An OMC perspective on the commissioning

T. Persson
On behalf of the OMC-team
The goal for the commissioning 2022 is to do basically all these steps! Only possible thanks to the experience from Run 2
Introduction

• The presentation is divided into 3 parts:
  • Injection
  • Squeezed optics + Ramp
  • Calibration optics
    • Ballistic optics
    • 60 deg phase advance optics
What do we propose to start with in terms of corrections?

• Global $\beta$-beat correction (injection)

• Local coupling corrections
  • Very similar to Run 2 and validated during beam test
  • Possible that the MQSXs will stop working under Run 3
    • As a proof-of-principle, we propose to tilt the Q3s (or the Q2s but would have to be opposite direction) for one of the IRs to demonstrate that this could replace the MQSX corrections

• The nonlinear IR correctors settings from Run 2 sextupolar $(a_3, b_3)$ and octupolar $(b_4, a_4)$
Octupole IR correction ($b_4$)

- Octupole correction based on amplitude detuning measurement in 2016
  - Improved the tune measurement from the BBQ
    - Improved K-modulation quality
Injection
Global correction

• Initial finding of the β-beat during the beam test
  • Explained by the swapped RQTL7.L3 B1/B2 and fixed (see Michi’s talk)
• The injection optics was then corrected
  • No x’ing angles and not all experimental solenoids at nominal
  • Likely we can re-use the corrections, but should re-measure to be sure
MCS feed-down looks similar to in 2018

- We change the setting of each of the MCS arc-by-arc
  - Measure the change to $C_p$
  - Stayed fairly constant between Run 2 and Run 3
- We can create a knob that changes the $b_3$ but still keeps the coupling constant
  - Test during commissioning
  -> If successful, we could implement in Fidel
  -> More stable coupling at injection
MCO and MCD

- We measured the $Q''$ and $Q'''$ during the beam test and the $Q'''$ was different from the Run 2
  - Would like to repeat measurement over larger $dp/p$
  - Measure amplitude detuning and decoherence checks to find a good setting for both the MCO and MCD (reduced strength)
Summary injection

- The revalidation of the global corrections should be done early in the commissioning
  - Check of the new MCS “uneven” compensation is very quick so could be done at the same time
- MCD and MCO measurements can be scheduled during a quiet period

<table>
<thead>
<tr>
<th>Type</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revalidate Global Correction</td>
<td>2 hours</td>
</tr>
<tr>
<td>MCS feed-down</td>
<td>1 hour</td>
</tr>
<tr>
<td>MCD and MCO correction</td>
<td>5 hours</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>8 hours</strong></td>
</tr>
</tbody>
</table>
Squeezed optics + Ramp
Optics Commissioning Strategy 2022

30 cm
- Local Corrections
- Global Corrections
- Re-iterate non-linear corrections

Ramp Measurements
- Refinement local coupling corrections
- Tbt + K-mod

60cm
- Global Corrections
- Tbt + K-mod

60-30cm
- Global Corrections
- Tbt + K-mod

30 cm
- Higher order feed-downs in the IRs
- Waist shift and collinarity luminosity scans
- 2-3 Nominal bunches

3 pilot bunches for these measurements
Optics Commissioning Strategy 2022

- **30 cm**
  - TbT + K-mod (without X’ing angle)
  - Local Corrections
  - Global Corrections
  - Refinement local coupling corrections
  - Re-iterate non-linear corrections

- **60cm**
  - TbT + K-mod
  - Ramp Measurements
  - TbT + K-mod

- **60-30cm**
  - TbT + K-mod
  - Global Corrections

- **30 cm**
  - TbT + K-mod
  - Higher order feed-downs in the IRs
  - Waist shift and collinarity luminosity scans
  - 2-3 Nominal bunches

- **3 pilot bunches for these measurements**

Time:
- TbT + K-mod
- TbT + K-mod
- TbT + K-mod
Turn-by-turn (TbT) + K-mod

Analysis code and OMC GUI

$\beta, \alpha, f_{1001}, f_{1010}, D_x$

New K-modulation application by G. Trad. M. Hofer connecting it to our analysis
New multiturn by: D. Jacquet, A. Calia, M. Hostettler, M. Schaumann
K-modulation

New application developed to trim the magnets (G. Trad)
The analysis has also been improved to incorporate the phase advance to constrain the results from k-modulation when reconstructing the $\beta^*$

Important when the distance between Q1 to the IP is close to the distance $\beta^*$

$\Rightarrow$ Ready to precisely measure the Van der Meer Optics ($\beta^* = 19$ m)
AC – dipole excitation

• In order to have a good measurement we need to excite the beam to around 2mm peak-to-peak in the arcs
  • Even higher for amplitude detuning

• If we excite and the collimators are too close, there is a risk of blowing up the beam
  • Worst case we need to dump and start a new cycle
    → Hours lost

• Personal experience is that moving the collimator is complicated and time consuming
  • Define early on in the commissioning a sequence: “collimator settings for optics measurements”
Optics Commissioning strategy 2022

- **TbT + K-mod**
- **30 cm**
  - Local Corrections
  - Global Corrections
  - Refinement local coupling corrections
- **60 cm**
  - Ramp Measurements
  - TbT + K-mod
  - Re-iterate non-linear corrections
  - Global Corrections
- **60-30 cm**
  - TbT + K-mod
- **30 cm**
  - Higher order feed-downs in the IRs
  - Waist shift and collinarity luminosity scans
  - 2-3 Nominal bunches

3 pilot bunches for these measurements
Local corrections

• Squeeze the optics to 30 cm
• Measure the local errors
  • Reminder from Run 2:
    - Not apparent where the change came from
      - Energy might have been a factor although the 2015 corrections were also valid for 2.51 TeV run!

Also a degradation seen during the run!
3 different methods to correct the local errors

- Segment-by-Segment
- Machine learning
- Action-phase-jump

- Ideally some time between the measurement and when we need to calculate and evaluate the correction (12h minimum)
Optics Commissioning strategy 2022

30 cm
- Local Corrections
- Global Corrections
- Refinement local coupling corrections

60 cm
- Ramp Measurements
- Tbb + K-mod
- Tbb + K-mod
- Re-iterate non-linear corrections

60-30 cm
- Tbb + K-mod
- Tbb + K-mod
- Global Corrections

30 cm
- Higher order feed-downs in the IRs
- Waist shift and collinarity luminosity scans
- 3 pilot bunches for these measurements
- 2-3 Nominal bunches

Time
Global Corrections

• The input is:
  • Phase advance BPMs
  • Normalized dispersion
  • K-modulation results from the Q1s at IP1 and IP5

• Correction
  • Response matrix created in MAD-X
  • Correction is based on pseudo-inverse of the response matrix

• In a separate correction step, but based on the same input data, we will also calculate a correction for the chromatic coupling as was done in Run 2

T. Persson et al., “LHC optics commissioning: A journey towards 1% optics control”
Optics Commissioning strategy 2022

30 cm

- Local Corrections
- Global Corrections
- Refinement local coupling corrections

Ramp Measurements

60cm

- Tbt + K-mod
- Tbt + K-mod
- Re-iterate non-linear corrections

60-30cm

- Global Corrections

3 pilot bunches for these measurements

30 cm

- Higher order feed-downs in the IRs
- Waist shift and collinarity luminosity scans

2-3 Nominal bunches

Time
The sextupolar error in the IR feed-down to beta-beat and coupling

Possible that the Run 2 correction is not valid anymore

If the sextupole correctors fail we will need to correct the coupling and \( \beta \)-beat (depending on crossing plane and if it is a skew or normal sextupole) as a function of crossing angle and \( \beta^* \)

150 \( \mu \text{rad} \) \( \rightarrow \) 100 \( \mu \text{rad} \)

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E.H. Maclean et al, New approach to LHC optics commissioning for the nonlinear era
**Optics Commissioning strategy 2022**

- **30 cm**
  - Local Corrections
  - Global Corrections
  - Re-iterate non-linear corrections

- **Ramp Measurements**
  - Refinement local coupling corrections

- **60cm**
  - Tbt + K-mod
  - Tbt + K-mod

- **60-30cm**
  - Tbt + K-mod
  - Tbt + K-mod

- **30 cm**
  - Higher order feed-downs in the IRs
  - Waist shift and collinarity luminosity scans

3 pilot bunches for these measurements

2-3 Nominal bunches
New method to measure the local coupling

- Difficult to measure the local coupling in the IR due to the phase advance
- New method tested during the last MD period in 2018
  - Gave promising results
- Principle of the rigid waist shift:
  - Unbalance the strength of the left and the right triplet
    - Breaks the left-right symmetry

F. Soubelet et al, Prospect for Interaction Region Local Coupling Correction in Run 3
Optics Commissioning strategy 2022

30 cm
- Local Corrections
- Global Corrections
- Refinement local coupling corrections

60 cm
- Ramp Measurements
- Tbt + K-mod
- Tbt + K-mod

60-30 cm
- Tbt + K-mod
- Tbt + K-mod
- Tbt + K-mod

30 cm
- Higher order feed-downs in the IRs
- Waist shift and collinarity luminosity scans

3 pilot bunches for these measurements
2-3 Nominal bunches
3 bunches

• Enables faster measurement and/or more data leading to better statistics
• At this stage we have validated that the optics is well under control
  • $\beta$-beat < 20 %
• Simulated failure scenarios with 3 bunches, roughly equally spaced around the ring
  • BLM triggers on total losses from 3 bunches sooner than it triggers on 1 bunch in the simulated cases!
  • Discussed with the MPP and agreed to be used when the beta-beat is below 20%

L. Malina
Ramp

• Would like to measure the ramp with 3 bunches for better statistics
  • Better measurement of the $\beta$-functions
  • No systematic uncertainty from the timing of the kicks

• Trimming out of the injection corrections similar to what was done in 2018
Optics Commissioning strategy 2022

- **30 cm**
  - Local Corrections
  - Global Corrections
  - Re-iterate non-linear corrections

- **60 cm**
  - Refinement local coupling corrections
  - TBT + K-mod

- **60-30 cm**
  - Global Corrections

- **30 cm**
  - TBT + K-mod
  - Higher order feed-downs in the IRs
  - Waist shift and collinarity luminosity scans
  - 2-3 Nominal bunches

Ramp Measurements

3 pilot bunches for these measurements

Time
Optics corrections from 60 cm to 30 cm

• We need 60cm-30cm be well corrected for
  • Machine protection
  • Deliver design luminosity to ATLAS and CMS

• Simulations showed that only correcting 1 optics is not sufficient
  • Propose to correct at 60 cm and 30 cm
60cm-30cm (Simulation)

- 50 seeds with errors corresponding to what we expect after local corrections

- All of the seeds are corrected within machine protection tolerance between 60 cm and 30 cm
- A few seeds are too large at 25cm assuming no additional corrections
  - In Run 2 we didn’t recorrect at 25 cm and still well within machine protection requirements
60cm-30cm (Simulation)

- Luminosity imbalance between ATLAS and CMS < 1 % for most seeds
- Around 2 % for the worst seed
Optics Commissioning strategy 2022

30 cm
- TBT + K-mod
- Local Corrections
- Global Corrections
- Refinement local coupling corrections

60 cm
- TBT + K-mod
- Ramp Measurements
- Re-iterate non-linear corrections

60-30 cm
- TBT + K-mod
- Global Corrections

30 cm
- TBT + K-mod
- Higher order feed-downs in the IRs
- Waist shift and collinarity luminosity scans

Time

3 pilot bunches for these measurements
2-3 Nominal bunches
Amplitude detuning with X’ing

- The amplitude detuning and the RDTs from $a_4$ change with the X’ing angle
  - Feed down from decapole and/or dodecapoles!
- Crucial to correct in HL-LHC:
- Getting experience now would be very valuable for the future!
Optics Commissioning strategy 2022

30 cm

- Local Corrections
- Global Corrections
- Refinement of local coupling corrections
- TbT + K-mod
- TbT + K-mod

Ramp Measurements

60 cm

- TnT + K-mod
- TnT + K-mod
- Re-iterate non-linear corrections
- Global Corrections

60-30 cm

- TnT + K-mod
- TnT + K-mod

30 cm

- Higher order feed-downs in the IRs
- Waist shift and collinarity luminosity scans
- 3 pilot bunches for these measurements
- 2-3 Nominal bunches

Time
Scans with luminosity

• Nominal bunches colliding in IP1 and IP5
  • Scanning dedicated waist shifts knobs
  • Tested in MD, but time-consuming
    • -> Only planes and beams where we have suspicion something could be wrong
  • Scan the collinearity knob in IR1 and IR5 for validation of the local coupling corrections

J. Coello et al, "New local optics measurements and correction techniques for the LHC and its luminosity upgrade"
## Summary Ramp + Squeezed

<table>
<thead>
<tr>
<th>Shift</th>
<th>Activities</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local correction</td>
<td>1. Measuring the local errors in the IR</td>
<td>6h</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global Corrections</td>
<td>1. Global corrections</td>
<td>20h</td>
</tr>
<tr>
<td></td>
<td>2. Refine Local coupling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Refine non-linear</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ramp + 60-30 cm</td>
<td>1. Measure the ramp</td>
<td>8h</td>
</tr>
<tr>
<td></td>
<td>2. Correct at 60cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Measure down to 30 cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higher order Feed-down</td>
<td>1. X’ing angle scans with amplitude detuning</td>
<td>8h</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity scans</td>
<td>1. Vary the collinearity knob and waist shift and optimize the luminosity</td>
<td>8 h</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>50h</td>
</tr>
</tbody>
</table>
Calibration optics
Ballistic Optics

• Can reconstruct the $\beta$ at a BPM and propagate it to the IP
  • Needs very precise calibration of the BPMs

• We can use the $\beta$ reconstruction from phase to compare with what we get from $\beta$ from amplitude, and then use this to calibrate BPMs relative to the arc BPMs

• **Also ballistic for IR4**
  • Turning off Q5 there which could help calibration of in instruments in that area
60 deg phase advance optics

• Would be a different optics with different settings
  • Helps in identifying underlying alignment and magnetic errors
  • In particular, the momentum compaction factor is different

<table>
<thead>
<tr>
<th>Parameter [Unit]</th>
<th>60° LHC</th>
<th>90° LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{\text{min}}/\beta_{\text{max}}$ [m]</td>
<td>63/182</td>
<td>32/177</td>
</tr>
<tr>
<td>$\eta_{\text{min}}/\eta_{\text{max}}$ [m]</td>
<td>2.5/4.1</td>
<td>1.1/2.2</td>
</tr>
<tr>
<td>Momentum Compaction [10^{-4}]</td>
<td>6.9</td>
<td>3.5</td>
</tr>
<tr>
<td>Transition Energy [GeV]</td>
<td>40.0</td>
<td>53.6</td>
</tr>
<tr>
<td>Natural Chromaticity at 450 GeV</td>
<td>-60</td>
<td>-83</td>
</tr>
<tr>
<td>Corrected Chromaticity at 450 GeV</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Sextupole Strength at 450 GeV [Tm^{-2}]</td>
<td>56</td>
<td>142</td>
</tr>
<tr>
<td>Tune at Injection Optics (H,V)</td>
<td>45.28/44.31</td>
<td>62.28/60.31</td>
</tr>
</tbody>
</table>
Mom. Comp. Factor Measurements

- Fit of relative energy (momentum) offset over frequency
- Problem: no device in LHC to measure energy → Use TbT measurements

\[ \delta_p = \frac{\langle \eta_x^\text{mdl} CO_x \rangle}{\langle \eta_x^\text{mdl} \rangle^2} \]

Measured closed orbit and model dispersion at arc BPMs

- Fit using

\[ \delta_p = -\left( \frac{1}{\gamma_{\text{rel}}^2 + \alpha_C} \right) \frac{\Delta f}{f} \]

\( E = 6.5 \text{ TeV} \) and therefore the relativistic gamma is negligible

Relative error between measurement and model about -3 %
Beam Position Monitor Errors

- Measured closed orbit used for momentum offset calculation

\[ \delta_p = \frac{\langle \eta_x \rangle \cdot \text{CO}_x}{\langle \eta_x^2 \rangle} \]

- What would call for confidence
- If average \( C_i \) or
- \( \delta_p^\text{meas} \) would
- Slope of \( \delta_p \) of
- Momentum corrected

**Takeaway:** Around 3% error tentatively attributed to the arc BPMs -> **IR BPM calibration** from ballistic optics are also off because the method uses the arc BPMs.
Summary: calibration optics

- Measuring these optics would provide insight in BPM calibrations and offsets in the IR
  - Indirectly provide an additional measurement of the $\beta$-functions at the IP

<table>
<thead>
<tr>
<th>Type</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballistic optics</td>
<td>8 hours</td>
</tr>
<tr>
<td>60 deg phase advance</td>
<td>12 hour</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>20 hours</strong></td>
</tr>
</tbody>
</table>
Total time estimates

<table>
<thead>
<tr>
<th>Type</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection</td>
<td>8 hours</td>
</tr>
<tr>
<td>Squeezed</td>
<td>48 hours</td>
</tr>
<tr>
<td>Calibration optics</td>
<td>20 hours</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>76 hours</strong></td>
</tr>
</tbody>
</table>

- Comparable in terms of time to a normal commissioning in Run 2 (2017 was 76 hours!)
- The time estimates are based on the assumption that all systems are functional
Conclusion

• The beam tested provided valuable input and enabled us to identify the swapped RQTL7.L3 B1/B2

• The validity of the linear and non-linear corrections used in Run 2 remains to be tested
  • The more surprises the more challenging and time consuming calculating corrections will be

• Measuring the ballistic and the 60 deg phase advance optics would be important for understanding the calibration of the BPMs

• A very challenging but also very interesting time ahead for the Optics Measurements and Corrections in the LHC!
Commissioning 2017...

- 3 new optics commissioned
- 11 shifts (3-days 8-nights)
- 76 hours of measurements
First reaction was…

In the beam test we only had day shifts!
So the OMC-team is ready for both day and night shifts in 2022!
Backup
Counteracting the coupling decay at injection

- The coupling decay is linked to the powering of the MCS (b3-spool pieces)
  - By powering them differently (dynamic part)
    - Mitigate the coupling decay
    - Still compensating the chromaticity decay
- 3 new optics commissioned
- 11 shifts (3-days, 8-nights)
- 76 hours of measurements
Proposed MCS correction

- What is the impact of this "non local" decay compensation
  - Negligible effect on the Q''
  - Chromatic β-beating almost identical
  - Smaller difference than the missing arc (a78) in Run II
Can we change the crossing angles to equalize the luminosity? (coupling)

- Even after sextupole correction the feed-down to coupling is still noticeable. For changes in 10 μrad the effect is small.
- A global correction could be applied for every crossing angle to correct if a problem

<table>
<thead>
<tr>
<th>(\Delta[C^-] \times 10^{-3} )</th>
<th>(\Delta[C^-] / (Q_{x,frac} - Q_{y,frac}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\beta^* = 0.4 \text{ m} )</td>
<td>(\leq 1.5 )</td>
</tr>
<tr>
<td>(\beta^* = 0.3 \text{ m} )</td>
<td>(\leq 0.4 )</td>
</tr>
<tr>
<td>No correction</td>
<td>(\leq 1.5 )</td>
</tr>
<tr>
<td>After correction</td>
<td>(\leq 0.4 )</td>
</tr>
</tbody>
</table>
Overview of the proton commissioning in Run 2

- First commissioning after LS1
- +K-modulation
- Re-use local corrections
  - Nonlinear correction
  - With X-ing
- Re-use global corrections
  - a4 from RDTs