Impedance model of the LHC: summary of the present understanding of the measurements


WP2 meeting – 10.03.2020
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➢ Coupled bunch instability rise time
➢ Single bunch instability rise time
➢ Single bunch real tune shift
  - Contribution of individual collimators
➢ Intrabunch motion
➢ Summary
Experimental data available*

- Couple bunch instability rise time
  - 450 GeV and 3.5 TeV, 50ns, $Q' \sim 0$, $G=0$
- Single bunch instability rise time
  - 450 GeV, $-30 < Q' < -5$, $G = 0$
  - 3.5 TeV, $Q' \sim 2$, $G = 0.1$
  - 6.5 TeV, $Q' \sim 15$, $G = 0.005$, 0.01
- Single bunch real tune shift
  - 450 GeV, 3.5 TeV, $Q' \sim 0$
  - 4 TeV, $Q' \sim 5$
  - 6.5 TeV, $Q' \sim 2$ and 5

* Detailed list of references in appendix
The rise time of the most unstable coupled bunch mode (Q’~0, G=0) mostly depends on the real impedance of the beam screen around 8kHz.
No strong discrepancy (less than a factor 2) could be highlighted at injection with 48 bunch trains of bunches spaced by 50 ns

- The ADT was switched off
Coupled bunch instability rise time – 3.5 TeV

➢ With the same beam (48b, 50ns, G=0), coupled bunch instabilities were about twice as fast as expected at top energy.
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- A difference between injection and flat top could indicate an additional unexpected contribution of the collimators or of the magneto-resistivity of the beam screen at low frequency.
Coupled bunch instability rise time – 3.5 TeV

➢ With the same beam (48b, 50ns, G=0), coupled bunch instabilities were about twice as fast as expected at top energy
  ➢ A difference between injection and flat top could indicate an additional unexpected contribution of the collimators or of the magneto-resistivity of the beam screen at low frequency.
➢ Yet, the accuracy of the flat top measurement is rather low due to:
  ➢ The large uncertainty on the chromaticity (e.g. uncompensated feed-down from the octupoles)
  ➢ The fact that the beams were stable without octupoles at flat top indicates the presence of another source of Landau damping (lattice NL, $Q''$)
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→ A confirmation using new tools (long ADTObsBox buffers) and experience (control of linear coupling, lattice NL and feed-down) would be needed
Single bunch instability rise time with a negative chromaticity
Single bunch instability rise time with a negative chromaticity

- At low chromaticity, the rise time is dominated by the contribution of the real part of the beam screen impedance
  - For high negative chromaticities, the collimator impedance dominates
Most measurements are compatible with an impedance between 1 to 2 times the model. Unfortunately the accuracy of the measurement is rather limited.

- Only 2h were dedicated to this measurement (including setup)
- First measurements at low chromaticities were affected by a residual ADT gain
- The signal quality with a high chromaticity was low and would have required more setup time
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→ Large potential for improvement
Single bunch rise time in operational conditions

- Depending on the damper gain, mode 1 or 2 are the most unstable when operating with $Q' \sim 15$
  - Both are dominated by the collimator impedance at top energy
Instabilities are mostly slower than expected (based on the linear model) due to Landau damping.
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- Measurements taken close to the instability threshold seem most accurate
Single bunch instability rise time – 6.5 TeV

TCSG Impedance MD 2016. Expectation w/o Landau damping: 6s

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- The unstable mode type follows the expectations

Complex tune shift MD (2018): ADT switched off at end of fill

Expectation w/o Landau damping

G ~ 0.005
G = 0
Single bunch instability rise time – 6.5 TeV

Instabilities are mostly slower than expected (based on the linear model) due to Landau damping
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Automated analysis of ADT activity monitor data over several fills showed an average compatible with DELPHI predictions

Complex tune shift MD (2018): ADT switched off at end of fill

End of squeeze 2017 (parasitic to physics)
The issue with rise time measurement

- Similarly to octupole threshold measurements, the rise time measurements suffers from the uncertainty on Landau damping (i.e. knowledge of the emittance, tail distribution and non-linearities).

  → At flat top an experimental procedure that circumvents fully this issue was not found yet, as the octupoles are needed during the ramp and they can not be switched off fast enough.

2010 measurement: 9.8s
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The total tune shift at injection was not re-measured in Run 2
Over the years the total real tune shift at flat top was measured about 1.5 times higher than modelled.
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The discrepancy was slightly reduced in Run 2 w.r.t. Run 1, which may be attributed to:

- The refinement of the impedance model
- Improvement of the measurement technique
Total single bunch real tune shift – 6.5 TeV

In COMBI, a multiplication of the wake by a factor 1.5 was needed to reproduce the measured shift in B1H during a BTF measurement.

→ Slightly higher than measured with kicks (1.3)
Thanks to the possibility to perform multiple kicks with collimators moving in and out, their contribution can be singled out with much higher precision than global quantities.

The contribution of the TCSGs is closest to prediction in 2018:

- The refinement of the impedance model
- Improvement of the measurement technique
Single bunch real tune shift – Individual collimators

The variability of the measurement was greatly reduced since the first measurements in 2016 thanks to

- Experience with machine and beam setup (minimising decoherence while maintaining the beam stability)
- Usage of multiple low amplitude kicks avoiding scraping and contributions from amplitude detuning
- Fast cycling of the collimator position to average out the machine tune jitter
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- The tune shift was measured significantly higher in 2018
  → Irradiation ? misalignment ?
Single bunch real tune shift – Individual collimators, B1

Horizontal

Vertical
Single bunch real tune shift – Individual collimators, B1

Measurements affected by intensity losses with too large kicks
Single bunch real tune shift – Individual collimators, B1

The TCPs were measured together in 2012 and yielded 1.1 times the predictions (V only)

→ Compatible with 2016 data

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- A significant degradation of the TCP.C6L7 is observed between 2016 and 2018
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- Some collimators (including one TCP) induced a tune shift more than twice the expected one
  - A significant degradation of the TCP.C6L7 is observed between 2016 and 2018
- The total tune shift might be affected by few collimators exhibiting a larger impedance
  → Non-conformities ?
  → Incomplete model ?
  → Impact of the orbit ?
The TCPs were measured together in 2012 and yielded 1.8 times the predictions (V only)

→ The incompatibility with 2016 measurements may be attributed to the measurement technique
Summary – Real impedance

➢ The coupled bunch instability rise times observed at 3.5 TeV could indicate an unknown source of impedance at low frequency but should be confirmed profiting from the new tools and experience
  – The agreement obtained at injection suggest a good modelling of the beam screen impedance at low frequency
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  → More investment (in MD time) is needed to improve the uncertainty
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➢ Single bunch instability rise time measurements at flat top are usually affected by Landau damping. The corresponding uncertainty usually shades the contribution from the impedance
Summary – Imaginary impedance

- Currently the real tune shift is the most accurate beam-based measurement of the impedance available.
- Total real tune shifts are in the order of 1.5 times larger than expected.
- The tune shift induced by individual collimators ranges from a perfect agreement with the model to 3 times larger. The cause for these differences is not known and should be further investigated.

<table>
<thead>
<tr>
<th>Year</th>
<th>Measurement</th>
<th>B1H</th>
<th>B1V</th>
<th>B2H</th>
<th>B2V</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>Tune shift vs. IR7 secondary collimators gaps$^1$</td>
<td>1.3</td>
<td>1.4</td>
<td>1.1</td>
<td>1.4</td>
</tr>
<tr>
<td>2017</td>
<td>Tune shift vs. bunch intensity$^2$</td>
<td>1.2</td>
<td>1.4</td>
<td>1.3</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>Tune-shift vs. bunch intensity$^3$</td>
<td>1.4</td>
<td>1.6</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>2018</td>
<td>Full machine tune shift at flat-top$^4$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Growth-rate vs. negative chromaticity</td>
<td>1.4</td>
<td>1.6</td>
<td>1.4</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Detailed references

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  - D. Amorim, PhD Thesis and D. Amorin, et al. HSC meeting 04.03.2019
A 100 μm orbit offset might increase impedance by 10-20%