The LHC collider I

Challenges
LHC accelerator physics
LHC technology
Operation and protection

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Graduate Days
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Energy and Luminosity

- Particle physics requires an accelerator colliding beams with a centre-of-mass energy substantially exceeding 1TeV.
- In order to observe rare events, the luminosity should be in the order of $10^{34} \text{[cm}^{-2}\text{s}^{-1}]$ (challenge for the LHC accelerator).
- Event rate:

\[
\frac{N}{\Delta t} = L[\text{cm}^{-2} \cdot \text{s}^{-1}] \cdot \sigma[\text{cm}^2]
\]

- Assuming a total cross section of about 100 mbarn for pp collisions, the event rate for this luminosity is in the order of $10^9$ events/second (challenge for the LHC experiments).
- Nuclear and particle physics require heavy ion collisions in the LHC (quark-gluon plasma .... )
LHC simulated event

$10^9$ events / second
CERN and the LHC
CERN is the leading European institute for particle physics. It is close to Geneva across the French Swiss border. There are 20 CERN member states, ~7 observer states, and many other states participating in research.
LEP: $e^+e^-$

Circumference
26.8 km

**LHC**
proton-proton Collider
7 TeV/c in the LEP tunnel

LHC will also collide heavy ions
LHC: From first ideas to realisation

1982 : First studies for the LHC project
1983 : Z0 detected at SPS proton antiproton collider
1985 : Nobel Price for S. van der Meer and C. Rubbia
1989 : Start of LEP operation at 45 GeV (Z-factory)
1994 : Approval of the LHC by the CERN Council
1996 : Final decision to start the LHC construction
1996 : LEP operation at 100 GeV (W-factory)
2000 : End of LEP operation
2002 : LEP equipment removed (second life for sc cavities ?)
2003 : Start of the LHC installation
2005 : Start of hardware commissioning
2007/8 : Commissioning with beam
The LHC is the largest machine that has ever been built, and probably the most complex one.

To make the LHC a reality: Accelerators physics and ....

- Electromagnetism und Relativity
- Thermodynamics
- Mechanics
- Physics of nonlinear systems
- Solid state physics und surface physics
- Quantum mechanics
- Particle physics and radiation physics
- Vacuum physics

+ Engineering

Mechanical, Cryogenics, Electrical, Automation, Computing
Outline

- **Accelerator Physics: An Introduction**
- LHC layout and beam transport
- The quest for high luminosity and the consequences
- Wrapping up: LHC Parameters
- The CERN accelerator complex: injectors and transfer
- LHC technology
- LHC operation and machine protection
- Conclusions
Lorentz Force

The force on a charged particle is proportional to the charge, and to the vector product of velocity and magnetic field:

$$\mathbf{F} = q \cdot (\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

For an electron or proton the charge is:

$$q = e_0 = 1.602 \cdot 10^{-19} \text{ [C]}$$

Acceleration (increase of energy) only by electrical fields – not by magnetic fields:

$$\Delta E = \int_{s_1}^{s_2} \mathbf{F} \cdot ds$$

$$\frac{dE}{dt} = \mathbf{v} \cdot \mathbf{F}$$

$$\frac{dE}{dt} = q \cdot (\mathbf{v} \cdot \mathbf{E} + \mathbf{v} \cdot (\mathbf{v} \times \mathbf{B})) = q \cdot \mathbf{v} \cdot \mathbf{E}$$
Acceleration

Acceleration of a particle by an electrical potential

\[ U = \int_{s_1}^{s_2} \vec{E} \cdot d\vec{s} \]

Energy gain given by the potential

\[ \Delta E = \int_{s_1}^{s_2} \vec{F} \cdot d\vec{s} = \int_{s_1}^{s_2} q \cdot \vec{E} \cdot d\vec{s} = q \cdot U \]

For an acceleration to 7 TeV a voltage of 7 TV is required
Acceleration with RF fields

- $U = 1000000 \text{ V}$
- $d = 1 \text{ m}$
- $q = e_0$
- $\Delta E = 1 \text{ MeV}$

Time varying field

$E_z(t) = E_0 \cdot \cos(\omega \cdot t + \varphi)$

Maximum field about 20 MV/m

Consequence: bunched beam
RF cavity

\[ \vec{B}(t) \text{ orthogonal} \]

LHC RF frequency 400 MHz
Revolution frequency 11246 Hz

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RF systems: 400 MHz

400 MHz system:
16 sc cavities (copper sputtered with niobium) for 16 MV/beam were built and assembled in four modules
To get to 7 TeV: Synchrotron – circular accelerator and many passages in RF cavities

LINAC (planned for several hundred GeV - but not above 1 TeV)

LHC circular machine with energy gain per turn some MeV acceleration takes about 20 minutes

....requires deflecting magnets (dipoles)
Deflection by magnetic fields

For a charged particle moving perpendicular to the magnetic field the force is given by:

\[ \mathbf{F} = m \cdot \mathbf{a} = q \cdot \mathbf{v} \cdot \mathbf{B} \]

The particle moves on a circle

\[ \mathbf{F}_{\text{Lorentz}} = q \cdot \mathbf{v} \cdot \mathbf{B} \]
\[ \mathbf{F}_{\text{Centrifugal}} = m \cdot \frac{\mathbf{v}^2}{R} \]
\[ R = m \cdot \mathbf{v} / q \cdot \mathbf{B} \]
with \( \omega = \frac{\mathbf{v}}{R} \) one gets: \( \omega = \frac{q}{m} \cdot \mathbf{B} \)
\[ \mathbf{B} = \frac{E}{R \cdot q \cdot c} \]
The force on a charged particle is proportional to the charge, and to the vector product of velocity and magnetic field:

\[ \vec{F} = q \cdot (\vec{E} + \vec{v} \times \vec{B}) \]

\[ B = \frac{p}{e_0 \cdot R} \]

- Maximum momentum 7000 GeV/c
- Radius 2805 m fixed by LEP tunnel
- **Magnetic field** \( B = 8.33 \) Tesla
- Iron magnets limited to 2 Tesla, therefore superconducting magnets are required
- Deflecting magnetic fields for two beams in opposite directions
Deflection by magnetic fields

An electrical field is assumed, with a strength of: \( E := 7 \cdot 10^6 \frac{V}{m} \)

A transverse magnetic field is assumed with \( B := 8.3 T \)

With the Lorentz Force \( F = e_0 \cdot (E + c \cdot B) \) the force on the proton is given by:

\[
F_{B\text{\_field}} := e_0 \cdot c \cdot B \\
F_{E\text{\_field}} := e_0 \cdot E
\]

\[
F_{B\text{\_field}} = 3.986 \times 10^{-10} N \\
F_{E\text{\_field}} = 1.121 \times 10^{-12} N
\]

\[
\frac{F_{B\text{\_field}}}{F_{E\text{\_field}}} = 355.469
\]

For the gravitation: \( F_G := g \cdot m_e \)

\[
F_G = 8.933 \times 10^{-30} N
\]

Radius of a proton in a B field with \( B = 8.3 T \) is

\[
R = 7 \cdot 10^{12} \frac{eV}{c} \cdot \frac{1}{e_0 \cdot B} = 2.813 \times 10^3 m
\]
Energy loss for charged particles by synchrotron radiation

Power emitted for one particle: \[ P_S = \frac{e_0^2 c}{6 \pi \epsilon_0 (m_0 c^2)^4 \rho^2} E^4 \]

with \( E \) = energy, \( m_0 \) = rest mass, \( e_0 \) = charge, and \( \rho \) = radius
Energy loss for charged particles electrons / protons in LEP tunnel

\[ E_{lep} := 100\text{GeV} \quad E_{lhc} := 7000\text{GeV} \]

Energy loss for one particle per turn:

\[ U_{lep} = 3.844 \times 10^9 \text{eV} \quad U_{lhc} = 8.121 \times 10^3 \text{eV} \]

Total power of synchrotronradiation:

Number of electrons in LEP: \( N_{lep} := 10^{12} \)
Number of protons in LHC \( N_{lhc} := 10^{14} \)

\[ P_{total\_lep} := N_{lep} \cdot P_{lep} \quad P_{total\_lhc} := N_{lhc} \cdot P_{lhc} \]

\[ P_{total\_lep} = 1.278 \times 10^7 \text{W} \quad P_{total\_lhc} = 2.699 \times 10^3 \text{W} \]

The power of the synchrotronradiation emitted at the LHC is very small, but the radiation goes into the supraconducting magnets at 1.9 K ... 20 K
...just assuming to accelerate electrons to 7 TeV

assuming LEP with electrons at 7 TeV:

\[ \gamma_{lep} := \frac{7 \cdot 10^{12}}{m_e \cdot c^2} \text{ eV} \]

\[ U_{lep} := e_0^2 \cdot \frac{\gamma_{lep}^4}{3 \cdot \varepsilon_0 \cdot \rho} \]

\[ U_{lep} = 9.23 \times 10^{16} \text{ eV} \]

...better to accelerate protons
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LHC Layout

eight sectors
eight arcs
eight long straight sections (insertions) about 700 m long

Main dipole magnets: making the circle

IR1: ATLAS
IR2: ALICE
IR3: Momentum Beam Cleaning (warm)
IR4: RF + Beam instrumentation
IR5: CMS
IR6: Beam dumping system
IR7: Betatron Beam Cleaning (warm)
IR8: LHC-B

Injection

Beam dump blocks
Beam transport

Need for getting protons on a circle: dipole magnets

Need for focusing the beams:

- Particles with different injection parameters (angle, position) separate with time
  - Assuming an angle difference of $10^{-6}$ rad, two particles would separate by 1 m after $10^6$ m. At the LHC, with a length of 26860 m, this would be the case after 50 turns (5 ms !)

- Particles would „drop“ due to gravitation

- The beam size must be well controlled
  - At the collision point the beam size must be tiny

- Particles with (slightly) different energies should stay together
Focusing using lenses as for light

- **Dipole magnet** – B-field in aperture constant
- **Quadrupole magnet** – B-field zero in centre, linear increase (as an optical lens)
Assuming proton runs along $s (=y)$, perpendicular to $x$ and $z$

\[
B_z(x) = \text{const} \cdot x
\]

\[
B_x(z) = \text{const} \cdot z
\]
Focusing of a system of two lenses for both planes

To focus the beams in both planes, a succession of focusing and defocusing quadrupole magnets is required: FODO structure.

\[ f_1 := 100 \text{ m} \]
\[ f_2 := -100 \text{ m} \]
\[ d := 50 \text{ m} \]

\[ F := \left( \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 \cdot f_2} \right)^{-1} \]

\[ F = 200 \text{ m} \]
A cell in the LHC arcs

Vertical / Horizontal plane (QF / QD)

Quadrupole magnets controlling the beam size „to keep protons together“ (similar to optical lenses)

LHC Cell - Length about 110 m (schematic layout)

- Quadrupole magnets (MQF, MQD)
- Sextupole magnets (MS, MCS)
- Octupole magnets (MO, MO)
- Decapole magnets (MCDO)

- Main dipole magnets (MB)
- Orbit corrector magnets (MQS, MO)

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Magnets and beam stability

- **Dipole magnets**
  - To make a circle around LHC

- **Quadrupol magnets**
  - To keep beam particles together
  - Particle trajectory stable for particles with nominal momentum

- **Sextupole magnets**
  - To correct the trajectories for off momentum particles
  - Particle trajectories stable for small amplitudes (about 10 mm)

- **Multipole-corrector magnets**
  - Sextupole - and decapole corrector magnets at end of dipoles

- Particle trajectories can become instable after many turns (even after, say, $10^6$ turns)
Particle stability and superconducting magnets - Quadrupolar- and multipolar fields

Particle oscillations in quadrupole field (small amplitude)

Harmonic oscillation after coordinate transformation

Circular movement in phase space

Particle oscillation assuming non-linear fields, large amplitude

Amplitude grows until particle is lost (touches aperture)

No circular movement in phasespace
Dynamic aperture and magnet imperfections

- Particles with small amplitudes are in general stable
- Particles with large amplitudes are not stable
- The dynamic aperture is the limit of the stability region
- The dynamic aperture depends on field errors - without any field errors, the dynamic aperture would be large

- The magnets should be made such as the dynamic aperture is not too small (say, 10 $\sigma$ the amplitude of a one sigma particle, assuming Gaussian distribution)

- The dynamic aperture depends also on the working point and on the sextupole magnets for correction of chromatic effects
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High luminosity by colliding trains of bunches

Number of „New Particles“ per unit of time:

\[
\frac{N}{\Delta T} = L \text{[cm}^{-2} \cdot \text{s}^{-1}] \cdot \sigma \text{[cm}^{2} \])
\]

The objective for the LHC as proton – proton collider is a luminosity of about \(10^{34} \text{[cm}^{-2}\cdot\text{s}^{-1}]\)

- LEP (e+e-) : \(3-4 \times 10^{31} \text{[cm}^{-2}\cdot\text{s}^{-1}]\)
- Tevatron (p-pbar) : \(~ 10^{32} \text{[cm}^{-2}\cdot\text{s}^{-1}]\)
- B-Factories: \(> 10^{34} \text{[cm}^{-2}\cdot\text{s}^{-1}]\)
Luminosity parameters

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

with:
- \( N \) = Number of protons per bunch
- \( f \) = revolution frequency
- \( n_b \) = number of bunches per beam
- \( \sigma_x \cdot \sigma_y \) = beam dimensions at interaction point

What happens with one particle experiencing the force of the em-fields or \( 10^{11} \) protons in the other beam during the collision?
Limitation: beam-beam interaction
Electromagnetic force on a particle in the counterrotating beam

Optimising luminosity by increasing N

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

Electromagnetic field of one beam act on other beam. Calculation by transforming into frame of test particle and calculate Lorentz Force:

\[
F(r) = \frac{N \cdot e^2}{2\pi \cdot \varepsilon_0} \cdot \frac{(1 + \beta^2)}{r} \cdot \left[ 1 - \exp\left( -\frac{r^2}{2 \cdot \sigma^2} \right) \right]
\]

Bunch intensity limited due to this strong non-linear field to about \( N = 10^{11} \)
Beam beam interaction determines parameters

Number of protons per bunch limited to about $10^{11}$

$f = 11246 \text{ Hz}$

Beam size given by injectors and by space in vacuum chamber

Beam size $16 \, \mu\text{m}$, for $\beta = 0.5 \, \text{m}$

$L = \frac{N^2 f n_b}{4\pi \sigma_x \sigma_y} = 3.5 \times 10^{30} \, [\text{cm}^{-2} \text{s}^{-1}]$

with one bunch

with 2808 bunches (every 25 ns one bunch)

$L = 10^{34} \, [\text{cm}^{-2} \text{s}^{-1}]$
Large number of bunches

Bunch structure with 25 ns spacing

- Experiments: more than 1 event / collision, but should not exceed a number in the order of 10-20
- Limit number of collision points as far as possible
- Vacuum system: photo electrons
Large number of bunches

- **Crossing angle** to avoid beam beam interaction (only long range beam beam interaction present)
- Interaction Region quadrupoles with gradient of 250 T/m and 70 mm aperture
Focusing quadrupole for beam 1, defocusing for beam 2
High gradient quadrupole magnet triplet with large aperture (US-JAPAN)
Total crossing angle of 300 $\mu$rad
Beam size at interaction point 16 $\mu$m, in arcs about 0.3 mm
Example for an LHC insertion with ATLAS or CMS
Outline

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- **The CERN accelerator complex: injectors and transfer**

- **LHC technology**

- **LHC operation and machine protection**

- **Conclusions**
Very high beam current

Many bunches and high energy - Energy in one beam about 330 MJ

- Dumping the beam in a safe way
- Beam induced quenches (when $10^{-7}$ of beam hits magnet at 7 TeV)
- Beam stability and magnet field quality
- Beam cleaning (Betatron and momentum cleaning)
- Synchrotron radiation - power to cryogenic system
- Radiation, in particular in experimental areas from beam collisions (beam lifetime is dominated by this effect)
- Photo electrons - accelerated by the following bunches
Challenges: Energy stored in the beam

One beam, nominal intensity (corresponds to an energy that melts 500 kg of copper)

Transverse energy density: even a factor of 1000 larger
<table>
<thead>
<tr>
<th><strong>Momentum at collision</strong></th>
<th>7 TeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum at injection</td>
<td>450 GeV/c</td>
</tr>
<tr>
<td>Dipole field at 7 TeV</td>
<td>8.33 Tesla</td>
</tr>
<tr>
<td>Circumference</td>
<td>26658 m</td>
</tr>
<tr>
<td><strong>Luminosity</strong></td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2808</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$1.1 \cdot 10^{11}$</td>
</tr>
<tr>
<td>DC beam current</td>
<td>0.56 A</td>
</tr>
<tr>
<td><strong>Stored energy per beam</strong></td>
<td>350 MJ</td>
</tr>
<tr>
<td><strong>Normalised emittance</strong></td>
<td>3.75 µm</td>
</tr>
<tr>
<td>Beam size at IP / 7 TeV</td>
<td>15.9 µm</td>
</tr>
<tr>
<td>Beam size in arcs (rms)</td>
<td>300 µm</td>
</tr>
<tr>
<td><strong>Arcs</strong></td>
<td></td>
</tr>
<tr>
<td>Counter-rotating proton beams in two-in-one magnets</td>
<td></td>
</tr>
<tr>
<td><strong>Magnet coil inner diameter</strong></td>
<td>56 mm</td>
</tr>
<tr>
<td>Distance between beams</td>
<td>194 mm</td>
</tr>
</tbody>
</table>

**High beam energy in LEP tunnel**
Superconducting NbTi magnets at 1.9 K

**High luminosity at 7 TeV**
Very high energy stored in the beam
Beam power concentrated in small area

**Limited investment**
Small aperture for beams
Centre-of-mass energy must well exceed 1 TeV, LHC installed into LEP tunnel
- Colliding protons (and heavy ions)
- Magnetic field of 8.3 T with superconducting magnets

Luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Need for “two accelerators” in one tunnel with beam parameters pushed to the extreme – with opposite magnetic field

Economical constraints and limited space
- Two-in-one superconducting magnets
Outline

● Accelerator Physics: An Introduction
  • Why protons? Why in the LEP tunnel? Why superconducting magnets? Why “two” accelerators in one tunnel?
● LHC layout and beam transport
● The quest for high luminosity and the consequences
● Wrapping up: LHC Parameters
● The CERN accelerator complex: injectors and transfer
● LHC technology
● LHC operation and machine protection
● Conclusions
LHC injector complex

High intensity beam from the SPS into LHC at 450 GeV via TI2 and TI8
LHC accelerates to 7 TeV

Beam size of protons decreases with energy: $\sigma^2 = 1 / E$
Beam size large at injection
Beam fills vacuum chamber at 450 GeV
Getting beam into the LHC

Beam size of protons decreases with energy: $\sigma^2 = 1 / E$

- Beam size large at injection
- Beam “fills” vacuum chamber at 450 GeV

If the energy would be lower ...

- larger vacuum chamber and larger magnets – increased cost
- magnets and power converter limitations (dynamic effects, stability, …)
- issues of beam stability

Injection from the SPS at 450 GeV, via two transfer lines, into the LHC
Injector Complex

- Pre-injectors: Linac, PS Booster and Proton Synchrotron deliver protons at 26 GeV to the SPS

- The SPS accelerates protons from 26 GeV to 450 GeV

- Both, the pre-injectors and the SPS were upgraded for the operation with nominal LHC beam parameters

- Already today, beams are available close to the nominal beam parameters required for the LHC

- The TI8 injection line has been commissioned
Results of Transfer Line TI8 test

LHC Transfer Line TI8

First beam test 23 October 2004

TV screen at end of line
The LHC collider II

Challenges
LHC accelerator physics
LHC technology
Operation and protection
Centre-of-mass energy must well exceed 1 TeV, LHC installed into LEP tunnel

- Colliding protons, and also heavy ions
- Magnetic field of 8.3 T with superconducting magnets
- Large amount of energy stored in magnets

Luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$

- Need for “two accelerators” in one tunnel with beam parameters pushed to the extreme – with opposite magnetic dipole field
- Large amount of energy stored in beams

Economical constraints and limited space

- Two-in-one superconducting magnets
Outline

• Main systems in LHC arcs
• LHC main dipole magnets
  – How does it work?
  – Superconductivity
  – From fabrication to installation
• From magnets to electrical circuits
• Magnet operation and machine protection
• Beam operation and machine protection
  – Risks
  – Beam dumping system
  – Collimation system
  – Strategy for Protection of the LHC machine
• From construction to operation
• Conclusions
Main systems in LHC arcs
Training LHC Powering

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1232 main dipoles + 3700 multipole corrector magnets

392 main quadrupoles + 2500 corrector magnets

Regular arc: Magnets

1232 main dipoles + 3700 multipole corrector magnets

392 main quadrupoles + 2500 corrector magnets
Supply and recovery of helium with 26 km long cryogenic distribution line

Connection via service module and jumper

Static bath of superfluid helium at 1.9 K in cooling loops of 110 m length
Training LHC Powering

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Insulation vacuum for the cryogenic distribution line

Insulation vacuum for the magnet cryostats

Beam vacuum for Beam 1 + Beam 2

Regular arc: Vacuum
Along the arc about several thousand electronic crates (radiation tolerant) for:

- quench protection,
- power converters for orbit correctors and instrumentation (beam, vacuum + cryogenics)
1232 Dipolmagnets
Length about 15 m
Magnetic Field 8.3 T
Two beamtubes with an opening of 56 mm
Coils for Dipolmagnets
In practice the above current distributions are approximated by real conductors, so the field contains also higher order harmonics.
Training LHC Powering

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Superconducting cable for 12 kA

15 mm / 2 mm

Temperature

1.9 K cooled with Helium

Force on the cable:

\[ F = B \times I_0 \times L \]

with

\( B = 8.33 \, \text{T} \)

\( I_0 = 12000 \, \text{Ampere} \)

\( L = 15 \, \text{m} \)

\( F = 165 \, \text{tons} \)
Dipole magnet cross section

- Ferromagnetic iron
- Nonmagnetic collars
- Supraconducting coil
- Beam tubes
- Steel cylinder for Helium
- Insulation vacuum
- Vacuum tank
- Supports
Discovery of superconductivity

- 1908 -- Kamerlingh Onnes liquifies Helium

1911 -- R-T for Mercury

"... Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive state ..."
Superconducting material determines:

- $T_c$ critical temperature
- $B_c$ critical field

Production process:

- $J_c$ critical current density

Lower temperature $\Rightarrow$ increased current density

Typical for NbTi:

- $2000$ A/mm$^2$
  - @ $4.2$K, $6$T

LHC: for $10$ T operation at less than $1.9$ K required

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Helium: Phasediagram

$T > T_\lambda$: He I

$T < T_\lambda$: He II
(superfluid Helium)

$T_\lambda = 2.17$ K

LHC:

$T = 1.9$ K
$P \approx 1.2$ bar

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Specific heat of Helium as function of T

Phasetransition at 2.18 Kelvin

Superfluid Helium (He II)

<table>
<thead>
<tr>
<th></th>
<th>He II, 1.9K</th>
<th>He I, 4.2K</th>
<th>Water, 300K</th>
<th>SC @ 8T, 1.9K</th>
<th>SC @ 8T, 4.2K</th>
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</thead>
<tbody>
<tr>
<td>thermal cond.</td>
<td>~100,000</td>
<td>0.02</td>
<td>1</td>
<td>~400</td>
<td>~400</td>
</tr>
<tr>
<td>viscosity</td>
<td>0.01 – 0.1</td>
<td>3</td>
<td>1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_p$</td>
<td>4</td>
<td>5</td>
<td></td>
<td>0.0001</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

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Superconducting wire

Filament diameter \( \Phi 6 \, \mu m \)  
Wire diameter \( \Phi 1 \, mm \)

Typical value for operation at 8 T and 1.9 K: 800 A

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Fabrication of superconducting dipoles

Dipole assembly in industry
Cryostating and measurements (main dipoles and other magnets)

SMA18 cryostating hall at CERN for installing dipole magnets into cryostats

SM18: 12 measurement stations are prepared for cold tests of possibly all superconducting magnets
First cryodipole lowered on 7 March 2005

Only one access point for 15 m long dipoles, 35 tons each
Transport in the tunnel with an optical guided vehicle

about 1600 magnets to be transported for 15 km

at 3 km/hour
Transfer on jacks
Challenges for dipole production

• The field quality must be excellent (relative field errors much less than 0.1 %, positioning of collars to some 10 µm)

• The geometry must be respected – and the magnet must be correctly bent (banana shape)

• All magnets had to be produced in time, delivered to CERN, installed in the cryostats, cold tested, and finally installed into the LHC tunnel

• The magnets must reach without quenching a field of at least 8.3 Tesla, and possibly 9 Tesla
Operational margin of a superconducting magnet

Applied Magnetic Field [T]

Normal state

Superconducting state

Bc critical field

quench with fast loss of
~5 \cdot 10^6 protons

Tc critical temperature

quench with fast loss of
~5 \cdot 10^9 protons

Bc critical field

8.3 T

1.9 K

0.54 T

9 K

1.9 K
Power into superconducting cable after a quench

Cross section: \( A_{sc} := 10 \cdot \text{mm}^2 \)

Current: \( I_{sc} := 10000 \cdot \text{A} \)

Length of superconductor: \( L_{sc} := 1 \cdot \text{m} \)

Copper resistance at 300 C: \( \rho_{cu} := 1.76 \cdot 10^{-6} \cdot \text{ohm} \cdot \text{cm} \)

Power into superconductor: \( P_{sc} := \rho_{cu} \cdot I_{sc}^2 \cdot \frac{L_{sc}}{A_{sc}} \rightarrow P_{sc} = 1.76 \times 10^5 \text{ watt} \)

Specific temperature of copper at 300 C: \( c_{v_{cu}} := 3.244 \cdot \frac{\text{joule}}{\text{K} \cdot \text{cm}^3} \)

Temperature increase of copper: \( \delta T := \frac{P_{sc}}{A_{sc} \cdot L_{sc} \cdot c_{v_{cu}}} \)

Temperature increase within one second: \( \delta T = 5.425 \times 10^3 \frac{\text{K}}{\text{s}} \)
Quench - transition from superconducting state to normalconducting state

- Quenches are initiated by an energy in the order of mJ (corresponds to the energy of 1000 protons at 7 TeV)
- Movement of the superconductor by several µm (friction and heat dissipation)
- Beam losses
- Failure in cooling

- To limit the temperature increase after a quench
  - The quench has to be detected
  - The energy is distributed in the magnet by force-quenching the coils using quench heaters
  - The magnet current has to be switched off within << 1 second
Current in a dipole magnets after a quench, when heaters are fired (7 TeV) - 7 MJ within 200 ms into magnet.
If this does not work...

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

P. Pugnat
From magnets to electrical circuits
Magnet inventory: about 10000 magnets

Powered in series

- Main dipole magnets (13 kA)
- Focusing and defocusing arc quadrupole magnets (13 kA)
- Lattice sextupole magnets in arcs (600 A) to correct the trajectories for off-energy particles
- Multipole and other correctors in arcs (trim quadrupoles, sextupoles, decapoles, octupoles, 600 A) to correct field imperfections, to suppress instabilities, etc.

Powered individually

- 752 arc orbit corrector magnets powered individually (60 A) to ensure that the beam follows the design orbit (within about 0.5 mm)
- Correctors to adjust beam parameters (trim quadrupoles, orbit correctors, etc., 80 – 600 A) in arcs and insertions
- Insertion main dipole and quadrupole magnets (4 – 8 kA) to ensure beam crossing / to increase the interbeam distance / to focus beams for experiments etc.
From superconducting magnet to electrical circuit

- The magnet needs to be cooled at 1.9K or 4.5K
  - Installed in a cryostat
- The magnet needs to be powered
  - Power converter at room temperature to supply the current
- The magnet must be connected
  - By superconducting cables inside the cryostat
  - By normal conducting cables outside the cryostat
- The superconducting cables must be connected to normal conducting cables
  - Connection via current leads inside special cryostat (DFB)
Interconnection of magnets inside cryostat

- Cryostated magnets with length 15 m for dipoles, 5 m for SSS
- Many cryostated magnets interconnected to make the 3 km long continuous arc cryostat
- All superconducting bus bars need to be connected for each interconnect
- Magnet in the center of the arc still powered from DFB
- Only 60 A orbit correctors powered locally
Power converters and water cooled cables

Power converter 6 kA

Water cooled cables 13 kA
DFBs with current leads - feeding current from warm to cold

DFB and HTS current leads
Interconnecting busbars
One out of 1700 interconnections (19/3/2007)

600 A bus bars (NLine)

6 kA bus bars
Magnet operation and machine protection
Energy stored in LHC main dipole magnets

\[ E_{\text{dipole}} = 0.5 \cdot L_{\text{dipole}} \cdot I_{\text{dipole}}^2 \]

Energy stored in one dipole is 7.6 MJoule
For all 1232 dipoles in the LHC: 9.4 GJ

- Too much energy for one electrical circuit
  - charging the energy requires too much voltage
  - discharging the energy is even more critical
- Subdivide LHC powering into 8 sectors
- 154 main dipole magnets in series for one sector
- Stored energy in other magnets much less, but failure could also lead to damage
What does this mean?

10 GJoule……

- corresponds to the energy of 1900 kg TNT
- corresponds to the energy of 400 kg Chocolate

- corresponds to the energy for heating and melting 12000 kg of copper

- corresponds to the energy produced by one nuclear power plant during about 10 seconds

Could this damage equipment: How fast can this energy be released?
LHC Powering in 8 Sectors

- Main DC power feed at even points (MB, MQ)
- Some DC power feed at odd points

Powering Sectors allow for progressive “Hardware Commissioning” started two years before beam.
Charging the energy: LHC magnetic cycle

- Coast
- Beam dump
- Energy ramp
- Coast

- Injection phase
- Preparation and access

- Start of the ramp

- 450 GeV
- 7 TeV

L. Bottura
LHC powered in eight sectors, each with 154 dipole magnets
Time for the energy ramp is about 20-30 min (Energy from the grid)
Time for discharge is about the same (Energy back to the grid)
• assume one magnet quenches
• assume the magnets in the string have to be discharged in, say, 200 ms

\[
U_{\text{discharge}_1} := \frac{L_{\text{dipole}} \cdot I_{\text{dipole}}}{0.2\text{s}}
\]

\[
U_{\text{discharge}_1} = 6.426 \times 10^3 \text{ V}
\]

\[
U_{\text{discharge}_{154}} := \frac{154L_{\text{dipole}} \cdot I_{\text{dipole}}}{0.2\text{s}}
\]

\[
U_{\text{discharge}_{154}} = 9.896 \times 10^5 \text{ V}
\]

Discharge with about 1 MV: not possible
• when one magnet quenches, quench heaters are fired for this magnet
• the current in the quenched magnet decays in about 200 ms
• the current in all other magnets flows through the bypass diode that can stand the current for about 100-200 seconds
Beam operation and machine protection
LHC magnetic cycle - Beam injection

injection phase
12 batches from the SPS (every 20 sec)
one batch 216 / 288 bunches

450 GeV
7 TeV

L. Bottura
Assuming that the beams are colliding at 7 TeV

Single beam lifetime larger than 100 hours…..

- **corresponds to a** loss of about 1 kW / beam
- **far** below the cooling power of the cryogenic system, **even if all particles would be slowly lost at 1.9 K**
- **losses should be** either distributed across the machine or captured in the warm cleaning insertions

Collision of beams with a luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$

- lifetime of the beam dominated by collisions
- $10^9$ protons / **second lost per beam / per experiment** (in IR 1 and IR 5 - high luminosity insertions) - this is about 1.2 kW
- large heat load **to close-by superconducting quadrupoles**
- heavy shielding **around the high luminosity IPs**
End of data taking in normal operation

- Luminosity lifetime estimated to be approximately 10 h (after 10 hours only 1/3 of initial luminosity)
- Beam current somewhat reduced - but not much
- Energy per beam still about 200-300 MJ
- Beams are extracted in beam dump blocks

- The only component that can stand a fast loss of the full beam at top energy is the beam dump block - all other components would be damaged
- At 7 TeV, fast beam losses with an intensity of about 5% of one “nominal bunch (from 2808)” could damage superconducting coils
LHC ring
3 insertions for machine protection systems

IR1: ATLAS
IR2: ALICE
IR3: Momentum Beam Cleaning (warm)
IR4: RF + Beam instrumentation
IR5: CMS
IR6: Beam dumping system
IR7: Betatron Beam Cleaning (warm)
IR8: LHC-B

Injection
Injection
Beam dump blocks
Beam losses into material

- Proton losses lead to particle cascades in materials
- The energy deposition leads to a temperature increase
- For the maximum energy deposition as a function of material there is no straightforward expression
- Programs such as FLUKA are being used for the calculation of the energy deposition

Magnets could quench…..
  - beam lost - re-establish condition takes several hours

The material could be damaged…..
  - melting
  - losing their performance (mechanical strength)

Repair could take several weeks or more
Damage of material for impact of a pencil beam

Maximum energy deposition in the proton cascade (one proton) \( E_{\text{max,Cu}} := 1.5 \cdot 10^{-5} \, \text{J/kg} \)

Specific heat of copper is \( c_{\text{Cu,spec}} = 384.5600 \, \frac{\text{J}}{\text{kg K}} \)

To heat 1 kg copper by, say, by \( \Delta T := 500 \, \text{K} \), one needs: \( c_{\text{Cu,spec}} \cdot \Delta T \cdot 1 \, \text{kg} = 1.92 \times 10^5 \, \text{J} \)

Number of protons to deposit this energy is: \( \frac{c_{\text{Cu,spec}} \cdot \Delta T}{E_{\text{max,Cu}}} = 1.28 \times 10^{10} \)

Maximum energy deposition in the proton cascade (one proton) \( E_{\text{max,C}} := 2.0 \cdot 10^{-6} \, \text{J/kg} \)

Specific heat of graphite is \( c_{\text{C,spec}} = 710.6000 \, \frac{\text{J}}{\text{kg K}} \)

To heat 1 kg graphite by, say, by \( \Delta T := 1500 \, \text{K} \), one needs: \( c_{\text{C,spec}} \cdot \Delta T \cdot 1 \, \text{kg} = 1.07 \times 10^6 \, \text{J} \)

Number of protons to deposit this energy is: \( \frac{c_{\text{C,spec}} \cdot \Delta T}{E_{\text{max,C}}} = 5.33 \times 10^{11} \)
SPS experiment: Beam damage at 450 GeV

Controlled SPS experiment
- $8 \cdot 10^{12}$ protons clear damage
- beam size $\sigma_{x/y} = 1.1\text{mm}/0.6\text{mm}$ above damage limit

- $2 \cdot 10^{12}$ protons below damage limit

0.1 % of the full LHC beams

V.Kain et al
Schematic layout of beam dump system in IR6

- Septum magnet deflecting the extracted beam
- H-V kicker for painting the beam
- Fast kicker magnet
- Beam Dump Block

About 700 m
About 500 m
Beam Dump Block - Layout

- Beam absorber (graphite)
- About 8 m
- Concrete shielding

L. Bruno
initial transverse beam dimension in the LHC about 1 mm

beam is blown up due to long distance to beam dump block

additional blow up due to fast dilution kickers: painting of beam on beam dump block

beam impact within less than 0.1 ms

about 35 cm
Temperature of beam dump block at 80 cm inside

L. Bruno: Thermo-Mechanical Analysis with ANSYS
Beam dump must be synchronised with particle free gap.

Strength of kicker and septum magnets must match energy of the beam.

“Particle free gap” must be free of particles.

Requirement for clean beam dump:

- Particle free abort gap of 3 µs
- Kicker magnets constant angle
- Illustration of kicker risetime
### Lifetime of the beam with nominal intensity at 7 TeV

<table>
<thead>
<tr>
<th>Beam lifetime</th>
<th>Beam power into equipment (1 beam)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 h</td>
<td>1 kW</td>
<td>Healthy operation</td>
</tr>
<tr>
<td>10 h</td>
<td>10 kW</td>
<td>Operation acceptable, <strong>collimation must absorb large fraction of beam energy</strong> (approximately beam losses = cryogenic cooling power at 1.9 K)</td>
</tr>
<tr>
<td>0.2 h</td>
<td>500 kW</td>
<td><strong>Operation only</strong> possibly for <strong>short time</strong>, collimators must be very efficient</td>
</tr>
<tr>
<td>1 min</td>
<td>6 MW</td>
<td>Equipment or operation <strong>failure</strong> - operation not possible - <strong>beam must be dumped</strong></td>
</tr>
<tr>
<td>&lt;&lt; 1 min</td>
<td>&gt; 6 MW</td>
<td><strong>Beam</strong> must be <strong>dumped VERY FAST</strong></td>
</tr>
</tbody>
</table>

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Failures will be a part of the regular operation and MUST be anticipated
Basic concept of two stage collimation

Jaws (blocks of solid materials such as copper, graphite, ….) very close to the beam to absorb more than 99.9 % of protons that would be lost

Primary collimators: Intercept primary halo
Impact parameter: \(\sim 1 \ \mu m\)
Scatter protons of primary halo
Convert primary halo to secondary off-momentum halo

Secondary collimators: Intercept secondary halo
Impact parameter: \(\sim 200 \ \mu m\)
Absorb most protons
Leak a small tertiary halo
Beam +/- 3 sigma

~5 mm

Beam in vacuum chamber with beam screen at 450 GeV
Beam in vacuum chamber with beam screen at 7 TeV

Beam +/- 3 sigma

~1.3 mm

56.0 mm
Collimators at 7 TeV, squeezed optics

Example: Setting of collimators at 7 TeV - with luminosity optics

Beam must always touch collimators first!
RF contacts for guiding image currents

Beam spot

2 mm
Accidental kick by the beam dump kicker at 7 TeV
part of beam touches collimators (about 20 bunches from 2800)
Accidental kick by the beam dump kicker at 7 TeV
part of beam touches collimators (about 20 bunches from 2808)
The LHC Phase 1 Collimator

Vacuum tank with two jaws installed

Designed for maximum robustness:

Advanced Carbon Composite material for the jaws with water cooling!

R. Assmann et al
First collimator in the tunnel
Optimisation of Beam Cleaning system

- Requirements for collimation system take into account failure scenarios and imperfect operation
  - Worst case is the impact of about 20 bunches on the collimator due to pre-firing of one dump kicker module

- Material for collimator: low Z material is favoured
- Impedance to be considered - conducting material is favoured
- more exotic materials are considered: copper loaded graphite, beryllium, partially plated copper ....
<table>
<thead>
<tr>
<th>Single turn beam loss during injection and beam dump</th>
<th>Passive protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Avoid such failures (high reliability systems - work is ongoing to better estimate reliability)</td>
<td></td>
</tr>
<tr>
<td>• Rely on collimators and beam absorbers</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Multiple turn beam loss due to many types of failures</th>
<th>Active Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Failure detection (from beam monitors and / or equipment monitoring)</td>
<td></td>
</tr>
<tr>
<td>• Issue beam abort signal</td>
<td></td>
</tr>
<tr>
<td>• Fire Beam Dump</td>
<td></td>
</tr>
</tbody>
</table>

In case of **any failure** or **unacceptable beam lifetime**, the **beam** must be **dumped immediately**, safely into the **beam dump block**
Beam Interlock System

Based on R. Schmidt's drawing
Primary strategy for protection: Beam loss monitors at collimators and other aperture limitations continuously measure beam losses

- Beam loss monitors indicate increased losses => MUST BE FAST

When beam losses exceed threshold

- Beam loss monitors break Beam Permit Loop
- Beam dump sees “No Beam Permit” => dump beams
From construction to operation
Commissioning of all technical systems that do not require beam: “Hardware commissioning”

- about 10000 magnets (most of them superconducting)
- 26 km cryogenic distribution line
- 26 km cryogenic magnets
- 4 vacuum systems, each 27 km long
- > 1600 magnet powering circuits with power converters (60A to 13000kA)
- quench protection and powering interlock systems
- commissioning of about 90% of the investment

> 10000 electronics crates for operation and protection
LHC Powering in 8 Sectors

Powering individual sectors: eight accelerators, only coupled by the beam.

One sector 1.5\textcdot mass of HERA
Hardware commissioning sequence

• Commissioning power converters on short circuit (including cooling and ventilation, controls, others, …)

When all magnets installed and interconnected

• Pumping vacuum system to nominal pressure
• Cooling down sector to 1.9 (4.5) Kelvin
• Connection of power converter to magnets via current leads
• Commissioning of the power converter + interlock system + magnet protection system (low current)
• Commissioning of magnet powering + magnet protection system (high current)
• Powering of all magnets in a sector to nominal current
Power converters installed and commissioning on short circuits in tunnel

- 81 power converters in UA83
- 156 kA and 1.2 MW dissipated: PCs and Cables

F. Bordry, 11-2005
High current power converter

Location: UA83 (Beginning)
Equipt type: LHC2-4-6-8kA
SP1 T°C: 46°
% conf.: 90%
Date: 2005-10-13 11h00

F.Bordry, 11-2005
24h endurance test of power converters and electrical network

(13-14 October 2005)
Cooldown of sector 7-8

Magnet temperature profile along sector 78 at 12:15 Apr 09

Evolution of magnet temperatures in Sector 78

Temperature [K]

Move cursor to yellow square to identify magnet

Point 7   Mid Arc   Point 8

3 km
Cooldown details

LHC sector 78 - First cooldown - Phase 4.5 K to 1.9 K

4.5 K refrigerator supply temperature
(before expansion valve)

Magnet average temperature

1.8 K refrigeration unit supply temperature
(equivalent saturation temperature)

Pumpdown to 15 mbar in magnet heat exchanger

Time (UTC)

- 4.5 K refrigerator supply temperature
- 1.8 K refrigeration unit cooling temperature
- Magnet temperature (average over sector)

1. Tuning of cold compressors & turbines with temporary stop of magnet cooling
2. Stop of active cooling in weekend with only on-call activity limited to secure hardware
3. Stop of magnet cooling for logic improvement in 1.8K refrigeration unit
4. Random emergency stop in cryogenic surface building with stop of sector 78 cooling
5. Micro-electrical stop followed by utility stops
Status summary

- Magnet production completed
- Installation and interconnections in progress, few magnets still to be put in place
- Cryogenics
  - One sector being cooled down
  - Large part finished and operational (e.g. cryoplants)
  - QRL being installed and partial commissioning started
- Powering system: commissioning started
  - Power converters installed and commissioning on short circuits in tunnel, 80% done
- Other systems (RF, Beam injection and extraction, Beam instrumentation, Collimation, Interlocks, Controls)
  - Essentially on schedule for first beam in 2007/8
- Injector complex ready
Recalling LHC challenges

- Enormous amount of equipment
- Complexity of the LHC accelerator
- New challenges in accelerator physics with LHC beam parameters pushed to the extreme

Updated schedule expected for May
It would be wonderful to always report on smooth progress, but this is not the case.....and unrealistic

- The LHC is a machine with unprecedented complexity
- The technology is pushed to its limits
- The LHC is a ONE-OFF machine
- The LHC was constructed during a period when CERN was asked to substantially reduce the personnel

- Problems came up and were solved / are being solved: dipole magnets, cryogenics distribution line, collimators, inner triplet, ....

In my view, such project can only be successful not because of the absence of problems, but because problems are detected and addressed with competent and dedicated staff and collaborators
Conclusions

- The LHC is a global project with the world-wide high-energy physics community devoted to its progress and results.

- As a project, it is much more complex and diversified than the SPS or LEP or any other large accelerator project constructed to date.

Machine Advisory Committee, chaired by Prof. M. Tigner, March 2002

- No one has any doubt that it will be a great challenge for both machine to reach design luminosity and for the detectors to swallow it.

- However, we have a competent and experienced team, and 30 years of accumulated knowledge from previous CERN projects has been put into the LHC design.

L. Evans, Project Leader
Acknowledgement

The LHC accelerator is being realised by CERN financed by the CERN member states, in collaboration with institutes from many countries over a period of more than 20 years.

Main contribution come from the USA, Russia, India, Canada, special contributions from France and Switzerland.

Industry plays a major role in the construction of the LHC.

Thanks for the material from:

and thanks to the organisers for inviting me giving this presentation
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