LHC Status and Outlook
EPS-HEP 2017 conference
Frédérick Bordry
Venice, Italy, 10th July 2017
LHC Run 2

The LHC was operated between 2010 and 2013 at 7 TeV and 8 TeV: **Run 1**.

Run 1 was followed by a ~2 year long shutdown to prepare the LHC for high energy operation.

Goals of the 4 year long Run 2 that extends from 2015 to 2018:

- Operate the LHC at 13 TeV.
- Operate with a bunch spacing of 25 ns.
  
  - During Run 1 LHC was operated with 50 ns spacing (e-cloud).
- Deliver ≥ 120 fb⁻¹ of integrated luminosity.

2015: recovery and learning year
2016: 1ˢᵗ production year and to push the machine towards design performance.
LHC 2015: projection

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

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*

Special runs

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

Status of LHC and HL-LHC
EPS-HEP 2015 conference
Frédérick Bordry
Vienna, Austria, 27th July 2015
2016 LHC a rich harvest of collisions

Peak luminosity > $1.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
OVER 25 fb$^{-1}$ in both ATLAS and CMS 😊

Ingredients for the excellent results in 2016:
• Building on 2015 as the year to commission the machine at this energy
• **High machine availability** $\sim 50\%$ (many HW issues fixed)
• High luminosity lifetime (improved knowledge of machine parameters for operation)
• High peak luminosity (small beam size from injectors and stronger focussing)

Still room for improvement in 2017 & 18
• More bunches, higher bunch intensity, stronger focussing
2016: LHC Limitations

SPS beam-dump
Nb of bunches per injection limited to 96
Total number of bunches: 2200

LHC Injection kickers
Outgassing from ceramic
Bunch population limited to around $1.1 \times 10^{11}$

Electron cloud
Still significant heat-load within cryogenic limits
Dynamics – well handled by cryogenics feed-forward – no impact on operations in the present conditions

UFOs
Frequency has happily conditioned down
2016 LHC: Electron clouds

- At high intensity the LHC is operated in the presence of electron clouds.
- There is a slightly decreasing trend of electron cloud heat-loads in 2016 with ~20% gained over the year (gain of 2015 40%).
  - Most electron could ‘scrubbing’ is performed parasitically to physics operation.
  - The beams are stabilized with a transverse feedback, octupoles and head-on beam-beam (Landau damping).
- Device essential for the operation of the accelerator complex
- New SPS internal dump (innovative design) constructed in ~8 months following failure of 2016
- Completely new design – “prototype” for new dump for LS2 (LIU)
SPS: from paper to reality in 8 months

Courtesy of Marco Calviani and Simone Gilardoni
Operation of the dump successfully so far

- Reached up to almost nominal power at \(~55\) kW average deposited beam power
- Long irradiation periods at beginning of the run necessary for graphite conditioning – now reached (required for safe operation at 288 bunches)
ramp with a short to ground appearing ~1.5s after the 1st magnet quench
Earth Fault Burner! capacitive current discharge
Beam energy: Run 2 @ 13 TeV c.m.

NO change of beam energy in 2017 and 2018

Goal is to prepare the LHC to run at 14 TeV during Run 3.

Study how to reinforce the insulation (and to clean) during LS2 the electrical part connecting the dipole bypass diode. DONE

Powering tests before and during LS2 should be defined: S1-2 to 7 TeV at end of Run 2?

Work will be done during LS2
7 interconnections must be opened for the re-connection and the validation of the auxiliary circuits (correctors)

21 weeks required for the warm-up, exchange of the magnet, cool-down and the re-commissioning of the sector

4½ weeks (7 days/7) will be necessary to disconnect and re-connect the dipole
### LHC Status and Outlook

**EPS-HEP 2017 conference**

**Frédéric Bordry**

**Venice, Italy, 10\(^{th}\) July 2017**

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#### LHC schedule: Q1 and Q2

<table>
<thead>
<tr>
<th>Week</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>2</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>Tu</td>
<td>3</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>We</td>
<td></td>
<td>23</td>
<td>27</td>
</tr>
<tr>
<td>Th</td>
<td></td>
<td>30</td>
<td>6</td>
</tr>
<tr>
<td>Fr</td>
<td></td>
<td>6</td>
<td>13</td>
</tr>
<tr>
<td>Sa</td>
<td></td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>Su</td>
<td></td>
<td>27</td>
<td>27</td>
</tr>
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</table>

*Controls interventions*

**Technical stop (EYETS)**

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#### Powering tests

<table>
<thead>
<tr>
<th>Week</th>
<th>April</th>
<th>May</th>
<th>June</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>3</td>
<td>1st May</td>
<td>Whit</td>
</tr>
<tr>
<td>Tu</td>
<td>10</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>We</td>
<td></td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>Th</td>
<td>G. Friday</td>
<td>Ascension</td>
<td>Scrubbing</td>
</tr>
<tr>
<td>Fr</td>
<td></td>
<td>22</td>
<td>28</td>
</tr>
<tr>
<td>Sa</td>
<td></td>
<td>28</td>
<td>12</td>
</tr>
<tr>
<td>Su</td>
<td></td>
<td>17</td>
<td>MD 1</td>
</tr>
</tbody>
</table>

*Machine check-out*
LHC powering tests

1572 superconducting circuits commissioned!

- More than 10,000 tests executed and analyzed in about 1 month
- Early debugging and increased automation proved to be the key elements for the success

- Dipole magnets in S12 needed 2 training quenches to reach the current level required for 6.5 TeV operation (11080 A)
- 7 quenches were needed after LS1
- The quenches occurred on different magnets wrt after LS1 campaign
2017: beams back in LHC from Friday 28\textsuperscript{th} April
LHC beam commissioning

- Planned LHC start-up after EYETS: 5 weeks
- Actual LHC start-up:
  1\textsuperscript{st} beam injection 2 days ahead of schedule (28\textsuperscript{th} April)
  3.5 weeks to first physics (23\textsuperscript{rd} May)
Very well tuned start-up sequence (new ATS optics)
One week of scrubbing
First e-cloud observations in 2017

- Heat load in S12 found much higher (as expected due to warm-up and venting), but fast conditioning.
- Heat load “ranking” of the other sectors stayed unchanged.
- Up to now no more issues with vacuum in injection regions (upgrade of pumping).

Conditioning evident on Sector 1-2, less so on the others
## LHC 2017: Parameters and Plans

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch population $N_b \ [10^{11} \ p]$</td>
<td>1.15</td>
<td>~1.2</td>
<td>~1.1</td>
<td>~1.2</td>
</tr>
<tr>
<td>No. bunches $k$</td>
<td>2780</td>
<td>2244</td>
<td>2220</td>
<td>2556</td>
</tr>
<tr>
<td>Emittance $\varepsilon \ [\text{mm mrad}]$</td>
<td>3.5</td>
<td>~3.5</td>
<td>~2.2</td>
<td>~2.2</td>
</tr>
<tr>
<td>$\beta^* \ [\text{cm}]$</td>
<td>55</td>
<td>80</td>
<td>40</td>
<td>40 (33)</td>
</tr>
<tr>
<td>Full crossing angle $\mu$rad</td>
<td>285</td>
<td>290</td>
<td>370 / 280</td>
<td>300 (340)</td>
</tr>
<tr>
<td>Peak luminosity $[10^{34} \ cm^{-2}s^{-1}]$</td>
<td>1.0</td>
<td>0.51</td>
<td>1.4</td>
<td>~1.7 (1.9)</td>
</tr>
<tr>
<td>Integrated luminosity $[\text{fb}^{-1}]$</td>
<td>4.5</td>
<td>40</td>
<td></td>
<td>~45</td>
</tr>
</tbody>
</table>

### Push LHC performance
- Mitigate e-cloud by scrubbing with longer trains
- Increase the number of bunches => 2556
- Increase the bunch intensity
- Possibly decrease the $\beta^*$ from 40cm to 33 cm

### Prepare for HL-LHC
- Run with ATS optics (Achromatic Telescopic squeeze)
- Test levelling schemes (crossing angle, $\beta^*$)
- Use full RF detuning

Continue to increase performance and to maintain availability ~50%
2017 LHC: a good start!

- Very steep performance ramp up
- 2556 bunches
- Peak Luminosity $1.58 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$
  (fill #5882)
- Integrated luminosity: 6.4 fb$^{-1}$
2017 LHC: Electron clouds

Very smooth during intensity ramp-up (nb of bunches)
2017 LHC: Emittance evolution from Injection to stable beam

Fill 5887: B2, started on Thu, 29 Jun 2017 19:51:42

- Significant growth over 40 min & e-cloud shape
- At high energy
- After 40 mins at injection
- Right after injection

Potential improvement
LHC schedule 2017

a new production year at 13 TeV

Goal 45fb$^{-1}$
(145 days of physics)
keeping the LHC availability close to 50% (stable beams)

15 days of MD;
+ 3 days, later during 2017 according integrated luminosity

Special runs: VdM scans,…
and … 5 TeV pp reference run (for Pb-Pb and p-Pb physics analysis)
LHCC recommendations in Sept.17
### Run 2 and Run 3

<table>
<thead>
<tr>
<th>Year</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Months</td>
<td>JAN</td>
<td>FEB</td>
<td>MAR</td>
<td>APR</td>
</tr>
</tbody>
</table>

- **Shutdown/Technical stop**
- **Protons physics**
- **Commissioning**
- **Ions**

### Ion runs end of 2018 (Pb-Pb)

- **Run 2**
  - 45 fb\(^{-1}\) in 2017 and \(\approx 45 \, fb\(^{-1}\) in 2018 (\(\sum 90 \, fb\(^{-1}\); breakdown depending on the special runs)
  - **YETS 2017/2018**: 15 (13+2) weeks but drastic optimization of the “recommissioning with beam” period (less than 2 weeks!)
  - Prepare for HL-LHC and post-LS2 LIU era (MD time in 2018)

- **Run 3**
  - \(\geq 120 \, fb\(^{-1}\) (13 TeV)
  - \(\sum 300 \, fb\(^{-1}\) (\(\geq 14 \, TeV\))

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The HL-LHC Project: $300 \text{ fb}^{-1} \rightarrow 3000 \text{ fb}^{-1}$

- New IR-quads $\text{Nb}_3\text{Sn}$
  (inner triplets)
- New 11 T $\text{Nb}_3\text{Sn}$
  (5.5 m dipoles)
- Crab Cavities
- Collimation upgrade
- Cryogenics upgrade
- 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 $\Theta$ 150 mm – 140 T/m
($B_{\text{peak}} \approx 12.3$ T)
operational field, designed for 13.5 T

$\Rightarrow$ Nb$_3$Sn technology
($LHC: 8$ T, $70$ mm )
**Nb$_3$Sn quadrupole: complexity increase vs Nb-Ti**

- Development of Nb3Sn Conductor with Jc almost 3 times of ITER

- Laminated structure for series production

- Section of MQXF mechanical model

- Second long (4 m) Nb3Sn coil


**Nb$_3$Sn quadrupole: 1$^{\text{st}}$ long prototype under construction**

Second short (1.5 m) under preparation for test at CERN

Insertion of coil package inside mechanical structure of the first IT quad prototypes (4.2 m long) in LBNL-USA

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**Courtesy of Frédéric Savary**
Nb$_3$Sn 11 T dipole: a lot of new features

By-pass cryostat

15660 mm

11 T dipole cold mass

Interconnect

Space for Collimator

Pole loading structure

Cable insulation with Mica (better coverage and rad-hard)

Courtesy of Lucio Rossi
Manufacturing 5.5 m long coil

**Milestone:**
Magnet prototype (5.5m) by December 2017
HL-LHC Main achievement 2016

The 11 T dipole 2 m long model reached a $B_{\text{max}}$ of 12.5 T

Test of the first full cross-section (150 mm aperture) Triplet Quadrupole, 1.5 m long, half CERN, half USA: it went beyond ultimate ($B_{\text{max. eq.}}$ of 12.5 T)
HL-LHC magnet “zoo”: global collaboration

- Triplet QXF (LARP and CERN)
- Orbit corrector (CIEMAT)
- Separation dipole D1 (KEK)
- 11 T dipole (CERN)
- Recombination dipole D2 (INFN)
- Q4 (CEA)
- D2/Q4 orbit corrector (CERN)
- Skew quadrupole (INFN)
- Sextupole (INFN)
- Octupole (INFN)
- Decapole (INFN)
- Dodecapole (INFN)

Approximately 150 single magnets and 50 cold masses for HL-LHC
Crab Cavity: Proton machine (HL-LHC)

- LHC Luminosity upgrade requires larger bunch charge and smaller $\beta^*$.  
- To prevent parasitic bunch crossings, a larger crossing angle is needed.  
- This leads to geometric luminosity loss at small $\beta^*$.  
- A crab cavity is a deflecting cavity that kicks the head of each bunch one way, the tail the opposite way, such that the crossing angle is compensated for the bunch overlap in the collision point.

![Crab Cavity Diagram]

Luminosity vs. $\beta^*$ for a non-zero crossing angle (lower curve) and possible luminosity for complete bunch overlap (upper curve)
February 2017 three (naked) Crab Cavities were tested: all went well beyond the operating voltage of 3.4 MV
- One US-LARP DQW (tested at JLab) went up to 5.4 MV
- One US-LARP RFD (tested at Jlab) reached 4.03 MV.
- One CERN DQW (test at SM18) went up to 5.04 MV

Good results for the CC testing in the SPS in 2018
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**LHC / HL-LHC Plan**

Run I
- Run 1
  - LS1: splice consolidation button collimators R2E project
  - experiment beam pipes

Run II
- Run 2
  - 13 TeV
  - EYETS
  - injector upgrade cryo Point 4 Civil Eng. P1-P5
  - experiment upgrade phase 1

Run III
- Run 3
  - LS2
  - 14 TeV
  - cryo limit interaction regions
  - experiment upgrade phase 2

Run IV, V...
- Run 4-5...
  - LS3
  - 14 TeV
  - HL-LHC installation

Today
- 7 TeV
- 8 TeV

76% nominal luminosity

30 fb⁻¹
- 2011
- 2012
- 2013
- 2014
- 2015
- 2016
- 2017
- 2018

150 fb⁻¹
- 2019
- 2020

300 fb⁻¹
- 2021
- 2022
- 2023

3000 fb⁻¹
- 2024
- 2025
- 2026

2037

**Civil engineering**
- Lay-out, permits, tenders, preparation
- Excavation period
- Surface buildings

**Components**
- Prototypes/Specs
- FAV
- Installation

**Tech Infrastructure**
- Specifications
- FAV
- Installation

FAV = Fabrication, Assembly and Verification
Conclusions

- Run 2: LHC operates at 13 TeV with record performance
  - High availability ~ 50% and peak luminosity > $1.55 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
  - 2017: a very good start; 6 fb$^{-1}$ (29th June 2017)
  - 2017 + 2018: goal 90 fb$^{-1}$ and to reach 1.8-2.0 $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

- LS2 preparation well advanced: mainly LIU, HL-LHC Civil Engineering and preparing to run at 14 TeV during Run 3

- (Run 1 + Run 2 + Run 3) $\Rightarrow$ Goal 300 fb$^{-1}$

- The high luminosity project HL-LHC will allow to collect ten times more data (2026 - mid 2030ies) $\Rightarrow$ Goal of 3’000 fb$^{-1}$

- The HL-LHC project is well established in terms of: beam parameters, technical requirements, needed technological developments.
- It is a “landmark project” in the ESFRI roadmap and formally approved by the CERN Council
- R&D work is well advanced and construction of some components started.

**HL-LHC is now a construction PROJECT**
During the performance Italian Artist Sven Sachsalber looked for a needle in haystack (November 2014)

…he has gone through periods of doubt and serious discouragement … but after 2 days, he found it!

"Cercare un ago in un pagliaio"
A big thanks to all teams involved with LHC and injectors present and future operation

2017: a GOOD START, keep going!

It is more difficult to stay on top than to get there

Mia Hamm
Increase injector reliability and lifetime to cover HL-LHC run (until ~2040) closely related to consolidation program

⇒ Upgrade/replace ageing equipment (power supplies, magnets, RF…)
⇒ Improve radioprotection measures (shielding, ventilation…)

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

September-November 2016: Commissioning with beam of 12 PIMS accelerating structures (built in collaboration CERN-NCBJ-FZJ).

160 MeV design energy

Installation of the last beam line element, August 2016

LINAC4 Inauguration 9th May 2017