Optics and Corrections

T. Persson
On behalf of the OMC-team
Overview of the proton commissionings

- First commissioning after LS1
  - Re-use local corrections
  - Nonlinear correction
  - With X-ing
- +K-modulation
  - Nonlinear correction
- • Re-use global corrections
  • a4 from RDTs
Commissioning strategy 2015

1. Measure the virgin Machine
2. Measure with Local Corrections
3. TbT Measure + K-Modulation

Linear Commissioning (No X-ing)

- Calculate Local Corrections
- Calculate Global Corrections
The local corrections were very different after LS1

→ Need for new local corrections

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!
Correction strategy for the RMS and peak beta-beat down to good levels.

A waist shift was observed at the IPs.

No imbalance but a few percent luminosity loss.

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### Final β-beating 2015

#### Peak beta-beat

- **uncorrected**
- **local corr.**
- **global corr.**

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<table>
<thead>
<tr>
<th>IP</th>
<th>Beam</th>
<th>$\beta_x^*$ [cm]</th>
<th>$\beta_y^*$ [cm]</th>
<th>$w_x$ [cm]</th>
<th>$w_y$ [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>88 ± 1</td>
<td>86 ± 1</td>
<td>25 ± 2</td>
<td>23 ± 1</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>82 ± 1</td>
<td>83 ± 1</td>
<td>18 ± 2</td>
<td>21 ± 1</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>86 ± 1</td>
<td>86 ± 5</td>
<td>22 ± 2</td>
<td>24 ± 9</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>87 ± 1</td>
<td>83 ± 2</td>
<td>24 ± 2</td>
<td>16 ± 5</td>
</tr>
</tbody>
</table>
Commissioning strategy 2016

1. Measure the virgin Machine
2. Measure with Local Corrections
3. TbT Measure + K-Modulation
4. Calculate Local Corrections
5. Calculate Global Corrections

K-Modulation

Time
Local corrections

- The local phase corrections are degenerate. Possible to find several combinations that correct the phase
  - No guarantee that the waist or $\beta_{IP}$ is well corrected
## Final Corrections 2016

<table>
<thead>
<tr>
<th>IP</th>
<th>(\beta_{IP} ) [m]</th>
<th>(\beta_{IP} ) err [m]</th>
<th>Waist [m]</th>
<th>waist err [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ip1b1.X</td>
<td>0.398</td>
<td>0.007</td>
<td>0.047</td>
<td>0.009</td>
</tr>
<tr>
<td>ip1b1.Y</td>
<td>0.401</td>
<td>0.002</td>
<td>-0.009</td>
<td>0.009</td>
</tr>
<tr>
<td>ip1b2.X</td>
<td>0.398</td>
<td>0.001</td>
<td>0.009</td>
<td>0.001</td>
</tr>
<tr>
<td>ip1b2.Y</td>
<td>0.402</td>
<td>0.001</td>
<td>0.072</td>
<td>0.010</td>
</tr>
<tr>
<td>ip5b1.X</td>
<td>0.399</td>
<td>0.003</td>
<td>-0.007</td>
<td>0.006</td>
</tr>
<tr>
<td>ip5b1.Y</td>
<td>0.400</td>
<td>0.001</td>
<td>-0.02</td>
<td>0.010</td>
</tr>
<tr>
<td>ip5b2.X</td>
<td>0.395</td>
<td>0.003</td>
<td>0.070</td>
<td>0.013</td>
</tr>
<tr>
<td>ip5b2.Y</td>
<td>0.396</td>
<td>0.004</td>
<td>-0.025</td>
<td>0.011</td>
</tr>
<tr>
<td>Average</td>
<td>0.403</td>
<td>0.003</td>
<td>0.016</td>
<td>0.010</td>
</tr>
</tbody>
</table>

**RMS \(\beta\)-beat in IP %** 1%
Effect of crossing angles

- Optics measured in June (commissioning without crossing angles in April)
  - Difference between the two measurements shown in plot below
  - Consistent with simulation of the IR sextupoles errors + crossing angles

An increase of the peak $\beta$-beat in the order of $\sim 3\%$ due to crossing angles + IR sextupole errors
Overview of the proton commisonings

- **K-modulation**
  - First commisioning after LS1

- **Re-use local corrections**
  - Nonlinear correction
  - With X-ing

- **Re-use global corrections**
  - a4 from RDTs

\[ \beta^* \text{ [cm]} \]

- 2015
- 2016
- 2017
- 2018

**ATS**
Commisiong strategy 2017

Linear Comissioning (No X-ing)

- Measure the virgin Machine
- Measure with Local Corrections
- TbT Measure + K-Modulation

Linear with X-ing

- Octupolar Corrections
- Local Corrections
- Global Corrections
- Sextupolar Corrections
- Global Corrections

K-Modulation

Non linear commisioning
New for the year
Local corrections had been calculated during MD in 2016.

- Some degradation was observed but still in the range where it was considered acceptable.

Re-Use Local correction
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
Correction removed the contribution to the footprint from octupole errors in IR1 and IR5 for flat-orbit.
Sextupolar IR corrections

- Improved the stability of the linear optics as a function of X’ing angle

β-beating between crossing angles
Flat-orbit vs X’ing

- The X’ing angles introduce β-beating
- The sextupolar correction removes most of it
- Re-iteration of the linear correction ➔ Same quality of correction as with flat orbit
Any differences with ATS?

- Optics corrections were in the same level for ATS and nominal optics
- A change in the coupling structure
  - Not an issue, was easily correctable but correction created higher strength for the skew quadrupoles (only Beam 1)

![Graph showing comparison between ATS and nonATS](image)
Commissioning strategy 2018

Nonlinear

Octupolar Corrections
Skew Octupolar Corrections
Global Corrections

Improved Sextupolar Corrections
Global Corrections

Linear with X-ing

TbT Measure + K-Modulation

Measure with Local Corrections

K-Modulation

Time
**β-beating**

**2018 vs 2017**

RMS $\Delta \beta/\beta = 2.5\%$ at 25cm

Re-used the correction from 2017 without any degradation in optics quality
Skew octupole Corrections ($a_4$)

- Skew octupolar sources are known to:
  - Reduce dynamic aperture
  - Increase of octupole threshold for small tune separation (X. Buffat, 8th LHC Operations Evian Workshop)

- Reduced the $a_4$ RDTs for beam 1 with 75%. No change for beam 2

- 1 out of 4 $a_4$ correctors is not working

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F. Carlier, LMC 2018
Effect of $a_4$ and $b_3$ corrections in IR1

Without any nonlinear corrections the feed-down to $|C^-|$ during X’ing angle leveling would be $\sim 2 - 2.5 \times 10^{-3}$ at $\beta^* = 30$ cm

E. H. Maclean, LMC 2018
Feed down from higher orders to the $a_4$ RDTs

The RDTs from $a_4$ change with the x’ing angle ➔ Feed down from decapole and/or dodecapoles!
Amplitude detuning with X’ing

The X’ing angle causes an amplitude detuning that is almost half of the uncorrected!
Impact on footprint

- Distortion of the footprint
- Coming from decapole and/or dodecapoles (under investigation)
- Asymmetric between Beam 1 & Beam 2
  → Can not correct with IR-correctors, need to use MO
- Would need to change the powering of MOD by +142 A and MOF -108A to get back to the unperturbed (grey) footprint

Impact on footprint

\[ \sqrt{(2J_x)^2 + (2J_y)^2} = 45 \mu m \approx 3.5\sigma \]
Ion Commissioning 2018
A big step in $\beta^*$ for IP2

Re-did local (normal quadrupolar) correction at IP1 and IP2

A new automatic local coupling matching was used:

- Unfortunately, the corrections were trimmed in with a swap between MQSX3.L and MQSX3.R
- If trimmed in correctly we would have been close to what was found optimal with luminosity
- This was fixed by re-balancing the strength of MQSX3 left and right using the colinearity knob (S. Fartoukh)
Why is the local coupling hard to measure?

- Because of the phase advance and symmetry an increase of MQSX3.L and decrease of MSQX3.R (colinearity knob is doing this) by the same amount has almost no effect outside the IR.
  - Difficult to have good measurements inside the IR due to the phase advances
  - If we break the symmetry by increasing the strength of the left triplet and decrease the right
    - A non optimal MQSX setting gives a change of the global $|C-|$
New method to measure the local coupling

- Tested during the last MD period

- Principle of the rigid waist shift:
  - Unbalance the strength of the left and the right triplet
    - Breaks the left-right symmetry
Rigidity waist shift knob

- The colinearity knob gives no contribution to the global observable $|C-|
  - After applying the rigidity knob there is a dependency
Simulation of......

(Local coupling at IP2)
Tracking simulation: Ideal machine (beam 1) + trim of the colinearity knob = 10 (MQSX.3L2 = 10^{-3} \, m^{-2} \, and \, MQSX.3R2 = -10^{-3} \, m^{-2})

Start with 50% larger emittance in horizontal compared to vertical
→ **Beam size is 15% larger in horizontal and 30%** in vertical in IP2 compared to IP1
→ **33% lower luminosity** (neglecting effect from crossing angles) compared to the 50% that was observed in the machine
→ Almost identical beam size increase for beam 2 (less than 1% difference)
Transverse Global Coupling (C-)
Automatic coupling correction tool

- The studies to make an automatic coupling tool started already in Run I
  - Attracted additional focus due to the link between coupling and instabilities (L.R. Carver et al. Phys. Rev. Accel. Beams 21, 044401)
- In 2017 a collaborative effort was made to turn it into an operational tool (OP, ABP, RF, CO, BI)
  - Plans for a similar tool for tune measurement
  - Code parallelized in 2018
  - More than 2000 measurements since August 2018
    - Most of them at injection where we observe a drift
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
Proposed MCS correction

- What is the impact of this "non local" decay compensation
  - Negligible effect on the $Q''$
  - Chromatic $\beta$-beating almost identical
  - Smaller difference than the missing arc (a78) in Run II
Collaborations and Codes

- The automatic coupling correction tool is an example of a successful collaboration
  - Developed in a team ➔ Several people are able to maintain the software and make modifications
- Other examples of codes are the K-modulation and the multi-turn software
  - Developed by individuals and then new features have been added by others
  - People leave or change roles (both in the OMC-team and OP)
- Plan to have a mini workshop to discuss common codes and needs with OP
  - Also discuss how to optimize commissioning tasks between OP and the OMC-team
Conclusion

• We have learned something new every commissioning:
  • 2015: New energy
  • 2016: K-modulation to correct the waist
  • 2017: Correct with X-ing + sextupolar and octupolar corrections
  • 2018: Use RDTs to correct skew octupolar error ($a_4$)

• Reproducibility:
  • After LS1 the errors were very different
  • Possible that it will be the same after LS2
  • $\beta$-beating within a few percent when re-measured during the same year

• The automatic coupling correction tool is heavily used in operation and in MDs:
  • Proposal to change the powering of the $b_3$-spool pieces to mitigate the coupling decay at injection
A look into the past and into the future...

Slide from 2015

Slide for 2021?

from 2017
Thank you for your attention!

Many thanks to OP, BI, CO, RF for all the support and collaborations throughout the years!!

It is a privilege to work with all of you!
Back up slides
Does the coupling change the beam size?

- Normally we think of coupling as a rotation in phase space
- But also have a direct impact on the beam size
Local coupling correction strategy for Run III

- Main problem was due to the swap between the right and left MQSX when implementing the correction
  - Automatic conversion from MAD-X to LSA
  - Include the check of the local coupling corrections in our validation procedures
- The MD after the ion run, provided us with new crucial measurements to evaluate if we can correct the local coupling to required level
  - New method was tested
Flat-orbit vs X’ing

- Still a slight degradation from the X’ing
  ➔ A linear optics correction with X’ing in
2018: 6 shifts, 51 hours
2017: 11 shifts, 76 hours

Courtesy L. Malina
Collaboration between many groups

Beams Department | Accelerators and Beam Physics
J. Coello de Portugal
E. Fol
L. Malina
T. Persson
P. Skowronski
R. Tomas

Beams Department | Radio-Frequency

Beams Department | Operation

Beams Department | Controls

M. Hostettler, A. Calia, K. Fuchsberger, H. Hemelsoet

Hruska, Marek
Gabriel, Mathieu

Valuch, Daniel
Söderén, Martin
\[ \sqrt{(2J_x)^2 + (2J_y)^2} = 45 \mu m \approx 3.5 \sigma \]

<table>
<thead>
<tr>
<th>( \partial Q_x / \partial J_x )</th>
<th>( \partial Q_y / \partial J_x )</th>
<th>( \partial Q_y / \partial J_y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+32)</td>
<td>(0)</td>
<td>(-40)</td>
</tr>
</tbody>
</table>

LHCB1

| Value | \( |I_{MO}| \) correction |
|---|---|
| \( \Delta |I_{MOF}| = +108 \) | \(0\) |

LHCB2

| Value | \( |I_{MO}| \) correction |
|---|---|
| \( \Delta |I_{MOD}| = +142 \) | \(+20\) | \( \Delta |I_{MOD}| = -70 \) |
When the cogging measurement was repeated, it was concluded that no waist shift was present (November 18th)

- Our focus turned to coupling
- Plan to remeasure and check the coupling
- The test of the colinearity knob with luminosity fixed the issue (November 19th)

The Colinearity knob (S. Fartoukh):

- Trimmed on top of the previous corrections
- $\Delta MQXS.3L2 = +\text{knobStrength}\times 10^{-4} \text{ m}^2$
- $\Delta MQXS.3R2 = -\text{knobStrength}\times 10^{-4} \text{ m}^2$
- Optimal was found to be knobStrength=-10
- (knobStrength=-12 for opposite polarity)

If no left/right swap → Corrections much closer to what was found with the colinearity knob
<table>
<thead>
<tr>
<th>Circuit</th>
<th>$\Delta k \ (10^{-5} \ m^{-2})$</th>
<th>Polarity</th>
<th>LSA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2012</td>
<td>2015</td>
<td>2016</td>
</tr>
<tr>
<td>IR1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ktqx1.l1</td>
<td>1.0</td>
<td></td>
<td>1.23</td>
</tr>
<tr>
<td>ktqx1.r1</td>
<td>1.0</td>
<td>–1.23</td>
<td>+</td>
</tr>
<tr>
<td>ktqx2.l1</td>
<td>1.0</td>
<td>0.35</td>
<td>0.65</td>
</tr>
<tr>
<td>ktqx2.r1</td>
<td>–1.4</td>
<td>–0.7</td>
<td>–1.0</td>
</tr>
<tr>
<td>ktqx3.l1</td>
<td></td>
<td>1.22</td>
<td>–</td>
</tr>
<tr>
<td>ktqx3.r1</td>
<td></td>
<td></td>
<td>–1.22</td>
</tr>
<tr>
<td>kq9.11b1</td>
<td>1.5</td>
<td></td>
<td>–</td>
</tr>
<tr>
<td>IR5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ktqx1.l5</td>
<td></td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>ktqx1.r5</td>
<td></td>
<td>–2.0</td>
<td>–2.0</td>
</tr>
<tr>
<td>ktqx2.l5</td>
<td>0.7</td>
<td>1.9</td>
<td>0.27</td>
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<tr>
<td>ktqx2.r5</td>
<td>1.05</td>
<td>1.9</td>
<td>1.48</td>
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<tr>
<td>ktqx3.l5</td>
<td></td>
<td></td>
<td>1.49</td>
</tr>
<tr>
<td>ktqx3.r5</td>
<td></td>
<td></td>
<td>–1.49</td>
</tr>
<tr>
<td>kq4.15b2</td>
<td>3.80</td>
<td></td>
<td>–</td>
</tr>
</tbody>
</table>
# Results from k-modulation taken during the MD (Beam 2)

<table>
<thead>
<tr>
<th></th>
<th>β* Horizontal [m]</th>
<th>β* Vertical [m]</th>
<th>Waist Shift Horizontal [m]</th>
<th>Waist Shift Vertical [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colinearity -12 (operational setting of the machine for opposite polarity)</td>
<td>0.514</td>
<td>0.502</td>
<td>-0.08</td>
<td>-0.01</td>
</tr>
<tr>
<td>Colinearity -5</td>
<td>0.5084</td>
<td>0.5051</td>
<td>-0.049</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Small change in the measured horizontal and vertical $\beta^*$ and waist shift as a function of the setting of the colinearity knob

The results are consistent with simulation → k-modulation is measuring $\beta_x$ and $\beta_y$,
→ For a situation with strong coupling beam size is **not** equal to $\sqrt{\beta_x \varepsilon_x}$

**Pro:**
- Measurement insensitive to local coupling errors
  → Can be used for our normal quadrupolar corrections