BEAM LOSSES THROUGH THE CYCLE

G. Papotti, A. Gorzawski, M. Hostettler, R. Schmidt
CERN, Geneva, Switzerland

Abstract

We review the losses throughout the nominal LHC cycle for physics operation in 2012 and for a few fills in 2011. The loss patterns are studied and categorized according to timescale, distribution, time in the cycle, which bunches are affected. Possible causes and correlations are identified, e.g. to machine parameters or BBQ amplitude signal.

INTRODUCTION

In cycling accelerators it is customary to study thoroughly the beam intensity evolution in the cycle as, in case the losses show reproducible features, they might help identify which machine parameters can be modified so to improve transmission. At the LHC this kind of study has had little importance until the 2011 run as in general losses were negligible before collisions and transmission was very close to 100%, apart from few unfortunate fills.

For the 2012 run, "tight" collimator settings [1] were chosen for physics operation at the high luminosity experiments ATLAS and CMS so to guarantee protection even with β^* as low as 60 cm. Collimator jaws closer to the beam resulted in higher losses compared to previous years as more beam tails were consistently scraped away. Additionally, the increased impedance is considered one of the causes for the instabilities that were observed throughout proton physics operation [2]. These factors resulted in an overall transmission (from end of injection to start of collisions) that was appreciably lower than 100% and losses that were about a factor 10 higher than in the previous years.

In this document, we attempt a first thorough study of the losses in the LHC proton physics fills cycle. The study is mostly targeted to 2012, with an eye to 2011 for comparison. In the first part of the paper, the losses are looked at while being separated according to beam mode so that a possible correlation to major machine settings change can be highlighted. Beam modes of interest are: acceleration (separated into two: between 450 GeV and 500 GeV, e.g. capture losses; and between 500 GeV and 4 TeV, here called Ramp), Flat Top, Squeeze, Adjust, first 5 minutes in Stable Beams. Losses during injection were analysed separately [3]. Differences in bunch-by-bunch loss patterns are looked into in the second part of this paper and some reproducible structures are highlighted.

BEAM LOSSES PER BEAM MODE

Post Mortem Power Loss Module

The intensity versus beam mode data used for this part of the analysis was extracted by means of software partly already developed in the framework of the Post Mortem (PM) Analysis [4]. A PM Power Loss module has been put in place in 2012, and for every fill dumped with a PM timing event it calculates the maximum power loss per beam per mode according to

$$P = \frac{\Delta n}{\Delta t} E_{cal} \tag{1}$$

where

$$E_{cal} = \frac{64\, E_{\mathrm{TeV}}}{4\,\mathrm{TeV}\,10^{11}\mathrm{p}} \tag{2}$$

is a calibration factor that gives the energy loss per proton at 4 TeV and $\Delta n = n_1 - n_2$ is the intensity decrease in number of protons (from DC-BCT data smoothed with a Savitzky-Golay algorithm) over the time $\Delta t = t_2 - t_1$. The maximum dissipated power is calculated by sliding the time window Δt over the duration of the beam mode under analysis. The calculation is repeated for four different time window lengths: 1 s, 5 s, 20 s and 80 s.

Another feature of the Power Loss module is that it provides the total intensity per beam at mode changes. This is the basis for the following analysis, where the intensity difference over a given beam mode is analysed over the year and correlated with settings change. The data was extracted for all proton physics fills of 2012 that reached 4 TeV (from fill number 2470 to 3341). The number of fills taken into account per beam mode is as follows: 404 fills for Ramp, 401 for Flat Top, 393 for Squeeze, 356 for Adjust and 274 for Stable Beams.

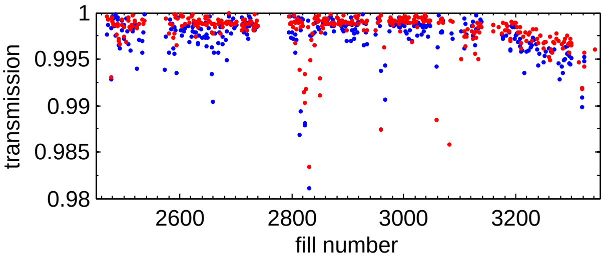
We define the transmission T as:

$$\mathrm{T} = \frac{\mathrm{I_{END}}}{\mathrm{I_{START}}} \tag{3}$$

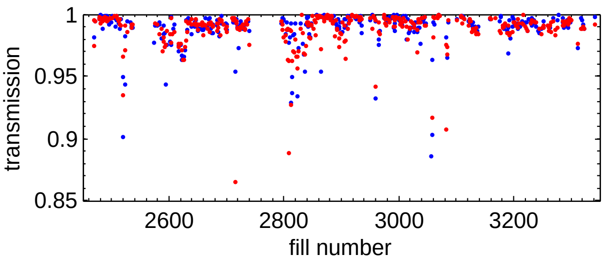
where $\mathrm{I_{START}}$ is the total intensity for one beam at the start of the beam mode and $\mathrm{I_{END}}$ is the total intensity at the end of the beam mode. In particular, $\mathrm{T} = 1$ for zero losses ($\mathrm{I_{END}} = \mathrm{I_{START}}$) and $\mathrm{T} = 0$ if all beam is gone before the end of the mode ($\mathrm{I_{END}} = 0$). In all plots in Fig. 1 and 2, the transmission over the beam mode is plotted for each fill, in blue for ring 1 and in red for ring 2.

Capture losses (450 GeV to 500 GeV)

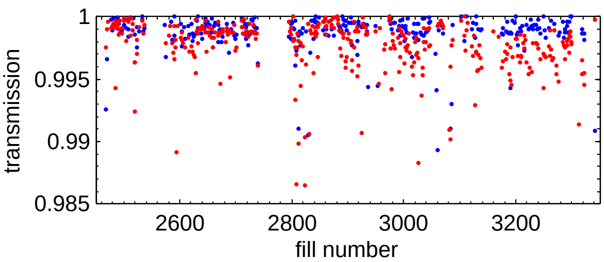
Fig.1a shows the transmission between 450 GeV and 500 GeV. It can be seen that transmission is generally worse for ring 1 than for ring 2. Energy matching between the SPS and the LHC was performed at fill number 2687, and it can be seen that capture losses improved then, especially for beam 1. A localized worsening of capture losses is present after the second technical stop (fill number 2780), possibly traced back to beam quality worsening at the injectors.



(a) Capture losses.



(b) Ramp losses.



(c) Flat top losses.

Figure 1: Beam losses per mode per 2012 fill (capture, ramp and flat top). Note the different vertical scales.

The increase in capture losses towards the end of the run is apparent. A second energy matching was performed then to try and improve the situation (fill number 3271), but the effect was negligible. The increase in losses is probably rather due to the enhancement of satellite population to increase the Alice luminosity, performed after the third Machine Development block (fill number 3178).

Losses during the ramp (500 GeV to 4 TeV)

In Fig. 1b, the transmission during acceleration (between 500 GeV and 4 TeV) is shown. As a general comment, losses are non-negligible, mostly at the percent level. This pairs with the observation, often made in the control room, that the single beam lifetime decreases appreciably towards the end of the ramp, e.g. when the primary collimators close in and the transverse tails are scraped away.

The transmission improved towards the end of the run, i.e. after the third technical stop, probably when the new Q20 optics was introduced at the SPS for operational LHC beams [5], allowing the transfer of beams with smaller transverse size.

The analysis of the maximum power loss during the ramp (see Eqn. 1) highlighted that the peak losses happened for almost all fills either at the end of the ramp (20 s time window). It also showed that the highest power losses were for beam 1. For the longest time window (i.e. 80 s), the highest power loss was mostly towards 4 TeV, and peak losses were similar in amplitude for the two rings.

Flat Top losses

The time spent at the flat top was rather short for most fills (e.g. a few minutes). This time was used for manual checks on the tune trim quadrupoles and relative trims, and to load the squeeze functions on power converters and other systems. Consequently, losses were in general negligible, but it is noticeable that they are slightly higher for beam 2, for which the single beam lifetime was generally worse than for beam 1 (see Fig. 1c). The beam 2 lifetime also slightly worsened around the time at which the octupole polarity was reversed (fill number 2924, a worse lifetime could be due to the abundant increase in chromaticity that followed shortly).

Losses during Squeeze

Fig. 2a shows the transmission during the Squeeze mode. Throughout the year, the beam 2 losses are worse than the ones for beam 1, and losses get generally worse after the octupole polarity change and the increase in chromaticity.

Looking at the maximum power losses with 20 s time window, the peak is very reproducible for beam 1 ($\approx$ 10 kW), and less for beam 2 (generally $<$ 30 kW). The time in the mode at which the peak power loss happened is very reproducible for beam 2 (see Fig. 3). In fact, the peak power losses cluster around a few definite times, namely: $\approx$ 420 s (or $\approx \beta^* = 3$ m), $\approx$ 820 s (or $\approx \beta^* = 0.7-0.8$ m), $\approx$ 930 s (or $\approx \beta^* = 0.6$ m, as the total function length is 925 s).

Losses during Adjust

The Adjust beam mode is the one during which the beams are put into collisions. The main change during 2012 coincided with the use of two collision beam processes instead of one. This change had been put in place to go from one longer beam process, beginning with transverse optics gymnastics in Interaction Point (IP) 8 and followed by collapsing of separation bumps in all IPs at the same time, to two shorter beam processes in which collisions in IP1, 2 and 5 were established first, followed by the IP8 gymnastics. The double collision beam process allowed taking advantage of the stabilization properties of head-on beam-beam tune spread from IP1 and 5 as soon as possible to counteract the instabilities that had often been observed and that had caused the loss of many fills. Additionally, it resulted in more reproducible figures for transmission and peak power losses (see Fig. 2b).

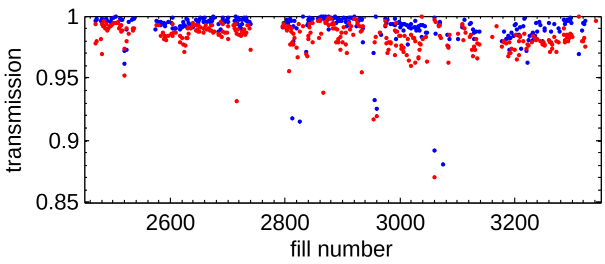
Losses at start of Stable Beams

The transmission in the first 5 minutes in Stable Beams also profited by the change of the collision beam process in Adjust: as it can be seen in Fig. 2c, the transmission generally improved and became much more reproducible. In this case, it is beam 1 that had usually higher losses than beam 2. This was also often commented on by the shift crews, highlighting that, while beam 2 used to lose more in the rest of the cycle, beam 1 lost more at the start of Stable Beams. This can intuitively be explained by the fact that the transverse tails of beam 1 were not scraped as much as the ones of beam 2 earlier on, so got scraped at start of collisions.

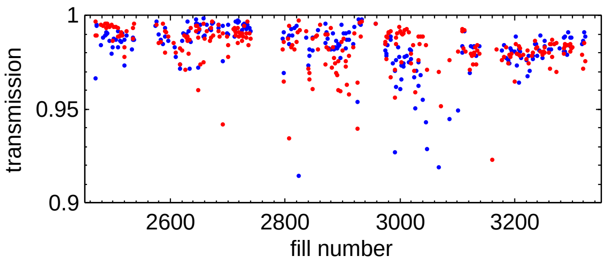
Comparison with losses in 2011

The difference between 2011 and 2012 proton physics operation is quantified in Table 1, where it can be seen that losses in 2012 were about a factor 10 higher than in 2011.

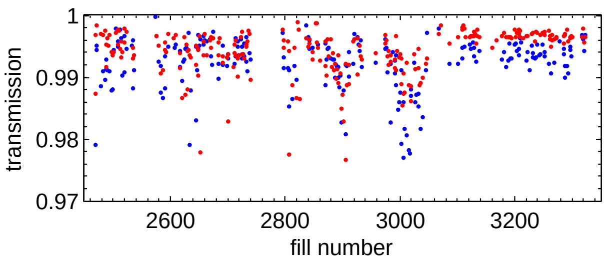
The 2011 peak power loss analysis was also performed and a few observations follow. Peak power losses in 2011 are generally a factor 2 to 3 lower than in 2012, with peaks < 30 kW for beam 1 and < 10 kW for beam 2 (note that beam 1 was consistently worse than beam 2). Note also that the clustering at certain times in the Squeeze beam mode was not observed.



(a) Squeeze losses.



(b) Adjust losses.



(c) Stable beams losses.

Figure 2: Beam losses per mode per 2012 fill (Flat Top, Squeeze and Adjust). Note the different vertical scales.

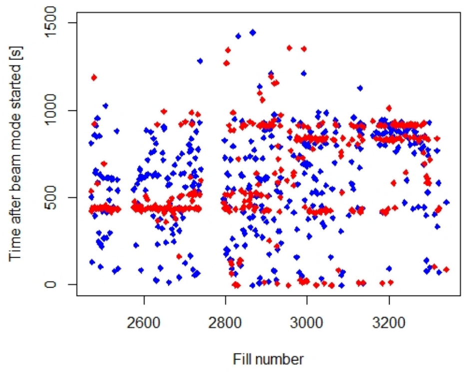


Figure 3: Time at which the maximum power loss (20 s sliding window) happened after the start of the squeeze beam mode.

BUNCH-BY-BUNCH DIFFERENCES

Two main bunch-by-bunch differences in the beam losses are explained next: one is a reproducible loss structure that develops during Stable Beams in beam 1; the other is additional losses related to transverse emittance blow up due to instabilities that developed in many fills in the second part of the run.

Other cases of punctual bunch-by-bunch differences were observed throughout 2012, but will not be expanded on here as the causes were found and rapidly corrected, e.g. different settings on the transverse damper during commissioning (e.g. fill number 2593) or insufficient beam quality from the injectors (for example, loss of proper longitudinal structure at the PS, fill number 3109).

Bunch-by-bunch loss structure in stable beams

A very reproducible loss structure developing during long physics fills was observed throughout 2012. The first ≈ 30 bunches of each SPS batch in beam 1 lose up to 10% less in Stable Beams compared to the later bunches. An example of such structure is shown in Fig. 4: the beam 1 integrated losses after 11.5 hours in Stable Beams are shown for the different SPS batches. It is also possible to see the

Table 1: Losses per beam mode, comparison between 2011 and 2012. The last line refers to the total transmission, for fills that lasted until stable beams. Statistics for 2011 are calculated over 200 fills, from fill 1615 to fill 2266.

Losses	**2011**		**2012**	
	beam 1	**beam 2**	**beam 1**	**beam 2**
Capture	0.14%	0.10%	0.52%	0.34%
Ramp	0.71%	0.11%	1.17%	1.22%
Flat top	0.07%	0.02%	0.57%	0.48%
Squeeze	0.08%	0.04%	1.22%	1.99%
Adjust	0.46%	0.30%	1.76%	1.65%
Total	0.81%	0.66%	3.82%	4.74%

gaps between the PS batches. A similar structure was also noticed in 2011 [6] but was never visible on beam 2 losses.

The bunch-by-bunch luminosity is known for the four main experiments and can be used to calculate the burn-off component in the total losses in collisions. Note that the luminosity production at IP2 is negligible compared to the other IPs, so only IP1, 5 and 8 are taken into account in this analysis. It is worth noting that the SPS-batch loss structure remains visible after removal of the burn-off component. The spread in beam 1 losses after burn-off removal is $\approx 7\%$ after 8 hours of collisions. A similar structure, but much smaller in amplitude ($\approx 3\%$) is also visible in beam 2.

A clear cause for this bunch-by-bunch difference has not been identified yet. Due to the asymmetry in the loss shape, no simple correlation with the beam-beam force could be identified (e.g. with number of long range encounters).

Longitudinal shaving for bunches with increased emittances

For many fills at the end of the 2012 proton physics run, it was observed [7] that bunches in beam 1 could be divided into two families, namely:

- bunches developing a shorter bunch length have higher losses and larger transverse emittance;
- bunches getting longitudinally longer have smaller losses and smaller transverse emittance.

These characteristics built up during collisions and were related to the occurrence of transverse instabilities and emittance blow up for beam 1 at the end of the squeeze, before bringing the beams into collisions. The effect was not observed on beam 2.

CONCLUSIONS AND FUTURE WORK

Beam losses through the proton physics nominal cycle were non-negligible in 2012, and the transmission was on average $\approx 96\%$ to be compared to the $\approx 99.3\%$ in 2011. Features in the losses per beam mode per ring could be

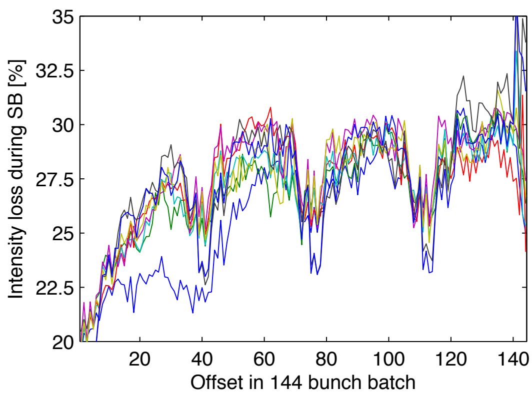


Figure 4: Integrated losses after 11.5 hours from the start of Stable Beams (SB) for beam 1 in fill 3363.

highlighted: degradation of capture losses towards the end of the run, possibly related to enhanced satellite population; losses of $\approx 1.2\%$ during acceleration, mostly towards the end of the ramp when primary collimator jaws close in; peak power losses at precise moments in the squeeze function for beam 2; losses in Adjust became much more reproducible since the use of the split collision beam process.

Observations of bunch-by-bunch losses in stable beams showed a reproducible SPS-batch structure (for ring 1 mostly), for which a clear cause could not be found yet. Additional losses were observed for bunches with larger transverse emittance due to instabilities that developed at the end of the Squeeze.

The authors suggest the development of a new tool for fill-by-fill data analysis e.g. to observe the evolution of the luminosity performance or of the losses on a weekly basis. This would allow a more prompt reaction to problems that might generate from the drift of parameters and a ready handle to verify the improvement of settings.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the fruitful discussions with G. Arduini, C. Bracco, E. Metral, N. Mounet, T. Pieloni and G. Roy during the preparation of the workshop session.

REFERENCES

[1] R. Bruce, “Collimation settings and performance”, LHC Performance Workshop, Chamonix, 6-10 Feb. 2012.

[2] E. Metral, “Review of the instabilities observed during the 2012 run and actions taken”, these proceedings.

[3] C. Bracco, “Injection and dump systems”, these proceedings.

[4] M. Zerlauth, O. Oyvind Andreassen, V. Baggiolini, A. Castaneda, R. Gorbonosov, D. Khasbulatov, H. Reymond, A. Rijllart, I. Romera Ramirez, N. Trofimov, “The LHC Post Mortem Analysis Framework”, 12th International Conference On Accelerator And Large Experimental Physics Control Systems, Kobe, Japan, 12-16 Oct. 2009.

[5] R. Steerenberg, “Post LS1 25 ns and 50 ns options from the injectors (incl. emittance blow-up)”, these proceedings.

[6] G. Papotti, “Observations on luminosity curves”, presentation at the LHC Beam Operation Committee on 22 May 2012.

[7] M. Hostettler, G. Papotti, G. Arduini, “Observations on bunch length histogram splitting and selective emittance blow-up in LHC Beam 1”, CERN-ATS-Note-2013-003 PERF.