Limitations and Constraints in the Levelled Luminosity … from the machine and the experiments, impact of bunch-to-bunch fluctuations

The availability of high-intensity beams from the injections after LS2 allows the operation of LHC at levelled luminosity.

Outline

- Recap: what are the limits to the levelled value of the luminosity?
  - Review of the constraints from the machine and the experiments

- What about bunch-to-bunch fluctuations in luminosity while in levelling?
  - Review the observations from Run 2
  - First estimates and indications for the Run 3 operation
Luminosity Levelling in LHC Run 3

Introduction

Run 2 : Operation

- Luminosity decay in time for the HI Experiments ATLAS & CMS
  - Luminosity levelling with offset at constant PU for LHCb and ALICE

- Variation of crossing angle and $\beta^*$ to optimize the running conditions and the integrated luminosity

Run 3 : levelled luminosity

- Luminosity levelled at $2.0 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ for the HI Experiments ATLAS & CMS
  - Levelled with offset at constant PU for LHCb and ALICE

- Combined variations of $\beta^*$ and crossing angle to maintain the levelled value and optimized conditions

Details in the presentations of S.Kostoglou, R. Tomas
Luminosity Levelling in LHC Run 3

What sets the levelling value?

Constraints from the IT cryogenic system

**Maximum cooling capacity ITR1**

New: EYETS 12th April 2017

- ITR1 cold mass cooling capacity test during EYETS
- TTmax TT line B EH raw value

EH raw heating was 350 W while keeping the process stable. The real maximum cold mass heat load compensated by the cryogenic system was 350*0.87=305 W (without any contingency).

**Note:**
- the cryogenic system has an "inertia" of ~20 min before it dumps the beam.
- for the same reason there is no sensitivity on bunch variations or other high-frequency effects.
- the energy deposition in the inner triplet magnets does not depend on the crossing angle/β* values, only on total luminosity.
Luminosity Levelling in LHC Run 3
Limitation from the IT cryogenics

Fill 6643 – 2018 @ 6.5 TeV

FLUKA simulation estimates are compatible/verify the cryogenic measurements:

- 120-125 W deposited in the IT magnets @ 6.5 TeV for $1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
  - This is also confirmed in short-period tests in Run 2 where luminosities in the range and above $2.0 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ were achieved. → 240-250 W of load to the magnets

- Scaling for Run 3 we obtain 250-260 W at $2.0 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ @ 6.8 TeV that is thus defined as the operational setting for Run 3
  - Worth investigating with a test during the intensity ramp up the maximum possible operational luminosity levelling reach
Luminosity Levelling in LHC Run 3

Constraints from experiments

- The HI experiments ATLAS/CMS set a limit not to exceed ~60 PU events per crossing average, to remain optimal with the trigger and DAQ systems.
  - Further, the luminosity should be adjusted to remain within 5% during levelling.

- An operational scenario is defined, respecting both constraints from the cryogenics and the experiments.
  - PU events ~52 for nominal scenario, may reach ~58 for alternative options with fewer bunches.

Note:
- Since we stay ~12% below the target PU events, that may be considered as margin by the experiments to absorb bunch-to-bunch fluctuations in luminosity?
**Luminosity Levelling in LHC Run 3**

**Run 3 Operations**

<table>
<thead>
<tr>
<th></th>
<th>Run 2</th>
<th>Run 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BCMS</td>
<td>Peak Luminosity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[10^4 Hz/μb]</td>
</tr>
<tr>
<td>Total in beam</td>
<td>2556</td>
<td>2744</td>
</tr>
<tr>
<td>Colliding in ATLAS/CMS</td>
<td>2544</td>
<td>1.77</td>
</tr>
<tr>
<td>Colliding in <em>LHCb</em></td>
<td>2332</td>
<td>0.05</td>
</tr>
<tr>
<td>Colliding in ALICE_{pp}</td>
<td>2215</td>
<td>0.003</td>
</tr>
<tr>
<td>Fill duration/LL time</td>
<td>7.8h</td>
<td>15.9/12</td>
</tr>
</tbody>
</table>

Some features of Run 3 to keep in mind:

- **Almost double the fill duration, a large fraction at levelled conditions for ATLAS & CMS**

- **LHCb Phase I upgrade after >2023 :**
  - In Run 2 the LHCb was starting with a luminosity of 2.2% raising to 12.5% at EOF compared to HI experiments. In Run 3 LHCb will run at 2.0 \times 10^{33} cm^{-2}s^{-1} that is a constant 10% wrt the ATLAS/CMS luminosity
  - Also, the Phase I upgrade to \times 4 in luminosity has to be achieved with +1.6% or -9% of bunches wrt Run 2, that results to substantially increased PU rate
Bunch-to-bunch fluctuations & Luminosity

Introduction

• LHC is a multi-bunch machine and due to multiple effects the luminosity in each collision pair can vary

• Bunch-to-bunch variations in the beam parameters (intensity, emittance) affect the instantaneous luminosity thus the PU rate in the experiments
  • Three areas to consider:
    • Beam preparation in the upstream accelerator chain and injection to LHC
    • Effects at low-energy (FB) and the ramp
    • Effects in collisions

• From Run 2 luminosity follow up and analysis we have a good understanding of the driving factors

• Work is ongoing for Run 3 for the update of the Luminosity Model
Bunch-to-bunch fluctuations & Luminosity
Injector chain – LHC Flat Bottom

• Intensity Losses at FB
  • Effect of e-cloud to the bunch trains

Fill 7334 - Intensity evolution

4%
Bunch-to-bunch fluctuations & Luminosity
Injector chain – LHC Flat Bottom

- Emittance blow up and Intensity Losses
  - Clear effect of e-cloud to the bunch trains that is enhanced with time spent at FB

~30 min

e-cloud pattern in the trains

early injected

last injected
Bunch-to-bunch fluctuations & Luminosity
Injector chain – LHC Flat Bottom

Emittance blow up and Intensity Losses

- Studied in Run 2 as part from the “Luminosity Model” build-up
- First studies for Run 3 configuration with increased bunch intensities, work ongoing

Reminder: In Run 2 with the latest updates in the model, we still have approx. 50% of the emittance growth at FB that remains unaccounted

<table>
<thead>
<tr>
<th>2018</th>
<th>Emit. growth [µm/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.21</td>
</tr>
<tr>
<td>V</td>
<td>0.42</td>
</tr>
<tr>
<td>extra</td>
<td>0.10</td>
</tr>
<tr>
<td>noise</td>
<td>0.14</td>
</tr>
<tr>
<td>unknown</td>
<td>0.11</td>
</tr>
</tbody>
</table>
Bunch-to-bunch fluctuations & Luminosity Injection, FB to Stable – Summary Run 2

Run 3 goal: preserve the same performance at start of collisions as in Run 2 but with the higher intensities!
Bunch-to-bunch fluctuations & Luminosity

Stable beams - collisions

Bunch luminosity evolution

- Initial \(~14\%\) b-t-b fluctuations at start of collisions
- Grow up during the fill, up to \(~25\%\) after 14h in collisions
  - Depends on beam conditions,
  - major player: combined effects of HO and e-cloud – clear e-cloud pattern visible

Target : maintain in the shadow of the Poisson fluctuations

- Constraints from experiments?

13\% @ 60 PU

\[ \epsilon_{\text{bunch}} = \frac{\sqrt{\sum_{i=1}^{N} \epsilon_i^2}}{N} \]

\[ \frac{\Delta L}{L} = \frac{1}{\sqrt{N}} \left( \sum_{i=1}^{N} \frac{\epsilon_i^2}{\sigma_i^2} \right)^{1/2} \]

Measured Luminosity from Experiments - Fill 7334

Bunch ints lumini [Hz/μb]

BID number

t=0.00 h

25 30

0 4 6 8 10 12 14 16 18 20 22 24 26 28 30

Time in collisions [min]

<ΔL>/mean

0 0.1 0.2 0.3

0 0.2 0.4 0.6 0.8

0 275 300

ATLAS

CMS
Bunch-to-bunch fluctuations & Luminosity

Stable beams - collisions

**bttb-luminosity variations**
- major component: the intensity variations
- Evolution depends on beam type → e-cloud appearance
- And collision configuration → beam-beam HO, φ, β*

**Bunch counting**
- Select “outlier” bunches that are above 10 or 20 % from the average beam luminosity
  - Note: that there are few bunches with much higher luminosity almost x 2!

---

**Graphs**
- Bunch-to-bunch Luminosity Variation - Fill 7334
- CMS, ATLAS
- Beam intensity vs. time in collisions [min]
- Beam emittances
- Fraction of the total luminosity
- How many in series
- Bunches above threshold
- Series (>1) of such bunches
- Max series length

---

25.11.2021
I. Efthymiopoulos | Evian21 - Run 3
Bunch-to-bunch fluctuations & Luminosity
Stable beams - collisions

• Select bunch classes to investigate and understand losses
Bunch-to-bunch fluctuations & Luminosity
Stable beams - collisions

• Study of losses in physics and MD fills - Findings
  • It is the e-cloud in the triplets that originates most of the losses
  • Crossing angle has a sizeable effect, larger $\beta^*$ helps to reduce losses

2017 - $\beta^* = 40 \text{ cm} \ 25 \text{ ns}$

2018 - $\beta^* = 30 \text{ cm}$

2018 – long fill $\beta^*$ steps

Note: impact of LHCb at HI for Evian’22!!
Bunch-to-bunch fluctuations & Luminosity
Stable beams - collisions

- **Special ATS telescope MD** (S. Fartoukh et. al.)
  - 730 bunches colliding at IP1, IP5
  - large $\beta^*$ → small beta function in the triplets
  - close to nominal beam-beam configuration
  - large telescopic factor $\sim$3

- Beam losses almost exclusively due to burn-off
- No luminosity variations observed during collisions only first $\sim$30 minutes shown here

*Note:* impact of LHCb at HI for Evian’22!!
Summary

- LHC in Run 3 thanks to the LIU upgrades in the injectors will operate with levelled luminosity at $2.0 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
  - This value is compatible with the constrains and requirements from the cryogenics system of the inner triplet magnets – worth verifying it in real life!
  - It is also compatible with the requirements by the experiments, leaving a 12% margin in PU limit for ATLAS and CMS

- Bunch-to-bunch (btb) fluctuations in luminosity were observed in Run 2 and would remain in Run 3
  - The global picture would be similar, however there are new effects with the higher intensities that may alter the picture. However, we have good understanding of the driving effects (combination of e-cloud and collisions), and we can consider mitigation options should these fluctuations become an issue.
  - Work is ongoing to update the Luminosity Model, our basic tool for the LHC emittance and luminosity follow up that was nicely tuned for Run 2 – stay tuned!

- In Run 2 at the start of collisions the btb fluctuations were around 10%, that is compatible with the PU statistics; the goal for Run 3 is to preserve it but with the increased intensities
  - This would require substantial effort and MDs to understand the effects at FB and the RAMP, to the beam emittance

- The experiments need to be aware of these fluctuations that may affect them differently compared to Run 2 due to levelling
  - This is valid for ATLAS and CMS but also for LHCb that would run for first time in Run 3 with high pile up.

There will be a learning curve to understand, tune and settle the final parameters to both machine and experiments such to optimally exploit the upgraded machine!
Thank You!