Status of the LHC

Rüdiger Schmidt - CERN
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Paris

Challenges
Status
Future

On behalf of the CERN staff and the outside collaborators
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

The Status and the complexity of the LHC is documented in more than 80 papers at this conference - this talk is considered as a very brief overview.
Outline

- Parameters and layout
- The LHC and some of its challenges
- Injectors and transfer
- Magnets and other systems
- Accelerator physics and LHC operation
- Validation of systems: String 2
- From building components to colliding beams
- Conclusions
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum at collision</td>
<td>7 TeV/c</td>
</tr>
<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>Luminosity</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>Stored energy per beam</td>
<td>350 MJ</td>
</tr>
<tr>
<td>Normalised emittance</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>Arcs: Counter-rotating proton beams in two-in-one magnets</td>
<td></td>
</tr>
<tr>
<td>Magnet coil inner diameter</td>
<td>56 mm</td>
</tr>
<tr>
<td>Distance between beams</td>
<td>194 mm</td>
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**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
Layout of the LHC ring: 8 arcs, and 8 long straight sections

- RF + Beam instrumentation
- Beam dump system
- Betatron Cleaning
- Momentum Cleaning

One sector = 1/8
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

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

Connection via service module and jumper
Insulation vacuum for the cryogenic distribution line

Regular arc: Vacuum

Beam vacuum for Beam 1 + Beam 2

Insulation vacuum for the magnet cryostats
Along the arc about several thousand electronic crates (radiation tolerant) for:

- quench protection
- power converters for orbit correctors
- instrumentation (beam, vacuum + cryogenics)

Presentation R. Rausch, WEALA003
Interconnection between magnets: LEP
One of 1800 interconnection between two superconducting magnets: LHC

6 superconducting bus bars 13 kA for B, QD, QF quadrupole

20 superconducting bus bars 600 A for corrector magnets (minimise dipole field harmonics)

13 kA Protection diode

42 sc bus bars 600 A for corrector magnets (chromaticity, tune, etc....) + 12 sc bus bars for 6 kA (special quadrupoles)

To be connected:

• Beam tubes
• Pipes for helium
• Cryostat
• Thermal shields
• Vacuum vessel
• Superconducting cables

Posters: MOPLE080 MOPDO014
Challenges: Energy stored in the beam

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

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

- The SPS accelerates beam 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
Twelve out of 72 bunches on the last turn of the PS (30 ns/div).

Mountain range display of bunch splitting at 1.4 GeV (30 ns/div).

Zoom on one bunch (bottom, 1 ns/div).

Courtesy R. Garoby.
2001: emittance blowup along the ramp, due to the beam induced electron cloud instability (secondary electrons accelerated and multiplied due to high beam intensity) but still below nominal for LHC - at reduced beam current

2002: beam scrubbing reduced secondary emission => no blow up along injection plateau - studies continue

Emittance as a function of momentum during the 2001 run (reduce beam current)
Two new transfer line tunnels from SPS to LHC are being built. The beam lines use normal conducting magnets.

Length of each line: about 2.8 km

Magnets are all available, made by BINP / Novosibirsk

Commissioning of the first line for 2004

Dipole magnets waiting for installation
LHC: Superconducting Magnets

Arc 15-m dipoles and quadrupoles

Insertion dipoles and quadrupoles

Corrector magnets

See Poster session MOPLE this afternoon

Presentation by T. Taylor on Super LHC magnets - MOYGB002

Dipole assembly in industry
After many years of R&D, six prototypes have been built by industry.

Later, 90 pre-series magnets were ordered from three firms and are now in production. Several ten collared coils were made.

Three contracts for the fabrication of all magnets were awarded.

Planning of the cold mass production.
Superconducting main dipoles: cable delivery status and future schedule

Cable production now following the adjusted planning

A. Verweij
Training of pre-series main dipole magnets

- Magnetic Field at Quench B [Tesla]

- Magnetic Field at Quench B

- No Quench

- Provoked Quench

- Ultimate field 9 Tesla

- Nominal field 8.38 Tesla

- A. Siemko
Field harmonics: Correction of the sextupole harmonics in the main dipole magnets

Small changes of the cross section to improve b3 multipole
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

A. Rijllart - MOPDO013
Main arc quadrupole magnets and special quadrupole magnets for the matching sections

Contribution from CEA/Saclay and CNRS (France) to the LHC:

- Prototypes of arc quadrupoles were developed and constructed
- Production was launched in industry
  - Tooling for the fabrication is operational
  - Fabrication of the coils started
  - Delivery of the first magnet in the cryostat expected for the second half of 2002

Insertion quadrupoles will be also fabricated by industry - 1st pre-series for the end of year 2002
Sextupoles and decapoles to be installed at the extremities of the main dipoles

Delivery must precede dipole magnet fabrication (contribution from India and fabrication in industry)
Insertion magnets: Dipoles from BNL (USA) for beam separation / recombination

- 3rd D1 on Test Stand
- 1st D2 on Test Stand
- 2nd D2 awaiting test
- 3rd D2 on cryostat insertion fixture
- 4th D2 awaiting cryostat insertion

Poster session MOPLE
Insertion magnets: Quadrupoles from KEK (Japan) and FERMILAB (USA)

Challenging inner triplet quadrupole magnets with very high gradient from KEK and FERMILAB

Arrival of magnet from KEK at FERMILAB to be installed into the triplet cryostat
Normal Conducting Magnets: Double aperture quadrupole magnets for the cleaning insertions (warm)

One third of the magnets have been produced (collaboration with TRIUMF / Canada)
Four new 18 kW plants are added to four existing plants from LEP.

26 km long Cryoline: three 100 m prototypes were built and validated.

Contract for construction and installation of the line has been awarded.

Installation starts in 2003.

One new plant is being commissioned.
Cryogenic System: Preparation of Cold Compressor Tests

First cold hydrodynamic compressors have been delivered from IHI (Japan) / industry and are being tested at CERN - with promising results.
RF systems: 400 MHz and possibly 200 MHz

400 MHz system:
all 16 sc cavities (copper sputtered with niobium) for 16 MV/beam were built and assembled in four modules

200 MHz warm system:
Decision for implementation to be taken in 2004 - to ease the injection process

Power test of the first module
Beam vacuum system

Beam screen is required for most of the machine

Ensures vacuum stability

Captures synchrotron radiation at 5-20 K

Beam stability => Low impedance: thin copper layer
MOPLE047 MOPLE048

Electron cloud effects:
- Minimise reflectivity
- Beam scrubbing (as in SPS)

Electron clouds: Several contributions in various sessions
Powering and Quench Protection

- Almost 1800 circuits from 60 A to 24 kA distributed around the 27 km LHC accelerator => 1800 Power Converter

- The eight sectors of the LHC are largely independent - accurate tracking of current is required

- Very high performance is needed for the 24 main circuits with main dipole and quadrupole magnets at \( I = 12 \, \text{kA} \)
  - For the main circuits the current needs to be controlled at the ppm level (12 mA at 12 kA)

- Protection of 8000 magnets, 1800 High Temperature Superconductor current leads, and a large number of superconducting bus bars
Machine protection: Magnet energy

Energy in dipole magnets: 10 GJoule
… per sector reduced to 1.3 GJoule

Uncontrolled release of energy is prevented:

- Fire quench heaters
- Current by-passes magnet via power diode
- Extract energy by switching a resistor into the circuit - the resistor with a mass of eight tons is heated to 300 °C

All components of the system have been validated, and production started (part in collaboration with Russia and India)

13 kA switches from Protvino Russia
Accelerator physics and operation

- **Dynamic aperture of 11 sigma**: for all magnets the maximum tolerated multipoles were specified.

- Preparations based on very well controlled slow ramp with PELP function (parabolic, exponential, linear and parabolic).

- Accurate modelling of beam dynamics through the cycle:
  - Magnetic multipoles
  - Dynamic effects in superconducting magnets
  - Beam beam effects - head on / parasitic crossings

- Preparation of **slow feedback** for tune and orbit, and possibly chromaticity - prototyping at the SPS.

- Online magnetic measurements (**multipole factory**) for feed-forward to corrector circuits.
**Machine protection: Beam energy**

**For 7 TeV:** fast beam loss between $10^6$ and $10^7$ protons could quench a dipole magnet.

**The beam dump block is the only system that can stand the full 7 TeV beam - $3 \times 10^{14}$ protons**

**Beam Cleaning:** Capture particles in the warm sections of the LHC with an efficiency of better than 99.9% to avoid losses that could quench superconducting magnets.

In case of equipment failure, beam instabilities etc:

- Capture initial beam losses that could damage LHC equipment.
- Beam Loss Monitors close to collimators and other aperture restrictions produce a fast and reliable signal to dump the beam if beam losses become unacceptable.

E.Gschwendtner THPRI083
Collimators must always touch beam first!

Collimators are close to the beam during energy ramp

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

- Definition of requirements for collimation system - taking 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
- Optimisation of the robustness of the cleaning system
- Material for collimator is being reconsidered - low Z material is favoured
- Proceed with the technical design of the collimators

several papers: MOPLE032  TUAGB001 MOPLE030 WEPLE044 and presentation R.Assmann, TUAGB001
Prototype LHC cell: the 110 m long String 2

Full size model of one LHC cell (six dipoles and two quadrupoles)

2001: 3 dipoles and 2 quadrupoles
Cooled down to 1.9 K and one dipole and two quadrupole circuits were powered to nominal current

Cell has been completed (now six dipoles) and is today being cooled down

Experiment were performed in 2001 and will continue soon
String 2: First Powering of dipole magnets
String 2: Start of the LHC dipole circuit ramp (0-20s) simulates ramp after injection of beam at 450 GeV

50 ppm of full current = 350 MeV

Q. King et al. ICALEPS 2001
Results were achieved with a new method of digital regulation together with an ultra high precision current measurement system.
Integration and Installation

- Space in tunnel and underground areas is limited
- Equipment for many systems need to be installed
- 3-D computer model for tunnel and underground areas
Conclusions

- Civil engineering is nearly completed
- Most contracts with industry for equipment supply have been awarded
- Fabrication of equipment under the responsibility of other labs goes well

**Planning can now be based on deliveries and contractual documents**

The LHC is installed and commissioned in eight (rather) independent sectors - that allows for **activities to be performed in parallel**

Installation of LHC started with “general services” March 2002
Conclusions

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<tr>
<th>From now to 2006</th>
<th>Fabrication of equipment</th>
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<tr>
<td></td>
<td>Installation of completed components</td>
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<td>Very thorough <strong>commissioning</strong> of the <strong>hardware systems</strong> starting in 2005, <strong>sector by sector</strong>, as key for successful fast start up with beam</td>
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</table>

String 2 gave us a lot of confidence as we observed a smooth commissioning of the hardware systems

In **2006 - one beam injected and transported** across two sectors (25% of the ring)

**Start-up with two beams in spring 2007**