Heavy Ion Operation after LS2

John Jowett

Thanks for collaboration and contributions to many people including:

R. Alemany, Michaela Schaumann, P. Hermes, T. Mertens, (+ABP)
S. Redaelli (+ collimation team), J. Wenninger (+OP),
B. Goddard, D. Manglunki, M. Meddahi, G. Rumolo, R. Scrivens (+LIU-Ions team),
A. Lechner (+FLUKA, BLM/quench teams),

Valuable discussions with:

F. Bordry, Oliver Brüning, E. Elsen, F. Gianotti, L. Rossi,
LPCs old and new, LHC Experiments, ...
Evolution of expectations for post-LS2 Heavy Ions

- RLIUP Workshop, October 2013 (with CMAC)
  - Complete analysis of last 3.5 Z TeV Pb-Pb run in 2011 (and 4 Z TeV p-Pb run in 2013)
  - All conceivable injector and LHC upgrades
    - Eg, stochastic cooling in collision

- HL-LHC LARP Workshop, October 2015
  - Still based on last Pb-Pb run in 2011 and p-Pb in 2013
  - Shortfall with respect to experiments’ luminosity request
  - Meanwhile LIU and HL-LHC project scope more precisely defined
  - Waiting for data on performance (especially quench) limits from 2015 Pb-Pb run to clarify need for hardware upgrades

- Now ...
  - We have the data from Pb-Pb in 2015 at (almost) full energy of LHC so hardware upgrade needs are now clear
  - Revision of HL-LHC (=post-LS2 for HI) performance expectations
• Short review of 2015 heavy ion run
  – Encountering limits
  – Basis for updated predictions

• BFPP luminosity limit
  – Recap
  – Mitigation with orbit bumps in IR1 and IR5
  – Mitigation with bump+collimator in IR2
  – BFPP quench test – unexpected result
  – Conclusion on need for new collimators in IR2

• Collimation quench test
  – Quench test (see talk by S. Redaelli)
  – Conclusion on need for new collimators in IR7

• HL-LHC Luminosity predictions
  – Requested parameters to meet (ALICE) requirement
  – Predictions based on new LIU baseline and 2015 performance
Three runs at equivalent energy

• Experiments wanted to compare 3 combinations of colliding species at same centre-of-mass energy per colliding nucleon pair:

\[
\sqrt{s_{NN}} = 5.02 \text{ TeV with } \begin{cases} 
    \text{p-p} & E = 2.51 \text{ TeV Nov 2015} \\
    \text{p-Pb} & E = 4Z \text{ TeV Jan-Feb 2013} \\
    \text{Pb-Pb} & E = 6.37Z \text{ TeV Nov-Dec 2015} 
\end{cases}
\]

• Two new LHC configurations to be commissioned and put into production within one month run in Nov-Dec 2015
  
  – Very complicated first 10 days, switching back and forth between p-p and Pb-Pb optics and species
  
  – Further interruptions for special MDs, ion source refill, van der Meer scans, ALICE polarity reversal, ...

J.M. Jowett, LHC Performance Workshop, Chamonix, 28/1/2016
Expect to achieve LHC “first 10-year” baseline Pb-Pb luminosity goal of 1 AA nb\(^{-1}\) = 43 NN pb\(^{-1}\) in Run 2 (=2015+2018)

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.

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

\[ \Rightarrow E_b = \begin{cases} 6.37Z \text{ TeV} & \text{in Pb-Pb} \\ 4Z \text{ TeV} & \text{in p-Pb} \end{cases} \]

But annual 1-month runs are getting shorter and more complicated ... 2015 included p-p reference data and included LHCb.

2012 pilot p-Pb run not shown (1 fill but major physics output)
Integrated luminosity in each fill

ALICE levelled at saturation value $L = 1 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ (design)

Design luminosity

25/11 30/11 07/12 18 days

ALICE polarity reversal

BFPP quench test & recovery

LHCb should have about 2% of ATLAS

ATLAS
ALICE
CMS
Luminosity evolution: prediction vs reality

**Luminosity difference/calibration between ATLAS & CMS?**

CTE simulation (burn-off, radiation damping, IBS, debunching from RF bucket, crossing angles, etc) for individual bunches, One ingredient of HL-LHC predictions.

Simulation without LHCb (Michaela Schaumann)
Single-bunch intensity distributions (last fill)

Earliest injected train suffers most intensity loss on way to physics. Detailed analysis continuing.

Units of $10^8$ Pb/bunch.

Tom Mertens
LEAD-LEAD LUMINOSITY LIMIT FROM BOUND-FREE PAIR PRODUCTION
Electromagnetic and photonuclear processes in Pb-Pb collisions

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: $^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \rightarrow ^{208}\text{Pb}^{82+} + ^{207}\text{Pb}^{82+} + n$,
$\sigma = 96\ \text{b}, \quad \delta = -0.00485$

EMD2: $^{208}\text{Pb}^{82+} + ^{208}\text{Pb}^{82+} \rightarrow ^{208}\text{Pb}^{82+} + ^{206}\text{Pb}^{82+} + 2n$,
$\sigma = 29\ \text{b}, \quad \delta = -0.00970$

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).
Orbit bumps are effective mitigation for CMS (or ATLAS)

- Primary loss location close to the connection cryostat - details slightly optics-dependent (If necessary, bumps should avoid quenches at the start of physics)
- Extra BLMs were specifically added for heavy-ion operation in loss region
- Variations of bump possible, uses moderate fraction of available corrector strengths
- We applied bumps like these with ~ 3 mm amplitude around CMS and ATLAS from the beginning of the run
Orbit bumps alone are not effective for ALICE

- IR2 has different quadrupole polarity and dispersion from IR1/IR5
- Primary BFPP loss location is further upstream from connection cryostat
- Solution is to modify connection cryostat to include a collimator to absorb the BFPP beam – **but design must be launched now to be ready for LS2 installation**
- With levelled luminosity in ALICE, quenches are not expected in Run 2
- (No 11-T dipoles needed.)
Tests of strategy during 2015 Pb-Pb run

• For safety, mitigation bumps were implemented at 3 mm amplitude in validated physics setup
  – Expected to move losses around ATLAS/CMS into connection cryostat
    • Not quite true on left of IP5 – luminosity losses at start of later fills came close to (raised) BLM dump thresholds
    – Moved losses beyond connection cryostat in IR2
      • Levelled luminosity not expected to be a concern

• MD study around IP5 would attempt to quench by manipulating bump to move losses back into connection cryostat in controlled way
  – Based on latest estimates of steady state quench level, we did not expect a quench ... but we tried anyway.
  – But potentially an extremely clean measurement.
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):
  \[ L \approx 2.3 \times 10^{27} \, \text{cm}^{-2}\text{s}^{-1} \]
  \[ \Rightarrow \] 0.64 MHz event rate, about 45 W of power in Pb\(^{81+}\) beam into magnet.
Luminosity and BLM signals during measurement

![Graph showing BLM signals and CMS luminosity over time. The graph includes markers for different BLM signals and luminosity values. The time axis is labeled as Time from INJPHYS in hours, ranging from 3.40 to 3.80. The vertical axis represents the BLM signal in Gy/s, ranging from 0.0000 to 0.0014. The luminosity is shown in units of 10^30 cm^-2 s^-1. There are annotations indicating 'Inverting BFPP Orbit Bump' and 'Increasing Luminosity in Steps.' Different colored lines represent various BLM signals and their corresponding luminosity values.](image-url)
Comparison between simulated and measured BLM signals for two different loss locations (BLM patterns are very sensitive to the exact BFPP loss location). Some small differences still need to be assessed in more detail.

Estimated peak power density along MB coils: peak power at the inner edge of the cable and the radially averaged power over the cable (relevant quantity to assess the quench limit) estimated at ~15mW/cm³ in the quench test.

Contrary to the BLM pattern, the peak power in the coils does not change if we shift the loss distribution up- or downstream as we stay deep inside the MB.
Hard to understand why we were so happy since the quench limit is lower than recent estimates.
Consequences of the BFPP quench result

- Resolves long-standing (since mid-1990s) uncertainty on steady state quench and BFPP luminosity limit
  - Factor 2-3 lower than recent expectations
  - Main errors BFPP cross section, luminosity

- Efficacy of BFPP bumps clear – we already needed them in 2015 to avoid luminosity quenches around ATLAS and CMS!
  - FLUKA analysis confirms this is still OK for further increase in luminosity.
  - Radiation effects and heat load may still be issues.

- Closes the case for collimators in the LHC dispersion suppressors around ALICE (where the bump mitigation alone does not work), discussed since Chamonix 2003 ...

- The design work for integration of TCLD collimators in the connection cryostats needs to start now so that they can be installed during LS2.
We also intend to publish a paper in a journal with full analysis.

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Summary

In the 2015 Pb-Pb collision run of the LHC the power of the secondary beams emitted from the interaction point by the bound-free pair production (BFPP) process reached new levels while the propensity of the bending magnets to quench is higher at the new magnetic field levels. This beam power is about 70 times greater than that contained in the luminosity debris and is focussed on a specific location. As long foreseen [1, 2, 3], orbit bumps were introduced in the dispersion suppressors around the highest luminosity experiments to mitigate the risk by displacing and spreading out these losses.

Because the impact position and intensity of these secondary beams is well known and can be tracked easily with the Beam Loss Monitors (BLMs), the BFPP1 beam ($^{208}$Pb$^{81+}$ ions), which is the most intense, provides a tool to accurately measure the steady state quench limit of the LHC main dipoles [4]. At the moment the exact quench limit is not known, but this knowledge is important to assess the need for special collimators to intercept these secondary beams.

This note describes the procedure and preliminary results of a test conducted on the main dipole in cell 11 left of IP5, using the BFPP1 beam to provoke a quench of this magnet.
Collimation quench test and intensity reach

• First collimation quench test where a quench was achieved with heavy ion collimation took place a few days later
  – See earlier talk by Stefano Redaelli

• Standard LHC criterion (no quench for effective beam lifetime of 12 min), and first analysis of the measurement (P. Hermes)

• First collimation quench test where a quench was achieved
  – Quench occurred in MBB 9L7 (expected MQY 9L7)
  – Quench at power of 15kW with around 340W at the magnet
  – Maximum stored beam energy : < 10.8MJ
  – Achieved $1.6 \times$ BLM threshold at MBB 9L7 (RS09)
Consequences (full analysis going on)

• The Pb beam intensity in 2015 was already very close to the limit
  – Expect difficult operation with beam dumps by BLM thresholds
  – Post-LS2 Pb beam scenarios (LIU baseline, see later) foresee factor 2 increase in Pb intensity
  – According to the standard criterion, this is unacceptable.
  – Measurement was at $6.37 \text{ Z TeV}$, must still be extrapolated to $7 \text{ Z TeV}$
  – Requires mitigation by collimators upstream of loss location at Q9
  – I.e. (TCLD + two 11 T dipoles unit) to replace standard dipole on each side of IP7.
  – See other studies on Pb beam collimation
  – Collimation by bent crystal?
HL-LHC (=POST-LS2 FOR HEAVY IONS) PROJECTIONS
ALICE’s requested operating conditions

• Maximum interaction rate of 50 kHz in Pb-Pb (ALICE upgrade in LS2)
• LoI assumed: peak luminosity of $6 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ and an average luminosity of $2.4 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$.
• The upgrade programme assumes an integrated luminosity of 10 nb$^{-1}$ in PbPb at top energy
• In addition
  – one special PbPb run at reduced magnetic field for low-mass dileptons (O~ 3 nb$^{-1}$)
  – one p-Pb run with about 50 nb$^{-1}$
  – pp reference run at 82/208 × top energy
• Time horizon: to be completed by LS4 under the basic assumption of about one month LHC heavy ion operation per year.

**Requested** luminosity after LS2, updated from 2012 ALICE LoI

- Possible running scenario after upgrade:
  - 2021 - Pb-Pb 2.85 nb\(^{-1}\)
  - 2022 - Pb-Pb 2.85 nb\(^{-1}\)
  - 2023 - pp reference run
  - 2024,2025.6 - LS3
  - 2027 - Pb-Pb 2.85 nb\(^{-1}\)
  - 2028 - \(\frac{1}{2}\) Pb-Pb 1.5 nb\(^{-1}\) + \(\frac{1}{2}\) p-Pb 50 nb\(^{-1}\)
  - 2029 - Pb-Pb 2.85 nb\(^{-1}\)
  - 2030  LS4

- A degree of flexibility remains to redistribute Pb-Pb vs p-Pb vs p-p reference if experiments wish.
- In the following we concentrate on potential Pb-Pb luminosity in a single run.

*We have been using the ALICE document as a reference but other experiments’ requirements are broadly similar – see talk by J. Wessels at HL-LHC-LARP meeting October 2015.*

*No request for other species than Pb.*
LHC heavy-ion runs, past & approved future + species choices according to ALICE 2012 LoI (could evolve if required)

LHC will have done 12 ~one month heavy ion runs between 2010 and 2030 (LS4). Four done already.
LIU baseline (Jan 2016) parameters at start of collisions

• Simplified scenario
  – All bunches are equal (consider single bunch pair simulation)
  – Initial bunch intensity (start of stable beams)
    $\langle N_b \rangle = 1.7 \times 10^8 < \text{Maximum in 2015} \ (\text{c.f. design } 0.7 \times 10^8)$
  – Initial emittance (start of stable beams)
    $\varepsilon_{xn} = 1.5 \times 10^{-6}$ (= design, typical in operation so far)
  – Crossing angles 170, 100, 170 $\mu$rad
  – Other bunch parameters as Design Report nominal
  – Three luminosity-sharing scenarios, just for illustration of the possibilities (equal scenario is the “official” one!):

\[
\beta^* = \begin{cases} 
(\infty, 0.5, \infty) & \text{m} \quad \text{(only ALICE colliding)} \\
(1.0, 0.5, 1.0) & \text{m} \quad \text{(ATLAS/CMS at half ALICE)} \\
(0.5, 0.5, 0.5) & \text{m} \quad \text{(equal)} 
\end{cases}
\]

Notes: Neglecting loss between injection and collision – partly compensates use of mean rather than RMS. Also emittances will probably be better than this.
Simulation of average colliding bunch pair

Interplay of radiation damping, IBS, luminosity burn-off couples all 4 quantities. Different evolution according to luminosity-sharing scenario.
A possible filling scheme for HL-LHC Pb-Pb

48 bunch SPS train after slip-stacking

22 injections of 48-bunch trains give total of 1056 in each beam.
960 bunch pairs collide in each of ALICE, ATLAS CMS.
84 bunch pairs collide in LHCb.

J.M. Jowett, LHC Performance Workshop, Chamonix, 28/1/2016

Collisions sequences in the experiments
Experiments’ luminosities in an ideal (prolonged) fill

ALICE, levelling at maximum acceptable (rates around 50 kHz), assuming 1100 bunches colliding

ATLAS or CMS, *assumed* levelling at corresponding levels to ALICE (not strictly necessary, just an assumption to simplify presentation).
**Integrated luminosity in fill**

\[ \beta^* = (\infty, 0.5, \infty) \text{m} \]

\[ \beta^* = (1.0, 0.5, 1.0) \text{m} \]

Ultimate luminosity to share

\[ L_{\text{int,max}} = \frac{k_c N_b}{\sigma_c} \]

Potential for a stochastic cooling system
Effect of turn-around time on average luminosity

\[ \langle L \rangle = \frac{1}{T_f + T_p} \int_0^{T_p} L(t) \, dt \]

\[ \beta^* = (0.5, 0.5, 0.5) \text{ (equal)} \]

Turn around time = (3, 5, 7, 9) h

Turn around time = 3 h

Shown for each luminosity sharing scenario
Assumes the operators know that the next turn-around time will be the same value.

Break-down of the minimum turn-around time as for p-p

<table>
<thead>
<tr>
<th>Phase</th>
<th>Duration [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp down/pre-cycle</td>
<td>60</td>
</tr>
<tr>
<td>Pre-injection checks and preparation</td>
<td>15</td>
</tr>
<tr>
<td>Checks with set-up beam</td>
<td>15</td>
</tr>
<tr>
<td>Nominal injection sequence</td>
<td>30</td>
</tr>
<tr>
<td>Ramp preparation</td>
<td>5</td>
</tr>
<tr>
<td>Ramp</td>
<td>25</td>
</tr>
<tr>
<td>Squeeze/Adjust</td>
<td>40</td>
</tr>
<tr>
<td>Total</td>
<td>190</td>
</tr>
</tbody>
</table>
$L_{\text{int,annual}} = \eta \langle L \rangle T_{\text{run}}$

\[= (50\%) (2.01 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}) (24 \text{ day}) \]

\[\approx 2 \text{ nb}^{-1} \]

where we (pessimistically?!) assume an operation efficiency $\eta = 50\%$ and $T_{\text{run}} = 24$ day (i.e., no p-p reference run or similar).

Implies about 38 ideal fills (start-up absorbed in efficiency).

\[\approx 8 \text{ nb}^{-1} \text{ in the 4 Pb-Pb runs foreseen after LS2}.\]
Another estimate (Michaela Schaumann)

• Very new (yesterday ...)
• Detailed luminosity model based on
  – Analytical fitting of bunch-by-bunch luminosity data from experiments to determine bunch parameter distribution in physics and relate to variations along injected bunch trains
  – CTE simulations of time-evolution (IBS, debunching, radiation damping, burn-off, etc) during fills
  – Combinations to predict evolution of future luminosity

  – Includes intensity degradation from injection to Stable Beams like 2015 (above estimate does not)

• Thesis references:
  – [https://cds.cern.ch/record/2065692](https://cds.cern.ch/record/2065692)
Bunch Luminosity Distribution

All Fills in Stable Beams
2011 data source ATLAS
2015 data source CMS

2011: \( \langle N_b \rangle = 1.18 \pm 0.57 \)
2015: \( \langle N_b \rangle = 3.69 \pm 1.98 \)
Bunch intensities at the beginning of Stable Beams

\[ \langle N_b \rangle = 1.21 \pm 0.24 \quad \text{2011} \]
\[ \langle N_b \rangle = 1.4 \pm 0.25 \quad \text{2013} \]
\[ \langle N_b \rangle = 1.63 \pm 0.31 \quad \text{2015} \]
Bunch Intensities Injection vs. Stable Beams

Injection: $\langle N_b \rangle = 1.83 \pm 0.38$

Collision: $\langle N_b \rangle = 1.62 \pm 0.32$
Updated Luminosity Model (2015 decay)

Model based on Bunch-by-Bunch Intensities and emittances measured at beginning of Stable Beams in 2015 (last few fills of the run)

Initial Bunch Intensity, Fill 4720

Horizontal Initial Emittance, Fill 4720

Vertical Initial Emittance, Fill 4720

Calculated and Measured Initial Luminosity, Fill 4720

Data: $\sum \mathcal{L}_b = 2.9E27 \text{ cm}^{-2}\text{s}^{-1}$

Model: $\sum \mathcal{L}_b = 2.9E27 \text{ cm}^{-2}\text{s}^{-1}$
Continuation with $\beta^*=0.5\text{ m at } 7\text{ Z TeV (2018?)}$

**Initial Bunch Intensity**

- **Average last train:** $2.2e8$
- $\langle N_b \rangle = (2.0 \pm 0.2) \times 10^8$
- Bunch Spacing: 100/150ns

**Initial Emittances**

- **Average last train:** $1.5(H)/1.4(V)$
- $\langle \epsilon_{n,H} \rangle = (1.7 \pm 0.2) \mu\text{m}$
- $\langle \epsilon_{n,V} \rangle = (1.5 \pm 0.1) \mu\text{m}$
- Bunch Spacing: 100/150ns

**Instantaneous and Integrated Luminosity**

- $\mathcal{L}(t=0) = 5.5 \text{ cm}^{-2}\text{s}^{-1}$
- $\mathcal{L}_{\text{Int/fill}} (t=5\text{h}) = 32.5 \mu\text{b}^{-1}$
- $\mathcal{L}_{\text{Int/run}} (t=5\text{h}, 30\text{ fills}) = 1. \text{ nb}^{-1}$

**No Levelling!**

- $\Sigma L_b = 5.5 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$
- Bunch Spacing: 100/150ns

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J.M. Jowett, LHC Performance Workshop, Chamonix, 28/1/2016

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Estimate for Jan 2016 LIU Baseline post-LS2

Initial Bunch Intensity

Average last train: $1.7 \times 10^8$

$N_b = (1.5 \pm 0.2) \times 10^8$

Bunch Spacing: 50/100ns

Initial Emittances

Average last train: $1.2(H)/1.2(V)$

$\langle \epsilon_n \rangle = (1.4 \pm 0.2) \mu m$

$\langle \epsilon_x \rangle = (1.3 \pm 0.1) \mu m$

Bunch Spacing: 50/100ns

Instantaneous and Integrated Luminosity

$\mathcal{L}(t=0) = 8.2 \text{ cm}^{-2}\text{s}^{-1}$

$\mathcal{L}_{\text{int/fill}}(t=5h) = 58.1 \mu b^{-1}$

$\mathcal{L}_{\text{int/run}}(t=5h, 30 \text{ fills}) = 1.7 \text{ nb}^{-1}$

No Levelling!

Initial Bunch Luminosity

$\sum \mathcal{L}_b = 8.2 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$

Bunch Spacing: 50/100ns

1152 Colliding Bunches

Michaela Schaumann
LIU Baseline with 3h Stable Beams – 38 Fills per Run

Instantaneous and Integrated Luminosity

\[ \mathcal{L}(t=0) = 8.2 \, \text{cm}^{-2} \text{s}^{-1} \]

\[ \mathcal{L}_{\text{Int/fill}}(t=3\text{h}) = 45.5 \, \mu\text{b}^{-1} \]

\[ \mathcal{L}_{\text{Int/run}}(t=3\text{h}, 38 \text{ fills}) = 1.7 \, \text{nb}^{-1} \]
## Ideal parameters to meet ALICE request

Table 4: Time-averaged (during intervals of fully successful operation) and integrated luminosities over a run in each luminosity-sharing scenario.

<table>
<thead>
<tr>
<th>Luminosity-sharing scenario $\beta^*/m$</th>
<th>ALICE</th>
<th>ATLAS/CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\langle L \rangle / 10^{27}$ cm$^{-2}$s$^{-1}$</td>
<td>$L_{int,annual} / nb^{-1}$</td>
</tr>
<tr>
<td>$(\infty, 0.5, \infty)$</td>
<td>4.14</td>
<td>4.29</td>
</tr>
<tr>
<td>(1.0, 0.5, 1.0)</td>
<td>3.19</td>
<td>3.30</td>
</tr>
<tr>
<td>(0.5, 0.5, 0.5)</td>
<td>2.80</td>
<td>2.91</td>
</tr>
</tbody>
</table>

Working backwards from ALICE annual request to give a specification for RMS injected intensity goal:  $N_b = 2.1 \times 10^8$

CERN internal EDMS note.
Other issues, lack of time ...

• Proton-lead runs
• Radiation to electronics, damage by BFPP and other losses
• Primary collimator asymmetry to reduce losses on tertiary collimators (TCTs) near experiments
• Bunch spacing and crossing angle at ALICE
  – Zero Degree Calorimeter, spectator neutron constraints
  – Parasitic beam-beam encounters, reduced bunch spacing
  – Possible 25 ns one day?
• ALICE vertical shift of IP not compatible with smaller $\beta^*$, detector must be re-positioned in LS2
• Opportunity for pilot Xe-Xe or p-Xe run in 2017 (use approach of 16 hour 2012 p-Pb pilot run)
Conclusions

• We learned a lot in the Pb-Pb run at the end of 2015
  – Resolved long-standing uncertainty on steady-state quench limit
  – Pb-Pb operation well predicted by luminosity model
  – LHC is (still) very flexible, reproducible and available
  – About 35% of the “HL-LHC” Pb-Pb performance is in hand

• Latest post-LS2 projections are more optimistic
  – Based on 2015 run + new (Jan 2016) LIU baseline projected injector performance

• To reach projected performance:
  – New collimators needed in connection cryostats around ALICE, must be installed in LS2
    • Design and integration must be launched
  – Very strong case for (collimators + 11 T dipoles) in IR7
BACKUP SLIDES
Final integrated luminosity (delivered)

- ALICE 433 $\mu$b$^{-1}$
LHC Luminosity Model used for Pb-Pb

• CTE program
  – Macro-particle, macro-turn simulation of slow kinetic effects
  – Luminosity burn-off (very strong! Due to ultraperipheral “near-miss” electromagnetic interactions > 500 barn )
  – Luminosity with crossing angles (150,100,150) µrad
  – IBS with non-Gaussian longitudinal distribution
  – Debunching longitudinally (small here)
  – Synchrotron radiation damping (strong!), quantum excitation (tiny)
    – Simulates one bunch from each beam, experiencing collisions at several (different) IPs

• Spectrum of bunch parameters combined by interpolation and fitting of simulations
Stored energy in beams (Jan 2016 LIU baseline)

- $\beta^* = (\infty, 0.5, \infty) m$
- $\beta^* = (0.5, 0.5, 0.5) m$
- $\beta^* = (1.0, 0.5, 1.0) m$
IR2 losses: understanding and mitigations (2015)

- STIER: what ions are causing the TCT loss in IR2?

<table>
<thead>
<tr>
<th>Isotope (A,Z)</th>
<th>TCP jaw</th>
<th>Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(207,82)</td>
<td>left</td>
<td>92.5</td>
</tr>
<tr>
<td>(204,81)</td>
<td>right</td>
<td>3.6</td>
</tr>
<tr>
<td>(202,80)</td>
<td>left</td>
<td>2.2</td>
</tr>
<tr>
<td>(199,79)</td>
<td>right</td>
<td>0.3</td>
</tr>
</tbody>
</table>

$$^{208}\text{Pb}^{82+} + ^{12}\text{C} \xrightarrow{\gamma} ^{207}\text{Pb}^{82+} + n + ^{12}\text{C}$$

Pascal D. Hermes, CERN, University of Münster

Simulation Tools for Heavy-Ion Collimation
Spectrometer ON_ALICE = -7/6.37 (start of Pb-Pb run)

Spectrometer bump angle -77 µrad, external bump +137 µrad for Beam 1.

May constrain ALICE $\beta^*$ for rest of Run 2 (important to fix in LS2). To be studied.
Spectrometer ON_ALICE=+7/6.37 after reversal

\[(10\sigma_x, 10\sigma_y, 5\sigma_z)\) envelope for \(\epsilon_x=4.57408 \times 10^{-9}\) m, \(\epsilon_y=4.57408 \times 10^{-9}\) m, \(\sigma_p=0.0001137\)

Beam-beam separation
Often alarmingly close to dump thresholds ...

Arrival at flat top.
Excellent availability and quality of beams from injectors!
Summary

• Within a 1 month heavy-ion run:
  – Rapid commissioning of *two* new configurations of LHC
  – Excellent availability of injectors and LHC
  – p-p reference run at 5.02 TeV (set by p-Pb in 2013) providing > 25 pb\(^{-1}\) to ATLAS, CMS (~1 week)
  – Luminosity in the first Pb-Pb run since 2011 at new energy of 5.02 TeV has *reached design saturation value for ALICE* and more than *trebled design luminosity for ATLAS & CMS*
    • Incidentally: first collisions with > 1 PeV total energy
  – Integrated luminosity goal achieved
  – Pb-Pb collisions provided to LHCb for the first time
  – Concrete results on *Pb-Pb performance limitations, especially quench limits*, in view of future upgraded performance

• Official plan until LS2:
  – 2016: p-Pb collisions
  – 2017: no heavy-ion run
  – 2018: next Pb-Pb collisions
Introduction
Example for measured LHC lossmap

TCLD concept

- Replacement of one or two DS dipoles by two shorter and stronger dipoles
- Use the freed space to install TCLD collimators
- How is the ion cleaning performance going to improve?
Simulation Result

No TCLD

One TCLD

Two TCLDs

Log cleaning inefficiency (m⁻¹)

Longitudinal Coordinate (m)