Some open questions for nonlinear optics corrections/commissioning in HL-LHC

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and the Optics Measurement and Correction (OMC) Team
Is existing strategy of local correction of specific RDTs using the IR-sextupoles optimal for DA?
‘Nominal’ IR-nonlinear corrections based upon minimization of selected RDTs

Dynamic Aperture Studies for the LHC Separation Dipoles; CERN-LHC-Project-Note-349

\[
c(b_n; p, q) \equiv \int_{IR} ds \ K_n(s) \beta_x^p \beta_y^q e^{\pm i[(p-2l)\phi_x \pm (q-2m)\phi_y]}
\]

\[
\approx \int_{IR_{\text{left}}} ds \ K_n(s) \beta_x^p \beta_y^q + (-1)^n \int_{IR_{\text{right}}} ds \ K_n(s) \beta_x^p \beta_y^q
\]

Correct IR-errors by minimizing \(c(b_n;p,q)\) and \(c(a_n;p,q)\) for two combinations of \(p\) & \(q\)
\[ c(b_n; p, q) \equiv \int_{IR} ds K_n(s) \beta_x^{\frac{p}{2}} \beta_y^{\frac{q}{2}} e^{i[(p-2l)\phi_x \pm (q-2m)\phi_y]} \]
\[ \approx \int_{IR_{\text{left}}} ds K_n(s) \beta_x^{\frac{p}{2}} \beta_y^{\frac{q}{2}} + (-1)^n \int_{IR_{\text{right}}} ds K_n(s) \beta_x^{\frac{p}{2}} \beta_y^{\frac{q}{2}} \]

**Normal sextupole \((\Delta H \propto [x^3 - xy^2])\) correction:**
- Minimize \(c(b_3;1,2)\) and \(c(b_3;2,1)\)
- Correcting \(xy^2\) \& \(x^2y\)

**Skew sextupole \((\Delta H \propto [x^2y - y^3])\) correction:**
- Minimize \(c(a_3;0,3)\) and \(c(a_3;3,0)\)
- Correcting \(y^3\) \& \(x^3\)

**Normal/skew sextupole corrections include weightings on**
\[ \beta_x^{\frac{p}{2}} \beta_y^{\frac{q}{2}} \] **which correspond to the skew/normal multipole**
Compare sextupole RDTs for beam1 for nominal correction and alternate $\beta$ weightings
Nominal correction is a compromise between beam1 / 2

\[ \beta_{x,y}^{\text{Beam1}} \Leftrightarrow \beta_{y,x}^{\text{Beam2}} \]

\[ \rightarrow \text{Improved sextupole correction for beam1 deteriorates beam2} \]
Any impact from different weighting of correction with beta?

- LHCB1, $10 \times 10^3$ turns tracking (PTC)
- $\beta^* = 15 \text{ cm}$, $Q' = 2$, flat-orbit, MO$=\pm570$ A
- seed-1 $a_3 + b_3$ errors in IRs only
Very little effect on short-term DA for negative MO polarity

Nominal correction macro

Beam1 optimized macro
Do see an impact for positive MO polarity

Caveats:

- May not be relevant for long-term DA
- May not be relevant for more realistic model
Are there any options to optimize on a broader range of sextupole RDTs?

- **A weighted minimization of all the relevant RDTs**
  → also proposed in CERN-LHC-Project-Note-349

- **A more global approach using additional circuits**
  → could a combined correction using IP1/5 MCX and other families of MSS give a better DA?  
  → May also be relevant in case higher-order feed-down spoils common correction of LHCB1/2?
Are RDTs/DA the highest priority for IR-nonlinear corrections?
→ expect large $\Delta \beta / \beta$ due to feed-down at end-of-squeeze


- All normal/skew IR-sextupole corrections to date in LHC have been based upon feed-down
  → weighting with $\beta_{x,y}$ differ from RDTs

- Should correction priorities/methods change for HL-LHC?
  → To what extent do corrections optimized on feed-down deteriorate the dynamic aperture?

  e.g. Q-feed-down response matrix vs RDT-based correction for IP5-$b_3$

<table>
<thead>
<tr>
<th></th>
<th>RDT corr</th>
<th>Feed-down corr</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>kcsx3.l5</td>
<td>$+0.00029$</td>
<td>$+0.00024$</td>
<td>17%</td>
</tr>
<tr>
<td>kcsx3.r5</td>
<td>$-0.00107$</td>
<td>$-0.00100$</td>
<td>7%</td>
</tr>
</tbody>
</table>
Struggled to correct large FD to linear coupling from IP2 this year
→ corrected beam1 but left large feed-down in beam 2

- Till now concerned with FD to $|C^-|$ for instabilities
- IP2-$b_3$ errors + correction influenced collinearity knob at level of 10 – 20% (potentially relevant to luminosity)
- Will have to improve our measurement/correction techniques to deal with large feed-down to coupling
Normal octupole correction in Run2 based on minimization of amplitude detuning

- Systematic $b_4$ in LHC triplets makes correction simple as contribution to cross-term cancels between left/right sides
- 2 KCOX families per IR allows minimization of remaining direct detuning terms

<table>
<thead>
<tr>
<th>Detuning coefficients $[10^3 \text{ m}^{-1}]$</th>
<th>$\beta^* = 0.4 \text{ m}$ (no correction)</th>
<th>$\beta^* = 0.3 \text{ m}$ (with correction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCB1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{\partial Q_x}{\partial \epsilon_x}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{\partial Q_x}{\partial \epsilon_y}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{\partial Q_y}{\partial \epsilon_x}$</td>
<td>$43 \pm 1$</td>
<td>$-3 \pm 1$</td>
</tr>
<tr>
<td>$\frac{\partial Q_y}{\partial \epsilon_y}$</td>
<td>$0 \pm 1$</td>
<td>$5 \pm 3$</td>
</tr>
<tr>
<td></td>
<td>$-50 \pm 1$</td>
<td>No measurement</td>
</tr>
<tr>
<td>LHCB2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{\partial Q_x}{\partial \epsilon_x}$</td>
<td></td>
<td></td>
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<tr>
<td>$\frac{\partial Q_x}{\partial \epsilon_y}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{\partial Q_y}{\partial \epsilon_x}$</td>
<td>$38 \pm 1$</td>
<td>$-2 \pm 1$</td>
</tr>
<tr>
<td>$\frac{\partial Q_y}{\partial \epsilon_y}$</td>
<td>$1 \pm 1$</td>
<td>$-3 \pm 2$</td>
</tr>
<tr>
<td></td>
<td>$-44 \pm 1$</td>
<td>$2 \pm 1$</td>
</tr>
</tbody>
</table>
Beam-based $b_4$ correction in HL-LHC looks more complicated than LHC

- Cross-term detuning comparable to direct
- Significant residual detuning remains after applying nominal KCOX
  - from residual detuning generated in IRs
  - from 2nd order contribution from arc sextupoles
Expected residual detuning after correction at 15cm comparable to entire correction in LHC at 40cm

- Potential issue for K-modulation since observed in 2017 correcting $40 \times 10^3 \text{ m}^{-1}$ significantly improved online tune measurement
Compared to detuning from MO, residual direct detuning is small.

Residual detuning from IRs & second order contribution from sextupoles are both significant fractions of the cross-term detuning generated by the maximum MO powering.

<table>
<thead>
<tr>
<th></th>
<th>HL-LHC, 15cm, -570A</th>
<th>2017 @ 40cm</th>
<th>2017 @ inj</th>
</tr>
</thead>
<tbody>
<tr>
<td>$dQ_x/d\epsilon_x$ $[10^3\ m^{-1}]$</td>
<td>-450</td>
<td>+164</td>
<td>+40</td>
</tr>
<tr>
<td>$dQ_y/d\epsilon_y$ $[10^3\ m^{-1}]$</td>
<td>-458</td>
<td>+153</td>
<td>+39</td>
</tr>
<tr>
<td>$dQ_{x,y}/d\epsilon_{y,x}$ $[10^3\ m^{-1}]$</td>
<td>+160</td>
<td>-108</td>
<td>-30</td>
</tr>
<tr>
<td>cross/direct</td>
<td>$\sim -0.36$</td>
<td>$\sim -0.68$</td>
<td>$\sim -0.75$</td>
</tr>
</tbody>
</table>

→ ratio of cross-term to direct-terms from MO is significantly smaller at 15cm in HL-LHC

Correction of residual cross-term with MO doesn’t look particularly viable.

Can we optimize IRNL correction for cross-term detuning? Also relevant to $h_{2002}$ which is closer to working point.
Conclusions

- Existing sextupole-RDT correction looks optimal for negative MO
- For positive MO polarity maybe benefit by trying to optimize additional RDTs
- In HL-LHC expect large cross-term detuning generated in IR → should explore $b_4$ corrections to optimize cross-term detuning
- Lots of open questions relating to commissioning of IR-errors:
  → what is the correction priority? (DA/RDTs vs feed-down)
  → does correction via feed-down deteriorate DA?
  → Can we benefit from a more global correction strategy?
  → What are the implications of residual nonlinear errors left after corrections applied (to operation and to commissioning)

All these questions also apply to higher-order multipoles as well!