ANALYSIS OF 2016 BEAM LOSSES AT THE LHC

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Abstract

The analysis of operational beam losses at the LHC is crucial to assess the performance of the accelerator. In the context of the LHC collimation studies, systematic analyses are carried out during the operation to assess the performance of the beam halo collimation. Various tools have been developed for this purpose, which are now also used for more general applications. In this paper, the analysis of losses throughout the cycle, as computed from the measurements of collimator beam losses and from the LHC beam current monitors, is presented. The BLM analysis at primary collimators of the betatron and off-momentum cleaning insertions allows also a decomposition of losses that provides an insight of the main source of losses (transverse horizontal or vertical, or off-momentum). The results of this analysis are also discussed.

INTRODUCTION

The LHC collimators are the closest aperture restrictions at the Large Hadron Collider (LHC) in all operational phases. Primary collimators (TCPs) of the betatron (IR7) and off-momentum (IR3) cleaning insertions represent respectively the transverse and off-momentum aperture bottlenecks of the accelerator, as required to protect the cold magnets from operational losses that could cause quenches. Primary beam losses from diffusive mechanisms are consistently observed at the location of the 4 primary collimators: horizontal, vertical and skew in IR7 and horizontal in IR3. The monitoring of TCP local losses provides a means to diagnose the losses precisely, thanks to the high dynamics range of the beam loss monitoring (BLMs) system of about 8 orders of magnitudes. Dedicated calibrations of the BLM signals are used to calibrate the BLM signals in protons/s and use this measurement to compute beam lifetime. This method is presented in detail in [1].

This analysis is carried out systematically for all the operational phases until the physics mode is established (see [2] for an analysis of losses during the collision process). Our main focus is on the phases at 6.5 TeV where the beam stored energy is larger and operational losses are a concern for collimation and machine protection purposes. The resulting beam losses are presented per mode and in each case, the loss decomposition analysis is also presented. This was achieved thanks to a new analysis of BLM loss maps that uses reference loss patterns and an SVD-based algorithm to identify the horizontal, vertical and off-momentum content of losses [3].

2016 MACHINE CONFIGURATION

The relevant parameters of the 2016 configuration are given per phase of the operational cycle in Table 1. The combined ramp and squeeze was deployed for the first time at the LHC in 2016, reaching β^* values of 3 m in ATLAS and CMS at 6.5 TeV. This was followed by a classical squeeze performed at constant beam energy. The "adjust" mode where collisions are prepared follows the squeeze. The "stable beams" mode corresponds to the quiet data taking period and is declared when collisions are setup and optimized for all experiments. Note that the crossing angles in IR1/5 were changed in Sep. 2016 from 185 μrad to 140 μrad. This change was implemented during the adjust mode by changing the crossing angle at constant β^* values in IR1/5. Therefore, no changes were made in the squeeze beam process.

The operational cycle in 2016 was particularly complex because of the need for adding, before entering in collision, a special bump around IR5 for the Roman pots based CT-PPS experiment. This is referred to as "TOTEM bump". A total of three distinct "collision beam processes" were implemented respectively to switch ON this new bump at the end of the squeeze, to bring ATLAS and CMS in collisions, and then to bring ALICE and LHCb in collisions. This gymnastic brought the average duration of the adjust mode to about 16 minutes [4, 5]. High-luminosity collisions were established in ATLAS and CMS a few minutes before preparing collisions in the low-luminosity points.

The primary betatron and off-momentum cuts, expressed in units of betatron beam size $\sigma_{3.5\mu\mathrm{m}}$that uses the nominal 3.5 μm emittance, are also listed in Table 1. The real betatron cuts have to be scaled by using the real beam emittance. The off-momentum cuts were typically of the order of 2×10^{-3}. Collimators in IR3 and IR7 reach their final settings for physics at the end of the combined ramp-and-squeeze and were kept the same throughout the year. See the companion paper [6] for more details on the 2016 collimation system 2016.

Figure 1 shows the proton stored beam energy as a function of the fill number in 2016, taking into account only fills that made it to stable beams. After the initial intensity ramp up, typical values of 250 MJ were routinely achieved, only interrupted by mini-intensity ramp up periods that followed schedule stops of proton operation (Technical Stops, TSs, and Machine Developments, MDs, are indicated in Fig. 1 by the black dashed lines). The bunch intensity was limited to 1.1×10^{11} protons per bunch because of vacuum problems with the injection kickers [7]. The total number

Table 1: Main beam parameters and primary collimator settings for the 2016 LHC run configurations. A change in crossing angle in IR1/5 was implemented in TS2, from 185 μrad to 140 μrad.

Parameter	Unit	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6
		Injection	Top energy	Squeezed	Collision1	Collision2	Collision3
Energy	GeV	450	6500	6500	6500	6500	6500
Maximum number of bunches	unit	2220					
Bunch intensity	10^{11}	1.10					
Transverse beam emittance	μm	2.2	2.5	2.5	2.5	2.5	2.5
β^* in IR1/5	m	11.0	3.0	0.4	0.4	0.4	0.4
β^* in IR2	m	10.0	10.0	10.0	10.0	10.0	10.0
β^* in IR8	m	10.0	6.0	3.0	3.0	3.0	3.0
Half crossing angle IR1 (V)	μrad	-170	-185	-185	-185(-140)	-185(-140)	-185(-140)
Half crossing angle IR5 (H)	μrad	+170	+185	+185	+185(+140)	+185(+140)	+185(+140)
Half crossing angle IR2 (V)	μrad	+170	+200	+200	+200	+200	+200
Half crossing angle IR8 (H)	μrad	-170	-250	-250	-250	-250	-250
Half separation IR1 (H)	mm	-2.0	-0.55	-0.55	0.55	0.0	0.0
Half separation IR5 (V)	mm	+2.0	+0.55	+0.55	0.55	0.0	0.0
Half separation IR2 (H)	mm	+3.5	+2.0	+2.0	+2.0	+2.0	0.0
Half separation IR8 (V)	mm	-3.5	-1.0	-1.0	-1.0	-1.0	0.0
"TOTEM BUMP" IR5 (H)	mm	–	–	–	ON	ON	ON
Primary cut IR7 (H, V, S)	$\sigma_{3.5\mu m}$	5.7	5.5	5.5	5.5	5.5	5.5
Primary cut IR3 (H)	$\sigma_{3.5\mu m}$	8.0	15.0	15.0	15.0	15.0	15.0

of bunches was also limited by the SPS extraction, from limitations to the beam dump block [8]. These limitations played a role in the overall beam loss performance in 2016.

BEAM LOSS AND LIFETIME MEASUREMENT TECHNIQUES

Details on how the lifetime is calculated in the context of collimation studies can be found in [1]. The technique based on the beam loss measurements has been recently further improved by adding an analysis of decomposition of losses by loss planes [9]. This decomposition is computed with an SVD method that relies on calibrated loss patterns from the validation loss maps carried out throughout the year to validate the setting of the collimation system [6].

During machine validation periods, controlled beam losses are generated on purpose in different planes. This is done with very low intensity in the machine ($< 3{\cdot}10^{11}$ protons) and is used to measure the collimation cleaning efficiency. The six basic loss maps used for the decomposition are:

- Beam 1 and Beam 2 horizontal and vertical losses due to high betatronic oscillations (4 difference scenarios);
- Beam 1 and Beam 2 off-momentum losses (2 different scenarios).

The signal from the IR7 BLMs immediately downstream of primary collimators contains information about the loss plane. In IR3 there is only one horizontal primary collimator that is sufficient to intercept off-momentum losses because by design a large horizontal normalized dispersion is created at this location. In these cases one can distinguish the different loss patterns between the transverse and off-momentum scenarios. The losses are mainly in IR7 (positions 19400 m to 20600 m from IP1) for transverse losses and the losses are distributed both in IR7 and in IR3 (located between 6100 and 7300 m) for off-momentum losses. The distributions of losses for each beam are also very different, as the BLM signals are peaked at the IR side where the respective primary collimators are located, and decreases in the beam direction. The identification of the loss plane, vertical vs horizontal, is less straightforward. It relies on the information from the ratio of losses measured downstream of the IR7 collimators.

The signals read from a selection of monitors (6 per beam) can be used to built a vector and the vector can be decomposed as linear combination of the 5 loss maps (4 transverse and 1 off-momentum). A singular value decomposition is applied to the scenario matrix and its Moore-Penrose pseudoinverse is then calculated. This enables the determination of the contributions from different loss scenarios. The measurement of the beam current is used to normalize the result of the decomposition in number of protons lost in each scenario. Details can be found in [9, 10].

Finally, the lifetime, assuming an exponential decay, is calculated with the following equation:

$$\tau_i = \frac{-1}{\ln\left(1 - \frac{R_i^{\mathrm{blm}}}{N_i}\right)}$$

where i is an iterator over time, R_i^{blm} is the proton loss rate from BLMs, calculated as the sum of protons lost on the 3 planes (horizontal, vertical and off-momentum), and N_i the beam intensity.

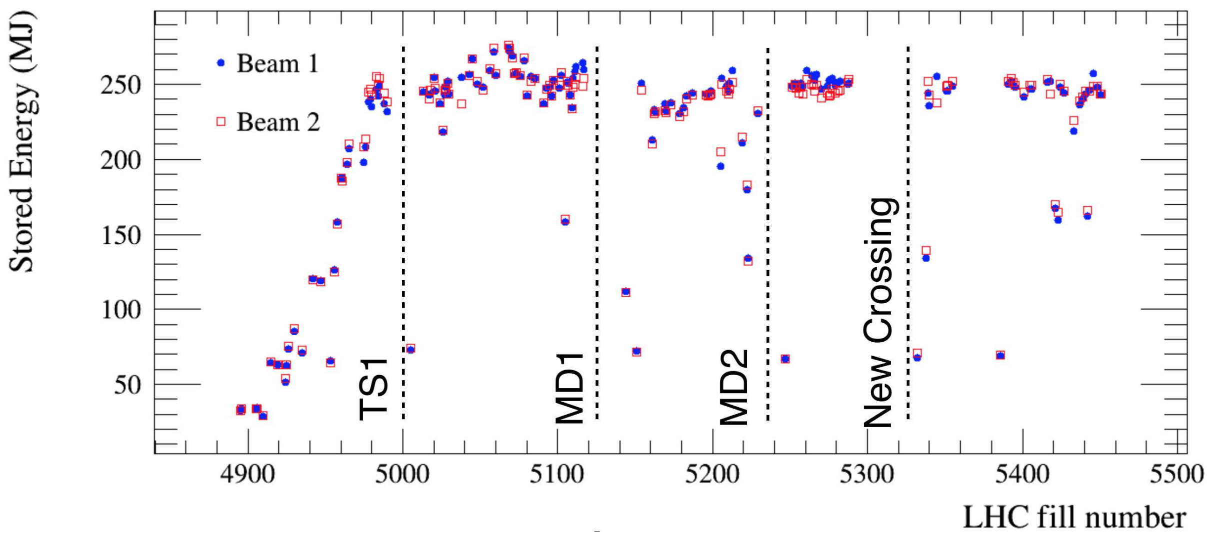

Figure 1: Stored beam energy for Beam 1 (blue) and Beam 2 (red) as a function of the fill number during the 2016 run for all fills that reached the stable beam mode. Vertical dashed lines indicate the time of some relevant interruptions of the proton beam operation: technical stop (TS) and machine development (MD) periods. A change in crossing angle in ATLAS and CMS took place in TS2, in Sep. 2016.

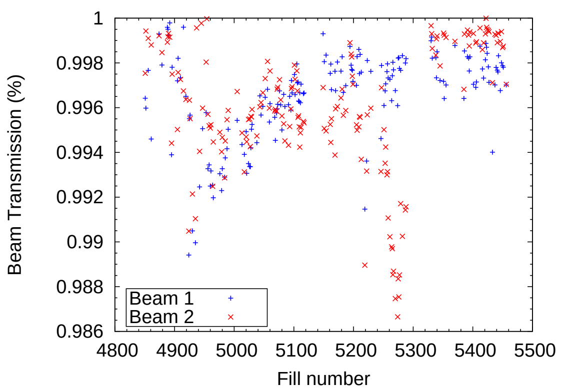

Figure 2: Beam transmission from start to end of the energy ramp as a function of the fill number, for all the fills that reached stable beams in 2016.

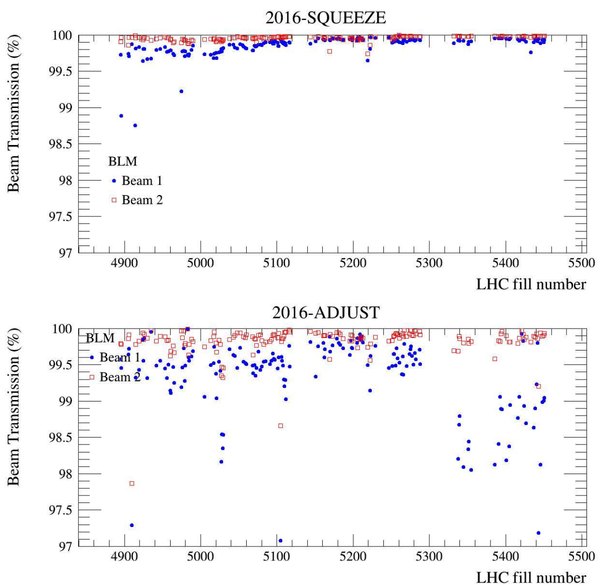

Figure 3: Beam transmission as a function of the fill number in the squeeze and adjust modes as computed from the BLM loss data analysis.

BEAM LOSSES IN 2016

Beam losses in the energy ramp are shown in Fig. 2 where the intensity transmission from start to end of the ramp is given as a function of the fill number. This analysis is carried out by using the fast beam current transformer (FBCT) data because the calibrations of the BLM signals to p/s is not optimized for the energy ramp when primary collimators are moving. Losses during the ramp are typically below 1 %. This is an excellent result that shows that the beam dynamics in this phase was very well controlled. Note that BCMS beams were deployed in the middle of July 2016, corresponding to fill numbers larger than 5100 and were kept for the rest of the year. The effect on losses with these beams, which features a smaller emittance than the standard beams, are not apparent.

The beam transmission as calculated from the BLM analysis in the squeeze and adjust modes is given as a function of the fill number in Fig. 3. The corresponding minimum beam lifetime is given in Fig. 4. Overall, the performance in 2016 was very good also in these phases. Losses remained well below 0.5 % throughout the squeeze beam process. They are slightly larger during the adjust. It is however important to note that the adjust mode in 2016 included some minutes with head-on collisions already established in IR1/5, so some losses can be attributed to the burn-off from high-luminosity collisions. By looking at the

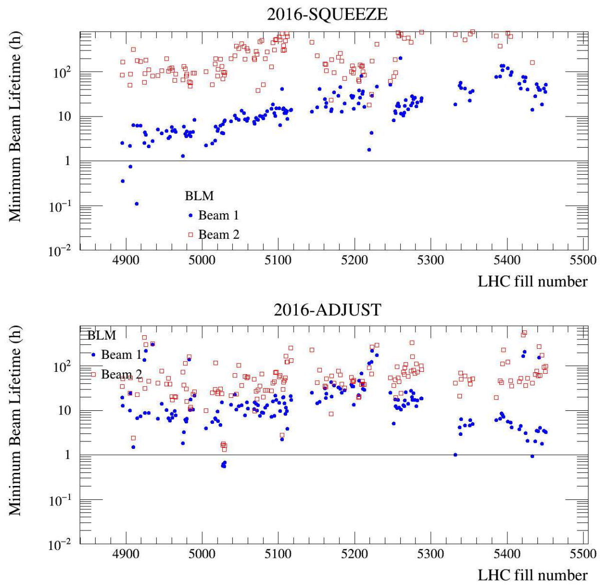

Figure 4: Minimum beam lifetime in the squeeze (top) and adjust (bottom) modes as computed from the BLM loss data analysis.

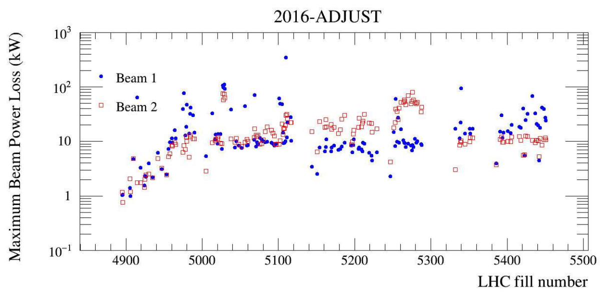

Figure 5: Peak power lost recorded in the adjust mode of all protons fills in 2016 that reached the stable beams mode, as a function of the fill number.

beam lifetime computed in this analysis (Fig. 4), one can see that peak losses remained under good control also in adjust, with minimum lifetime values consistently above 1 h (to be compared with the design value of 0.2 h for the collimation system). Larger losses of Beam 1 were observed throughout the year, in particular after the change of crossing angle. This feature, though not worrying as absolute losses were under good control, remains to be understood.

The corresponding peak power loss for the adjust mode, where losses were larger, is given in Fig. 5. This corresponds to primary beam losses lost from the beam core and intercepted by the primary collimators in IR7. Their energy is primarily disposed of within IR7. Thresholds of the BLMs in IR7 were set to allow a 200 kW peak loss [6], to be compared to the collimation system design limit of 500 kW [11]. It is clear that the LHC was operated with significant margins for beam losses. Note that no fill was lost because of IR7 losses, which is a remarkable result.

Squeeze and adjust losses, expressed as histogram distributions of the total loss per mode, are compared in Fig. 6 to

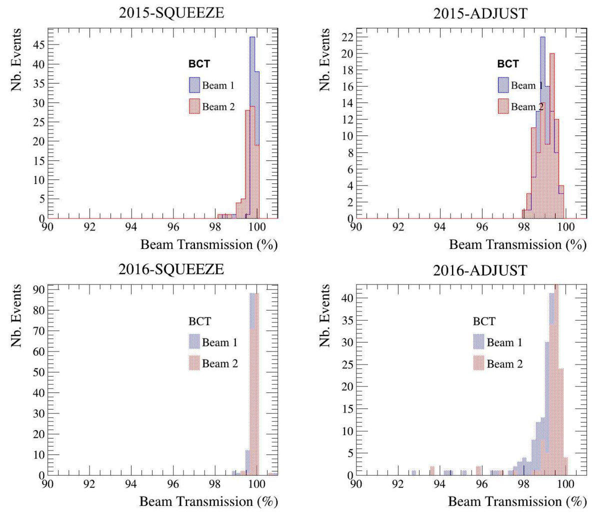

Figure 6: Distribution of peak losses in squeeze (left column) and adjust (right) in 2015 (top row) and 2016 (bottom).

the respective measurements from the 2015 run. Squeeze losses are significantly lower in 2016, despite the final β^* was smaller by a factor 2. This result can be attributed, amongst others, to a better control of the beam orbit during the squeeze [12]. In 2016, adjust losses are similar, or even slightly better, than in 2015, with the caveat already mentioned that in 2016 the collisions in IR1/5 were integrated for longer times to accommodate additional collision beam processes. Deeps of lifetime drops lead to total power losses that remained below the typical values achieved at the end of 2015.

A preliminary analysis of loss decomposition of squeeze and adjust losses, carried out with the formalism introduced in the previous Section, is shown in Fig. 7 and Fig. 8, respectively. For each beam, the fractions of total losses identified as betatronic horizontal, betatronic vertical and off-momentum are given. During the squeeze, the main plane of loss is changing over the run whereas in adjust one sees a dominant contribution (vertical for Beam 1 and horizontal for Beam 2) through the year. Between fills 5150 and 5250, squeeze losses of both beams show an increase of vertical content. This feature is not yet understood. Off-momentum losses that manifest themselves through impacts on the IR3 primary collimators are very low for Beam 1 but they could reach more than 50% of the losses for Beam 2 during squeeze. Note however that absolute loss levels were small in this mode.

During adjust, the losses are mainly in the transverse plane, with the largest contribution being the horizontal one. After the reduction of crossing angle (fills above 5300) there were several fills with higher vertical losses for Beam 1. This was corrected by an optimization of the vertical tune that was shifted away from the third order resonance [3]. This recovered the qualitative loss sharing observed before the crossing angle change (see Fig. 8).

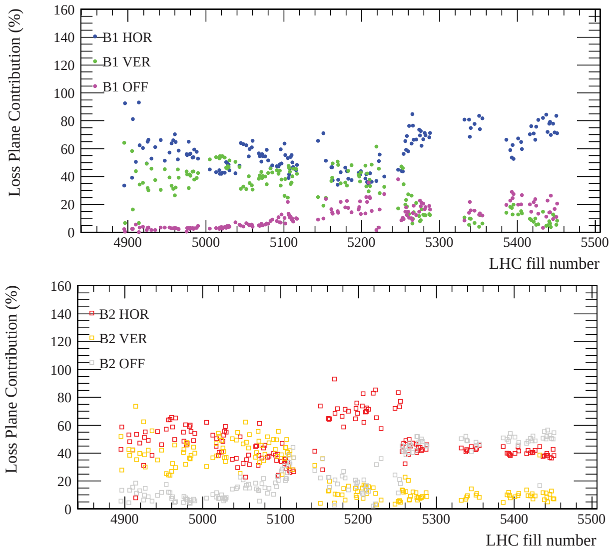

Figure 7: Decomposition of squeeze beam losses as a function of fill number, expressed in percentage of total losses.

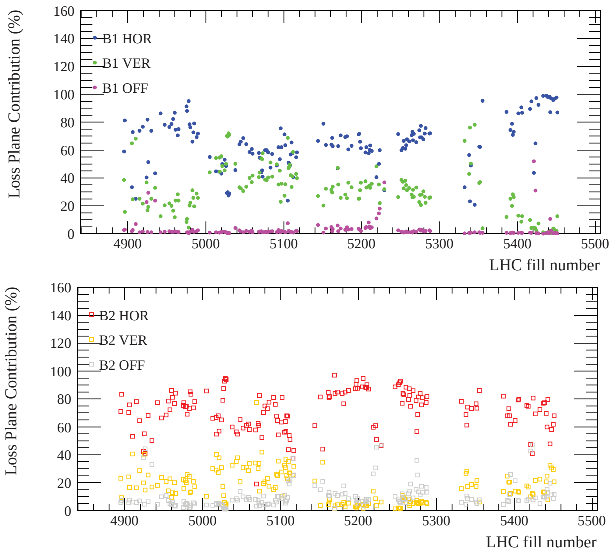

Figure 8: Decomposition of adjust beam losses as a function of fill number, expressed in percentage of total losses.

CONCLUSIONS

In 2016, the LHC beam losses were kept under very good control throughout the operational cycle. Typically, less than 1 % of the beams were lost in the energy ramp according the beam current measurements. The combined ramp and squeeze, deployed for the first time in operation, apparently played no significant detrimental role in the loss performance during the beam acceleration to 6.5 TeV. Squeeze losses were kept well below 0.5 % with stored beam energies of about 250 MJ routinely achieved in physics fills. This is definitely a remarkable result considering that the β^* in the high-luminosity experiments was 40 cm, i.e. a factor 2 smaller than in 2015 and 30 % less than the LHC design value of 55 cm for the operation at 7 TeV.

Losses in adjust, when the collisions are setup and optimized in all experiments, were also at very modest levels. Minimum beam lifetime values did not go below 1 h throughout the year, therefore remaining a factor 5 above the design value for collimation beam losses of 0.2 h. Maximum power losses were consistently below the 200 kW conservative set point for interlock settings on IR7 losses, and no dumps from beam loss were recorded. On the other hand, absolute losses in adjust did reach levels above 1-2 %. Even though this can be attributed partly to the complexity of the orbit gymnastic in the collision points, rather than to intrinsic problems of beam stability, this remains definitely an area for possible improvements in 2017.

Preliminary results of loss decomposition were also shown for squeeze and adjust losses. This work will continue in 2017 and be applied systematically to operational loss analysis, as it provides insights of the source of losses which cannot be derived from the standard loss analysis from beam current measurements.

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