Status of LHC and HL-LHC

Frédérick Bordry
27th July 2015
LHC Run 1 (2010-2012): a rich harvest of collisions

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

∑ \sim 30 \text{ fb}^{-1}

7 TeV and 8 TeV in 2012

- Prepare the LHC for operation at nominal energy 14 TeV
- Consolidate, Upgrade the LHC and Injector performance
- Major maintenance programme

Status of LHC and HL-LHC
EPS-HEP 2015 conference
Frédérick Bordry
27th July 2015
The main 2013-14 LHC consolidations

SMACC project: Closure of the last interconnection - 18.06.2014

18 000 electrical Quality Assurance tests
Since September 15th 2014:

1566 superconducting circuits commissioned through execution and analysis of more than 10,000 test steps (~13,800 test steps including re-execution)

Powering tests were completed at 8 am on Friday 3rd April 2015

172 training quenches
~600 secondary quenches
Only 1 quadrupole quench
Dipole Training Campaign

Each Sector Trained to 6.55 TeV (11080A) (100 A above the operational field)

Large variation in number of training quenches per sector

Detailed Analysis in Progress!
Maximum beam energy: 13 TeV c.m. in 2015

Decision to run at a **maximum** energy of 13 TeV c.m. during the powering tests and during 2015.

**NO change of beam energy in 2015.**

A decision regarding the possibility of increasing the energy will be taken after 2015 operation, based on data analysis of the powering tests and on the experience gained in all eight sectors at 6.5 TeV with beams.
First circulating beams in LHC on Easter Sunday
5th April 2015
First beams at 6.5 TeV! (12th April)
LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015
A lot of lessons learnt and experience from Run 1

- Excellent and improved system performance (LS1)
  - Beam Instrumentation
  - Transverse feedback
  - RF
  - Collimation
  - Injection and beam dump systems
  - Vacuum
  - Machine protection
- Improved software & analysis tools (LS1)
- Magnetically reproducibility
- Optically good, corrected to excellent
- Behaving well at 6.5 TeV
  - One additional training quench so far
- Operationally well under control
  - Injection, ramp, squeeze, de-squeeze

Beam commissioning in two months 😊 13 TeV
### LHC from 1st beam to Physics

**Start LHC commissioning with beam**

<table>
<thead>
<tr>
<th>Week</th>
<th>April</th>
<th>May</th>
<th>June</th>
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<tr>
<td>Mo</td>
<td>14</td>
<td>15</td>
<td>18</td>
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<td>Tu</td>
<td>15</td>
<td>16</td>
<td>21</td>
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<tr>
<td>We</td>
<td>16</td>
<td>17</td>
<td>22</td>
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<td>Th</td>
<td>17</td>
<td>18</td>
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</tr>
<tr>
<td>Fr</td>
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<td>Sa</td>
<td>19</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Su</td>
<td>20</td>
<td>21</td>
<td>26</td>
</tr>
</tbody>
</table>

- **FIRST BEAM** 5th April
- **FIRST STABLE BEAM** 3rd June

**PILOT PHYSICS**

- 8 weeks beam commissioning
- Pilot physics – up to ~40 bunches per beam
- 5 days special physics at $\beta^* = 19$ m for LHCf, (VdM, TOTEM & ALFA - postponed)
- Technical stop as foreseen – 15th-19th June

**LHCf PHYSICS**

- Scrubbing for 50 ns operation

---

Courtesy Mike Lamont
### Request: 10 nb\(^{-1}\)

<table>
<thead>
<tr>
<th>fill</th>
<th>Stable beams</th>
<th>nb(^{-1})</th>
<th>bunches</th>
</tr>
</thead>
<tbody>
<tr>
<td>3846</td>
<td>1h55m</td>
<td>0.1</td>
<td>39 pilots</td>
</tr>
<tr>
<td>3847</td>
<td>2h16m</td>
<td>0.28</td>
<td>39 pilots</td>
</tr>
<tr>
<td>3848</td>
<td>2h42m</td>
<td>0.91</td>
<td>12 nominal</td>
</tr>
<tr>
<td>3850</td>
<td>2h49m</td>
<td>1.95</td>
<td>39 nominal</td>
</tr>
<tr>
<td>3851</td>
<td>11h13m</td>
<td>6.81</td>
<td>39 nominal</td>
</tr>
<tr>
<td>3855</td>
<td>14h15m</td>
<td>6.49</td>
<td>39 nominal</td>
</tr>
</tbody>
</table>

\[ \sum > 16 \text{ nb}\(^{-1}\) \]
Weekend 13\textsuperscript{th}-14\textsuperscript{th}: June: start of intensity ramp-up 50 bunches

<table>
<thead>
<tr>
<th>Number of bunches</th>
<th>50</th>
</tr>
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<tbody>
<tr>
<td>Number of colliding bunches (ATLAS/CMS)</td>
<td>38</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>$1.45 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>$3.8 + 3.5 \text{ pb}^{-1}$</td>
</tr>
<tr>
<td>Peak $&lt;$Events$/\text{BX}$</td>
<td>$\sim 27$</td>
</tr>
</tbody>
</table>
50 ns intensity ramp-up: up to 476 nominal bunches

<table>
<thead>
<tr>
<th>Fill</th>
<th>Stable Beams</th>
<th>Peak lumi [cm(^{-2})s(^{-1})]</th>
<th>Int. lumi pb(^{-1})</th>
<th>Nc</th>
<th>Ibunch</th>
<th>emittance [micron]</th>
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</thead>
<tbody>
<tr>
<td>July 13(^{th})</td>
<td>3392</td>
<td>5h18</td>
<td>1.32 (10^{33})</td>
<td>20.6</td>
<td>414</td>
<td>1.10 (10^{11})</td>
</tr>
<tr>
<td>July 14(^{th})</td>
<td>3396</td>
<td>4h40</td>
<td>1.60 (10^{33})</td>
<td>18.9</td>
<td>414</td>
<td>1.12 (10^{11})</td>
</tr>
</tbody>
</table>

- 50 ns – injecting around nominal bunch intensity with low emittance (not BCMS)
- Instabilities at injection under control, low blow-up through the cycle
Aperture restriction in one sector:
- Measured at injection and 6.5 TeV
- UFO stopped after 2nd beam screen warm-up
- Reference orbit is bumped by +1mm in V and -3mm in H at 15R8.
- Probably not a limiting aperture for operation
- But stability of the object remains a concern

...to come
- How does it behave with higher intensities? bunch trains? ...

Still have to face the intensity ramp-up
- UFOs, e-cloud, beam induced heating, instabilities,… especially 25 ns
- R2E : QPS electronics cards
- ULO (Unidentified Laying Object)
## LHC 2015 – Q3/Q4 (V1.6)

### Timeline

<table>
<thead>
<tr>
<th>Week</th>
<th>July</th>
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<th>Sep</th>
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<tr>
<td>Su</td>
<td>33</td>
<td>37</td>
<td></td>
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</tbody>
</table>

- **July 31:** Scrubbing for 25 ns operation
- **August 3:** Intensity ramp-up with 50 ns beam
- **August 31:** Intensity ramp-up with 25 ns beam
- **September 24:** MD 1
- **September 27:** TS2
- **September 30:** Jeune G

### Machine Development

**Fill Number:** 4062

**Injection Physics Beam**

- **Beam:** 1, 2
- **Intensity:** 1.28E+14, 8.54E+13
- **Stored E:** 9.22, 6.13
- **Particle:** Proton
- **Bunches:** 1884, 1308
- **Beam Energy:** 0.45 TeV

**Date:** 26-07-2015 15:53:15

**Details:**

- Scrubbing run 25ns, 72 bunches per injection will refill with tighter spacing.

**Beam intensity and Energy**

- **Energy [TeV]**
- **Intensity**

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CERN

Status of LHC and HL-LHC

EPS-HEP 2015 conference

Frédérick Bordry

27th July 2015
LHC goal for 2015

Priorities for the 2015 run:
- Establish proton-proton collision at 13 TeV with 25 ns and low $\beta^*$ to prepare production run in 2016 and 2017-2018.

  Optimisation of physics-to-physics duration

- Pb-Pb run at the end of 2015

The goal for Run 2 luminosity is $1.3 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ and operation with 25 ns bunch spacing (2800 bunches), giving an estimated pile-up of 40 events per bunch crossing.

“A maximum pileup of ~50 is considered to be acceptable for ATLAS and CMS”
Status of LHC and HL-LHC
EPS-HEP 2015 conference
Frédérick Bordry
27th July 2015

LHC 2015: projection
Including intensity ramp-ups and steadily increasing physics efficiency

25 ns
- Electron-cloud
- UFOs
- Higher intensity per injection
- Higher total beam current (R2E e.g. QPS cards)
- More long range collisions
- Larger crossing angle, higher beta*

"Prediction is very difficult, especially if it's about the future." --Nils Bohr

Special runs

Possible $\beta^*$ reduction (80 cm towards 40 cm) plus fast ramp-up

50 ns MD & 25 ns scrubbing TS2
**Integrated luminosity goals:**

- **2015:** 5-8 fb\(^{-1}\)
- **Run2:** \(~120-140\) fb\(^{-1}\) (better estimation by end of 2015)
- **300 fb\(^{-1}\) before LS3**

2015 Priority: Establish Production running with 25ns bunch spacing
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

**Fully in line with the P5 recommendations, May 2014**

---

**Near-term & Mid-term High-energy Colliders**

**LARGE HADRON COLLIDER**

- The HL-LHC is strongly supported and is the first high-priority large-category project in our recommended program. It should move forward without significant delay to ensure that accelerator and experiments can continue to function effectively beyond the end of this decade and meet the project schedule.

- **Recommendation 10**: Complete the LHC phase-1 upgrades, and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.
Increase intensity/brightness in the injectors to match HL-LHC requirements

⇒ Enable Linac4/PSB/PS/SPS to accelerate and manipulate higher intensity beams (efficient production, space charge & electron cloud mitigation, impedance reduction, feedbacks, etc.)
⇒ Upgrade the injectors of the ion chain (Linac3, LEIR, PS, SPS) to produce beam parameters at the LHC injection that can meet the luminosity goal

Increase injector reliability and lifetime to cover HL-LHC run (until ~2035) closely related to consolidation program

⇒ Upgrade/replace ageing equipment (power supplies, magnets, RF…)
⇒ Improve radioprotection measures (shielding, ventilation…)
LINAC4 – PS Booster:
- $^1H$ 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.
Goal of High Luminosity LHC (HL-LHC):

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

- Prepare machine for operation **beyond 2025 and up to 2035-37**
- Devise beam parameters and operation scenarios for:
  - enabling a total integrated luminosity of **3000 fb⁻¹**
  - implying an integrated luminosity of **250-300 fb⁻¹ per year**, 
  - design for µ ~ **140 (~ 200)** (⇒ peak luminosity of **5 (7) 10^{34} cm^{-2} s^{-1}**)
  - design equipment for ‘ultimate’ performance of **7.5 10^{34} cm^{-2} s^{-1}** and **4000 fb⁻¹**

⇒ Ten times the luminosity reach of first 10 years of LHC operation
LHC Upgrade Goals: Performance optimization

\[ L = \frac{n_b \times N_1 \times N_2 \times f_{rev}}{4 \times \beta^* \times n} \times F(f, \beta^*, e, ss) \]

- Use \( F \) & \( \beta^* \) to level the luminosity avoiding too high a pile up in the experiments  ➔ Levelling
- Improve machine efficiency  ➔ minimize number of unscheduled beam aborts
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
Squeezing the beams: High Field SC Magnets

Quads for the inner triplet
Decision 2012 for low-β quads
Aperture $\varnothing$ 150 mm – 140 T/m
($B_{\text{peak}} \approx 12.3$ T)
operational field, designed for 13.5 T
=> Nb$_3$Sn technology

(LHC: 8 T, 70 mm)
Quadrupoles of LARP

**Target:**

- **200 T/m gradient at 1.9 K**

**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
**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-7 & IR-2
- LS3 2020+: IR1,5 as part of HL-LHC

\[ B_{dL} = 119.2 \text{ Tm} @ I_{\text{nom}} = 11.85 \text{ kA} \]

in series with MB with 20% margin

<table>
<thead>
<tr>
<th>LS2</th>
<th>Coldmass + Spares</th>
<th>Total</th>
</tr>
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<td></td>
<td>12 + 2</td>
<td>14 CM</td>
</tr>
<tr>
<td></td>
<td>5.5 + 2</td>
<td>10 CM</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>24 CM</td>
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</table>

<table>
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<th>Total</th>
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<tbody>
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<td>24 + 4</td>
<td>28 CM</td>
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<tr>
<td></td>
<td>16 + 4</td>
<td>20 CM</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>48 CM</td>
</tr>
</tbody>
</table>
11 T Magnet – Nb3Sn technology
Status on recent developments & tests at CERN

MBHSP0001-102 training

- Test target, 7.6 TeV, 12 T
- Nominal current, 7 TeV

- Quench current (A)
- Quench number

- MBHSP101
- ▲ coil 106 inner
- □ coil 106 outer
- ▲ coil 108 inner
- □ coil 108 outer
- ○ undefined
- × No quench

Courtesy of Frédéric Savary
Geometric Luminosity Reduction Factor:

- Reduces the effect of geometrical reduction factor
- Independent for each IP

\[ F = \frac{1}{\sqrt{1 + \left(\frac{c}{z}\right)^2}} \]  
\[ \text{effective cross section} \]

- Noise from cavities to beam?
- Challenging space constraints
Latest cavity designs toward accelerator

RF Dipole: Waveguide or waveguide-coax couplers

3 Advanced Design Studies with Different Coupler concepts

Concentrate on two designs in order to be ready for test installation in SPS in 2016/2017

Present baseline: 4 cavity/cryomodule TEST in SPS under preparation for 2017
Excellent first results: e.g. RF dipole > 5 MV
¼ w and 4-rods also tested (1.5 MV)

Initial goal was 3.5 MV however ΔV > 5-6 MV would ease integration
In-kind contributions and collaborations for design, prototypes and production

Discussions are ongoing with other countries, e.g. Canada,…

Q1-Q3 : R&D, Design, Prototypes and in-kind USA
D1 : R&D, Design, Prototypes and in-kind JP
MCBX : Design and Prototype ES
HO Correctors: Design and Prototypes IT
Q4 : Design and Prototype FR

CC : R&D, Design and in-kind USA
CC : R&D and Design UK
### LHC roadmap

**LS2** starting in **2019**  
=> **24 months + 3 months BC**

**LS3** LHC: starting in **2024**  
=> **30 months + 3 months BC**

Injectors: in **2025**  
=> **13 months + 3 months BC**

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</tbody>
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**LHC Injectors**

**PHASE 1**

- **2022**: Run 3
- **2024**: LS 4
- **2025**: Run 4

**PHASE 2**

- **2029**: LS 4
- **2032**: Run 5
- **2035**: LS 5

---

**Status of LHC and HL-LHC**

EPS-HEP 2015 conference
Frédérick Bordry
27th July 2015
LHC roadmap: Integrated luminosity

LS1 = consolidation for maximizing energy reach of the LHC (8 to 14 TeV)
LS2 = LIU for beam intensity upgrade
LS3 = HL-LHC for luminosity upgrade
Conclusions

- Lot of lessons learnt in Run 1 and tremendous works done in LS1
- Re-commissioning of the LHC superconducting circuits went well – even though some surprises! (like earth faults)
- Magnet training roughly according to expectations (deeper analysis is now needed to understand their behaviour and decide upon energy increase after 2015 operation)
- Fantastic progress in beam commissioning and physics preparation
- The LHC looks good at 6.5 TeV with unsqueeze and squeeze optics
  - Magnetic reproducibility
  - Good optics
  (prepared squeezed optics up to $\beta^* 40$ cm)

Optics: Squeeze down to $\beta^* 40$ cm
Conclusions

▪ Next challenge: e-cloud (scrubbing campaign) and ramp-up in beam intensity (25 ns)

▪ Fundamentals look sound, no show stoppers for the moment
  Some teething concerns (e.g. SEU on QPS electronics cards, ULO,…)

▪ Priority for the 2015 run:
  Establish proton-proton collisions at 13 TeV with 25ns and low $\beta^* (~ 40\text{cm})$
  to prepare production run in 2016 and 2017-2018

▪ LHC Injector Upgrade (LIU => LS2) and High Luminosity LHC (HL-LHC => LS3) projects: well defined and now in construction phase.

▪ Full exploitation of the LHC with optimised planning out to 2035.
Thanks for your attention

The LHC is enjoying benefits of the decades long international design, construction, installation, LS1 upgrade effort and commissioning.
Progress with beam represents phenomenal effort by all the teams involved, injectors included.
Now preparation for the production of new collision data to see what nature has in store at these new unexplored energies (Terra Incognita)

Run 1

"It is much too early to expect any discovery, we will have to be patient”  CERN DG