
CERN

Accelerators for Beginners and the CERN Complex

Rende Steerenberg – BE/OP

Contents

- Why Accelerators and Colliders ?
- The CERN Accelerator Complex
- Cycling the Accelerators & Satisfying Users
- The Main Ingredients of an Accelerator
- A brief word on the Future

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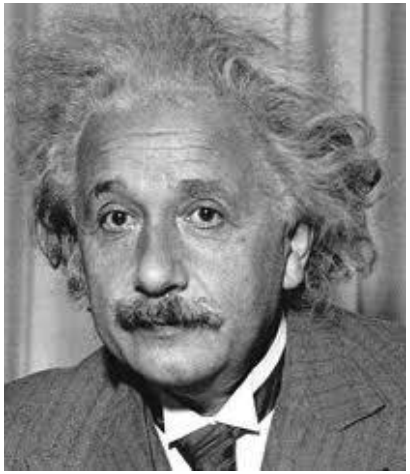
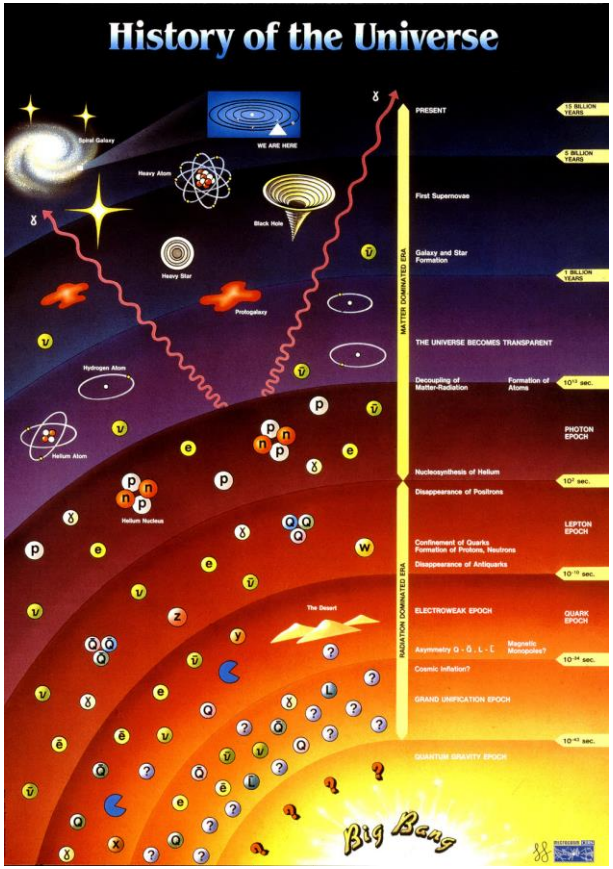
Creating Matter from Energy

$E = m c^2$

During the Big Bang Energy was transformed in matter





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

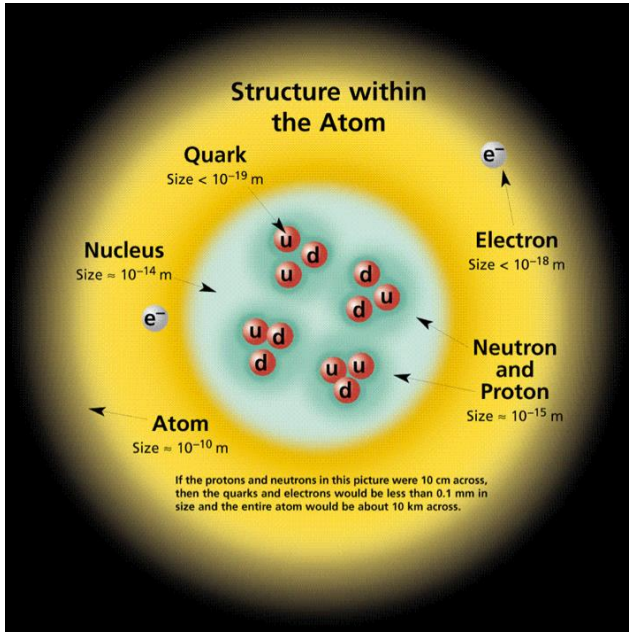
In the detectors we observe the matter created

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

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

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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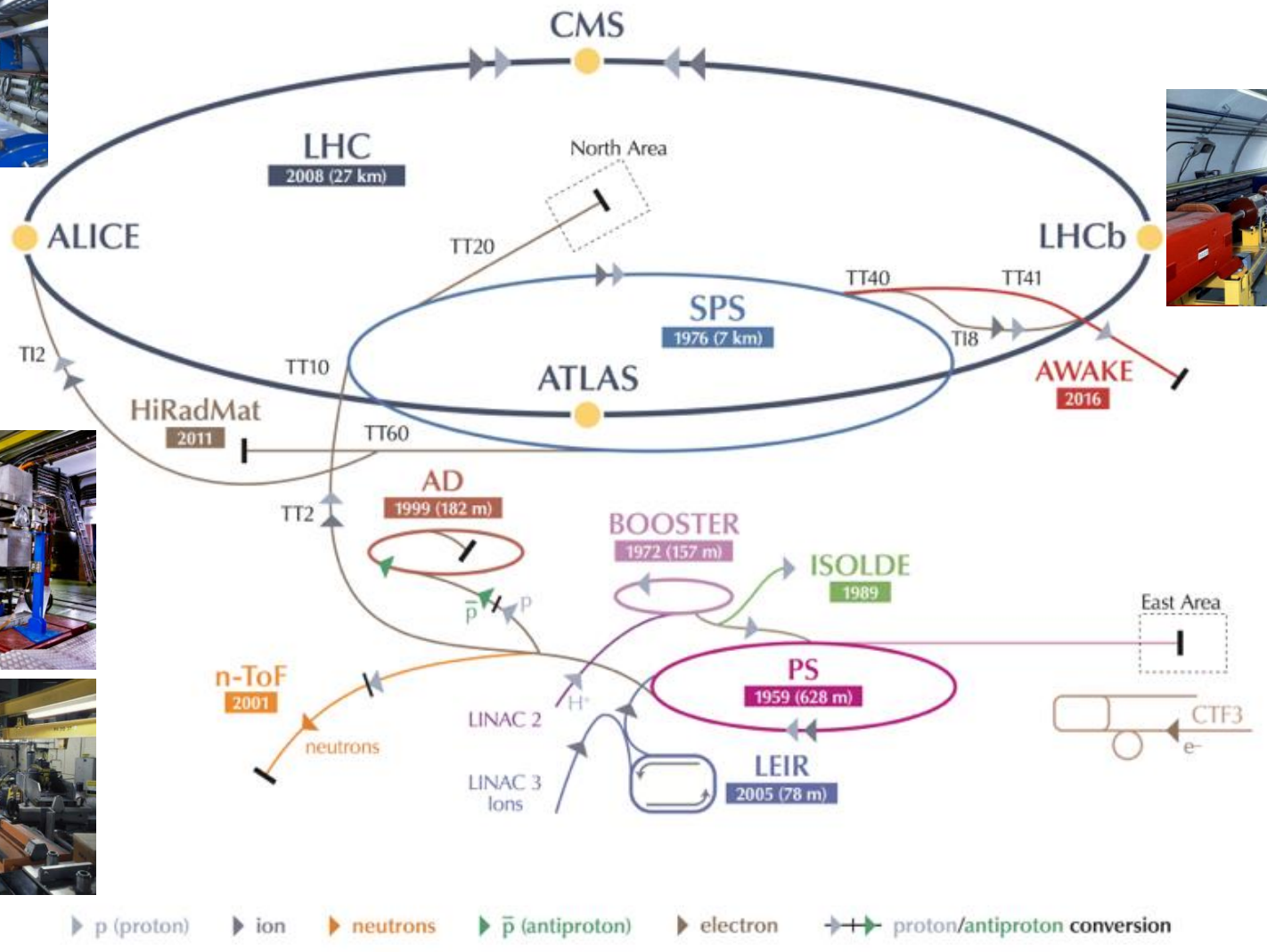
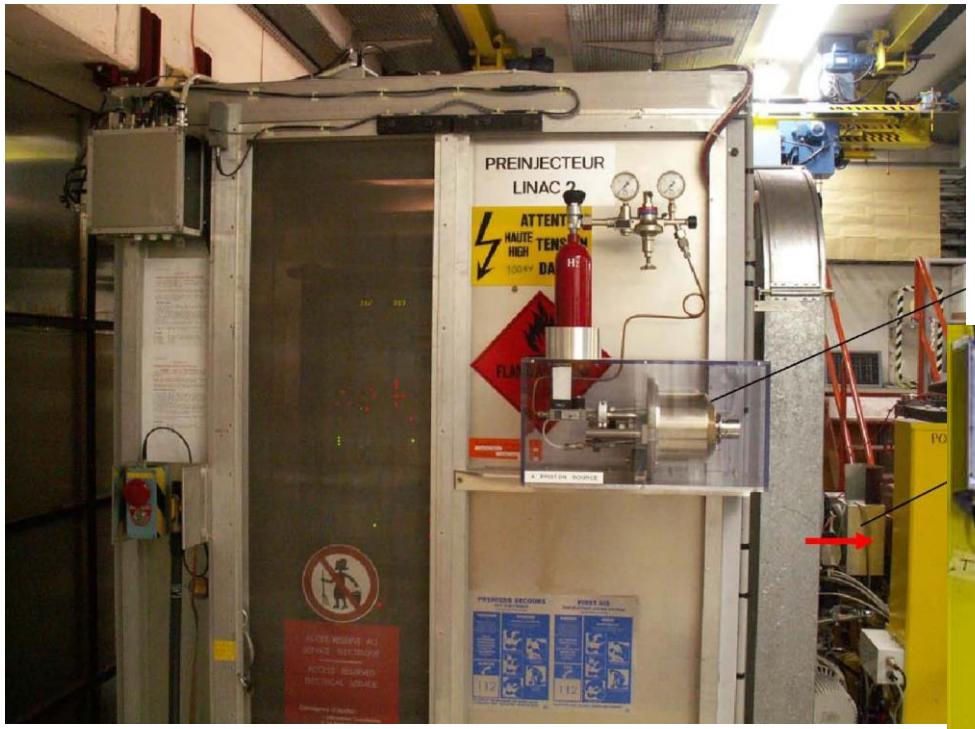
The CERN Accelerator Complex



LINAC 2



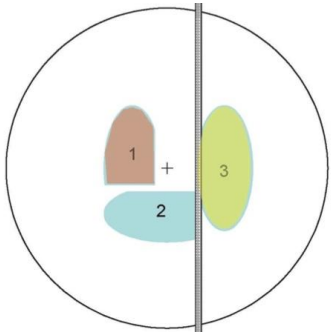
- Duoplasmatron proton source
- Extract protons at 90 keV from H_2

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

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

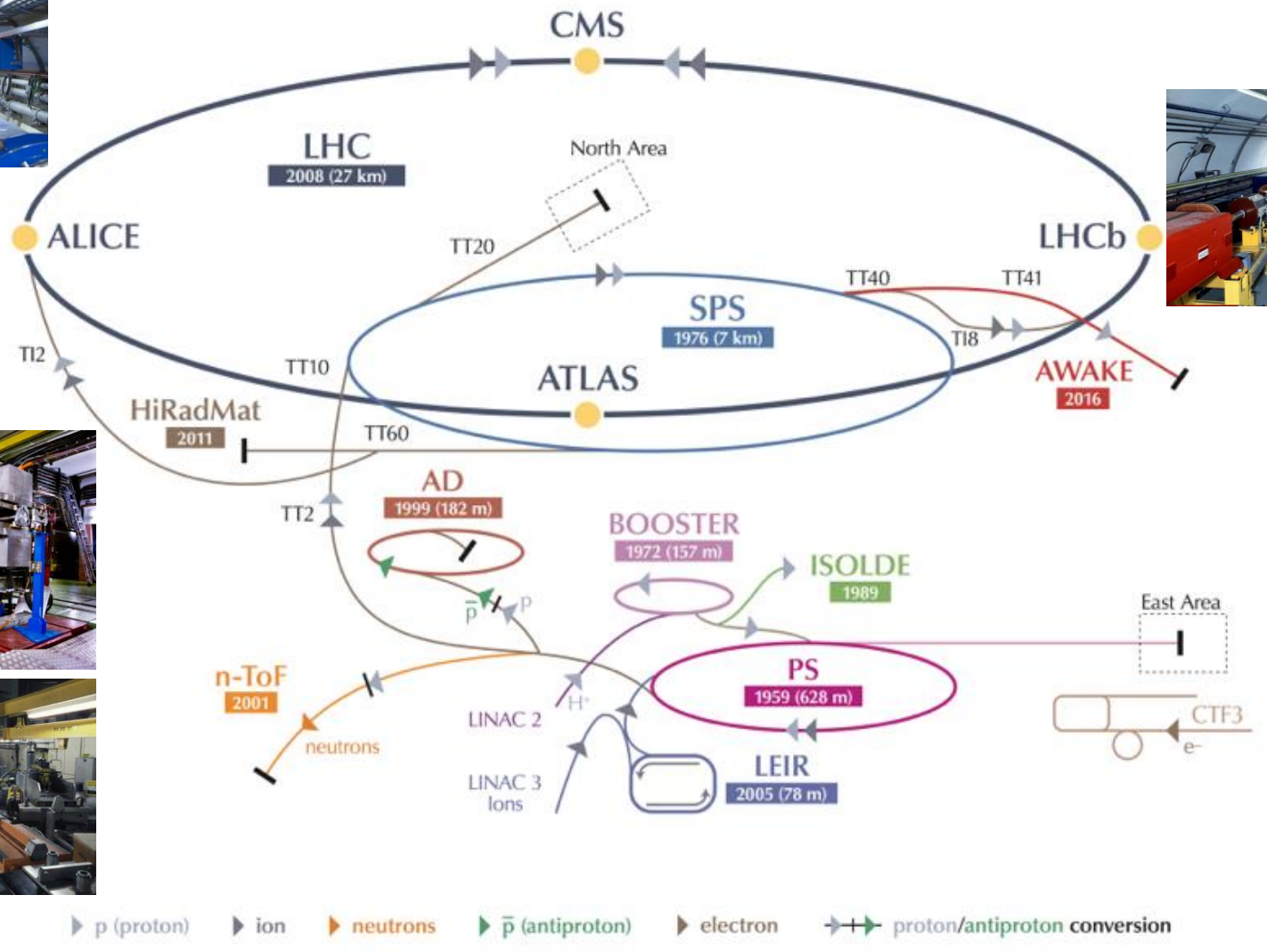
- The LINAC2 pulse is distributed over the four rings, using kicker magnets
- Each ring will inject over multi-turns, accumulating beam in the horizontal phase space



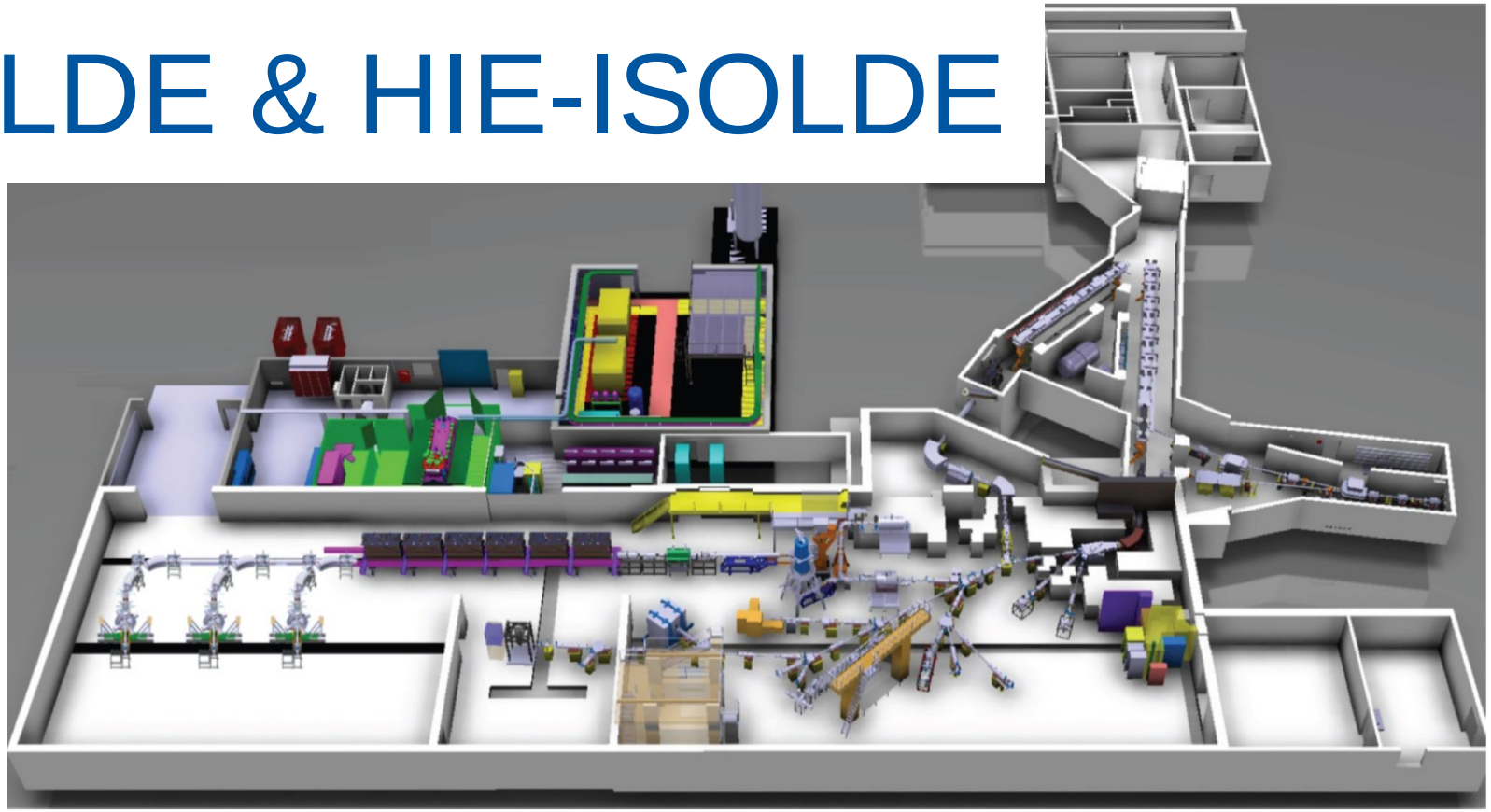
- This means that the beam size (transverse emittance) increases when the intensity increases → ~ constant density

The PS Booster determines the transverse Brightness of the LHC beam

The CERN Accelerator Complex

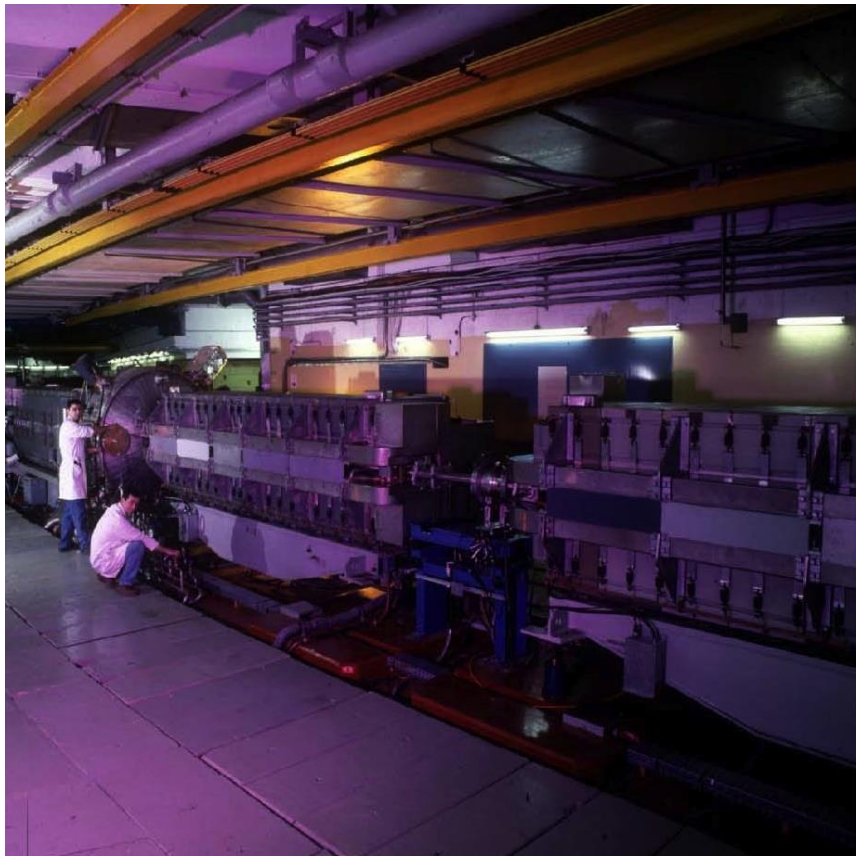


ISOLDE & HIE-ISOLDE



- 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

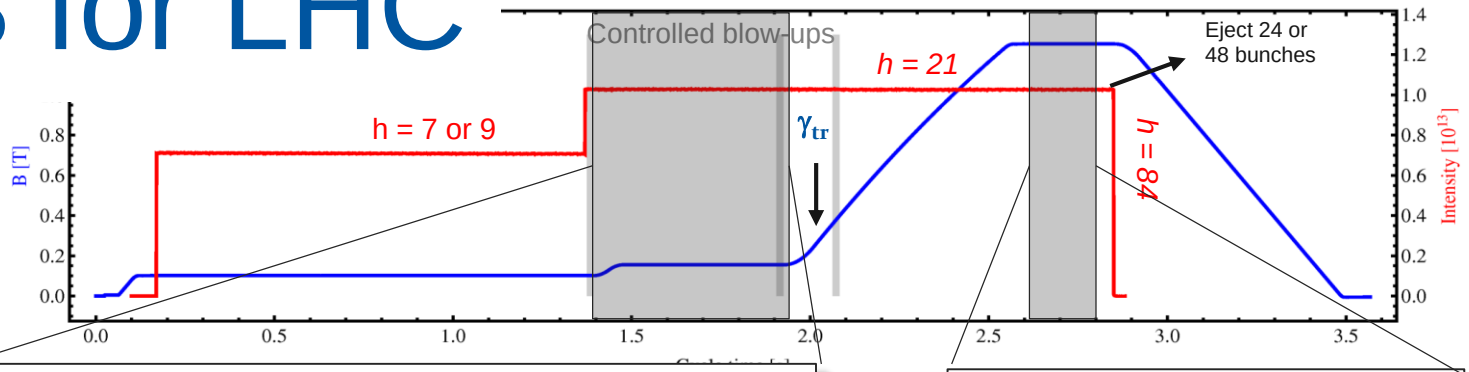
PS

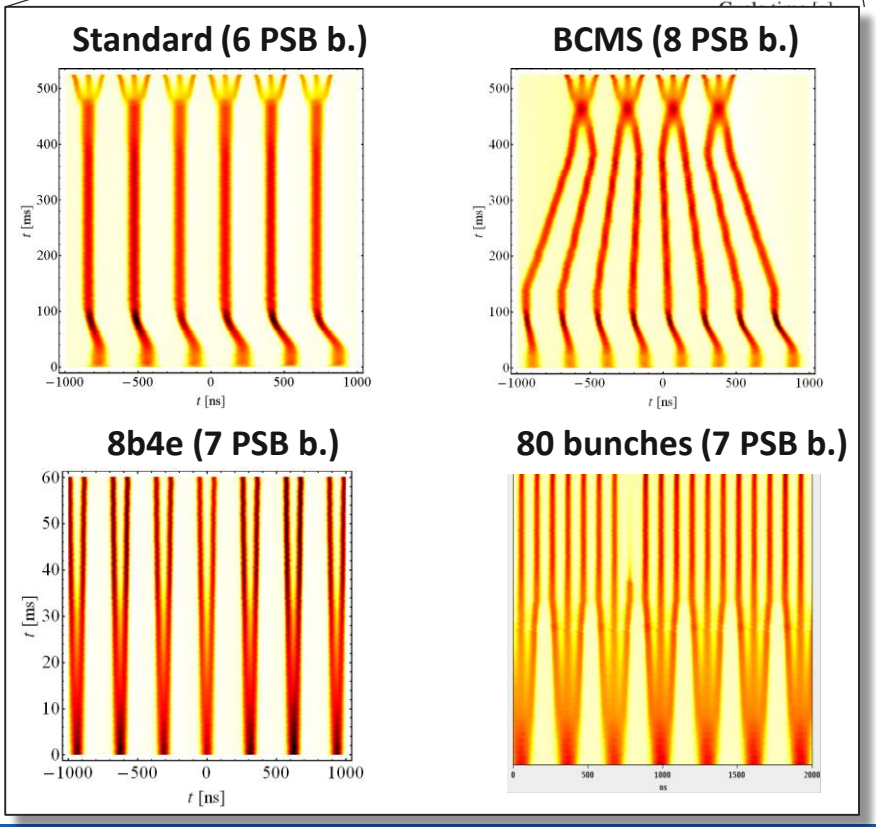


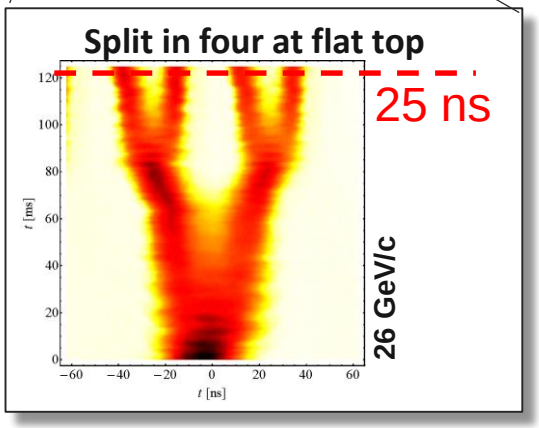
- The oldest operating synchrotron at CERN
- Circumference of 628m
  - 4 x PSB circumference
- Increases proton energy from 1.4 GeV to a range of energies up to 26 GeV
- Cycle length varies depending on the final energy, but ranges from 1.2s to 3.6s

- 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

PS for LHC



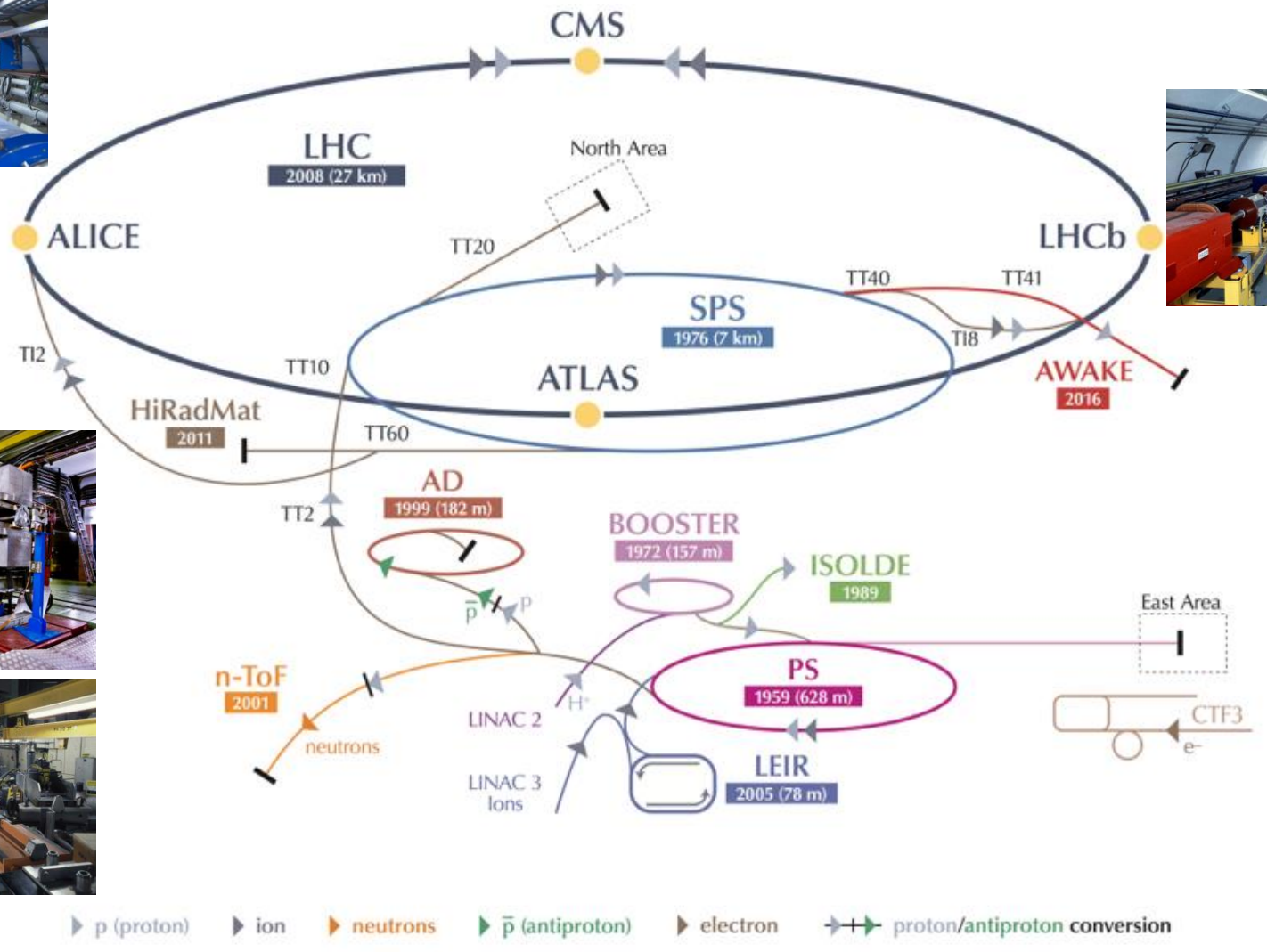




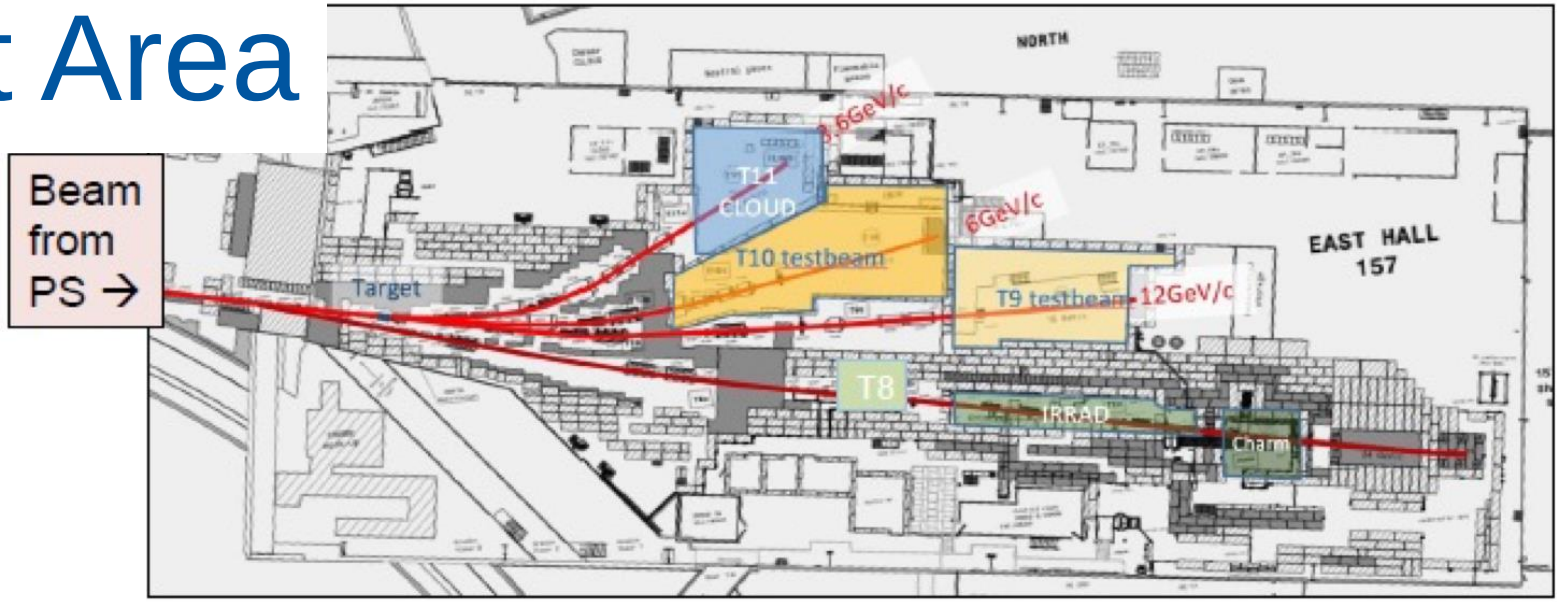
Standard: 72 bunches @ 25 ns
BCMS: 48 bunches @ 25 ns

The PS defines the longitudinal beam characteristics

The CERN Accelerator Complex

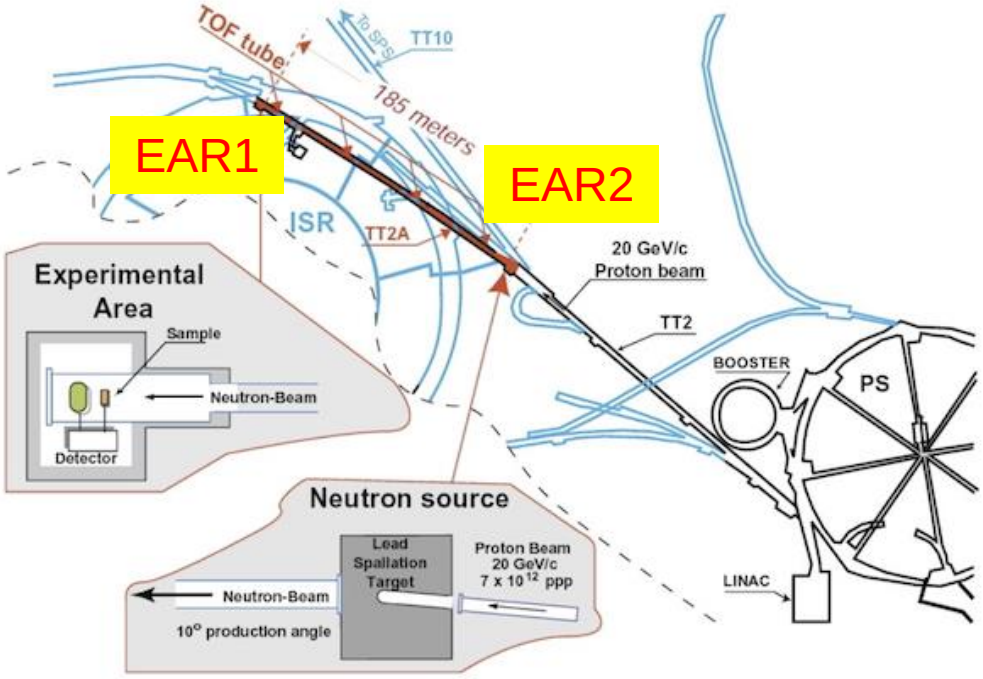


East Area



- 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

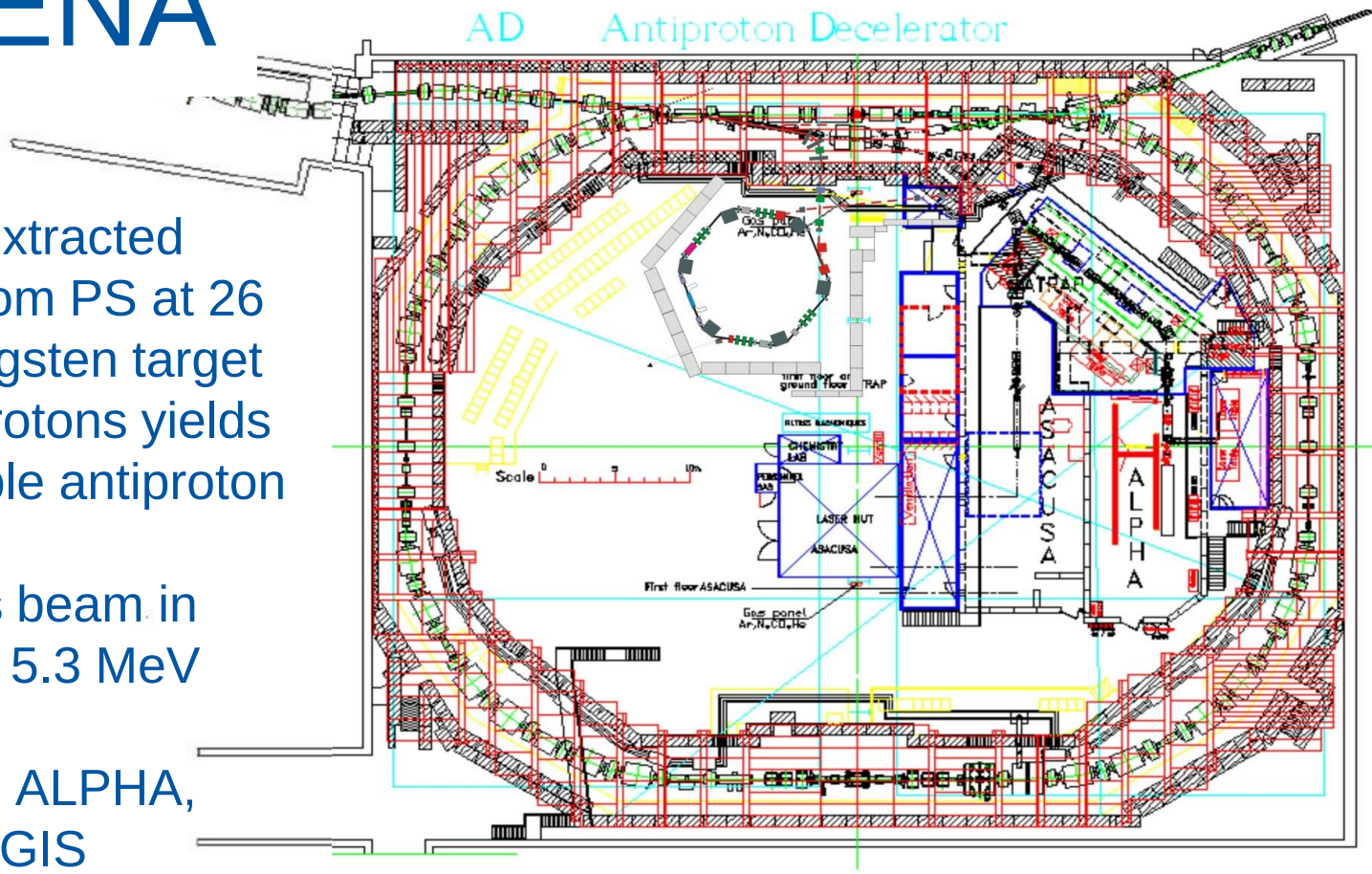


- Receives fast extracted single bunch of protons from PS at 20 GeV/c on a lead spallation target
- Every proton yields about 300 neutrons, spanning an energy range from the MeV region up to the GeV region (slow and fast)

- 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 tungsten target
- Every million protons yields about one usable antiproton at 3.5 GeV/c.
- AD decelerates beam in stages down to 5.3 MeV
- Experiments:
  - ASACUSA, ALPHA, ATRAP, AEGIS

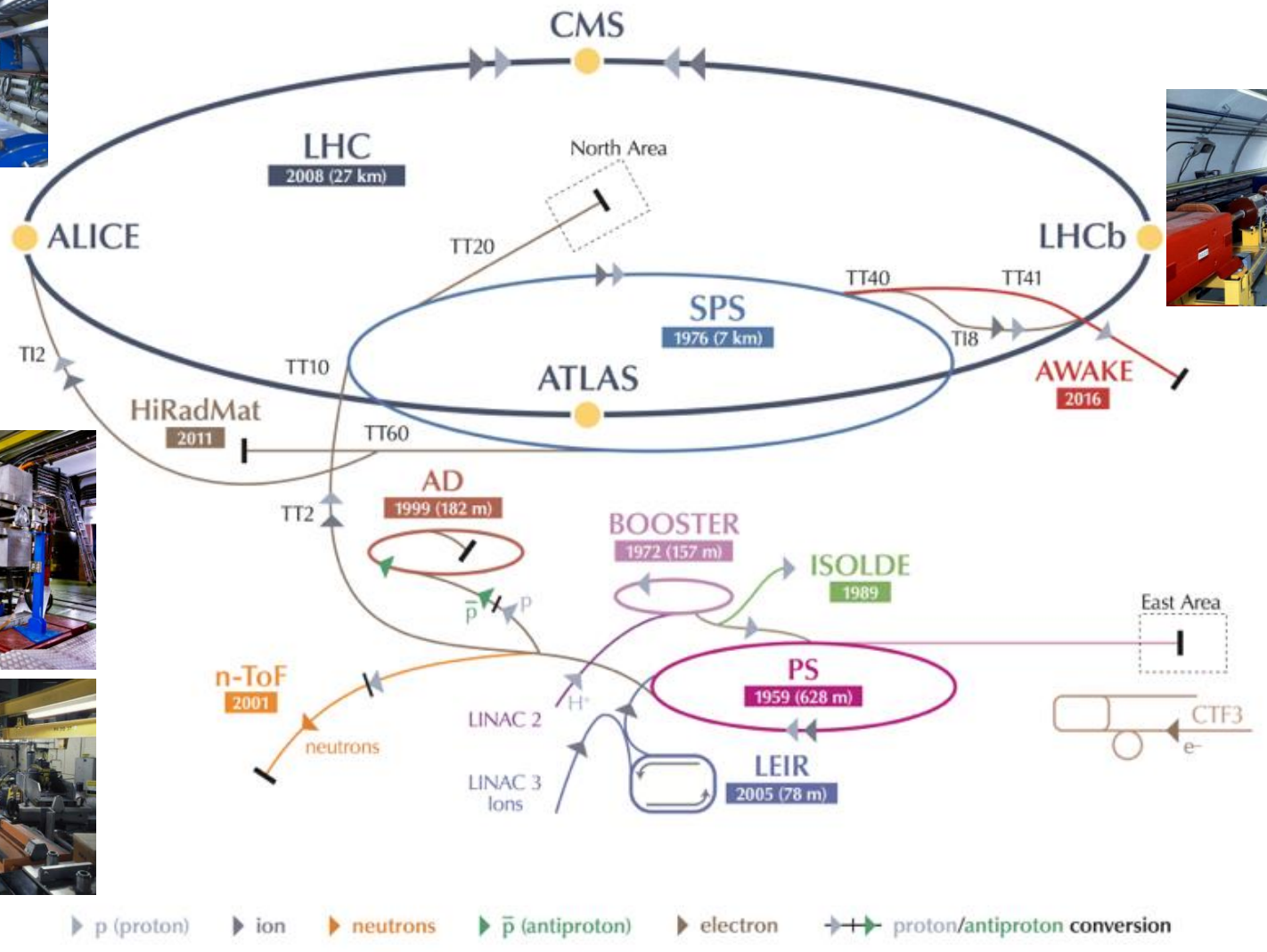
- Presently the ELENA ring is under commissioning
  - Decelerates further down to 100 keV
  - Beam intensity ~ 3×10^7 antiprotons

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

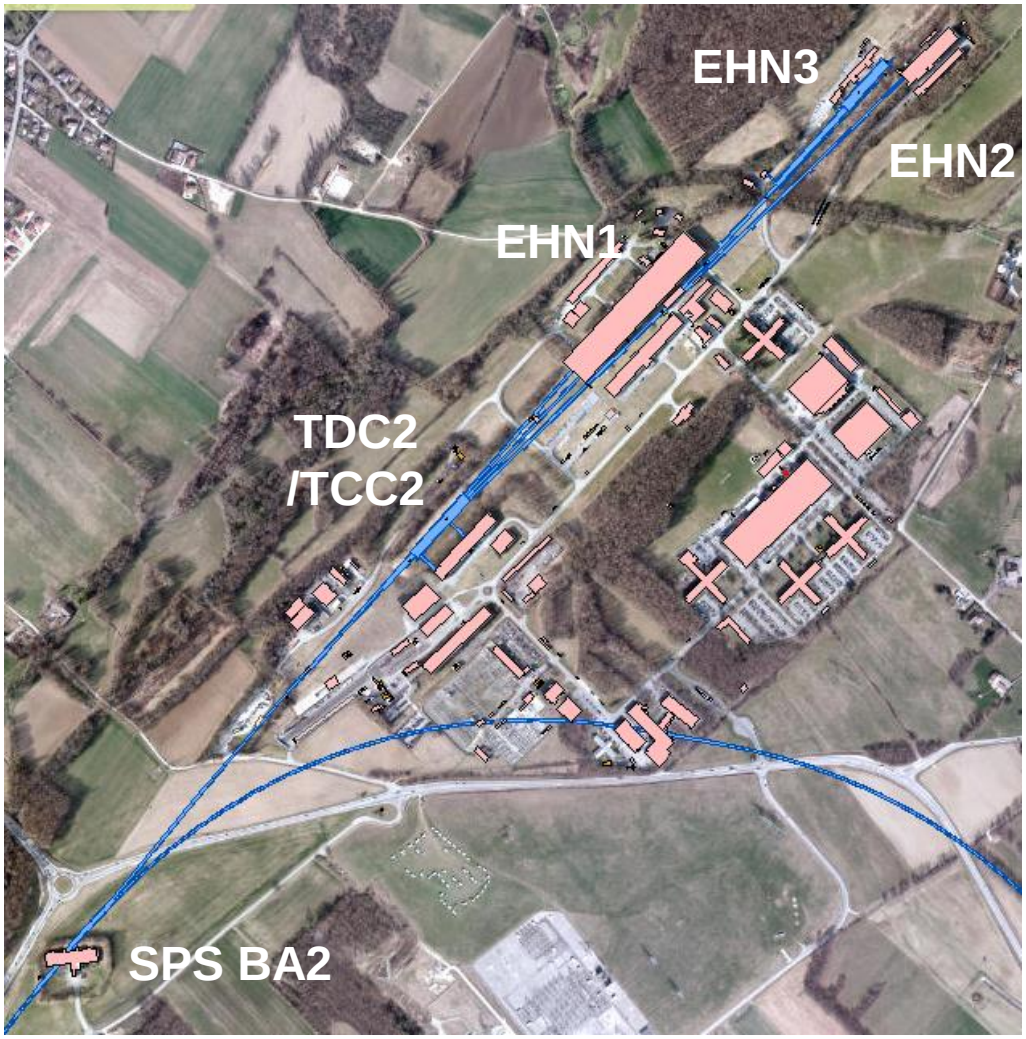
- Provides slow extracted beam to the North Area
- Provides fast extracted beam to LHC, AWAKE and HiRadMat

The CERN Accelerator Complex



North Area

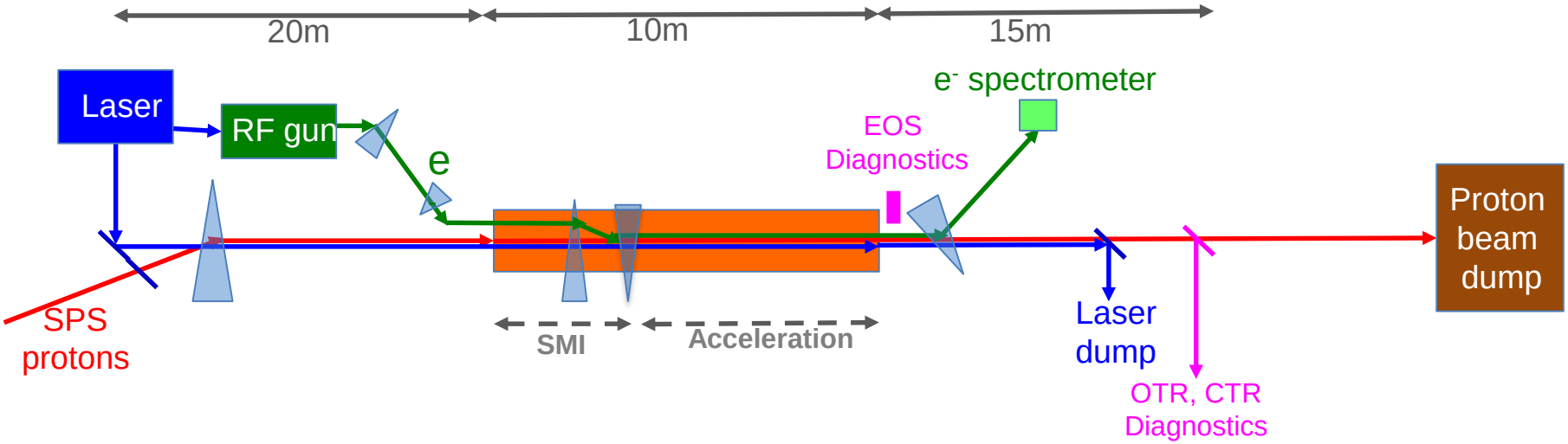
- Receives slow extracted proton beam from the SPS at 400 GeV/c
- Beam spill of ~4.5 s for a cycle length of 10.8s
- Extraction from SPS-BA2
- Beam is sent on various targets
- 7 beam lines with a total length of nearly 6 km
- 3 experimental halls
  - EHN1 (being extended)
  - EHN2
  - EHN3



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

AWAKE

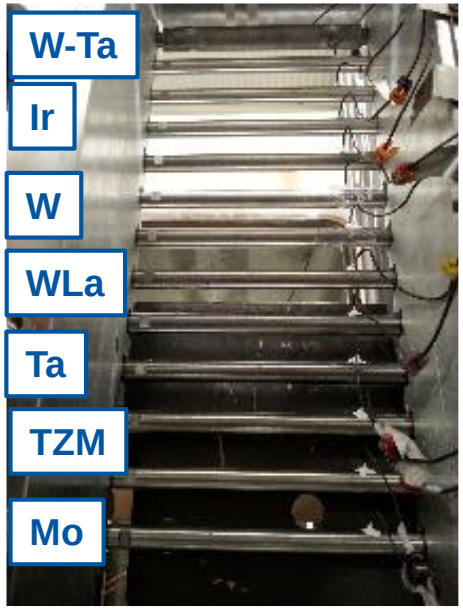
- Proof of principle for **Proton Driven Plasma Wakefield Acceleration**
- Facility situated in previous CNGS target area



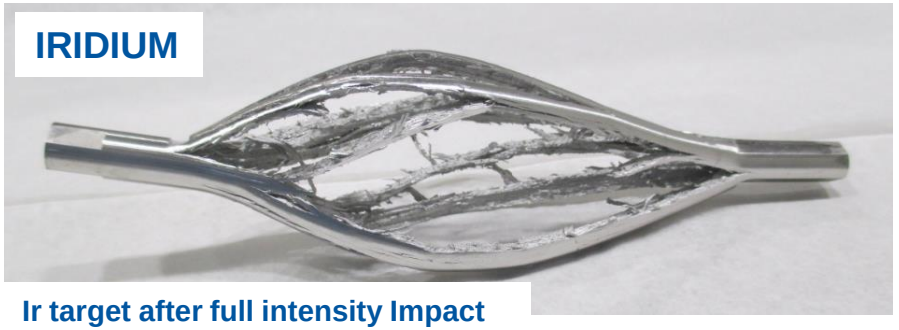
- Proton beam will induce a strong Wakefield in the a Plasma that is created using a laser
- 10-20 MeV electron will “surf’ on the waves in the Plasma and will be accelerated to multi-GeV range

HiRadMat

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

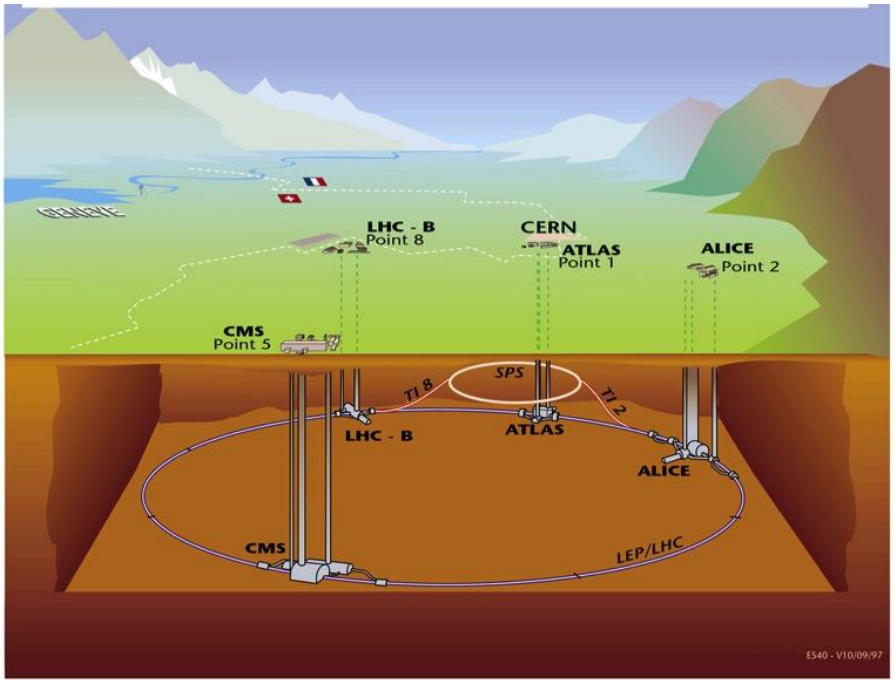


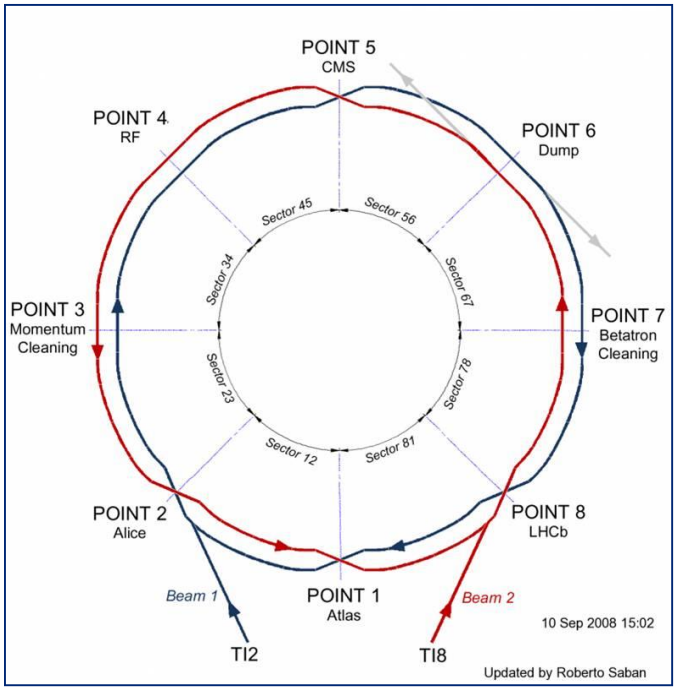
- Built for the LHC Upgrades and target tests
- Makes use of the Infrastructure of a previous Neutrino facility
- Uses LHC type beams from the SPS at 450 GeV



Ir target after full intensity Impact

LHC

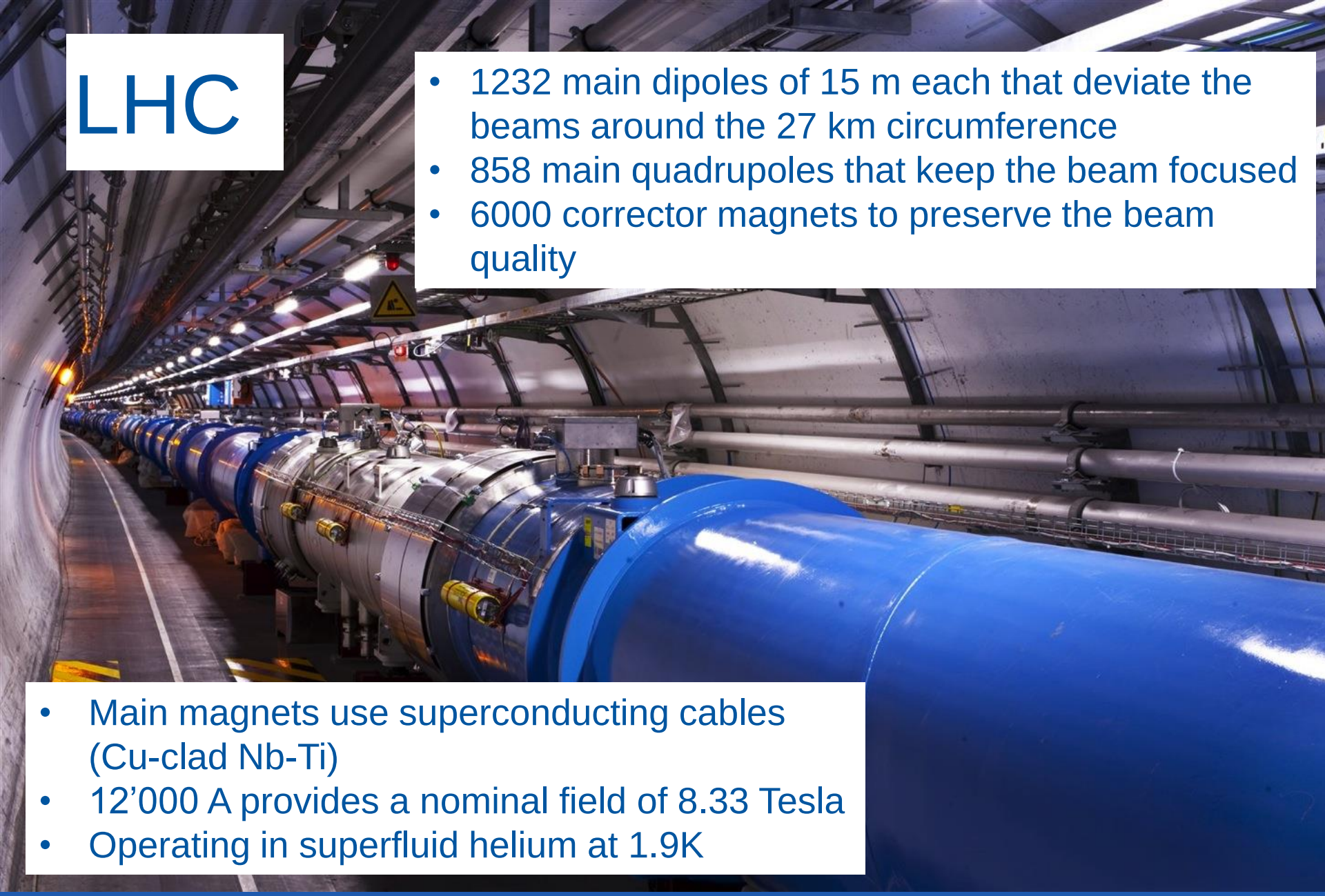




- Situated on average ~100 m under ground
- Four major experiments
- Circumference 26.7 km
- Two separate beam pipes going through the same cold mass 19.4 cm apart
- 150 tonnes of liquid helium to keep the magnets cold

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

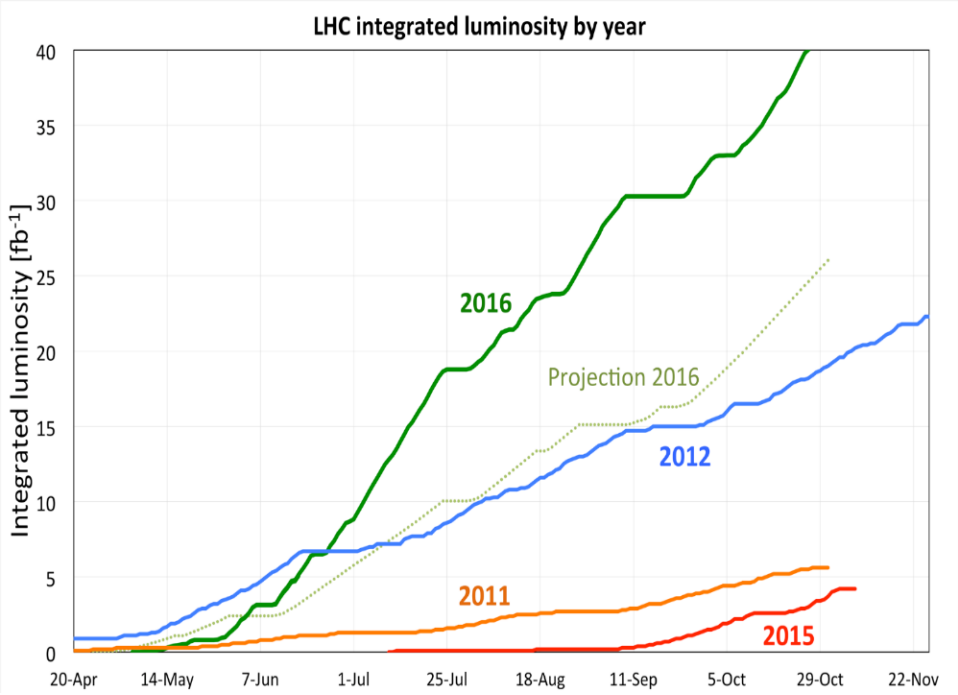
$$LUMINOSITY = \frac{N_{event/sec}}{s_r} = \frac{N_1 N_2 f_{rev} n_b}{4 \pi s_x s_y} F$$

Intensity per bunch

Number of bunches

Geometrical Correction factors

Beam dimensions

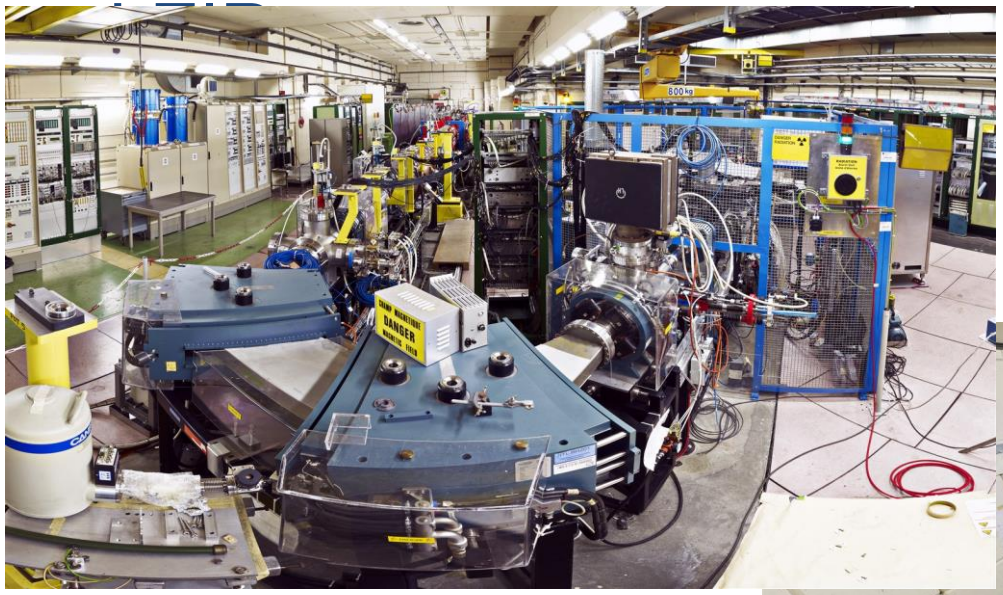


Maximise Luminosity:

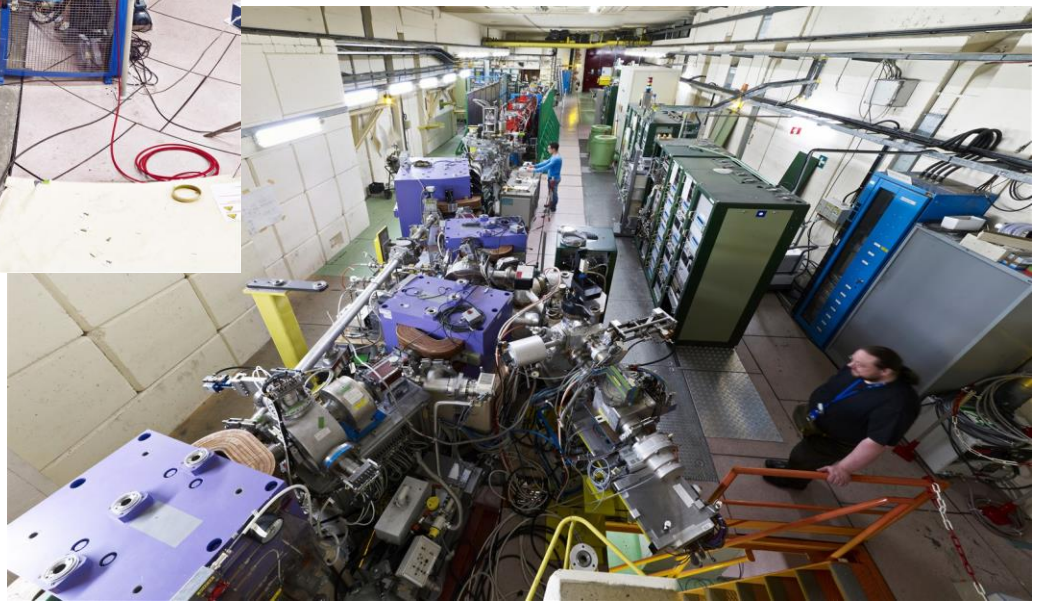
- Bunch intensity
- Transverse beam size
- Beam size at collision points (optics functions)
- Crossing angle
- Machine availability

LINAC3

The CERN LINAC 3 provides different ion species

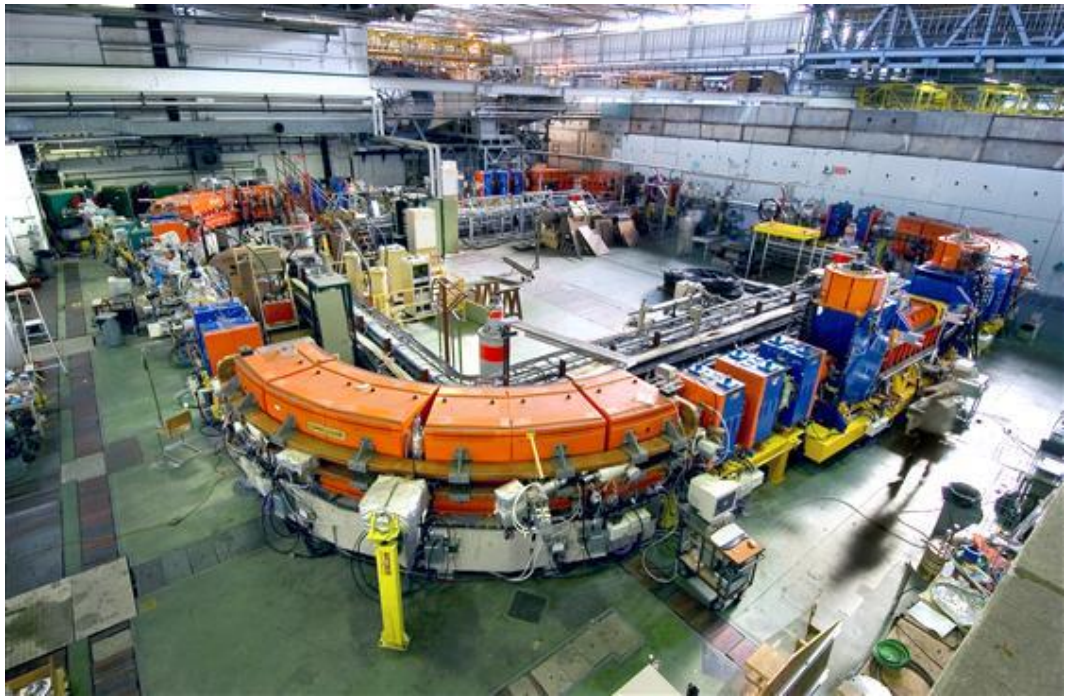


The ion source in the blue cage with the spectrometer in the front, follow by the LINAC behind



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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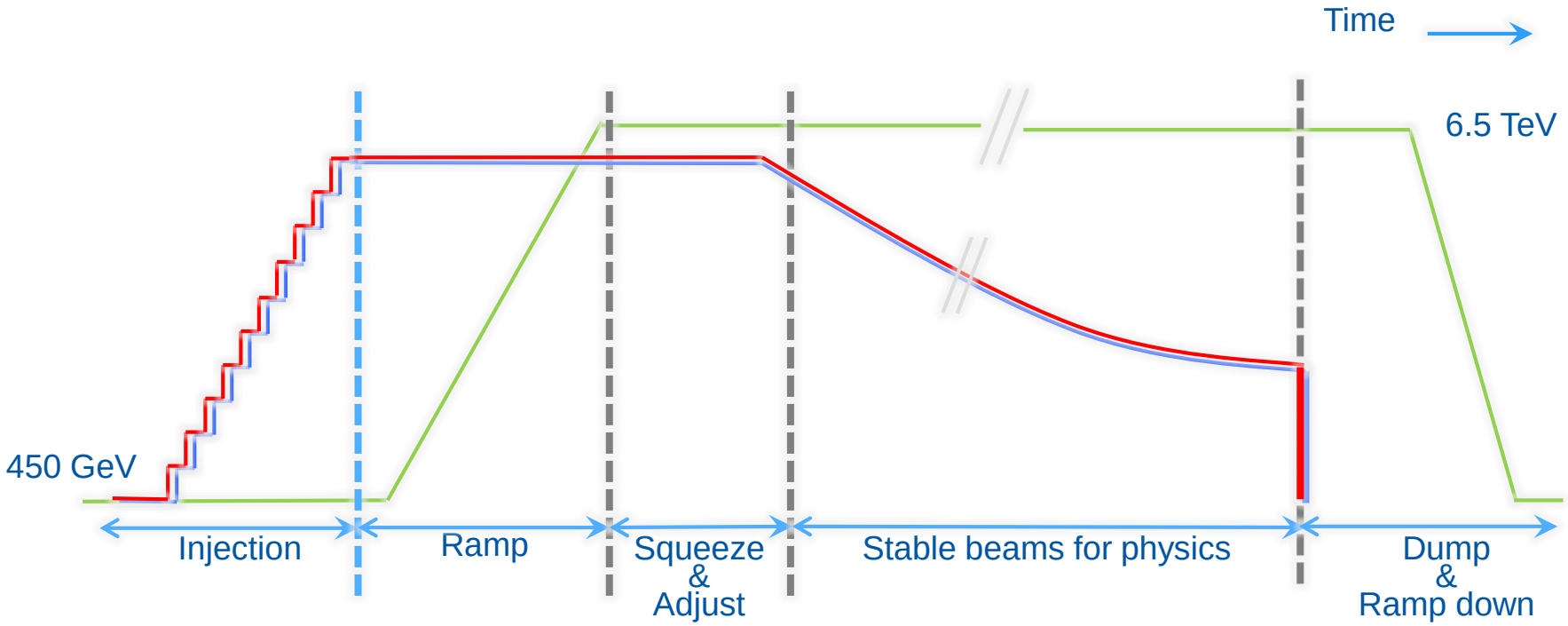
The LHC Cycle



= 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.

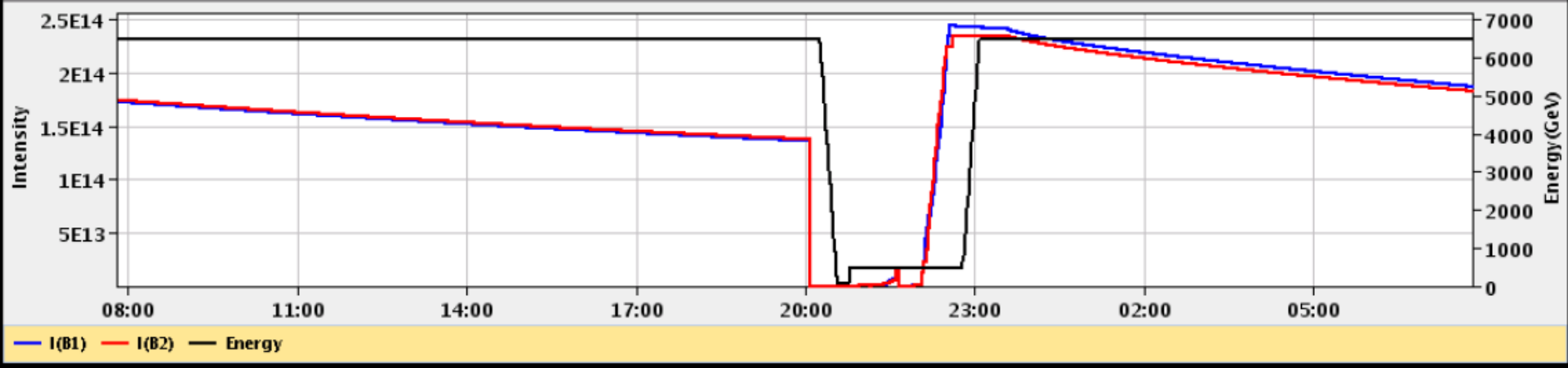
In 2015 and 2016 it ran at 6.5 TeV per beam, 13 TeV c.o.m

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

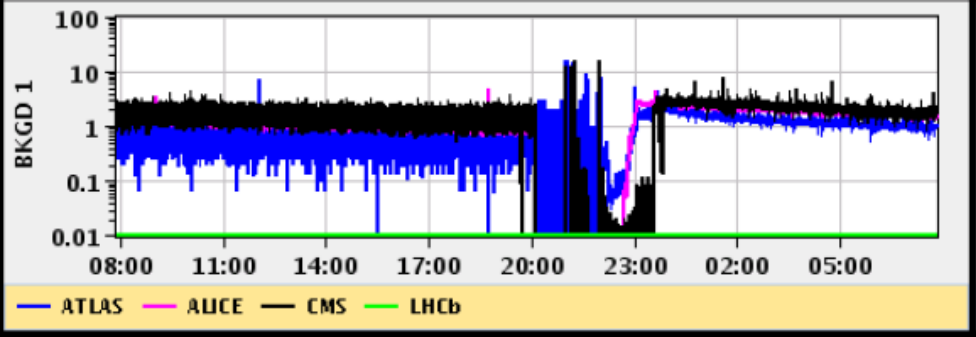
	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Lumi [(ub.s)^-1]	7346.231	1.672	7730.174	355.048
BRAN Luminosity [(ub.s)^-1]	7462.0	1.8	6917.8	181.2
Fill Luminosity (nb)^-1	265785.063	49.302	293245.594	10312.992
Beam 1 BKGD	0.927	1.401	1.645	0.000
Beam 2 BKGD	4.488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

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

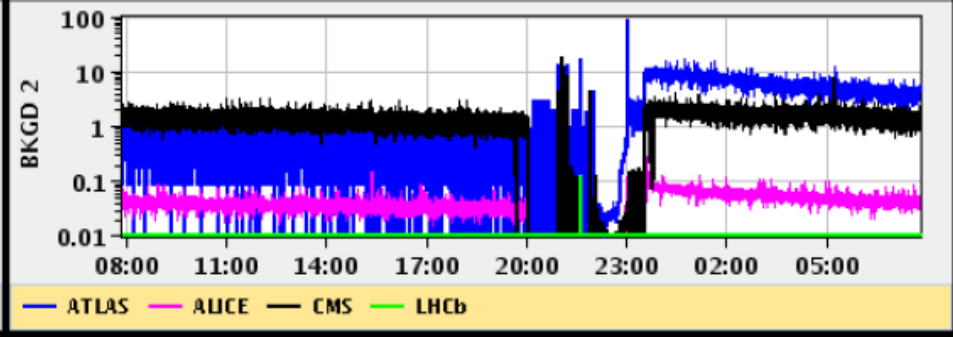
Performance over the last 24 Hrs — Updated: 07:48:42



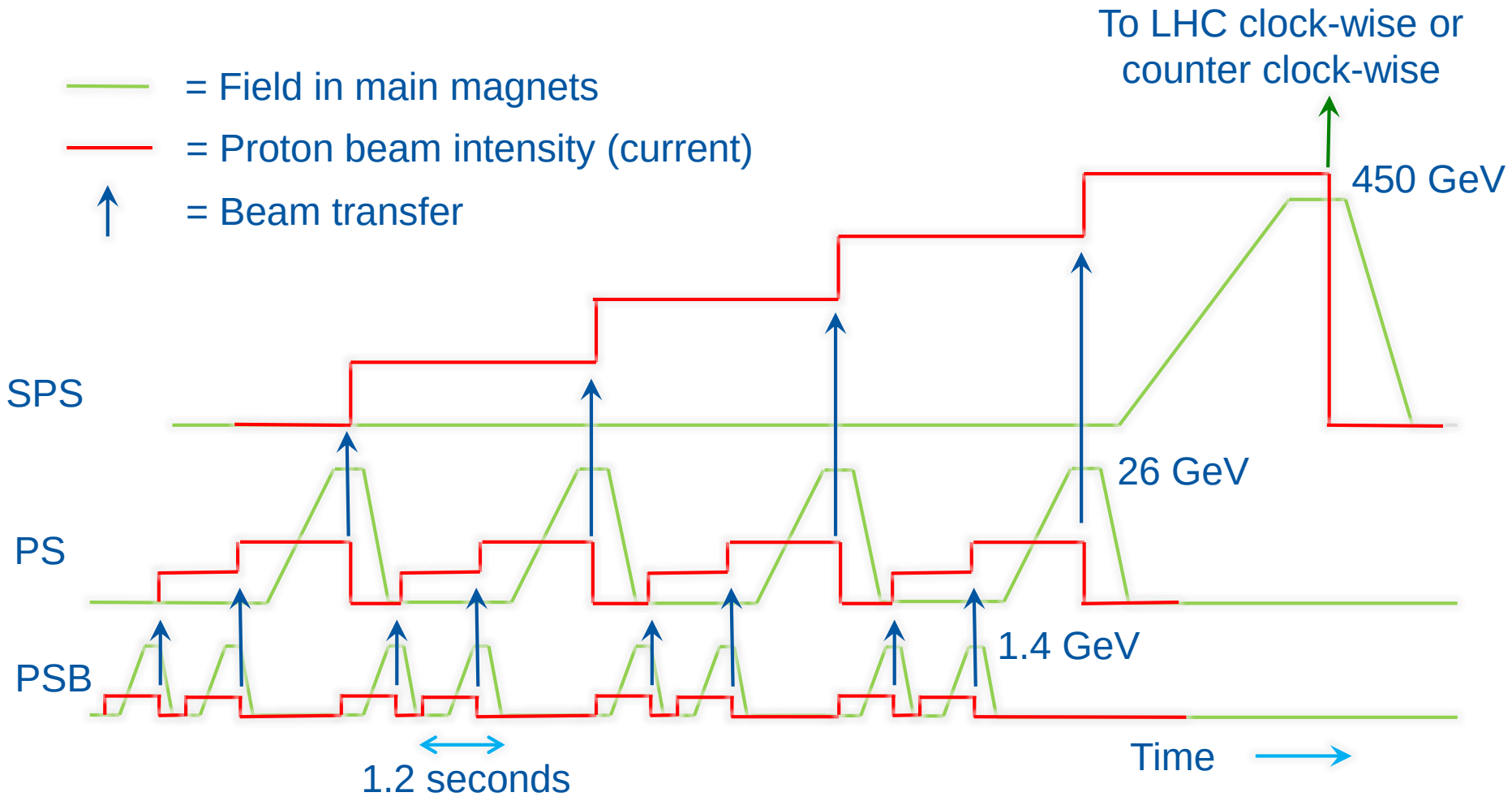
Beam 1 BKGD — Updated: 07:48:41



Beam 2 BKGD — Updated: 07:48:41



Filling the LHC and Satisfying Fixed Target users



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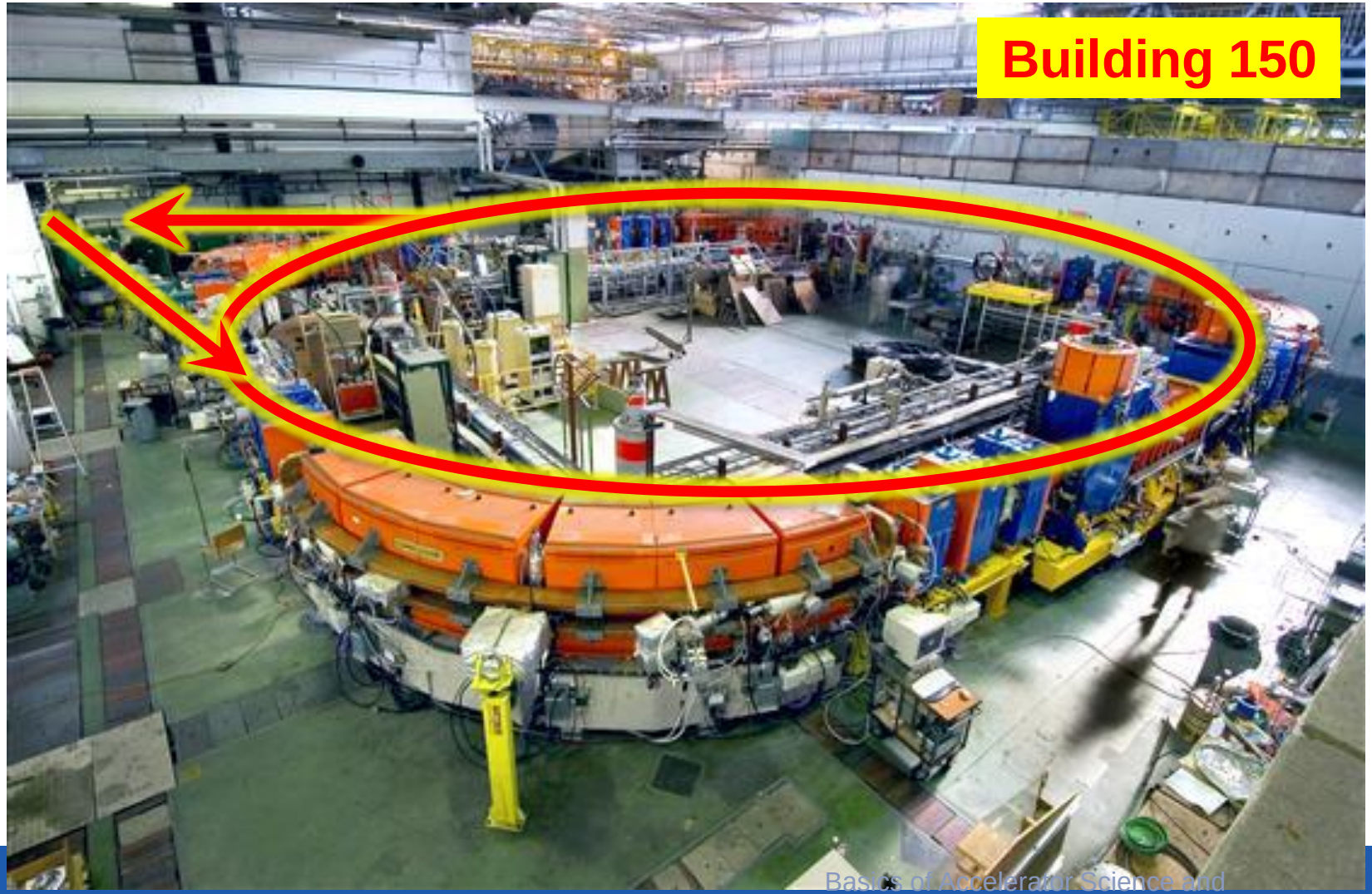
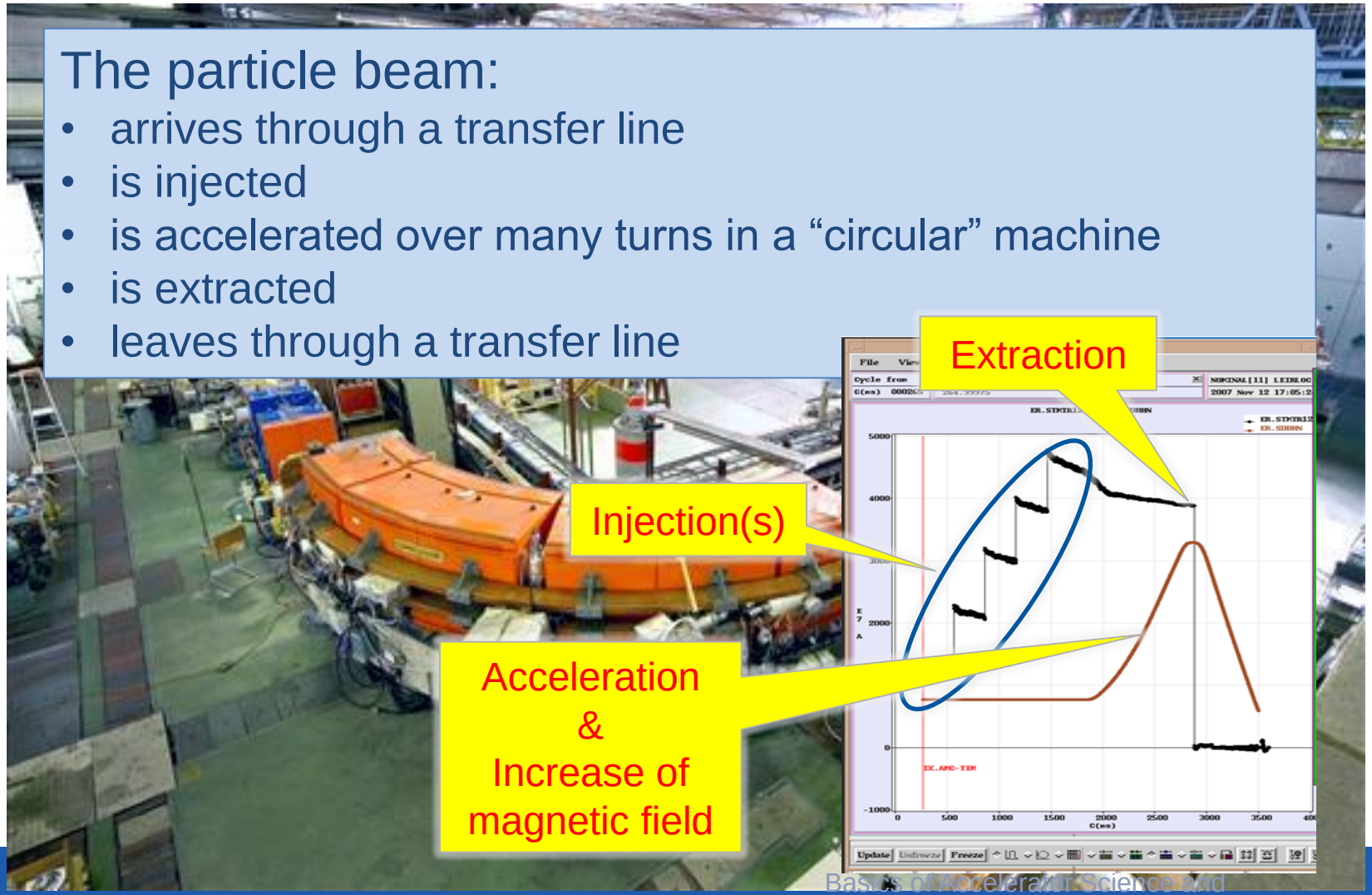
LEIR as an Example



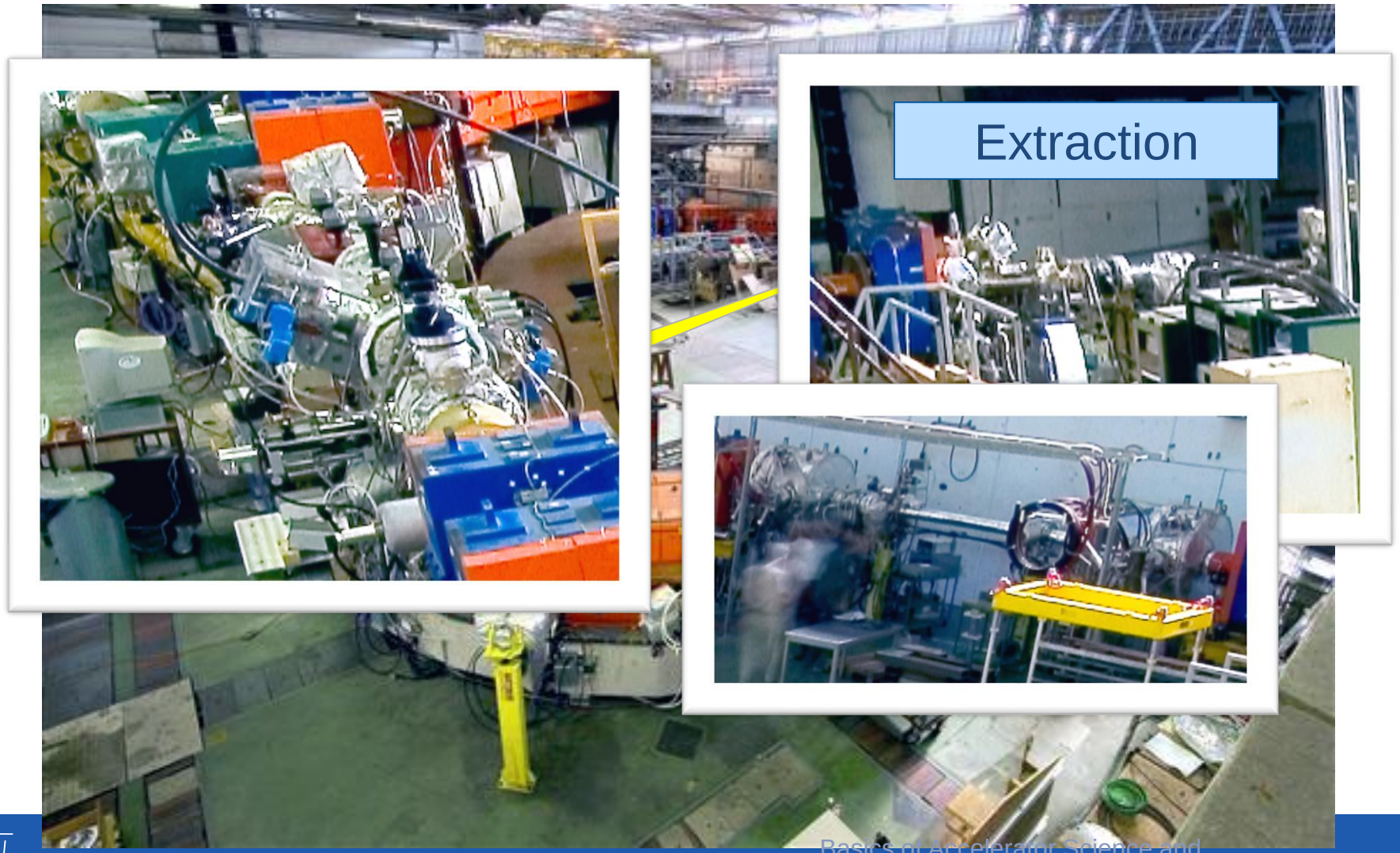
LEIR as an Example

The particle beam:

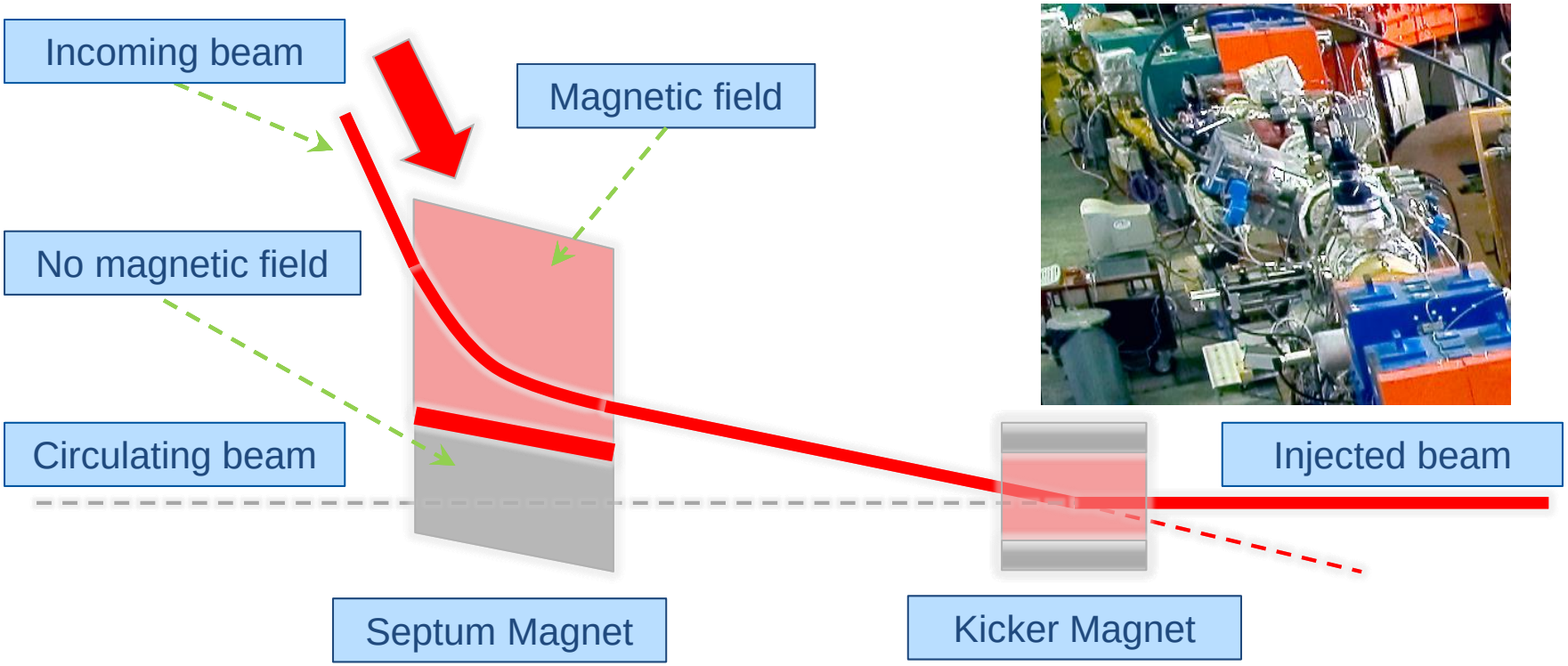
- arrives through a transfer line
- is injected
- is accelerated over many turns in a “circular” machine
- is extracted
- leaves through a transfer line



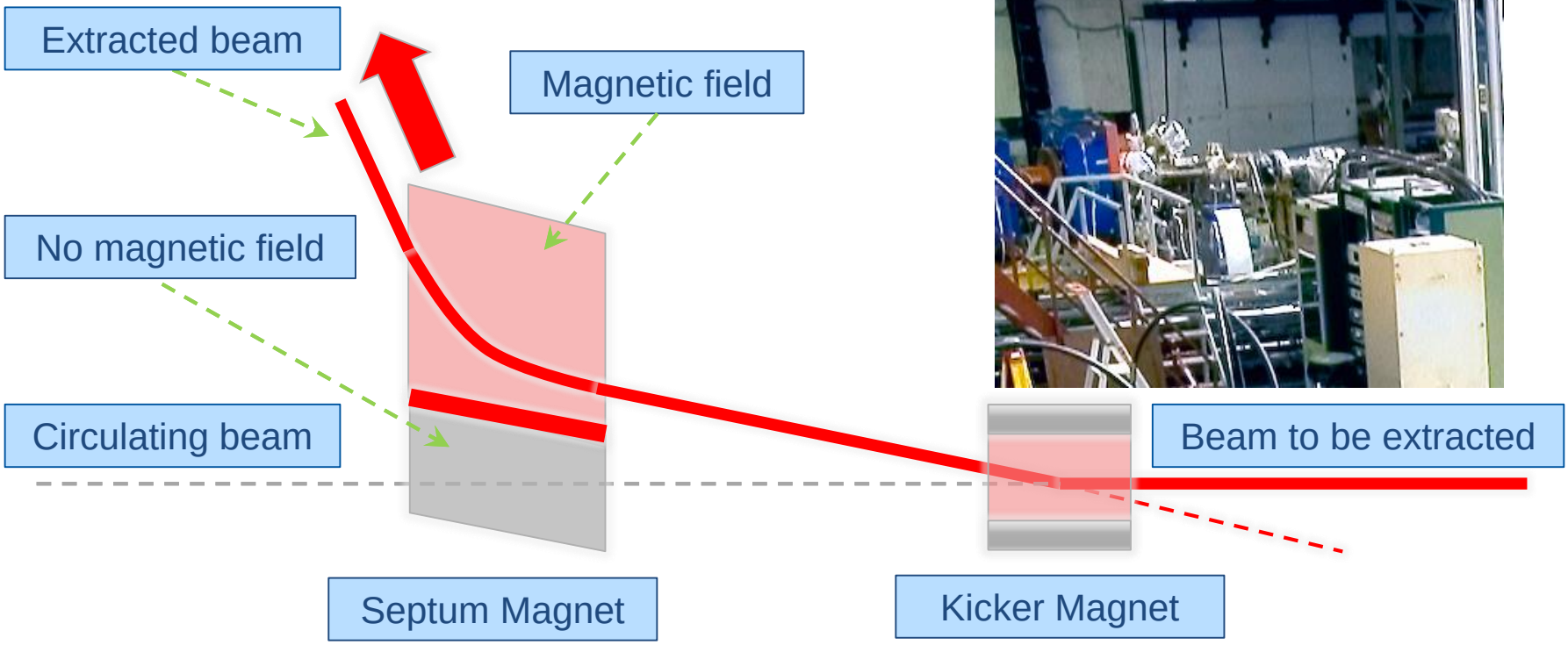
Injecting & Extracting Particles



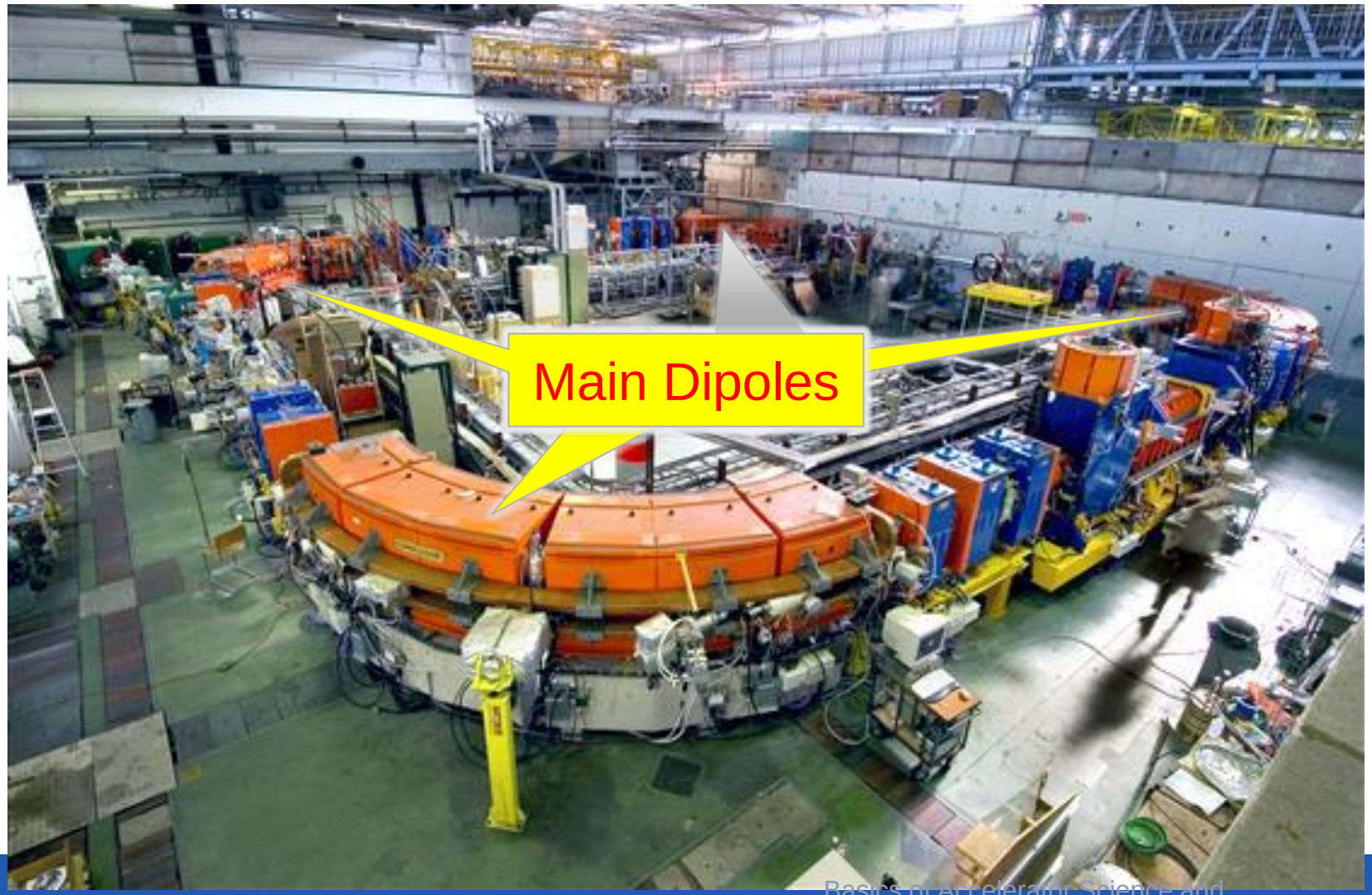
Injecting & Extracting Particles



Injecting & **Extracting** Particles

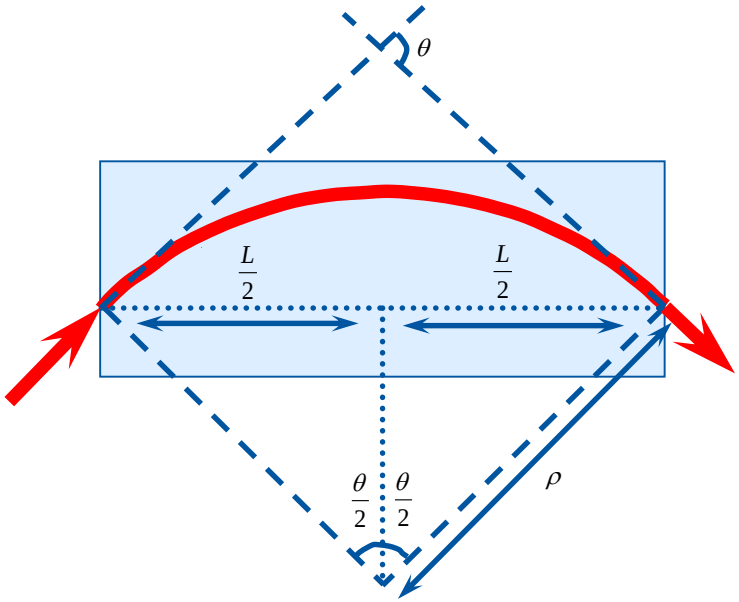


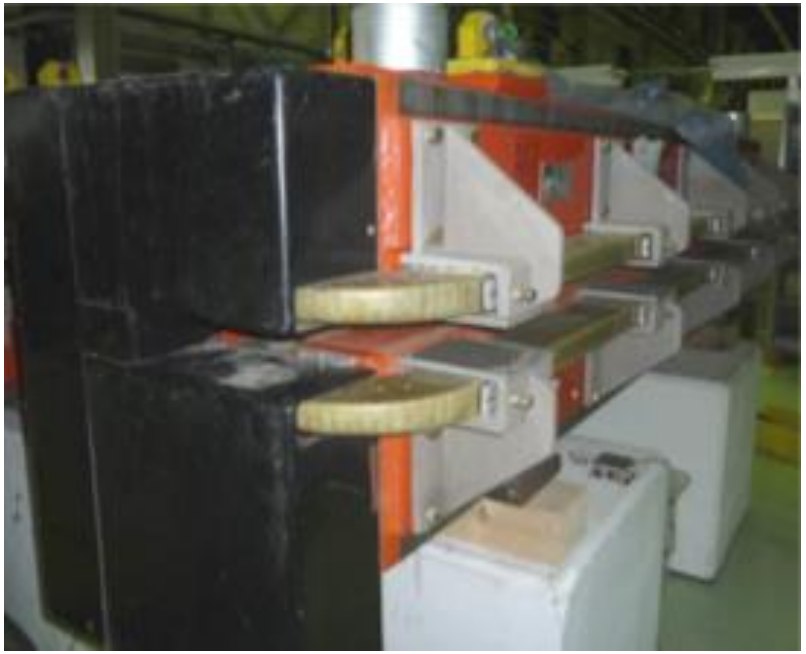
Make Particles Circulate



Deviating Charged Particles

Charged Particles are deviated in magnetic fields



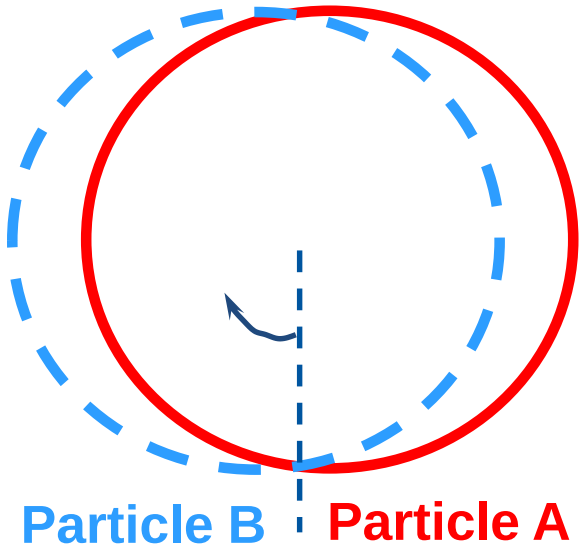


Lorentz force:

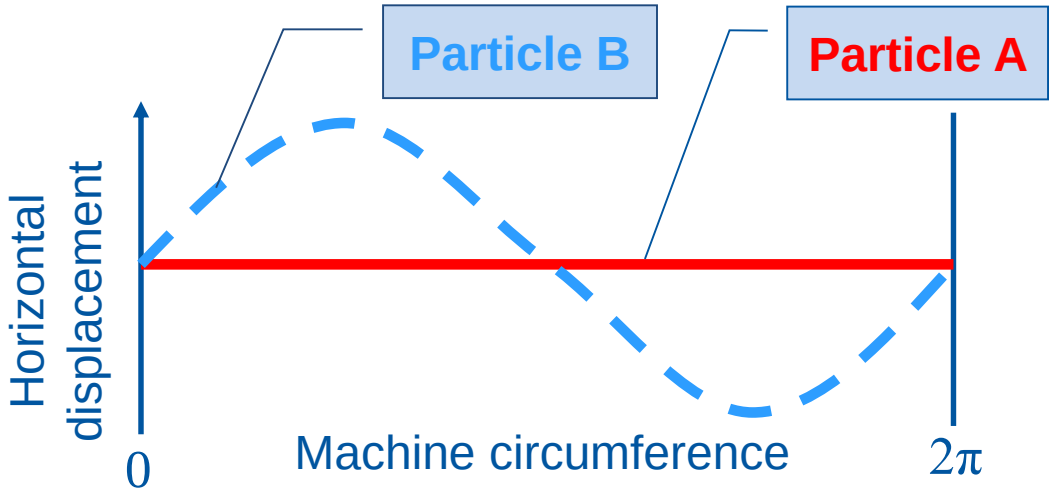
$$F = e\, v \times B$$

Oscillatory Motion of Particles

Two charged Particles in a homogeneous magnetic field



Horizontal motion

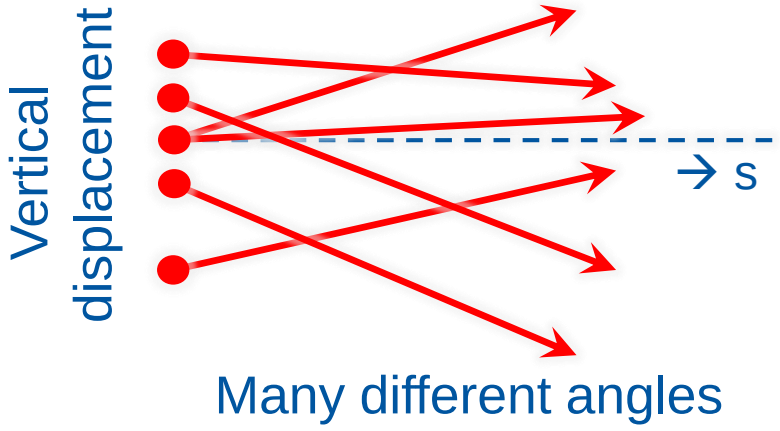


Different particles with different initial conditions in a homogeneous magnetic field will cause oscillatory motion in the horizontal plane → **Betatron Oscillations**

Oscillatory Motion of Particles

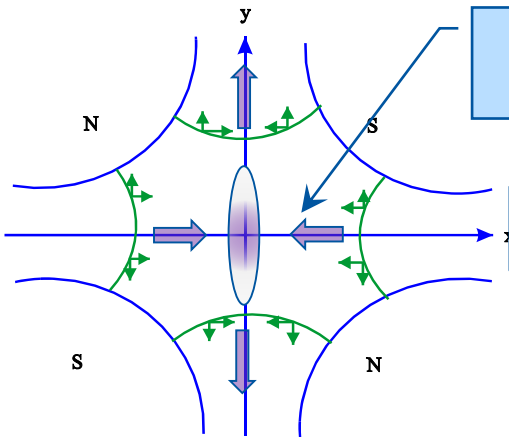
The horizontal motion seems to be “stable”…. What about the vertical plane ?

Many particles many initial conditions



Focusing Particle Beams

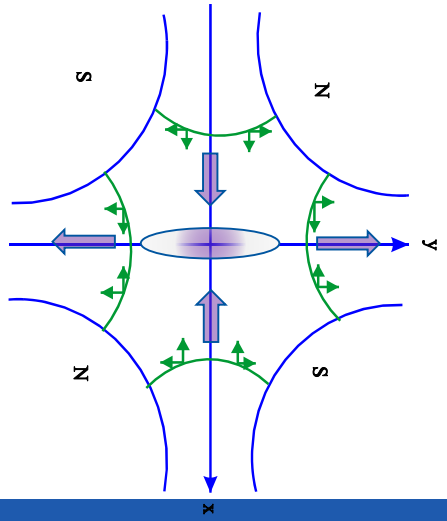
Focusing particles, a bit like light in a lens



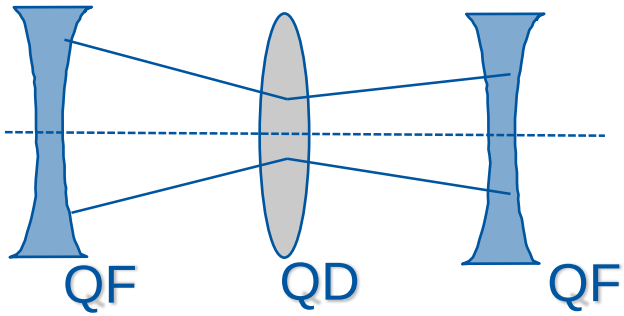
Force on particles

Focusing Quadrupole

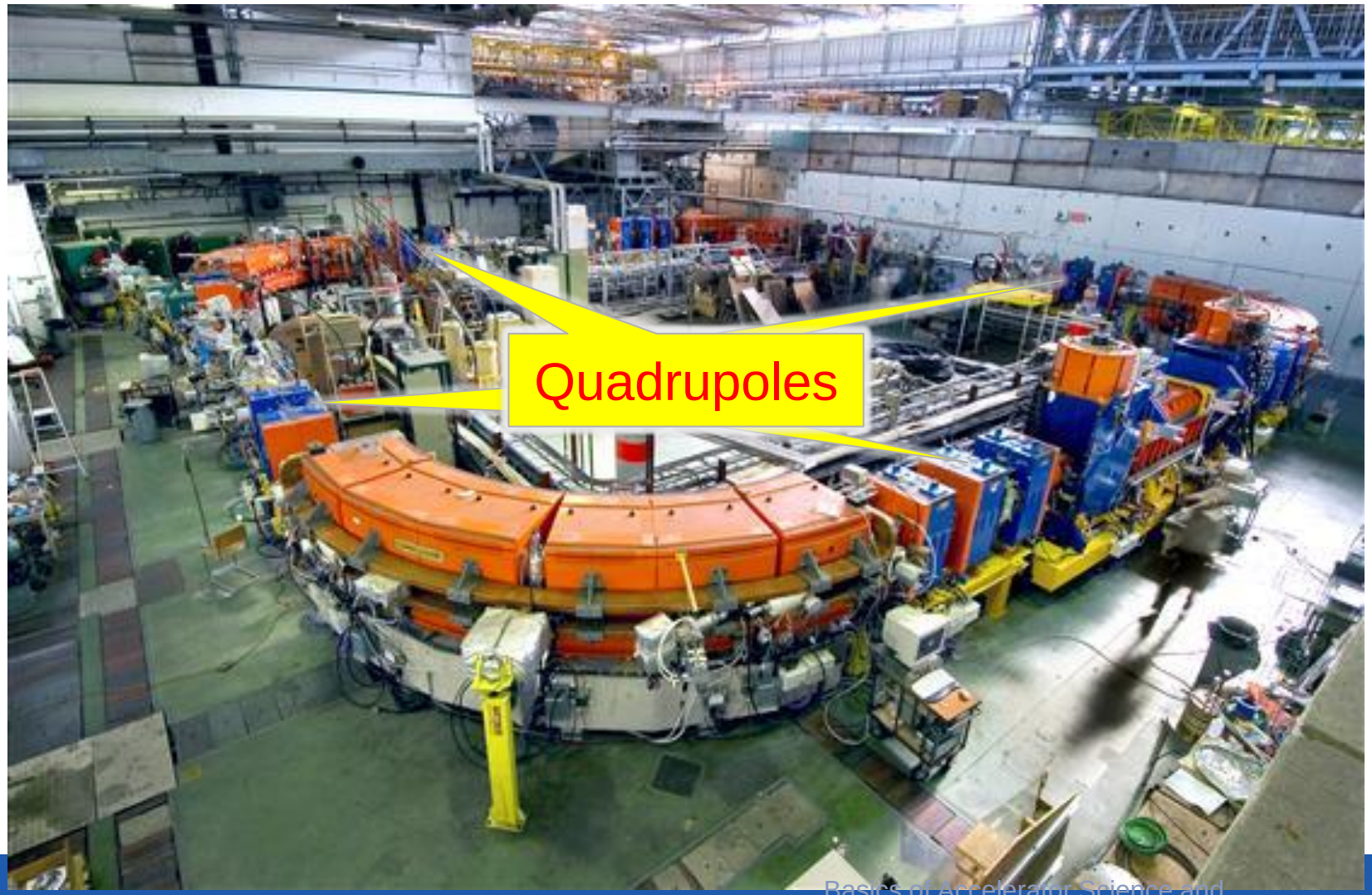
Rotated by 90º



De-focusing Quadrupole

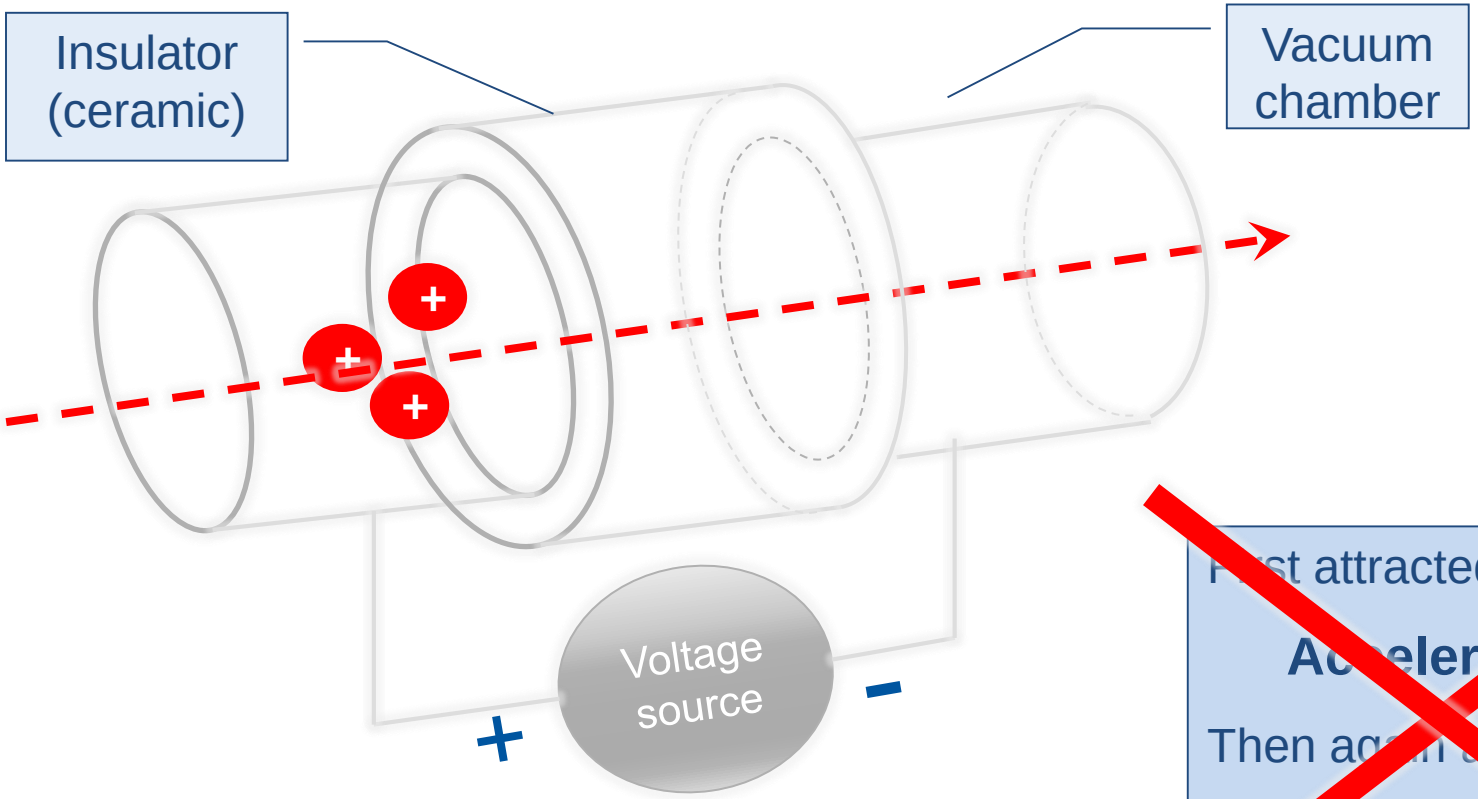


Focusing the Particle Beam



Accelerating Particles

Accelerating Beams



First attracted

Acceleration

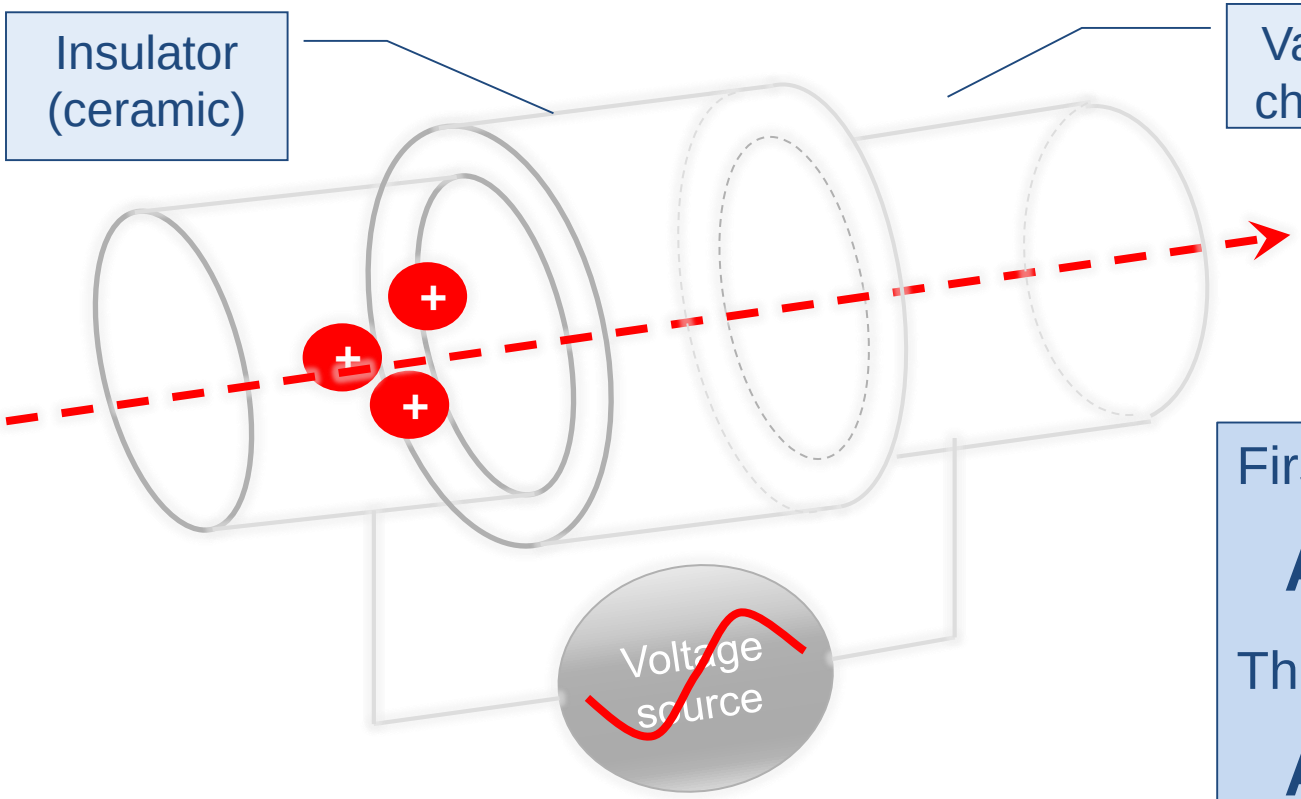
Then again attracted

Deceleration

Net result:

No Acceleration

Accelerating Beams



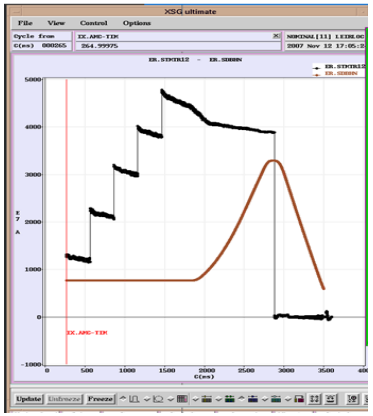
First attracted

Acceleration

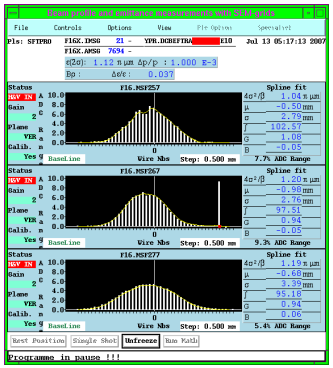
Then repelled

Acceleration

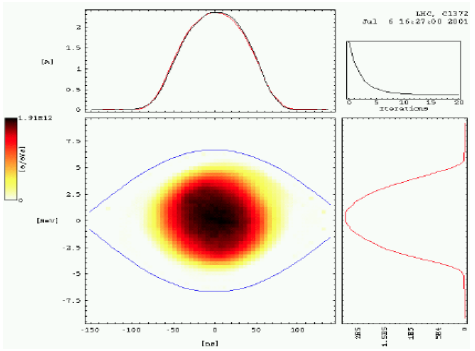
The Eyes of Operations



Beam intensity or current measurement



Transverse beam profile/size measurement



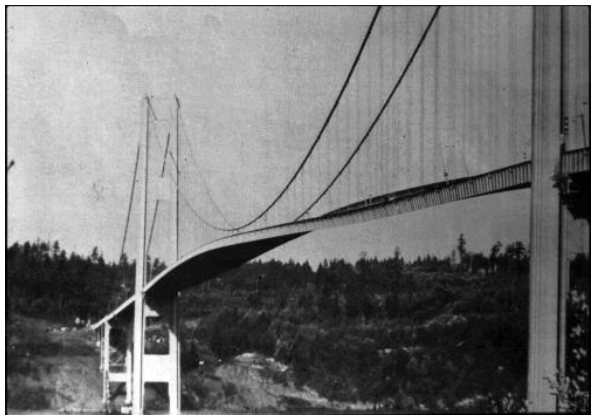
Longitudinal beam profile measurements

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

Any many more beam properties…..

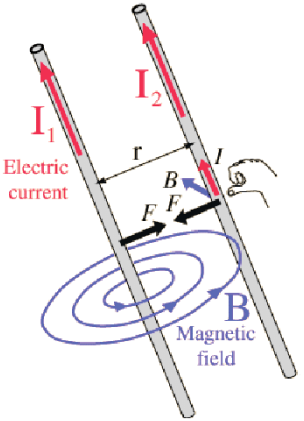
Possible Limitations

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

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

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

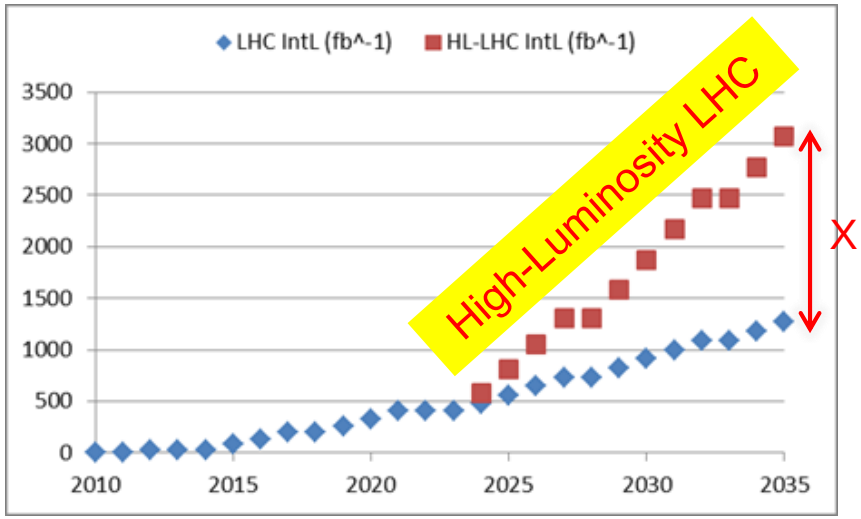
Number of bunches

Geometrical Correction factors

Beam dimensions

- More or less fixed:
  - Revolution period
  - Number of bunches

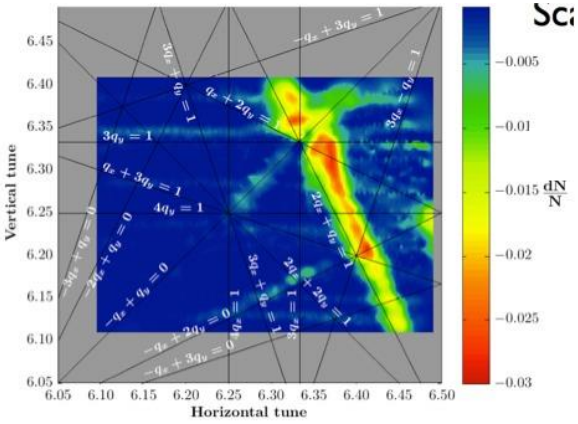
- Parameters to optimise:
  - Number of particles per bunch
  - Beam dimensions
  - Geometrical correction factors



LIU: What will be changed ?

- 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



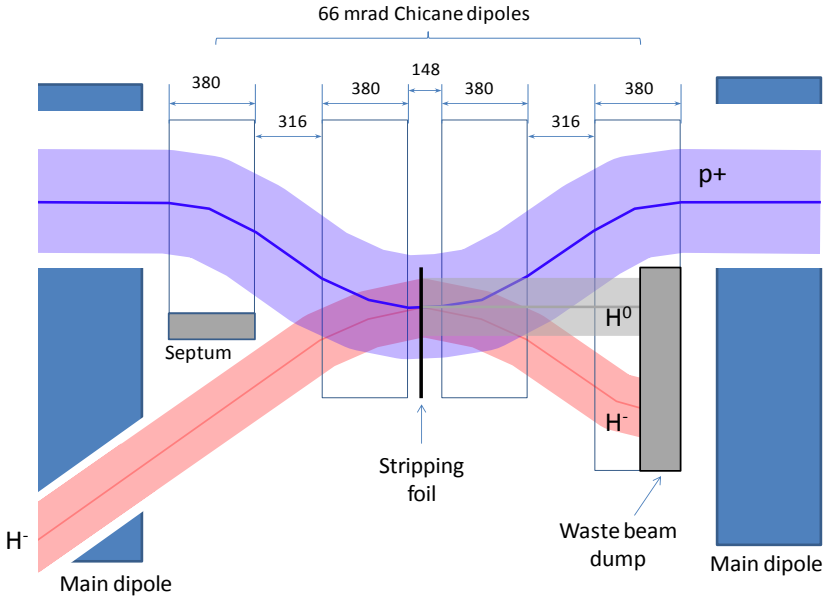
Courtesy of A. Huschauer

- SPS
  - Machine Impedance reduction (instabilities)
  - New 200 MHZ RF system
  - Vacuum chamber coating against e-cloud

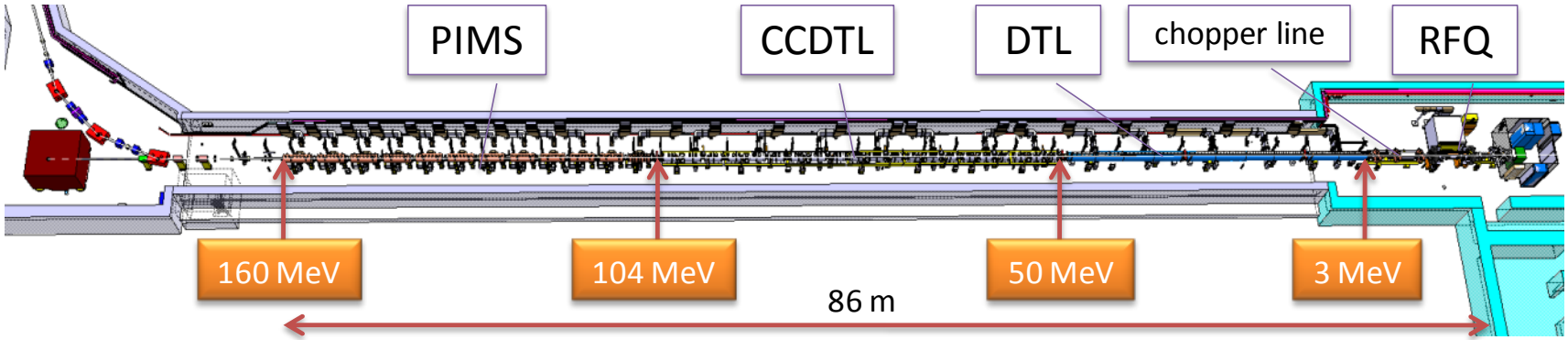
These are only the main modifications and this list is not exhaustive

LINAC4

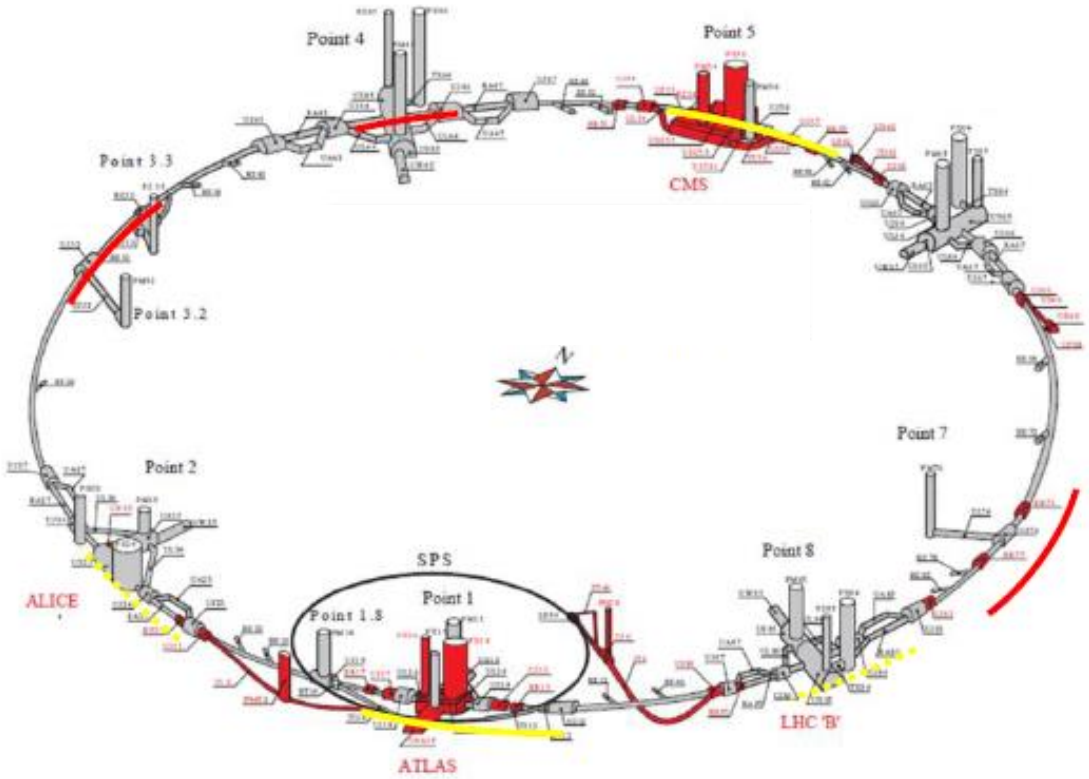
- Produce and accelerate H^- at 160 MeV
- Inject H^- into the PSB and strip the electrons → protons in the PSB
- During the following turns interleave the circulating protons with H- that will be stripped



Injecting multiple turns will increase **intensity** and **density**



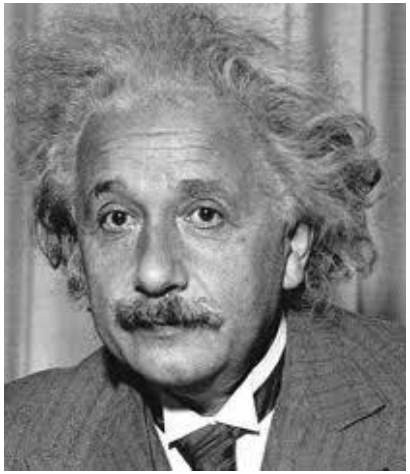
HL-LHC: What will be changed ?



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

Major intervention on more than 1.2 km of the LHC
These are only the main modifications and this list is not exhaustive

Everything must be made as simple as possible. But not simpler….



Albert Einstein