OBSERVATIONS FROM LHC PROTON-PROTON PHYSICS OPERATION

M. Hostettler* (University of Bern), G. Papotti, CERN, Geneva, Switzerland

Abstract

This paper describes two distinct effects observed during the operation of the LHC in 2012. First, the impacts on beam parameter evolution of the end-of-squeeze instabilities encountered in the second half of the 2012 run. Second, the very reproducible loss pattern of Beam 1 observed (while a similar pattern was negligible, if present at all, for Beam 2). Statistics for 2012 are provided and the impact on luminosity production is highlighted.

INTRODUCTION

The LHC operational cycle

The LHC operational cycle for proton physics consists of injecting beams of proton bunches from the injector complex into both rings, accelerating them from injection energy (450 GeV) to the flat-top energy (4 TeV in 2012) and bringing them into collisions. A full cycle, called a *Fill*, is divided into different phases, which are commonly referred to as *Beam Modes*. This publication covers two effects observed in the part of the cycle after the acceleration phase, which consists of the following beam modes:

- *Squeeze*: The betatron squeeze, where the yet separated beams are squeezed to the target collision optics (in 2012: $\beta^* = 60$ cm).
- *Adjust*: The phase where the separation between the beams in the interaction points is collapsed and the beams are brought into collisions.
- *Stable Beams*: The beam mode manually declared by the operators after all adjustments have been done, signaling to the experiments the start of physics data taking. Physics production fills generally remain in this beam mode for several hours until the beams are eventually dumped.

The LHC filling scheme

The LHC features a 400 MHz RF system corresponding to a bucket length of 2.5 ns and a harmonic number of $h = 35640$ [1]. For most proton physics production fills in 2012, the LHC was filled with 50 ns spaced bunches. From the SPS, 8 batches of 144 bunches, 3 batches of 72 bunches and one batch of 6 bunches (witness bunches for transfer line verification) were injected into each ring of the LHC, totaling to 1374 bunches per beam[1], as shown in Fig. 1.

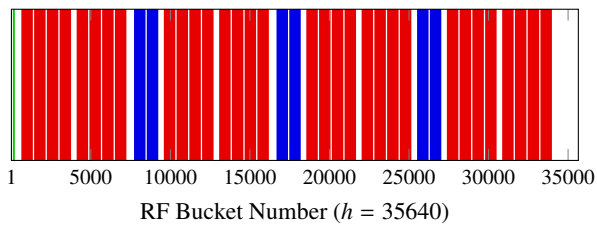


Figure 1: The LHC filling scheme for Beam 1 used in 2012, consisting of 8 batches of 144 bunches (red), 3 batches of 72 bunches (blue) and 6 witness bunches (green). The filling scheme for Beam 2 is identical apart from the position of the witness bunches.

BEAM PARAMETER EVOLUTION AFTER THE END-OF-SQUEEZE INSTABILITIES

In the second half of 2012, instabilities were frequently observed at the end of the Squeeze beam mode [2] in the LHC. These instabilities, despite not causing significant intensity losses or beam dumps, lead to a non-negligible transverse emittance increase of ~0.5 μm for the affected bunches.

Fig. 2 shows, in blue, the horizontal[2] bunch size measurement acquired for a different bunch every second from the scanning Synchrotron Light Telescope (BSRT) system and, in red, the amplitude of the vertical Base-Band-Tune (BBQ) measurement. It can be seen that at ~19:20, the BBQ amplitude increases, indicating the presence of an instability. At the same time, certain bunches develop a higher transverse emittance (the horizontal bunch size measurements separate into two bands).

When the beams that experienced the end-of-squeeze instabilities go into Stable Beams, two distinct families of bunches can be seen, according to the evolution of their parameters: bunches with a larger emittance develop both higher losses and a shorter bunch length, possibly due to limits in off-momentum dynamic aperture. This effect has historically been labelled "Bunch length histogram splitting" as it was visible in the LHC control room fixed displays as a double peaked histogram of Beam 1 bunch lengths. It has been discussed in detail in a previous publication [3], so it will not be treated any further in this paper. The underlying instabilities are subject to current beam-beam studies [2].

The impact on the luminosity is mainly emittance-driven:

* michael.hostettler@cern.ch, michihostettler@students.unibe.ch

[1] Until June 2012, a slightly different filling scheme including 12 witness bunches per beam (and therefore 1380 bunches in total) was used. No change of the loss pattern was observed due to the different filling scheme.

[2] No vertical bunch size measurement was available due to technical difficulties.

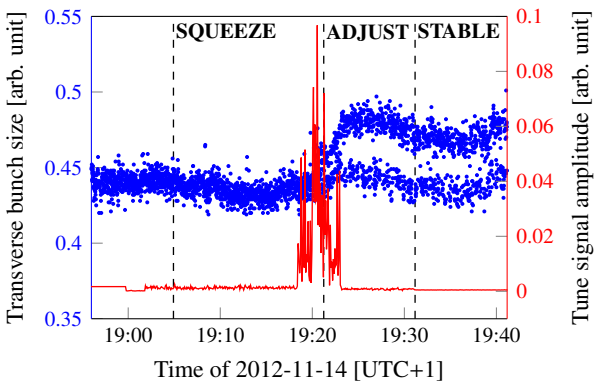


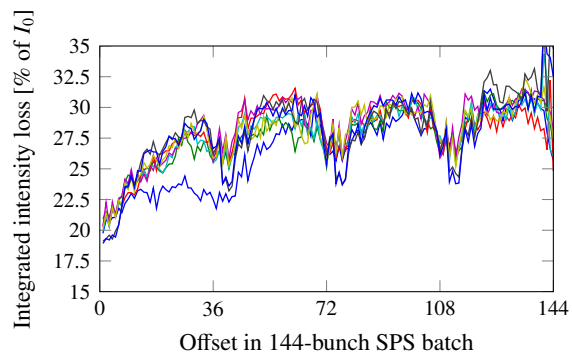
Figure 2: Horizontal bunch sizes of beam 1 (measured for a different bunch every second by the BSRT) and vertical tune signal amplitude (measured by the BBQ system) for fill 3287, indicating the presence of an instability at ~19:20. Note the two distinct emittance families thereafter.

the emittance, derived from the luminosity, at the start of the Stable Beams period was generally ~2.4 μm in 2012, while the emittance of bunches affected by the instability was ~3 μm, with up to 70% of all bunches affected for particular fills in late 2012. This corresponds to loss of up to 10% in both peak and integrated luminosity, e.g. from a peak instantaneous luminosity of more than 7000 $\mu b^{-1}s^{-1}$ for "good" fills to ~6500 $\mu b^{-1}s^{-1}$ for fills with ~50% bunches affected.

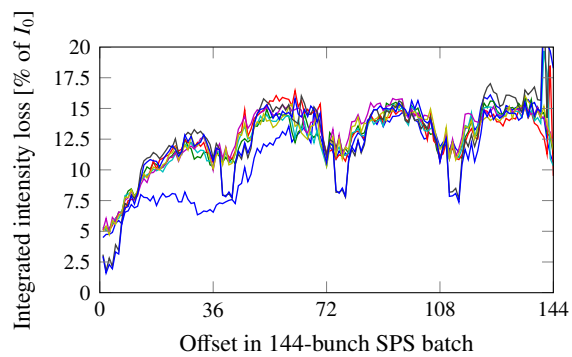
LOSS PATTERN OF BEAM 1 IN STABLE BEAMS

A very reproducible loss pattern was observed during long physics fills in 2012: The integrated losses of the first ~30 bunches of each SPS batch in Beam 1 are up to 10% lower compared to later bunches after 11 h in Stable Beams, while such a pattern was always negligible, if present at all, for Beam 2. In the following analysis, only the batches of 144 bunches are considered for simplicity, although the batches of 72 bunches show the same behavior. A similar pattern was already noticed during 2011 operation [4].

The bunch-by-bunch luminosity published by the main experiments and the total process cross-section [5] allow calculating the intensity lost due to luminosity burn-off. Removing the burn-off component from the total losses does not change the overall loss pattern, as depicted in Fig. 3. The cause of the pattern is yet unknown, in particular, no correlation to the number of long-range interactions was identified. However, the loss structure of Beam 1 clearly depends on the preceding gaps with no beam (see Fig. 1): After each 36 bunches, a local decrease in losses is visible after the SPS injection kicker gap, and the first bunches in the first SPS batch after the large LHC dump kicker gap lose even less compared to the same bunches in later SPS batches (lower blue curves in Fig. 3).



(a) Total intensity losses.



(b) Intensity losses with burn-off component removed.

Figure 3: Integrated losses of Beam 1 for fill 3363 after 11 h in Stable Beams, grouped by SPS batches of 144 bunches each (a). Note that removing the burn-off component does not change the loss pattern (b).

Statistics and correlation to the bunch length

Fitting a linear function to the integrated losses of the first 30 bunches of each SPS batch allows quantifying the difference in losses among those and therefore the strength of the effect; averaging over all 144 bunches of each SPS batch shows the impact on the total losses. This is shown in Fig. 4 for one sample fill.

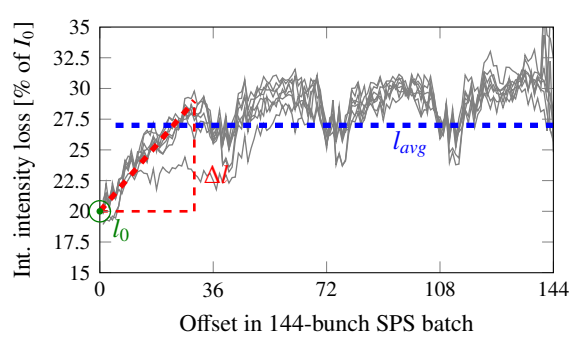
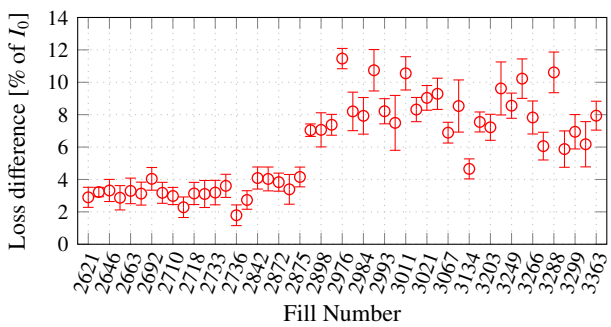
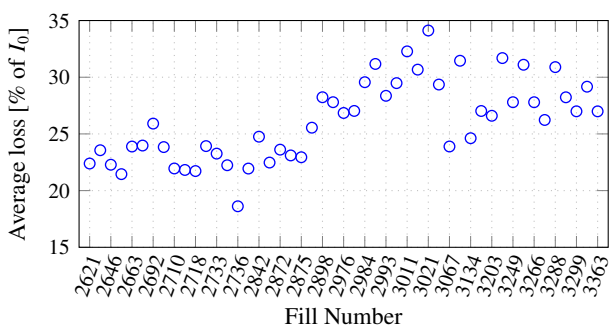


Figure 4: Quantitative analysis of the Beam 1 loss pattern for fill 3363, with the average loss of the first bunch of each 144 SPS batch in green, the average slope over the first 30 bunches of each SPS batch in red, and the total average loss in blue.

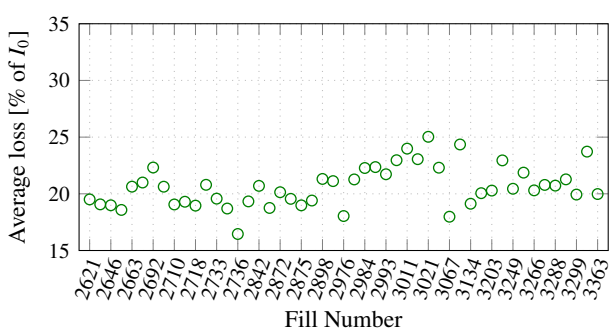
Fig. 5 shows this analysis applied for all fills of 2012 which lasted at least 11 h in Stable Beams. It is to be noted that Δl, the observed difference over the first 30 bunches, suddenly increases from less than 5% to up to 10% after fill 2875 (see Fig. 5a). This is suspected to be correlated to the increase of the bunch length target for the ramp from 1.2 ns to 1.3 ns from fill 2880 onwards, indicating that the pattern is correlated to longitudinal losses. An increase of l_{avg}, the average intensity loss of all bunches, is also observed for the same fills (Fig. 5b), while l_0, the intensity loss of the first bunch of each SPS batch, remains at the same level (Fig. 5c).



(a) Δl: Average loss difference over the first 30 bunches of each SPS batch. The error bars indicate the fit quality.



(b) l_{avg}: Average loss of all bunches.



(c) l_0: Average loss of the first bunch of each SPS batch.

Figure 5: Statistics of the loss pattern of Beam 1 after 11 h in Stable Beams for 2012. Note the sudden increase of both the slope and the average losses after fill 2875, probably related to an increased bunch length.

Impact on luminosity

Increased losses lead to a lower total intensity and therefore to a lower integrated luminosity for the same fill duration due to a decreased luminosity lifetime, which is defined as τ in

$$L(t) = L_0 \exp\left(-\frac{t}{\tau}\right) \tag{1}$$

In the bunch-by-bunch luminosity lifetime calculated by fitting Eq. 1 to the the luminosity per colliding bunch pair published by the ATLAS experiment for a time window of 2 h set at 8 h after the start of Stable Beams, the impact of the Beam 1 loss pattern is visible, as depicted in Fig. 6.

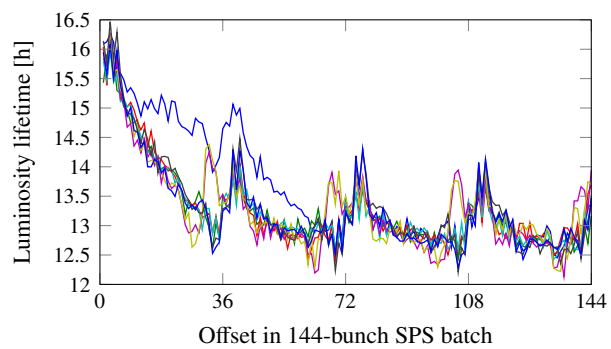


Figure 6: Bunch-by-bunch luminosity lifetime for fill 3363, calculated from ATLAS data after 8 h of Stable Beams. It shows an inverted image of the Beam 1 loss pattern observed.

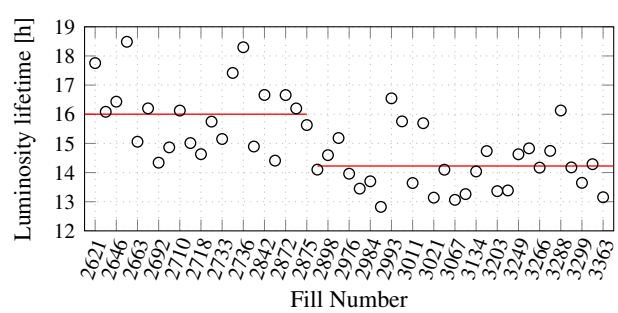


Figure 7: Total luminosity lifetime, calculated out of the ATLAS luminosity data after 8 h in Stable Beams, for the fills considered in Fig. 5. The luminosity lifetime got worse after fill 2875, probably due to the increased total intensity loss. The red lines indicate the average up to and after fill 2875.

The increased total losses after fill 2875 are also visible on the total luminosity lifetime. As shown in Fig. 7, the luminosity lifetime after fill 2875 is on average ~1.5 h lower in the long term compared to earlier fills. Despite of a rather large spread of the values, the bunch-by-bunch pattern observed (Fig. 6) indicates a correlation to the loss pattern in question. Assuming the same peak luminosity, this decrease in luminosity lifetime corresponds to a ~7%

loss in integrated luminosity for a fill lasting 11 h in Stable Beams.

CONCLUSIONS

Observations on two distinct effects affecting the LHC luminosity production were studied and presented in this paper. First, instabilities at the end of the betatron squeeze increased the transverse emittances of selected bunches by ~0.5 μm. Up to 70% of all bunches in Beam 1 were affected in late 2012, resulting in a loss of up to 10% of both peak and integrated luminosity.

Second, bunch-by-bunch observations on the integrated intensity losses of Beam 1 bunches showed a very reproducible pattern building up over several hours in Stable Beams on 144-bunch SPS batches, while no such pattern was observed on Beam 2. A clear cause for the pattern has not been identified yet, but the differences in losses over a SPS batch as well as the average losses increased after an increase in bunch length, indicating a correlation to longitudinal losses. The shorter luminosity lifetime due to the increased losses leads to a loss of ~7% of integrated luminosity for long fills.

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