Status and near future of the Large Hadron Collider (LHC)

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Inputs from various colleagues/teams, in particular J. Wenninger, R. Bruce, M. Solfaroli
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The Large Hadron Collider (LHC)

- Circumference of 27 km
- Eight arcs, 2-in-1 magnet design
- Two warm regions for beam collimation
- Super-conducting RF system
- One beam dump region (warm)
- Beam injection: IR2 and IR8
- Four experimental regions

- **ATLAS** and **CMS**: high luminosity experiments, \( L \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
  
  Determine most challenging performance figures...

- **LHCb**: medium luminosity experiment, \( L \sim 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \)
  
  Levelled luminosity (by separation)

- **ALICE**: low luminosity / ion experiment, \( L \sim 10^{31} \text{ cm}^{-2}\text{s}^{-1} \)
  
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- **TOTEM, ALFA** and **AFP**: physics experiments
  
  Participate to high-luminosity runs + special runs.
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- **TOTEM, ALFA** and **AFP**: physics experiments

  Participate to high-luminosity runs + special runs.

Several operational challenges and demands for high flexibility while handling \( \sim 300\text{MJ} \) beams!
### The LHC Run II and Run III

<table>
<thead>
<tr>
<th>Year</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>FEB</td>
<td>MAR</td>
<td>APR</td>
<td>MAY</td>
</tr>
<tr>
<td>JUN</td>
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<td>Apr</td>
<td>May</td>
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<td>Sep</td>
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<td>Mar</td>
<td>Apr</td>
<td>May</td>
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<td>Jul</td>
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<tr>
<td>Aug</td>
<td>Sep</td>
<td>Oct</td>
<td>Nov</td>
<td>Dec</td>
</tr>
</tbody>
</table>

- **Run I (2010-13):** operations at **3.5-4.0 TeV**, delivered **~30fb⁻¹**
- **2015:** “Recovery year” before moving into full production years 2016-18.

- **Long Shutdown 2 (LS2)**
- **Σ 300 fb⁻¹** (14 TeV)
- **>120 fb⁻¹** (13 TeV)
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Luminosity at a circular collider

Fixed the **beam energy**, the **key parameter** for the experiments is the event rate \( \frac{dN}{dt} \). For a physics process with **cross-section** \( \sigma \), it is proportional to the collider’s **luminosity**: \( \frac{dN}{dt} = \sigma \times L \).

\[
L = \frac{n_b N^2 f \gamma}{4\pi \beta^* \epsilon} F
\]

*depends on machine parameters: charge per bunch \( N \), number of bunches \( n_b \) and transverse beam sizes \( \sigma \): optics and beam emittance.*

We have seen a continuous improvement of the relevant parameters from the start of LHC operation!

\[
F = \frac{1}{\sqrt{1 + \Theta^2}} ;
\]

\[
\Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}
\]
Geometry at the collision points

Crossing angle requirements are determined by the beam emittance and bunch charge. Reduction of aperture and loss of peak luminosity during the collisions can be optimised during the fill.

~40% loss due to geometric effect

2018 operation point
Luminosity levelling techniques

Under certain conditions (too high peak luminosity) and depending on the experiments request, it is desirable to adapt the luminosity dynamically with beams in collision – luminosity levelling.

Three techniques successfully deployed at the LHC:

- **Levelling by beam offset** *(since 2011)*
- **Levelling by crossing angle** *(since 2017)*
- **Levelling by $\beta^*$ (= beam size at IP)** *(since 2018)*

In 2018 we make use of all these techniques in each fill!
Since 2017: “combined ramp&squeeze” where part of the optics changes are done in the shadow of the energy acceleration! Now reach 1 m in IP1/5 and the final 3 m in IP8.
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☑️ Conclusions
Achieved running configuration

<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</strong> per beam (MJ)</td>
<td>312</td>
<td>362</td>
</tr>
<tr>
<td><strong>β</strong>* [cm]</td>
<td>30→25</td>
<td>55</td>
</tr>
<tr>
<td><strong>p/bunch</strong> (typical value) [10^{11}]</td>
<td>1.1</td>
<td>1.15</td>
</tr>
<tr>
<td><strong>Typical normalized emittance</strong> [µm]</td>
<td>~1.8</td>
<td>3.75</td>
</tr>
<tr>
<td><strong>Peak luminosity</strong> [10^{34} cm^{-2}s^{-1}]</td>
<td>2.1</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Crossing angle</strong> IP1/5 [µrad]</td>
<td>285</td>
<td>320</td>
</tr>
</tbody>
</table>

Established a very good performance: twice the design luminosity despite lower energy and number of bunches.
Achieved running configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2018</th>
<th>Design</th>
<th>Run III</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy [TeV]</strong></td>
<td>6.5</td>
<td>7.0</td>
<td>7.0</td>
</tr>
<tr>
<td><strong>No. of bunches</strong></td>
<td>2556</td>
<td>2808</td>
<td>~2760</td>
</tr>
<tr>
<td><strong>Max. stored energy per beam (MJ)</strong></td>
<td>312</td>
<td>362</td>
<td>&gt; 500</td>
</tr>
<tr>
<td><em><em>β</em> [cm]</em>*</td>
<td>30→25</td>
<td>55</td>
<td>40-30</td>
</tr>
<tr>
<td><strong>p/bunch (typical value) [10^{11}]</strong></td>
<td>1.1</td>
<td>1.15</td>
<td>1.8</td>
</tr>
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<td>~1.8</td>
<td>3.75</td>
<td>1.5-2.0</td>
</tr>
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<td><strong>Peak luminosity [10^{34} cm^{-2}s^{-1}]</strong></td>
<td>2.1</td>
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<td>340</td>
</tr>
</tbody>
</table>

Established a **very good performance**: twice the design luminosity despite lower energy and number of bunches.
2018: optimized running scenarios

- At smaller bunch intensities later in the fill, better reach in $\beta^*$ as limits from beam-beam, triplet heat load, and pileup are relaxed.
- Allows reaching reach 25 cm while staying above 7 $\sigma$ beam-beam separation.
  - Event pile-up remains $\leq 60$ up to $1.3\times10^{11}$ ppb.
  - Thanks to a reduction of crossing angle that frees aperture!
How it works in practise

All three levelling techniques are used in operation.

- **Crossing angle** and \( \beta^* \) levelling **enhance** the luminosity at **lower bunch intensity** for ATLAS and CMS, when the pile up is already reduced.
- **Important test** of \( \beta^* \) levelling for Run 3 and HL-LHC.
- **Offset levelling** is **used in LHCb / ALICE to ensure constant luminosity**.

![Graph showing luminosity over time for ATLAS, CMS, and LHCb with annotations for crossing angle levelling, \( \beta^* \) levelling, and offset levelling.](Graph.png)

If not dumped prematurely, a good fill can produce \(~0.5\ fb^{-1}\ (~12\ h)\).
Record: almost 1 fb-1 in 24h
Peak luminosity in 2018

Record: ATLAS and CMS work at $2.1 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$
(higher “virtual” peak of $2.2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ in 2017, but levelled down to $1.5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$)

Data from: http://lpc.web.cern.ch
- Fills not dumped prematurely produce regularly around 0.5 fb$^{-1}$ in ATLAS/CMS

- Many fills are well below, though … indication of several premature dumps in fills of good peak performance.

- CMS recorded 0.79 fb$^{-1}$ in one fill … while ATLAS was levelled down by offset for a low-pileup run

Data from: [http://lpc.web.cern.ch](http://lpc.web.cern.ch); plot by R. Bruce
About half of the fills dumped by operators
Other half dumped prematurely by faults
  • Reducing this would increase slope of luminosity production
  • Margin to improve

Data from: http://lpc.web.cern.ch
Overall 2018 availability so far

- Physics: 51%
- Downtime: 31%
- Operation: 16%
- Magnet cycle: 2%

Ref. period: May-September (without MDs)

Good performance overall: time in stable beam ~ 50% (reaching 54%)
Machine availability above 80%!
Events driving downtimes in 2018

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

- SPS dipole replacement
  - Magnet damaged by beam, causing vacuum leak

- Example of other faults
  - A few issues with the cryogenics system
  - Various trips of LHC power converters and quench protection system
  - Trip of ALICE dipole
  - Quenches
    - Quenches triplet magnets
    - UFO in 21R3 quenched 8 magnets
  - Sparks at dump dilution kickers
  - Injection kickers
Possible performance limitations

- **“UFO”: Unidentified Falling Objects**
  - Falling dusk particles (most credible theory) generate beam losses and possible quenches
  - Conditioning!

- **Electron cloud**
  - Electron cloud produced and accelerated by the beam in an avalanche effect (multi-pacting)
  - Degrading vacuum, poor beam quality, excessive loads on cryogenics system
  - Under control in 2018, concern for the future

- **“16L2”: UFO-like losses observed in 2017 at a specific location in sector 12 [cell 16L2]**
  - Caused by frozen air that “falls” into the beam
  - Beam loss spike followed by a fast beam instability
  - About **60 dumps in 2017**, requiring new filling scheme
  - 6 dumps in 2018 after various mitigations

Details in backup slides.
Status of 2018 luminosity production

On a good track to achieve the 2018 goal of 60fb$^{-1}$!

“Flat” regions: special runs, machine developments (MDs), faults.

Data from https://twiki.cern.ch/twiki/bin/viewauth/LhcMachine/LhcCoordinationMain
LHCb reached already the goal of 2 fb$^{-1}$. Now aiming at reaching 10fb$^{-1}$ by the end of the Run II!
Peak performance Run I and Run II

Design luminosity:
- Run 1: \(1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
- Run 2: \(2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)

Peak luminosity:
- Run 1: \(7.6 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}\)
- Run 2: \(2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)

Peak luminosity limited to \(\approx 2.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\) by the cryogenic cooling capacity
Status of integrated luminosity

The yearly integrated luminosities exceed now 50 fb$^{-1}$ thanks to

- **Record peak luminosity**,
- **Excellent machine reproducibility**,
- **Better efficiency** of $\sim 50\%$ of the time spent in physics data taking compared to $\sim 35\%$ between 2009-2015.

Expect to integrate over 60 fb$^{-1}$ in 2018

2018 surpassed 2017
Overall performance so far

- Reached goal of 150 fb\(^{-1}\) in Run 1 and Run 2 combined (~120 fb\(^{-1}\) in Run 2 only)

- Good hope to reach 150 fb\(^{-1}\) in Run 2 alone

---

Champagne from ATLAS
Until the end of the year

- Still interesting period ahead!
- Another 4-5 weeks of proton physics before the end of pp run
- Special physics run: high-β* at injection
  - Forward physics measurements
  - Issues with high background under study
- Heavy-ion run from beginning of November

Today

- Still interesting period ahead!
- Another 4-5 weeks of proton physics before the end of pp run
- Special physics run: high-β* at injection
  - Forward physics measurements
  - Issues with high background under study
- Heavy-ion run from beginning of November
Successful lead-lead (2015) and proton-lead (2016) runs took place after each proton run before going into winter shutdown.

Peak luminosities:

- **Pb-Pb**: $3 \times 10^{27}$ cm$^{-2}$s$^{-1}$
- **p-Pb**: $8 \times 10^{29}$ cm$^{-2}$s$^{-1}$
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☑ Conclusions
A major upgrade of the LHC injectors is foreseen during Long Shutdown 2 (2019-2020) to reach the HL-LHC beam parameter targets during Run 3.

During Run 3 the LHC may operate at 7 TeV following the LS2 consolidation and a major magnet training campaign (~500 quenches).

With the LHC operating beyond design luminosity in 2018, the prospects to reach 150 fb\(^{-1}\) integrated in Run 3 (2021-2023) are very good despite the short duration of the run.
Towards 7TeV

- All dipole magnets were trained for 6.5 TeV operation in 2015. Just **over 150 quenches** were required to reach 6.5 + \( \varepsilon \) TeV.

  *Spread in number of quenches between sectors is due to the mixture of producers.*

  *Two sectors pushed to 6.75 TeV in December 2016*

- Current estimate to train magnets to **7 TeV** is \( \sim 500 \) training quenches.
LHC: Projected target performance

- Peak luminosity
- Integrated luminosity

300 fb⁻¹ target

M. Lamont, 2017
Luminosity upgrade: key ingredients

Luminosity formula for round beams with crossing angle:

\[ L = \frac{N_1 N_2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F \]

1) maximize bunch intensities, \( N_i \)
2) minimize the beam emittance, \( \varepsilon_n \)
3) minimize beam size, \( \sqrt{\varepsilon_n \beta^* / \gamma} \) (constant beam power);
4) maximize number of bunches, \( k_b \) (beam power);
5) compensate for geometric ‘F’;
6) Improve machine ‘Efficiency’

➔ Injector complex (LIU), impedance reduction, new collimation systems
➔ triplet aperture
➔ 25ns
➔ Crab Cavities
➔ minimize number of unscheduled beam aborts
Predicted luminosity (baseline)

A bright and luminous future ahead of us!
Conclusions

☑ The LHC operation proceeds very well!

Unprecedented complexing to fulfil experiment’s requirements, under control. In 2018: various levelling technique, combined ramp&squeeze, new optics…

☑ Excellent luminosity production achieved in Run II!

Machine performance pushed to 2 twice the design

Thanks to small $\beta^*$ and small-emittance beams from injectors.

Good availability, with some bumps on the way.

Close to 2018 target of 60fb$^{-1}$, with still a few weeks of proton run ahead

Surpassed already the Run II goal of 150fb$^{-1}$ already.

Looking forward to seeing the lead ion run.

☑ A major injector upgrade is planned for LS2 (2019-2020)

Brighter beams will become available during Run III.

Important consolidation and upgrades starting in 4 months.

☑ Plan to run the LHC at 7 TeV in Run III following the LS2 consolidation and a major quench training campaign.

Reaching 150fb$^{-1}$ in Run III alone within reach in light of the present good performance and availability.
Reserve slides
2018 heavy-ion run

- 24 days of physics run envisaged

- Completely new machine configuration
  - New optics through the cycle – commissioning started
  - Intend to switch to 75 ns bunch spacing (to be confirmed by injectors)
    - ~40% more bunches. Highest Pb intensity ever!

- Potential to reach very high peak luminosities
  - Planned to level all experiments
  - Plan to test 6 times design luminosities (ATLAS/CMS)
  - LHCb also squeezed and will be taking data

- Approaching already the HL-LHC regime!

- Challenges: collimation, small beam-beam separation at ALICE polarity switch
LHCb and ALICE

- **LHCb**:
  - separation levelling around $4.4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
  - typical production around 20 pb$^{-1}$ in a good fill

- **ALICE**
  - separation levelling around $3.5 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$
  - typical production around 150 nb$^{-1}$ in a good fill
## 2018 schedule

<table>
<thead>
<tr>
<th>Phase</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Commissioning+ intensity ramp up</td>
<td>34</td>
</tr>
<tr>
<td>Scrubbing</td>
<td>1</td>
</tr>
<tr>
<td>Proton physics 25 ns</td>
<td>131</td>
</tr>
<tr>
<td>Special physics runs</td>
<td>8 + 1</td>
</tr>
<tr>
<td>Machine development</td>
<td>20</td>
</tr>
<tr>
<td>Setting-up fo Pb-Pb ion run</td>
<td>4</td>
</tr>
<tr>
<td>Pb-Pb ion run</td>
<td>24</td>
</tr>
<tr>
<td>Technical stops (3)</td>
<td>13</td>
</tr>
<tr>
<td>Technical stop recovery (3)</td>
<td>5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>241 days</strong></td>
</tr>
</tbody>
</table>
After a recovery year in 2015, the LHC moved into production in 2016, pushing the performance step by step from one year to the next despite intensity limitations.
The most credible theory is that **Unidentified Falling Objects** are dust particles that fall into the beam and generate beam losses due to inelastic collisions with the beam. These losses result in **energy deposition** on the superconducting magnets, risking to **quench** them.

**UFO were already Identified during Run 1**

Every year **10-20 dumps** due to UFOs, rarely magnets quench:

- **Loss monitor thresholds adjusted** to balance the risk of spurious dumps and need for quench prevention
- **A clear conditioning** has been observed along the years
“16L2”

- In June 2017 strange beam losses were observed together with small UFO-like losses.

- **Mitigations** were put in place in 2017:
  - Change of beam type to ‘8b4e’ (low e-cloud) → smooth operation up to \( \sim 1.25 \times 10^{11} \) p/bunch but limitation on number of bunches (especially for LHCb).
  - Orbit bump (dependency of losses on orbit corrector current).
  - Installation of a solenoid to reduce e-cloud.
  - Partial warm up (to 80K) of the sector (winter stop 2017-18), pumping out the N\(_2\) gas.
  - In 2018, 16L2 problem is still present, but operation with 25 ns beams is possible (contrary to 2017).
"16L2" in 2017

Main mitigation steps of the year:

- Change of 16L2 orbit corrector (MCB) current
- Change to 8b4e filling scheme
- Installation of solenoid

Day with ≥ 1 dump by 16L2

Courtesy of D. Mirarchi
Loss observation for 16L2

- **Three stages of loss rate:**
  1. **Steady loss** in 16L2 arising during the ramp along the entire fill (~ few 1e-6 Gy/s)
  2. **Sharp rise of losses** in 16L2 “UFO-like” (1e-3 ÷ 1e-2 Gy/s)
  3. **Very fast rise of losses** at collimators triggering a dump (few ms)

- **Regular UFO**
  - FFT BLM: Revolution frequency in 16L2
  - dBLM: Vertical losses from all bunches

- **16L2 event**
  - FFT BLM: Tune at primary collimators
  - BLM: Losses in the plane of MQ.16L2 polarity

Something touched at every turn

Beams undergo betatron oscillations
Scattered particles reach primary collimators
At high intensity the LHC is operated in the presence of electron clouds. Conditioning observed in 2015 and 2016 has stopped.

- The difference between sectors is not understood. This was not present in Run 1, it appeared in 2015 – cause not understood.
- Intensity may be limited in Run 3 by this effect.

The 8 sectors (arcs) behave differently.
Electron cloud — II

- Efficient conditioning with initial 24h scrubbing and during intensity ramp-up
- Stable normalized heat-loads and well below current limits, however still large spread (>2) between sectors which is not understood \(\rightarrow\) LIU & HL-LHC
The LHC accelerator complex

 Injector complex will undergo a major upgrade in the long shutdown 2: LIU project
Key systems of the HL-LHC project

- **New IR-quads Nb$_3$Sn (inner triplets)**
- **New 11 T Nb$_3$Sn (short) dipoles**
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
### Largest HEP accelerator project!

**Displacement Suppressor (DS) in P2 + P7**
- **Modifications**
  1. In IP2: new DS collimators in the connection cryostat.
  2. In IP7 new DS collimation with 11 T dipoles

**Matching Section (MS)**
- **Change/new lay-out**
  1. TAXN
  2. D2
  3. Crab cavities
  4. Correctors
  5. Q5
  6. Q5@1.9K in P6
  7. New collimators

**Interaction Region (ITR)**
- **Complete change and new lay-out**
  1. TAXS
  2. Q1-Q2a-Q2b-Q3
  3. D1
  4. All correctors
  5. Heavy shielding (W)

---

More than 1.2 km of LHC !!
Infrastructure.
Civil engineering (surface+ underground)
Target for FP7 HiLumi design study:

A peak luminosity of \( L_{\text{peak}} = 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \) with levelling, allowing an integrated luminosity of \( 250 \text{ fb}^{-1} \) per year, enabling the goal of \( L_{\text{int}} = 3000 \text{ fb}^{-1} \) twelve years after the upgrade.

In 2015-2016, established an ultimate performance reach with same hardware and same beam parameters, by using engineering margins:

\[ L_{\text{peak ult}} \approx 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \] and \( \text{Ultimate Integrated } L_{\text{int ult}} \sim 4000 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th>Protons per bunch in collision</th>
<th>( 2.2 \times 10^{11} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of bunches</td>
<td>2760</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>2.5 micron</td>
</tr>
<tr>
<td>Beta*</td>
<td>15 cm</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>510 microrad</td>
</tr>
<tr>
<td>Geometric reduction factor</td>
<td>0.369</td>
</tr>
<tr>
<td>Levelled luminosity [ultimate]</td>
<td>( 5.32 [7.5] \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} )</td>
</tr>
<tr>
<td>Levelled &lt;pile-up&gt; [ultimate]</td>
<td>140 [200]</td>
</tr>
<tr>
<td>Operational efficiency [ultimate]</td>
<td>50% [60%]</td>
</tr>
</tbody>
</table>