Options for ion operational scenarios with increased performance

R. Bruce
Acknowledgement: H. Bartosik, G. Iadarola, J.M. Jowett

WP2 meeting, 28/09/2021
Introduction

Recently updated operational scenario for Pb-Pb and p-Pb in Runs 3-4
- Improved filling schemes and modelling
- See CERN report and EPJ Plus paper; WP2 talk, TCC talk

Range of filling schemes with varying number of collisions at LHCb
- Motivated by recent request from LHCb for significant luminosity - comes at the expense of the other experiments
- Updated performance estimates for typical one-month run
  - Only studied one-month performance due to large uncertainties in detailed planning

### Table 6
Integrated luminosity (given in nb⁻¹) during a one-month Pb-Pb run at each experiment for the considered filling schemes from Ref. [13], assuming an operational efficiency of η=0.5 h and 24 days available for physics operation in Eqs. (5)–(6)

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The first number is calculated using CTE and the number in square brackets is calculated using MBS

From [EPJ Plus paper]

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Requests from experiments

- WG5 in the 2018 HL-LHC / HE-LHC physics workshop dealt with heavy-ion physics
- Yellow report with proposal for extended heavy-ion running: CERN-LPCC-2018-07
- Request up to the end of Run 4:

  - \( \text{Pb–Pb at } \sqrt{s_{NN}} = 5.5 \text{ TeV, } L_{int} = 13 \text{ nb}^{-1} \) (ALICE, ATLAS, CMS), \( 2 \text{ nb}^{-1} \) (LHCb)
  - \( \text{pp at } \sqrt{s} = 5.5 \text{ TeV, } L_{int} = 600 \text{ pb}^{-1} \) (ATLAS, CMS), \( 6 \text{ pb}^{-1} \) (ALICE), \( 50 \text{ pb}^{-1} \) (LHCb)
  - \( \text{pp at } \sqrt{s} = 14 \text{ TeV, } L_{int} = 200 \text{ pb}^{-1} \) with low pileup (ALICE, ATLAS, CMS)
  - \( \text{p–Pb at } \sqrt{s_{NN}} = 8.8 \text{ TeV, } L_{int} = 1.2 \text{ pb}^{-1} \) (ATLAS, CMS), \( 0.6 \text{ pb}^{-1} \) (ALICE, LHCb)
  - \( \text{pp at } \sqrt{s} = 8.8 \text{ TeV, } L_{int} = 200 \text{ pb}^{-1} \) (ATLAS, CMS, LHCb), \( 3 \text{ pb}^{-1} \) (ALICE)
  - \( \text{O–O at } \sqrt{s_{NN}} = 7 \text{ TeV, } L_{int} = 500 \mu \text{b}^{-1} \) (ALICE, ATLAS, CMS, LHCb)
  - \( \text{p–O at } \sqrt{s_{NN}} = 9.9 \text{ TeV, } L_{int} = 200 \mu \text{b}^{-1} \) (ALICE, ATLAS, CMS, LHCb)
  - \text{Intermediate AA, e.g. } L_{int}^{A_{r}A_{r}} = 3–9 \text{ pb}^{-1} \) (about 3 months) gives NN luminosity equivalent to Pb–Pb with \( L_{int} = 75–250 \text{ nb}^{-1} \)
Future heavy-ion runs

Present planning:
- Would have four Pb-Pb runs (one two-month run in 2024) and two p-Pb runs until the end of Run 4
  - In addition, have to fit pp reference runs
- Allows to calculate approximate luminosity requirement for one-month run

Tentative schedule, **could well change**
(Jan 2020 schedule updated with LS2 extension)

![Long Term Schedule for CERN Accelerator complex]

- Present planning:
  - Would have four Pb-Pb runs (one two-month run in 2024) and two p-Pb runs until the end of Run 4
  - In addition, have to fit pp reference runs
- Allows to calculate approximate luminosity requirement for one-month run

★ **Guess on future heavy-ion runs – detailed schedule still to be defined**
★ **Oxygen pilot run?**
Estimated vs required performance

- Approximate requirements from experiments for one month:
  - Pb-Pb
    - 2.6 nb\(^{-1}\) at IP1/2/5
    - 0.4 nb\(^{-1}\) at IP8
  - p-Pb
    - 600 nb\(^{-1}\) at IP1/5
    - 300 nb\(^{-1}\) at IP2/8

- Estimated performance
  - For Pb-Pb: expect in the range of 2.2-2.7 nb\(^{-1}\) for IP1/2/5, 0.2-0.5 nb\(^{-1}\) at IP8 in a one-month run
  - For p-Pb: expect in the range of 550-700 nb\(^{-1}\) for IP1/5, ~300 nb\(^{-1}\) at IP2, 50-150 nb\(^{-1}\) at IP8 in a one-month run

- We’re in the right ballpark, but with present schedule assumptions, no filling scheme simultaneously fulfills requirements at all IPs
  - For p-Pb, miss at least a factor 2 at IP8
  - Note: approximate figures for p-Pb without detailed filling schemes

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From *EPJ Plus paper*
One-month performance vs target

- In Pb-Pb, lower luminosity at IP1/5 than IP2 due to crossing angle
  - Spectrometer bump at IP2 makes net angle smaller; external angle is the same
  - Up to about 10% missing at worst IP for the best filling scheme

- In p-Pb, LHCb is the main problem

- Targets not reached simultaneously for any filling scheme

- Possibly no reason for panic – applying the same assumptions for 2018, get significantly lower luminosity than achieved in the machine
  - Operational efficiency >50% achieved
Improvements?

- Need to study improvements to find a scenario that reaches targets with present assumptions
  - For now, exploring different paths of improvement, i.e. trying to answer “what would have to be done to reach target on paper”
  - For now, not exploring the feasibility of each path – possibly need beam tests

- Assuming for now that Pb bunch intensities from injectors and LHC operational efficiency are fixed
  - Might be conservative, but cannot know now

- Ways to improve LHC performance (Pb-Pb)
  - Improving further the filling schemes
    - Work out detailed filling schemes in p-Pb with realistic 50 ns proton beam
  - Skip levelling at IP1/5
  - Smaller crossing angle: present baseline is 170 μrad half external angle at each IP
    - Gives net half angles of 170 μrad / 100 μrad / -305 μrad
  - Smaller β*: present baseline assumes 0.5m / 0.5 m / 1.5 m
    - Possibly more aperture and strength margin in IR8
  - Change levelling assumptions at IP2/8
    - Presently assumed levelling is 6.4E27 cm²s⁻¹ at IP1/2/5 (ALICE detector saturation and “fair sharing”), 1E27 cm²s⁻¹ at IP8 (avoid quenches from BFPP)

- Performance improvements for p-Pb
  - Similar methods as for Pb-Pb (filling schemes, β*, crossing angle)
  - In addition, increase proton bunch intensities (weak bunches of 3E10 p assumed so far)

Following slides: Checking each option, re-running luminosity studies with CTE using the same assumptions as in baseline scenario, unless stated otherwise
Pb-Pb filling schemes

- Best scheme (i.e. best compromise) so far seems to be 1240b_1088_1088_398

- Does a “better” scheme exist, with more collisions at each experiment?
  - “Brute-force” scan of collisions – checked more than $5 \times 10^{10}$ permutations of longer gap between trains and the position of shorter trains
  - Found many equivalent permutations, but no better schemes
  - Cannot exclude that a better scheme exists – almost infinite parameter space. But maybe not so likely, and not evident to find

- Possible route forward: take longer trains from SPS with 8*8 bunches or more, instead of presently assumed 7*8 bunches
  - Would result in more beam degradation in the SPS => not obvious that we actually gain
  - See Hannes’ talk at Chamonix 2017
Skip levelling at IP1/5

- Levelling at IP1/5 probably not needed to avoid BFPP quenches – FLUKA studies indicate significant margin

- Redoing beam evolution study with CTE, for the range of filling schemes, followed by calculation of 1-month luminosity using standard method (re-calculating optimal fill time, 50% OP efficiency)

- Only very minor improvement at IP1/5 (gives slightly more equal sharing of luminosity between IP1/2/5)
Decreased crossing angles

- Smaller crossing angle limited by beam-beam and parasitic collisions
  - Good hope that decrease is possible (see talk by Sofia)
  - At IP2, have UPPER 100 urad limit from ZDC acceptance

- At IP8: no preference from LHCb on spectrometer polarity.
  - Could use opposite polarity of spectrometer to crossing bump, e.g. half external angle = -235 µrad, spectrometer = +135 µrad

- First try: using 100 µrad net half angle at IP1/5, as already in baseline for IP2 – better, but not enough

- Second try: using 70 urad net half angle at all IPs, as studied by Sofia – almost there, still miss 2% in best case

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**Net crossing 100/100/100/305**

**Net crossing 70/70/70/70**
Smaller crossing, smaller IP8 $\beta^*$

- Assuming 100 $\mu$rad net half angle at all IPs, $\beta^* = 1$ m at IP8: very close to targets; miss by 2% in best scheme

- Assuming 70 $\mu$rad net angle at all IPs, $\beta^* = 1$ m at IP8: reach target exactly at IP1/2/5, get more at IP8

- Could consider switching between filling schemes during the run to distribute more to IP1/2/5
Decreased $\beta^*$ at all IPs

- Decreasing $\beta^*$ only, even to 40 cm at IP1/2/5 and 50 cm at IP8, keeping nominal crossing: still no scheme satisfying all – IP1/5 limiting

- 100 urad crossing at all IPs, $\beta^*=0.45$ m at IP1/2/5, $\beta^*=1$ m at IP8 => Reach targets at all IPs with one scheme, with quite some margin at IP8
  - Could consider switching filling schemes throughout the run to get more margin also at IP1/2/5 – to be discussed and agreed with the experiments
Pushed configuration

- Assuming aggressively $\beta^* = 40 \text{ cm}$ at IP1/2/5, $\beta^* = 50 \text{ cm}$ at IP8, 100 urad net angle at all Ips => comfortably reach targets with some margins for several filling schemes

- This configuration might not be feasible – further studies required
Increased leveling targets

- Increasing IP8 levelling target $L=1.5\times10^27$
  - Note: in 2015 quench test, quenched at $L=2.3\times10^27$
  - Don’t know if we can do this in IP8 – limiting luminosity might be different. Needs further study

- Increasing IP1/2/5 levelling to $L=7\times10^27$
  - Will be slightly above limiting 50 kHz rate at ALICE in the beginning of the fill – possibly OK, to be seen
  - Used as tentative levelling value in previous iteration at Chamonix 2017

- Result: Increasing levelling targets to these values alone is not enough

- In combination with 100 urad net half crossing at all IPs and $\beta^*=1\text{m}$ at IP8:
  - 2% short for any single scheme
  - Can reach targets if we combine two filling schemes, running half of the time with each
Missing a factor 2 at LHCb – not easy…. Need significant improvement

Even with very pushed machine configuration ($\beta^*=40$ cm at IP1/2/5, $\beta^*=50$ cm at IP8, 100 urad net angle at all IPs), almost at target

Other option: work on proton beams
- Increase proton bunch intensity
- Work out detailed filling schemes – should be done anyway
Increasing proton intensity

Present baseline assumed so far: $3 \times 10^{10}$ p/bunch
- With higher p intensities, beam burns off quickly, which is bad for ALICE (levelled at $5 \times 10^{29}$)

Alternative approach:
- *increase to $1.3 \times 10^{11}$ p/bunch* (already had this with 50 ns beams – higher is only better)
- level IP1/5 at $1 \times 10^{30}$
- don’t level IP8
- => *can reach targets*, without any change of optics or crossing angle!

Caveats: Using approximate approach with Pb filling schemes and overall 5% penalty on integrated luminosity
- Clearly need to check realistic schemes before concluding
- Possibly check beam-beam : any consequences of running in this weak-strong scenario?
- Some studies done in thesis by Marc

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[Graph showing integrated luminosity vs. collisions at IP1 with IP1/5, IP2, and IP8 labeled.]
Proton filling schemes

- **Goal:** match a 50 ns proton beam that matches as well as possible the 50 ns Pb beam. Not evident:
  - SPS Pb batches have 8 bunches, 100 ns batch spacing, typically 7 trains = 56 Pb bunches
  - Proton schemes based on 6*n bunches, 200 ns gap between batches

- With Gianni: one potential solution seems to be proton 30 bunches per train
  - Two proton trains almost fit the 7 Pb trains
  - Direct overlap shows collisions at IP1/5 – but we need to have many collisions at all IPs
Developing candidate filling schemes

- First try: basic scheme with quadrant symmetry
  - Adjusting abort gap keeper to longest train
  - Can fit 5 Pb/p trains per quadrant
  - To fill up the rest of the quadrant: make last train longer, or inject shorter train
  - Seems most efficient to make p train longer (4*30 instead of 2*30) and add a shorter Pb train

- Scheme gives decent amount of collisions at IP1/5, but less at IP2/8
  - 1152 Pb, 1260 protons
  - 1083 / 714 / 26 collisions at IP1/2/8
Optimizing p-Pb filling schemes (1)

- Trying to move around trains to displace collisions to LHCb – gives large penalty at IP1/2/5, larger than for Pb-Pb
  - Brute-force scan of all permutations within each quadrant (displacing single trains to get collisions at LHCb) =>
    - if >800 collisions at IP1/2/5, max 137 collisions at IP8 => not good
  - Example with more IP8 collisions: 724 / 724 / 427 collisions => not enough at IP1/2/5, not really efficient use of bunches
  - Similar to what was done in 2016 with fewer bunches
Second approach: neglecting quadrant symmetry, fill up both rings as much as possible
  22 trains each for p (2*30) and Pb (7*8)
  Longer kicker gaps between Pb trains to match p structure  
  “Default scheme”: many collisions at IP1/5/8, no collisions at IP2
  Brute-force scan with 0-3 longer gaps between trains in each beam, all permutations checked
  Found range of candidate filling schemes - still a bit worse than assumed when scaling the Pb schemes

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<td>1166</td>
<td>0</td>
<td>870</td>
</tr>
<tr>
<td>1232</td>
<td>1320</td>
<td>901</td>
<td>843</td>
<td>432</td>
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<td>602</td>
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<td>1232</td>
<td>1320</td>
<td>765</td>
<td>724</td>
<td>735</td>
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Using 25 ns proton scheme

So far tried to match the Pb beam as closely as possible, using 50 ns protons

- With 50 ns, no “natural” collisions at LHCb if quadrant symmetry is respected
- With 25 ns, collisions do occur naturally at LHCb
- Try to collide 50 ns Pb beam with 25 ns p beam – obviously many p bunches would be “wasted”, but the aim is to have as many collisions as possible
- Possibly need to think about beam-beam – will get many parasitic encounters. Some studies done in thesis by Marc
- First try: similar length as 2*30 b 50-ns scheme: take 2*60b at 25 ns

- With a little fiddling, could get about 900 collisions in all IPs
- Could possibly find even better scheme with brute-force scan, and checking other train lengths for protons

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<td>897</td>
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Simulated beam evolution with new p-Pb schemes

- Assuming 1.3E11 p/bunch – proton beam intensity is almost unchanged
- Assuming baseline machine configuration without changes in crossing or $\beta^*$
- Exploring different levelling scenarios at all IPs – here are some examples. Could still be optimized to find the best compromise
Integrated luminosity in 1-month run

- Several of the new filling schemes, both 50 ns and 25 ns, satisfy all experiments simultaneously (relies on 1.3E11 p/bunch)

- The levelling scenarios can still be optimized to have a more equal share, or one could switch between filling schemes during a run

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Estimated 1-month luminosity
Summary

- Assuming baseline parameters, and 50% OP efficiency
  - We’re 10% short of the luminosity target in Pb-Pb,
  - We miss factor 2 at LHCb for p-Pb

- For both Pb-Pb and p-Pb, there are ways to reach the targets, acting on machine configuration and beams. Still need some checks to verify feasibility

- For Pb-Pb, could reach the target in several ways. Examples:
  - 70 μrad net angle at all IPs, β*=1m at IP8
  - 100 urad crossing at all IPs, β*=0.45 m at IP1/2/5, β*=1m at IP8
  - Higher levelling (7E27 / 1.5E27), β*=1m at IP8, 100 urad net half angle at all IPs
  - Of course, any combination or more pushed configuration would only improve
  - Feasibility of decreased β*, crossings, and levelling targets has not been verified – need further studies, ideally with beam
  - Could also increase luminosity through higher operational efficiency and/or higher than nominal intensity, but cannot count on this

- For p-Pb, improvements of machine configuration are possibly not enough to gain factor >2 at LHCb
  - A very pushed machine configuration with β*=0.4 m at IP1/2/5 and β*=0.5 m at IP8, combined with smaller crossing angles, gives luminosity very close to targets – might not be feasible in operation
  - Increasing proton bunch intensities to 1.3E11 gives needed improvement – but think about possible constraints
  - New realistic filling schemes developed for p-Pb with 50 ns and 25 ns proton beams – for both beam types, schemes found where all experiments reach their respective targets from WG5 with p intensity of 1.3E11
    - Constraints for using 25 ns proton beams? Beam-beam to be checked? Beam instrumentation with very asymmetric beams?
    - Leveling targets and filling schemes still to be further optimized
Thanks for the attention