Accelerators

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  - Mike Lamont
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  - Michaela Schaumann
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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
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Basic accelerator concepts

- **Injection and filling of the machine**
- **Beam circulation at high energies during hours**
- **Acceleration**
- **Collimation**
- **Beam steering to initiate/stop collisions in one or many experiments**
- **Extraction**
- **Keep circulation in constant orbit at even higher energies during hours or days**
Newton-Lorentz force

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

\[ \vec{F} = \frac{d\vec{p}}{dt} = e(\vec{E} + \vec{v} \times \vec{B}) \]

Particle charge

Electric field

Magnetic field

Particle instantaneous velocity

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)

\[ F_L = e v B \quad F_c = \frac{m v^2}{\rho} \]

\[ \frac{m v^2}{\rho} = e v B \rightarrow \frac{p}{e} = \rho B \rightarrow 0.3B[T] \approx \frac{p[GeV/c]}{\rho[\text{m}]} \]

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.

Radius

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.

\[
B_x = g \cdot y \quad B_y = g \cdot x
\]

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

**Distance followed at LHC:** \(13 \times 10^{12} \text{ m}\)

**Distance to the Moon:** \(3.8 \times 10^8 \text{ m}\)

**Distance to the Sun:** \(1.5 \times 10^{11} \text{ m}\)

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.

Image from [CERN-2016-002](#)
Pure Multipole Fields

Example of multiple fields

Dipole

Quadrupole

Sextupole

Image from CERN–2010–004
Transverse Motion: equation

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**
Initial conditions for the amplitude and phase.

- Emittance
- Initial Phase

Amplitude of the oscillation $\Rightarrow$ Beam Envelope

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

- Beta-function
- Phase-advance

Defined by the BEAM

Defined by the LATTICE

Periodic functions.
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 example of this is the Methodical Accelerator Design (MAD-X) that describes particle accelerators, simulate beam dynamics and optimise the optics. In case you want to play [http://cern.ch/madx](http://cern.ch/madx)

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

LHC beams contain about $3 \times 10^{14}$ 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.
Number of complete oscillations per turn:

\[ Q_x = \frac{1}{2\pi} \int \frac{ds}{\beta_x(s)} \]

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
Beam Tune (2)

**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

LHC:
\[ Q_x = 64.31 \]
\[ Q_y = 59.32 \]
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

\[ \epsilon_n = \beta_{\text{rel}} \gamma_{\text{rel}} \epsilon \]
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)

\[
\vec{F} = \frac{d\vec{p}}{dt} = e(\vec{E} + \vec{v} \times \vec{B})
\]

**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

\[ +V_v \quad \text{vacum chamber} \quad 0V \]

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.

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.

Cockcroft-Walton high voltage generator (600kV - 1964)
Limitation of Electrostatic Acceleration

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.

Van de Graff’s generator at Round Hill MA
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**

Acceleration gaps (electrical field) \[ L = v \frac{T}{2} \]

Drift-tubes (field free)

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

**Bunched Beam**

\[ \uparrow v \implies \uparrow L \]

**Energy gain:**

\[ E = neV_{RF} \sin \phi_s \]

\( n \): number of gaps  
\( e \): charge  
\( V_{RF} \): applied voltage  
\( \phi_s \): 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

Unilac at GSI, Darmstadt

CERN LINAC2
Until 2018 was the first accelerator in the proton acceleration chain for LHC
Replaced during LS2 by LINAC4

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

\[ T_{RF} = \frac{2\pi \rho}{v} \quad \text{Radius} \quad \frac{mv^2}{\rho} = evB \]

Revolution frequency (cyclotron frequency)

\[ \omega_{RF} = \frac{2\pi}{T_{RF}} = \frac{qB}{m_0\gamma} \]

Does NOT depend on the radius as long as particles are non-relativistic

For High Energies the RF frequency has to change with \( \gamma \)

\[ \omega_{RF}(t) = \frac{qB}{m_0\gamma(t)} \]

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

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

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

Example LHC

$$f_{RF} = 400 \text{ MHz}$$
$$f_{rev} = c/27 \text{ km}$$

$h \approx 35640$
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

Synchronous particle

Other particles oscillate around the synchronous point forming **BUNCHES**

Slower particle

Faster particle

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)
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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 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).

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.
PS Booster

1\textsuperscript{st} Synchrotron in the chain with 4 superposed rings
Circumference of 157m
Increases proton energy from \textbf{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 \textbf{transverse emittance}.

\begin{itemize}
  \item **ISOLDE**: High-Intensity 10-13 turns are injected = large transverse emittance
  \item **LHC**: 2-3 injected turns = small transverse emittance
\end{itemize}

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 1.4 GeV to a range of energies up to 26 GeV depending on the user
- East area: 24 GeV
- SPS: 14 GeV or 26 GeV
- AD: 26 GeV
- n-TOF: 20 GeV
Cycle length goes from 1.2 s to 3.6 s

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

Present scheme

PSB h=5
1. PS batch of 20 bunches
2. PS h=20

PSB h=1
1. PS batch of 8 bunches
2. Two-batch filling for LHC
3. PS h=8

1. 1st batch
2. 2nd batch
3. 1.2 sec later
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

- **PS ejection:** 72 bunches on h=84 in 1 turn
- **320 ns beam gap**
- **Quadruple splitting at 25 GeV**
- **Acceleration of 18 bunches on h=21 to 25 GeV**
- **Triple splitting at 1.4 GeV**
- **PS injection:** 6 bunches (2+4) in 2 batches on h=7
- **Empty bucket**

**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 to 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

- Green line: Field in main magnets
- Red line: Proton beam intensity (current)
- Blue up arrow: Beam transfer

SPS

PS

PSB

1.2 seconds

Time

To LHC clock-wise or counter clock-wise

450 GeV

26 GeV

1.4 GeV
Constructed to investigate the physics at the TeV scale
### Summary CERN complex

<table>
<thead>
<tr>
<th>Machine</th>
<th>Size</th>
<th>Energy</th>
<th>Nominal Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LINAC2</td>
<td>33 m</td>
<td>90 keV → 50 MeV</td>
<td>140mA - 180mA</td>
</tr>
<tr>
<td>PS Booster</td>
<td>157 m</td>
<td>50 MeV → 1.4 GeV</td>
<td>1.05x10^{12} protons/ring</td>
</tr>
<tr>
<td>PS</td>
<td>4 x PSB = 628 m</td>
<td>1.4 GeV up to 26 GeV</td>
<td>0.85x10^{13} protons/pulse</td>
</tr>
<tr>
<td>SPS</td>
<td>11 x PS = 6.9 km</td>
<td>26 GeV up to 450 GeV</td>
<td>1.5x10^{11} protons/bunch</td>
</tr>
<tr>
<td>LHC</td>
<td>27 km</td>
<td>450 GeV up to 7000 GeV</td>
<td>1.5x10^{11} protons/bunch</td>
</tr>
</tbody>
</table>
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THANK YOU!