Status of the LHC machine: Run2 performance, LS2 and Run 3 outlook

Frédérick Bordry
8th HL-LHC Collaboration Meeting
CERN
15th October 2018
### 2010-2037 ... LHC Physics exploitation

<table>
<thead>
<tr>
<th>Period</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 - 2012</td>
<td>Run 1; 7 and 8 TeV</td>
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<tr>
<td>2013 - 2014</td>
<td>LS1</td>
</tr>
<tr>
<td>2015 - 2018</td>
<td>Run 2; 13 TeV</td>
</tr>
<tr>
<td>2019 - 2020</td>
<td>LS2: Maintenance, upgrade and <strong>LIU</strong></td>
</tr>
<tr>
<td>2021 - 2023</td>
<td>Run 3; 14 TeV</td>
</tr>
<tr>
<td>2024 - 2025</td>
<td>LS3: maintenance and HL-LHC installation</td>
</tr>
<tr>
<td>2026 – 2037…</td>
<td>HL-LHC operation</td>
</tr>
</tbody>
</table>

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LHC 2010-2012: Run 1

\[ \Sigma \sim 30 \; \text{fb}^{-1} \]

<table>
<thead>
<tr>
<th>Year</th>
<th>Luminosity (fb^{-1})</th>
<th>Energy (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>0.04</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>7 TeV CoM Commissioning</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>6.1</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>… exploring limits</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>23.3</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>8 TeV CoM production</td>
<td></td>
</tr>
</tbody>
</table>

7 TeV cm in 2010 and 2011
8 TeV cm in 2012
Up to 1380 bunches with $1.5 \times 10^{11}$ protons
## Run 2: 2015 – 2018

### 13 TeV, 25ns

<table>
<thead>
<tr>
<th>Year</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>MJD</td>
<td>JFMAM</td>
<td>JASOND</td>
<td>JFMAM</td>
<td>JASOND</td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td>4 fb$^{-1}$</td>
<td>40 fb$^{-1}$</td>
<td>EYETS</td>
</tr>
</tbody>
</table>

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

**Goal Run1+ Run2 = 150 fb$^{-1}$**

**Goal 60 fb$^{-1}$**
2017 goal: 45 fb$^{-1}$

Peak luminosity $2.2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

With luminosity levelling at $1.5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

Lower $\beta^*$ 30 cm (new ATS optics)

Availability: 81%

LHC takes <0.03 % of the CERN protons

Achieved: 50 fb$^{-1}$
Situation at the end of first BS thermal cycle to 80 K
(No pumping though pumping port)

Surface covered with N2, O2, Ar

H2O coverage not affected by thermal cycle

LHC “16L2”: Air inlet as “most probable” cause
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**LHC: Cryogenics Heat Load BCMS versus 8b4e**

**8b4e = 8 bunches + 4 empty buckets**

For same LHC bunch intensity PSB bunch intensity and transverse emittance is ~50% of standard scheme but limitation on the bunch numbers and pile-up
- Introduced separation levelling for all experiments (Separation levelling is used since many years for ALICE and LHCb)
- Dynamic orbit bump changes overlap of colliding bunches
- Initial spike before leveling reaching $2.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
LHC: sector 1-2 warming-up at the start of the YETS 2017-2018

Estimated quantity of extracted air

\[ M_{N_2} = 8.4 \text{ g} \]

\[ V_e = 10.5 \text{ cm}^3 \text{ per beamline} \]

\[ V_{STP} = 7 \lambda (\text{air at 1 bar, room temperature, per beamline}) \]

Estimated quantity of extracted water vapour

\[ M_{H_2O} = 0.1 \text{ g (per beamline)} \]

Results from gas analysis in 16L2

Clear signature of atmospheric gas

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LHC: sector 1-2 warmed up up to 90 K and cooled down
LHC 2018: Smooth & Fast Intensity Ramp-up

Intensity ramp up plan: 3 - 12 - 72 - 300 - 600 - 900 - 1200 - 1800 - 2400 – 2550

- With interleaved beam commissioning and intensity ramp up **1227 bunches in only 10 days** (excl. scrubbing)
  - In 2017 it took 15 days
- **2556 bunches** reached after **17 days**
  - In 2017 it took 24 days.

- This is thanks to excellent machine availability and dedicated teams, signing off checklists for every step at any moment
LHC : Overview of pp run since May

- Most of the time, high-intensity fills stacked next to each other
- Few longer faults

Rocky recovery after TS1 due to several independent issues

PS RF issue after 18 kV transformer

SPS magnet replacement
Faults with longest duration

PS RF issue following 18 kV transformer failure
(end of July)
- Several knock-on effects of transformer failure: Trip of transmission lines and injectors, PSB main power supply failed, RF problem in the PS (longest recovery)
- No beam for 1.5 days, then only single bunches and later 12b trains possible

SPS dipole replacement
(~ 20 August)
- Magnet damaged by beam, causing vacuum leak
- Replacement only possible after radiation cooldown
- Very fast losses starting in cell 16L2 believed to be caused by beam interacting with macro-particles of frozen air
- 4 dumps due to 16L2 since end of May, 3 in stable beams
- Long time now since last event 😐
LHC: Evolution of arc UFO rates in 2015–2018

*2015 events do not include dumps and quenches in cell 15R8 (ULO location)

**2017/18 events do not include dumps and quenches in cell 16L2

Fill-by-fill arc UFO rates (cells >12) in stable beams (only fills with ≥1 h in STABLE and with >100 b per beam)
- Full machine (2556 bunches) reached on May 5th
- Four “16L2 storms” encountered with successful recovery
- Bunch intensity is not really pushed to avoid issues with 16L2
- Steadily close to $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (twice the LHC design value)
# LHC Beam parameters achieved

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2018</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong> [TeV]</td>
<td>6.5</td>
<td>7.0</td>
</tr>
<tr>
<td><strong>No. of bunches</strong></td>
<td>2556</td>
<td>2808</td>
</tr>
<tr>
<td><strong>Max. stored energy per beam (MJ)</strong></td>
<td>312</td>
<td>362</td>
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<tr>
<td><em><em>β</em> [cm]</em>*</td>
<td>30(\rightarrow) 25</td>
<td>55</td>
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<tr>
<td><strong>p/bunch (typical value) [10^{11}]</strong></td>
<td>1.1</td>
<td>1.15</td>
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<tr>
<td><strong>Typical normalized emittance [μm]</strong></td>
<td>(\sim) 1.8</td>
<td>3.75</td>
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<tr>
<td><strong>Peak luminosity</strong> [10^{34} cm^{-2}s^{-1}]</td>
<td>2.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>
LHC 2018: Beam Availability and Performance

Fault / Downtime 31%
Pre-cycle 2%
Stable beams 51%
Operations 16%

LHCb: 2.27 fb⁻¹
ATLAS: 59.9 fb⁻¹
CMS: 61.8 fb⁻¹
LHCb:
- separation leveling around $4.4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- typical production around 20 pb$^{-1}$ in a fill not dumped prematurely

ALICE
- separation leveling around $3.5 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$
- typical production around 150 nb$^{-1}$ in a fill not dumped prematurely

Fill 7127, 5th September 2018
**LHC: outlook on rest of 2018**

<table>
<thead>
<tr>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
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<tbody>
<tr>
<td>Mo</td>
<td>β* = 90 m run</td>
<td>2027</td>
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<tr>
<td>Tu</td>
<td>MD 2</td>
<td>2028</td>
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<td>We</td>
<td>MD 3</td>
<td>2029</td>
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**Oct**

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**Whole program was completed! Both experiment achieved that target goal of one million events in respectively good background conditions.**

**Low energy high beta run 900 GeV**

**Magnet training tests to aiming for 7 TeV after LS2**

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Run1 + Run 2: Luminosity Production

### Integrated Luminosity [fb$^{-1}$]

<table>
<thead>
<tr>
<th>Period</th>
<th>Int. Luminosity [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>29.2</td>
</tr>
<tr>
<td>Run 2: 2015</td>
<td>4.2</td>
</tr>
<tr>
<td>Run 2: 2016</td>
<td>39.7</td>
</tr>
<tr>
<td>Run 2: 2017</td>
<td>50.2</td>
</tr>
<tr>
<td>Run 2: 2018</td>
<td>60.8</td>
</tr>
<tr>
<td>Total Run1 + Run 2</td>
<td>184.1</td>
</tr>
</tbody>
</table>

Sunday 14.10.2018
The Long Shutdown 2 (LS2)

- Perform major **Maintenance and Consolidations**
- Increase intensity/brightness in the injectors to match HL-LHC requirements (*LIU Project*)
- Increase **injector reliability and lifetime** to cover HL-LHC run (until ~2035) closely related to consolidation programs (in synergy with LIU Project)
- Anticipate **HL-LHC work**

<table>
<thead>
<tr>
<th>Year</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
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<tbody>
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<td>2028</td>
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</tbody>
</table>

**LHC Injectors**

- **2016**
- **2017**
- **2018**
- **2019**
- **2020**
- **2021**
- **2022**
- **2023**
- **2024**
- **2025**
- **2026**
- **2027**
- **2028**

**LS2**
LS2 (2019-2020 period): coordination of multi projects

Consolidation & upgrades

The main projects during LS2

Consolidation

LIU (incl. L4 connection)
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
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
LIU / HL-LHC beam parameter target at the PS to SPS extraction: $2.6 \times 10^{11}$ p/b in 1.9 μm

- **2017**: Despite new RF longitudinal damper system, beam intensity limited to $2.1 \times 10^{11}$ p/b

- **2018**: Additional RF upgrades implemented together with extensive beam optimisation allowed reaching the target intensity $2.6 \times 10^{11}$ p/b

- Intensity reach and reproducibility being studied until end of Run 2. Beam performance review scheduled in January 2019 to define the final operational strategy – incl. decision on Landau cavity mitigation
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15th October 2018
HL-LHC: Civil Engineering Pt 1 and Pt5 has started
HL-LHC first stone ceremony, 15th June 2018
### Run 3 outlook

$$\Sigma (\text{Run1} + \text{Run2} + \text{Run 3}) > 300 \text{ fb}^{-1}$$

<table>
<thead>
<tr>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
</tr>
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<tbody>
<tr>
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<td>JFMAMJASOND</td>
<td>JFMAMJASOND</td>
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<tr>
<td></td>
<td></td>
<td>10-15 fb^{-1}</td>
<td>~75-80 fb^{-1}</td>
<td>~75-80 fb^{-1}</td>
</tr>
</tbody>
</table>

**2021:** beam commissioning in the injectors after LIU upgrade  
LHC 14 TeV commissioning and operation

**2022-2023:** production years at 14 TeV;  
$\text{Lpeak} \sim 2.0-2.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$; luminosity levelling

$$\sim 350 \text{ fb}^{-1}$$
Successful Run 1 and Run 2 : > 185 fb\(^{-1}\)
Solid preparation for LS2 activities. In full swing to start less of 2 months
LIU ready for installation and successful MD in 2018
HL-LHC Civil Engineering: a good start

Run 3 at 14 TeV
End of 2023 : ~350 fb\(^{-1}\) => HL-LHC installation during LS3 (2024-2025)
Thanks for your attention