The LHC future: from Run 3 to the ultimate performance
Run 2: p-p operation

- **During Run 2:**
  - Demonstrated reliable operation with 6.5 TeV beams
  - Exploited 25 ns bunch spacing to operate with >2500 bunches
  - Reached design luminosity \( L_{\text{IP1/5}} = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \) … and doubled it!
  - Delivered 160 fb\(^{-1}\) to ATLAS and CMS

![Graph showing the integrated luminosity for different periods from 2015 to 2018. The total luminosity is 160 fb\(^{-1}\).]
Availability

- 2% Pre-Cycle
- Stable Beams (Physics data taking) - 49%
- Operations - 23%
- Fault / Downtime - 26%

2018 data
Heavy ion operation

HL-LHC instantaneous luminosity (∼6x10^{27} cm^{-2}s^{-1}) i.e. 6 times the LHC design value was already demonstrated in IP1 and IP5.

Pb-Pb luminosity record in 2018

Further improvements incoming in 2022
HL-LHC - goals

Prepare machine for operation beyond 2025 and up to ~2040

Operation scenarios for:

• Total integrated luminosity of 3000 fb\(^{-1}\) in around 10-12 years
• An integrated luminosity of ~250 fb\(^{-1}\) per year
• **Nominal**: levelled luminosity of \(5 \times 10^{34} \text{ cm}^2\text{s}^{-1}\) (events/crossing ~130)
• **Ultimate**: levelled luminosity of \(7.5 \times 10^{34} \text{ cm}^2\text{s}^{-1}\) (events/crossing ~200)
Higher Intensity

Increase bunch population

Smaller $\beta^*$

Reduced emittance

Smaller beam size at IP

$\mathcal{L} = \frac{N^2 f_{rev} k_c}{4\pi \beta^* \epsilon_{xy}} F$

Crossing angle reduction factor

$\frac{1}{\sqrt{1 + \left(\frac{\sigma_z \phi}{\sigma_x \phi/2}\right)^2}}$

Increase $F$

Shorter bunches, smaller crossing angle, crab cavities
Injector upgrade (bunch population, emittance)

Crossing angle compensation (crabs)

Operate in a high luminosity regime
# HL-LHC: key nominal 25 ns parameters (GPDs)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>7 TeV</td>
</tr>
<tr>
<td>Protons per bunch</td>
<td>$2.2 \times 10^{11}$</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2760</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>2.5 $\mu$m</td>
</tr>
<tr>
<td>Beta*</td>
<td>15 cm</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>500 $\mu$rad</td>
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<tr>
<td>Geometric reduction factor (F)</td>
<td>0.342</td>
</tr>
<tr>
<td>“Virtual” luminosity (with crabs)</td>
<td>$1.7 \times 10^{35}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Levelled luminosity</td>
<td>$5 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Levelled $&lt;$pile-up$&gt;$</td>
<td>$\sim 130$</td>
</tr>
</tbody>
</table>
Operational scenario

Nominal levelling time \( \sim 7 \) hours

No levelling - peak \( \sim 2 \times 10^{35} \, \text{cm}^{-2}\text{s}^{-1} \)

Levelling at \( 5 \times 10^{34} \, \text{cm}^{-2}\text{s}^{-1} \)

Nominal levelling time \( \sim 7 \) hours
LHC Injectors Upgrade

Deployed in LS2 (2019-20)

Linac 4
- Higher energy 160 MeV
- H- ions → charge exchange injection into the PSB

PSB
- 160 MeV, charge exchange injection, reduced space charge → improved brightness
- Top energy: 1.4 GeV to 2 GeV
  - New main power supply
  - New RF systems

SPS
- RF system upgrade → solid state power amplifiers
- Impedance mitigation
- Robust beam dump and protection devices
Run 3 at 6.8 TeV

Targeted consolidation and upgrades during LS2 followed by a long training campaign

Benefiting from the Injector upgrade

Proton-proton

• Levelled to a maximum luminosity $2.05 \times 10^{34}$ cm$^{-2}$s$^{-1}$ in ATLAS and CMS
• Levelled to a target of $\sim 1.4 \times 10^{31}$ cm$^{-2}$s$^{-1}$ and $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ in ALICE and LHCb respectively
• $\sim 1.8\times10^{11}$ proton/bunch in 2023 – 2025 - long levelling times!
Squeeze

- Small beam size at interaction point implies larger beams in the triplet magnets
- Larger beams implies a larger crossing angle
- For the LHC, aperture concerns dictates caution
- For the HL-LHC → new wide aperture magnets
HL-LHC: IR magnets

New wide-aperture superconducting magnets for the interaction regions
- **Large aperture**: 150 mm
  - Allows for **smaller beam size** at the interaction points
  - Allows introduction of **tungsten shielding** to protect the magnet from luminosity debris
- **Nb$_3$Sn technology** → Larger operational peak fields (11.4 T)
HL-LHC Nb$_3$Sn magnets

- Wire reception tests
- Cable manufacturing and reception tests
- Cable insulation
- Coil winding
- Coil reaction
- Impregnation
- Collaring
- Cold mass assembly
DE NOUVELLES TECHNOLOGIES POUR LE LHC À HAUTE LUMINOSITÉ (HL-LHC)

GÉNIE CIVIL
2 nouveaux tunnels de service de 300 mètres et 2 nouveaux puits à proximité d’ATLAS et de CMS.

CAVITÉS-CRABE
16 cavités-crabe supraconductrices pour les expériences ATLAS et CMS, permettant d’incliner les faisceaux avant les collisions.

AIMANTS DE FOCALISATION
12 quadrupôles plus puissants pour les expériences ATLAS et CMS, conçus pour concentrer plus fortement les faisceaux avant qu’ils n’entrent en collision.

LIAISONS SUPRACONDUCTRICES
Des lignes de transmission électrique à base de matériaux supraconducteurs haute température pour transporter du courant jusqu’aux aimants depuis les nouveaux tunnels de service à proximité d’ATLAS et de CMS.

COLLIMATEURS
15 à 20 nouveaux collimateurs et 60 collimateurs de remplacement pour renforcer la protection de la machine.

COLLIMATEURS À CRISTAUX
De nouveaux collimateurs à cristaux dans la zone d’insertion de nettoyage IR7 pour un nettoyage plus efficace des faisceaux pendant l’exploitation avec des ions.
June 2022: MQXFBP2 and corrector MCBXFBP1 on the alignment bench
Separation/re-combination dipole (D2 - INFN) cold mass assembly – Large Magnet Facility
CRANEbot will handle a VAX module without the need for human intervention.
Point 1 surface buildings
Underground works at P5

PM57 shaft

US57 cavern

UR55 gallery
Then another miracle happens...

<table>
<thead>
<tr>
<th>Year</th>
<th>ppb [10^{11}]</th>
<th>Virtual lumi. [10^{34} cm^{-2} s^{-1}]</th>
<th>Days in physics</th>
<th>θ [μrad]</th>
<th>β^*_start [cm]</th>
<th>β^*_end [cm]</th>
<th>CC</th>
<th>Max. PU</th>
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<td>1.8</td>
<td>4.4</td>
<td>90</td>
<td>380</td>
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<td>500</td>
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<td>15</td>
<td>on</td>
<td>200</td>
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</tbody>
</table>

![Graph of Peak Luminosity and Integrated Luminosity vs. Year]

25
Conclusions

Run 1 & 2 legacy
- Complex operations well mastered
- Excellent system performance and availability

Run 3
- First Stable Beams at 16:00 tomorrow…

LHC Injectors Upgrade
- Successful deployment in LS2, essential for what follows

HL-LHC
- Paving the way from Run 3 to Ultimate performance
- Completion of prototypes and start of series production for many components – interesting times!

Acknowledgements and thanks to everyone in ATS, our colleagues from across the organization, and our international collaborators.