Outlook for Nuclear Collisions in the LHC after Run 2

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On behalf of many colleagues past and present in CERN Accelerator and Technology Sector

Special thanks to R. Bruce, N. Fuster, A. Lechner, D. Mirarchi, M. Schaumann for slides.
Abstract

• Last reported at EPS HEP 2011 – after first Pb-Pb run in 2010.
• LHC Run 2 ended with the **2018 Pb-Pb collision run**, during which a luminosity 6 times beyond the design was achieved by further exploiting mitigations of the phenomena limiting luminosity that had been established in the 2015 run.
• Similar records were achieved with **p-Pb collisions in 2016**, a complex run, within a tight time frame, providing data sets at different energies, both in minimum-bias and high-luminosity modes.
• In **2017 a short Xe-Xe collision run** demonstrated the collider's flexibility with new species and further extended the physics programme.
• We discuss the prospects for achieving the luminosity goals defined for Runs 3 and 4 and the potential for colliding lighter nuclei.
12 one-month heavy-ion runs between 2010 and 2030. 6/12 done.

Upgrade: new collision mode
16h p-Pb pilot run

*1st p-Pb high luminosity run @ 4 Z TeV*

Pb-Pb @ 6.37 Z TeV
3.5 x design luminosity

Pb-Pb @ 3.5 Z TeV
0.5 x design luminosity

1st Pb-Pb collisions @ 3.5 Z TeV

p-Pb @ 4 Z TeV @ 6.5 Z TeV

Pb-Pb @ 6.37 Z TeV
6.1 x design luminosity

"Upgrade": new species
12h Pb81+ operation

HL-LHC

Currently no heavy-ion runs foreseen in Run 5 & 6, but a revised schedule is under discussion.

Runs with lighter nuclei (eg, Ar-Ar, …) proposed for after 2030, see HL-LHC physics report (input to European strategy)
Typical one-month heavy-ion run – highly schematic

- Commissioning new optics with protons
- First injection of ion beams,
- Run through cycle to collisions
- Validation steps through cycle: loss maps, asynchronous dumps to assure rigorous control of losses machine protection
  - Only once the cycle is established, cannot be changed again!
  - Beam-loss monitor dump threshold settings carefully tuned
- Beam intensity ramp-up in physics (constrained by machine protection)
- Luminosity production
- Van der Meer scans with normal physics optics
- Reverse ALICE muon spectrometer polarity
- Re-validate new configuration
- Intensity ramp-up again
- Luminosity production in new configuration
- Small number of essential machine development (MD) studies

Minute and careful planning of every step and beam-time management is crucial. Rapid adaptation and solutions to unforeseen problems.
First woman/man-made collisions with total CM energy > 1 PeV

Heavy-ion runs of LHC are very short but very complex. Experiments have many requests for changes of conditions.

This run was preceded by a week of equivalent energy p-p collisions to provide reference data.

Completely different from classical operation of Tevatron or LHC p-p.
Luminosity limit: Ultraperipheral interactions (quasi-real photons)

“Strongest magnetic fields in the universe” (David D’Enterria, FCC Week 2019) of \( \sim 10^{15} \) T cause bound-free pair production and electromagnetic dissociation of nuclei.

BFPP: \( ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \rightarrow ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{81+} + e^+, \)

\[ \sigma = 281 \text{ b}, \quad \delta = 0.01235 \]

EMD1: \( ^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \rightarrow ^{208}\text{Pb}^{82+} + ^{207}\text{Pb}^{82+} + n, \)

\[ \sigma = 96 \text{ b}, \quad \delta = -0.00485 \]

Each of these makes a secondary beam emerging from the IP with rigidity change that may quench bending magnets.

\[ \delta = \frac{1 + \Delta m / m_{\text{Pb}}}{1 + \Delta Q / Q} - 1 \]

Strong luminosity burn-off of beam intensity.

Discussed for LHC since Chamonix 2003 … see several references.

Hadronic cross section is 8 b (so luminosity debris contains much less power).
BFPP Quench MD – first luminosity quench in LHC

- BLM thresholds in BFPP loss region raised by factor 10 for one fill 8/12/2015 evening.
- Prepared as for physics fill, separated beams to achieve moderate luminosity in IP5 only.
- Changed amplitude of BFPP mitigation bump from -3 mm to +0.5 mm to bring loss point well within body of dipole magnet (it started just outside).
- Put IP5 back into collision in 5 μm steps.
- Unexpectedly quenched at luminosity value (CMS):
  \[ L \approx 2.3 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1} \]

  \[ \Rightarrow \quad 0.64 \text{ MHz event rate, about 45 W of power in Pb}^{81+} \text{ beam into magnet} \]

Using strong-field QED to quench superconductor!
Intended to resolve decades of uncertainty about steady-state quench level of LHC dipole magnets. But some uncertainties in interpretation because of chamber misalignment in this particular DS.L5. Later a second collimation quench test with Pb was also successful.
Lessons from the 2015 Pb-Pb run

• Two new configurations within one month (p-p reference for a week and Pb-Pb) are possible.
• LHCb also takes Pb-Pb collisions at lowest ever $\beta^*=1.5$ m
  – Complicates filling schemes
• BFPP bumps successfully remove the peak luminosity limit for ATLAS, CMS (see later)
• Separation levelling used in ALICE (also in ATLAS, CMS)
• First controlled quench of an LHC dipole using BFPP beam from the collision point
• First successful collimation quench test (with any beam)
• After two Pb-Pb runs in 2010, 2011, the High Luminosity Pb-Pb phase started in 2015
2016

\[ p \rightarrow \text{Pb} \rightarrow p \]
Part 1: 1 week at 5 TeV, levelled luminosity for ALICE

Longest ever LHC fill, 37.75 h in Stable Beams at **constant luminosity** in ALICE (half intensity!)

Full intensity, ATLAS, CMS, LHCb join in for physics, ended by trip

Scheduled interruptions (ion source, VIP visit, RP)

Fills could have been much longer still. Lifetime good enough to give bonus minimum-bias programmes to ATLAS, CMS as well as ALICE.

LHCb colliding p-He (gas).

Special conditions admittedly, but astonishing availability!

Protons in Beam 1, Pb in Beam 2
Common BPMs and moving encounters had constrained charge of p and Pb bunches to be similar.

Increase in p intensity to $\sim 3 \times 10^{10}$/bunch enabled by new synchronous orbit mode of beam position monitors (R. Alemany, J. Wenninger, beam instrumentation group ...)

Pb intensity to $\sim 2.1 \times 10^8$/bunch

25% increase in ATLAS/CMS from filling scheme

Peak luminosity a factor $\sim 6$ beyond original “design” value


Could have gone higher still by further increase of p intensity but limited at present by Pb beam luminosity debris in magnets of Sector 12.
## Goals of p-Pb run surpassed

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$</th>
<th>Experiments</th>
<th>Primary goal</th>
<th>Achieved</th>
<th>Additional achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>5 TeV p-Pb</strong> (Beam energy 4 Z TeV)</td>
<td>ALICE (priority)</td>
<td>700 M min bias events</td>
<td><strong>780 M</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ATLAS, CMS</td>
<td></td>
<td></td>
<td>&gt;0.4 /nb min bias</td>
</tr>
<tr>
<td></td>
<td>LHCb</td>
<td></td>
<td></td>
<td>SMOG p-He etc</td>
</tr>
<tr>
<td><strong>8 TeV p-Pb or Pb-p</strong> (Beam energy 6.5 Z TeV)</td>
<td>ATLAS, CMS</td>
<td>100 /nb</td>
<td><strong>194,183 /nb</strong></td>
<td></td>
</tr>
<tr>
<td><strong>8 TeV p-Pb</strong></td>
<td>ALICE, LHCb</td>
<td>10 /nb</td>
<td><strong>14,13 /nb</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LHCf</td>
<td>9-12 h @ $10^{28}$ cm$^{-2}$s$^{-1}$</td>
<td><strong>9.5 h@ $10^{28}$ cm$^{-2}$s$^{-1}$</strong></td>
<td>Min bias ATLAS, CMS, ALICE</td>
</tr>
<tr>
<td><strong>8 TeV Pb-p</strong></td>
<td>ALICE, LHCb</td>
<td>10 /nb</td>
<td><strong>25,19 /nb</strong></td>
<td></td>
</tr>
</tbody>
</table>

Note: ALICE and LHCb are asymmetric experiments, with different coverage according to beam direction.

Reminder: first 1 month p-Pb/Pb-p run at 5 TeV in 2013 gave 31/nb to ALICE, ATLAS, CMS and 2/nb to LHCb.
Lessons from the 2016 Pb-Pb run

• Remains the most complicated run of LHC so far.
• ≥ 4 new configurations within one month (Min. bias at 5.02 TeV, p-Pb, LHCf and Pb-p at 8.16 TeV) were possible.
• LHCb also takes p-Pb collisions at lowest ever β*=1.5 m
  – Complicates filling schemes
• Proton intensity raised by synchronous operation of common BPMs
• First heavy-ion run where luminosity debris of Pb beam was significant, so we could not reach peak luminosity limit for ATLAS, CMS
  – Better TCL settings should overcome this in future runs
• Separation levelling used in ALICE (also in ATLAS, CMS)
• After two p-Pb runs in 2012, 2013, the High Luminosity p-Pb phase started in 2016
2017 - NO RUN SCHEDULED ... AT FIRST

But Xe beams were available in the injectors for fixed target physics ...
Reminder: Xe-Xe collisions in LHC, 13 October 2017

This run used p-p optics for fast set-up
⇒ ALICE had $\beta^*=10$ m so lower luminosity than ATLAS/CMS
Avoid this in future O-O run ⇒ prefer to use a heavy-ion optics.

Papers at IPAC2018
https://accelconf.web.cern.ch/AccelConf/ipac2018/

MOPMF039 First Xenon-Xenon Collisions in the LHC

MOPMF038 Cleaning Performance of the Collimation System with Xe Beams at the Large Hadron Collider

TUPAF020 Performance of the CERN Low Energy Ion Ring (LEIR) with Xenon

TUPAF024 Impedance and Instability Studies in LEIR With Xenon

Data on Xe-Xe used in many physics papers at Quark Matter 2018 and later

O-O and p-O in LHC, LMC 17/7/2019
Results from Xe-Xe run of LHC at Quark Matter conference, May 2018

Rich physics harvest from 16 h (6.5 h Stable Beams) Xe-Xe run of LHC on 12/10/2017.

Results reported by all LHC experiments, clarifying the transitions between Pb-Pb, p-Pb and p-p.

Illustrates “beyond-design” potential of LHC.

Input to HL/HE-LHC Physics Workshop case for possible future runs with lighter nuclei.
Pb-Pb in 2018: new optics with smallest ever $\beta^*$ in ALICE, LHCb

- Optics design by S. Fartoukh, new combined ramp & squeeze
- Gradual divergence from identical to pp optics in 2010 to a completely new cycle in 2018
- Initial problem with beam size in ALICE now understood
- Fixed for reversed-polarity part of run
- Some lessons for optics correction procedure in future
IR2 ALICE +ve: external angle passed through zero in every fill

Horizontal parallel separation increased to ±3 mm
IP shift bump still off
Transition through zero external bump to unfavourable polarity with respect to IP (neutrons moving down)
No sign of beam-beam effects.
Ion source fault: No ions available after TS3
- Many commissioning tasks were advanced with protons.
- Degraded beam quality during the first week of the run.
  - Resulting in lower beam intensity and longer turn around time.
  - Shorter levelling periods and less time in physics.

ALICE luminosity lower than expected:
- **Cause:** beam deformation and reduced overlap at IP introduced by strong local betatron coupling in IR2.
- **Solution:** correction with skew-quadrpoles implemented during ALICE polarity reversal.
  - Luminosity sharing strategies used until solution was found.
    - Filling schemes (number and distribution of bunches).
    - Luminosity levelling target of ATLAS/CMS.
A high peak luminosity Pb-Pb fill in 2018 with 100 ns

- Leveling in ATLAS and CMS gradually increased to $6 \times 10^{27}$ cm$^{-2}$s$^{-1}$
- ALICE leveled at design luminosity $1 \times 10^{27}$ cm$^{-2}$s$^{-1}$
- After correction of local coupling, ALICE level times increased to ~ 8 h.
Commissioning (longer than expected)

100ns Bunch Spacing
- 648b
- 592b

75ns Bunch Spacing
- 733b
- 670b

Repetition of luminosity calibration for special physics run (protons)

Intensity ramp-up 100ns beams

Ion source fault
no ions available

1st Pb-Pb Stable Beams

Ion source refill

New Record Peak luminosity in every fill up to $6.4 \times 10^{27} \text{cm}^{-2}\text{s}^{-1}$

ALICE polarity switch & fix of IR2 coupling

M. Schaumann
During the system validation observed higher losses than expected (at EoS/Physics) required to refine the collimator settings.

**TCSP in IP6**
- High losses at the level of the TCP observed on the right TCSP jaw.
- Solution adopted: opening the right jaw by 2 mm. The losses were reduced by 99%.

**TCTPH in IP1**
- High losses observed on the TCTPH in IP1 (even higher at EoS).
- Solution adopted: open the TCTPH to 11σ. The losses were reduced by 80%.

Heavy-ion collimation is much less efficient than protons because nuclei fragment and dissociate on interaction with collimators, leading to many more potential loss zones. Great progress simulating this complex beam physics.
Significant BFPP beams in all IPs (horizontal envelopes)

IR1 far beyond quench level, mitigated by bump

IR5 far beyond quench level, mitigated by bump

IR2 levelled below quench level, will change after LS2 (TCLD)

IR8 levelled below quench level. No mitigation foreseen.

Bumps were adjusted empirically, good agreement with calculation, except left of IP5, location of 2015 BFPP quench test.

Chamber misalignment.

Bump spreads losses
Collimation-related threshold changes essential for Pb halo losses:

1) **Adjusted the dumping hierarchy for Pb losses in IR7**
   - With proton thresholds, would dump first at cold magnets in DS (cleaning inefficiency about a factor of 100 worse for Pb than for protons)
   - Decreased master thresholds at two skew secondary collimators to dump first at these collimators

2) **Aligned corrections for collimation losses to the energy of the Pb run**
   - In proton operation FT corrections only active above 6.39 TeV (Pb run: 6.37 TeV)
   - Extended all collimation-related FT corrections to 6.37 TeV

3) **Removed bottlenecks due to leakage of ion fragments from IR7**
   - Increased the master thresholds at DS magnets according to 2015 Pb quench test to avoid premature dumps

Despite all optimizations in DS, **10 Hz dumps in IR7 were unavoidable**:

![Diagram showing 10 Hz dump Fill #7459](image)
BFPP-related threshold changes essential for luminosity reach:

1) Prevent premature dumps due to BFPP ions in IR1/5
   - Several threshold and orbit bump optimizations around BFPP loss location (connection cryostats) -> could reach the target luminosity ($6-7 \times 10^{27} \text{cm}^{-2}\text{s}^{-1}$) while still protecting against quenches

2) Prevent premature dumps due to BFPP ions in IR8
   - Luminosity reach in LHCb higher than in previous years ($10^{27} \text{cm}^{-2}\text{s}^{-1}$) thanks to 75 nsec bunch spacing
   - BFPP loss location around Q10 -> Q10s had low thresholds to reduce the risk of symmetric quenches -> would have prevented reaching the target lumi
   - Decided to temporarily decrease QPS thresholds, which allowed increasing the Q10 BLM thresholds
Validation of energy deposition simulations for proton and heavy ion losses in the CERN Large Hadron Collider


Phys. Rev. Accel. Beams 22, 071003 – Published 11 July 2019
A high peak luminosity Pb-Pb fill in 2018 with 75 ns

• Design peak luminosity is exceeded by factor 5 in ATLAS/CMS.
  → Almost reaching nominal HL-LHC target luminosity
  → Demonstrated feasibility in ATLAS/CMS

• ALICE levelled to design saturation value most of the time in Stable Beams.

• Factor 100 increase in LHCb fill luminosity over 2015.
Comparison of BFPP losses with dump thresholds (specially set in BFPP loss zones) shows that we can go considerably further.

\[ L = 6 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1} \]

\[ = 6 \times \text{design} \]

\[ = (47 \text{ kHz hadronic event rate}) \]

Nominal HL-LHC levelling value is

\[ L = 7 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1} \]
Scheduled from 00:00 to 06:00, 3 Dec, the last few hours of Run 2. Intended to resolve ambiguities from misaligned chamber in 2015 BFPP quench experiment.

Thanks to PS, LEIR and Linac3 teams who all scrambled in the middle of the night to repair a series of faults and intervene.

- PS main magnet fault
- LEIR performance degraded, cannot fix?
- HI source instability and unexpected deterioration of stripper foil after Linac3

We hope to measure the steady-state quench level of the LHC dipole in **Nov 2021** ...
Lessons from the 2018 Pb-Pb run

- BFPP bump mitigation allows HL-LHC peak luminosity in ATLAS/CMS without quenches (> 6 × design).

- Collimation losses remain critical, avoid premature dumps.

- 75 ns filling scheme works very well, bunches at limit of stability in SPS
  - Provides many more collisions for LHCb, who can take them!
  - Peak luminosity up to $10^{27}$ cm$^{-2}$s$^{-1}$ does not quench LHCb

- “Invisible” local coupling at IR2 reduced ALICE luminosity in first half of run
  - Solved by skew-quad knob that reversed error in settings
  - Avoid same problem in future with specific checks
  - More generally, one should plan set-up phases with just-in-time validation
    - We had planned to validate reversed polarity earlier, before finding the solution. This would have been lost time.  
      So leave validation until just before luminosity operation.
OUTLOOK FOR FUTURE HEAVY-ION RUNS OF LHC
Table 1: Representative simplified beam parameters at the start of the highest luminosity physics fills, in conditions that lasted for $> 5$ days, in each annual Pb–Pb run (Ref. [2] and references therein). The original design values for Pb–Pb [1] collisions and future upgrade Pb–Pb goals are also shown (in this column the integrated luminosity goal is to be attained over the 4 Pb–Pb runs in the 10-year periods before and after 2020). Peak luminosities are averages for ATLAS and CMS (ALICE being levelled). The smaller luminosities delivered to LHCb from 2013–2018 are not shown. Emittance and bunch length are RMS values. The series of runs with $\sqrt{s_{NN}} = 5.02$ TeV also included pp reference runs, not shown here. Design and record achieved nucleon-pair luminosities are [boxed], and some key parameters related to p–Pb parameters in Table 2 are set in red type, for easy comparison. The upgrade peak luminosity is reduced by a factor $\approx 3$ from its potential value by levelling.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>design</th>
<th>achieved</th>
<th>upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weeks in physics</td>
<td>-</td>
<td>4 3.5 2.5 3.5 -</td>
<td></td>
</tr>
<tr>
<td>Fill no. (best)</td>
<td>-</td>
<td>1541 2351 4720 7473 -</td>
<td></td>
</tr>
<tr>
<td>Beam energy $E[Z \text{TeV}]$</td>
<td>7</td>
<td>3.5 6.3 6.37 7</td>
<td></td>
</tr>
<tr>
<td>Pb beam energy $E[A \text{TeV}]$</td>
<td>2.76</td>
<td>1.38 2.51 2.51 2.76</td>
<td></td>
</tr>
<tr>
<td>Collision energy $\sqrt{s_{NN}} [\text{TeV}]$</td>
<td>5.52</td>
<td>2.51 5.02 5.02 5.52</td>
<td></td>
</tr>
<tr>
<td>Bunch intensity $N_b [10^8]$</td>
<td>0.7</td>
<td>1.22 1.07 2.0 2.2 1.8</td>
<td></td>
</tr>
<tr>
<td>No. of bunches $k_b$</td>
<td>592</td>
<td>137 338 518 733 1232</td>
<td></td>
</tr>
<tr>
<td>Pb norm. emittance $\epsilon_N [\mu\text{m}]$</td>
<td>1.5</td>
<td>2. 2.0 2.1 2.0 1.65</td>
<td></td>
</tr>
<tr>
<td>Pb bunch length $\sigma_z \text{ m}$</td>
<td>0.08</td>
<td>0.07–0.1 0.08</td>
<td></td>
</tr>
<tr>
<td>$\beta^*$ [m]</td>
<td>0.5</td>
<td>3.5 1.0 0.8 0.5 0.5</td>
<td></td>
</tr>
<tr>
<td>Pb stored energy MJ/beam</td>
<td>3.8</td>
<td>0.65 1.9 8.6 13.3 21</td>
<td></td>
</tr>
<tr>
<td>Luminosity $L_{AA} [10^{27}\text{cm}^{-2}\text{s}^{-1}]$</td>
<td>1</td>
<td>0.03 0.5 3.6 6.1 7</td>
<td></td>
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<tr>
<td>NN luminosity $L_{NN} [10^{30}\text{cm}^{-2}\text{s}^{-1}]$</td>
<td></td>
<td>43 1.3 22 156 264 303</td>
<td></td>
</tr>
<tr>
<td>Integrated luminosity/expt. $[\mu\text{b}^{-1}]$</td>
<td>1000</td>
<td>9 160 433,585 900,1800 10$^5$</td>
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<tr>
<td>Int. NN lumi./expt. $[\text{pb}^{-1}]$</td>
<td>43</td>
<td>0.38 6.7 19.25 39.80 4.3 $\times 10^2$</td>
<td></td>
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</tbody>
</table>
Table 2: Representative simplified beam parameters at the start of the highest luminosity physics fills, in conditions that lasted for $> 5$ days, in the one-month $p$–$Pb$ runs (Ref. [2] and references therein). The very short pilot run in 2012 is not shown. The original “design” values for $p$–$Pb$ [4] collisions are also shown (in this column the integrated luminosity goal was supposed to be obtained over a few runs. Peak luminosities are averages for ATLAS and CMS (ALICE being levelled). The smaller luminosities delivered to LHCb from 2013–2016 and in the minimum-bias part of the run in 2016 are not shown. Emittance and bunch length are RMS values. Single bunch parameters for these $p$–$Pb$ or $Pb$–$p$ runs are generally those of the $Pb$ beam. Design and record achieved nucleon-pair luminosities are [boxed], and some key parameters related to $p$–$Pb$ parameters in Table [1] are set in red type, for easy comparison.

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<td>43</td>
<td>24</td>
</tr>
<tr>
<td>Integrated luminosity/experiment [$\mu b^{-1}$]</td>
<td>$10^5$</td>
<td>32000</td>
</tr>
<tr>
<td>Int. NN lumi./expt. [$\mu b^{-1}$]</td>
<td>21</td>
<td>6.7</td>
</tr>
</tbody>
</table>
LHC “first 10-year” baseline Pb-Pb luminosity goal was 1 nb\(^{-1}\) of Pb-Pb luminosity (only) in Runs 1+2.

Goal of the first p-Pb run was to match the integrated nucleon-nucleon luminosity for the preceding Pb-Pb runs but it already provided reference data at 2015 energy.

Equivalent energy runs
\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \quad (\sqrt{s}=1.045 \text{ PeV in Pb-Pb}) \]

\[ E_b = \begin{cases} 
6.37Z \text{ TeV} & \text{in Pb-Pb (2015,2018)} \\
4 Z \text{ TeV} & \text{in p-Pb (2013,part 2016)} \\
2.51 \text{ TeV} & \text{in p-p (2015)}
\end{cases} \]

ALICE integrated luminosity in 2018 was equivalent to spending 10.4 days, 100% of the time, at constant levelled saturation luminosity.
Proton-nucleus programme status after 2016

Design

Integrated proton–nucleus luminosity [nb$^{-1}$]

Time [weeks from start physics]
How close are we to the HL-LHC goals?

Upgraded ALICE will take similar luminosity to ATLAS/CMS (needs TCLDs in IR2).

With 75 ns for full run, 2018 could have produced more.

More bunches from slip-stacking in future.

“Goal” = estimates by M. Jebramcik, assuming same 50 ns Pb beam, with slip-stacking, as for Pb-Pb and matching proton beam. Even upgraded ALICE will be levelled. Assuming ATLAS, CMS are not, for now. HL-HE-LHC Physics Workshop is now requesting more runs with p-Pb than in former plan.
Beam parameters for potential runs with lighter ions

- Experience with other species in LHC injectors for fixed target
  - Less stringent requirements on beam quality (emittance)

Postulate simple form for bunch intensity dependence on species charge only

\[ N_0(Z, A) = N_0(82, 208) \left( \frac{Z}{82} \right)^p \]

where \( p = \begin{cases} 
1.9 & \text{fixed target experience} \\
0.75 & \text{Xe run vs best Pb} 
\end{cases} \)

Use this highly simplified scaling to project future luminosity performance as a function of \( p \).
Assume that other quantities (like geometric beam size), filling scheme, other loss rates, etc, are equal.

Treat results only as tentative and indicative only!

Study range of \( p \)-values
\( p=1.5 \) seems reasonable
• Show ratio of time-averaged luminosity to Pb-Pb
• Analytical calculation with burn-off only
• Lower cross sections for ultraperipheral collisions so more beam particles converted to hadronic luminosity
• Assuming 2.5 h turnaround time, 3 experiments with full luminosity
• Nucleon-nucleon luminosity in 1-month run: gains ranging up to a factor ~13 for lightest considered ion (O) at p=1.5
• The dramatic improvements in transmitted Pb intensity in 2015-16 were the result of many detailed studies and improvements
• Projections have large uncertainties!

Detailed plans now in preparation for short O-O (QGP system size, etc) and p-O (cosmic rays) runs in 2023.
Summary and conclusions

• The LHC can collide more types of beam, with much higher performance, than originally foreseen.
  – Including asymmetric beams (p-Pb) despite the two-in-one magnet design
  – LHC ion injector chain working far beyond design parameters
  – Rich physics output (see heavy-ion parallel and plenary talks)

• First short runs with new species can have significant physics output.

• Planning the set-up of 1-month runs is critical, especially as one cannot backtrack after validations.

• Control of heavy-ion beam losses, like collimation, BFPP, is critical, complicated and may surprise. But simulations are increasingly reliable guide to details of mechanisms.
  – Crystal collimation (very successful tests in MD, not described here) holds promise!

• BLM settings also require careful analysis and tuning.

• We have come close to the full “HL-LHC” performance in Pb-Pb and p-Pb.
BACKUP SLIDES
Pb-Pb BFPP cross-section (heuristic)

Pair production $\propto Z_1^2 Z_2^2$

Radial wave function of 1s$_{1/2}$ state of hydrogen-like atom in its rest frame

$$R_{10}(r) = \left(\frac{Z_1}{a_0}\right)^{3/2} 2\exp \left( -\frac{Z_1 r}{a_0} \right)$$

$$\Rightarrow \Psi(0) \propto Z_1^{3/2} \Rightarrow |\Psi(0)|^2 \propto Z_1^3$$

Cross section for Bound-Free Pair Production (BFPP) (various authors)

$$Z_1 + Z_2 \to (Z_1 + e)_{1s_{1/2}...} + e^+ + Z_2$$

has very strong dependence on ion charges (and energy)

$$\sigma_{pp} \propto Z_1^5 Z_2^2 \left[ A \log \gamma_{CM} + B \right]$$

$$\propto Z_1^7 \left[ A \log \gamma_{CM} + B \right] \text{ for } Z_1 = Z_2$$

Total cross-section $\propto Z_2^2 Z_1^5$


Cross section for (various authors)

- 0.2 b for Cu-Cu RHIC
- 114 b for Au-Au RHIC
- 281 b for Pb-Pb LHC
Bunch intensities in 2018

As usual, integrated luminosity is roughly proportional to total injected intensity.

Major increase with switch from 100 ns to 75 ns scheme during 2018 run.
Analysis of lifetime as described in

- CWG 232, spikes: https://indico.cern.ch/event/760786/
- CWG 233, lifetime: https://indico.cern.ch/event/763571/

There are 3 dumps missing in 2018 because the dump wasn’t triggered in the RS_09, which was used for the analysis.

Thus, in total we had 7 dumps in 2018, all due to 10Hz oscillations.
Separations at outermost encounters have been increased by larger horizontal separation.

Beam-beam tune-shifts remain small.

No adverse effects observed in any fill.
Horizontal parallel separation still at ±3 mm, could have started to bring it down before this point

IP shift bump still off

Reversed external bump to unfavourable polarity with respect to IP (neutrons moving down)
Production fills with long ALICE levelling
Peak Luminosity in 'Stable Beams'

Luminosity [10^34 cm^-2 s^-1]

Preliminary

- ATLAS
- CMS
- LHCb
- ALICE

Polarity change in ALICE 7/31st beam from now on.

Date

## Achieved and HL-LHC/LIU baseline (2017) Parameters

<table>
<thead>
<tr>
<th></th>
<th>Pb-Pb (2018 achieved)</th>
<th>HL-LHC request</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong> [TeV]</td>
<td>6.37 Z</td>
<td>7 Z</td>
<td>☹️ LS2 magnet training</td>
</tr>
<tr>
<td>Particle Charge Z</td>
<td>82</td>
<td>82</td>
<td>☹️</td>
</tr>
<tr>
<td>$\beta^*$ at IP 1/2/5/8 [m]</td>
<td>0.5 / 0.5 / 0.5 / 1.5</td>
<td>0.5 / 0.5 / 0.5 / ?</td>
<td>☹️</td>
</tr>
<tr>
<td>Emittance [μm]</td>
<td>~2.0</td>
<td>1.65</td>
<td>☹️</td>
</tr>
<tr>
<td>Bunch Intensity [10^8 ions]</td>
<td>~2.3</td>
<td>1.8</td>
<td>☹️ Slip stacking</td>
</tr>
<tr>
<td><strong>No. Bunches</strong></td>
<td>733</td>
<td>1232</td>
<td>☹️ Slip stacking</td>
</tr>
<tr>
<td><strong>Bunch Spacing</strong></td>
<td>100ns → 75ns</td>
<td>50ns</td>
<td>☹️ Slip stacking</td>
</tr>
<tr>
<td>Peak Luminosity IP1/2/5/8 [10^{27}cm^{-2}s^{-1}]</td>
<td>6.4 / 1 / 6.4 / 1</td>
<td>7 / 7 / 7 / ?</td>
<td>☹️ Luminosity levelling?</td>
</tr>
</tbody>
</table>

Green values are above LHC design

Some collisions in LHCb (not considered in detail yet)
Physics configuration with negative orbit bump moves BFPP impact point into connection cryostat – no magnet to quench.

Reversing bump moves loss point into the centre of a magnet. Increase luminosity at IP until quench.
Betatron cleaning measured for the two beams and planes.

Observed a degradation by more than two orders of magnitude with respect to protons on the inefficiency in the DS after the betatron cleaning insertion as well as additional loss spikes in the arcs.

Collimator settings

<table>
<thead>
<tr>
<th>Collimator</th>
<th>Half gap [σ]</th>
<th>B2H [σ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCP/TCSP/TCLA</td>
<td>7</td>
<td>5/6.5/10</td>
</tr>
<tr>
<td>TCP/TCSP/TCLA</td>
<td>3</td>
<td>15/18/20</td>
</tr>
<tr>
<td>TCTP</td>
<td>1/2/5/8</td>
<td>9/37/9/15</td>
</tr>
<tr>
<td>TCL</td>
<td>1/5</td>
<td>out</td>
</tr>
<tr>
<td>TCSP/TCDQ</td>
<td>6</td>
<td>7.3/7.3</td>
</tr>
</tbody>
</table>
A good understanding of the agreement between simulations and measurements is crucial for determining possible future operational limitations.

A first comparison shows a good overall agreement of losses along the ring, although some discrepancies are present.

Asymmetric TCP simulations also performed.

Simulations very sensitive to the impacting beam parameters at the TCP, CO and aperture misalignments. Detailed studies are on going.
Simulations:
- 87% of losses in the TCTPH come from the LEFT TCP jaw.
- Energy lost in the TCTPH dominated by first turn heavy-ion fragments.
- By opening the TCTPH to 11 $\sigma$ the energy lost on the TCTPH in IP1 is reduced by $\sim$30%.

Measurements:
- 50-90% reduction of BLM signal of TCTPH in IP1 with both adopted changes on the settings:
  - Asymmetric TCP settings (left TCP opened by 0.5 $\sigma$).
  - TCTPH opened to 11 $\sigma$.

Quite good understanding of where the secondary beam is deposited in the beam line but not in absolute values.

N. Fuster, R. Bruce et al
Simulations:
- Losses only observed on the right TCSP jaw (L jaws in the shadow of TCDQ).
- Dominated by first turn effect.
- With 2016 settings ($8.3\sigma$) we observed one order of magnitude less energy of first impacts on the R TCSP jaw.
- By opening the R TCSP jaw by 2 mm losses are reduced by 99%.

Measurements:
- With 2 mm ($11.2\sigma$) opening of the R TCSP jaw the losses reduced by 98%.

Quite good understanding of where the second beam is deposited in the beam line but not in absolute values.

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N. Fuster, R. Bruce et al
Complex run made possible by extraordinary quality of LHC construction and operation, excellent performance of ALL the injectors together.

Luminosity during the whole run

Fast switch back to original conditions to top-off ALICE minimum-bias data-taking.

Levelled 19h50 in Stable Beams, dumped at 06:02 Monday 5 Dec.