LHC status & prospects
Dr. Frédérick Bordry
Large Hadron Collider Physics (LHCP) conference
New York - 2nd June 2014
Outline

- LHC recall and Run 1
- LS1 status
- Run 2 (from LS1 to LS2) $\Rightarrow 13-14 \text{ TeV}$
- LS2 and Run 3 $\Rightarrow 300 \text{ fb}^{-1}$
- High Luminosity LHC project
- LHC Roadmap up 2035 $\Rightarrow 3’000 \text{ fb}^{-1}$
- Post-LHC machine
LHC (Large Hadron Collider)

14 TeV proton-proton accelerator-collider built in the LEP tunnel

Lead-Lead (Lead-proton) collisions

1983: First studies for the LHC project
1988: First magnet model (feasibility)
1994: Approval by the CERN Council
1996-1999: Series production industrialisation
1998: Declaration of Public Utility & Start of civil engineering
1998-2000: Placement of the main production contracts
2004: Start of the LHC installation
2005-2007: Magnets Installation in the tunnel
2006-2008: Hardware commissioning
2008-2009: Beam commissioning and repair
2010-2035: Physics exploitation
June 1994
first full scale prototype dipole

1994 project approved by council (1-in-2)

ECFA-CERN workshop

June 2007 First sector cold

April 2008
Last dipole down

25 years

Main contracts signed

2002 String 2

November 2006
1232 delivered

9T - 1m single bore

Decision for Nb-Ti

9T - 10 m prototype

September 10, 2008
First beams around
2010-2012 (Run 1): LHC integrated luminosity

CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC

- 2010: 0.04 fb^{-1}
  - 7 TeV CoM Commissioning
- 2011: 6.1 fb^{-1}
  - 7 TeV CoM ... exploring limits
- 2012: 23.3 fb^{-1}
  - 8 TeV CoM ... production

BEH boson announce

L_{peak} = 0.77 \times 10^{34}

7 TeV and 8 TeV in 2012
Up to 1380 bunches with 1.5 \times 10^{11} protons
LS1 starts as the shutdown to repair the magnet interconnects to allow nominal current in the dipole and lattice quadrupole circuits of the LHC.

All this in the shadow interconnects.
LS 1 from 16th Feb. 2013 to Dec. 2014

- **LHC**: 16th Feb. 2013 to 2nd June 2014
- **SPS**: 16th Feb. 2013 to Dec. 2014
- **PS**: 16th Feb. 2013 to Dec. 2014
- **PS Booster**: 16th Feb. 2013 to Dec. 2014

**Available for works**
- **Physics**
- **Beam commissioning**
- **Shutdown**
- **Powering tests**

**Timeline**
- **2013**: 16th Feb.
- **2014**: 16th Feb. to 2nd June
- **2015**: 16th Feb. to Dec.
LHC Injectors start-up

LHC-injectors … getting ready for beams
- PSB & PS: hardware tests started in April
- Cold check-out phases well advanced
- SPS: powering tests will start by end of June
The main 2013-14 LHC consolidations

Opening: 100%
1695 Openings and final reclosures of the interconnections

Closure: 95%

100 % done
Complete reconstruction of 3000 of these splices

100 % done
Consolidation of the 10170 13kA splices, installing 27 000 shunts

100 % done
Installation of 5000 consolidated electrical insulation systems

100 % done
300 000 electrical resistance measurements

100 % done
10170 orbital welding of stainless steel lines

80 % done
18 000 electrical Quality Assurance tests

80 % done
10170 leak tightness tests

80 % done
3 quadrupole magnets to be replaced

90 % done
Consolidation of the 13 kA circuits in the 16 main electrical feedboxes

100 % done
15 dipole magnets to be replaced

100 % done
Installation of 612 pressure relief devices to bring the total to 1344

Done
Done
Superconducting Magnets And Circuits Consolidation Dashboards

SMACC

Updated 21-May-2014

Baseline (14.03.2013)
Completed
Forecast

3 weeks

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The other activities

- Vacuum
- UPS-RE82
- 18 kV & 3.3 kV circuit breakers
- Before
- After
- Cryo plant
- Pumping station
- Helium spill test
- P7 enclosure
- ACS transport

Courtesy of Katy Foraz
13 TeV operation
LS1 status

LHC injectors getting ready for beams

LHC: all signals are green for beam on January 2015
LHC schedule: Run2 and LS2

LS2 starting in **2018 (July)**  ➞ 18 months + 3 months BC

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<tr>
<th>Year</th>
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<th>Q4</th>
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<td>2019</td>
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**(Extended) Year End Technical Stop: (E)YETS**

**Run 2:**
Start with **13 TeV** and later decision towards **14 TeV** according to magnet training
Expectations after Long Shutdown 1 (2015)

- Collisions at least at $13 \text{ TeV } c.m.$
- **25 ns** bunch spacing
  Using new injector beam production scheme (BCMS), resulting in brighter beams.

- $\beta^* \leq 0.5 \text{m}$ (was 0.6 m in 2012)
- Other conditions:
  - Similar turn around time
  - Similar machine availability

- Expected maximum luminosity: $1.6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \pm 20\%$
  - Limited by inner triplet heat load limit, due to collisions debris

<table>
<thead>
<tr>
<th>Number of bunches</th>
<th>Intensity per bunch</th>
<th>Transverse emittance</th>
<th>Peak luminosity</th>
<th>Pile up</th>
<th>Int. yearly luminosity</th>
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<tbody>
<tr>
<td>25 ns BCMS</td>
<td>2508</td>
<td>$1.15 \times 10^{11}$</td>
<td>1.9 $\mu$m</td>
<td>$1.6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$</td>
<td>~43</td>
</tr>
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</table>

Batch Compression and Merging and splitting (BCMS)

Courtesy of the LIU-PS project team
### Potential performance

<table>
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<tr>
<th>Number of bunches</th>
<th>Ib LHC [1e11]</th>
<th>Collimator scenario</th>
<th>Emit LHC (SPS) [um]</th>
<th>Peak Lumi [cm^{-2}s^{-1}]</th>
<th>~Pile-up</th>
<th>Int. Lumi [fb^{-1}]</th>
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<tbody>
<tr>
<td>25 ns</td>
<td>2760</td>
<td>1.15</td>
<td>S1</td>
<td>3.5 (2.8)</td>
<td>9.2e33</td>
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<tr>
<td>25 ns low emit</td>
<td><strong>2508</strong></td>
<td>1.15</td>
<td><strong>S4</strong></td>
<td>1.9 (1.4)</td>
<td><strong>1.6e34</strong></td>
<td><strong>43</strong></td>
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<tr>
<td>50 ns</td>
<td>1380</td>
<td>1.6</td>
<td>S1</td>
<td>2.3 (1.7)</td>
<td>1.7e34</td>
<td>levelling 40</td>
</tr>
<tr>
<td>50 ns low emit</td>
<td>1260</td>
<td>1.6</td>
<td>S4</td>
<td>1.6 (1.2)</td>
<td>2.2e34</td>
<td>108</td>
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</table>

- 13 TeV
- 1.1 ns bunch length
- 150 days proton physics, HF = 0.2

*All numbers approximate*

* different operational model – caveat - unproven
LINAC4 – PS Booster:
- H⁻ injection and increase of PSB injection energy from 50 MeV to 160 MeV, to increase PSB space charge threshold
- New RF cavity system, new main power converters
- Increase of extraction energy from 1.4 GeV to 2 GeV

PS:
- Increase of injection energy from 1.4 GeV to 2 GeV to increase PS space charge threshold
- Transverse resonance compensation
- New RF Longitudinal feedback system
- New RF beam manipulation scheme to increase beam brightness

SPS
- Electron Cloud mitigation – strong feedback system, or coating of the vacuum system
- Impedance reduction, improved feedbacks
- Large-scale modification to the main RF system

These are only the main modifications and this list is far from exhaustive
Project leadership: R. Garoby and M. Meddahi
**LHC schedule: LS3 ³ and Run 3**

LS2 starting in **2018 (July)**  =>  **18 months + 3 months BC**

LS3  LHC: starting in **2023**  =>  **30 months + 3 months BC**

Injectors: in **2024**  =>  **13 months + 3 months BC**

*(Extended) Year End Technical Stop: (E)YETS*

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**30 fb⁻¹**

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<td>Q1</td>
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<td>Q3</td>
</tr>
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</table>

**LHC**

- **Run 2**
- **LS 2**
- **Run 3**

**Injectors**

**300 fb⁻¹**

**PHASE 1**

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**LS3 : HL-LHC installation**
c) Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.

HL-LHC from a study to a PROJECT
300 fb\(^{-1}\) → 3000 fb\(^{-1}\)
including LHC injectors upgrade LIU
(Linac 4, Booster 2GeV, PS and SPS upgrade)
“...exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine...”

=> High Luminosity LHC (HL-LHC)

HiLumi LHC-LARP

Daresbury Laboratory, UK
3rd Joint Annual Meeting
11-15 November 2013

Kick-off meeting: 11th Nov. 2013 (Daresbury)

http://cern.ch/hilumilhc


LEP: Construct. Physics Upgr

LHC: Design, R&D Proto Constr

HL-LHC: Design
The HL-LHC Project

- New IR-quads $\text{Nb}_3\text{Sn}$ (inner triplets)
- New 11 T $\text{Nb}_3\text{Sn}$ (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- ...

Major intervention on more than 1.2 km of the LHC

Project leadership: L. Rossi and O. Brüning
Squeezing the beams: High Field SC Magnets

Quads for the inner triplet
Decision 2012 for low-\(\beta\) quads
Aperture \(\Omega \) 150 mm – 140 T/m
\(B_{\text{peak}} \approx 12.3\) T

\(LHC: 8\) T, 70 mm

More focus strength,
\(\beta^*\) as low as 15 cm (55 cm in LHC)

*thanks to ATS (Achromatic Telescopic Squeeze) optics*

In some scheme even \(\beta^*\) down to 7.5 cm are considered

- Dipoles 11 T for LS2
- Dipoles for beam recombination/separation capable of 6-8 T with 150-180 mm aperture

\(LHC: 1.8\) T, 70 mm
LQS01a: 202 T/m at 1.9 K
LQS01b: 222 T/m at 4.6 K
227 T/m at 1.9 K

LQS02: 198 T/m at 4.6 K 150 A/s
208 T/m at 1.9 K 150 A/s limited by one coil

LQS03: 208 T/m at 4.6 K
210 T/m at 1.9 K

Target:
200 T/m gradient at 1.9 K

1st quench: 86% s.s. limit

3.3 m coils
90 mm aperture

Courtesy: G. Ambrosio FNAL and G. Sabbi, LBNL
LS2 : collimators and 11T Dipole

- LS2 2017-18: Point-X, 7 & IR-2
- LS3 2020+: IR1,5 as part of HL-LHC

\[ J_{BdL} = 119.2 \text{ Tm} @ I_{\text{nom}} = 11.85 \text{ kA} \]

in series with MB with 20% margin

<table>
<thead>
<tr>
<th>LS2</th>
<th>LS3</th>
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<tr>
<td>12 coldmass + 2 spares = 14 CM</td>
<td>8 coldmass + 2 spares = 10 CM</td>
</tr>
<tr>
<td>Total</td>
<td>24 CM</td>
</tr>
<tr>
<td>24 coldmass + 4 spares = 28 CM</td>
<td>16 coldmass + 4 spares = 20 CM</td>
</tr>
<tr>
<td>Total</td>
<td>48 CM</td>
</tr>
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</table>
Nb$_3$Sn 11T Dipole R&D

Single aperture model  
Twin aperture model
Crab Cavities, Increase “Head on”

Aim: reduce the effect of the crossing angle

Without crabbing

\[ \theta_c \]

Without crabbing

\[ \theta_c \]

New crossing strategy under study to soften the pile-up density: some new schemas have interesting potential as “crab-kissing”, to be discussed with all experiments

- 3 proto types available
- Cavity tests are on-going
- Test with beam in SPS foreseen in 2015-2016
- Beam test in LHC foreseen in 2017
Setting up International collaboration

Baseline layout of HL-LHC IR region

with national laboratories but also involving industrial firms
Luminosity Levelling, a key to success

- High peak luminosity
- Minimize pile-up in experiments and provide “constant” luminosity

- Obtain about 3 - 4 fb\(^{-1}\)/day (40% stable beams)
- About 250 to 300 fb\(^{-1}\)/year
### Baseline parameters of HL for reaching 250 - 300 fb⁻¹/year

<table>
<thead>
<tr>
<th></th>
<th>25 ns</th>
<th>50 ns</th>
</tr>
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<tr>
<td># Bunches</td>
<td>2808</td>
<td>1404</td>
</tr>
<tr>
<td>$p/bunch \times 10^{11}$</td>
<td>2.0 (1.01 A)</td>
<td>3.3 (0.83 A)</td>
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<tr>
<td>$\varepsilon_L \ [\text{eV.s}]$</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>$\sigma_z \ [\text{cm}]$</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>$\sigma_{\delta p/p} \times 10^{-3}$</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>$\gamma \varepsilon_{x,y} \ [\mu \text{m}]$</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>$\beta^* \ [\text{cm}] \ (\text{baseline})$</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>X-angle [\mu rad]</td>
<td>590 (12.5 $\sigma$)</td>
<td>590 (11.4 $\sigma$)</td>
</tr>
<tr>
<td>Loss factor</td>
<td>0.30</td>
<td>0.33</td>
</tr>
<tr>
<td>Peak lumi [$10^{34}$]</td>
<td>6.0</td>
<td>7.4</td>
</tr>
<tr>
<td>Virtual lumi [$10^{34}$]</td>
<td>20.0</td>
<td>22.7</td>
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<tr>
<td>$T_{\text{leveling}} \ [\text{h}] @ 5\times 10^{34}$</td>
<td>7.8</td>
<td>6.8</td>
</tr>
<tr>
<td>#Pile up @5E34</td>
<td>123</td>
<td>247</td>
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25 ns is the option

However: 50 ns should be kept as alive and possible because we DO NOT have enough experience on the actual limit (e-clouds, $l_{beam}$)

Continuous global optimisation with LIU
LHC roadmap: schedule beyond LS1

LS2 starting in 2018 (July) => 18 months + 3 months BC
LS3 LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC

(Extended) Year End Technical Stop: (E)YETS

### 30 fb⁻¹

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- **LHC**
- **Injectors**

#### PHASE 1

- **YETS**
- **Run 2 EYETS**
- **YETS LS 2**
- **Run 3 YETS**

### 300 fb⁻¹

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<th>Year</th>
<th>2022</th>
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- **LHC**
- **Injectors**

#### PHASE 2

- **YETS LS 3**
- **Run 4**

### 3'000 fb⁻¹

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- **LHC**
- **Injectors**

**LHC schedule approved by CERN management and LHC experiments spokespeople and technical coordinators (December 2013)**
CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.

“to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update”
Magnet design (20 T): very challenging but not impossible.
300 mm inter-beam
Multiple powering in the same magnet (and more sectioning for energy)
Work for 4 years to assess HTS for 2x20T to open the way to 16.5 T/beam.
Otherwise limit field to 15.5 T for 2x13 TeV
Higher INJ energy is desirable (2xSPS)

The synchrotron light is not a stopper by operating the beam screen at 60 K.
The beam stability looks «easier» than LHC thanks to dumping time.
Collimation is possibly not more difficult than HL-LHC. Reaching 2x10^{34} appears reasonable.

Beam handling for INJ & beam dump: need more room for LHC kickers.
First studies on a new 80 km tunnel in the Geneva area

- 42 TeV with 8.3 T using present LHC dipoles
- 80 TeV with 16 T based on Nb₃Sn dipoles
- 100 TeV with 20 T based on HTS dipoles

HE-LHC: 33 TeV with 20T magnets
80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements (FCC-hh) with possibility of e+-e- (FCC-ee) and p-e (FCC-he)

**FCC** (Future Circular Colliders) CDR and cost review for the next ESU *(2018-2019)* (including injectors)

16 T $\Rightarrow$ 100 TeV in 100 km
20 T $\Rightarrow$ 100 TeV in 80 km

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Future Circular Collider Study Kick-off Meeting

12-15 February 2014, University of Geneva, Switzerland

LHC status & prospects
Frédérick Bordry
Large Hadron Collider Physics (LHCP) conference – New York – 2nd June 2014

http://indico.cern.ch/e/fcc-kickoff

340 International Participants
HL-LHC \((3000 \text{ fb}^{-1})\)

LHC 13-14 TeV \((300 \text{ fb}^{-1})\)

LHC 7-8 TeV \((30 \text{ fb}^{-1})\)

Samivel