CERN

Accelerators

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CERN BE-BI-BL

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Acknowledge

- These lectures are based on material from:
  - Mike Lamont
  - Rende Steerenberg
  - Verena Kain
  - Frank Tecker
  - Michaela Schaumann
  - Anton Lechner

References

- Previous editions of this school
- The CERN Accelerator School
  - Slides and Proceedings available on the web.
  - CERN-2016-002
  - CERN-2010-004
  - Beam Instrumentation CAS
- Summer Students Lectures
  - Slides and Recordings available on the web
- Future projects: HL-LHC, CLIC, ILC

Outline

- Day 1:
  - Basic accelerator concepts
  - CERN Complex
- Day 2:
  - LHC
  - HL-LHC (upgrade v2)
  - Future projects: FCC and CLIC

Outline

- Day 1:
  - **Basic accelerator concepts**
  - CERN Complex
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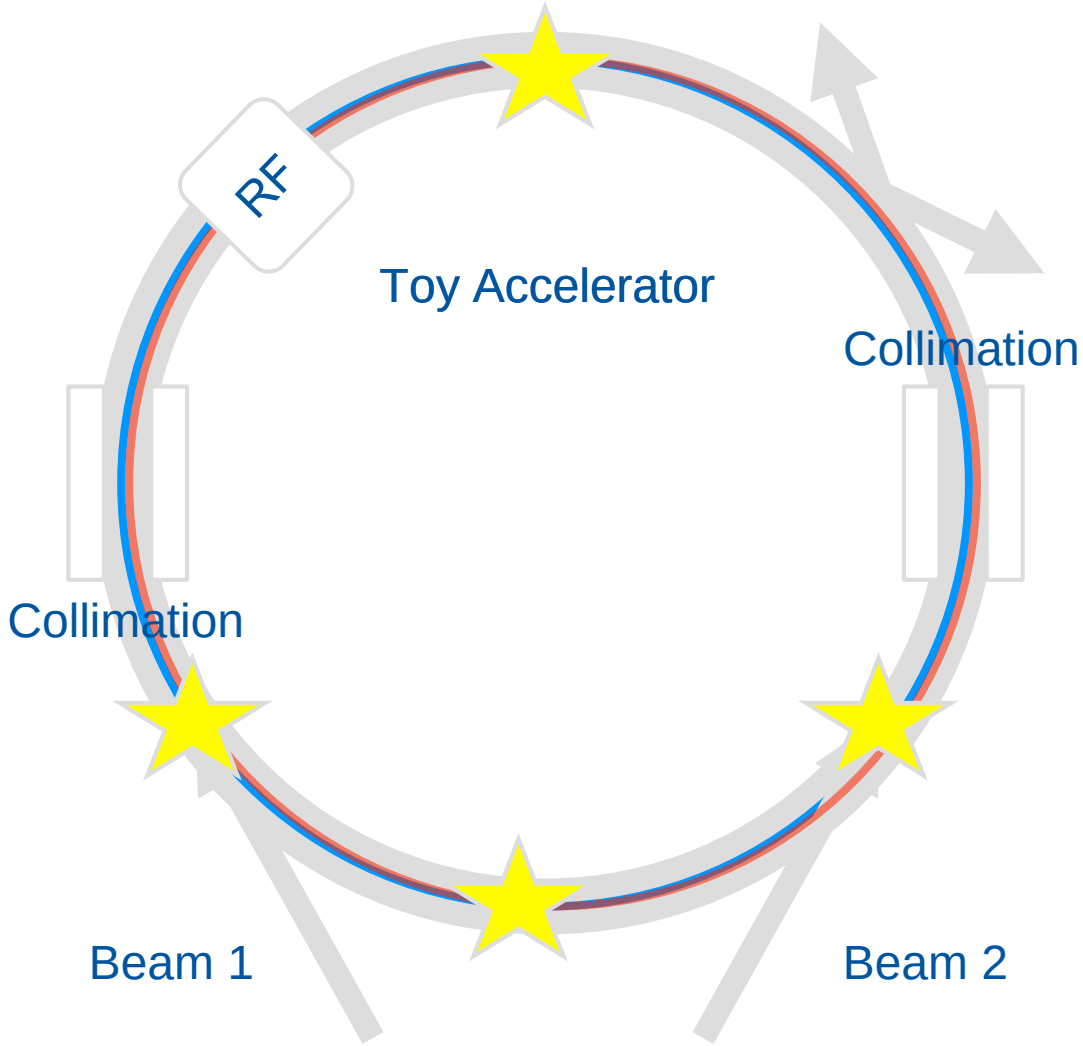
Basic accelerator concepts

Injection and filling of the machine

Beam circulation at high energies during hours

Acceleration



Keep circulation in constant orbit at even higher energies during hours or days

Collimation

Beam steering to initiate/stop collisions in one or many experiments

Extraction

Newton-Lorentz force

Newton-Lorentz force describes the interaction of charged particles with electro-magnetic fields:

Electric field

Particle instantaneous velocity

Magnetic field

Particle charge

$$\vec{F} = \frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = \underline{e(\vec{E}} + \underline{\vec{v} \times \vec{B})}$$

Longitudinal Motion

Parallel to the direction of motion. Used to accelerate charged particles.

Transverse Motion

Perpendicular to the direction of motion. Used to keep circulating orbit and beam steering.

Transverse Motion: trajectory

In order to **keep circular trajectory**, Lorentz force should compensate the Centrifugal force (**Constant magnetic field in the vertical direction → dipole**)

$$F_L = evB \qquad F_c = \frac{mv^2}{\rho}$$

Radius

$$\frac{mv^2}{\rho} = evB \rightarrow \frac{p}{e} = \rho B \rightarrow \boxed{0.3B[\mathrm{T}] \approx \frac{p[\mathrm{GeV}/c]}{\rho[\mathrm{m}]}}$$

$$p = mv$$

Magnetic Rigidity

Because particles need to follow a circulate trajectory the ***magnetic field should increase proportionally to the particles momentum****.*
For a fixed radius, ***the needed B dipole field is defined by the magnetic rigidity.***

Transverse Motion: focusing

Non-ideal particles or dipole field will deviate the particles from the design trajectory defocusing the beams.

Quadrupole magnets are used to restore the beam size (gradient).
Focusing field depends linearly on transverse position.

$$B_x = g \cdot y \qquad B_y = g \cdot x$$

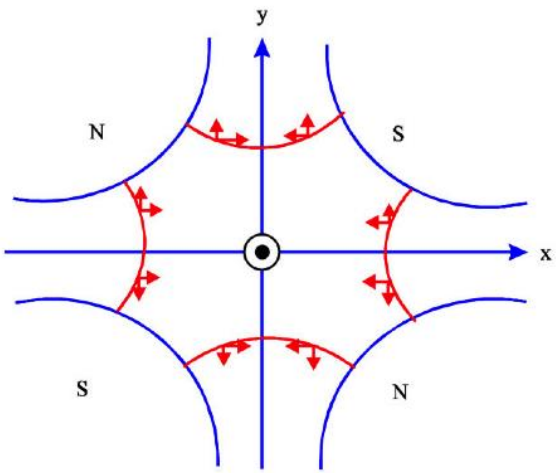


Image from CERN-2016-002

Circulation of particles at LHC:
- Revolution frequency = 11245 Hz
- Typical time in collisions = 12 h
- Perimeter of LHC = 27 km

Distance followed at LHC: 13×10^{12} m

Distance to the Moon: 3.8×10^{8} m

Distance to the Sun: 1.5×10^{11} m

A focusing quadrupole in the horizontal plane will be defocusing in theoretical plane and vs.

FODO cell: Focusing + O + Defocusing + O

Higher order fields are used for additional corrections: beam stability, tune, chromaticity, etc.

Pure Multipole Fields

Example of multiple fields

Dipole

Quadrupole

Sextupole

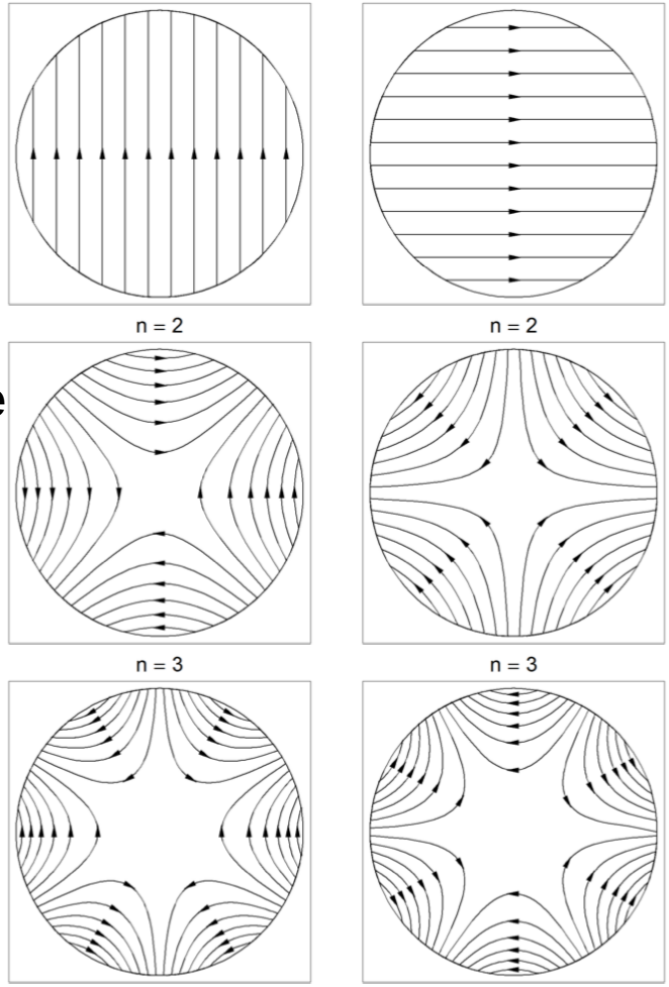
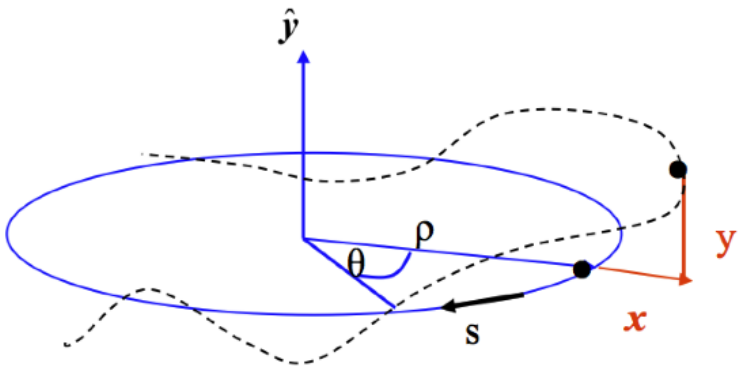


Image from CERN–2010–004

Transverse Motion: equation



Frenet-Serret coordinate system

Equation of motion including only the linear magnetic fields, i.e. dipole and quadruples

$$F_r = ma_r = eB_y v$$

$$B_y(x) = B_y + \frac{\partial B_y}{\partial x} x$$

Given that the quadrupolar strength is not constant along the accelerator but it is a periodic function (every turn)

$$x(x) = \sqrt{\epsilon}\sqrt{\beta(s)}\cos(\psi(s) + \phi)$$

Transverse plane we have a quasi-harmonic oscillation, **Betatron Oscillation**

Closer look to Equation of Motion

Initial conditions for the amplitude and phase.

Emittance

Initial Phase

$$x(x) = \sqrt{\epsilon}\sqrt{\beta(s)}\cos(\psi(s) + \phi)$$

Beta-function

Phase-advance

Periodic functions.

Amplitude of the oscillation => Beam Envelope

Defined by the BEAM

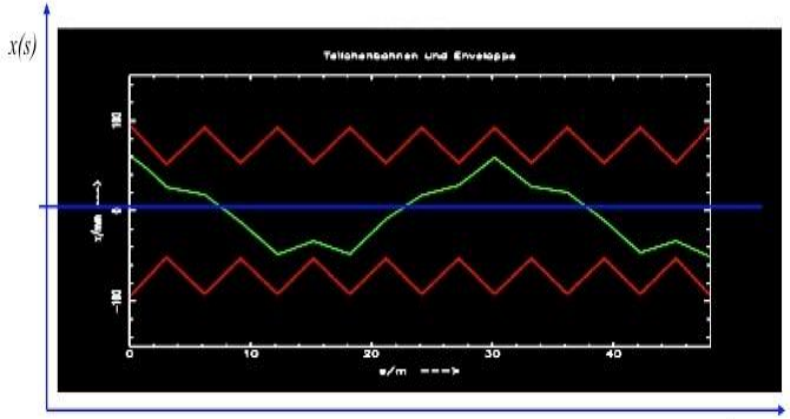
Defined by the LATTICE

Beta Function (1)

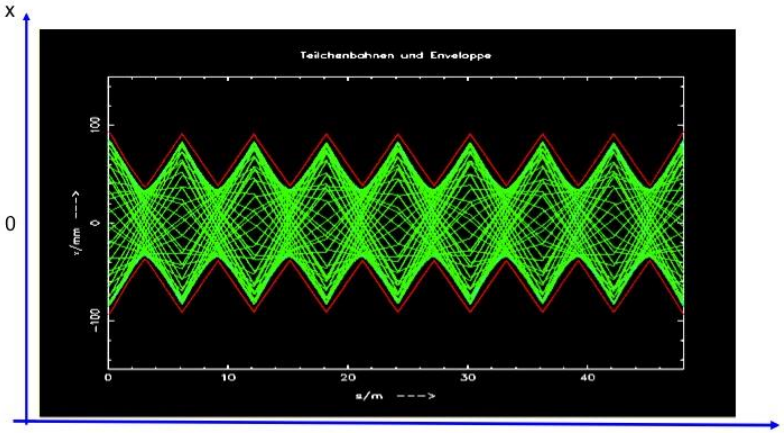
The Beta-function is a periodic function entirely defined by the lattice (the magnets).

This function is calculated by means of accelerator design software codes. An examples of this is the **Methodical Accelerator Design (MAD-X)** that describe particle accelerators, simulate beam dynamics and optimise the optics.
In case you want to play http://cern.ch/madx

Beta-function & Emittance describe the transverse beam size: beam envelope



Trajectory of a single particle



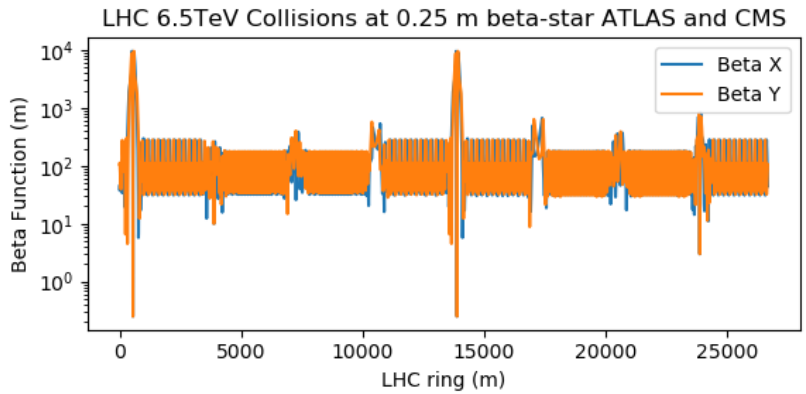
Trajectory of a many particles defining the beam envelope

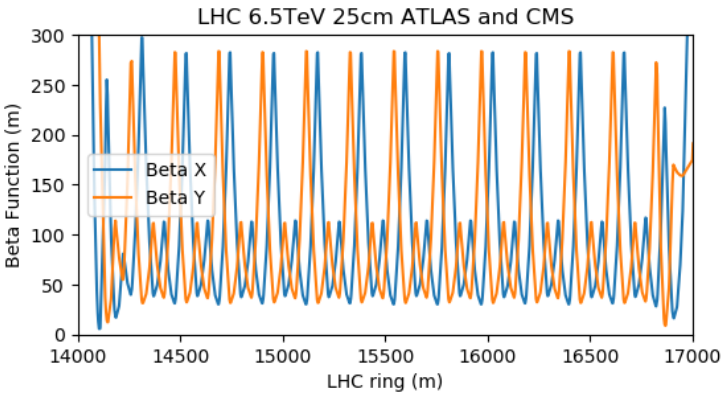
s

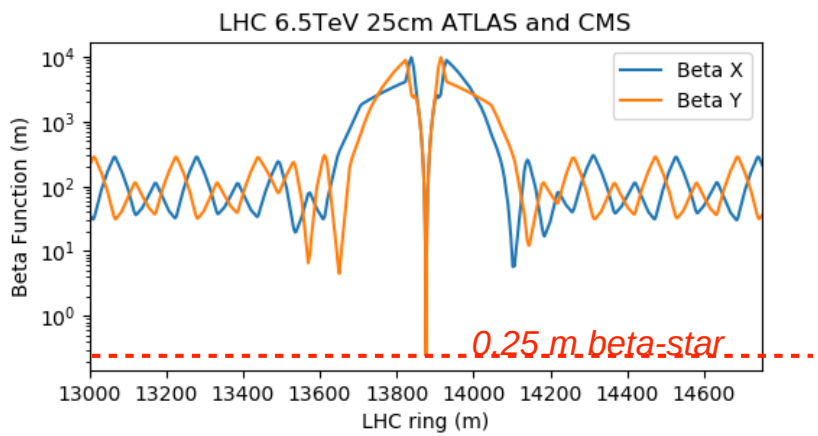
LHC beams contain about $3x10^{14}$ protons/beam

Beta Function at LHC

Examples of real optics used in the LHC at the very small beta-star of 0.25 m in ATLAS and CMS.







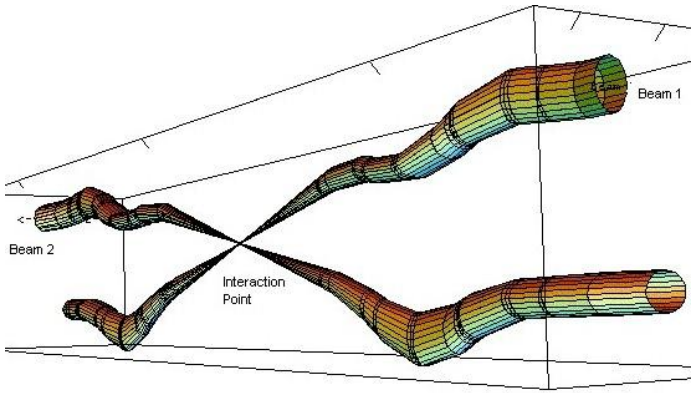


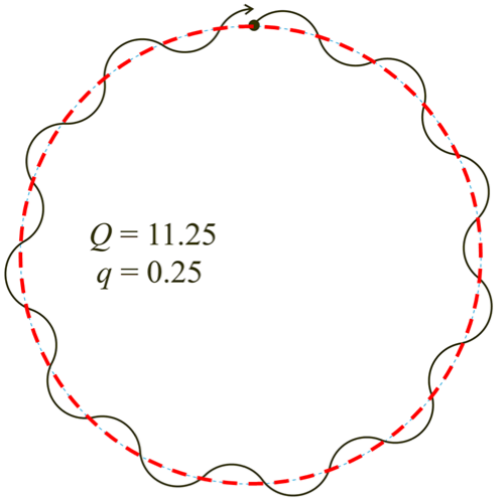
Image credit: J.Jowett

Beam Tune (1)

Number of complete oscillations per turn:

$$Q_x = \frac{1}{2\pi} \oint \frac{\mathrm{d}s}{\beta_x(s)}$$

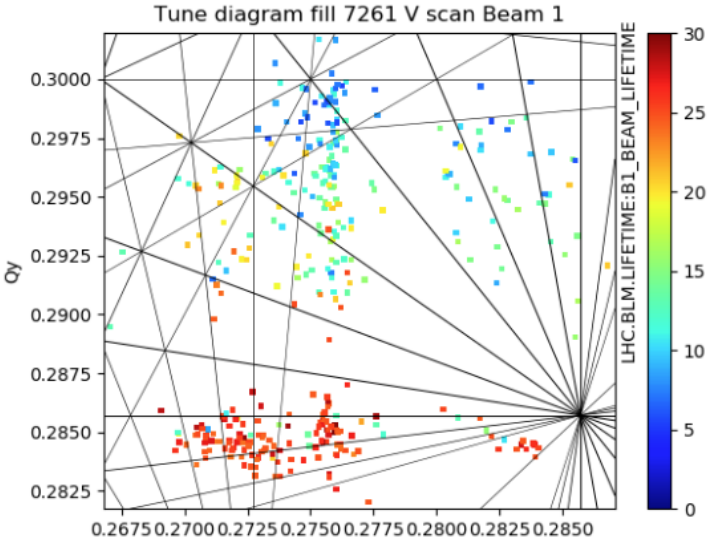
x: horizontal tune
y: vertical tune



Most important is the fractional part of the tune.

Avoid integer tunes because any imperfection will be just enhanced at every turn → beam lost

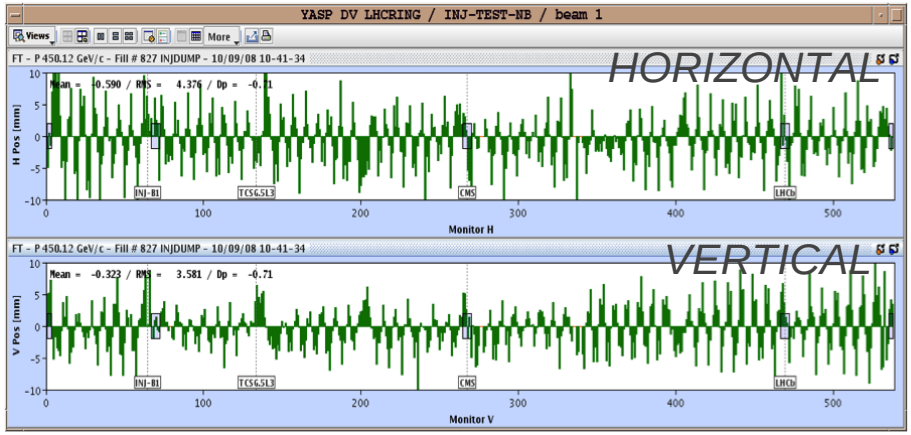
Beam tunes are monitored and controlled to the level of +/- 0.001



Courtesy of L.Coyle

Beam Tune (2)

LHC:
Qx = 64.31
Qy = 59.32



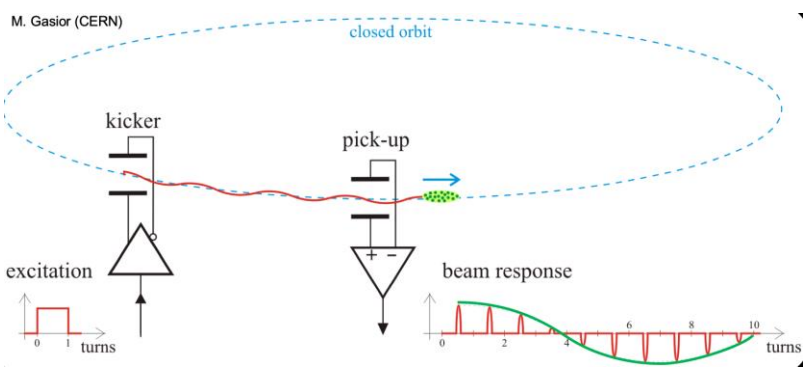
Integer tune:

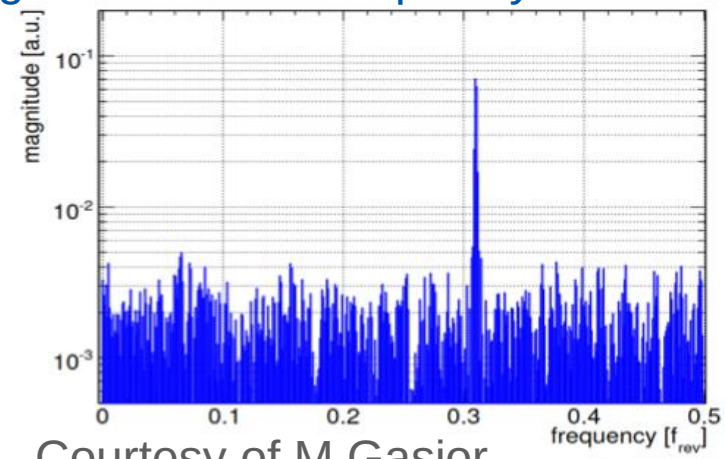
Seen in orbit response by ~550 dual plane Beam Position Monitors (BPM Electrodes)

Fractional Tune:

Turn-by-turn signal on single electrode after a small beam excitation (kick)

Fast Fourier transform (FFT) of oscillation data gives resonant frequency





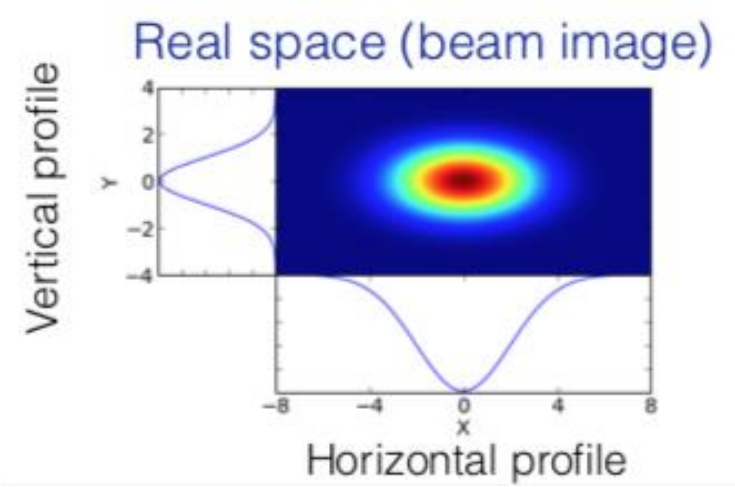
Courtesy of M.Gasior

Beam Emittance (1)

Beam Emittance is a property of the beam.

Together with the beta-function gives the complete definition of the beam size (standard deviation).

$$\sigma_x(s) = \sqrt{\epsilon \beta_x(s)}$$



Emittance cannot be changed by focusing/defocusing but it shrinks with beam energy.

Normalized Emittance is constant with energy

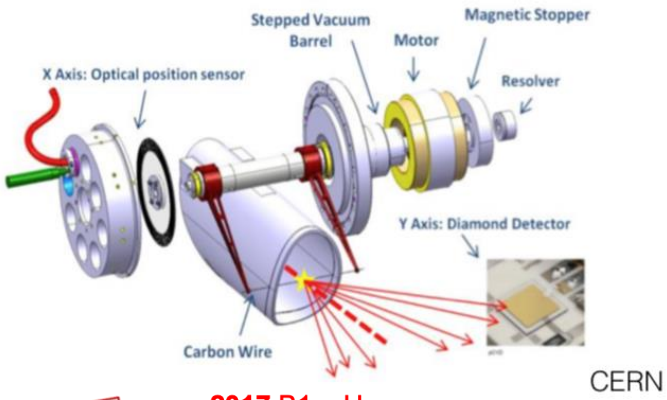
$$\epsilon_n = \beta_{\mathrm{rel}} \gamma_{\mathrm{rel}} \epsilon$$

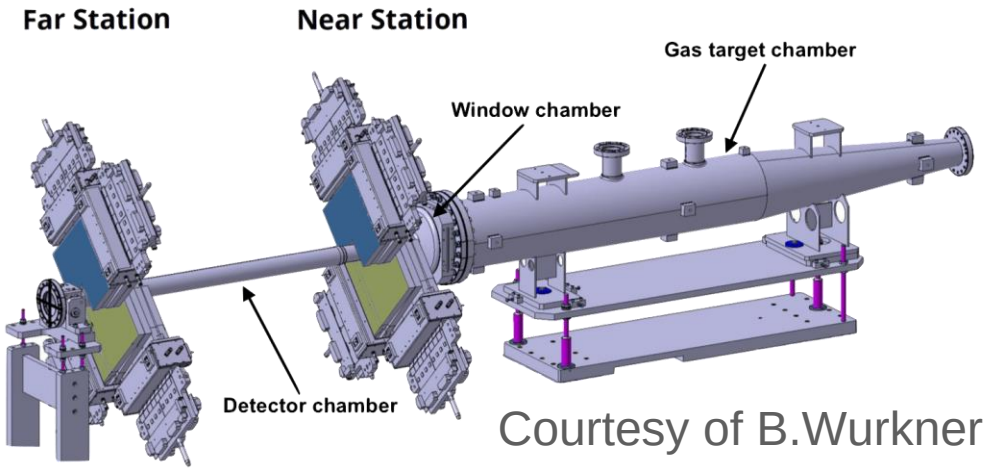
Beam Emittance (2)

Different mechanisms are used to measure the transverse beam size (and de-convolute it to global emittance).

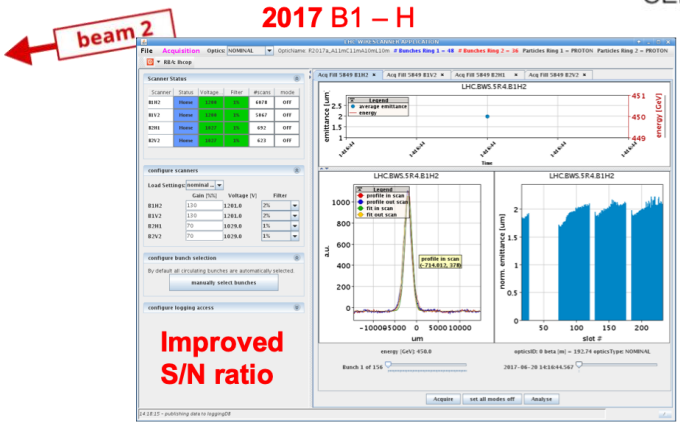
Some interact with the beam, they can only be used at low intensities or low energies, like fast rotations wire scanners.

Other measure the induced ionisation in the rest gas, like ionisation profile monitors or synchrotron radiation, like LHC BSRT.





Courtesy of B.Wurkner



Acceleration

- Why we would like to accelerate particles?
  - Reach of higher energetic collisions (ions, protons and leptons)
  - Compensate for energy loss due to emission of synchrotron radiation (leptons)

$$\vec{F} = \frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = \underline{e(\vec{E}} + \underline{\vec{v} \times \vec{B})}$$

Longitudinal Motion

Parallel to the direction of motion. Used to accelerate charged particles.

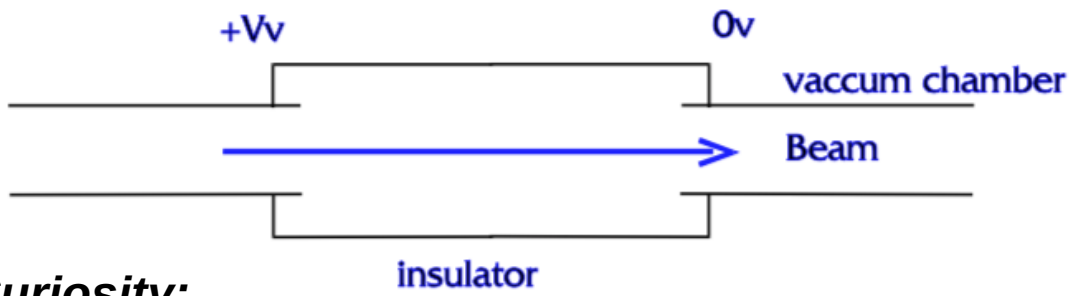
Transverse Motion

Perpendicular to the direction of motion. Used to keep circulating orbit and beam steering.

Acceleration has to be done by an electric field in the direction of the motion

Electrostatic acceleration

Simplest way to generate an electric field in the motion direction: voltage difference



Gain on kinetic energy is proportional to V (the potential)

Curiosity:

The energy unit (electron Volt): 1 eV is the energy that 1 elementary charge e gains when it is accelerated in a voltage of 1 Volt.

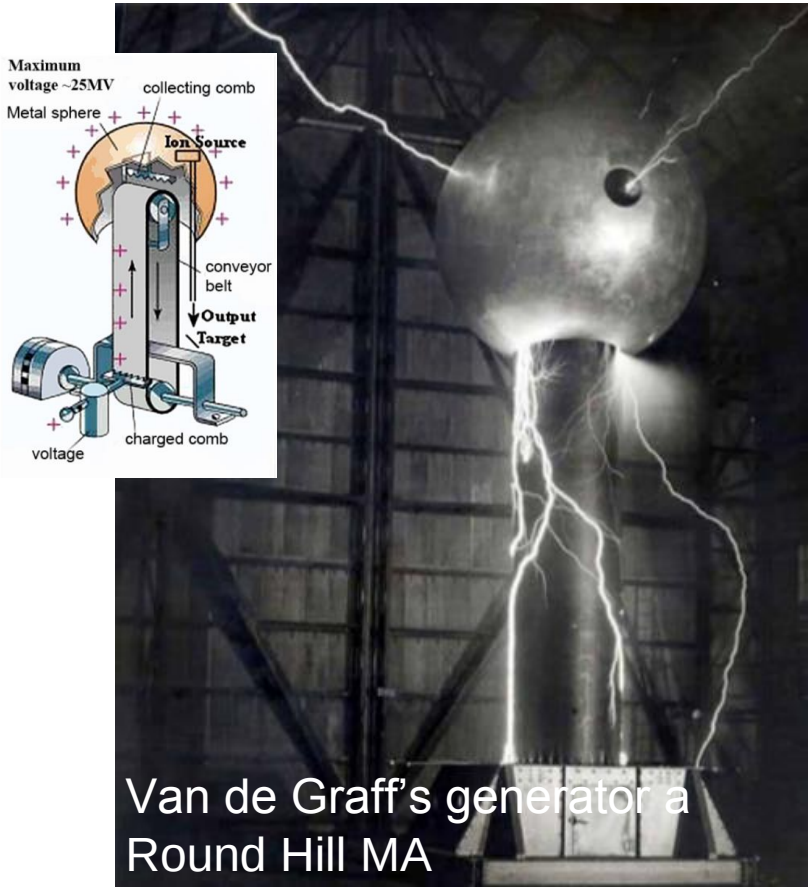
Cockcroft-Walton high voltage generator (600kV - 1964)

Electrostatic machines are still used at lower energy, as a 1st stage of acceleration, radiotherapy, particle source, etc.

Limitations:

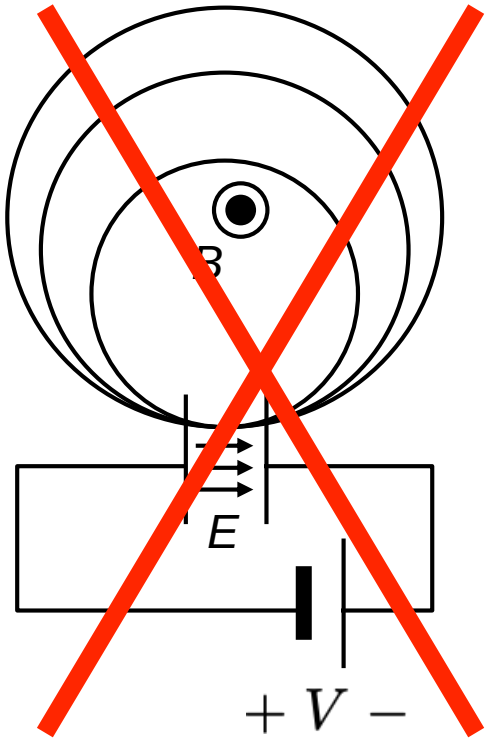
Max. Voltage ~ 10MV due to insulation problems.

Limitation of Electrostatic Acceleration



Van de Graff's generator a Round Hill MA

But we still want to accelerate towards higher and higher energy…



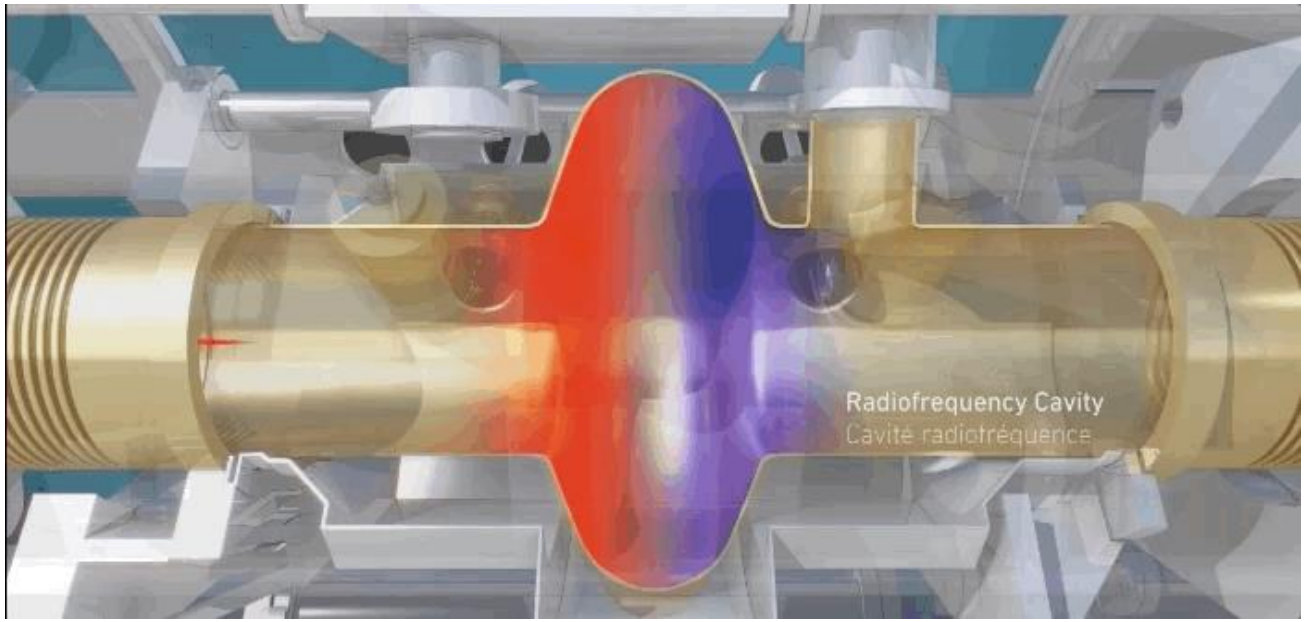
Acceleration forbidden by Maxwell laws.

$$\nabla \times \mathbf{E} = -\frac{d\mathbf{B}}{dt}$$

$$\oint_C \mathbf{E} \cdot d\mathbf{s} = -\frac{\partial}{\partial t} \int_S \mathbf{B} \cdot \mathbf{n}\, da$$

There is no acceleration without time-varying magnetic flux

Radio-frequency acceleration

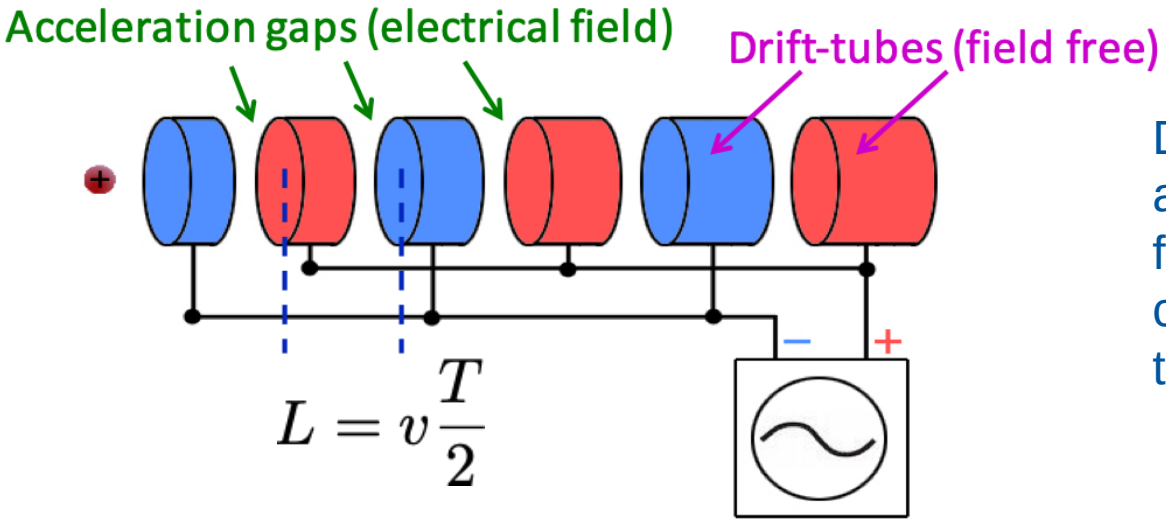


Apply an E-field which is reversed while the particle travels inside the tube → it gets accelerated at each passage.

Build the acceleration with one or more series of drift tubes with gaps in between them.

Could accelerate in linear and circular machines

LINAC: linear accelerator



$$L = v\frac{T}{2}$$

Distance (L) between the acceleration gaps needs to fulfil the synchronism condition with T the period of the RF oscillator.

Bunched Beam

$$\uparrow v \quad \Longrightarrow \quad \uparrow L$$

Energy gain:

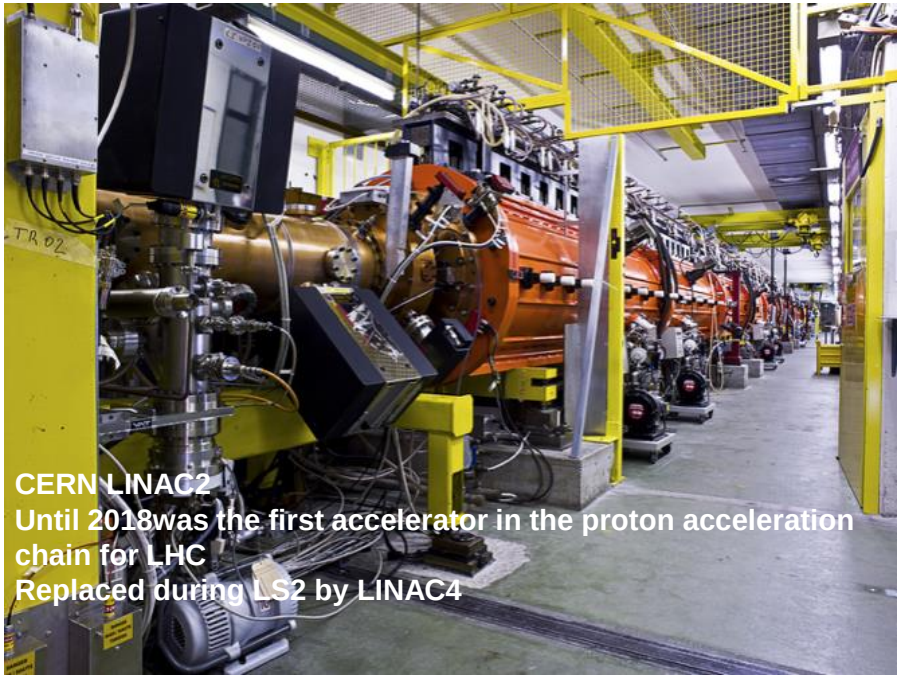
$$E = neV_{\mathrm{RF}} \sin \phi_{\mathrm{s}}$$

n : number of gaps
e : charge
V_{RF} : applied voltage
ϕ_{s} : synchronous phase

From LINAC to Circular Machines

LINACs are today the first stage in many accelerator complexes

Limited by the particle energy reach due to length and single pass



Circular Accelerators

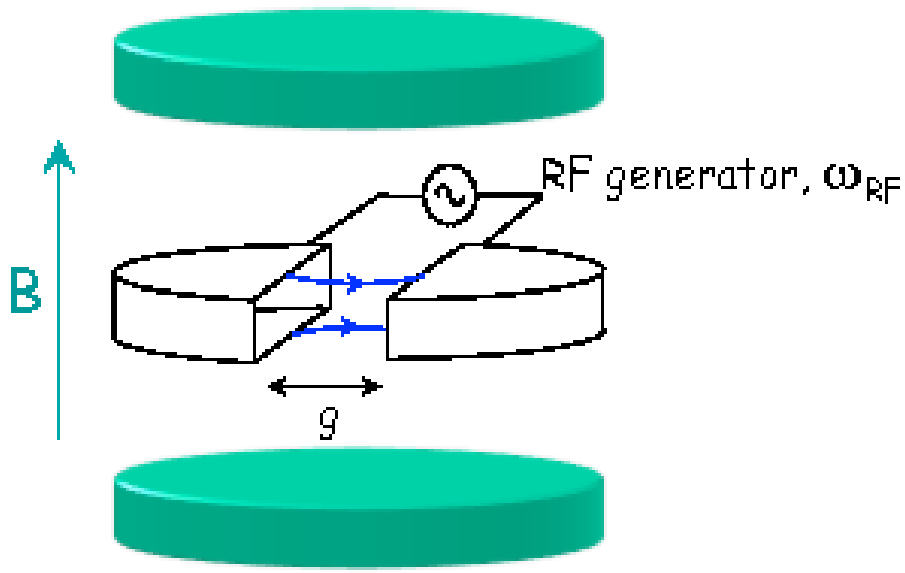
Use of circular structures in order to apply over and over the accelerating fields.
Particles are bend onto circular trajectories → **Many passages through RF structure**

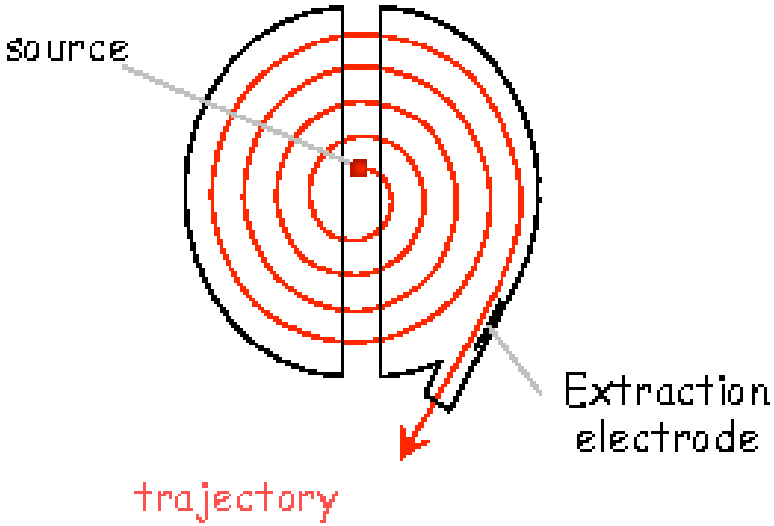
Circular machines: Cyclotron

Electrodes with a D shape in a constant B field (for the bending)

Particle source at the centre

Acceleration by E in between electrodes (varying E-field).
Every passage the polarity is changed.





B-field creates a spiral trajectory. Larger speed corresponds to larger radius.

Circular machines: Cyclotron

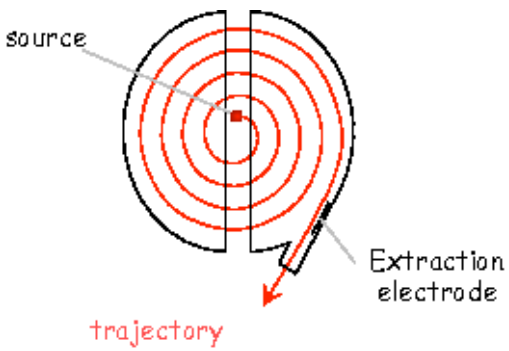
Condition of synchronism, can be calculated with the period and the Lorentz and Centrifugal force.

$$T_{\mathrm{RF}} = \frac{2\pi\rho}{v} \qquad \frac{mv^2}{\rho} = evB$$

Radius

Period

Speed



$$w_{\mathrm{RF}} = \frac{2\pi}{T_{\mathrm{RF}}} = \frac{qB}{m_0\gamma}$$

Revolution frequency (cyclotron frequency)
Does NOT depend on the radius as long as particles are non-relativistic

For High Energies the RF frequency has to change with $\boldsymbol{\gamma}$

$$w_{\mathrm{RF}}(t) = \frac{qB}{m_0\gamma(t)}$$

Concept of Synchrocyclotron

Limitations:
Size of the magnet ~ 500 MeV

Circular machines: Synchrotron

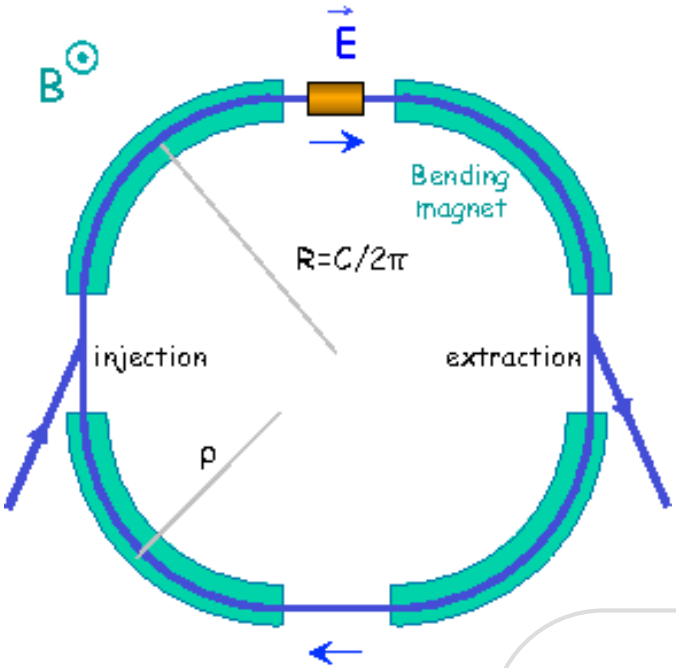
Circular accelerator

Particle trajectory with constant radius.
Invented in 1943

Both magnetic field (B) and RF should vary together

Condition of synchronism:

The particle needs to arrive after 1 turn with the same phase



$$w_{\mathrm{RF}} = h w_{\mathrm{rev}} \quad h : \text{harmonic number}$$

h is the number of stable synchronous particle locations (segments of LHC circumference): **BUCKETS**

Example LHC

Which is a synchrotron machine

$$f_{\mathrm{RF}} = 400 \text{ MHz}$$

$$f_{\mathrm{rev}} = c/27 \text{ km}$$

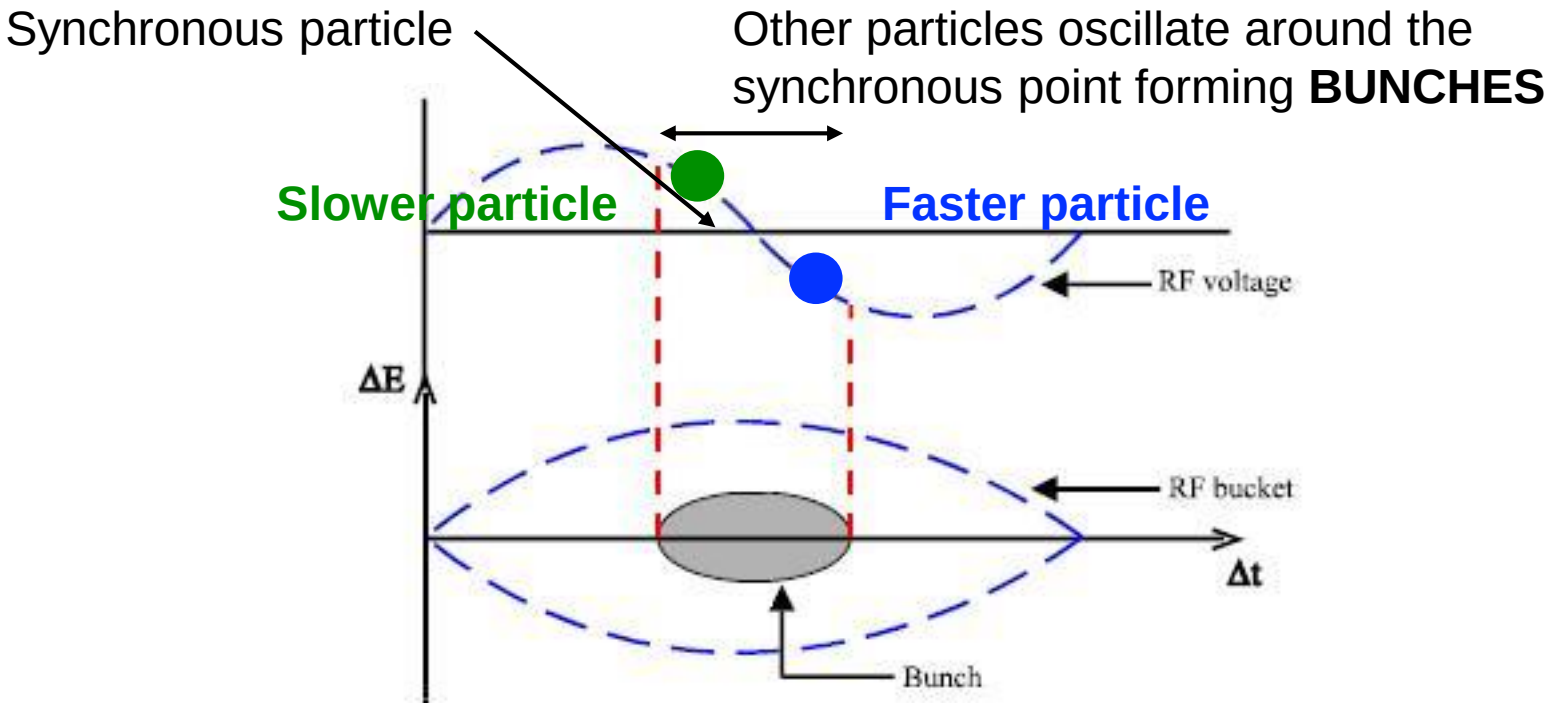
$$h \approx 35640$$

Synchrotrons

1959 construction of the first “larger” synchrotron machines

- CERN-PS (Proton Synchrotron): 60 year still in operation, still in use for the injection to the LHC.
- BNL-AGS (Alternating Gradient Synchrotron)

Longitudinal Motion and phase stability



Particles outside the **capture area** drift outside the bucket and are: no longer accelerated:

loosing energy at each turn —> reducing the revolution radius —> eventually being lost at collimators (or other locations)

Outline

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  - Basic accelerator concepts
  - **CERN Complex**
- Day 2:
  - LHC
  - HL-LHC (upgrade v2)
  - Future projects: FCC and CLIC

CERN injection Complex

LHC last ring in the chain

LINAC 2

BOOSTER

ISOLDE: isotope research

PS

East Area for fixed target physics

n-ToF: Neutron time-of-fly facility.

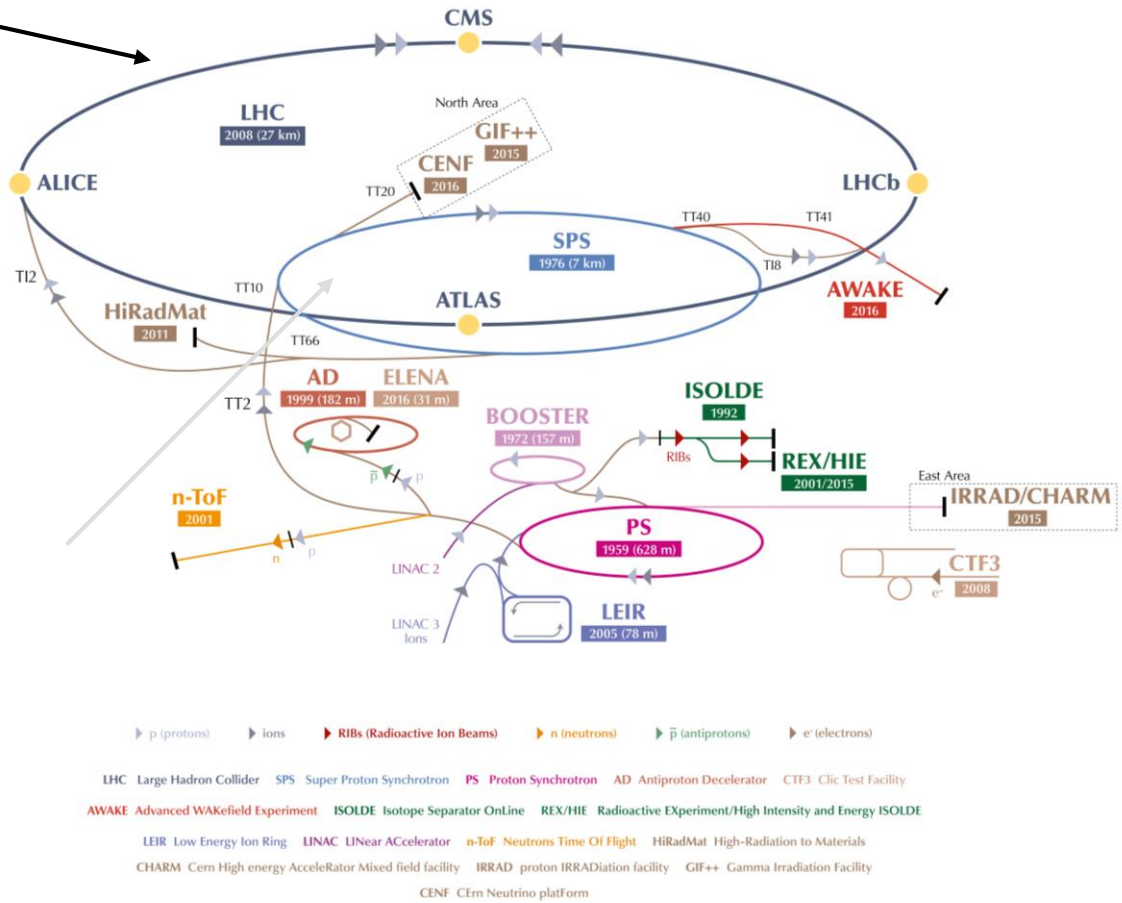
AD (anti-proton decelerator)

SPS

North Area

Awake

HiRadmat



LINAC 2

LINAC 2 is equipped with a **Duoplasmatron source.** A metal cylinder with H gas forming a discharge plasma surrounded with E-field to break down the gas into protons and electrons (90kV HV).

Mock-up of Duoplasmatron source

Acceleration with 3-tank drift tube at 202.56MHz **from 90keV to 50 MeV over a length of 33 m.**

Pulsed machine providing beam **pulse every 1.2s** with beam current **from 140mA - 180mA.**

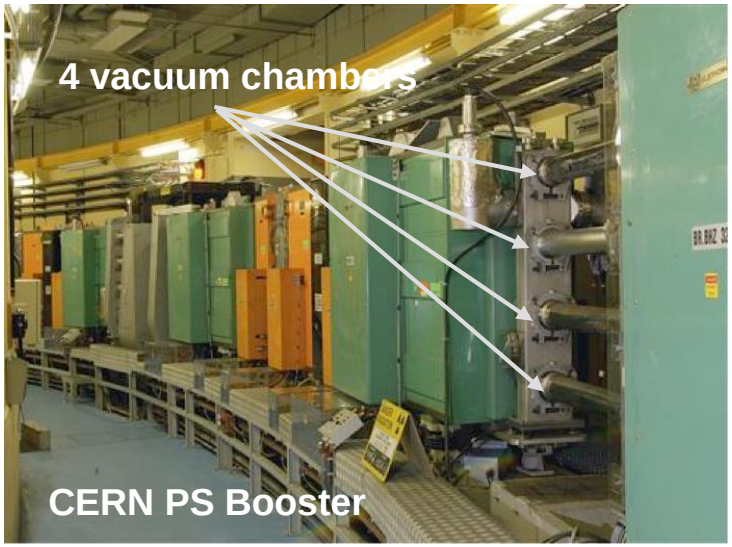

Linac 2 acceleration cavities

PS Booster

1st Synchrotron in the chain with 4 superposed rings

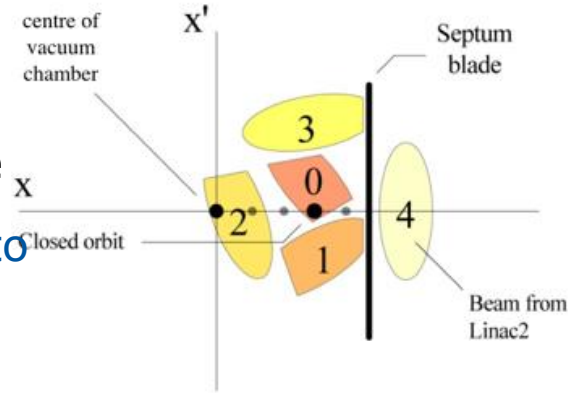
Circumference of 157m

Increases proton energy from **50MeV to 1.4GeV in 1.2s**



LINAC 2 pulse is distributed vertically in the 4 rings. Bunches are built as multi-turn PSB injection.Keeping charge density constant every injection in a different phase-space defining the **transverse emittance.**

- ✳**ISOLDE**: High-Intensity 10-13 turns are injected = large transverse emittance
- ✳**LHC**: 2-3 injected turns = small transverse emittance



After acceleration they will be combined and transferred to the PS.

PS: Protons Synchrotron

The oldest operating synchrotron at CERN (since 1959)

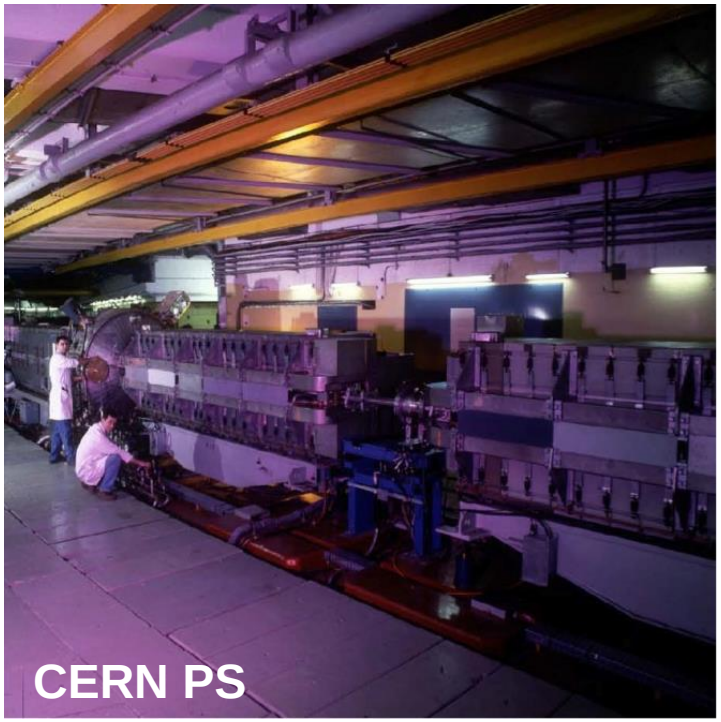
Circumference of 628 m

- 4 x PSB ring

Accelerates from 1.4GeV to a range of energies up to 26 GeV depending on the user

- East area: 24GeV
- SPS: 14GeV or 26GeV
- AD: 26 GeV
- n-TOF: 20 GeV

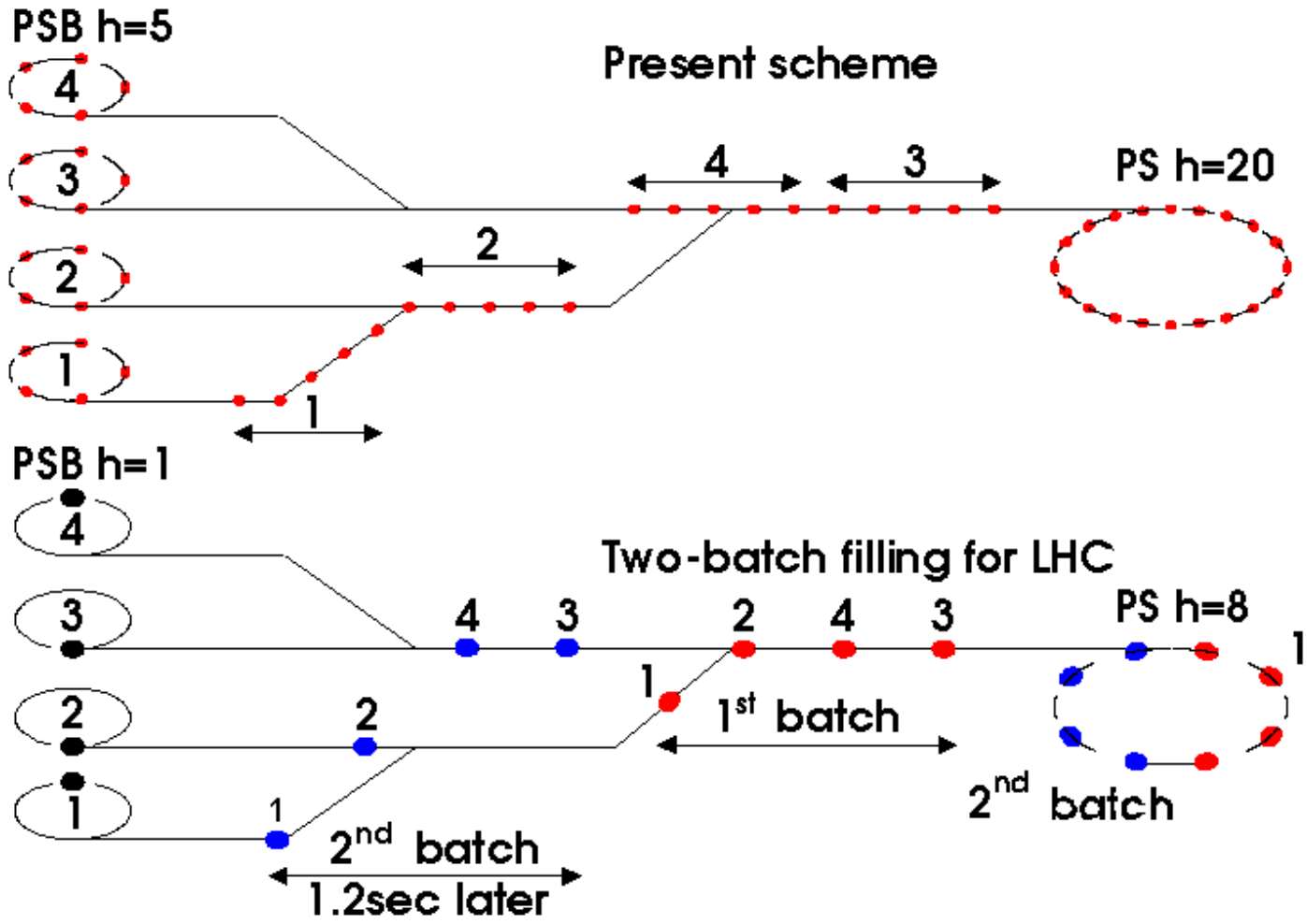
Cycle length goes from 1.2s to 3.6s



Various types of extractions: fast, slow and multi-turn (MTE)

Many different RF cavities: 10 MHz, 13/20 MHz, 40 MHz, 80 MHz,200 MHz

Injection PSB to PS



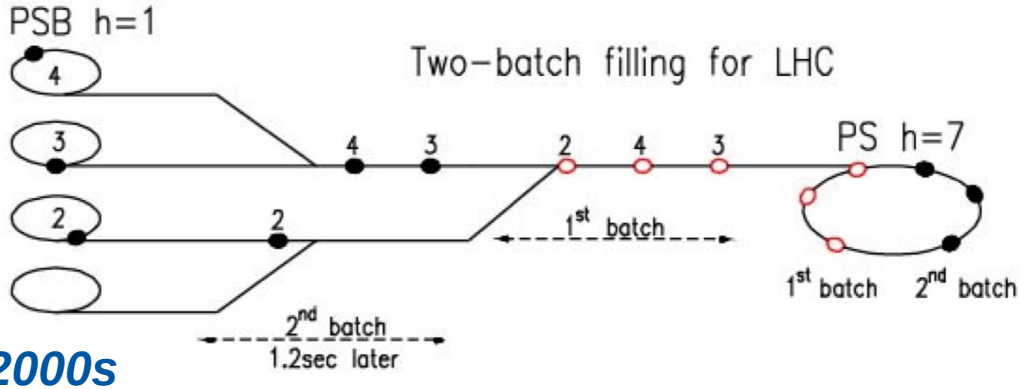
PS batch of 20 bunches

PS batch of 8 bunches

LHC filling and Bunch Splitting in PS

Filling of the LHC is based on PS batches of 72 bunches

How do we go from PSB h = 1 and PS h = 7 to PS batches of 72 bunches ?



Bunch splitting developed in the 2000s

Bunches arrive to the PS and are captured by the RF. Thanks to the multiple RF cavities the bunches are split by applying simultaneously two or more RF waveforms and an adiabatic change of the voltage.

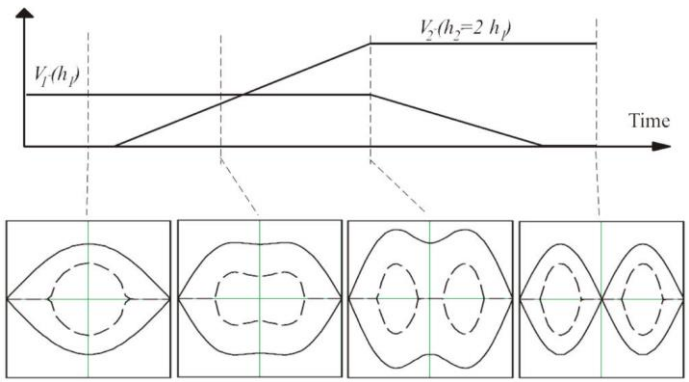
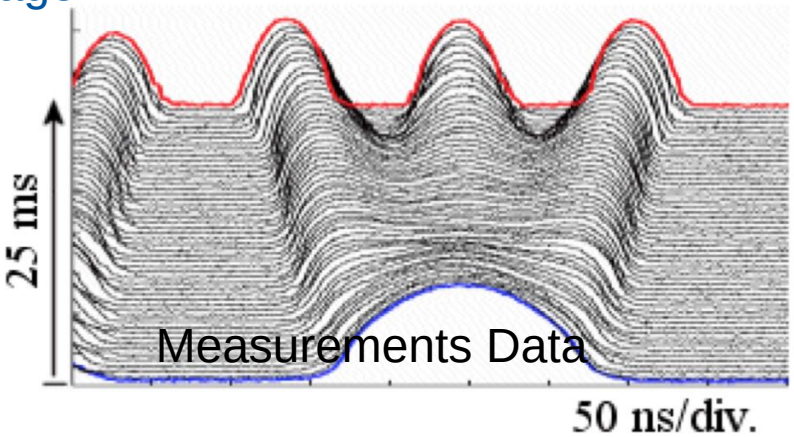


Image credit R.Bailey



LHC filling and Bunch Splitting in PS

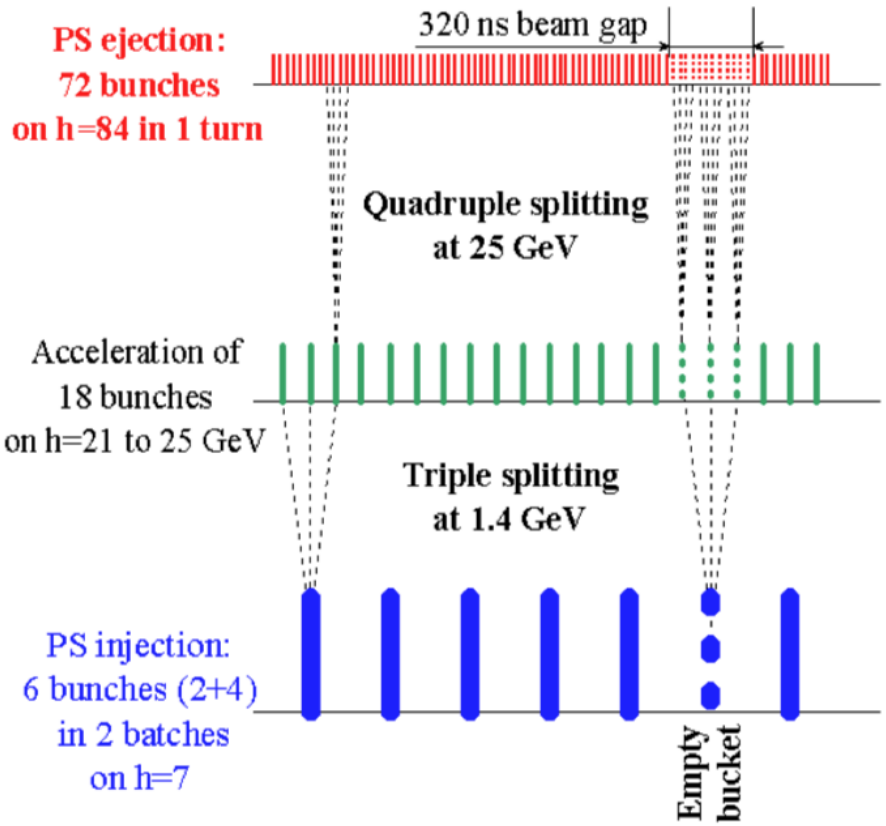
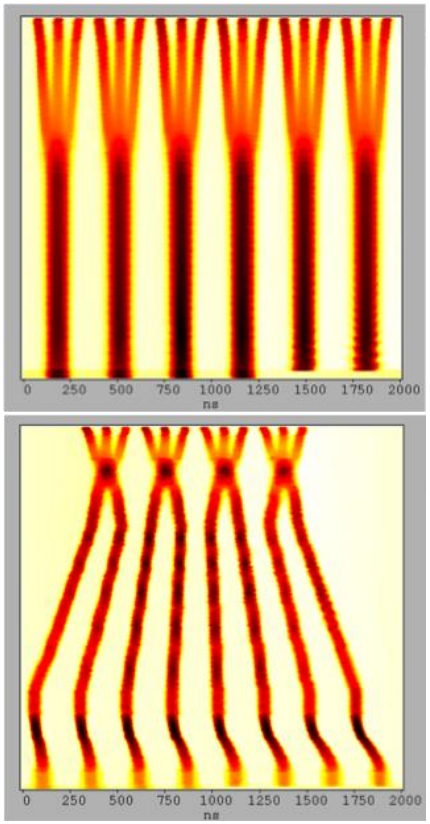


Image credit R.Garoby



Standard: 72 bunches @ 25 ns

BCMS: 48 bunches @ 25 ns

Smaller Emittance

SPS

The first synchrotron in the LHC chain **at 30m underground.**

Circumference of 6.9km

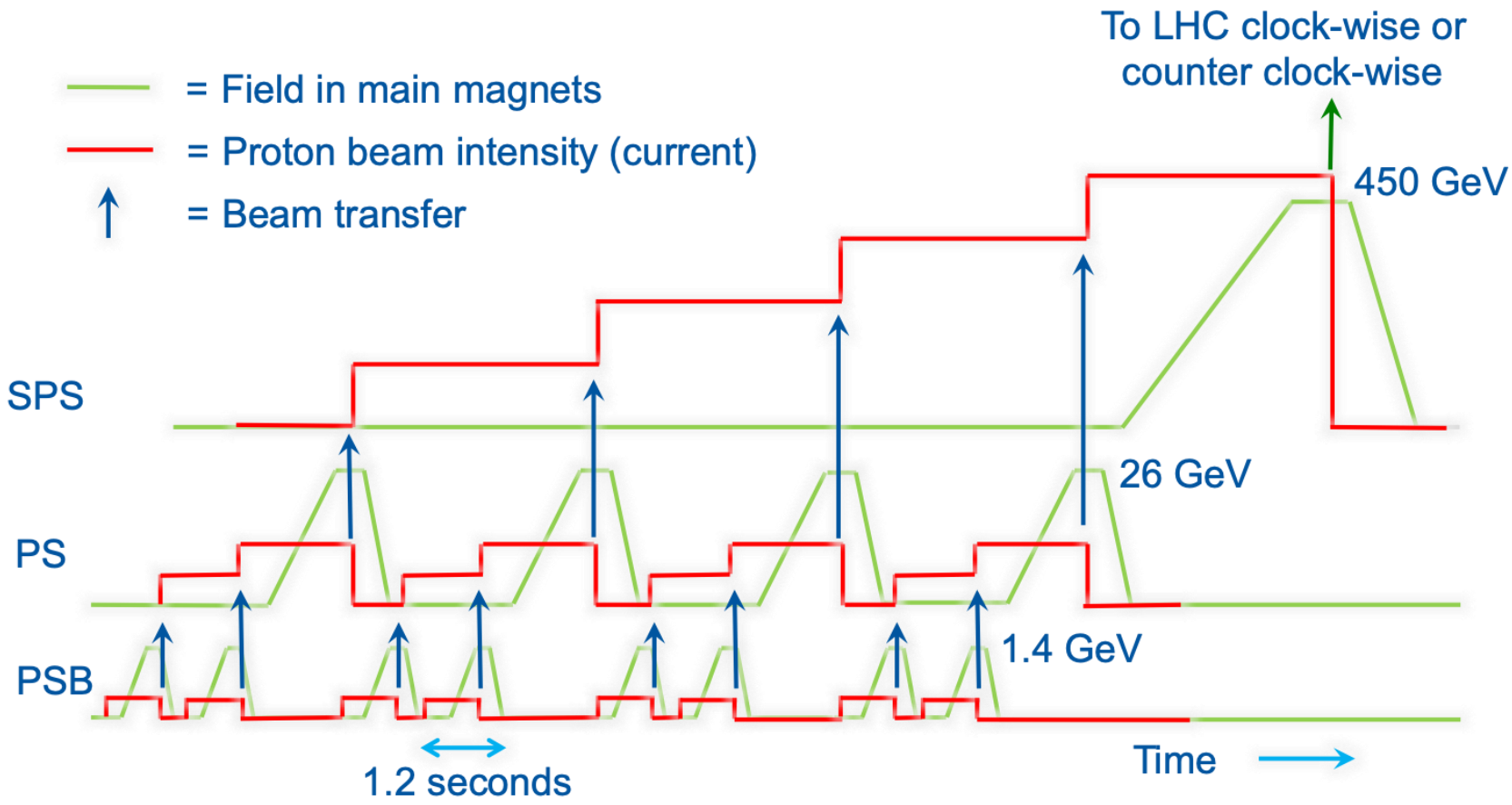
- 11 x PS ring

Accelerates from 26GeV to up 450GeV

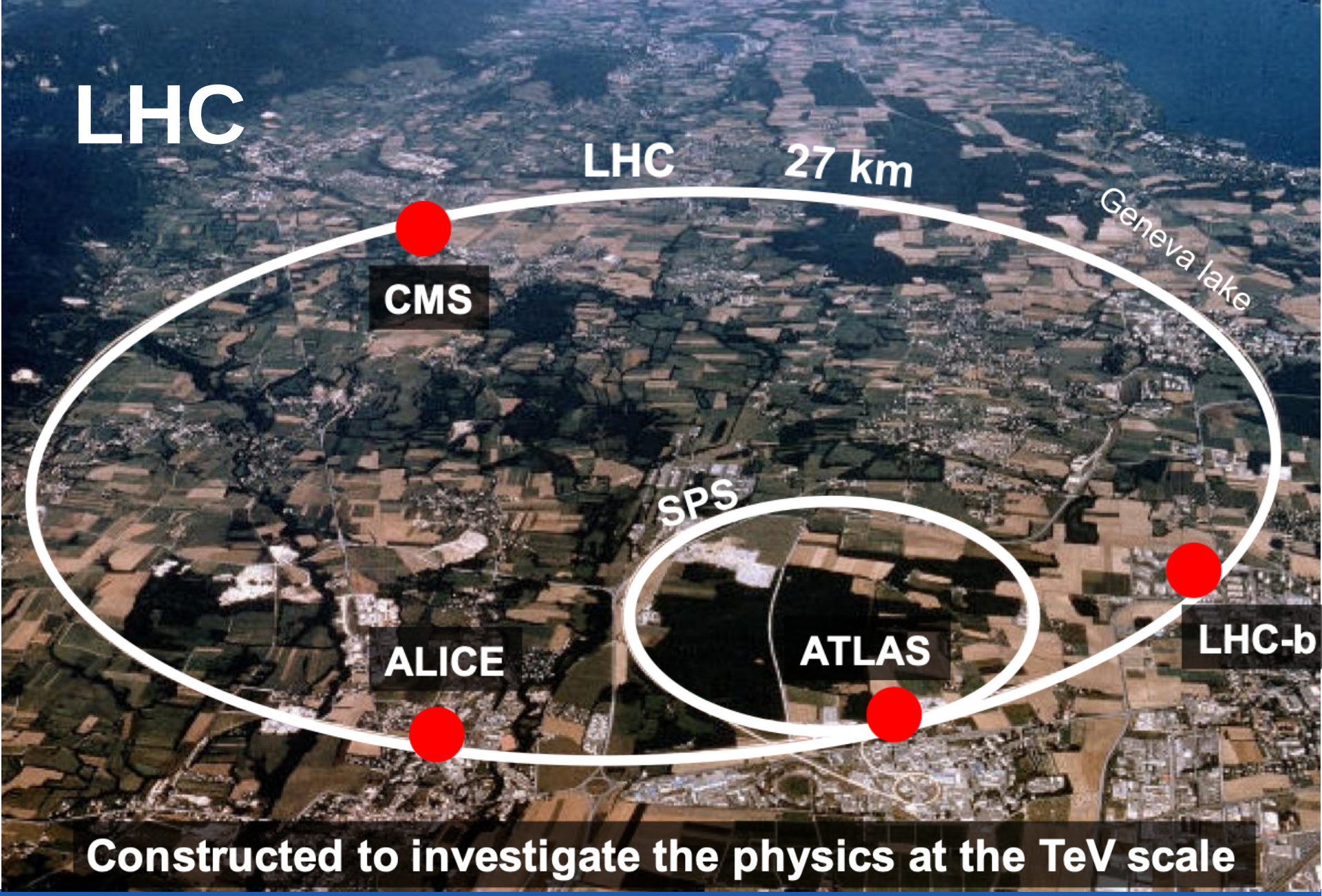
Store intensity up to 5e13 protons per cycle.

- Slow extraction to North Area
- Fast extraction to LHC, AWAKE and HiRadMat

Cycling CERN injection complex



LHC



Constructed to investigate the physics at the TeV scale

Summary CERN complex

Machine	Size	Energy	Nominal Intensity
LINAC2	33 m	90 keV → 50 MeV	140mA - 180mA
PS Booster	157 m	50 MeV → 1.4 GeV	1.05×10^{12} protons/ring
PS	4 x PSB = 628 m	1.4 GeV up to 26 GeV	0.85×10^{13} protons/pulse
SPS	11 x PS = 6.9 km	26 GeV up to 450 GeV	1.5×10^{11} protons/bunch
LHC	27 km	450 GeV up to 7000 GeV	1.5×10^{11} protons/bunch

Outline

- Day 1:
  - Basic accelerator concepts
  - CERN Complex
- Day 2:
  - LHC
  - HL-LHC (upgrade v2)
  - Future projects: FCC and CLIC

THANK YOU!