What do we understand on the emittance growth?

F. Antoniou, I. Efthymiopoulos, M. Hostettler, G. Iadarola, N. Karastathis, S. Kostoglou, S. Papadopoulou, Y. Papaphilippou, G. Trad

Special thanks to: G. Arduini, X. Buffat and T. Persson

9th LHC Operations Evian Workshop
31/01/2019
LHC Luminosity follow-up

Motivation
Understanding of the LHC emittance evolution for the overall optimisation of the operation conditions and the maximization of the delivered luminosity to the experiments

LHC Emittance Preservation WG → link: LHCEmittancePreservationWG
HSI LHC-lumi internal meetings → link: HSILumiMeetings

2015
Development of a luminosity model including contributions from IBS, SR and burn-off (MATLAB)
F. Antoniou, Y. Papaphilippou

2016
Luminosity modelling in Python, development of LHC follow-up scripts based on the tools developed for acquiring beam parameters data from the LHC systems (PyCOMPLETE)
F. Antoniou, G. Iadarola, Y. Papaphilippou

2017
Development of a self-complete, version-controlled, automated framework (Python2+BASH) to download LHC systems data, perform the offline analysis and prepare follow-up and sum. plots
N. Karastathis, Y. Papaphilippou

2018
Further development of the luminosity model, including additional mechanisms (coupling, noise, etc). Construction of preliminary web-page → link: LumimodWebPage
I. Efthymiopoulos, N. Karastathis, S. Papadopoulou, Y. Papaphilippou
● Run 2 emittances (BCMS) along the LHC cycle

● Luminosity model
  · Model description
  · At FB, extra emittance growth (on top of the model)
  · At SB, luminosity evolution prediction and extra emittance growth (on top of the model)

● Cumulated integrated luminosity

● Summary
2018 emittances along the cycle

Average emittance values [μm]

<table>
<thead>
<tr>
<th></th>
<th>B1H</th>
<th>B1V</th>
<th>B2H</th>
<th>B2V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection</td>
<td>1.4</td>
<td>1.3</td>
<td>1.4</td>
<td>1.4</td>
</tr>
</tbody>
</table>
2018 emittances along the cycle

Relative emittance blow-up [%]

- B1H: 15
- B1V: 14
- B2H: 14
- B2V: 12

Average emittance values [\(\mu\text{m}\)]

<table>
<thead>
<tr>
<th></th>
<th>B1H</th>
<th>B1V</th>
<th>B2H</th>
<th>B2V</th>
</tr>
</thead>
<tbody>
<tr>
<td>start Ramp</td>
<td>1.6</td>
<td>1.5</td>
<td>1.6</td>
<td>1.5</td>
</tr>
</tbody>
</table>
2018 emittances along the cycle

Average emittance values [μm]

<table>
<thead>
<tr>
<th></th>
<th>B1H</th>
<th>B1V</th>
<th>B2H</th>
<th>B2V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection</td>
<td>1.4</td>
<td>1.3</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>start Ramp</td>
<td>1.6</td>
<td>1.5</td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Stable Beams</td>
<td>2.0</td>
<td>1.7</td>
<td>1.5</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Unphysical B2H emittance at start of SB (smaller than at FB), according to BI this is within the 20% accuracy of BSRT. It improves after last BSRT calibration (Fill 7220)
BSRT calibration Fill results

BSRT calibration Fill 7220
Comparison of convoluted emittances from Emittance Scans and WS with Luminosity

- Agreement of Emittance Scans with the ones from Luminosity is 5-20%
- Emittances from WS up to 10-15% lower than the Luminosity ones

Revealing discrepancy between BSRT (calibrated against WS) and emittance from Luminosity → understanding this difference is important
Convoluted emittances at start of SB

Emittances from Luminosity agree within 10-15% with the ones from Emittance Scans and BSRT (see appendix)
Convoluted emittances at start of SB

Considering only Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%.

<table>
<thead>
<tr>
<th>Average emittance values [(\mu m)]</th>
<th>Relative emittance blow-up [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable Beams</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Emittances from Luminosity agree within 10-15% with the ones from Emittance Scans and BSRT (see appendix).
Run2 emittances along the cycle

2018 emittances along the LHC energy cycle are smaller compared to previous years.

Relative emittance growth from Inj. to start of Ramp

Relative emittance growth from start of Ramp to SB
Luminosity model description

Bunch-by-bunch modeling of three main mechanisms:

- Intrabeam scattering (IBS)
- Synchrotron radiation (SR)
- Luminosity burn-off

-\( \beta^* \), luminosity leveling, x-ing angle anti-leveling options

-in 2018, coupling of transverse emittances included, small impact (see appendix)

-sensitive to initial conditions (emittances, intensities, etc)
Bunch-by-bunch modeling of three main mechanisms:

- Intrabeam scattering (IBS)
- Synchrotron radiation (SR)
- Luminosity burn-of

-\(\beta^*\), luminosity leveling, x-ing angle anti-leveling options

-in 2018, coupling of transverse emittances included, small impact (see appendix)

-sensitive to initial conditions (emittances, intensities, etc)

The model can be applied under different assumptions by using data evolution as:

<table>
<thead>
<tr>
<th></th>
<th>Pure model</th>
<th>Extra losses</th>
<th>Extra emit. growth</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emittance</td>
<td>model</td>
<td>model</td>
<td>data</td>
<td>data</td>
</tr>
<tr>
<td>Intensity</td>
<td>model</td>
<td>data</td>
<td>model</td>
<td>data</td>
</tr>
</tbody>
</table>
Extra emittance growth at FB

Measured-Model emittance difference over time at FB vs bunch slot, for a Fill $d\varepsilon/dt \rightarrow$ extra emittance growth on top of IBS

Fill 7035
Extra emittance growth at FB

Measured-Model emittance difference over time at FB vs bunch slot, for a Fill
\( \frac{d\varepsilon}{dt} \rightarrow \text{extra emittance growth on top of IBS} \)

Assuming that the first bunches of a train experience no e-cloud, the \( \frac{d\varepsilon}{dt} \) of the 2nd bunch of 10 trains (3rd to 12th) gives the extra emittance growth on top of IBS and e-cloud.
Extra emittance growth at FB

- Extra growth **on top of IBS** smaller in horizontal than in the vertical.
- In vertical, where IBS growth is minor, the observed blow up beyond the model is $\sim 0.6\mu m/h$

---

**Measured-Model emit. difference over time at FB for all 2018 Fills**

<table>
<thead>
<tr>
<th>extra growth [$\mu m/h$]</th>
<th>B1H</th>
<th>B1V</th>
<th>B2H</th>
<th>B2V</th>
</tr>
</thead>
<tbody>
<tr>
<td>on top of IBS (all bunches)</td>
<td>0.34</td>
<td>0.64</td>
<td>0.41</td>
<td>0.61</td>
</tr>
</tbody>
</table>
Extra emittance growth at FB

• Extra growth on top of IBS smaller in horizontal than in the vertical.
• In vertical, where IBS growth is minor, the observed blow up beyond the model is ~0.6\(\mu\)m/h
• The contribution of e-cloud to the emittance growth is ~0.2 \(\mu\)m/h
• The rest of the extra emittance growth at FB is 0.2 \(\mu\)m/h in horizontal and 0.4 \(\mu\)m/h in vertical
• Ongoing studies to correlate this extra growth with noise estimations

Measured-Model emit. difference over time at FB for all 2018 Fills

<table>
<thead>
<tr>
<th>extra growth [(\mu)m/h]</th>
<th>B1H</th>
<th>B1V</th>
<th>B2H</th>
<th>B2V</th>
</tr>
</thead>
<tbody>
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<td>0.34</td>
<td>0.64</td>
<td>0.41</td>
<td>0.61</td>
</tr>
<tr>
<td>(all bunches)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>on top of IBS&amp;e-cloud</td>
<td>0.24</td>
<td>0.44</td>
<td>0.17</td>
<td>0.41</td>
</tr>
<tr>
<td>(2\text{nd} bunches of trains)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fill 7334 (one of the Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%)

Following the intensity evolution from data
Luminosity evolution prediction

Fill 7334 (one of the Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%)

Following the intensity evolution from data and the emittance from model
Luminosity evolution prediction

Fill 7334 (one of the Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%)

Following the intensity evolution from data and the emittance from model understanding the impact of the extra emittance blow up on the luminosity degradation.

Model → the luminosity expected in case there is no extra emit. growth (on top of the model)
Extra emittance growth at SB

Measured (BSRT)-Model emit. difference after 5h at SB vs Fill number
d\(\varepsilon/dt\) → extra emittance growth on top of IBS

(Taking into account only Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%)

<table>
<thead>
<tr>
<th></th>
<th>B1H</th>
<th>B1V</th>
<th>B2H</th>
<th>B2V</th>
</tr>
</thead>
<tbody>
<tr>
<td>extra</td>
<td>0.02</td>
<td>0.07</td>
<td>0.02</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Not constant extra growth along a fill in horizontal
Extra emittance growth at SB

Measured (BSRT)-Model emit. difference after 5h at SB vs Fill number
\( \frac{d\varepsilon}{dt} \rightarrow \text{extra emittance growth on top of IBS} \)

(Taking into account only Fills for which the convoluted emittances at start of SB from Luminosity and BSRT differ less than 10%)

<table>
<thead>
<tr>
<th>Fill Number</th>
<th>B1H</th>
<th>B1V</th>
<th>B2H</th>
<th>B2V</th>
</tr>
</thead>
<tbody>
<tr>
<td>extra</td>
<td>0.02</td>
<td>0.07</td>
<td>0.02</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Not constant extra growth along a fill in horizontal

In 2017, the extra emittance growth at SB was around 0.05\(\mu\text{m}/h\) and 0.1\(\mu\text{m}/h\) in the horizontal and the vertical plane, respectively

These values are close to what is observed as emittance growth from noise at SB (X. Buffat)
Cumulated integrated Luminosity

2018 Luminosity degradation due to mechanisms that are beyond the luminosity model

(only for 2018 Fills for which the BSRT can be trusted)

<table>
<thead>
<tr>
<th></th>
<th>Pure model</th>
<th>Extra losses</th>
<th>Extra emit. growth</th>
<th>Calculated</th>
</tr>
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<tbody>
<tr>
<td>Emittance</td>
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<td>model</td>
<td>data</td>
<td>data</td>
</tr>
<tr>
<td>Intensity</td>
<td>model</td>
<td>data</td>
<td>model</td>
<td>data</td>
</tr>
</tbody>
</table>
2018 Luminosity degradation due to mechanisms that are beyond the luminosity model

-5% -11% -22% -16%
-1% -10% -11% -12%

2018 BSRT emittances lower by ~10% than the luminosity ones → explains difference between measured (by the experiments) and calculated luminosity
Summary

- Performance followed up with **automated tools** through the whole run → giving feedback to MCs and guiding BSRT calibration

- In 2018, the comparison of WS and Emit. scans with Luminosity emittances during a BSRT calibration Fill, explains the **discrepancy observed between the different measurements** along the year → understanding this discrepancy is important

- The 2018 **emittances along the cycle** are smaller compared to previous years

- For both FB and FT energies, the observed **extra emittance growth (on top of the model)**:
  - is similar for both beams, larger in the vertical compared to the horizontal plane
  - at FB, e-cloud explains almost 50% of the observed extra growth. Impact of e-cloud to the observed extra growth at SB to be studied
  - the “unknown” extra emittance growth at FB is 0.2 μm/h in horizontal and 0.4 μm/h in vertical. Ongoing studies to correlate this extra growth with noise, which also predicts more growth in vertical at SB (see appendix)
  - no clear correlation with brightness (see appendix)

- Extra emittance blow up plays an important role in the degradation of the **cumulated integrated luminosity**. Extra losses have a smaller impact. In 2018 the impact of the extra losses is larger compared to 2017 (see Sofia’s talk)
Thank you!
extra slides
### Cumulated integrated luminosity

#### 2017

<table>
<thead>
<tr>
<th>Fill Number</th>
<th>0.0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pure Model</td>
<td>Extra losses</td>
<td>Extra emit. blow up</td>
<td>Calculated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emittance</td>
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<td>data</td>
<td>data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intensity</td>
<td>model</td>
<td>data</td>
<td>model</td>
<td>data</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Lumi-BSRT convoluted emit. agreement

Convoluted Emittance ratio (Luminosity)/(Emit. Scans), at start of SB

Convoluted Emittance ratio (Luminosity)/(BSRT)

Convolution Emittance at start of SB

Fill number

BSRT calibr.

TS

Luminosity @ startSB

Luminosity @ endSB

BSRT @ startSB

BSRT @ endSB
Run2 emittances along the energy cycle

2016: $t_{FB} = 42$, $t_{Ramp} = 57$ [min] and INJ intensity [1e11]: $B1 = 1.082$, $B2 = 1.065$

2017: $t_{FB} = 37$, $t_{Ramp} = 39$ [min] and INJ intensity [1e11]: $B1 = 1.115$, $B2 = 1.116$

2018: $t_{FB} = 33$, $t_{Ramp} = 42$ [min] and INJ intensity [1e11]: $B1 = 1.104$, $B2 = 1.100$
Emittance growth at FB

<table>
<thead>
<tr>
<th>B1H</th>
<th>B1V</th>
<th>B2H</th>
<th>B2V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>0.76</td>
<td>0.68</td>
<td>0.75</td>
</tr>
<tr>
<td>Model</td>
<td>0.31</td>
<td>$10^{-3}$</td>
<td>0.28</td>
</tr>
</tbody>
</table>

**Measured-Model difference**

| Extra growth | 0.45 | 0.68 | 0.47 | 0.61 |

on top of IBS
Measured-Model emittance difference over time at FB of all bunches of 10 trains vs Fill number

\( \frac{d\varepsilon}{dt} \rightarrow \text{extra emittance growth on top of IBS} \)

### B1 extra emit. blow up of all bunches of 10 trains @ FB

<table>
<thead>
<tr>
<th>Fill Number</th>
<th>H</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0.34±0.21</td>
<td>0.64±0.26</td>
</tr>
<tr>
<td>B2</td>
<td>0.41±0.31</td>
<td>0.61±0.25</td>
</tr>
</tbody>
</table>

### B2 extra emit. blow up of the 2nd bunch of 10 trains @ FB

<table>
<thead>
<tr>
<th>Fill Number</th>
<th>H</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0.45±0.16</td>
<td>0.68±0.17</td>
</tr>
<tr>
<td>B2</td>
<td>0.47±0.17</td>
<td>0.61±0.16</td>
</tr>
</tbody>
</table>
Extra emittance growth at FB

Measured-Model emit. difference over time at FB of the 2nd bunch of 10 trains vs Fill number
d\epsilon/dt \rightarrow \text{extra emittance growth on top of IBS and e-cloud}

B1 extra emit. blow up of the 2nd bunch of 10 trains @ FB

B2 extra emit. blow up of the 2nd bunch of 10 trains @ FB

<table>
<thead>
<tr>
<th>(Measured-Model emit.)/time_{FB} [\mu m/h]</th>
<th>B1H</th>
<th>B1V</th>
<th>B2H</th>
<th>B2V</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd bunches of trains</td>
<td>0.24</td>
<td>0.44</td>
<td>0.17</td>
<td>0.41</td>
</tr>
</tbody>
</table>
Including coupling in luminosity model

The transverse emittances, are coupled according to:

\[
\varepsilon_x = \varepsilon_{x0} - \left( \varepsilon_{x0} - \varepsilon_{y0} \right) \frac{|C|^2 / 2}{\Delta^2 + |C|^2}
\]

\[
\varepsilon_y = \varepsilon_{y0} + \left( \varepsilon_{x0} - \varepsilon_{y0} \right) \frac{|C|^2 / 2}{\Delta^2 + |C|^2}
\]

G. Guignard, CERN ISR-BOM/77-43, 1977

Resonance crossing

\[
\varepsilon_x = \varepsilon_{x0} - \left( \varepsilon_{x0} - \varepsilon_{y0} \right) \frac{|C|^2 / 2}{\Delta^2 + |C|^2 + \Delta \sqrt{\Delta^2 + |C|^2}}
\]

\[
\varepsilon_y = \varepsilon_{y0} + \left( \varepsilon_{x0} - \varepsilon_{y0} \right) \frac{|C|^2 / 2}{\Delta^2 + |C|^2 + \Delta \sqrt{\Delta^2 + |C|^2}}
\]


Including coupling in Luminosity model → for a coupling coefficient C=0.001 and an unperturbed tune-split \(\Delta_{FB}=0.025, \Delta_{FT}=0.01\)

Thanks to T. Persson
Including coupling in luminosity model

Including coupling in Luminosity model → for a coupling coefficient $C=0.001$ and an unperturbed tune-split $\Delta_{FB}=0.025$, $\Delta_{FT}=0.01$

Since in our FollowUp we use only the injected emittance and the emittance at the end of FB, we assume that C is constant and that it is 0.0015 at the FB end → The difference of coupling and no coupling in terms of emittance growth is +/-1e-3 mm/h

FB energy

FT energy

By including coupling in the luminosity model the vertical emittances of the model approach better the measured ones. Also, the estimation of the pure model luminosity agrees slightly better with the measured one.
Input beam parameters:
- an emit. at start of SB of 2.3um for both planes and beams and a bunch length of 1.1ns=0.0824m
- a betastar that is 30 cm
- a xing of 2*160urad
- a GainSB=0.025

- This values are close to what we observe as extra emit. growth at SB.
- The noise growth at SB is larger in the vertical plane. The extra growth (on top of IBS and ecloud) at FB is also larger in vertical.

Thanks to X. Buffat
Emittance growth due to noise at FB

Using the FB beam parameters, the extra emittance growth at FB and the $\delta_0$ values from the noise MD

Input beam parameters:
- an injected emit. of ~1.35um
- a GainFB=0.1
- $\Delta Q_{FB} = 0.025$, for estimations including ecloud

<table>
<thead>
<tr>
<th></th>
<th>$\delta_0$ hb1</th>
<th>$\delta_{BPM}$ hb1</th>
<th>$\delta_0$ vb1</th>
<th>$\delta_{BPM}$ vb1</th>
<th>$\delta_0$ hb2</th>
<th>$\delta_{BPM}$ hb2</th>
<th>$\delta_0$ vb2</th>
<th>$\delta_{BPM}$ vb2</th>
</tr>
</thead>
<tbody>
<tr>
<td>HB1</td>
<td>3.8e-5</td>
<td>66e-5</td>
<td>5.3e-5</td>
<td>93e-5</td>
<td>4.4e-5</td>
<td>71e-5</td>
<td>5.6e-5</td>
<td>89e-5</td>
</tr>
<tr>
<td>VB1</td>
<td></td>
<td></td>
<td>5.3e-5</td>
<td></td>
<td>4.4e-5</td>
<td></td>
<td>5.6e-5</td>
<td></td>
</tr>
</tbody>
</table>

The estimations for the noise emittance growth at FB are ~3 times lower than the observed extra emittance blow up (on top of IBS)

Thanks to X. Buffat
Measured emittance growth vs INJ brightness at FB, for B1

Measured emittance growth (on top of IBS)  
Measured emittance growth (on top of IBS&ecloud)
Extra emittance growth vs INJ brightness at FB, for B1

Extra emittance growth (on top of IBS)

Extra emittance growth (on top of IBS&ecloud)
Based on the slopes of bbb measured emit. blow up vs brightness

**measured emit. blow up over brightness at SB**

**Bad BSRT**

[Graph showing data points for B1H and B1V]
Based on the slopes of bbb extra emit. blow up vs brightness
A bunch-by-bunch model based on the three main mechanisms of luminosity degradation in the LHC: intrabeam scattering (IBS), synchrotron radiation (SR) and luminosity burn-off

**Emittance evolution:**
Intrabeam scattering (IBS), Synchrotron Radiation (SR), elastic scattering (including coupling)

\[
\frac{d\varepsilon}{dt} = \left( \frac{d\varepsilon}{dt} \right)_{IBS + SR} + \left( \frac{d\varepsilon}{dt} \right)_{elastic}
\]

\[
\left( \frac{d\varepsilon_x}{dt}, \frac{d\varepsilon_y}{dt}, \frac{d\sigma_s}{dt} \right)_{IBS + SR} = f \left( En, N_b(t_0), \varepsilon_x(t_0), \varepsilon_y(t_0), \sigma_s(t_0), dt \right)
\]

\[
\left( \frac{d\varepsilon_{x,y}}{dt} \right)_{elastic} = N_{1p} \beta^* \epsilon_x \lambda \sigma_{el} \left( \theta^2_{x,y} \right) \left( n_b N_p \right)
\]

**Bunch intensity evolution:** Luminosity burn-off

\[
\frac{dN}{dt} = \left( \frac{dN}{dt} \right)_{BOff}
\]

**Bunch length evolution:** IBS and SR

\[
\frac{d\sigma_s}{dt} = \left( \frac{d\sigma_s}{dt} \right)_{IBS + SR}
\]

Combination of the transverse emittance, bunch length and bunch intensity estimations (or observations) in a self consistent way to compute the luminosity at each time step

\[\beta^*, \text{ luminosity leveling, } x-ing \text{ angle anti-leveling options}\]

F. Antoniou et al., TUPTY020, proc. of IPAC’15
F. Antoniou et al., “Can we predict luminosity?”, proc. of Evian 2016