Impact of HL-LHC civil engineering work on the LHC: do we see it and what can we learn for HL-LHC

D. Gamba, M. Schaumann, R. Corsini


8th HL-LHC Collaboration Meeting – 18/10/2018
Outline

- Do we see it?
  - ...yes!
- Do we understand what we see?
  - Assumptions
  - Optics sensitivity LHC v.s. HL-LHC
  - Trying to quantify the amplitude of the effect we see
- What can we say about HL-LHC?
- Summary

References:
- M. Schaumann – Aug 2018 - LMC – link
- M. Schaumann – Aug 2018 - LBOC- link
- D. Gamba et al. – IPAC2018 link
- D. Gamba et al. – Jul 2017 - WP2 - link
- M. Fitterer et al. – Apr 2015 - WP15 - link
- Many other references available at this page
Main Events Overview (M. Schaumann)

Fill 6757 (4/06/2018)

- Same scales on all plots
- Fill 6757 higher excitation amplitude
  - stronger effect on beams
  - higher losses, deeper luminosity dips, higher vertical RMS orbit

Fill 6919 (13/07/2018)

From: Observation on HL-LHC CE vibration on the beam, M. Schaumann (link)
Optics sensitivity: assumptions

- Interested in frequencies \( f \) above a few Hz
  - Normally no spatial correlation
  - Not interested in strong single event, e.g. earthquakes, which can carry strong correlation
  - Motion normally not caught by present orbit feedback

- Assuming all perturbations induce simply a closed orbit variation
  - i.e. considering only \( f \ll f_{\text{rev}} \)

- Uncorrelated ground motion distributed along the whole machine with equal amplitude
  - main players are the triplets in IP1/5

- Beam/optics parameters
  - **LHC:** \( \varepsilon_N = 2 \, \mu m; 6.5 \, \text{TeV}; \beta^* = 30 \, \text{cm} \)
  - **HL-LHC:** \( \varepsilon_N = 2.5 \, \mu m; 7 \, \text{TeV}; \beta^* = 15 \, \text{cm} \)
Impact of quad misalignment on closed orbit

- Expected B1 closed orbit variation at IP5:

\[
\frac{\Delta x^*}{\sqrt{\beta^* \epsilon_g \Delta x_q}} = \frac{\sqrt{\beta_q (K1L)_q} \cos(2\pi \phi_q - \pi Q_x)}{\sqrt{\epsilon_g} 2 \sin(\pi Q_x)}
\]

- HL-LHC @15cm very similar to present LHC @30 cm
Possible beam observables

- **Luminosity**
  - Probably the most sensitive observable.

- **Beam intensity**
  - Very high dynamic range due to intensity variation along fill
  - More interesting to look at BLM-computed integrated losses
    - Very sensitive signal!

- **BPMs**
  - Position acquired at 25 Hz, but available only as mean over 1 s
    - Not suitable for vibrations of $f >$ a few Hz
  - The rms over 25Hz data is logged in Timber
    - Suitable to look at oscillations of a few Hz

- **DOROS BPMs**
  - Could acquire at much higher frequency, but also normally logging average over 1 s
  - Logging of spectra requested by Michaela, will happen soon

- **BBQ**
  - A lot of spectra, not amplitude calibrated.
  - Not very sensitive during standard operation

- **ADT**
  - Spectra being logged since a few months.
    - Rough amplitude calibration available
Luminosity [1]

\[ \mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi \sigma_x \sigma_y} W e^{\frac{B^2}{A}} SH \]

\[ W = e^{-\frac{1}{4\sigma_x^2} (d_2 - d_1)^2} \]

Reduction due to offset (e.g. horizontal -- x)

\[ A = \frac{\sin^2\left(\frac{\phi}{2}\right)}{\sigma_x^2} + \frac{\cos^2\left(\frac{\phi}{2}\right)}{\sigma_s^2} \]

\[ B = \frac{(d_2 - d_1) \sin\left(\frac{\phi}{2}\right)}{2\sigma_x^2} \]

\[ S = \frac{1}{\sqrt{1 + \left(\frac{\sigma_s}{\sigma_x} \tan\left(\frac{\phi}{2}\right)\right)^2}} \]

Reduction due to Hour Glass effect

\[ H = \sqrt{\pi} \frac{\beta^*}{\sigma_s} e^{-\left(\frac{\beta^*}{\sigma_s}\right)^2} \text{erfc}\left(\frac{\beta^*}{\sigma_s}\right) \]

For LHC: we can estimate that the effect of crossing angle variation is comparable to offset

For HL-LHC: in the limit of ideal full crabbing, is equivalent to head on collision, i.e. equivalence between crossing and separation plane

### Summary: impact on observables

**Luminosity loss [%]** \( W = e^{-\frac{1}{4\sigma^2} (d_2 - d_1)^2} \)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>10</th>
<th>~2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LHC</strong> Orbit sep. IP1/5 ([\sigma_{beam}])</td>
<td>0.2</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>HL-LHC</strong> Necessary quad. motion rms ([\mu m])</td>
<td>0.3</td>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>LHC</strong> rms orbit @TCP* ([\sigma_{beam}])</td>
<td>0.1</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>HL-LHC</strong></td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>LHC</strong> rms orbit @BPM* ([\mu m])</td>
<td>~50</td>
<td>~50</td>
<td>~240</td>
</tr>
<tr>
<td><strong>HL-LHC</strong></td>
<td>~240</td>
<td>~240</td>
<td>~120</td>
</tr>
</tbody>
</table>

- Numbers computed assuming **IP1/5 triplet only source** of perturbation.
  - Assuming both IP triplets oscillate by the same rms amplitude in one plane only.
  - If only one triplet oscillates => \( \sqrt{2} \) more quadrupole motion needed to give same effect.
- A reasonable threshold is **1% instantaneous luminosity loss**, which correspond to about **0.3 (LHC)** or **0.2 (HL-LHC)** \( \mu m \) triplets motion.
- An event causing **1% instantaneous luminosity loss** in **LHC** would cause a **2% luminosity loss** in **HL-LHC**

* Considering the most sensitive TCP/BPM/plane
Observables of ground motion

- **Geophones** are logging data since 2017
- Data logged into Timber in the form of PSD

  - 2018 run is the occasion to see perturbation on the beam due to ground motion
  - It could allow us to see if our expectations for HL-LHC are correct.
Integrated PSD: 2017 vs 2018 (P5)

- PSDs integrated over range of frequencies
  - Gives measured rms motion in that band

\[ \sigma^2(f_0 < f < f_1) = \int_{f_0}^{f_1} p(f) \, df \]

Possible to see **human activity** in band 3-10Hz and **above**
- Some **higher activity** (starting in **Oct. 2017** – not in the plot)
- **No obvious sign** of civil engineering works started in **May 2018**
Ground motion amplification

- The triplet quadrupole assembly can amplify (or damp) the ground motion:

  - **LHC:** measured on Q1 spare assembly in SM18 (M. Guinchard, Oct 2017, [link])
  - **HL-LHC:** simulated (1% damping) by D. Ramos and M. Martos
Integrated Amplified (LHC) PSD: 2017 vs 2018 (P5)

- PSD amplified and integrated \((f > 3\text{Hz})\)
  \[\sigma_{mag}^2(f_0 < f < f_1) = \int_{f_0}^{f_1} p(f)T^2(f)df\]

- The 20-40 Hz band is dominant
- 2017: relatively quiet, far from 1% lumi threshold
- 2018: some dangerous spikes

- About 1% luminosity loss expected
“Interesting” fills

- **Alarm system** set up by M. Guinchard and L.G. Scislo (EN-MME) on geophones to eventually stop the excavation works.

- Fills with beam that could have been affected by Ground Motion:
  - **Point 1**
    - 30/05/18: 13:00 -> fill 6741 (very small GM excitation)
    - 01/06/18: 08:00-13:00 -> fill 6749 -> considered
    - 10/09/18: 6:30-7:00 -> fill 7145 (very small GM excitation)
  - **Point 5**
    - 11/10/2017: around 8:00 fill 6291 (a few small spikes only)
    - 19/10/2017: around 8:00 -> fill 6308 -> considered
    - 20/10/2017: around 9:00 -> fill 6311 -> considered
    - 04/06/18: 08:11 -> Fill 6757 -> considered
    - 13/07/2018: Day -> Fill 6919 -> considered
    - 30/08/18: 5:50-13:20 -> Fill 7105 (very small GM excitation)
    - 03/09/18: 7:00 - 7:25 -> Fill 7122 -> considered
    - 04/09/18: 6:43 - 7:10 -> Fill 7124 (very small GM excitation)
Fill 6757 P1/P5 Amplified – LHC

Expected magnet motion: P1 PSD X

Expected magnet motion: P1 PSD Y

Expected magnet motion: P5 PSD Y

P1 - Vertical

P5 - Vertical
Fill 6757 impact on luminosity

- **Luminosity dips compatible with expectation** from ground motion measured, amplified, converted into orbit separation at IPs

- **ATLAS** much less sensitive to vertical ground motion generated next to CMS
Fill 6757 impact on orbit @BPMs

- **BPM** system logs data at 1 Hz, but it also provides the **rms** computed over 25 Hz data.

- **Vertical** rms orbit **compatible** with expectations

- It looks like we are **over-estimating** the horizontal motion
  - Possible discrepancy in the quadrupole transfer function?
Fill 6757 impact on orbit @ADT

- ADT data logged as spectra
- Integrating over band 3-100 Hz we get similar matching with expectation as for the BPMs
- Still “off” in horizontal
Fill 6757 impact on beam losses @TCP

- **Losses** of the order of a few $10^{-5}$ wrt beam intensity.
  - Difficult to translate losses into orbit variation at collimators
  - From ground motion, we would expect 20-30 um orbit jitter wrt to total aperture of TCP (2.7 mm H; 2 mm V)
    - If correct, losses compatible with over-population of tails wrt simple Gaussian
## Summary of observations

- Looking (by eye => very rough estimates) at different fills (see appendix)

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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>6308</td>
<td>&lt;0.1</td>
<td>0.2</td>
<td>&lt;0.1</td>
<td>0.1</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>6311</td>
<td>&lt;0.1</td>
<td>0.3</td>
<td>0.2</td>
<td>0.3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>6749</td>
<td>0.8</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>1</td>
<td>0.2</td>
<td>1.5</td>
</tr>
<tr>
<td>6757 (1)</td>
<td>&lt;0.1</td>
<td>0.6</td>
<td>0.5</td>
<td>0.5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>6757 (2)</td>
<td>&lt;0.1</td>
<td>0.4</td>
<td>0.4</td>
<td>0.3</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>7122</td>
<td>&lt;0.1</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

- Fill 6749 is the only affected by ground motion in P1, but is also the one “less predictable”: impact smaller than expected.
- Predictions on luminosity drops and orbit at BPMs well within a factor 2
- Prediction on orbit at ADT seems to be a factor 2 off
  - Information from this morning: factor 2 in the data published in Timber…
2018: LHC vs HL-LHC

- HL-LHC slightly more sensitive, but triplet more forgiving (on paper!)
- Very important to measure the transfer function of the new triplet quadrupoles:
  - A factor 2 would be enough to show ground motion into the beam
  - Plan to measure a main dipole in 2019, then the first quad prototype as soon as it is available.
Conclusions

- HL-LHC civil engineering showed up in LHC…
  - From July 2018, 11 days with multiple alarms linked to surface activity [M. Guinchard]
  - Events caused **luminosity dips** of the order of a few %, mainly at CMS.
    - Hardly noticeable for typical LHC operation

- The **ground motion sensors + transfer function measurements + optics simulation** allow to understand the observations

- **Actual LHC is very close to HL-LHC** in terms of optics sensitivity
  - Still, **main players remain the IP1/5 triplets.**
  - Estimated triplet transfer function seems to be a bit more forgiving than present triplet
    - Important to verify the transfer function estimate on actual hardware.

- Thanks for your attention and comments -
Appendix
From losses to orbit at TCP?!  

**Parameters Vertical plane**

**CONSTRAINS** →
- Double Gaussian: $l_1 > l_2$ and $\sigma_1 < \sigma_2$
- Lévy Student: $n > 2$

### B1

<table>
<thead>
<tr>
<th>DATA ACQUISITION</th>
<th>SCRAPING</th>
<th>MODEL</th>
<th>DOUBLE GAUSSIAN</th>
<th>LEVY STUDENT</th>
<th>DOUBLE GAUSSIAN MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>30/07/2018</td>
<td>FULL</td>
<td></td>
<td>$l_1$</td>
<td>$l_2$</td>
<td>$\sigma_1$ $\sigma_2$</td>
</tr>
<tr>
<td></td>
<td>FULL</td>
<td></td>
<td>0,69</td>
<td>0,3</td>
<td>0,6</td>
</tr>
<tr>
<td></td>
<td>FULL</td>
<td></td>
<td>0,73</td>
<td>0,26</td>
<td>0,58</td>
</tr>
<tr>
<td></td>
<td>FULL</td>
<td></td>
<td>0,54</td>
<td>0,45</td>
<td>0,11</td>
</tr>
</tbody>
</table>

### B2

<table>
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<th>DOUBLE GAUSSIAN</th>
<th>LEVY STUDENT</th>
<th>DOUBLE GAUSSIAN MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>30/07/2018</td>
<td>FULL</td>
<td></td>
<td>$l_1$</td>
<td>$l_2$</td>
<td>$\sigma_1$ $\sigma_2$</td>
</tr>
<tr>
<td></td>
<td>FULL</td>
<td></td>
<td>0,79</td>
<td>0,2</td>
<td>0,62</td>
</tr>
<tr>
<td></td>
<td>FULL</td>
<td></td>
<td>0,57</td>
<td>0,42</td>
<td>0,5</td>
</tr>
<tr>
<td></td>
<td>FULL</td>
<td></td>
<td>0,77</td>
<td>0,22</td>
<td>0,14</td>
</tr>
</tbody>
</table>

**From:** *Review of halo measurements at LHC with collimator scans, P. Racano*([link](#))
From losses to orbit at TCP?!

Beam tails reconstruction (2017)

- The regular LHC beam tails profile (left) consistent for the measurements in 2016/2017
- In general, there is **visible tail over population** especially for the HL-LHC like bunches (right)
- Profiles in the plots for the **emittance of 2um**

From: *Results of the beam diffusion measurements in the LHC at 6.5TeV*, A. Gorzawski ([link](#))
GM and Beam Spectrum Evolution

Fill 6757 (June)

Geophone

Fill 6919 (July)

From: Observation on HL-LHC CE vibration on the beam, M. Schaumann (link)
Beam Separation at IP1/5 due to Quadrupole Offset

Vertical offset of triplet in IP5 introduces a larger orbit effect in the IP5 compared to IP1 and vice versa.

Assumption:
30cm optics, 2um emittance

Horizontal offset of triplet in IP1/5 introduces a similar orbit effect in the both IPs.

From: Observation on HL-LHC CE vibration on the beam, M. Schaumann (link)
Note: correlated IR motion

Impact of a wave propagating along the local IR1 or remote IR5 on IP1 orbit separation: amplification factor as a function of $\lambda$

- Typical wave speed measured in the CERN tunnels:
  - 990 m/s (shear); 2200 m/s (pressure)
  - $f$ below a few Hz (most likely $f$ to be correlated) have “small” amplification factor w.r.t. fully uncorrelated case.

From 119th WP2 meeting (link) - sqrt(2) factor missing everywhere
Impact on Tune

- Impact of the orbit induced by 1 um offset of each triplet (P5) element on Tune – **LHC case**
Detailed appendix
Optics sensitivity tables and plots
Optics sensitivity tables

- Amplification factors from magnet motion to IP orbit separation

<table>
<thead>
<tr>
<th></th>
<th>IP1 (\sigma^*_{\text{beam}/\mu m})</th>
<th>IP5 (\sigma^*_{\text{beam}/\mu m})</th>
<th>IP2 (\sigma^*_{\text{beam}/\mu m})</th>
<th>IP8 (\sigma^*_{\text{beam}/\mu m})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\Delta x)</td>
<td>(\Delta y)</td>
<td>(\Delta x)</td>
<td>(\Delta y)</td>
</tr>
<tr>
<td>LHC all quads</td>
<td>0.783</td>
<td>0.616</td>
<td>0.771</td>
<td>0.621</td>
</tr>
<tr>
<td>LHC IR1/5 only</td>
<td>0.754</td>
<td>0.587</td>
<td>0.753</td>
<td>0.587</td>
</tr>
<tr>
<td>LHC IR5 only</td>
<td>0.506 \textbf{0.180}</td>
<td>0.559</td>
<td>0.559</td>
<td>0.041</td>
</tr>
<tr>
<td>HL-LHC all quads</td>
<td>1.054 \textbf{1.063}</td>
<td>1.051</td>
<td>1.059</td>
<td>0.392</td>
</tr>
<tr>
<td>HL-LHC IR1/5 only</td>
<td>1.028 \textbf{1.033}</td>
<td>1.029</td>
<td>1.031</td>
<td>0.309</td>
</tr>
<tr>
<td>HL-LHC IR5 only</td>
<td>0.755</td>
<td>0.762</td>
<td>0.696</td>
<td>0.697</td>
</tr>
</tbody>
</table>

- If we consider only one triplet we should get a \(\sqrt{2}\) smaller impact, with the exception of the vertical plane in LHC where the “remote” impact is smaller.

\(\sqrt{2}\) bigger than WRONG values presented at early WP2 meetings (link)
## Optics sensitivity tables

- Amplification factors from magnet motion to IP half/crossing variation

<table>
<thead>
<tr>
<th></th>
<th>IP1 [µrad/µm]</th>
<th>IP5 [µrad/µm]</th>
<th>IP2 [µrad/µm]</th>
<th>IP8 [µrad/µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Δθ_x/2</td>
<td>Δθ_y/2</td>
<td>Δθ_x/2</td>
<td>Δθ_y/2</td>
</tr>
<tr>
<td><strong>LHC all quads</strong></td>
<td>9.09</td>
<td>10.98</td>
<td>8.73</td>
<td>11.45</td>
</tr>
<tr>
<td><strong>LHC IR1/5 only</strong></td>
<td>8.38</td>
<td>10.67</td>
<td>8.38</td>
<td>10.68</td>
</tr>
<tr>
<td><strong>LHC IR5 only</strong></td>
<td>6.04</td>
<td>9.19</td>
<td>5.81</td>
<td>5.42</td>
</tr>
<tr>
<td><strong>HL-LHC all quads</strong></td>
<td>14.46</td>
<td>13.15</td>
<td>13.99</td>
<td>13.11</td>
</tr>
<tr>
<td><strong>HL-LHC IR1/5 only</strong></td>
<td>13.43</td>
<td>12.50</td>
<td>13.34</td>
<td>12.61</td>
</tr>
<tr>
<td><strong>HL-LHC IR5 only</strong></td>
<td>7.51</td>
<td>6.97</td>
<td>11.11</td>
<td>10.39</td>
</tr>
</tbody>
</table>

Impact on angle is preferentially local

IR1/5 triplets **not** main source
### Optics sensitivity tables

- Impact at **primary collimators** (max rms orbit at any TCP)

<table>
<thead>
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</thead>
<tbody>
<tr>
<td></td>
<td>Δx</td>
<td>Δy</td>
<td>Δx</td>
<td>Δy</td>
</tr>
<tr>
<td>LHC all quads</td>
<td>0.432</td>
<td>0.384</td>
<td>93</td>
<td>60</td>
</tr>
<tr>
<td>LHC IR1/5 only</td>
<td>0.386</td>
<td>0.343</td>
<td>83</td>
<td>53</td>
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<tr>
<td>LHC IR5 only</td>
<td>0.243</td>
<td>0.323</td>
<td>52</td>
<td>51</td>
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<tr>
<td>HL-LHC all quads</td>
<td>0.519</td>
<td>0.492</td>
<td>120</td>
<td>84</td>
</tr>
<tr>
<td>HL-LHC IR1/5 only</td>
<td>0.476</td>
<td>0.449</td>
<td>110</td>
<td>77</td>
</tr>
<tr>
<td>HL-LHC IR5 only</td>
<td>0.274</td>
<td>0.327</td>
<td>63</td>
<td>56</td>
</tr>
</tbody>
</table>

Single triplet has “same” impact than both triplets… => asymmetry
Optics sensitivity tables (LHC only)

- Impact at “arc” BPMs (most sensitive BPM location in parenthesis)

<table>
<thead>
<tr>
<th></th>
<th>B1 [µm/µm]</th>
<th>B2 [µm/µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Δx (BPM)</td>
<td>Δy (BPM)</td>
</tr>
<tr>
<td>LHC all quads</td>
<td>122 (6L7)</td>
<td>198 (5R5)</td>
</tr>
<tr>
<td>LHC IR1/5 only</td>
<td>111 (6L7)</td>
<td>181 (5R5)</td>
</tr>
<tr>
<td>LHC IR5 only</td>
<td>78 (11R7)</td>
<td>140 (5R1)</td>
</tr>
<tr>
<td></td>
<td>72 (6L7)</td>
<td>92 (5R5)</td>
</tr>
</tbody>
</table>

- Impact at Q1 IP1/5 BPMs (most sensitive location in parenthesis)

<table>
<thead>
<tr>
<th></th>
<th>B1 [µm/µm]</th>
<th>B2 [µm/µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Δx</td>
<td>Δy</td>
</tr>
<tr>
<td>LHC all quads</td>
<td>183 (1L5)</td>
<td>287 (1R1)</td>
</tr>
<tr>
<td>LHC IR1/5 only</td>
<td>150 (1L5)</td>
<td>256 (1R1)</td>
</tr>
<tr>
<td>LHC IR5 only</td>
<td>129 (1L5)</td>
<td>226 (1R1)</td>
</tr>
<tr>
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</table>
Optics sensitivity tables (LHC only)

- Impact at ADT pickup (pickup location in parenthesis)

<table>
<thead>
<tr>
<th></th>
<th>B1 [µm/µm]</th>
<th>B2 [µm/µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Δx (7L4)</td>
<td>Δy (7R4)</td>
</tr>
<tr>
<td><strong>LHC all quads</strong></td>
<td>45</td>
<td>69</td>
</tr>
<tr>
<td><strong>LHC IR1/5 only</strong></td>
<td>37</td>
<td>61</td>
</tr>
<tr>
<td><strong>LHC IR5 only</strong></td>
<td>23</td>
<td>57</td>
</tr>
</tbody>
</table>
Impact of quad misalignment on closed orbit

- Expected B1 closed orbit variation at IP5:

\[
\frac{\Delta x^*}{\sqrt{\beta^* \epsilon_g \Delta x_q}} = \frac{\sqrt{\beta_q} (K1L)_q \cos(2\pi \phi_{q^*} - \pi Q_x)}{\sqrt{\epsilon_g}} \cdot \frac{1}{2 \sin(\pi Q_x)}
\]

- HL-LHC @15cm very similar to present LHC @30 cm

![Graph showing impact of quad misalignment on closed orbit]
Impact of quad misalignment on closed orbit

- Expected B1 closed orbit (angle) variation at IP5:

\[
\frac{\Delta p_x^*}{\Delta x_q} = -\frac{(K1L)_q}{2 \sin(\pi Q_x)} \sqrt{\frac{\beta_q}{\beta^*}} \left[ \sin\left(2\pi \phi_{q^*} - \pi Q_x\right) + \alpha^* \cos\left(2\pi \phi_{q^*} - \pi Q_x\right) \right]
\]

- HL-LHC up to x2 more sensitivity to than LHC to be expected
LHC: impact of misalignments on \( \Delta x \)
LHC: impact of misalignments on $\Delta x'$
LHC: impact of misalignments on $\Delta y$
LHC: impact of misalignments on $\Delta y'$
Luminosity
Luminosity [1]

\[ \mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi \sigma_x \sigma_y} W e^{\frac{B^2}{A}} S H \]

- **W** = \( e^{-\frac{1}{4\sigma_x^2}(d_2-d_1)^2} \)
- **A** = \( \frac{\sin^2(\frac{\phi}{2})}{\sigma_x^2} + \frac{\cos^2(\frac{\phi}{2})}{\sigma_s^2} \)
- **B** = \( \frac{(d_2-d_1)\sin(\frac{\phi}{2})}{2\sigma_x^2} \)
- **S** = \( \frac{1}{\sqrt{1 + \left(\frac{\sigma_s}{\sigma_x} \tan(\frac{\phi}{2})\right)^2}} \)
- **H** = \( \sqrt{\pi} \frac{\beta^*}{\sigma_s} e^{\left(\frac{\beta^*}{\sigma_s}\right)^2} \text{erfc} \left(\frac{\beta^*}{\sigma_s}\right) \)

1. Reduction due to offset (e.g. horizontal -- x)
2. Reduction due to offset AND angle in the same (e.g. horizontal -- x) plane
3. Reduction due to crossing angle
4. Reduction due to Hour Glass effect

Instantaneous* luminosity reduction - offset

\[ W = e^{-\frac{1}{4\sigma_x^2} (d_2 - d_1)^2} \]

\[ \langle W \rangle = \frac{\sqrt{2}}{\sqrt{\sigma_d^2 / \sigma_b^2 + 2}} \]

Factor due to “static” orbit separation \((d_2 - d_1)\)

Factor due to “dynamic” orbit separation \(\sigma_d\)
i.e. assuming beam separation is oscillating around zero.

\[ \langle W \rangle \]

\[ \sigma_{\text{sep}} / \sigma_{\text{beam}} \]

\[ \sigma_s / \sigma_b \]

\[ \Rightarrow \text{Static} \approx \text{dynamic for small amplitudes} \]

* Instantaneous compared to LHC fill, integrated compared to revolution frequency
### Luminosity reduction factors

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Norm. Emit. [um]</td>
<td>3.75</td>
<td>2</td>
<td>2.5</td>
</tr>
<tr>
<td>Energy TeV</td>
<td>7</td>
<td>6.5</td>
<td>7</td>
</tr>
<tr>
<td>Bunch length rms [cm]</td>
<td>7.55</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Beta* [m]</td>
<td>0.55</td>
<td>0.3 to 0.25</td>
<td>0.64 to 0.15</td>
</tr>
<tr>
<td>Half Cros. angle [urad]</td>
<td>142.5</td>
<td>150 to 130</td>
<td>250 (0 with full CC)</td>
</tr>
<tr>
<td>S (crossing)</td>
<td>0.84</td>
<td>0.57 to 0.59</td>
<td>0.55 to 0.30 (1 with full CC)</td>
</tr>
<tr>
<td>H (hour glass)</td>
<td>0.99</td>
<td>0.95 to 0.95</td>
<td>0.99 to 0.88</td>
</tr>
</tbody>
</table>

- **Note:** in **HL-LHC** with **full crabbing** it would be as **head-on collision**.
  - In reality we will have 60 [urad] residual half crossing angle.

Luminosity reduction factors - imperfections

- Case of LHC ($\varepsilon_N = 2 \mu m; 6.5$ TeV; $\beta^* = 30$ cm)

\[ \sigma_x = 9.3 [\mu m]; \sigma_s = 9.0 [cm]; \]

- Assuming similar impact on orbit and half cros. angle, i.e.:
  \[ \sim 0.1 \sigma_x \approx 1 \mu m \approx 1 \mu rad \]

- **Crossing plane** dominated by angle variation
  - can increase inst. luminosity
  - on average, no luminosity loss in case of oscillation
  - **valid for small $\Delta\theta/2$,** otherwise the separation contribution becomes relevant...

- **Separation plane** dominated by orbit separation
  - Basically unaffected by residual $\Delta\theta/2$
Luminosity reduction factors - imperfections

NOTE:

- The impact of each 1 um displacement of each triplet element on total crossing angle variation is of the order of 4 urad in LHC and 8 urad in HL-LHC

- The impact on total orbit separation is of the order of 2 um for both LHC and HL-LHC
Luminosity with offset in crossing plane

LHC – no CC

HL-LHC – full CC

Nominal

With offset @IP

Offset @IP
Luminosity with offset in crossing plane

LHC – no CC

HL-LHC – full CC

Nominal

With offset @IP
Luminosity with offset in crossing plane

B2

B1

IP

Nominal

With offset @IP

LHC – no CC

HL-LHC – full CC
Luminosity with offset in crossing plane

LHC – no CC

HL-LHC – full CC
Luminosity with offset in crossing plane

LHC – no CC

HL-LHC – full CC
Ground motion sensors
Ground motion observations in LHC

- Geophones are logging data since 2017
- Data logged into Timber in the form of PSD

- 2018 run is the occasion to see perturbation on the beam due to ground motion
- It could allow us to see if our expectations for HL-LHC are correct.
Integrated PSD: 2017 vs 2018 (P5)

- PSDs integrated over range of frequencies
  - Gives measured rms motion in that band

\[
\sigma^2(f_0 < f < f_1) = \int_{f_0}^{f_1} p(f) \, df
\]

- Possible to see **human activity** in band 3-10Hz and above
- Some **higher activity** starting in **Oct. 2017**
- **No obvious sign** of civil engineering works started in **May 2018**
2018 P5

Ground motion: P5 PSD X

Ground motion: P5 PSD Y

Ground motion: P5 PSD Z
Triplet amplification
Amplification of LHC Q1 assembly

- Measured on Q1 spare assembly in SM18 in preparation of civil engineering works
  - See for example M. Guinchard, Oct 2017, link

- Only “valid” for $f > 3$ Hz
  - Response below 3 Hz is unknown.
  - Most likely flat close to 1
Amplification of HL-LHC triplet quadrupole

- Simplified model by D. Ramos and M. Martos.
- Strongly depends on dumping factor assumed in the model. Here a “pessimistic” 1% dumping.
  - To be crosschecked with measurement on a LHC dipole (mechanically very similar to new triplets) and on first prototype.
Assumed amplification functions

- **LHC**: measured on Q1 spare assembly in SM18 (M. Guinchard, Oct 2017, [link](#))
- **HL-LHC**: simulated by **D. Ramos** and **M. Martos**

- All computed as mean over different point measured/simulated.
Ground motion in 2018 – LHC vs HL-LHC
2018 P1/P5 Amplified - LHC

Expected magnet motion: P1 PSD X

Expected magnet motion: P1 PSD Y

Expected magnet motion: P5 PSD X

Expected magnet motion: P5 PSD Y
2018 P1/P5 Amplified – HL-LHC

Expected magnet motion: P1 PSD X

Expected magnet motion: P1 PSD Y

Expected magnet motion: P5 PSD X

Expected magnet motion: P5 PSD Y
Fills analysis
Fill 6308
Fill 6308 (t ≈ 8) impact on luminosity
Fill 6308 ($t \approx 8$) impact on orbit @BPMs
Fill 6308 \((t \approx 8)\) impact on orbit @TCP
Fill 6311
Fill 6311 \((t \approx 6)\) impact on luminosity
Fill 6311 \((t \approx 6)\) impact on orbit @BPMs
Fill 6311 ($t \approx 6$) impact on orbit @TCP
Fill 6749
Fill 6749 (P1) ($t \approx 13$) impact on luminosity
Fill 6749 \((t \approx 13)\) impact on orbit @BPMs
Fill 6749 \((t \approx 10)\) impact on orbit @TCP
Fill 6757 (1)
Fill 6757 P1/P5 Amplified – LHC
Fill 6757 (t ≈ 10) impact on luminosity
Fill 6757 \( (t \approx 10) \) impact on orbit @BPMs
Fill 6757 \((t \approx 10)\) impact on orbit @TCP
Fill 6757 (2)
Fill 6757 \((t \approx 13)\) impact on luminosity
Fill 6757 ($t \approx 13$) impact on orbit @BPMs
Fill 6757 \((t \approx 10)\) impact on orbit @TCP
Fill 6919 ($t \approx 6$) impact on luminosity
Fill 6919 (t ≈ 6) impact on orbit @BPMs
Fill 6919 \( (t \approx 6) \) impact on orbit @TCP
Fill 7122
Fill 7122 \((t \approx 7)\) impact on luminosity
Fill 7122 \((t \approx 7)\) impact on orbit @BPMs/ADT
Fill 7122 \((t \approx 7)\) impact on orbit @TCP