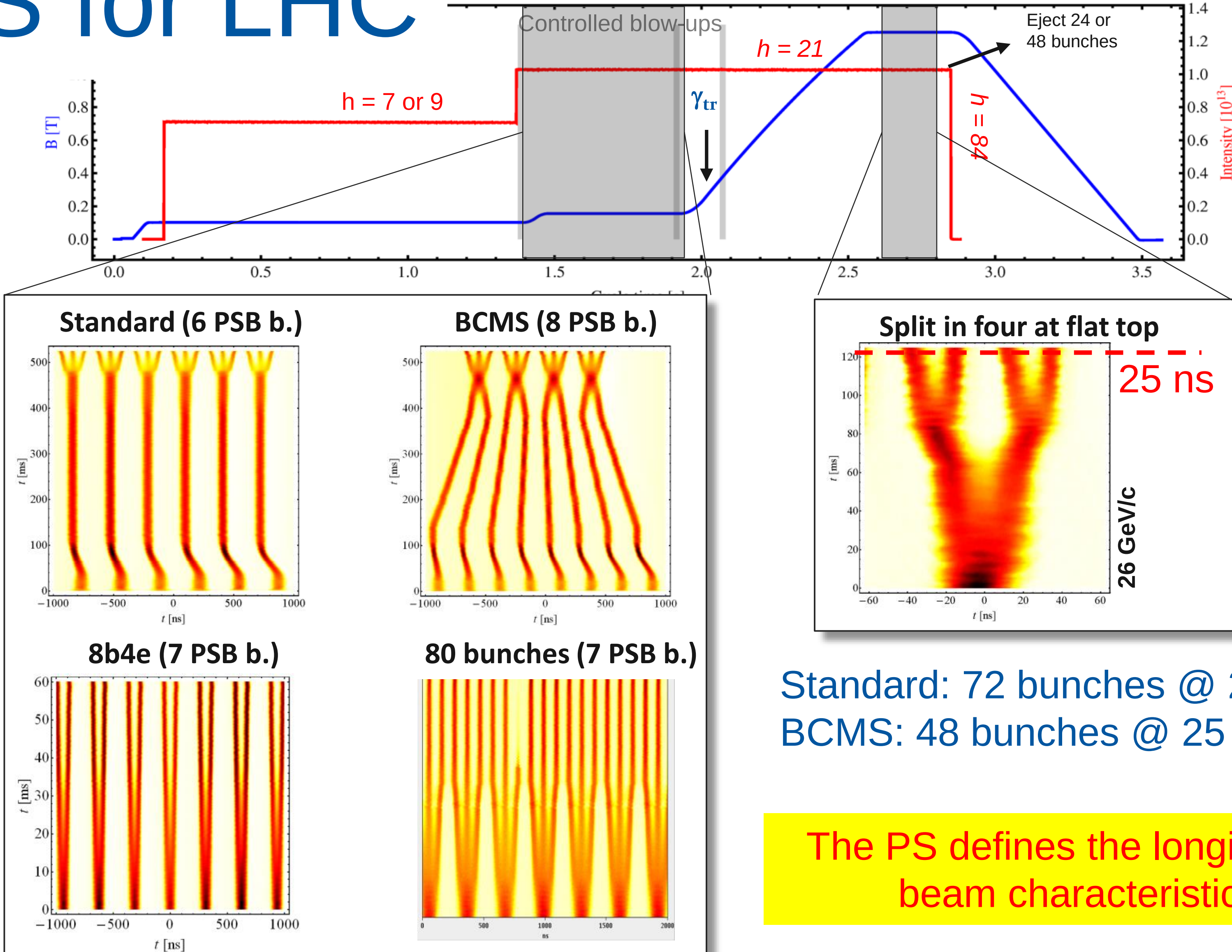
Neighbouring charges with the same polarity experience repelling forces

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

PS for LHC

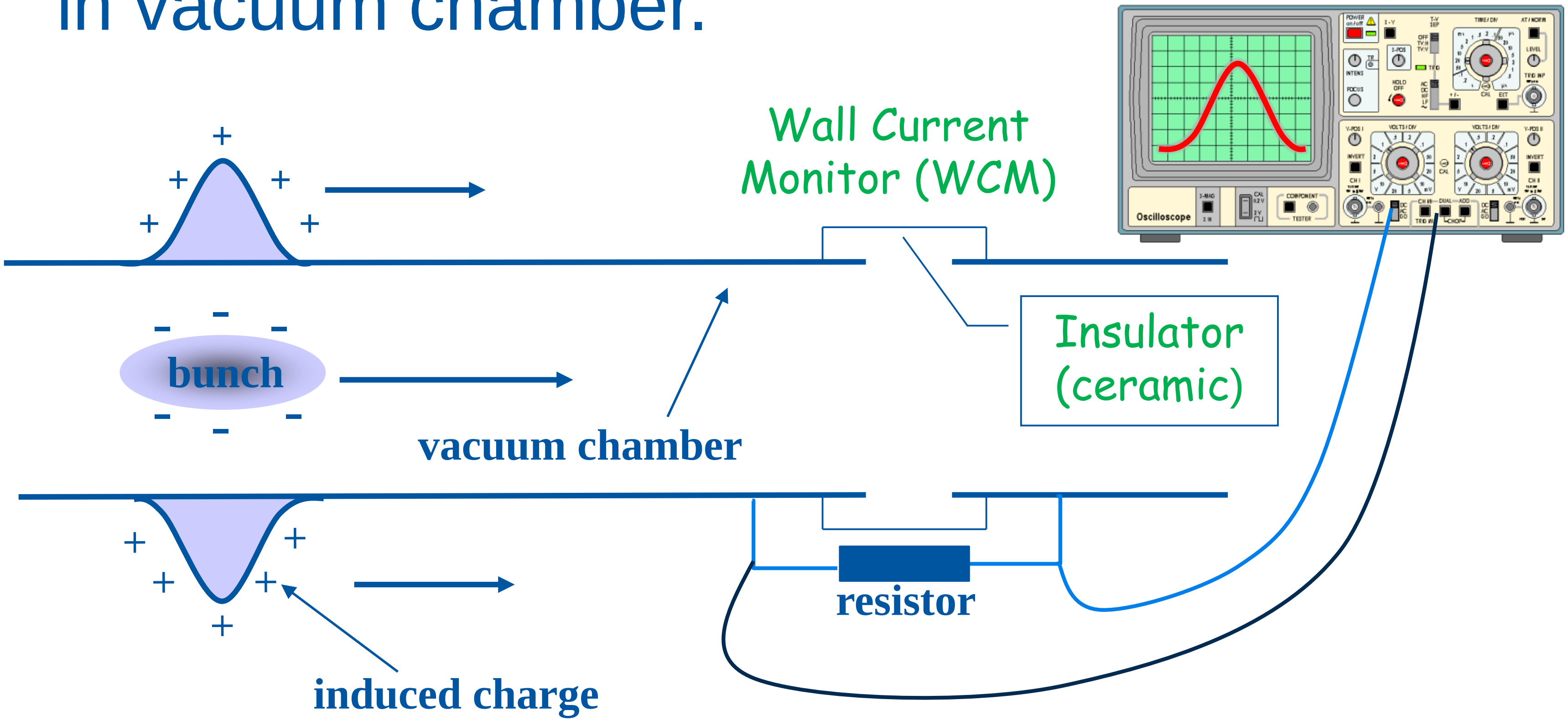


Standard: 72 bunches @ 25 ns
BCMS: 48 bunches @ 25 ns

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.

The CERN Long-Term Planning

LHC roadmap: according to MTP 2016-2020 V1

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC