Status of vibration studies

D. Gamba, R. Corsini, L. Wroe


119th HiLumi WP2 Meeting – 17/04/2018
Outline

- Recap on effects we are looking for
- Comparison of LHC and HL-LHC using analytical formula
  - Impact on IP orbit separation
  - Impact on orbit at collimators
- A look at data collected from geophones
  - Estimate impact on beam quantities

Note:
- Most of the content summarised in IPAC2018 paper (THPAF040)
- Topic already presented a few times, e.g.:
  - M.Fitterer et al. – April 2015 link
  - D.Gamba et al. – Jul 2017 link
- Many other references available on my page
Frequency regimes

- $f < \approx 1$ Hz:
  - slow orbit drifts;
  - reduction of available orbit corrector strength;
  - frequent machine re-alignments;

- $1 < f < \text{a few 100 Hz}$:
  - closed orbit jitter;
  - beam intensity and luminosity losses;

- $f > \text{a few 100 Hz}$:
  - emittance growth;
  - increase in tail’s population;
  - beam lifetime reduction.

Regime we are looking at

Particularly dangerous are the betatron motion sidebands:

- $f_{\text{rev}} \approx 11.2$ kHz; $Q \approx 0.31$
- $\Rightarrow$ first dangerous $f \approx 3.5$ kHz

See also “What we know on the LHC limits”, M. Fitterer, et al., Apr 2015, link
Questions (not covered here):

- Is it true that at low frequency we don’t have emittance growth?
    - Some possible intensity loss and/or emittance growth.
    - Results difficult to interpret
      - Might require some further studies

- Can we estimate the impact of high frequency ground motion on emittance?
  - See 118th WP2 meeting – X. Buffat (link)
    - No spectrum available above 1000 Hz.
    - ATL law predicts $1/f^4$ decay -> impact should be small. TBC
Impact of quad misalignment on closed orbit

- Expected B1 closed orbit variation at IP5:
  \[
  \frac{\Delta x_{IP}}{\sqrt{\beta^* \epsilon_g \Delta x_q}} = \frac{\sqrt{\beta_q(K1L)_q \cos(2\pi \phi_q - \pi Q_x)}}{\epsilon_g \sin^n(\pi Q)}
  \]

- HL-LHC up to \textbf{x2 more sensitivity} to errors than LHC to be expected
Looking at the whole machine: impact on IP1

- Horizontal B1-B2 separation at IP1
Looking at the whole machine: impact on IP1

- Vertical B1-B2 separation at IP1
Looking at the whole machine: impact on IP

- Summing up in quadrature all contributions
  - Assuming each element is moving independently, randomly, same amplitude

<table>
<thead>
<tr>
<th></th>
<th>IP1 [σ*_{beam/mm}]</th>
<th>IP5 [σ*_{beam/mm}]</th>
<th>IP2 [σ*_{beam/mm}]</th>
<th>IP8 [σ*_{beam/mm}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC all quads</td>
<td>Δx 360, Δy 274</td>
<td>Δx 360, Δy 375</td>
<td>Δx 175, Δy 177</td>
<td>Δx 176, Δy 185</td>
</tr>
<tr>
<td>LHC IR1/5 only</td>
<td>Δx 353, Δy 264</td>
<td>Δx 354, Δy 294</td>
<td>Δx 82, Δy 75</td>
<td>Δx 49, Δy 72</td>
</tr>
<tr>
<td>HL-LHC all quads</td>
<td>Δx 721, Δy 758</td>
<td>Δx 719, Δy 755</td>
<td>Δx 269, Δy 367</td>
<td>Δx 341, Δy 592</td>
</tr>
<tr>
<td>HL-LHC IR1/5 only</td>
<td>Δx 703, Δy 736</td>
<td>Δx 704, Δy 735</td>
<td>Δx 211, Δy 331</td>
<td>Δx 235, Δy 550</td>
</tr>
</tbody>
</table>

- Résumé:
  - HL-LHC about a factor 2 more sensitive than LHC.
  - Impact of IR1/5 is dominant
    - They might also become dominant for IP2/8
  - Biggest degradation (w.r.t. LHC) is in IP8 Vertical
Note1: cold mass modal shapes mode

- Previous values obtained assuming rigid, lateral displacement of each quadrupole.
- Ground motion is more likely to excite proper oscillation mode of the cold mass. e.g. Vertical Modes (See: M. Guinchard, 29/05/2017 link)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>23.5 Hz</td>
</tr>
<tr>
<td>2nd</td>
<td>65.9 Hz</td>
</tr>
</tbody>
</table>
Note1: Simulated quadrupole modes
Note1: Comparison different modes

- 0.1mm maximum offset of the quadrupole in all triplets
- Lower order oscillations that with large antisymmetry over the central axis have dominant effect
Note2: 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.
Looking at the whole machine: @ collimators

- **Max B1 horizontal orbit at any primary collimator**

Same result as for IP orbit separation: HL-LHC about x2 more sensitive than LHC
Looking at the whole machine: @ collimators

- **Max B1** vertical orbit at **any primary collimator**

![Graph showing vertical orbit at any primary collimator](image-url)
Looking at the whole machine: @ collimators

- Summing up in quadrature all contributions
  - Assuming each element is moving independently, randomly, same amplitude

<table>
<thead>
<tr>
<th></th>
<th>B1 ([\sigma_{beam/mm})]</th>
<th>B2 ([\sigma_{beam/mm})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta x)</td>
<td>(\Delta y)</td>
<td>(\Delta x)</td>
</tr>
<tr>
<td>LHC all quads</td>
<td>205</td>
<td>207</td>
</tr>
<tr>
<td>LHC IR1/5 only</td>
<td>179</td>
<td>187</td>
</tr>
<tr>
<td>HL-LHC all quads</td>
<td>393</td>
<td>454</td>
</tr>
<tr>
<td>HL-LHC IR1/5 only</td>
<td>367</td>
<td>425</td>
</tr>
</tbody>
</table>

- Résumé (same result as for IP orbit separation)
  - HL-LHC about a factor 2 more sensitive than LHC also at collimators.
Ground motion measurements

- Sensors are logging data since last year

"Ground vibration monitoring at CERN as part of the international seismic network", C. Charrondiere, et al., 2018, [link]
Typical PSD logged in Timber

\[ p(f) = \lim_{T \to \infty} \frac{1}{T} \left| \int_{-T/2}^{T/2} x(t) e^{-i\omega t} \, dt \right|^2 \]

- From a first view, very similar spectra in all places, directions.
Integrated PSD along the year (1/5/17 – 1/12/17)

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

- Surface less noisy @high f
- Most of the noise “energy” at low frequency (f< ~1 Hz)
  - Assumed to be correctable by orbit feedback.
- Low frequency part “correlated” between different points.
  - If “really” correlated motion, amplification factor optics -> beam much lower than uncorrelated estimate.
- High frequency part shows day/night/weekend beating
  - Note that different type of sensors are used on surface and in the tunnel [link]
Integrated PSD during a fill (6399 – 20/11/2017)

- Considering typical a whole fill PSD at P1
- Considering amplification factor of cold mass (See [link](#))
  - Direct multiplication on PSD
  - Conservative estimate!
- Integration of PSD for \( f > f_0 \)

![Graph showing integrated PSD during a fill](image-url)
Impact on measurable beam parameters

- Considering all ground motion for $f > 3$ Hz, with Q1 amplification applied to all magnets $\Rightarrow 0.04 \mu m$ r.m.s.
- Assuming limit value imposed for HL-LHC excavation work during 2018 LHC operation ($< 1 \mu m$ r.m.s. M. Fitterer, M. guinchard)

<table>
<thead>
<tr>
<th>$\sigma_{\text{magnetic axis}} [\mu m]$</th>
<th>0.04</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>HL-LHC</td>
<td>LHC</td>
</tr>
<tr>
<td>Orbit sep. IP1/5 [$\sigma_{\text{beam}}$]</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>Luminosity loss [%] $W = e^{-\frac{1}{4\sigma_{\text{beam}}^2}(d_2-d_1)^2}$</td>
<td>$&lt;0.1$</td>
<td>$&lt;0.1$</td>
</tr>
<tr>
<td>Max orbit @TCP [$\sigma_{\text{beam}}$]</td>
<td>0.01</td>
<td>0.02</td>
</tr>
</tbody>
</table>

- No visible effect on LHC today, but it might be possible to see something during HL-LHC excavation works
  - Motion of the order of 1 $\mu m$ would be unacceptable for HL-LHC!
Looking at some other signal

- Most signal are logged at low frequency (about every 1 s)
  - E.g. Luminosity or orbit at standard pickup (e.g. collimators)
  - Orbit variation at collimators during a fill up to 20 μm (0.03 \( \sigma_{beam} \))

One sample every hour extracted from Timber
Looking at some other signal

- Looking at ADT data (once every hour since 1\textsuperscript{st} November)

Difficult to see any correlation
Comparing spectra during stable beams

- Work ongoing by M. Schaumann ([link](#)) – also interested in earthquakes
Conclusions

- Analytical formula applied on whole ring confirms previous results:
  - IR1/5 triplet misalignments are the main sources of orbit perturbation
  - HL-LHC about x2 more sensitive than LHC
- Uncorrelated motion seems a good approximation
  - Correlated motion would be “dangerous” at high frequencies
    - In contrast with observation where motion more likely to be correlated at low frequencies.
  - Below a few Hz the correlation would lead to local compensation of orbit kicks.
- No observable effect on the beam today (in normal conditions)
  - Compatible with a (still) conservative estimate starting from geophone observation
  - A signal might come up during excavation works for HL-LHC
- HL-LHC estimation are based on the assumption that
  - HL-LHC triplet quadrupoles will behave similarly to the LHC Q1
    - See next presentation
  - Ground motion amplitude will not change in HL-LHC era
- TODO: keep an eye on 2018 geophone and beam data.

--- Thanks for your comments ---
## Modes EDMS #347269

### Table 1 – Lateral modes of SSS5, with and without transport restraints

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal shape</th>
<th>Frequency (Hz)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Without restraints</td>
<td>With restraints</td>
<td></td>
</tr>
<tr>
<td>Lateral 1</td>
<td><img src="image" alt="Lateral 1" /></td>
<td>7</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Lateral 2</td>
<td><img src="image" alt="Lateral 2" /></td>
<td>12</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Lateral 3</td>
<td><img src="image" alt="Lateral 3" /></td>
<td>14</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Lateral 4</td>
<td><img src="image" alt="Lateral 4" /></td>
<td>29</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Lateral 5</td>
<td><img src="image" alt="Lateral 5" /></td>
<td>40</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Lateral 6</td>
<td><img src="image" alt="Lateral 6" /></td>
<td>46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral 7</td>
<td><img src="image" alt="Lateral 7" /></td>
<td>54</td>
<td>55</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2 – Vertical modes of SSS5, with and without transport restraints

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modal shape</th>
<th>Frequency (Hz)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Without restraints</td>
<td>With restraints</td>
<td></td>
</tr>
<tr>
<td>Vertical 1</td>
<td><img src="image" alt="Vertical 1" /></td>
<td>22</td>
<td>22-23</td>
<td></td>
</tr>
<tr>
<td>Vertical 2</td>
<td><img src="image" alt="Vertical 2" /></td>
<td>27</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Vertical 3</td>
<td><img src="image" alt="Vertical 3" /></td>
<td>42</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>Vertical 4</td>
<td><img src="image" alt="Vertical 4" /></td>
<td>/</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>Vertical 5</td>
<td><img src="image" alt="Vertical 5" /></td>
<td>53</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>Vertical 6</td>
<td><img src="image" alt="Vertical 6" /></td>
<td>/</td>
<td>57</td>
<td></td>
</tr>
</tbody>
</table>
Definitions

- **PSD:**
  \[
  p(f) = \lim_{T \to \infty} \frac{1}{T} \left| \int_{-T/2}^{T/2} x(t)e^{-i\omega t} \, dt \right|^2
  \]
  Can be integrated to obtain variance of the signal:
  \[
  \sigma^2 = \int_{-\infty}^{+\infty} p(f) \, df
  \]
  \[
  \sigma^2(f_0 < f < f_1) = \int_{f_0}^{f_1} p(f) \, df
  \]

- **FFT:**
  \[
  \hat{x}(f) = \int_{-\infty}^{+\infty} x(t)e^{-i\omega t} \, dt
  \]
  If computed on a small sample of \( n \) points on period \( T \):
  \[
  c_n = \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} x(t) \, e^{-2\pi i (\frac{n}{T}) t} \, dt
  \]
Amplification of Q1 assembly

- Measured on Q1 spare assembly in SM18
  - See for example M. Guinchard, Oct 2017, link
- Only “valid” for $f > 3$ Hz
  - Response below 3 Hz is unknown