Beam lifetime in collision - LHC experience

G. Iadarola

Many thanks to:
G. Arduini, H. Bartosik, I. Efthymiopoulos, E. Metral, N. Karastathis,
S. Kostogluou, Y. Papaphilippou, K. Paraschou, G. Rumolo

Analysis based on **ABP python toolbox**:  
- [LHCLossesAnalysis](#), G. Iadarola et al.  
- [pytimber](#), R. De Maria et al.  
- [LHCMeasurementTools](#), scrubbing and lumi teams  
- [LHCFillingPatterns](#), G. Iadarola et al.  
- [CALS2Pandas](#), G. Sterbini, A. Poyet et. al.
• Introduction

• Analysis of a typical fill from 2018
  o Burn-off corrected losses
  o Comparison against burn-off loss rate
  o Accumulated losses and comparison against transverse emittances

• Additional information from tests and MD
  o A 25 h fill
  o Test fill with constant crossing angle
  o Situation in 2017 (25 ns)
  o Situation in 2017 (8b+4e)
  o Are we dominated by e-cloud in the arcs or in the IRs?
  o MD fill with one circulating beam
  o MD fill with large ATS telescope

• Summary and outlook for HL-LHC
During the last LHC Run in 2018 **slow losses were observed during collisions**, with significant **differences among the circulating bunches**

→ Resulting in a **large spread in the bunch-by-bunch luminosity** (see talk by I. Efthymiopoulos at **150th HiLumi WP2 Meeting**)

The following slides collect **observations** made with **different beam and machine configurations** aiming at:

• Identifying the **source of the losses**
• Get a some ideas on **how this effect will evolve in the HL-LHC era**

Integrating previous work on the topic, which is summarized in:

• **S. Kostoglou et al., “Luminosity, lifetime and modelling”, Evian ’19**
• **K. Paraschou et al. “Analysis on Bunch-by-Bunch Beam Losses at 6.5 TeV in the Large Hadron Collider ”, IPAC19**
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• Summary and outlook for HL-LHC
• BCMS beam
  o 25 ns bunch spacing
  o Injections of 3x48 bunches
  o Bunch intensity: \( \sim 1.2 \times 10^{11} \) p/bunch
  o Transverse emittances: \( \sim 2.0 \) \( \mu \)m

• 2556 bunches/beam

• \( \beta^* = 30 \) cm (reduced to 25 cm at the end of the fill)

• Half crossing angle reduced from 160 \( \mu \)rad to 130 \( \mu \)rad gradually during the fill

• \( L_{\text{peak}} = 1.9 \times 10^{34} \) Hz/cm\(^2\)
Continuous losses during collisions with crossing angle anti-levelling

A typical fill from 2018

- **BCMS beam**
  - 25 ns bunch spacing
  - Injections of 3x48 bunches
  - Bunch intensity: $\sim 1.2 \times 10^{11}$ p/bunch
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- **L_{peak} = 1.9 10^{34} Hz/cm^2**
For more quantitative comparisons we select **four groups of bunches:**

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A typical fill from 2018

Selected bunch families

Group 2: Losses remain relatively small for the bunches of in spite of the full number of LR encounters.

All trains of 3x48b within the beam are considered to evaluate the losses
Groups 3 and 4: much larger losses independently on the number of LRs:
→ the "e-cloud pattern" dominates the losses
→ loss rate remains \(~\text{constant during crossing-angle anti-levelling}\)

For more quantitative comparisons we select **four groups of bunches**:

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• **Summary and outlook for HL-LHC**
Losses observed at the beginning of collisions are rather large
→ LR-BB pattern can be identified
→ Loss rate comparable to burn-off
→ This is a transient effect disappearing within the first hour
After the initial transient:

- LR-BB pattern becomes practically invisible
- Loss rate smaller than burn-off but still not negligible
During the cross. angle anti-levelling:

→ loss rate stays roughly constant during the fill

→ becomes comparable to the burn-off as the luminosity decreases
A typical fill from 2018

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→ loss rate stays roughly constant during the fill
→ becomes comparable to the burn-off as the luminosity decreases
Losses increase significantly when $\beta^*$ is reduced.
Selected bunch families

Beam 1

Loss rates tend to be smaller for beam 2 but all the features discussed so far are still visible

⇒ In the following we will focus on B1

Beam 2

A typical fill from 2018
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• **Summary and outlook for HL-LHC**
As the loss rate is approximately constant, the accumulated losses are practically linear with time.
Accumulated losses

Even over a 9h fill, losses on the first bunches of the train are practically not measurable.

Total losses on the trailing bunches amount to $\sim 20\%$ of the initial intensity, i.e. the same amount lost due to burn-off.

To loose this amount of particles by scraping of a **Gaussian beam**, one needs to cut from the tails down to **1.5 sigmas**.
Are the different beam losses caused by **different transverse size at start of collisions**?

→ From BSRT measurements it seems that it is not the case

→ Bunches with very similar initial size show significantly different losses
Is there a correlation with emittance growth in stable beams?

- Emittance growth in Stable Beams is modest (~0.5 μm in 9 hours)
- There is no evident correlation with the bunch-by-bunch loss pattern
Summary of the main observations

- Losses are **stronger at the tail of the bunch trains**
- **Over a 9h fill**, losses amount to about **20% of the initial intensity** on the most affected bunches
- Time structure **looks like a constant spill more than a scraping** (loss mechanism does not depend strongly on the bunch charge)
- There is **no correlation with initial bunch-by-bunch emittance**
- There is **no correlation with the number of BB LR encounters**  
  → e-cloud acting on the bunches during the Stable Beams phase appears to be a key element in the underlying loss mechanism
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• Summary and outlook for HL-LHC
• Same features as observed before for the first part of the fill
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Very long 2018 fill (7056)

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Very long 2018 fill (7056)
Significant increase when reducing $\beta^*$
• Significant increase when reducing $\beta^*$
- Significant **increase when reducing** $\beta^*$
• Significant **increase when reducing** $\beta^*$
• Significant **increase when** reducing β*

At time given by dashed line above
• Loss rates decay in the last part with constant crossing angle and $\beta^*$
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• **Summary and outlook for HL-LHC**
Test fill with constant crossing angle

Crossing angle anti-levelling

Constant crossing angle
The crossing angle has a clear impact on the losses:

- When keeping the crossing angle constant, losses decrease during the fill
Test fill with constant crossing angle

Crossing angle anti-levelling

Constant crossing angle
Test fill with constant crossing angle

2018, T = 7h (135 urad)

Loss rate $[10^9$ p/h]

2018, T = 7h (160 urad)
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• Summary and outlook for HL-LHC
In 2017:

- LR-BB pattern visible on the transient happening at each angle step

2017

$\beta^* = 40 \text{ cm}$

25 ns

2018

$\beta^* = 30 \text{ cm}$
In 2017:
- Losses at the first stages of the fill were significantly smaller

2018
$\beta^* = 30$ cm

2017
$\beta^* = 40$ cm
25 ns
In 2017:

- The pattern was becoming more evident in the last stages of the fill as the angle was reduced.

2018

$\beta^* = 30$ cm

2017

$\beta^* = 40$ cm

25 ns
Selected bunch families

2018
$\beta^* = 30 \text{ cm}$

2017
$\beta^* = 40 \text{ cm}$

25 ns

Situation in 2017 (25 ns)
Situation in 2017 (25 ns)

2018, $T = 5h$

Loss rate [$10^9$ p/h]

2017, $T = 5h$

Loss rate [$10^9$ p/h]
Selected bunch families

Situation in 2017 (25 ns)

2018, $T = 8h$

2017, $T = 13h$
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• Summary and outlook for HL-LHC
In 2017:

- With the 8b+4e beam losses were extremely small

2017

$\beta^* = 30 \text{ cm}$

8b+4e

2017

$\beta^* = 40 \text{ cm}$

25 ns
Situation in 2017 (8b+4e)

2018, T = 8h

2017, T = 13h

Avg lumi [1e34 cm^-2.s-1]
0.0 0.5 1.0 1.5

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• Summary and outlook for HL-LHC
Are we dominated by e-cloud in the arcs or in the IRs?

The loss pattern is different compared to what is observed from e-cloud effects in other conditions:

- **200 ns gaps** between trains do not reset the buildup
Are we dominated by e-cloud in the arcs or in the IRs?

The loss pattern is different compared to what is observed from e-cloud effects in other conditions:

- **200 ns gaps** between trains do not reset the buildup
- This can happen in the Inner Triplets where the two beams share the same chamber
- Suggests that **losses in collisions are dominated by e-cloud in the Inner Triplets**

PyECLOUD simulation for the Inner Triplet
Are we dominated by e-cloud in the arcs or in the IRs?

The loss pattern is different compared to what is observed from e-cloud effects in other conditions:

- **200 ns gaps** between trains do not reset the buildup
- This can happen in the Inner Triplets where the **two beams** share the same chamber
- Suggests that **losses in collisions are dominated by e-cloud in the Inner Triplets**

→ consistent with strong sensitivity on $\beta^*$ and crossing angle
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• Summary and outlook for HL-LHC
Losses with a single beam in “collision configuration” could be measured during an MD dedicated to heat-load characterization

- Losses are found to be very small compared the two-beam case (DA in the absence of beam-beam is much larger)
- As expected the 200 ns gaps reset the buildup
One circulating beam (6966, 25ns)

Losses with a single beam in “collision configuration” could be measured during an MD dedicated to heat-load characterization:

- Losses are found to be very small compared to the two-beam case (DA in the absence of beam-beam is much larger).
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- Losses become stronger when reducing $\beta^*$.
Losses with a single beam in “collision configuration” could be measured during an MD dedicated to heat-load characterization

- Losses are found to be very small compared to the two-beam case (DA in the absence of beam-beam is much larger)
- As expected the 200 ns gaps reset the buildup
- Losses become stronger when reducing $\beta^*$ and going to less optimized tunes
  - Suggests that effect of triplets is still present
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• Summary and outlook for HL-LHC
The fact that losses in collisions are driven by e-cloud in the IRs and not in the arcs is **confirmed by an MD performed with special optics**\(^{(1)}\):

- **Relatively large** \(\beta^*\) \(\rightarrow\) small beta function in the triplets
- **Similar beam-beam separation** compared to physics configuration
- **Large telescopic factor (~3)** \(\rightarrow\) large in beta func. in four arcs

In these conditions **losses were found to be very small**

→ **This configuration is quite representative of the beginning of the HL-LHC fill**

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\(^{(1)}\) Talk by S. Fartoukh at LSWG 29/11/2018
https://indico.cern.ch/event/772189/contributions/3209049
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Summary of the observations

• During the last LHC Run in 2018 slow losses were observed during collisions, with significant differences among the circulating bunches
  o Over a 9h fill, losses amount to about 20% of the initial intensity on the most affected bunches (comparable to burn-off)
  o There is no correlation with the number of BB LR encounters, instead losses increase along the bunch trains
  o Time structure looks like a constant spill more than a scraping
  o There is no correlation with initial bunch-by-bunch emittance
→ e-cloud acting on the bunches during the Stable Beams phase appears to be a key element in the underlying loss mechanism

• The losses rate increases when reducing crossing angle and $\beta^*$
• Losses are very small with a single circulating beam in “collision configuration”

• Gaps of 200 ns do not reset the loss pattern
  → Suggests that the main driver is the e-cloud in the Inner Triplet
  → Consistent with observation made in MD with large telescopic factor
Outlook for HL-LHC

- Observations suggest that the main source of the observed losses is the e-cloud in the triplets
  
  $\rightarrow$ In HL-LHC this will be suppressed by the amorphous carbon coating

Moreover:

- The LHC configuration in 2018 was defined to run at constant DA of about 5 sigmas without e-cloud by slowly decreasing the crossing angle $\rightarrow$ goal was to maximize the luminosity

- In the HL-LHC during a large part of the $\beta^*$ levelling we will run with much larger DA (thanks to the relatively large beam-beam separation)
  
  $\rightarrow$ Tests with constant crossing angle in 2018 showed that this is clearly beneficial

- In the HL-LHC era the average burn-off loss rate will be $\sim$5 times larger (due to higher luminosity)
  
  $\rightarrow$ Additional losses from e-cloud will have less impact on the total loss rate and on the bunch-by-bunch luminosity decay

![Graph showing the relationship between $\beta^{*}_{IP1/5}$ and Fractional QX with N. Karastathis credit]
Thanks for your attention!