The LHC: the Large Hadron Collider

Simone Gilardoni CERN-AB/ABP
Simone.Gilardoni@cern.ch
Outline

- Why the LHC?
- CERN and the accelerator complex
- How LHC works: a synchrotron collider
- Luminosity
- Superconductivity and accelerators
- LHC optics
- How to protect the LHC
- Hints for the future

The idea is that the lectures:

a) should not be a monologue, stop me and ask if you don’t get the point
b) should show why things are like this, how they work, how they look like
All the ingredients are there: we need high energy particles produced by large accelerators to study the matter constituents and their interactions laws. This also true for the LHC

Small detail... Bohr was not completely right, the “new” elementary particles are not elementary but mesons, namely formed by quarks
History/Energy line vs discovery

- Leptons
  - Electron: 0.511 MeV
  - Muon: 105.65 MeV
  - Tau: 1777.05 MeV

- Quarks
  - Up: 3.25 MeV
  - Down: 6 MeV
  - Strange: 115 MeV
  - Charm: 1250 MeV
  - Bottom: 4250 MeV
  - Top: 173800 MeV

- Hadrons
  - Pion (charged): 139.57 MeV
  - Pion (neutral): 134.97 MeV
  - Proton: 938.27 MeV
  - Neutron: 939.56 MeV

- Bosons
  - Photon: 80410 MeV
  - Gluon: 91187 MeV
  - W: 80410 MeV
  - Z: 91187 MeV

Higgs and super-symmetry? Or something else maybe?

Obs: you can notice different particle species used in the different colliders:
- electron-positrons and hadron colliders (either p-p as Tevatron, p-p as LHC)

Constant increase in energy to discover heavier and heavier particles or rare processes.

Energy is not a free parameter for colliders: it is given by the physics one wants to do. Obviously, the higher the better ... but then, why the ILC has less energy than the LHC? (see next)
The proper particle for the proper scope

Electrons (and positrons) are (so far) point-like particles: no internal structure

\[ E_{\text{coll}} = E_b_1 + E_b_2 = 2E_b = 200 \text{ GeV (LEP)} \]

Pros: the energy can be precisely tuned to scan for example, a mass region. Precision measurement (LEP)

Cons: above a certain energy is no more possible to use electrons because of too high synchrotron radiation

Protons (and antiprotons) are formed by quarks (uud) kept together by gluons

The energy of each beam is carried by the proton constituents, and it is not the entire proton which collides, but one of his constituent

\[ E_{\text{coll}} \text{ (about 1 TeV LHC)} < 2E_b \text{ (14 TeV)} \]

Pros: with a single energy possible to scan different processes at different energies. Discovery machine (LHC)

Cons: the energy available for the collision is lower than the accelerator energy
What is the LHC?

**LHC: Large Hadron Collider**

**LHC** is a **collider** and **synchrotron storage ring**;
**ILC** is a collider but is not a synchrotron storage ring.

*Large: high energy needs large bending radius* due to the maximum magnetic field existing technology can produce *26.7 km circumference*.

*Hadrons: p p collision ⇒ synchrotron radiation and discovery machine.*

**Collider**: particles are stored in two separated rings which are **synchrotrons**, and accelerated from injection energy (450 GeV) to 7 TeV. At 7 TeV the two beams are forced to cross in collision points to interact. The beams are stored at 7 TeV for few 10 h to produce collisions. When the intensity is too low, the two rings are emptied and the process of injecting, accelerating, storing and colliding is restarted, until one finds the higgs or supersymmetry... then one needs a bottle of Champaign and a nobel price ...
Where is the LHC?

CERN Accelerator Complex

Intersection point | Tunnel Depth (m) | Tunnel Slope (%) | LEP 200 | LHC
--- | --- | --- | --- | ---
I (Meyrin) | 82.0 | 1.23 | Injection in arcs | ATLAS
II (St Genis) | 45.3 | 1.38 | L3 and RF | ALICE and Injection
III (Crozet) | 97.5 | 0.72 | Cleaning | |
IV (Echenevex) | 137.6 | 0.36 | ALEPH and RF | RF
V (Cessy) | 86.6 | 1.23 | CMS | |
VI (Versonnex) | 95.0 | 1.38 | Opal and RF | Dump
VII (Ferney) | 94.0 | 0.72 | Cleaning | |
VIII (Mategnin) | 98.8 | 0.36 | Delphi and RF | LHC-B and Injection

Where is the LHC?

Max depth: 135 m

London tube: 24 m depth

26.7 km Circumference
Synchrotron (1952, 3 GeV, BNL)

New concept of circular accelerator. The magnetic field of the bending magnet varies with time. As particles accelerate, the B field is increased proportionally. The frequency of the RF cavity, used to accelerate the particles has also to change.

Particle rigidity: $B \rho = \frac{p}{e}$

- $B = B(t)$ magnetic field from the bending magnets
- $p = p(t)$ particle momentum varies by the RF cavity
- $e$ electric charge
- $\rho$ constant radius of curvature

Magnetic elements for injection and extraction.

Weak focusing machine: no quadrupoles yet
Strong focusing machine, using quadrupoles, were proposed in 1952

Bending strength limited by used technology to max ~ 1 T for room temperature conductors.
Synchrotrons: strong focusing machine

Dipoles are interleaved with quadrupoles to focus the beam. Quadrupoles act on charged particles as lens for light. By alternating focusing and defocusing lens (Alternating Grandient quadrupoles) the beam dimension is kept small (even few mum$^2$).

Typical lattice is FODO focusing drift defocusing

Modern particles accelerators for high energy up to LHC energy (7 TeV) work in this way.
A synchrotron in a view: LEIR (Low Energy Ion Ring)

but this is for 4.2 MeV/nucl Pb ions... let climb the energy scale
Different approaches: fixed target vs collider

**Fixed target**

**Storage ring/collider**

\[ E_{CM} = \sqrt{2 \left( E_{beam}mc^2 + m^2c^4 \right)} \]

\[ E_{CM} = 2 \left( E_{beam} + mc^2 \right) \]

This usually is defined as \( \sqrt{s} \)
ISR, the first proton-proton collider
CERN accelerator complex overview

Chain/sequence of accelerators

- 50 MeV – 1.4 GeV
- 1.4 GeV – 26 GeV/c
- 26 - 450 GeV/c
- 450 GeV /c – 7 TeV /c

LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso
Basically the injector chains brings you ...

from nearly a bottle of hydrogen to a little bit before this
Where is the LHC?

CERN Accelerator Complex

Intersection point | Tunnel Depth (m) | Slope (%) | LEP 200 | LHC
--- | --- | --- | --- | ---
I (Meyrin) | 82.0 | 1.23 | Injection in arcs | ATLAS
II (St Genis) | 45.3 | 1.38 | L3 and RF | ALICE and Injection
III (Crozet) | 97.5 | 0.72 | Cleaning | CMS
IV (Echenevex) | 137.6 | 0.36 | ALEPH and RF | RF
V (Cessy) | 86.6 | 1.23 | Opal and RF | Cleaning
VI (Versonnex) | 95.0 | 1.38 | Delphi and RF | LHC-B and Injection
VII (Ferney) | 94.0 | 0.72 | | |
VIII (Mategnin) | 98.8 | 0.36 | | |

Where is the LHC?

Max depth: 135 m

London tube: 24 m depth
LHC layout and few parameters

<table>
<thead>
<tr>
<th>Particle type</th>
<th>protons (heavy ions, Pb82+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>450 GeV (injection)</td>
</tr>
<tr>
<td></td>
<td>7 TeV (collision energy)</td>
</tr>
<tr>
<td></td>
<td>2,75 TeV/u (ions collision)</td>
</tr>
<tr>
<td>Circumference</td>
<td>26658 m</td>
</tr>
<tr>
<td>Revolution frequency</td>
<td>11,245 kHz</td>
</tr>
<tr>
<td>Number of rings</td>
<td>1 (two-in-one magnet design)</td>
</tr>
<tr>
<td>Number of accelerators</td>
<td>2 (2 independent RF system)</td>
</tr>
<tr>
<td>Interaction Points (IP) or Collision Points or Low beta insertions</td>
<td>4 (ATLAS, CMS, ALICE, LHCb)</td>
</tr>
<tr>
<td>Cleaning insertions or collimation insertions</td>
<td>2</td>
</tr>
<tr>
<td>Beam dump extractions</td>
<td>2</td>
</tr>
<tr>
<td>RF insertion</td>
<td>1</td>
</tr>
</tbody>
</table>

LHC cost ~1,899.64 MEUR, without the tunnel... ONE F1 season costs about 1,500 MEUR
The LHC-lattice terminology

Reference Frame for the lectures:
- $x$ is the horizontal coordinate, positive means outside the ring
- $y$ is the vertical coordinate, positive means up
- $z$ is the direction of the particles,
  - positive clockwise for beam 1
  - positive anticlockwise for beam 2

Octant

Sector

Insertion

Arc - Midarc

DS - DS

LSS - LSS

DS - DS

Arc - Midarc

IP

Q<sub>33-11</sub>

Q<sub>10-7</sub>

Q<sub>7-10</sub>

Q<sub>11-33</sub>

IT - Inner Triplet

OT - Outer Triplet

MS - Separation/Recombination Magnet

DS - Dispersion Suppressor $\sim$ 174m

LSS - Straight Section $\sim$ 528m (Long straight section)

Arc $\sim$ 2460m
Basics components of the LHC

**Synchrotron:**
a) dipoles to bend particles with increasing field vs time i.e. vs energy

b) quadrupoles to focus the beam and keep it in the aperture. FODO

c) interaction point with final focusing to collide the two beams

---

**Regular ARC**

- MQ: Lattice Quadrupole
- MO: Landau Octupole
- MQT: Tuning Quadrupole
- MQS: Skew Quadrupole
- MSCB: Combined Lattice Sextupole (MS) or skew sextupole (MSS) and Orbit Corrector (MCB)
- BPM: Beam position monitor
- MBA: Dipole magnet Type A
- MBB: Dipole magnet Type B
- MCS: Local Sextupole corrector
- MCO: Local combined decapole and octupole corrector

---

**Example for an LHC insertion with ATLAS or CMS**

**Interaction points**
Let start with collisions
Luminosity

\[ N_{\text{event}} = L \sigma_{\text{event}} \]

Example for an LHC insertion with ATLAS or CMS

**pp cross section**

Cross section (mb) vs. \( \sqrt{s} \) (GeV)
Cross Sections and Production Rates

Rates for $L = 10^{34}$ cm$^{-2}$ s$^{-1}$: (LHC)

- Inelastic proton-proton reactions: $10^9$ / s
- $b\bar{b}$ pairs: $5 \times 10^6$ / s
- $t\bar{t}$ pairs: 8 / s
- $W \rightarrow e\nu$: 150 / s
- $Z \rightarrow e e$: 15 / s
- Higgs (150 GeV): 0.2 / s
- Gluino, Squarks (1 TeV): 0.03 / s

LHC is a factory for:
top-quarks, $b$-quarks, $W$, $Z$, ....... Higgs, .......

The only problem: you have to detect them!
Luminosity

Number of particles per bunch
\( N_{\text{beam1}} \times N_{\text{beam2}} = N^2 \)

Revolution frequency

Number of bunches

Beam dimension at the IP
\[ \sigma_{x,y}^* = \sqrt{\beta_{x,y}^* \cdot \epsilon_{x,y}} \]

At first look, the smaller the better

Geometric Reduction factor due to crossing angle
\[ F = \frac{1}{\sqrt{1 + \left( \frac{\theta_c \sigma_z}{2 \cdot \sigma^*} \right)^2}} \]
Definition of beam emittance

\[ \sigma_{x,y}^* = \sqrt{\beta_{x,y}^* \cdot \epsilon_{x,y}} \]

**Emittance:** Parameter which describes the spread of the particles in the phase space (xx') or (yy').

Optical machine parameter that depends on the lattice of the machine, in particular on the **QUADRUPOLES.**

The interaction POINT is built as a FOCAL POINT for the machine optics.

By knowing the setting of the quadrupoles and the beam emittance, one can compute the beam dimension in the entire LHC.

(See slide 49, 51 and 55 Hillert lecture)
Inner triplet: final focusing
⇒ how to make the beam small at the IP
Triplets before lowering in the tunnel

Each one of this object is represented by its transfer matrix.

This is a quadrupole.
20 min bias evts overlap
H→ZZ (Z →μμ)

Angle @ IP to avoid that the 2808 bunches collides in other places than the IP in the LSS.

\sim 30 unwanted collision per crossing

\[ F = \frac{1}{\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2 \cdot \sigma^*}\right)^2}} \]

- \(\Theta_c\): crossing angle
- \(\sigma_z\): RMS bunch length
- \(\sigma^*\): RMS beam size (ATLAS-CMS)
- \(F\): L reduc. Factor

<table>
<thead>
<tr>
<th>(\Theta_c)</th>
<th>crossing angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>285 (\mu\text{m})</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(\sigma_z)</th>
<th>RMS bunch length</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.55 cm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(\sigma^*)</th>
<th>RMS beam size (ATLAS-CMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.7 (\mu\text{m})</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(F)</th>
<th>L reduc. Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.836</td>
<td></td>
</tr>
</tbody>
</table>
Few LHC numbers ...

\[
L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x^* \cdot \sigma_y^*} \cdot F
\]

\[
F = \frac{1}{\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2 \cdot \sigma^*}\right)^2}}
\]

<table>
<thead>
<tr>
<th><strong>Luminosity</strong></th>
<th>(1 \times 10^{34} \text{ cm}^2/\text{s} \text{ (IP1 IP5)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Particle per bunch</strong></td>
<td>(1,15 \times 10^{11} )</td>
</tr>
<tr>
<td><strong>Bunches</strong></td>
<td>2808</td>
</tr>
<tr>
<td><strong>Revolution frequency</strong></td>
<td>11,245 kHz</td>
</tr>
<tr>
<td><strong>Crossing rate</strong></td>
<td>40 MHz</td>
</tr>
<tr>
<td><strong>Normalised Emittance</strong></td>
<td>3.75 (\mu m) rad</td>
</tr>
<tr>
<td><strong>(\beta)-function at the collision point</strong></td>
<td>0.55 m</td>
</tr>
<tr>
<td><strong>RMS beam size @ 7 TeV at the IP1-5</strong></td>
<td>16.7 (\mu m)</td>
</tr>
<tr>
<td><strong>Circulating beam current</strong></td>
<td>0.584 A</td>
</tr>
<tr>
<td><strong>Stored energy per beam</strong></td>
<td>362 MJ</td>
</tr>
</tbody>
</table>
Example of Luminosity vs time in a running collider

Luminosity decay due to:
1. beam collision ⇒ PHYSICS EVENTS
2. beam interaction with rest gas in the beam pipe
3. beam losses

Beam extracted from the machine. Luminosity too low to be useful for physics

Number of a certain type of physics events generated by collisions

This is not LHC... RHIC collider in USA used as an example.
Near the IPs

http://petermccready.com/portfolio/
From collision point to the LHC ring
LEP vs LHC: Magnets, a change in technology

Bending Field \( \rightarrow \) \[ p(\text{TeV}) = 0.3 \ B(T) \ R(\text{Km}) \]

(earth magnetic field is between 24000 nT and 66000 nT)

Tunnel R \( \approx \) 4.3 Km

LHC \( 7 \text{ TeV} \rightarrow B \approx 8.3 \text{ T} \rightarrow \) **Superconducting coils**

LEP \( 0.1 \text{ TeV} \rightarrow B \approx 0.1 \text{ T} \rightarrow \) **Room temperature coils**

---

Protons can go up in energy more than electrons because they emit less synchrotron radiation. Bending (dipoles) and focusing (quadrupoles) strengths require high magnetic fields generated by superconductors.
Synchrotron radiation

Radiation emitted by charged particles accelerated longitudinally and/or transversally

Power radiated per particle goes like:

\[ P = \frac{2c \times E^4 \times r_0}{3 \rho^2 \left( m_0 \times c^2 \right)^3} \]

- 4th power of the energy (2nd power)\(^{-1}\) of the bending radius
- (4th power)\(^{-1}\) of the particle mass

\[ r_0 = \frac{q^2}{4\pi \varepsilon_0 m_0 c^2} \]

- particle classical radius
- particle bending radius

Energy lost per turn per particle due to synchrotron radiation:

- e- some GeV (LEP)
- p some keV (LHC)

We must protect the LHC coils even if energy per turn is so low

Power lost per m in dipole: some W
Total radiated power per ring: some kW
LHC beam screen with cooling pipes

Beam screen to protect Superconducting magnets from Synchrotron radiation.

Holes for vacuum pumping

Atmosphere pressure = 750 Torr
Moon atmospheric pressure = $5 \times 10^{-13}$ Torr

Vacuum required to avoid unwanted collision far from the IPs and decrease the Luminosity

Typical vacuum: $10^{-13}$ Torr

There is $\sim 6500$ m$^3$ of total pumped volume in the LHC, like pumping down a cathedral.
Two-in-one magnet design

The LHC is one ring where two accelerators are coupled by the magnetic elements.

Nb -Ti superconducting cable in a Cu matrix
At 7 TeV:

$I_{\text{max}} = 11850 \text{ A} \quad \text{Field}=8.33 \text{ T}$

Stored energy about 7 MJ

Weight = 27.5 Tons

Length = 15.18 m at room temp.

Length (1.9 K) = 15 m - ~10 cm

Test bench for magnetic measurements at 1.9 K

PS: they are not straight, small bending of 5.1 mrad
From LEP to the LHC, iron-concrete yoke ...
Cos$\theta$ coil of main dipoles

A 2D cos$\theta$ current distribution generates a "quasi-perfect vertical field" in the aperture between the two conductors.

$$I = I_0 \cos \theta$$

$$B_{\theta} = \frac{\mu_0 I_0}{2 r_o} \cos \theta$$

$$B_{\theta} = \frac{\mu_0 I_0}{2 r_o} \sin \theta$$

Dipolar Vertical field
Quadrupoles are also two-in one

At 7 TeV:

I_{\text{max}} = 11850 \text{ A}

Field = 225 \text{ T/m}

Weight = 6.5 \text{ Tons}

Length = 3.1 \text{ m}
Quadrupoles being assembled before installation

Connection to QRL line
INTERLUDE:
THE TERMINATOR-3 ACCELERATOR

We apply some concepts to the accelerator shown in Terminator-3 [Columbia Pictures, 2003]

Estimation of the magnetic field

- Energy = 5760 GeV
- Radius \( \sim 30 \) m
- Field = \( \frac{5760}{0.3/30} \sim 700 \) T (a lot!)

Why the magnet is not shielded with iron?

- Assuming a bore of 25 mm radius, inner field of 700 T, iron saturation at 2 T, one needs \( 700 \times 25/2 = 9000 \) mm = 9 m of iron ... no space in their tunnel!
- In the LHC, one has a bore of 28 mm radius, inner field of 8 T, one needs \( 8 \times 25/2 = 100 \) mm of iron

Is it possible to have 700 T magnets??

Energy of the machine (left) and size of the accelerator (right)

A magnet whose fringe field is not shielded
Very, very short introduction to Superconductivity for accelerators

Superconductivity is a property of some materials. At very low temperature they can carry currents without voltage drop, i.e. their resistivity goes to zero. LHC cables: Nb-Ti working at 1.9 K

The conductor remains Superconductor if its status in Current Density, Temperature, B field phase space is below the Critical Surface

The distance between the working point and the critical surface for a fixed B field and Current Density is the temperature margin (critical temperature)

Transition to a normal conducting state is called magnet quench

What can increase the temperature in a magnet?
Beam losses can eat the temperature margin because of energy deposition.

Limit of accepted losses: ~ $10 \text{ mW/cm}^3$ to avoid $\Delta T > 2 \text{ K}$, the temperature margin.
How much is 10 mW/cm³?

A fluorescente (known as neon) tube can be typically 1.2 m long with a diameter of 26 mm, with an input power of 36 W.

This makes a power density of about 56 mW/cm³.

The power of a neon tube can quench about 5 LHC dipoles at collision energy.... because one does not need 10 mW/cm³ for the entire volume of a magnet, but for about 1 cm³.

If you do the same basic computation with a normal 100 W resistive bulbs is even worst
The length of the LHC dipoles (15 m) has been determined: by the best design for the tunnel geometry and installation and by the maximal dimensions of (regular) trucks allowed on European roads.
Lower temperature margin near the beam!

Limiting beam losses:

$10^8$ p/m at small grazing angle

for a total circulating intensity of $3.3 \times 10^{14}$ p

Other possible sources of quenches:

1. **mechanical friction**, for example during current ramp, between the conductors. Few $\mu$m are enough. Magnets are “trained” before installation and they keep memory of the training at least since the next quench.

2. **failure of the cooling system**. Depending on the case of failure, magnets can heat up slowly or not...

*but every dipole stores about 7 MJ at collision*

*the stored energy is about 350 MJ per beam*

So, one need:

1. to exclude the magnet from the ARC powering, since all the magnets are IN SERIES per ARC.

2. to discharge fast the power of the quenching magnet octant (time constant about 100 s), and dispersing by heating up the magnet the power that otherwise will accumulate near the quenching zone.

3. to extract the beam as fast as possible, meaning within one turn from the quench detection, before risking to damage mechanically the machine with the beam.

The different time scale of the two processes helps:

*1 beam turn every $\sim 90$ $\mu$s while a quench develops on at least few ms. However, quench detection, power extraction and beam extraction has to be fast and reliable.*
When something goes wrong.... bad quench...

During tests the energy of 7 MJ in one magnet was released into one spot in the coil (interturn short).

P. Pugnat
Quench levels are varying with energy ....

In a synchrotron, the magnetic field increases with energy to keep particles on the circular trajectory. This means that both the current as the field are larger at 7 TeV than at 450 GeV.

The Temperature margin is the reduced, one can loose less particles....
LHC cryogenics will need 40,000 leak-tight pipe junctions. 12 million litres of liquid nitrogen will be vaporised during the initial cooldown of 31,000 tons of material and the total inventory of liquid helium will be 700,000 l (about 100 tonnes).
Why 1.9 K and not 4.5 K (Hera-like)?

Gain of 3 T lowering the temperature for 4.5 K to 1.9 K. Gain in dipoles bending strength and hence of MAX energy.

The minimum temperature on the MOON is 126 K

From P. Lebrun
Cooling down one octant

Magnet temperature profile along sector 78 at 09:55 Jun 26

Move cursor to yellow square to identify magnet

3 km

The coldest place on earth...
Why particle accelerators?

- **Why accelerators**: need to produce under **controlled conditions** **HIGH INTENSITY**, at a **CHOSEN ENERGY** particle beams of **GIVEN PARTICLE SPECIES** to do an **EXPERIMENT**

- An experiment consists of studying the results of colliding particles either onto a fixed target or with another particle beam.

The universe is already doing collisions with different mechanisms:

while I am speaking about 66 \(10^9\) particles/cm\(^2\)/s are traversing your body, with this spectrum before being filtered by the atmosphere.

The universe is able to accelerate particles up to \(10^6\) MeV protons