CERN

Hadron Accelerators

Part 1 of 2

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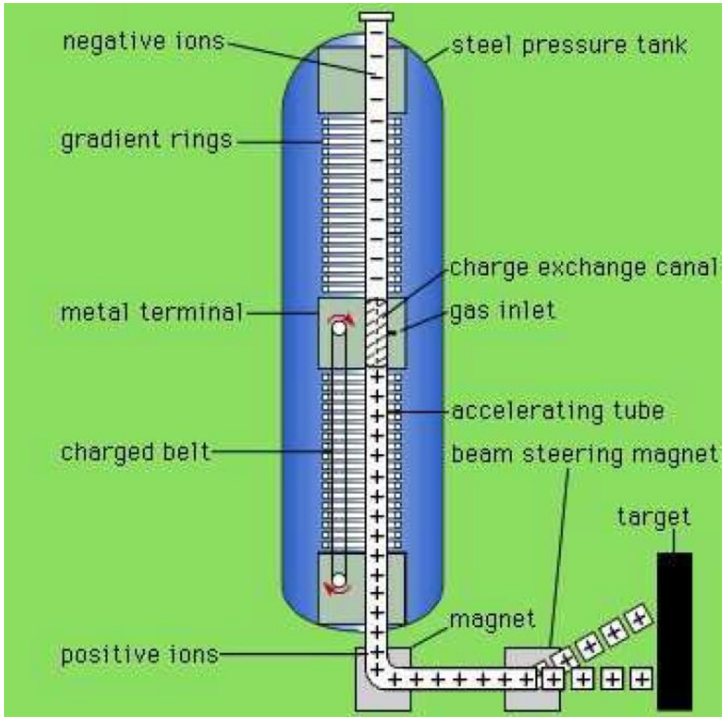
Topics

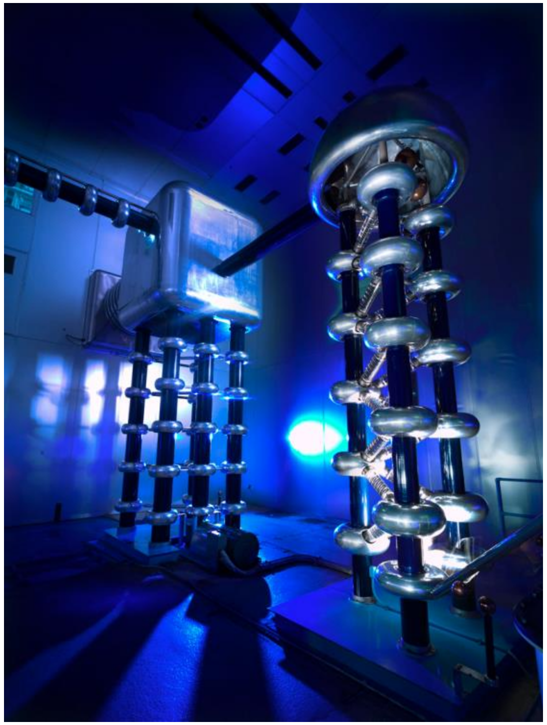
- A brief Word on Accelerator History
- The CERN Accelerator Complex
- A Brief Word on Relativity & Units
- Transverse Motion

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

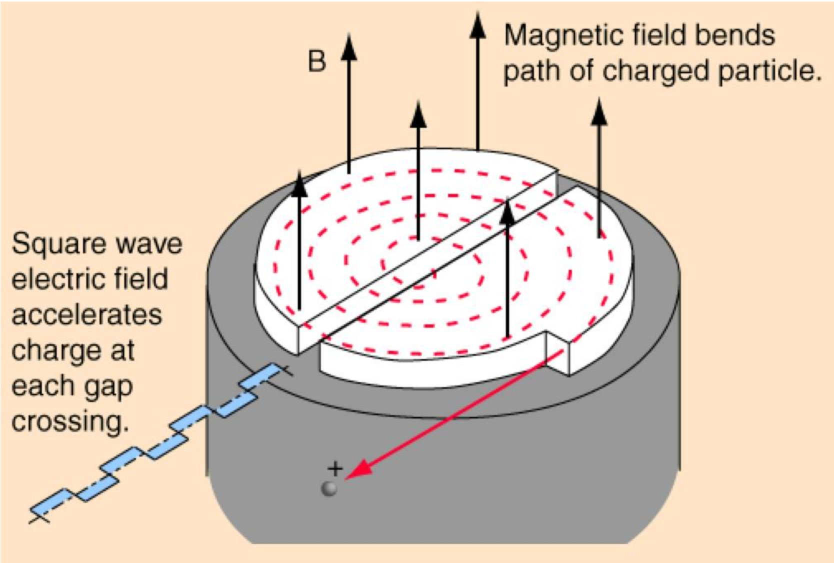




Cyclotron

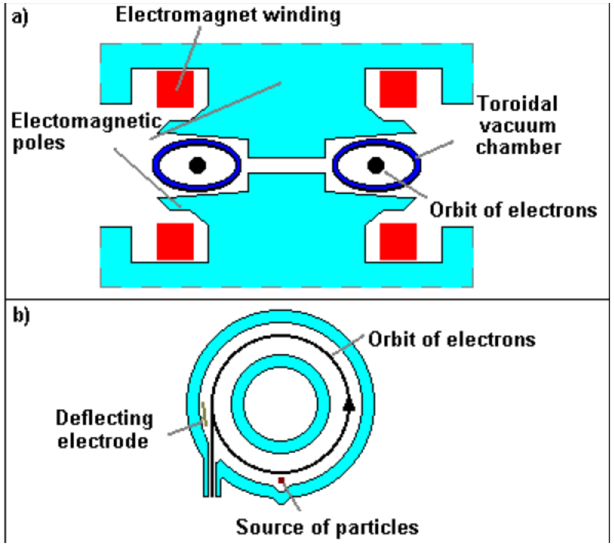
- 1932: 1.2 MeV – 1940: 20 MeV (E.O. Lawrence, M.S. Livingston)
- E = 80 keV for 41 turns
- Constant magnetic field
- Alternating voltage between the two D's
- Increasing particle orbit radius Development lead to the synchro-cyclotron to cope with the relativistic effects (Energy ~ 500 MeV)

In 1939 Lawrence received the Noble prize for his work.

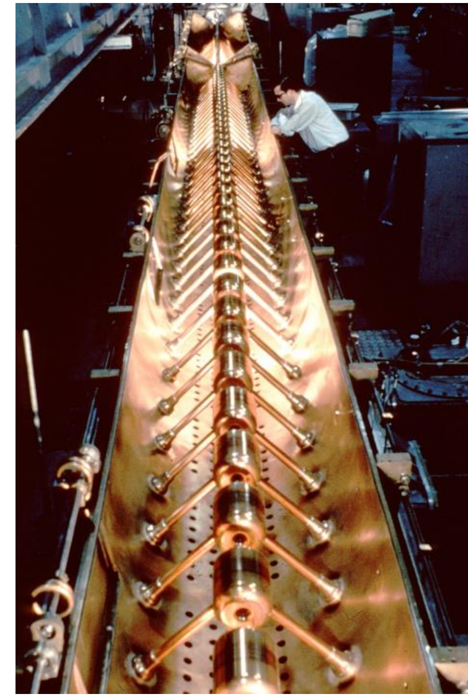


Betatron

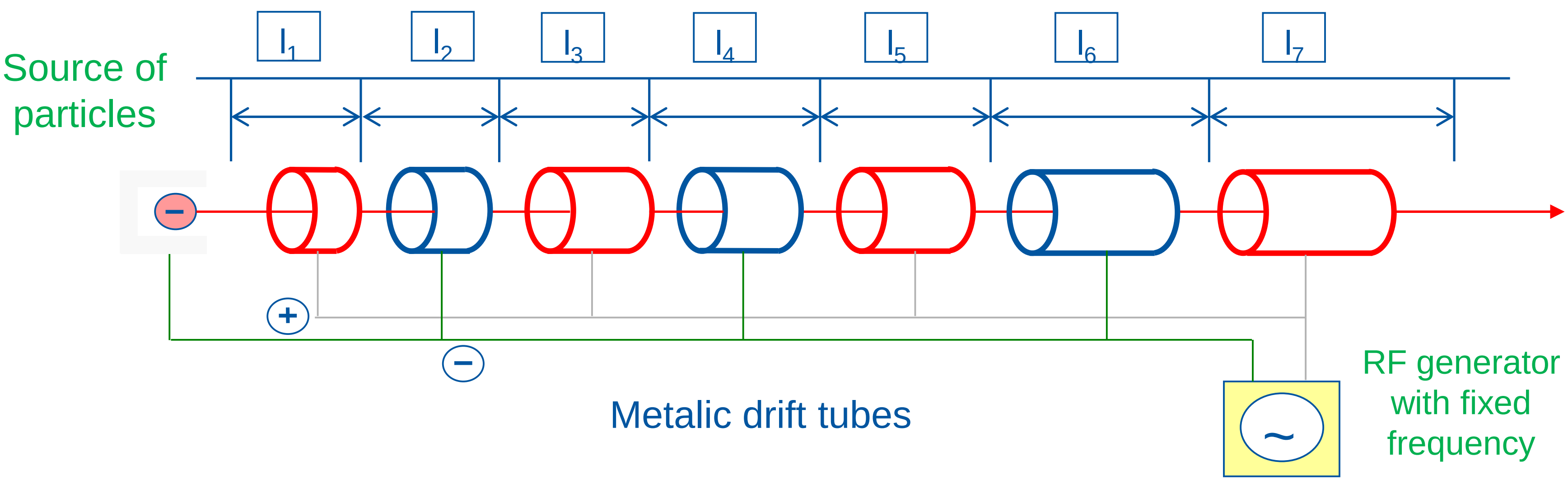
- 1940: Kerst 2.3 MeV and very quickly 300 MeV
- First machine to accelerate electrons to energies higher than from electron guns
- It is actually a transformer with a beam of electrons as secondary winding
- The magnetic field is used to bend the electrons in a circle, but also to accelerate them
-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



Linear Accelerator

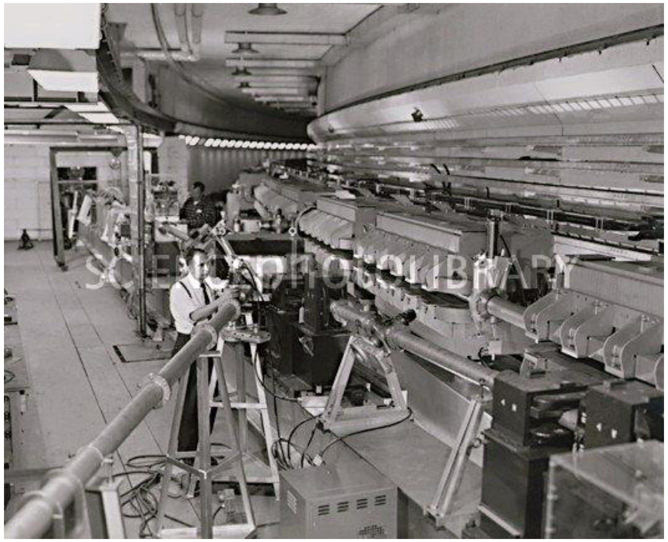


- Many people involved: Wideroe, Sloan, Lawrence, Alvarez,….
- Main development took place between 1931 and 1946.
- Development was also helped by the progress made on high power high frequency power supplies for radar technology.
- Today still the first stage in many accelerator complexes.
- Limited by energy due to length and single pass.



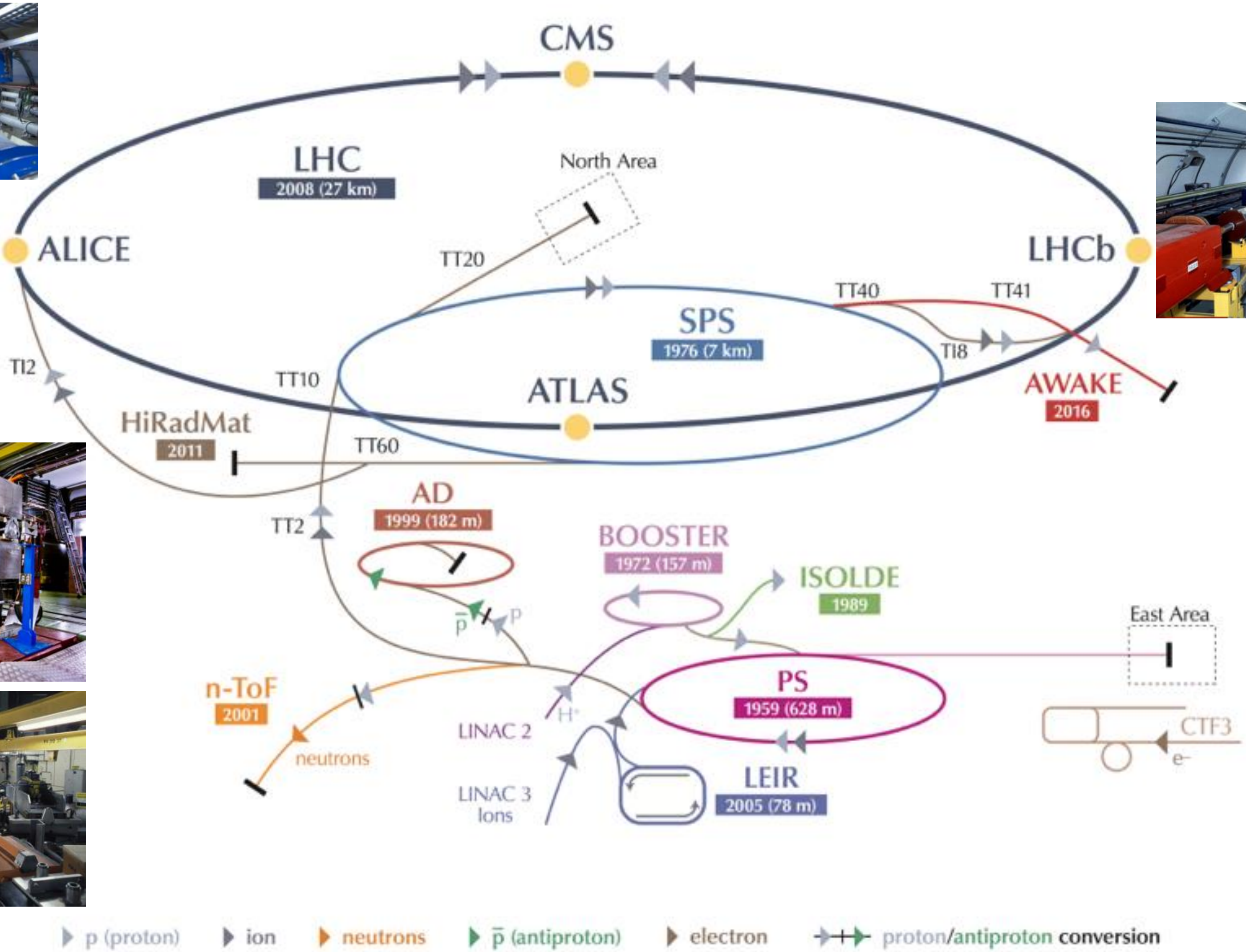
Synchrotrons

- 1943: M. Oliphant described his synchrotron invention in a memo to the UK Atomic Energy directorate
- 1959: CERN-PS and BNL-AGS
- Fixed radius for particle orbit
- Varying magnetic field and radio frequency
- Phase stability
- Important focusing of particle beams (Courant – Snyder)
- Providing beam for fixed target physics
- Paved the way to colliders

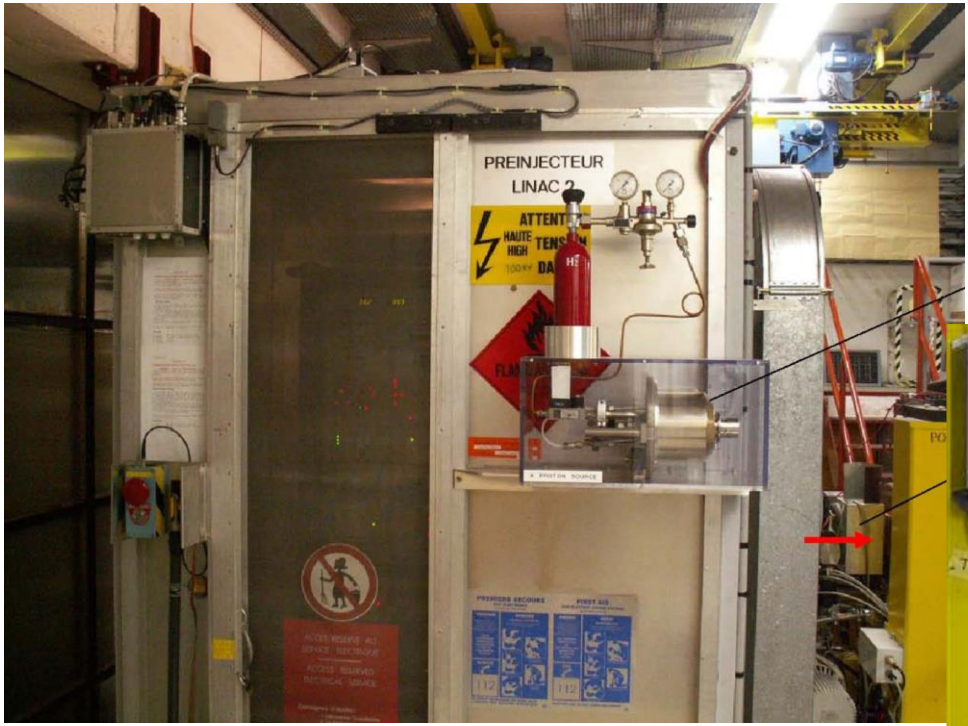


The CERN Accelerator Complex

The CERN Accelerator Complex



LINAC 2



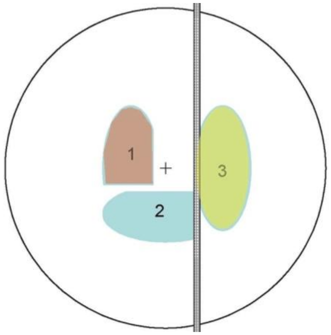
- Duoplasmatron proton source
- Extract protons at 90 keV from H_2

- 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

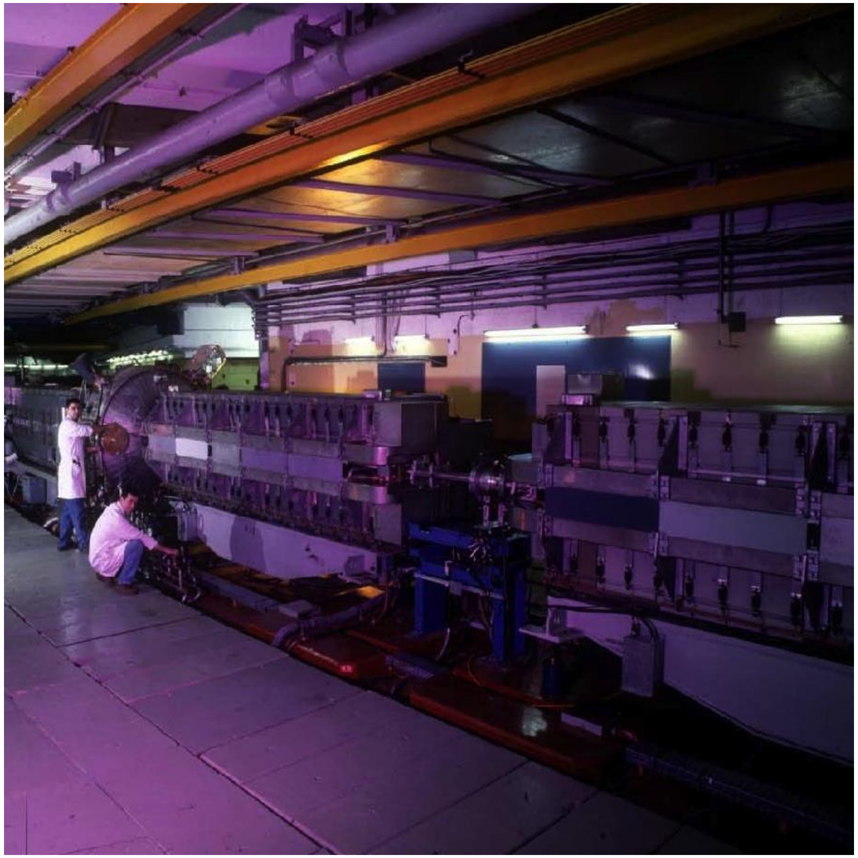
- The LINAC2 pulse is distributed over the four rings, using kicker magnets
- Each ring will inject over multi-turns, accumulating beam in the horizontal phase space
- This means that the beam size (transverse emittance) increases when the intensity increases → ~ constant density



The PS Booster determines the transverse Brightness of the LHC beam

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



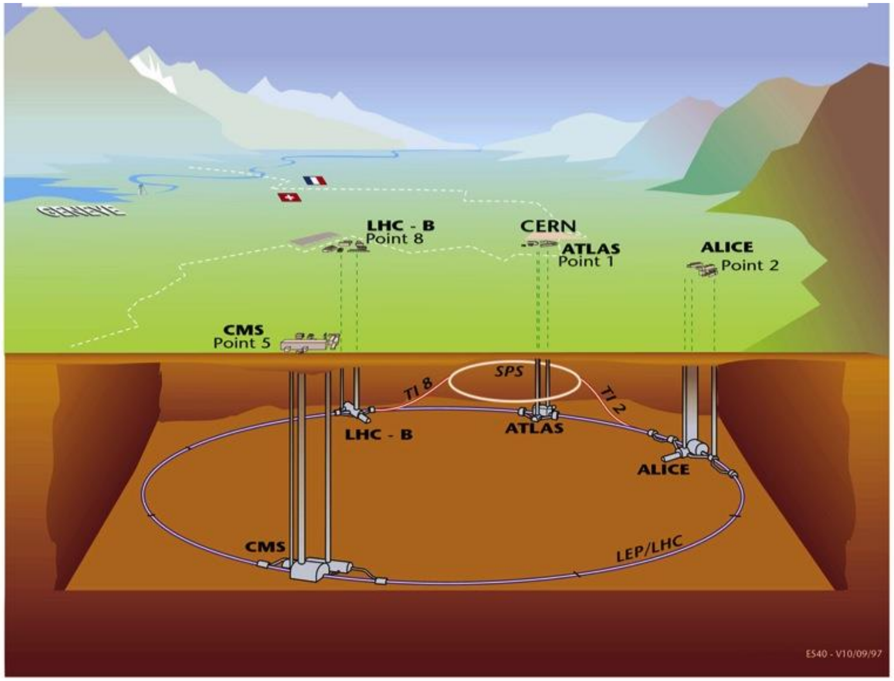
- The many different RF systems allow for complex RF gymnastics:
  - 10 MHz, 13/20 MHz, 40 MHz, 80 MHz, 200 MHz
- Various types of extractions:
  - Fast extraction
  - Multi-turn extraction (MTE)
  - Slow extraction

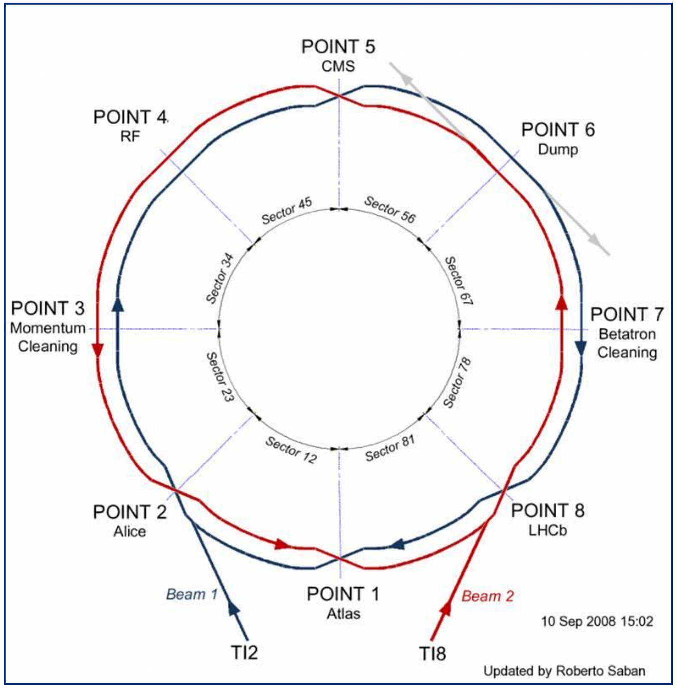
SPS

- 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

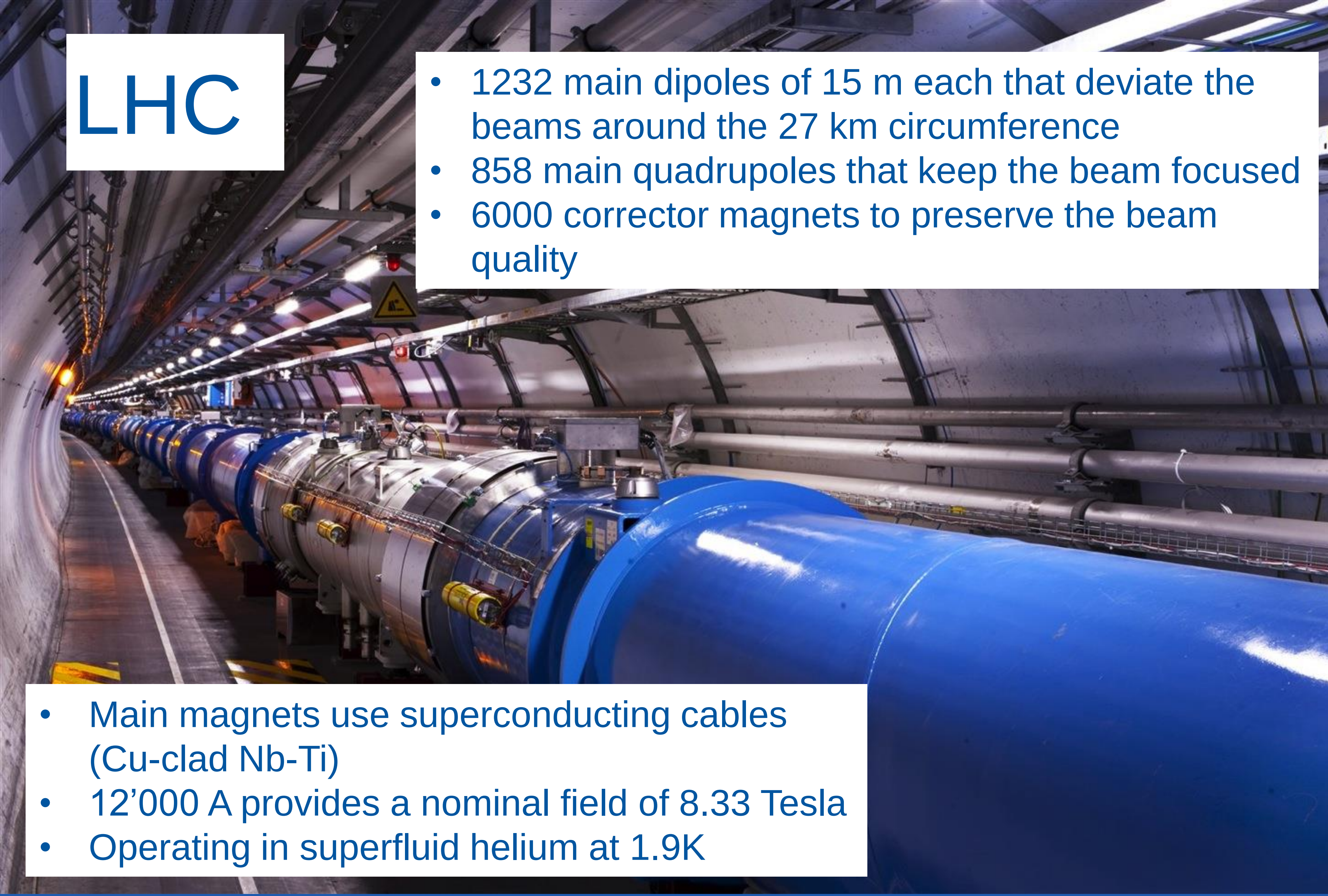
- Provides slow extracted beam to the North Area
- Provides fast extracted beam to LHC, AWAKE and HiRadMat

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

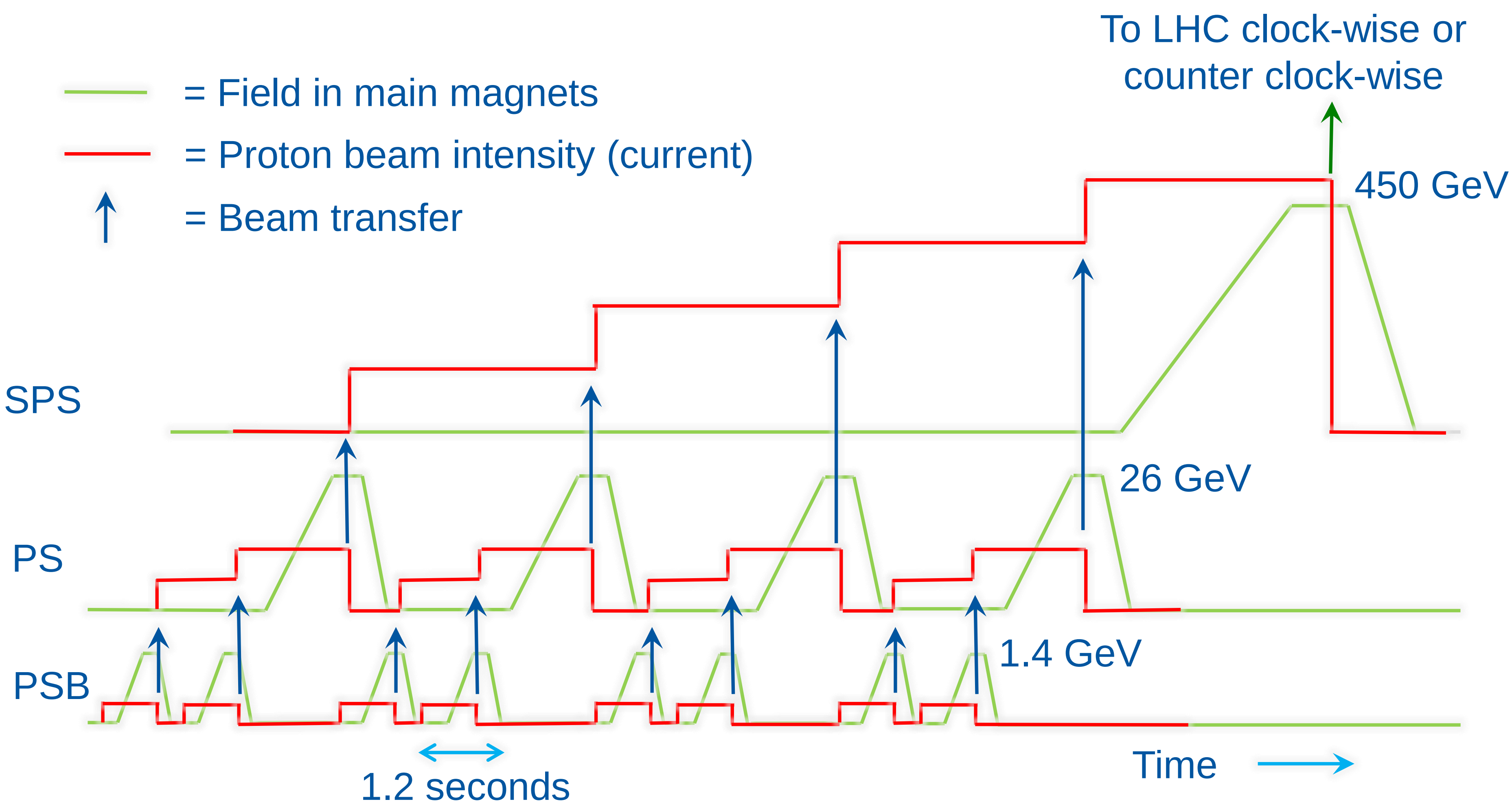


LHC

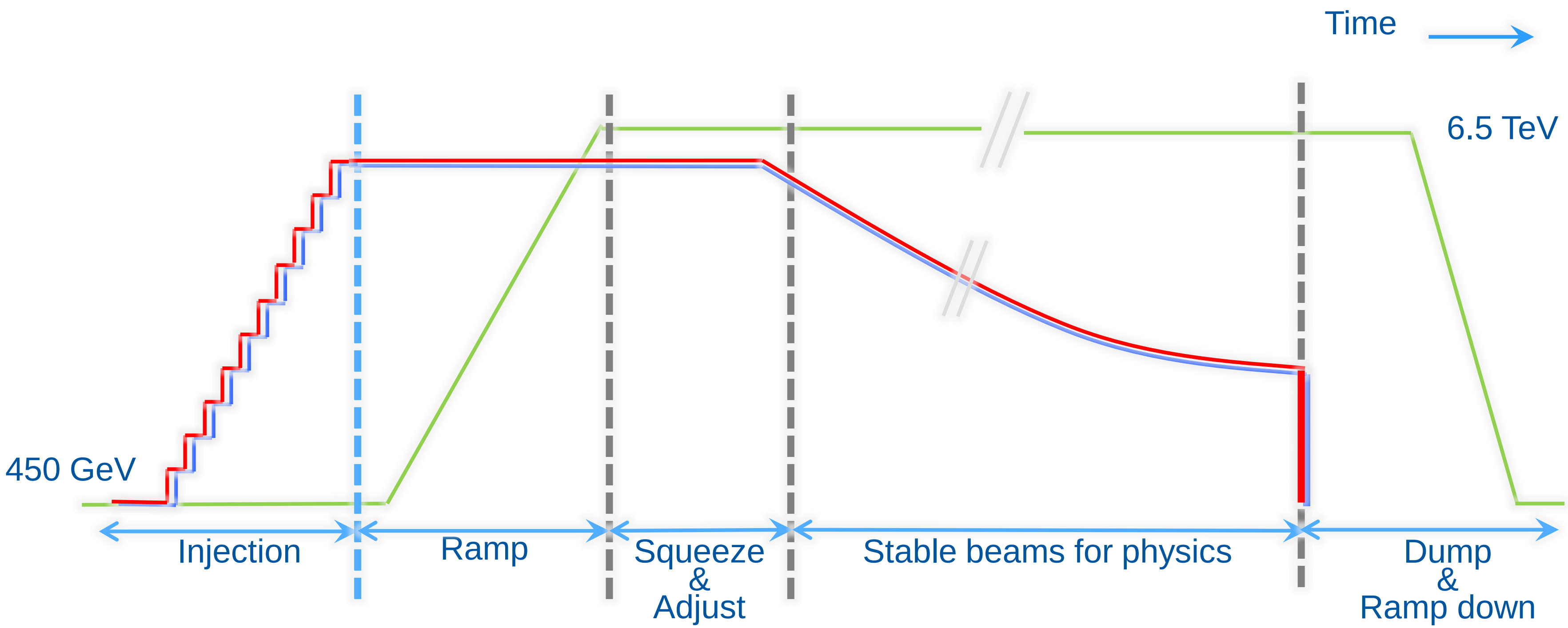
- 1232 main dipoles of 15 m each that deviate the beams around the 27 km circumference
- 858 main quadrupoles that keep the beam focused
- 6000 corrector magnets to preserve the beam quality

- 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

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.

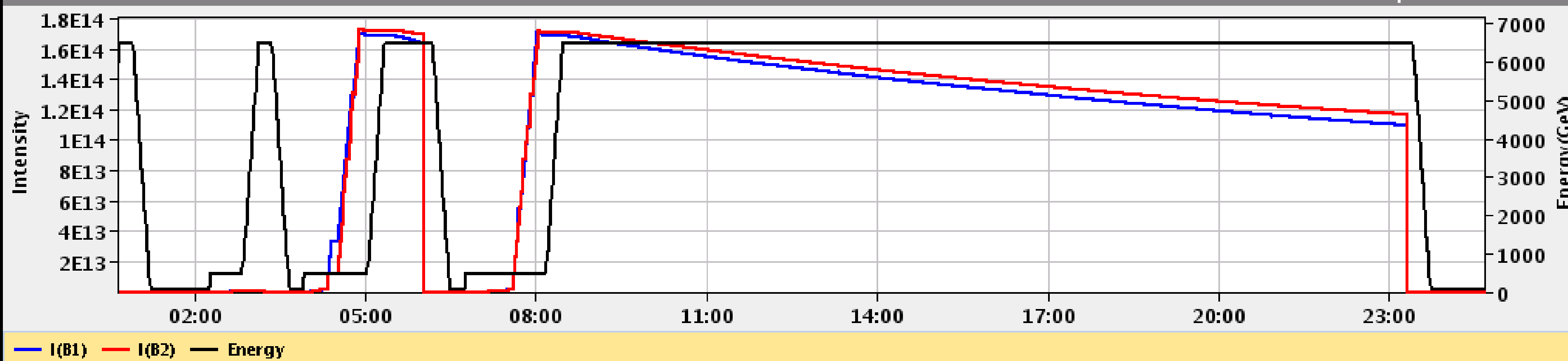
Since 2015 it runs at 6.5 TeV per beam, 13 TeV c.o.m

31-Aug-2017 00:39:46 Fill #: 6148 Energy: 59 GeV I(B1): 0.00e+00 I(B2): 0.00e+00

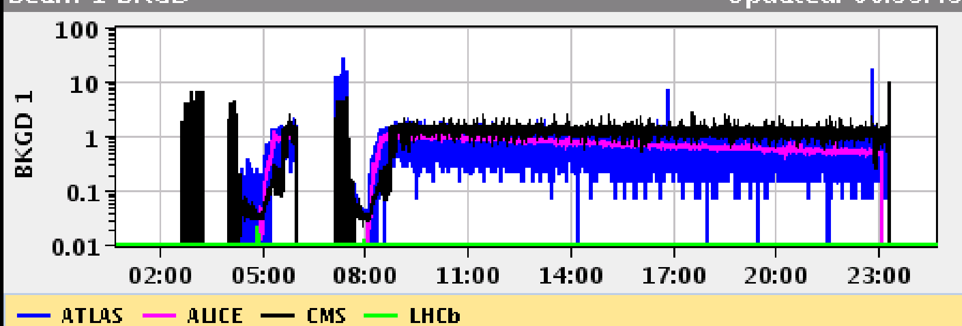
	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	STANDBY	STANDBY	CALIBRATION
Instantaneous Lumi [(ub.s)^-1]	-0.000	0.000	0.000	0.000
BRAN Luminosity [(ub.s)^-1]	1.7	0.0	3.6	0.0
Fill Luminosity (nb)^-1	316062.969	133.142	0.000	14258.708
Beam 1 BKGD	0.000	0.000	0.000	0.000
Beam 2 BKGD	0.000	0.000	0.000	0.000

LHCb VELO Position OUT Gap: -0.0 mm | NO BEAM | TOTEM: STANDBY

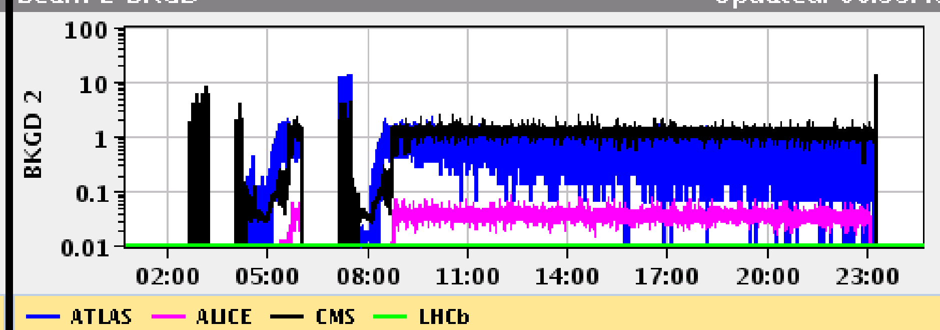
Performance over the last 24 Hrs Updated: 00:39:45



Beam 1 BKGD Updated: 00:39:43

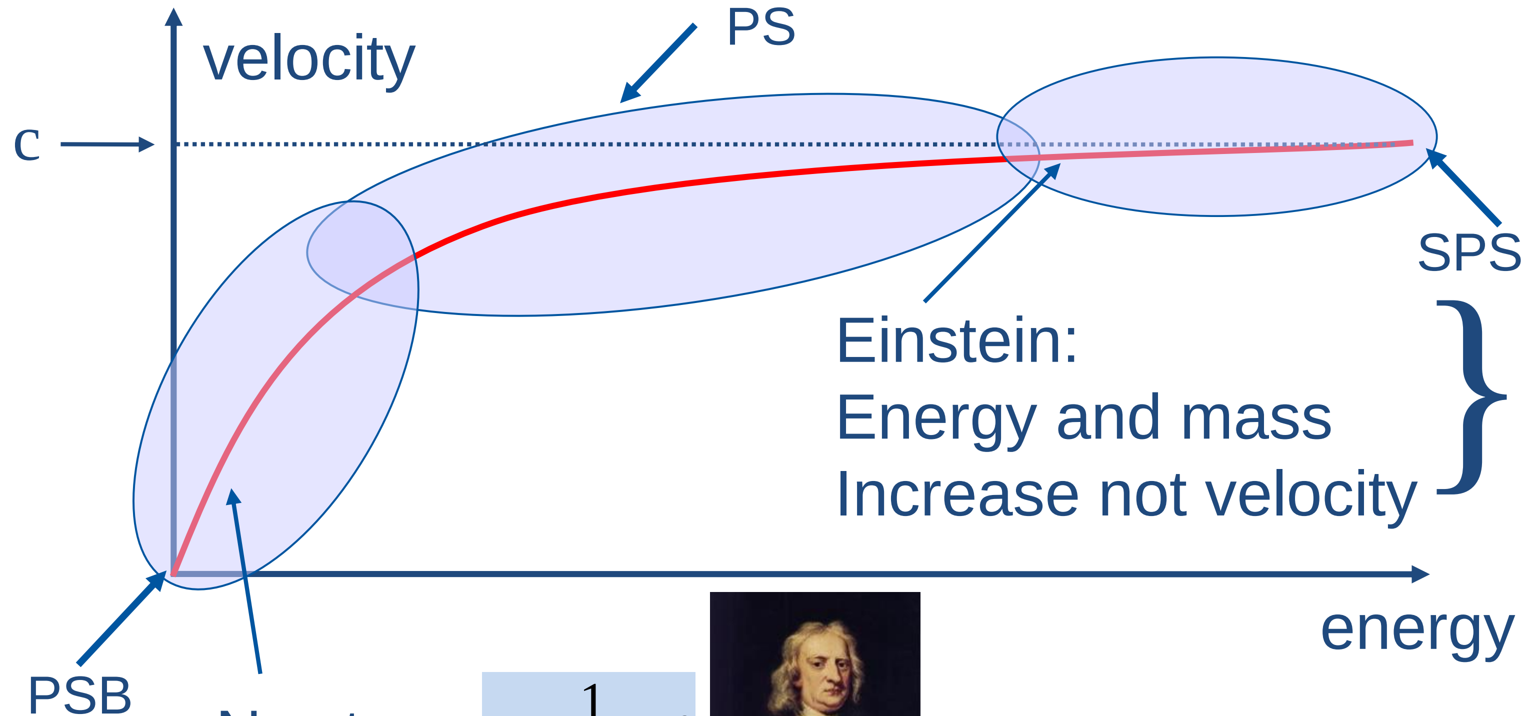


Beam 2 BKGD Updated: 00:39:43



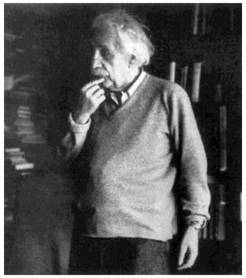
A Brief Word on Relativity & Units

Towards Relativity



Einstein:
Energy and mass
Increase not velocity

$$E = mc^2$$



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

Momentum

Einstein's formula:

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

The ratio between the total energy and the rest energy is

$$\gamma = \frac{E}{E_0}$$

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

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

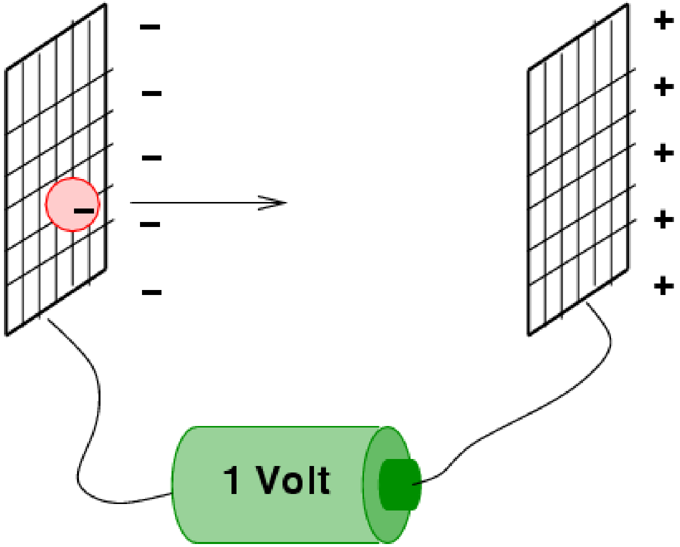
We can write: $$\beta = \frac{mvc}{mc^2}$$

Momentum is: $$p = mv$$

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

The Units for Energy

- 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 = 10^3, MeV = 10^6, GeV = 10^9, TeV = 10^{12}

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 engine going at 150 km/h

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

Energy versus Momentum

Momentum

Energy

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

- Therefore the **units** for
  - **momentum** are: MeV/c, GeV/c, …etc.
  - **Energy** are: MeV, GeV, …etc.

Attention:

when **β=1** **energy** and **momentum** are **equal**

when **β<1** the **energy** and **momentum** are **not equal**

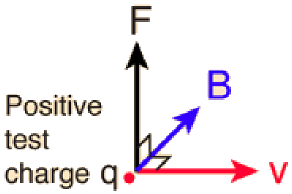
Transverse Motion

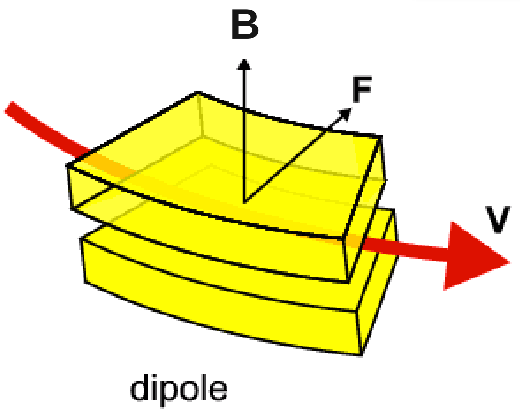
Lorentz Force

- Lorentz Formula: $$\vec{F} = \underbrace{q\vec{E}}_{\text{Electric force}} + \underbrace{q\vec{v} \times \vec{B}}_{\text{Magnetic force}}$$

- **Transverse motion** is dominated by **magnetic forces**:

$$\vec{F} = q\vec{v} \; x \; \vec{B}$$





- **Radius of curvature in the magnet**
- Linear motion before and after

Magnetic Rigidity

- The **Lorentz Force** can be seen as a **Centripetal Force**

$$F = q\vec{v} \times \vec{B} = \frac{mv^2}{\rho}$$

- ***ρ*** is the particle's **radius of curvature** in the magnetic field

$$B\rho = \frac{mv}{q} = \frac{p}{q}$$

- ***Bρ*** is the **magnetic rigidity**

$$B\rho[\mathrm{Tm}] = \frac{mv}{q} = \frac{p[\mathrm{GeV/c}]}{q} \Rightarrow B\rho = 3.3356\, p$$

- **Increasing the momentum** of a particle beam and keeping the **radius constant** requires **ramping the magnetic fields**

Ex. 1: Radius versus Radius of Curvature

- LHC circumference = 26658.883 m
  - Therefore the radius r = 4242.9 m
- There are 1232 main dipoles to make 360˚
  - This means that each dipole deviates the beam by only 0.29˚
- The dipole length = 14.3 m
  - The total dipole length is thus 17617.6 m, which occupies 66.09 % of the total circumference
- The bending radius ρ is therefore
  - ρ = 0.6609 x 4242.9 m → ρ = 2804 m
- Apart from dipole magnets there are also straight sections in our collider
  - These are used to house RF cavities, diagnostics equipment, special magnets for injection, extraction etc.

Ex. 2: High Energy LHC

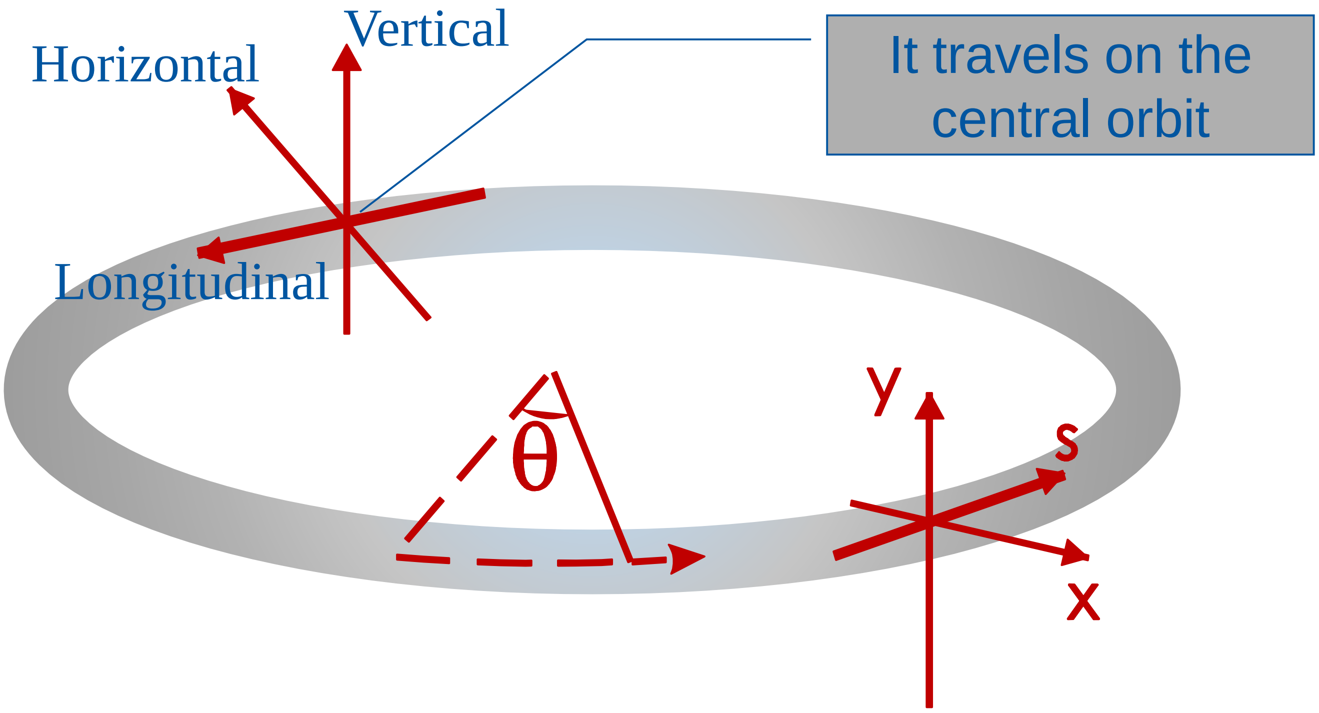
- Use the **existing LHC tunnel** and replace existing magnets with **high field superconducting magnets**
- Beam rigidity:

$$B\rho = 3.3356\, p$$

- **ρ = 2804 m** (fixed by tunnel geometry and filling factor)
- Vigorous R&D for **20 T dipole magnets is** on-going (Nb_3SN and HTS)

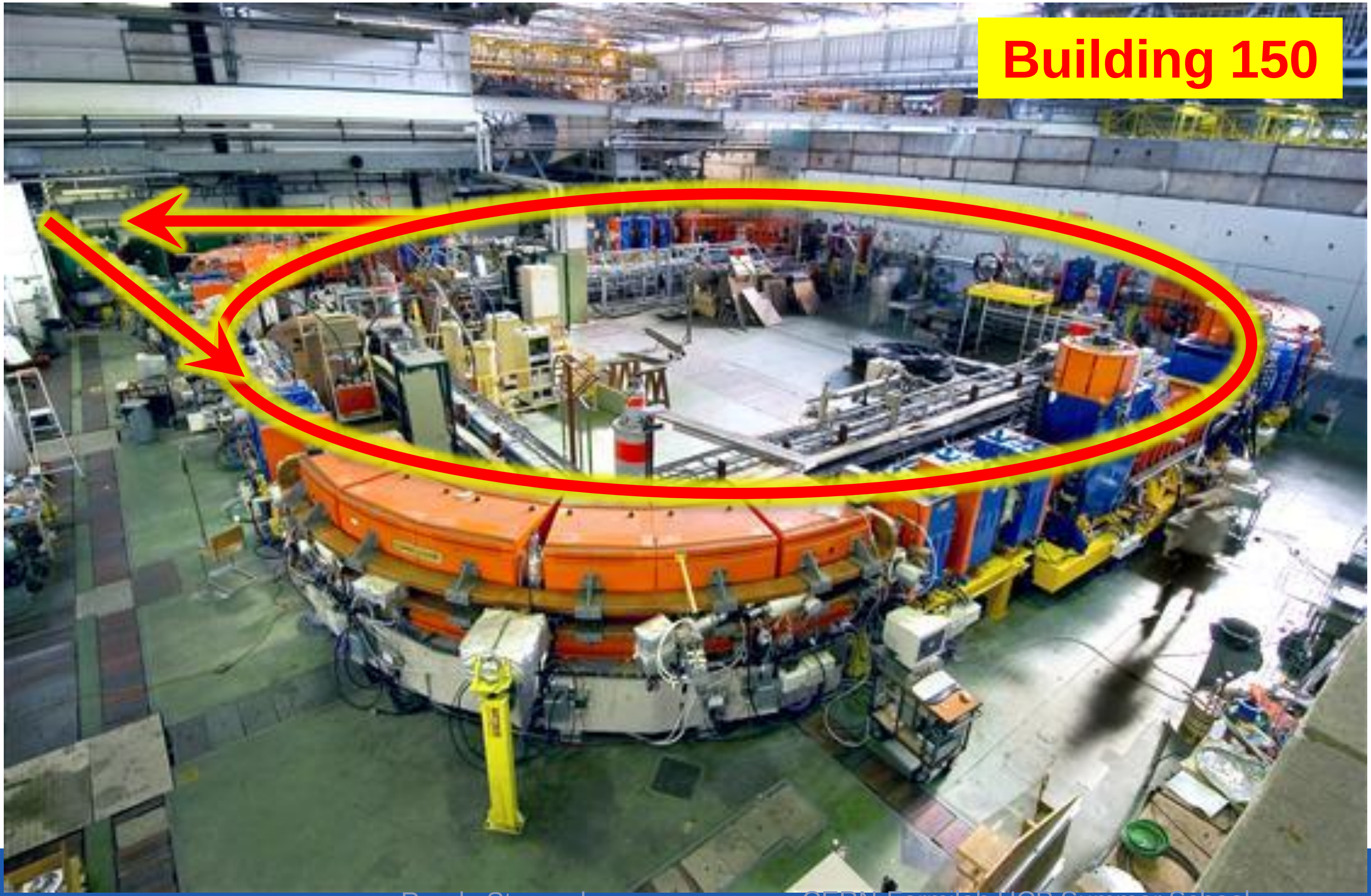
$$p = \frac{2804 \times 20}{3.3356} \Rightarrow \sim 16.5 \text{ TeV per beam} \Rightarrow \mathbf{33\ TeV_{cm}}$$

Coordinate System

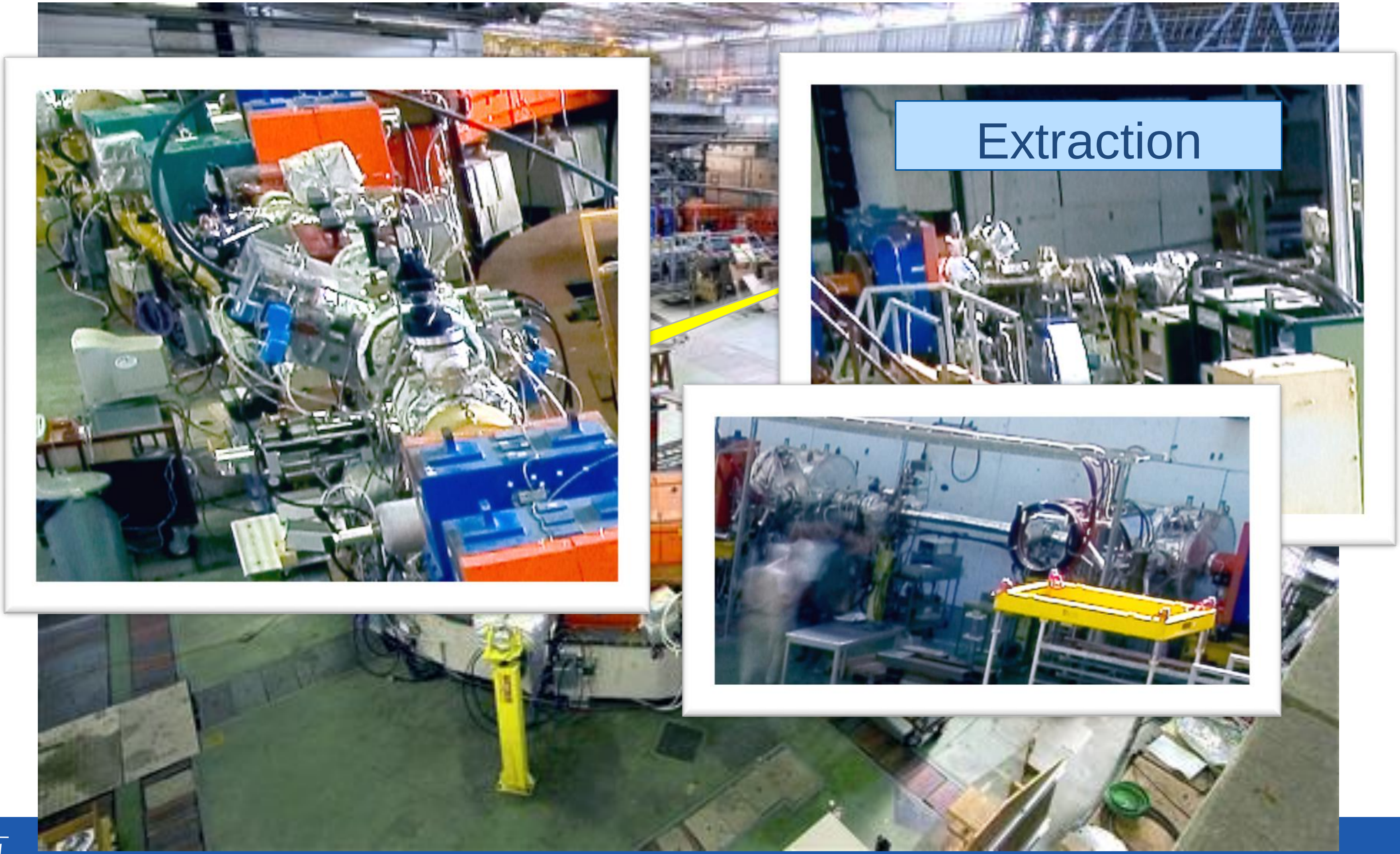


- We can speak of a: **Rotating Cartesian Co-ordinate System**

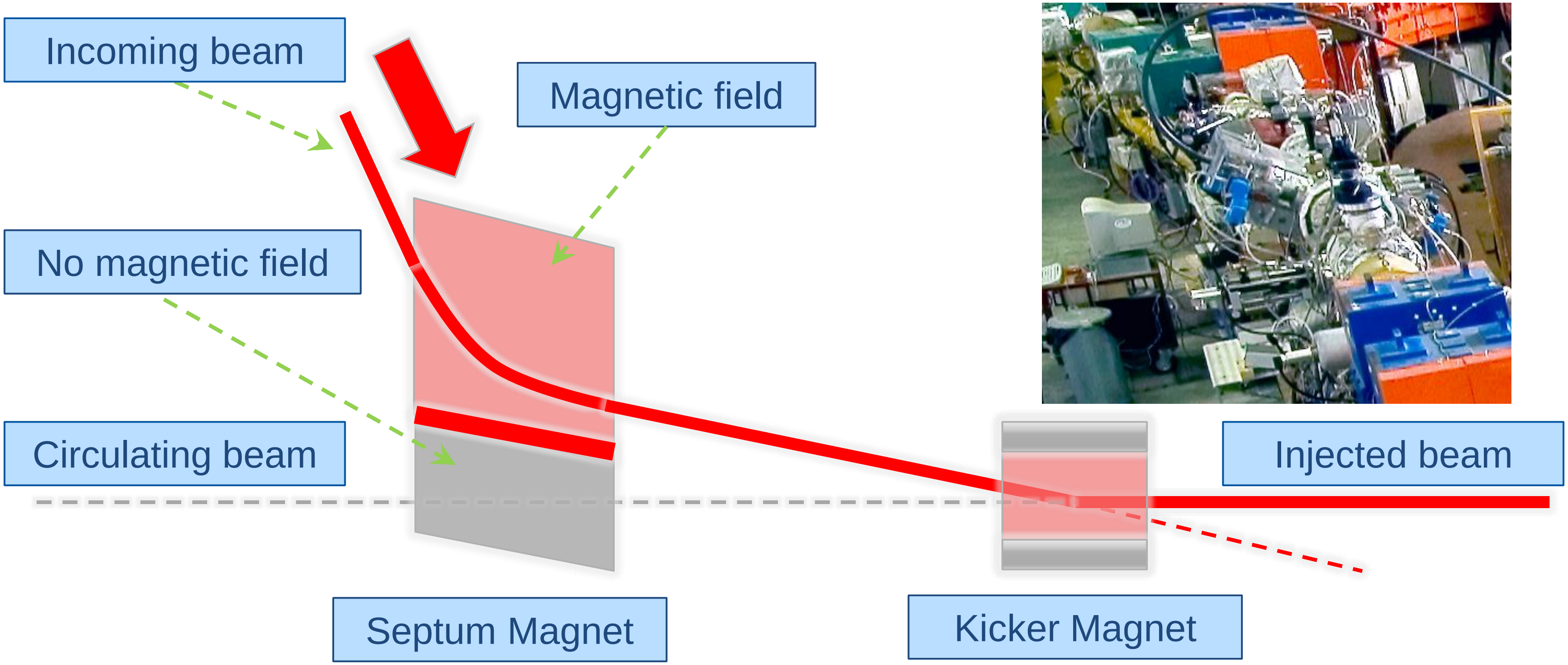
LEIR as an Example



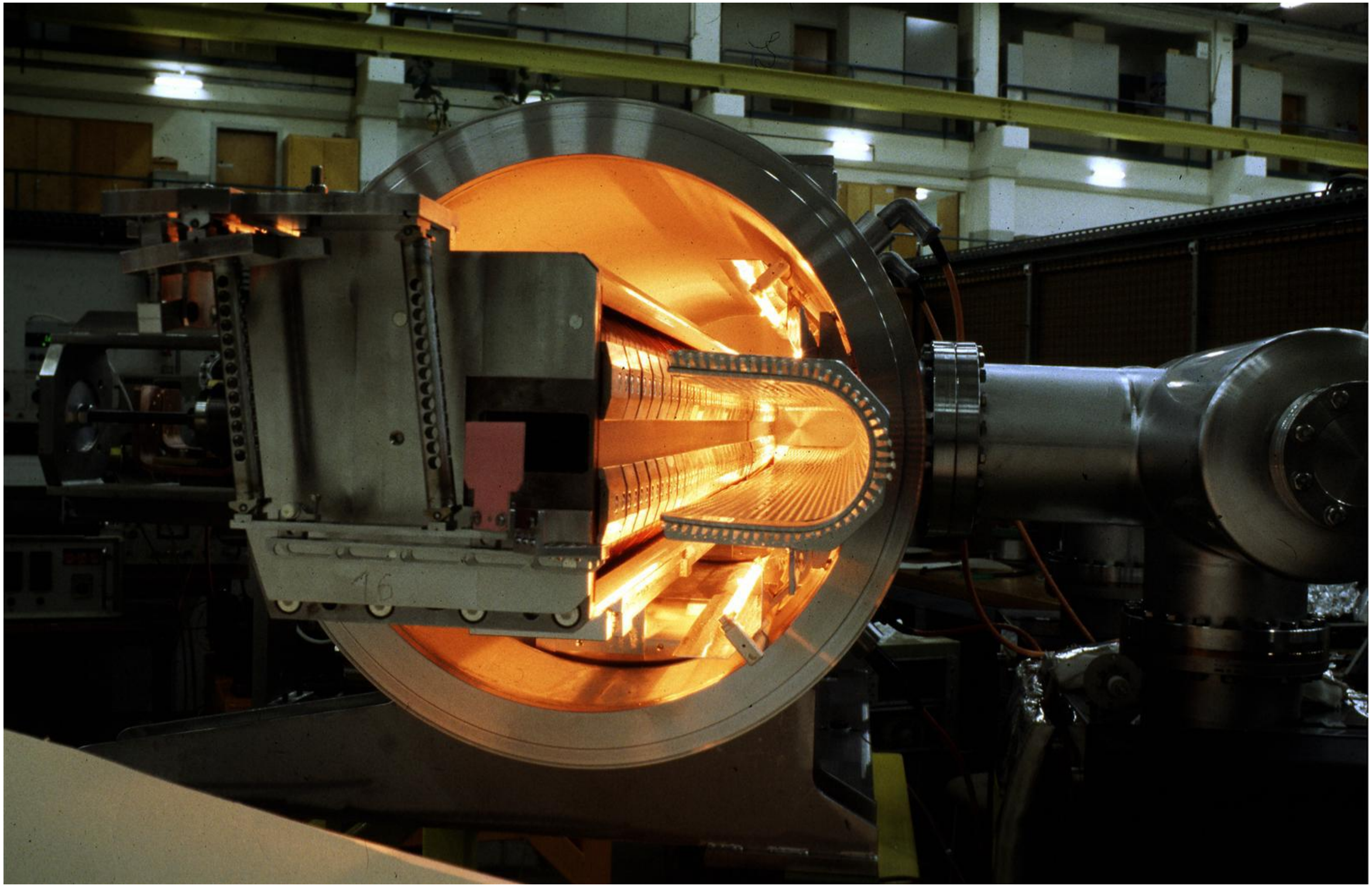
Injecting & Extracting Particles



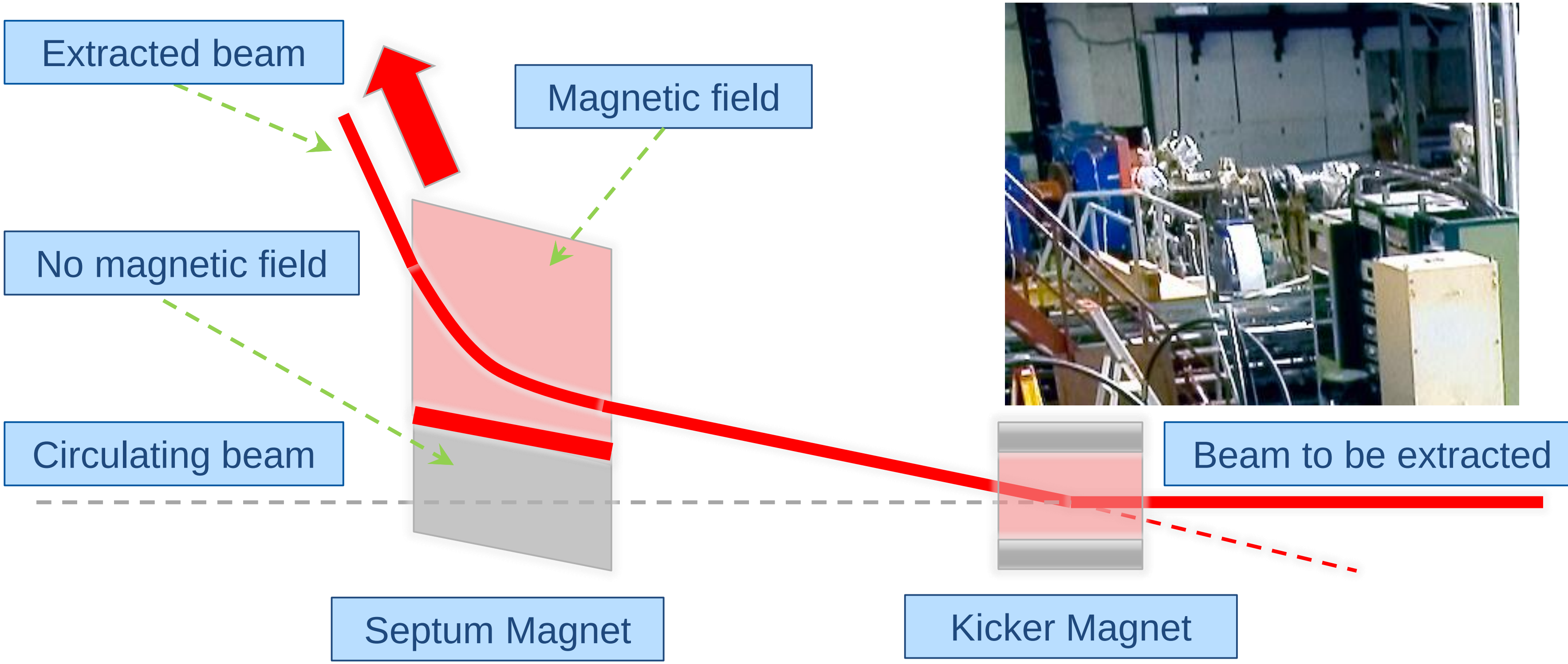
Injecting & Extracting Particles



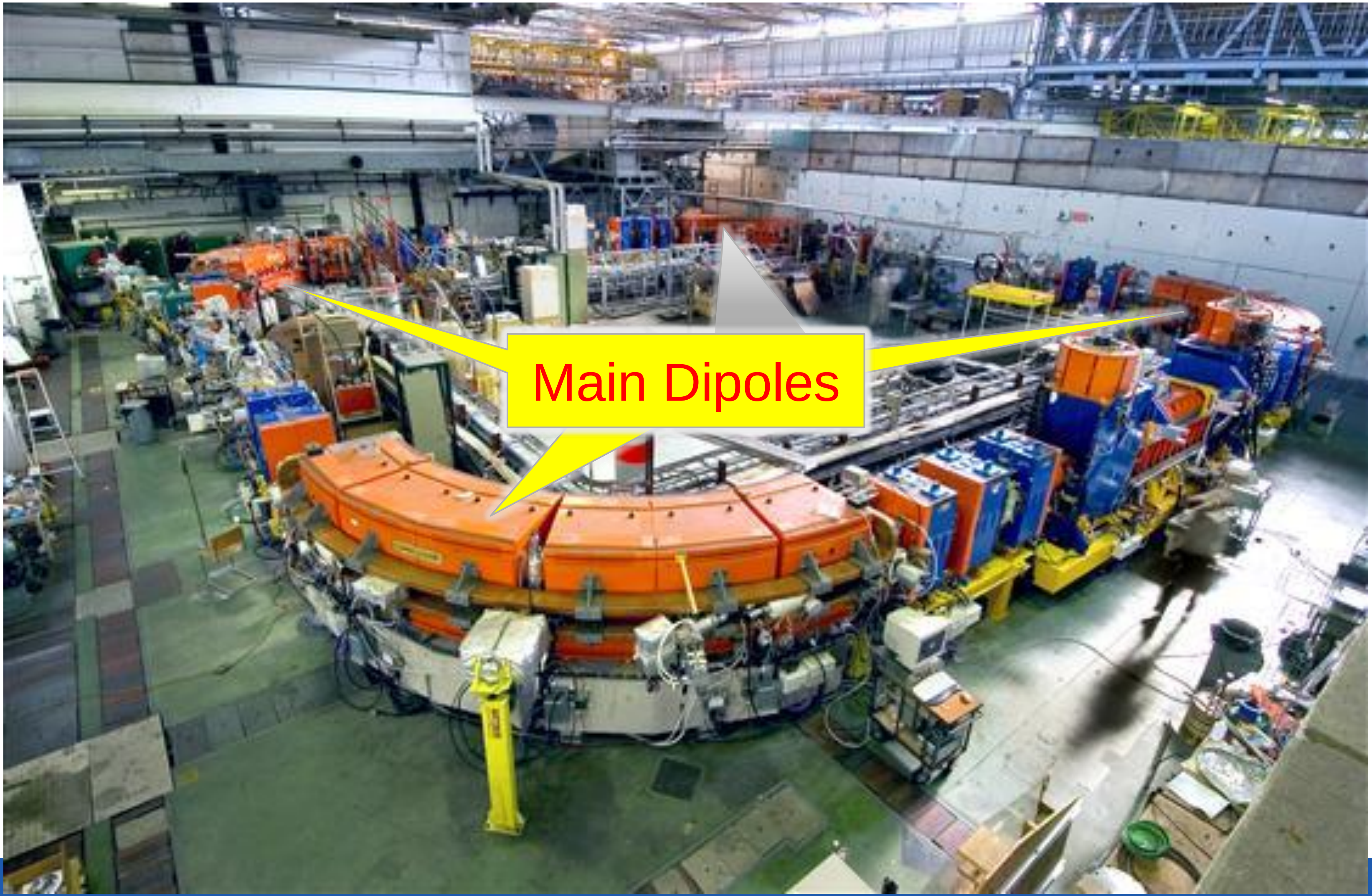
Septum Magnet



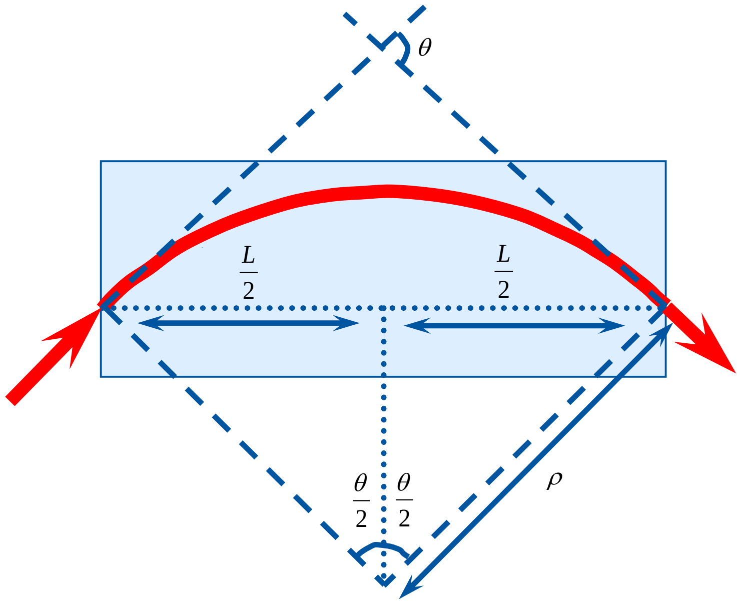
Injecting & **Extracting** Particles



Make Particles Circulate



Dipole Magnet

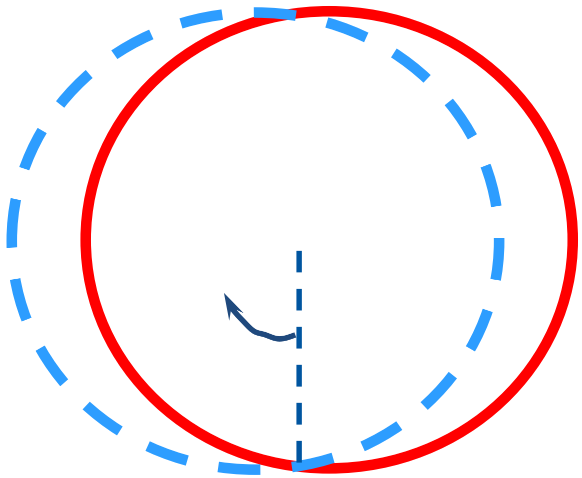


- A magnet with a uniform dipolar field deviates a particle by an angle θ in one plane
- The angle θ depends on the length L and the magnetic field B.

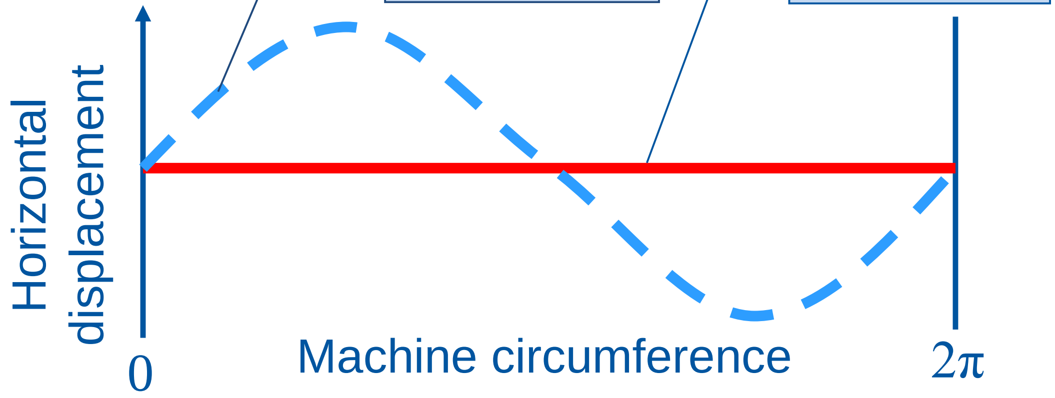
$$\sin\left(\frac{\theta}{2}\right) = \frac{L}{2\rho} = \frac{1}{2}\frac{LB}{(B\rho)} \rightarrow \sin\left(\frac{\theta}{2}\right) = \frac{\theta}{2} \rightarrow \theta = \frac{LB}{(B\rho)}$$

Oscillatory Motion of Particles

Two charged Particles in a homogeneous magnetic field



Horizontal motion

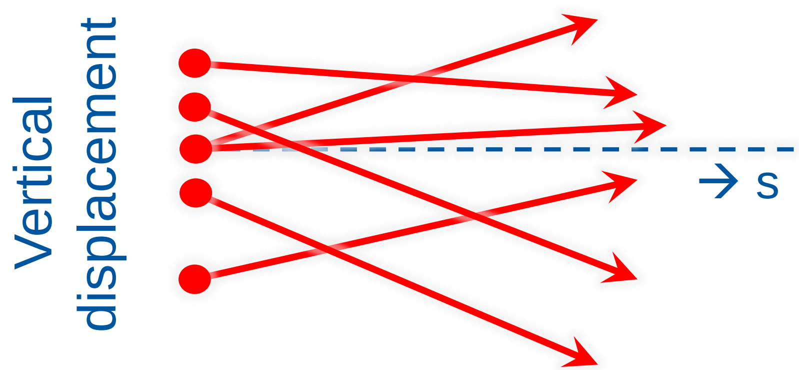


Different particles with different initial conditions in a homogeneous magnetic field will cause oscillatory motion in the horizontal plane → **Betatron Oscillations**

Oscillatory Motion of Particles

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

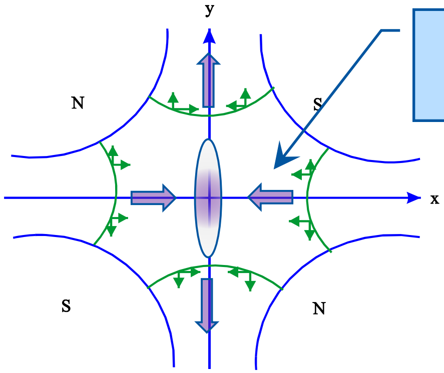
Many particles many initial conditions



Many different angles

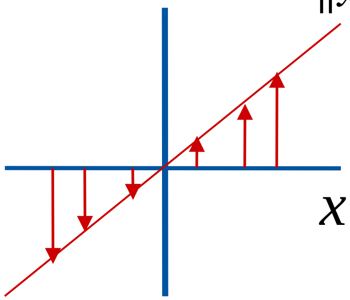
Focusing Particle Beams

Focusing Quadrupole

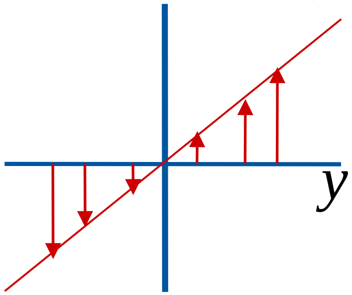


Force on particles

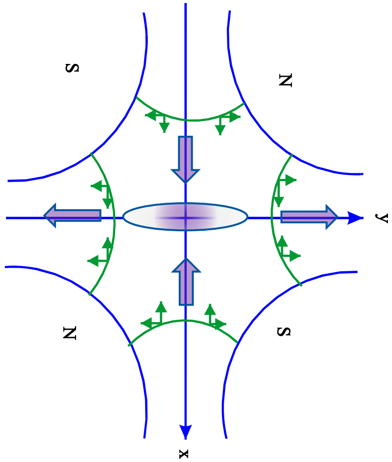
$$B_y = \frac{\partial B_y}{\partial x} x$$



$$B_x = \frac{\partial B_x}{\partial y} y$$



De-focusing Quadrupole



Field **gradient**

$$K = \frac{\partial B_y}{\partial x} [Tm^{-1}]$$

Normalised gradient

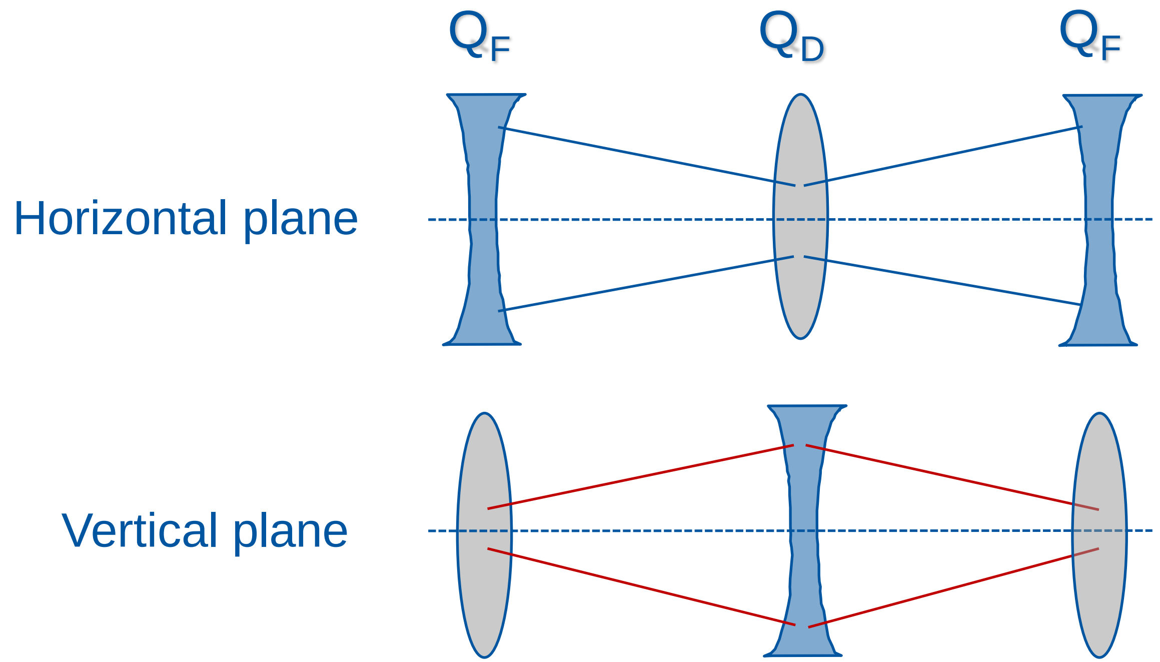
$$k = \frac{K}{B\rho} [m^{-2}]$$

FODO Cell

- Using a combination of focusing (Q_F) and defocusing (Q_D) quadrupoles solves our problem of 'unstable' vertical motion.
- It will keep the beams focused in **both planes** when the position in the accelerator, type and strength of the quadrupoles are well chosen.
- By now our accelerator is composed of:
  - **Dipoles**, constrain the beam to some closed path (orbit).
  - **Focusing and Defocusing Quadrupoles**, provide horizontal and vertical focusing in order to constrain the beam in transverse directions.
- A combination of focusing and defocusing sections that is very often used is the so called: **FODO lattice**.
- This is a configuration of magnets where focusing and defocusing magnets alternate and are separated by non-focusing drift spaces.

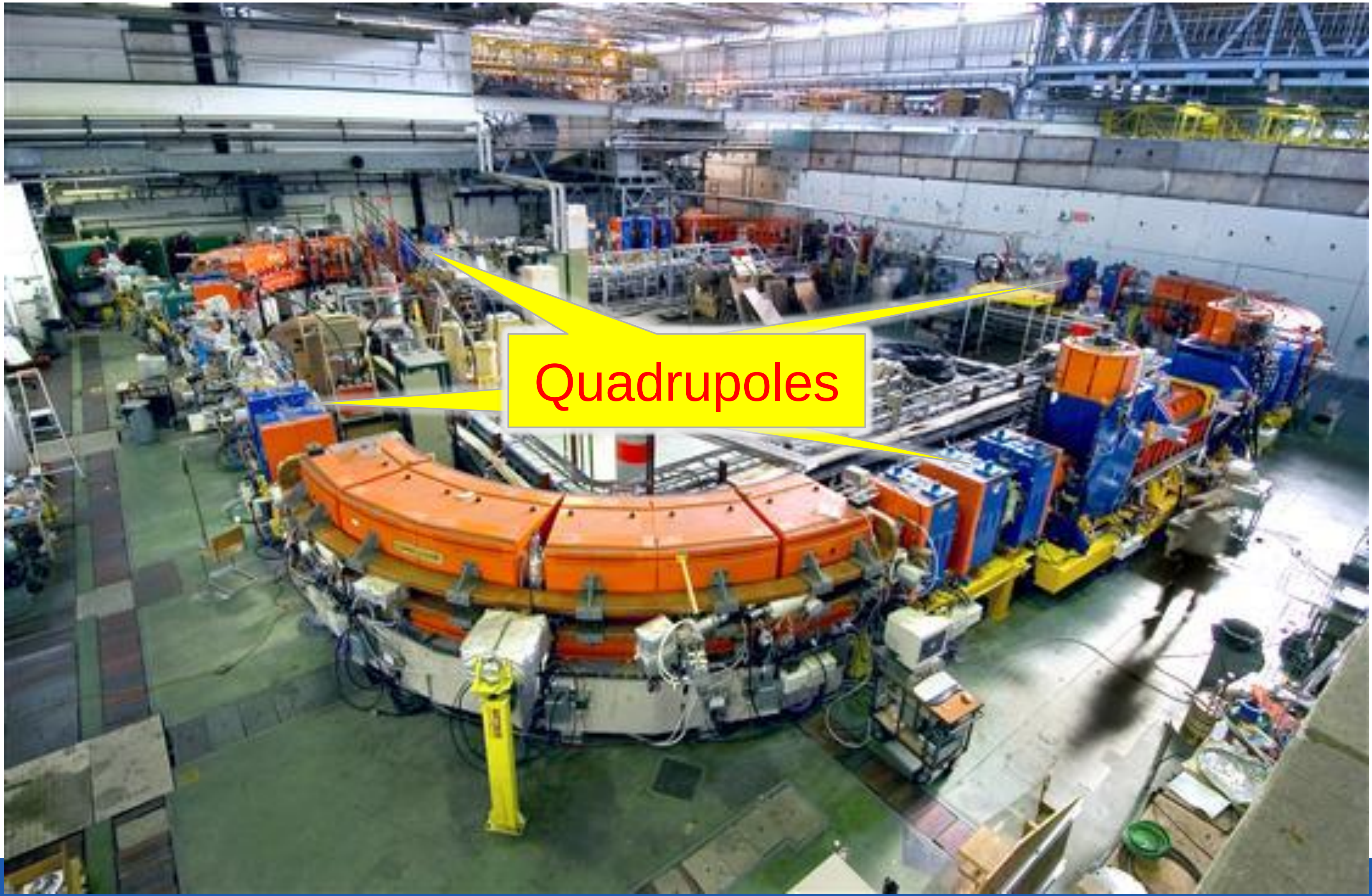
FODO Lattice

A quadrupole is defined focusing if it is oriented to focus in the horizontal plane and defocusing if it defocusses in the horizontal plane



This arrangement gives rise to **Betatron oscillations** within an envelope

Focusing the Particle Beam



Hill's Equation

- These **betatron oscillations** exist in both **horizontal** and **vertical** planes.
- The **number of betatron oscillations per turn** is called the **betatron tune** and is defined as Q_x and Q_y.
- Hill's equation describes this motion mathematically

$$\frac{d^2x}{ds^2} + K(s)x = 0$$

- If the restoring force, K is constant in 's' then this is just a **Simple Harmonic Motion** (Like a pendulum)
- 's' is the longitudinal displacement around the accelerator

General Solutions of Hill's Equation

Position: $x(s) = \sqrt{\varepsilon\beta_s}\cos(\varphi(s) + \varphi)$

Angle: $x' = -\alpha\sqrt{\varepsilon/\beta}\cos(\varphi) - \sqrt{\varepsilon/\beta}\sin(\varphi)\varphi$

- ε and φ are constants determined by the initial conditions
- β(s) is the periodic envelope function given by the lattice configuration

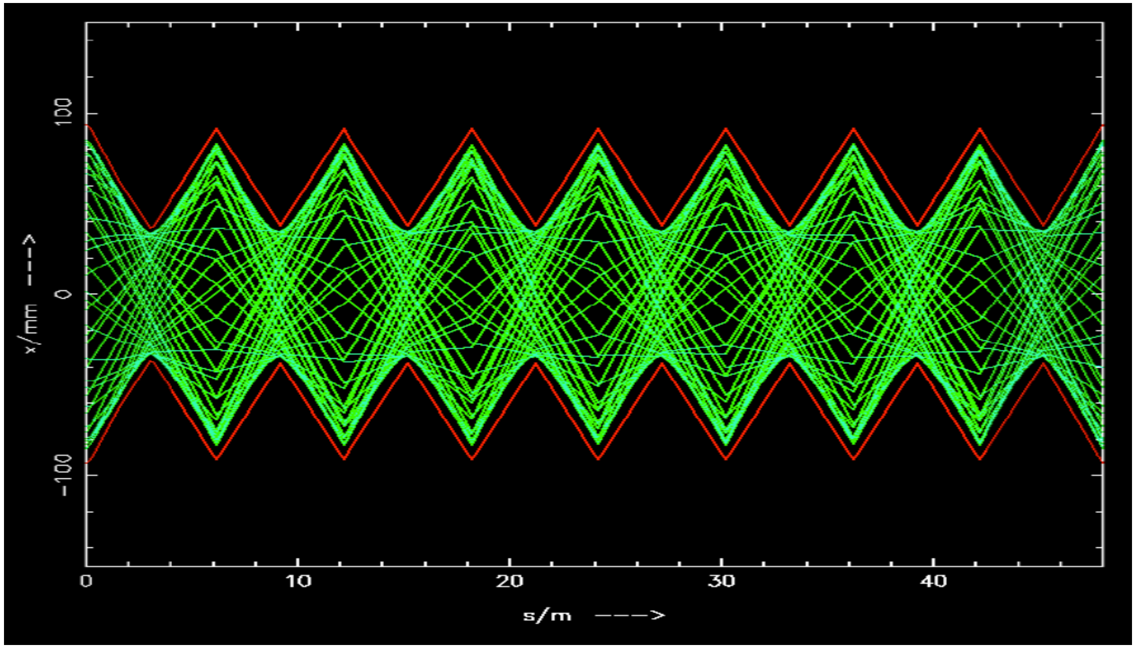
$$\varphi(s) = \int_0^s \frac{ds}{\beta(s)}$$

- φ(s) Is the phase advance over 1 turn around the machine

$$Q_{x/y} = \frac{1}{2\pi}\int_0^{2\pi} \frac{ds}{\beta_{x/y}(s)}$$

- Q_x and Q_y are the horizontal and vertical tunes: the number of oscillations per turn around the machine

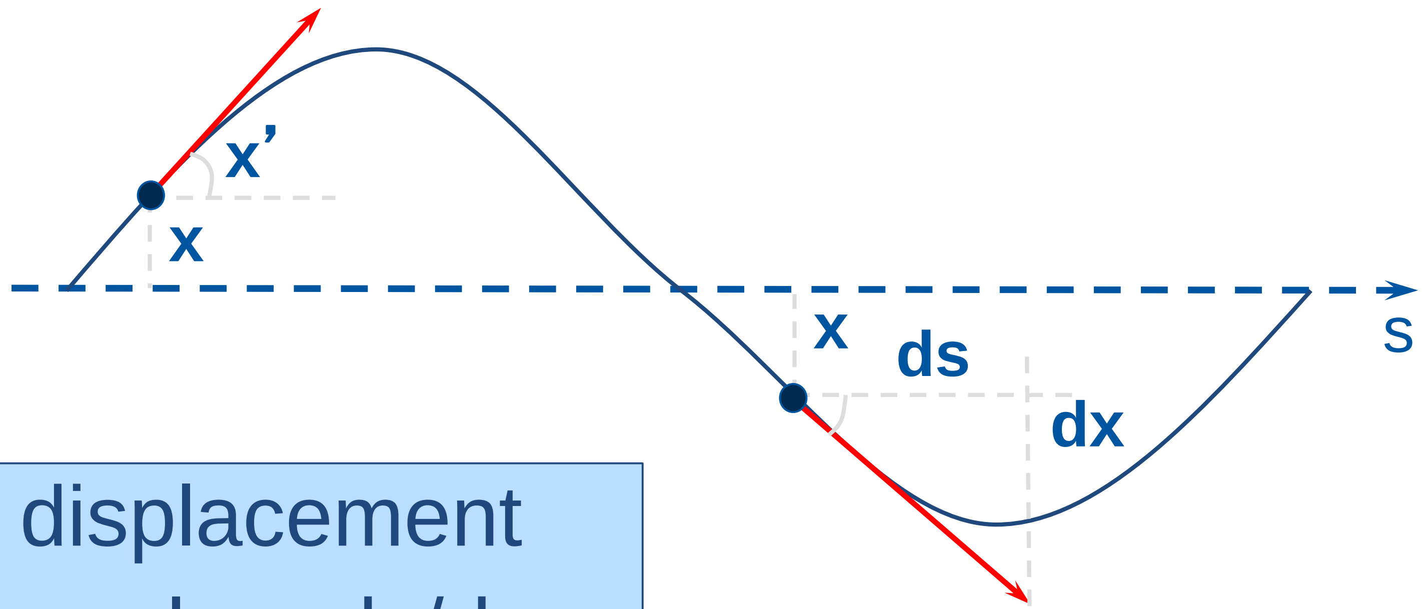
β function and individual particles



- The β function is the envelope function within which all particles oscillate
- The shape of the β function is determined by the lattice

Oscillations in Accelerators

Under the influence of the **magnetic fields** the **particle oscillate**

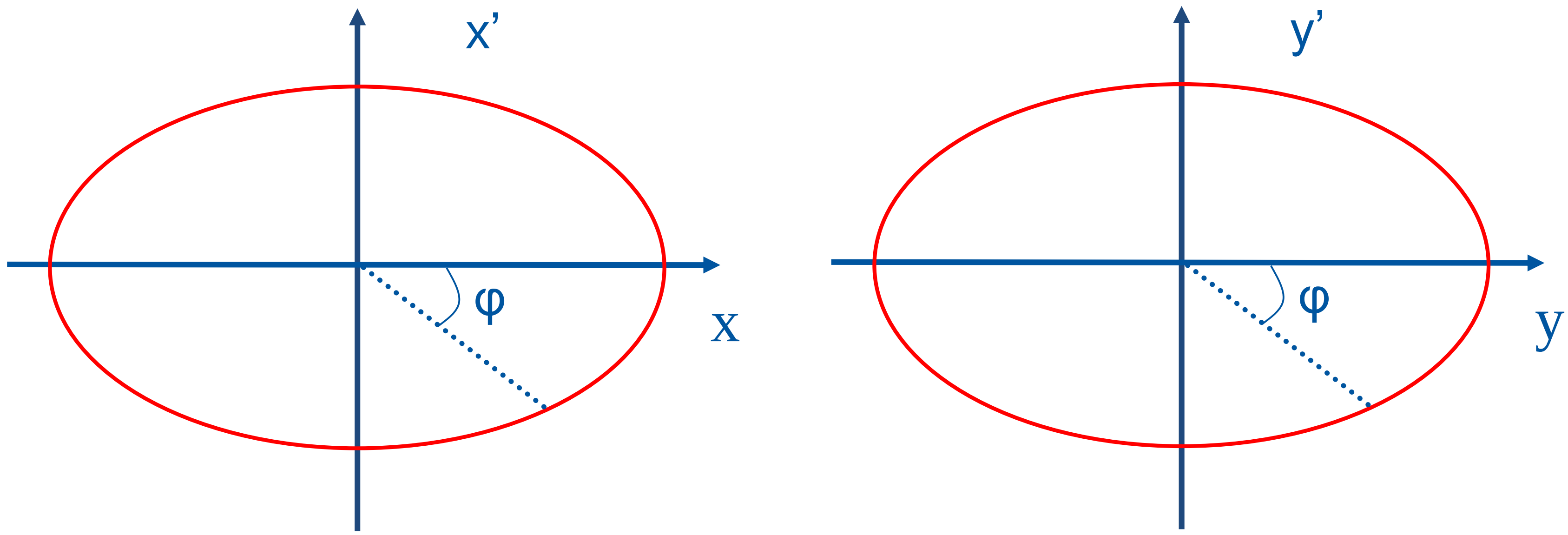


x = displacement

x' = angle = dx/ds

Transverse Phase Space Plot

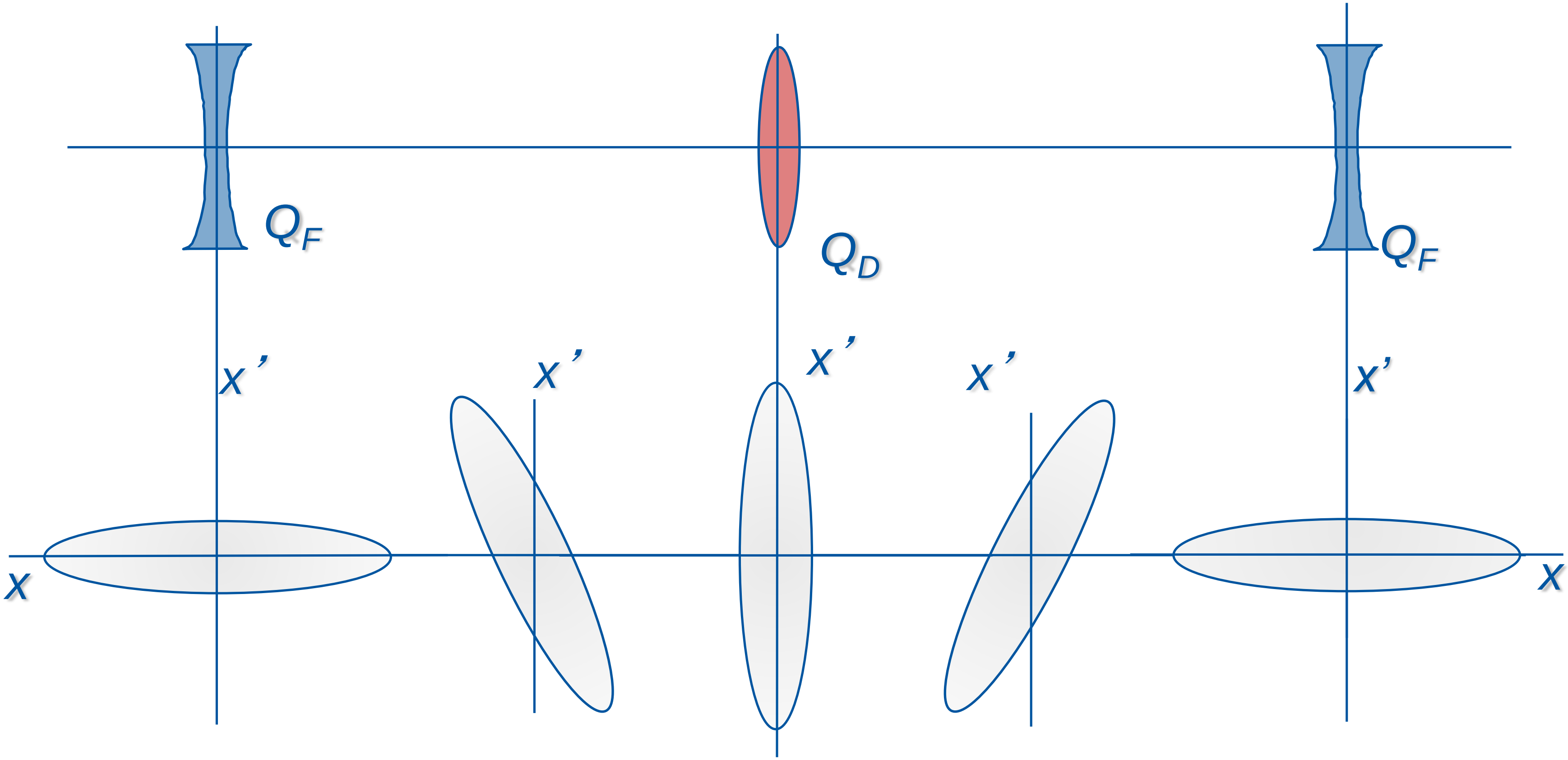
We distinguish motion in the Horizontal & Vertical Plane



Horizontal Phase Space

Vertical Phase Space

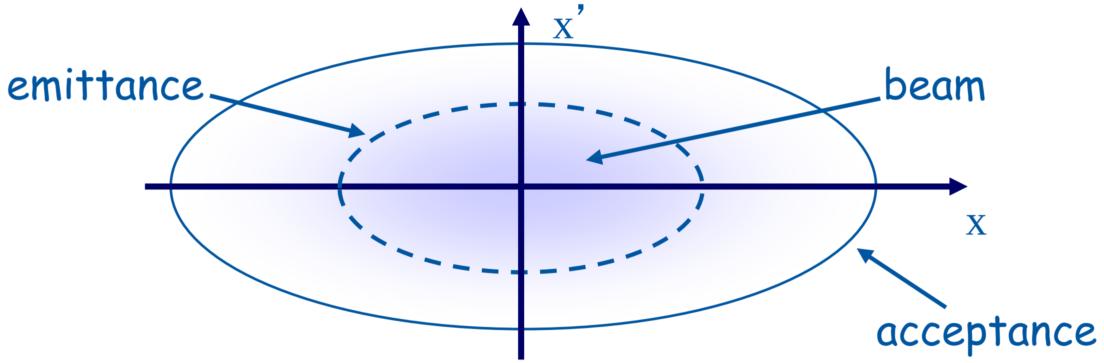
Phase Space Elipse Rotation



For each point along the machine the ellipse has a particular orientation, but the area remains the same

Transverse Emittance

- Observe all the particles at a single position on one turn and measure both their position and angle.
- This will give a large number of points in our phase space plot, each point representing a particle with its co-ordinates x, x'.



Symbol: ε
Expressed in 1σ, 2σ,..
Units: mm mrad

- The **emittance** is the **area** of the ellipse, which contains all, or a defined percentage, of the particles.
- The **acceptance** is the maximum **area** of the ellipse, which the emittance can reach without losing particles

Adiabatic Damping of Beam Size

- If we use the Gaussian definition emittance, then the rms beam size is given by:

$$\sigma_x = \sqrt{\beta_x \varepsilon}$$

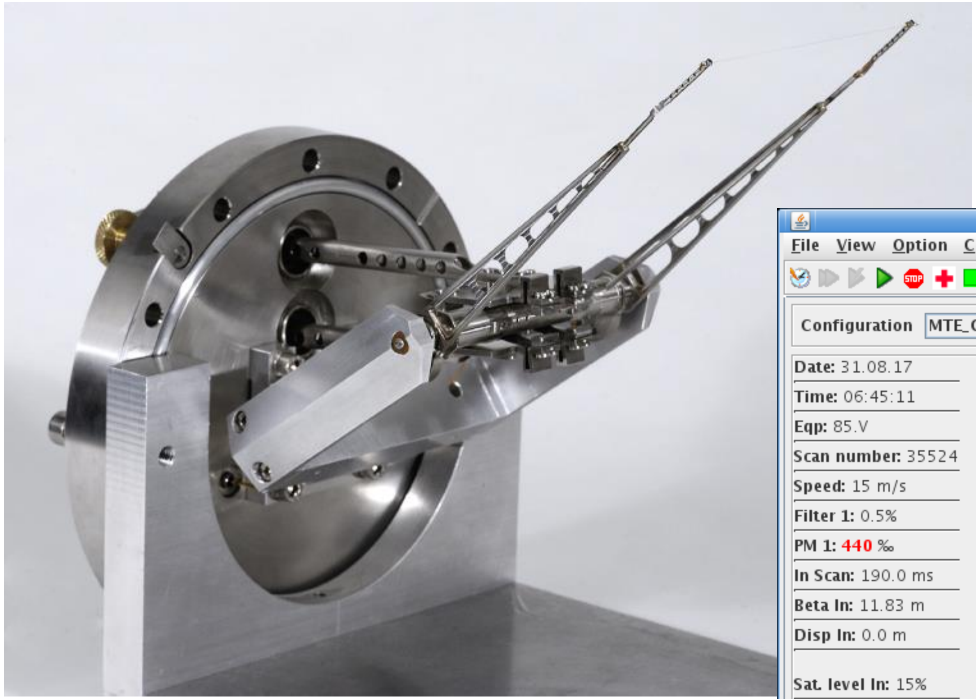
$$\sigma_y = \sqrt{\beta_y \varepsilon}$$

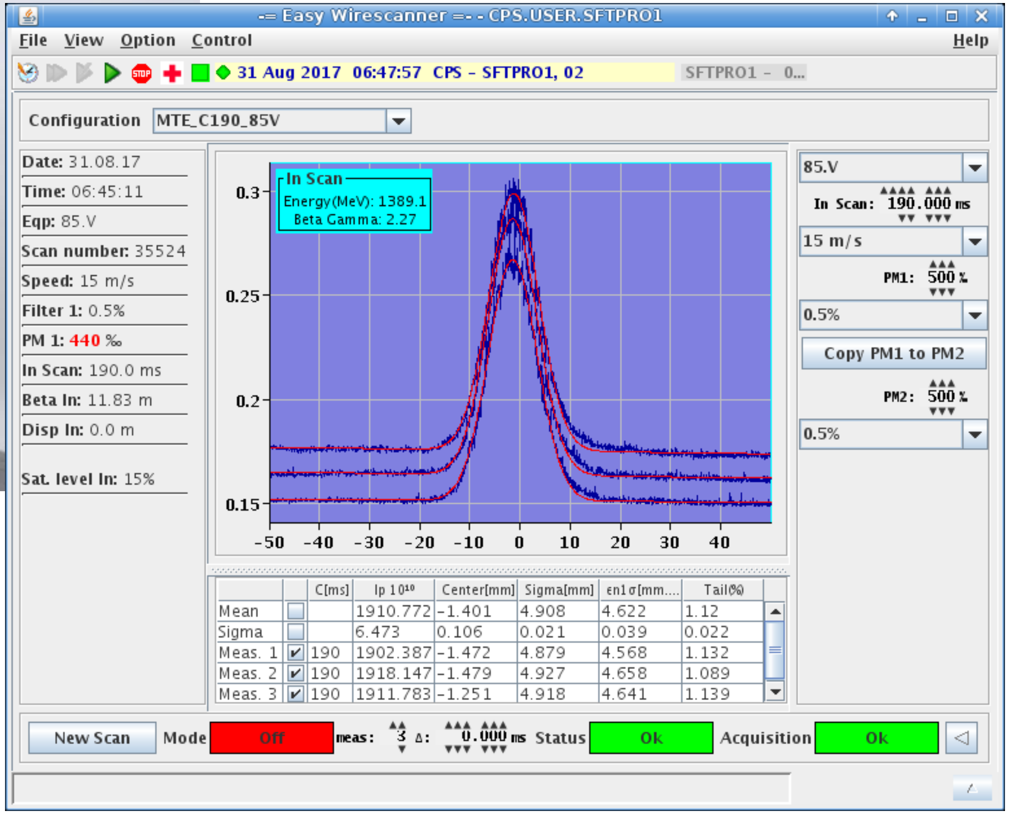
- The emittance is constant at constant energy, but accelerating particles will decrease the emittance, which is called adiabatic damping
- To be able to compare emittances at different energies it is normalised to become invariant, provided the is no blow up

$$\varepsilon_x^n = \beta\gamma\varepsilon_x$$

$$\varepsilon_y^n = \beta\gamma\varepsilon_y$$

Emittance measurement





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