HL-LHC IR non-linear correction and options

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Acknowledgements: S. Fartoukh for tracking tools
Outline

- Introduction
  - Current strategy of the use of non-linear correctors in DA simulation studies

- Recent studies
  - Correction quality vs powering for Beam 1
  - Attempt to correct D2 field quality

- Outlook
Introduction - I

- Situation in nominal LHC:
  - Non-linear corrector package provides compensation for non-linear errors in the IR (triplets, D1, D2).
  - Location of the correctors changed between V6.4 and V6.5 to provide more favourable optical conditions.
  - Correctors are used in simulations, but not in operations (see Ewen’s presentation)
Introduction - II

- Strategy to set the correctors’ strength (see S. Fartoukh, LHC Project Note 349): minimisation of driving terms.

\[
\begin{align*}
  c(b_n; p, q) & \equiv \int_{\text{IR}_{\text{left}}} ds K_{n-1}(s) \beta_x^{p/2} \beta_y^{q/2} + (-1)^n \int_{\text{IR}_{\text{right}}} ds K_{n-1}(s) \beta_x^{p/2} \beta_y^{q/2}, \quad q \text{ even} \\
  c(a_n; p, q) & \equiv \int_{\text{IR}_{\text{left}}} ds K_n^{(s)}(s) \beta_x^{p/2} \beta_y^{q/2} + (-1)^n \int_{\text{IR}_{\text{right}}} ds K_n^{(s)}(s) \beta_x^{p/2} \beta_y^{q/2}, \quad q \text{ odd},
\end{align*}
\]

- Selection of the driving terms to be corrected:
  - b3: \(c(b3; 1, 2)\) and \(c(b3; 2, 1)\)
  - a3: \(c(a3; 0, 3)\) and \(c(a3; 3, 0)\)
  - b4: \(c(b4; 4, 0)\) and \(c(b4; 0, 4)\)
  - a4: \(c(a4; 3, 1)\) and \(c(a4; 1, 3)\)
  - b6: \(c(b6; 0, 6)\) and \(c(b6; 6, 0)\)

The choice of the resonances is based on the proximity to the working point.
Introduction - III

- What is new in HL-LHC:
  - The D1 separation magnet is cold and its field quality will contribute to the strength requirement of the triplets’ correctors.
  - Additional corrector magnets have been requested: b5, a5, a6.

- Strategy to set these additional correctors:
  - a5: c(a5; 0, 5) and c(a5; 5, 0)
  - b5: c(b5; 5, 0) and c(b5; 0, 5)
  - a6: c(a6; 5, 1) and c(a6; 1, 5)

See HiLumi-Mil-M24_28 specification document
Impact of non-linear correctors on DA - I

- The so-called **SLHCV3.1b** layout, with a triplet gradient of 150 T/m, has been used and several configurations considered:
  - With or without the full correction system
  - With one single corrector not used
  - With an intermediate configuration in which the correctors corresponding to a5, b5, a6 are not used.

- **Setting up of numerical simulations:**
  - 59 phase space angles
  - 60 seeds
  - $10^5$ turns
  - The field errors are assigned to all magnets in the arcs and IRs based on the data of the magnetic measurements.
Impact of non-linear correctors on DA - II

- **Markers**: average DA over seeds and angles
- **Negative error bars**: minimum DA over seeds and angles
- **Positive error bars**: average DA over angles of the maximum over seeds.
- **Left plot**: $D_{\text{ave}}$ affected by $b_6$, but $D_{\text{min}}$ also by low order correctors.
- **Right plot**: for complete non-linear correction system $\sim 5 \sigma$ gained for $D_{\text{ave}}$ and $D_{\text{min}}$. $a_5, b_5, a_6$ correctors increase $D_{\text{ave}}$ and $D_{\text{min}}$ by about 2-3 $\sigma$. 
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Correction quality vs powering for Beam 1

In DA simulations the algorithm used to set non-linear correctors’ strength relies on:

- Perfect knowledge of optical parameters
- Perfect knowledge of field quality of IR magnets
- Perfect knowledge of transfer function of non-linear correctors

A more realistic situation has been considered, assigning the computed strength multiplied by a random factor according to:

- **Individual effects:** The strengths of correctors of one type (e.g. four $b_3$ correctors in IP1 & IP5) are scaled with the same factor in the range from 0.7 to 1.3, while the other correctors were set at their ideal strengths.

- **Combined effects:** All IP1 & IP5 corrector strengths were randomly and independently generated within the scaling range of 0.7 to 1.3.
Impact of individual $b_n$ correctors

- Strengths of $b_n$ correctors of a given order in IP1 & IP5 were scaled with the same factor while all other IT correctors were at ideal setting.
- $b_3$ correctors: Strong reduction of minimum and average DA at low corrector strengths. **Linear chromaticity has been preserved at +3.**
- $b_4$ correctors: Modest reduction of average DA at low corrector strengths.
- Minor impact of $b_5$ & $b_6$ correctors’ strength variation.
- A larger average DA at high corrector strengths is likely due to effects of non-linear field of the non-IP magnets (not accounted for in nominal corrector setting).

**Disclaimer:** correctors are for both beams. DA for Beam 2 should be checked too.
Impact of individual $a_n$ correctors

- Strengths of $a_n$ correctors of a given order in IP1 & IP5 were scaled with the same factor while all other IT correctors were at ideal setting.
- $a_4$ correctors: Modest reduction of minimum DA at low strength and of average DA at high strength. This indicates that the DA spread among 60 seeds is larger at lower strengths and smaller at higher strengths.
- Minor impact due to $a_3$, $a_5$, $a_6$ correctors’ strength variation.

Disclaimer: correctors are for both beams. DA for Beam 2 should be checked too
Combined effect of powering errors

• Simulate 10 different combinations of IT corrector strengths, where all the strengths are randomly and independently generated using uniform distribution within the strength scaling range from 0.7 to 1.3.
• Variation of minimum DA is within the range from -0.7 σ to +0.4 σ.
• Average DA is modestly reduced by < 0.3 σ.
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Attempt to correct D2 field quality

- It could be envisaged to use the non-linear correctors in the IT to compensate also for the field quality of the D2.

- Some considerations
  - Phase advance between IP and element (Beam 1/2 and IR1/5)

<table>
<thead>
<tr>
<th>Element</th>
<th>Round optics $\mu$ (deg)</th>
<th>Flat optics $\mu$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>89.7-90.2</td>
<td>89.4-91.2</td>
</tr>
<tr>
<td>D2</td>
<td>90.2-90.9</td>
<td>90.1-91.7</td>
</tr>
</tbody>
</table>

- D2 is a two-in-one magnet: a compensation of the field quality of D2 can be envisaged only for systematic multipoles ($b_3$ and $b_5$).

- To correct the two-in-one magnet with a single bore one, good correlation between the field quality of the two apertures is needed.
Preliminary results - I

- First attempt to correct the $b_3$ component of D2
- Strategy
  - Implement a correction of a fraction $f$ of the systematic $b_3$ component for Beam 1.
  - The number $f$ is used to represent the correlation between the field quality in the two apertures

Distributions of relative correctors’ strength:
- Orange: nominal correction
- Blue: including also $b_3$ in D2 with $f=1$

Strength is not an issue!
Preliminary results - II

Preliminary results of DA simulations with correction of $b_3$ in D2: only mild impact on Beam 2 ($DA_{\text{min}}$ and $DA_{\text{ave}}$). To be studied in further detail.
Outlook

Possible next steps

- Study further the correction of $b_3$ component of D2.
- Check the impact of correcting the $b_5$ systematic component of D2.
- Finalise the study of correction quality vs powering including also Beam 2.
- Devise alternative correction strategies.
- Implement in simulations the algorithm used/tested in MD studies (see Ewen’s presentation).
Thank you for your attention!