Long-range limit in the LHC: Lifetimes and dynamic aperture


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Outline

- Brief recap of the 2016 LR BB MD, the procedure and highlighting the differences between the recent study and the 2015 machine study.

- Analysis of decay rates as a function of crossing angle and bunch slot for intensity, luminosity and emittance data.

- Calculation of dynamic aperture from measurement as a function of crossing angle and bunch slot,

- Impact of proton burn off and the effect on the dynamic aperture

- Comparison to Sixtrack simulations.
Machine study procedure

- **LHC 2015 Machine study**
  - Single train of 48 bunches colliding at IP1 and IP5 + 1 head on only bunch, +1 non colliding bunch
  - $\beta^* = 80\text{cm}$
  - Minimum $\alpha = 118 \mu\text{rad}$
  - Chromaticity and Landau octupole current reduced at $\alpha = 118 \mu\text{rad}$
  - Detailed analysis and summary in note and IPAC paper

- **LHC 2016 Machine study**
  - Split into two fills (5136, 5137)
  - Fill 5136 was a repeat of the 2015 machine study at $\beta^* = 40\text{cm}$, one nominal train 48 colliding bunches at IP1/5 +1 head on only +1 non colliding bunch
  - Fill 5137 consisted of three trains. Including collisions in IP2 and IP8
  - Minimum angle reached in first fill $\alpha = 230 \mu\text{rad}$ and in the second $\alpha = 190 \mu\text{rad}$
  - We also reduced the octupole current and observed improving lifetimes, analysis is ongoing.
Since we were unable to reach the long-range limit in the first fill only the second fill is discussed here.

The fill was comparable to the standard operational scenario with collisions at 4 IPs allowing the additional impact of IP2/8 collisions to be observed and analysed.

A minimum crossing angle of $\alpha = 190 \, \mu \text{rad}$ was achieved.

Long-range beam-beam pattern observed from approximately $\alpha = 260 \, \mu \text{rad}$ and below, corresponding to a beam-beam separation of about $8.5 \sigma$.

No real long-range beam-beam pattern observed in beam 2. Begin to see some opening of the lifetimes at $\alpha = 190 \, \mu \text{rad}$.

All of the decay rates calculated in this analysis use the final converged value of $\lambda$. 

MD 2016: Fill 2
The decay rate varies over the duration of each crossing angle step, with the worse lifetimes observed initially after the crossing angle step and converging towards some final value towards the end of the crossing angle step.

In previous studies the decay rates were calculated by fitting the intensity over the entire crossing angle step.

In this study additional “sub-fitting” was used to observe how the lifetimes vary over the step by splitting the crossing angle step into segments.
Strong long-range beam-beam pattern observed in beam 1 but no significant effect from the LRBB on beam 2.

Some evidence of the LR BB limit observed in beam 2 at $\alpha = 190 \, \mu \text{rad}$.

In beam 1, the LR BB begins to impact decay rates at about $\alpha = 260 \, \mu \text{rad}$. This corresponds to a beam-beam separation at the first long-range interaction of about $8.5 \sigma$. 
Intensity decay as a function of crossing angle and LR Beam 1 nominal bunches

- Non linear dependence of the intensity decay rate as a function of crossing angle.
- Nominal bunches with the most long-range (in the center of the train) suffer the most as the crossing angle is reduced, with decay rates increasing significantly.
- Pacman bunches are not effected as strongly by the crossing angle, significant impact for \#LR > 24 leads to $\tau < 10$ hours.
Intensity decay as a function of crossing angle and LR Beam 2 for nominal bunches

- No real impact in beam 2 from the reduced crossing angle, except for the last step where the nominal bunches and bunches with about 24 LR interactions drop below $\tau = 10$ hours.

- Maybe some evidence that we approached the LR limit towards the end of the MD.

- Could not push to any smaller crossing angles, due to lifetimes in beam 1 being below 1 hour.
Intensity decay as a function of LR beam 1 for Pacman and nominal bunches

- Non linear dependence of the intensity decay rate as a function of long-range.
- Decay rate appears to increase parabolically with number of LR at small crossing angles, this agrees with preliminary scaling laws obtained and observed in the 2015 MD (see IPAC16 paper).
- At the smallest crossing angle of $\alpha=190\ \mu$rad the beam-beam separation is approximately $6.4\sigma$. 
Intensity decay as a function of LR beam 2 for Pacman and nominal bunches

- No quadratic dependence on the number of LR observed in beam 2.
- Decay rates are beginning to increase at $\alpha=190$ $\mu$ rad but not significantly compared to beam 1.
- Differences in the emittances between the two beams could provide an explanation as to why beam 2 does not suffer as much as beam 1.
Beam 1 intensity decay rate as a function of bunchslot, crossing angle and the number of LR

These figures show the bunch intensity decay rates as a function of the bunchslot and the number of LR at different crossing angles.

- Begin to approach lifetimes of \( \tau = 10 \) hours for nominal bunches at a crossing angle of about \( \alpha = 250-260 \) \( \mu \) rad

- Significant reduction in lifetime at \( \alpha = 210 \) \( \mu \) rad \( \tau < 10 \) hours
Impact of IP2/8 on decay rates

- No significant impact from the additional long-range interactions at IP2 and IP8 as expected.
- No additional contribution from these IPs due experimental requirements from the detectors. These experiments do require small $\beta^*$. Therefore the long-range beam-beam separation is larger and the diffusive mechanism does not have a significant impact.
- IP 8 has a small impact on the lifetimes compared to IP2, most likely due to the offset collision and size of the $\beta^*$, to be checked.
Luminosity decay rates as a function of crossing angle

Unlike the previous MD in 2015, the CMS detector also took luminosity data.

The CMS data has a better time resolution than the ATLAS data allowing improved accuracy whilst fitting and calculating the decay rate.

See the same trend as observed in the intensity data with comparable lifetimes calculated.
Luminosity decay rates as a function of Long-range interactions

- Similar pattern observed when comparing the decay rates to the number of long-range interactions.
- Not a smooth parabolic increase as seen before in the intensity data.
- This may be due to the differential emittances and the apparent asymmetry between the two beams.
Mean emittances as a function of crossing angle

B1 Horizontal

Crossing Angle [µ rad]

Emittance [µ m]

B1 Vertical

Crossing Angle [µ rad]

Emittance [µ m]

B2 Horizontal

Crossing Angle [µ rad]

Emittance [µ m]

B2 Vertical

Crossing Angle [µ rad]

Emittance [µ m]
RMS Emittance as a function of crossing angle for beam 1 and beam 2

- Here, the difference was taken between the rms and the emittance of the head on colliding only bunch at the first crossing angle step.

- These plots show the emittance change of the rms normalised emittance as a function of crossing angle.

- Beam 1 is loosing emittance as the crossing angle is reduced.
Beam 1 rms emittance as a function of bunchslot and crossing angle

- Interesting pattern observed for the nominal bunches.
- Bunches in the centre of the train have differing emittances.
- With emittances for nominal bunches towards the end of the train reducing more than bunches towards the front of the train.
B1: TRAIN 2

![Graph showing the emittance vs. bunchslot for different alpha values.](image)

- alpha = 310 µrad
- alpha = 280 µrad
- alpha = 270 µrad
- alpha = 260 µrad
- alpha = 250 µrad
- alpha = 240 µrad
- alpha = 230 µrad
- alpha = 210 µrad
- alpha = 190 µrad

**Axes:**
- Y-axis: Δ Emittance [µm]
- X-axis: Bunchslot

**Emittance Values:**
- 0.2
- 0.6
- 1.0
Beam 2 rms emittance as a function of bunchslot and crossing angle

- Similar pattern also observed in beam 2 before the long-range limit was reached
- This indicates that the effect may not be related to the long-range beam-beam effect
- This is still being investigated, could possibly be due to closed orbit or electron cloud? To be checked.
The dynamic aperture was calculated in the same way as done by the single particle effects group and in the same way as for the 2015 machine study.

\[ D(N) = \sqrt{-2 \times \log \frac{\Delta I}{I_0}} \]

The effect of proton burn off was removed and the lost particles were added back to the intensity before the dynamic aperture was calculated.

The measured dynamic aperture was compared to Sixtrack simulations by J. Barranco.

The measured and simulated dynamic aperture agree very well for the smaller crossing angles when we are in the long-range beam-beam limit, however there is some disagreement between the simulated and larger crossing angles which is being investigated.

The measured and simulated dynamic aperture at the smallest crossing angle is less than 3 \( \sigma \). This could possibly explain the reducing emittance.
The burn off was calculated using an inelastic scattering cross section $\sigma_{\text{inelastic}} = 80 \text{ mb}$ and it was assumed that the burn off at IP2/8 was negligible.

For a luminosity of 6 hz/ub this corresponds to approximately 44 collisions per IP per turn.

The effect on the decay rate in this case is actually relatively small compared to the intensity loss experienced due to long-range beam-beam.

Quick back of the envelop calculation shows that $\tau_{\text{PB}} \sim 37$ hours at the smallest crossing angle for a nominal bunch.

The lost particles from burn off were added back to the intensity.
Measured Dynamic aperture beam 1 for all bunches

- Plot of the measured dynamic aperture as a function of crossing angle compared to Sixtrack simulations.

- Pacman bunches do not suffer as much as the nominal bunches as the crossing angle is reduced as expected.
Measured Dynamic aperture beam 1 for nominal bunches

For the smaller crossing angles the agreement between the measured dynamic aperture and simulated dynamic aperture is good.

There is some disagreement between the measured and simulated dynamic aperture towards the larger crossing angles, this is likely due to other non-linearities of the machine, for example non-linear coupling will limit the dynamic aperture.
Beam 2 sees a small reduction in dynamic aperture towards the smaller crossing angle, but not as significant as the impact observed in beam 1.

No significant deviation from the dynamic aperture of the head on only bunch, showing that the long-range does not have a significant impact on beam 2.
Dynamic aperture as a function of crossing angle and bunchslot for beam 1

- As expected we observed a much reduced dynamic aperture for bunches in the center of the train and at small crossing angle.

- The dynamic aperture value obtained for the nominal bunches is small enough that the DA could be cutting into the core of the bunch.

- This could provide an explanation as to why we observe an apparent reduction in emittance.
Dynamic aperture as a function of crossing angle and bunchslot for beam 2

- No significant impact on the dynamic aperture in beam 2 from the LR BB, although we once again observe a drop in dynamic aperture for some bunches in the center of the train.
From the second fill (5137) of the MD, it can be seen that we can go to a crossing angle of $\alpha = 260 \ \mu \text{rad}$ before we observe any significant impact from the long-range beam-beam interaction.

This corresponds to a beam-beam separation of approximately $8.6 \sigma$.

Hence it is possible to operate the LHC at a smaller crossing angle, whilst increasing the luminosity and retaining good lifetimes.

Need to further refine simulations to understand why we are limited in dynamic aperture at larger crossing angles.

Possible contributions to the limitation of dynamic aperture may arise due to; the head-on BB effect, linear coupling, non-linearities in the machine etc.

A note is being written up now and further work is on-going...
Thanks for Listening
Further reading


- R. Assman, et al., ’Results of long range beam-beam studies - scaling with beam separation and intensity’., CERN-ATS-Note 2012-070 MD.

- R. Alemany., ’Results of long range beam-beam studies and observations during operation in the LHC’., CERN-ATS-Note-2011-120 MD.

- M. Albert, et al., ‘Head-on beam-beam collisions with high intensities and long range beam-beam studies in the LHC’., CERN-ATS-Note-2011-058 MD.


- T. Pieloni, et al., ’Beam-Beam Effects Long Range and Head-on’, LHC Operational Workshop, EVIAN 2015