Latest on noise effect on the beam

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Thanks to HL-LHC WP2 and WP6

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OUTLOOK

- Motivation
- What we see in LHC beams
- Simulation benchmarking in LHC
- Prediction for HL-LHC
- Conclusions
Introduction

GOAL
- estimate if/when the noise from the power converters impact the HL-LHC beam performance

METHOD
- analyze the effect of the power converter noise in LHC
- build a general framework for simulations and benchmark against LHC observations
- make predictions for HL-LHC

WORKING FOCUS
- We will address the dipolar and quadrupolar noise.
Introduction

1. Dipolar modulation
   largest impact close to the tune

2. Quadrupolar modulation
   possible large impact even at frequencies far away from the tune

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**Graphs**

**Left Graph**
- 5D, $E = 7$ TeV, $l_{oct} = -300$ A, $\varepsilon_n = 2.5$ $\mu$m rad, $\beta' = 15$ cm, $Q' = 15$
- $(Q_x, Q_y) = (62.31, 60.32)$, $\delta p/p = 25.78 \times 10^{-5}$, 49 angles
- $0.1 - 6.1 \sigma$, $f_r = 3500$ Hz, $A_t = 1.00 \times 10^{-6}$ $\mu$rad at PU Q7

**Right Graph**
- 5D, $E = 7$ TeV, $l_{oct} = -300$ A, $\varepsilon_n = 2.5$ $\mu$m rad, $\beta' = 15$ cm, $Q' = 15$
- $(Q_x, Q_y) = (62.31, 60.32)$, $\delta p/p = 25.78 \times 10^{-5}$, 49 angles
- $0.1 - 6.1 \sigma$, $f_r = 300$ Hz, $\Delta Q = 4.39 \times 10^{-11}$

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**Legend**
- **Main**
- **Sideband**

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**3.5 kHz**
- 3500 Hz

**300 Hz**
- 300 Hz
Observations in LHC beam spectrum

- In the LHC we see only dipolar oscillations.
- Those tones are dominated by 50 Hz harmonics. Visible in several instruments (BBQ, MIM, DOROS, ADTObsBox).
- ADTObsBox will be our privileged system (bbb, calibrated metric, sensitivity).

![Graph showing FFT measures for LHC beam spectrum with low and high frequency clusters highlighted.](image)
Clear correlation between the 50 Hz harmonics.
Are these tones an artefact? No.

- The phase difference between 2 close-by BPMs (Q7 and Q9) for a given tone corresponds to the betatronic phase advance between Q7-Q9.
Are these tones an artefact? No.

- Changing the tune there is a visible impact on the spectrum.
Which beam? which plane?

- B1 more excited than B2.
- H-plane more than V-plane (→ main bends).
- High frequency cluster (surprisingly) strong.
Impact of the main bends power supplies

- For **lower frequencies**, effect of the Sector Dipoles Active filters.
- → main dipoles are clearly a contributors.
What is the equivalent kick?

- As reference, a single kick of $\theta = 1e-11 \text{ rad}$ at $\beta = 100 \text{ m}$ gives oscillation in the order of $1e-3 \sigma$ (as observed).
- $1e-11 \text{ rad}$ has to be compared with the kick of the main bend ($\sim 5 \text{ mrad}$)
- It would be equivalent to $2e-9$ stability of one single MB at a frequency $1e-3$ apart from the tune.
Is the picture beam mode dependent? Mildly.
Does the damper enter in the game? Yes.

- Beam spectrum could be further attenuated by the damper.
- Reducing the damper affect 50 Hz harmonics.
Does the damper enter in the game? Yes.

- Beam spectrum could be further attenuated by the damper.
- Reducing the damper affect 50 Hz harmonics.
The measured beam spectrum is below the single bunch spectrum (input for the damper).
What is the source of the 8 kHz oscillations?

- A 8 kHz oscillation is expected to be significantly attenuated by the vacuum chamber.
What is the source of the 8 kHz oscillations?

- **Still not clear**: the present hypothesis is that it could be related first unstable mode of the resistive wall coupled-bunch instability (frev-Q). See [1-3].

- Following this hypothesis the 8 kHz cluster of tones is an interplay between noise from the main bends circuit, impedance (resistive wall) and damper.

- **Multi-bunch simulations** with noise, impedance, damper are still needed to verify it.

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Simulating the effect of the observed spectrum

- FMA without noise in LHC (reference)

5D, $E = 6.5$ TeV, $I_{\text{oct}} = 550$ A, $\epsilon_n = 2$ $\mu$m rad, $N_{b0} = 1.25e11$, $\beta^* = 30$ cm, $\text{xing} = 160$ $\mu$rad, $Q' = 15$

$(Q_x, Q_y) = (62.31, 60.32)$, $\delta p/p = 23.12 \times 10^{-5}$, 99 angles, 0.1 – 6.1 $\sigma$
Simulating the effect of the observed spectrum

Considering
“Low frequency cluster”
Lumped in the ADT PU Q7
Simulating the effect of the observed spectrum

Considering “High frequency cluster” Lumped in the ADT PU Q7
Simulating the effect of the observed spectrum

“Low frequency cluster” +

“High frequency cluster”

5D, $E = 6.5 \text{ TeV}$, $I_{\text{oct}} = 550 \text{ A}$, $\epsilon_{\text{in}} = 2 \mu \text{m rad}$, $N_{\text{h}} = 1.25 \times 10^7$, $\beta^* = 30 \text{ cm}$, $\text{xing} = 160 \mu \text{rad}$, $Q' = 15$

$(Q_x, Q_y) = (62.31, 60.32)$, $\delta p/p = 23.12 \times 10^{-5}$, 99 angles, $0.1 - 6.1 \sigma$
MD with controlled excitation and DA

- During 2018, MD were performed and a **qualitative agreement** was found between observation and simulation.
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Projections for dipolar perturbations in HL-LHC

- FMA without noise in HL-LHC (reference)

5D, $E = 7$ TeV, $I_{oct} = -300$ A, $\epsilon_n = 2.5$ µm rad, $N_{b0} = 1.2e11$, $\beta^* = 15$ cm, $x_{ing} = 250$ µrad, $Q' = 15$ ($Q_x, Q_y) = (62.315, 60.320)$, $\delta p/p = 27 \times 10^{-5}$, 99 angles, $0.1 - 6.1 \sigma$
Projections for dipolar perturbations in HL-LHC

Considering “Low frequency cluster” Lumped in the ADT PU Q7

5D, $E = 7$ TeV, $I_{oct} = -300 \, A$, $\varepsilon_\theta = 2.5 \, \mu m \ \text{rad}$, $N_{360} = 1.2e11$, $\beta^* = 15 \, \text{cm}$, $\text{xing} = 250 \, \mu\text{rad}$, $Q' = 15$ $(Q_x, Q_y) = (62.315, 60.320)$, $\delta p/p = 27 \times 10^{-5}$, 99 angles, $0.1 - 6.1 \, \sigma$
Projections for dipolar perturbations in HL-LHC

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Projections for dipolar perturbations in HL-LHC

“Low frequency cluster” + “High frequency cluster”

5D, $E=7 \text{ TeV}$, $L_{\text{oct}}=-300 \text{ A}, \varepsilon_n=2.5 \text{ µm rad}$, $N_{b0}=1.2e11$, $\beta^*=15 \text{ cm}$, $x_{\text{ing}}=250 \text{ µrad}$, $Q'=15$ $(Q_x, Q_y)=(62.315, 60.320)$, $\delta_{p/p}=27x10^{-5}$, 99 angles, $0.1 - 6.1 \sigma$
Assuming a lumped dipolar perturbation in the ADT PU in Q7.

Simulations shows that 0.1 µm level of excitation can degrade the machine DA.
From dipolar to quadrupolar noise: the Inner Triplet simulations for HL-LHC
Inner Triplet: Voltage-control regime

- Based on previous studies [4], scan individual frequencies for different strengths in order to determine where reduction of DA is observed.
- Compare with PC specifications [5].

Approximations:
- Impact from beam screen, cold bore not included.
- Inductance considered constant vs f.
- Impact from individual frequencies, not multiple harmonics.

Simulation parameters

<table>
<thead>
<tr>
<th>HLLHC.v13</th>
<th>7 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>εn=2.5 μm rad</td>
<td>I=1.2e11</td>
</tr>
<tr>
<td>I=-300 A</td>
<td>θcrossing=250 μrad</td>
</tr>
<tr>
<td>(Qx, Qy)=(62.31,60.32)</td>
<td>VRF = 16 MV</td>
</tr>
<tr>
<td></td>
<td>Δp/p=25.78e-5</td>
</tr>
</tbody>
</table>

V [dBµV]

Inner Triplet: DA studies

7 TeV, $I_{\text{QCT}}=-300$ A, $\epsilon_n = 2.5$ μm rad, $(Q_x, Q_y)=(62.31, 60.32)$, $Q_p = 15$, $I=1.2e11$, $\beta^* = 15$ cm, Noise IT right and left of IP1 & IP5

- Frequency scan as a function of $\Delta Q$ with ripples in all circuits of IP1 & IP5. Each point is an individual study.
- Conservative approach: same phase of noise in all locations. Switching frequency of the 18 kA circuit will be at 50-200 kHz.
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7 TeV, I_{oct}=-300 A, \varepsilon_n = 2.5 \mu m rad, (Q_x, Q_y) = (62.31, 60.32), Q_p = 15, I=1.2e11, \beta^* = 15 cm.

- Frequency scan as a function of \Delta Q with ripples in all circuits of IP1 & IP5. Each point is an individual study.
- Conservative approach: same phase of noise in all locations. Switching frequency of the 18 kA circuit will be at 50-200 kHz.
Conclusions

- **Dipolar excitation:**
  - Harmonics of 50 Hz have been observed in the beam spectrum. 2 regimes have been identified: the low (up to 3.6 kHz) and high (7-8 kHz) frequency cluster.
  - Both regimes are the result of a real beam excitation. A correlation of the 8 power converters of the Main Bends and the low frequency cluster has been identified (larger impact on B1H). The high frequency cluster is not affected by the status of the Active Filters: the present hypothesis is that is due to an interplay between noise, damper and impedance (first unstable couple bunch mode at 8 kHz).
  - Simulations in the LHC with a realistic beam spectrum (lumped dipolar perturbation in a single location) indicate that these harmonics lead to an increase of diffusion and can harm the beam lifetime.
  - These harmonics will also be present in the HL-LHC and, assuming the same noise spectrum, the impact on DA is significant, especially due to the high frequency cluster.

- **Quadrupolar excitation (Inner Triplet):**
  - Maximum output voltage is below the level where reduction of DA is expected.
  - Switching frequencies are expected to be heavily attenuated and do not pose a limitation to the beam performance.
Thank you!
Backup
Coupling of H/V plane in simulation

- Vertical motion observed in simulations.
Are these tones an artefact? No.

- For **lower frequencies** (<4 kHz) impact of the IP1/IP5 phase advance.
Harmonics of 50 Hz

B1H, Injection

Simulations
### Appendix

<table>
<thead>
<tr>
<th>Q1/Q2a/Q2b/Q3</th>
<th>RTQX3.L1</th>
<th>RTQX3.R1</th>
</tr>
</thead>
<tbody>
<tr>
<td>L [mH]</td>
<td>I_{rated} [kA]</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Q1/Q2a/Q2b/Q3</td>
<td>255</td>
<td>18</td>
</tr>
<tr>
<td>Trim Q1</td>
<td>69</td>
<td>2</td>
</tr>
<tr>
<td>Trim Q1a</td>
<td>34.5</td>
<td>0.035</td>
</tr>
<tr>
<td>Trim Q3</td>
<td>69</td>
<td>2</td>
</tr>
</tbody>
</table>

\[
\frac{\Delta Q}{\Delta I/I_{\text{rated}}} = \begin{cases} 
\frac{dI(f)}{I_{\text{nom}}} \\
T_{\text{Vacuum}}(f) \times T_{V_{\text{toB}}}(f) \\
\frac{dV(f)}{2\pi f L_{DC} I_{\text{nom}}} 
\end{cases}
\]

for \( f \leq f_0 \)

for \( f > f_0 \)

with: \( T_{V_{\text{toB}}}(f) = T''_{V_{\text{toB}}}(f) \times \)
Are these tones an artefact? No.

- The phase difference between 2 close-by BPMs (Q7 and Q9) for a given tone corresponds to the betatronic phase advance between Q7-Q9.