Beam-based vs model corrections in LHC IRs

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with many thanks to the whole OMC team
Beam-based vs model based corrections in LHC IRs

→ **which set of error tables to use?**

- **‘Pre-LS1 WISE’**
  - generated 2011
  - sextupole/octupole/decapole errors unseeded in triplets

- **‘Post-LS1 WISE’**
  - generated 2015
  - **multiple bug fixes implemented in LS1**  
    (more relevant for geometry?)
  - error estimate dependent on magnet powering
  - \(b_4\) in MQXB & \(a_6\) in MQXA unseeded in triplets
  - Warm MBXW have several multipoles unassigned
Normal sextupole corrections

Beam-based (IR1)  Beam-based (IR5)

Skew sextupole corrections

Beam-based (IR1)  Beam-based (IR5)  Beam-based (IR5)

Skew $K_{3L}^{(IR1\text{-right})}$ [10^{-3} m^{-3}]

(2017 initial correction)
(2017 iteration for $a_4$ corrs)
(2018 iteration for $a_4$ corrs)

Skew $K_{3L}^{(IR5\text{-right})}$ [10^{-3} m^{-3}]

(2018 first time commissioned)


Skew $K_{3L}^{(IR5\text{-left})}$ [10^{-3} m^{-3}]

(2018 first time commissioned)
Discrepancies

- Discrepancies with magnetic-model well beyond seeds
- No clearly significant benefit to 2011 vs 2015 error tables

Impact of normal/skew octupole corr on required sextupole corr’s

- Beam offset in MCOX spoils a3 correction
- Estimate $\sim$1mm offset
- Transparent to 2017/18 commissioning (b4 applied first)
Similar issue with skew octupole corrections in 2017/18
→ $a_3$ corrections in IR1 had to be iterated multiple times

![Graph showing LHCb2 Q_y vs IP1 vertical crossing angle (μrad)]

- 1mm H-offset of MCOSX R1
- We do care about corrector alignment

- Not currently attempting to include geometric errors
  → egeoc tables don’t show a comparable offset (0.2mm)

- Not surprising that sextupole corrections don’t agree:
  offset effects are comparable order-of-magnitude to discrepancies
Corrector alignment tolerance from DA is ± 1mm

Consistent IR-corrector misalignment at 1mm level will complicate HL-LHC commissioning

- lower-order corrections depend on first establishing higher-orders
- Becomes complicated if higher-order corrections also depend on higher-order perturbations from lower-orders
Sextupole errors in cold MBX (IR2)

- 2011: good agreement of feed-down to coupling in IR2 → completely dominated by b3 of cold D1

Attempts to correct in 2018 ION commissioning failed! → compensated 1 beam only. Still to be understood
Skew octupole correction

- Limited value comparing beam- vs model-based correction for $a_4$
  → MCOSX L1 is broken

- 2017: correct coupling feed-down in IR1 with single corrector

- 2018: global RDT correction ($f_{1210}$) via 3 correctors in IR1+5
  → Compare sum of L+R corrections

<table>
<thead>
<tr>
<th>Corrector strength</th>
<th>Beam-based</th>
<th>model-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sum_{IR1} K_{4,skew}$</td>
<td>$+1.0$ $+0.50$</td>
<td>$+0.93 \pm 0.06$</td>
</tr>
<tr>
<td>$\sum_{IR5} K_{4,skew}$</td>
<td>unused $-0.51$</td>
<td>$-0.52 \pm 0.06$</td>
</tr>
</tbody>
</table>

- Sign and magnitude of beam-based corrections are comparable to model
Normal octupole correction

Beam-based correction via detuning & feed-down to $Q_{x,y}$

- Model-based IR1 correction (feed-down agrees with model)
- Minimize residual detuning with IR5 correctors
Extremely good detuning post-correction (flat-orbit)

- Reduced quadratic part of tune variation
- Good local correction

**Graphs:**
- Post-correction, flat-orbit, 2017
- Flat-orbit, 2016
- BBQ data
- AC-dipole data
- Re-validated in late-2017 & 2018-MD1
- Good global correction

**Graph 1:**
- Beam 2 $\Delta Q_y$
- Driven $2J_y$ [$\mu m$]

**Graph 2:**
- Beam 2 $\Delta Q_y$
- ATLAS (=IR1) vertical crossing angle [$\mu$rad]
- 2017, with normal octupole correction
- 2015, no normal octupole correction
also improved lifetime ($\beta^* = 0.14\text{ m}$) and $4\text{Q}_x$ resonance strength

- Lots of reasons to think $b_4$ is well corrected
Significant discrepancy in a strong multipole component

→ expect larger correction in IR5 than IR1

→ actually find weaker correction in IR5
Is the $b_4$ discrepancy believable?

Amplitude detuning constrains sum of IR1+IR5 correction
→ see $\sim 30\%$ discrepancy in amplitude detuning
→ additional source elsewhere in the ring?

- Detuning vs $\beta^*$ consistent with IR1/5 discrepancy
- Correction for 2016 nominal optics still works well for ATS optics after sextupole correction
**Is the $b_4$ discrepancy believable?**

→ IR5 $b_4$ correction calculated purely based on detuning
→ compare quadratic part of IR1 vs IR5 tune feed-down pre-correction

![Graph showing comparison between IR5 and IR1 for LHCB2 Qy](image)

- Consistently find quadratic part of Q-feed-down in IR5 $<$ IR1
- e.g. quadratic fit to LHCB2 $Q_y$: $\frac{\partial^2 Q_y}{\partial \theta^2} |_{IR5} = 3.1 \times 10^{-8}$ $\frac{\partial^2 Q_y}{\partial \theta^2} |_{IR1} = -4.5 \times 10^{-8}$

Measurements of feed-down to tune are not consistent with larger $b_4$ errors in IR5 than in IR1 → this is consistent with beam-based corr’

Caveat: comparing measurements over multiple different years
Explanations? Error in magnetic model of $b_4$?

According to WISE tables, the triplet $b_4$ in IR5/8 appears systematically worse than IP1/2

→ is this correct? → if so, why?
Can IR alignment/offsets explain b4 discrepancy?

- Apply random misalignments to triplets in IR5 with Gaussian distribution
- $\sigma_{x,y} = 0.3 \, mm$, estimate from K-mod of typical offset of beam in Q1
At 0.3mm level alignments explain 10% of missing b4. Caveats:
→ only IR5
→ 0.3mm relevant to Q1,2. Q3 & MBX may be less controlled

Explanation via feed-down requires some extra non-conformity (orbit/alignment/higher-orders)
Model vs measurement of higher-orders?

→ see large change to detuning from crossing scheme

\[
\frac{\partial Q_x}{\partial 2J_x} = +32 \quad \Delta |I_{MOF}| = -108 \\
\frac{\partial Q_y}{\partial 2J_y} = 0 \\
\frac{\partial Q_y}{\partial 2J_y} = -40 \quad \Delta |I_{MOD}| = +142 \\
\frac{\partial Q_y}{\partial 2J_y} = 0 \quad \Delta |I_{MOD}| = -70
\]

Comparable magnitude as detuning generated by b4 at flat-orbit
Compare measured feed-down from IR5 crossing angle to predictions of WISE tables

- Observed feed-down comparable order-of-magnitude to model
- but doesn’t precisely reproduce observations
- Everything contributes… IR1, IR5… a5, b5, b6… triplet, D1…
Conclusions

- Discrepancies with magnetic model for IR-sextupole correction
  - Not surprising since observe comparable effects from alignment/orbit in higher-order correctors
- Global skew octupole corrections appear comparable to magnetic model
  - No definitive explanation found.
- Decapole / dodecapole sources in model do not reproduce beam-based obs’, but order of magnitude is comparable.
Reserve
## Skew octupole correction

<table>
<thead>
<tr>
<th>$[m^{-4}]$</th>
<th>$K_{4,skew}$ L1 $[m^{-4}]$</th>
<th>$K_{4,skew}$ R1 $[m^{-4}]$</th>
<th>$K_{4,skew}$ L1 $[m^{-4}]$</th>
<th>$K_{4,skew}$ R1 $[m^{-4}]$</th>
<th>Beam-based 2017</th>
<th>Beam-based 2018</th>
<th>model-based FiDeL</th>
<th>model-based WISE</th>
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<tbody>
<tr>
<td></td>
<td>broken</td>
<td>broken</td>
<td>+0.81 ± 0.04</td>
<td>+0.78 ± 0.007</td>
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<tr>
<td>$K_{4,skew}$ L1</td>
<td>+1.0</td>
<td>+0.50</td>
<td>+0.12 ± 0.05</td>
<td>+0.08 ± 0.006</td>
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<tr>
<td>$K_{4,skew}$ L1</td>
<td>unused</td>
<td>−0.25</td>
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Nominal corrections overcompensated detuning in 2016 with 40cm nominal optics → no big effect from ATS

Correction calculated before IR-sextupole corrs worked well post-sextupole commissioning → No strong effect from IR-sextupoles