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BEAM DIAGNOSTICS FOR STUDYING BEAM LOSSES IN THE LHC

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Abstract

The LHC is well covered in terms of beam loss instrumentation. Close to 4000 ionization chambers are installed to measure global beam losses all around the LHC ring, and diamond detectors are placed at specific locations to measure bunch-by-bunch losses. Combining the information of these loss detectors with that from additional instrumentation, such as current transformers, allows for enhanced understanding and control of losses. This includes a fast and reliable beam lifetime calculation, the identification of the main origin of the loss (horizontal or vertical betatron motion or off-momentum), or a feedback to perform controlled off-momentum loss maps to validate the settings of the collimation system. This paper describes the diagnostic possibilities that open up when such measurements from several systems are combined.

INTRODUCTION

The Large Hadron Collider (LHC) is designed to provide proton-proton collisions at the unprecedented beam energy of 7 TeV. It is hosted in the former LEP tunnel [1], about 100 m underground, and has a circumference of 26.7 km. In order to keep the proton beams on a circular trajectory at such high energies, 1 232 superconducting dipole magnets are used; each cooled down to 1.9 K and providing a magnetic field up to 8.33 T.

Even a small deposition of beam energy of the order of 100 mJ/cm^3 [2], risks to initiate a quench of the LHC magnets, resulting in a loss of superconductivity. This corresponds to a tiny fraction of the circulating beam, with the LHC operating regularly with stored beam energies of around 300 MJ. Figure 1 shows the total stored beam energy reached during LHC Run 2 (2015-2018) as a function of time when running at a collision energy of 13 TeV (6.5 TeV per beam).

In order to fulfill the machine protection requirements for the LHC, the beam has to be extracted within 3 LHC turns (1 LHC turn corresponding to 89 µs), in case of losses exceeding given thresholds. The fast detection of beam losses all along the machine is therefore crucial in order to ensure the protection of the LHC magnets and other equipment and guarantee a high operational efficiency. For this reason, more than 4 000 beam loss detectors are installed, covering all the critical loss locations. This includes the cold superconducting magnets, transfer lines for losses during beam injection, the dump lines for losses during extraction, and more than 100 LHC collimators monitoring the losses from beam halo cleaning. In addition to triggering a beam abort, the LHC beam loss monitoring (BLM) system provides additional information about the beam loss characteristics such as loss patterns or loss location. We describe here the use of the LHC BLM system for advanced beam diagnostics, covering both the standard ionization chamber detectors and the fast, bunch-by-bunch diamond-based beam loss detectors.

BEAM LOSS IONIZATION CHAMBER

The main LHC BLM system is composed of around 3 600 ionization chambers (IC BLM) and 400 secondary emission detectors (SEM) located throughout the LHC ring [3, 4]. Together they provide an overall view of the beam losses in the machine at any given time. Figure 2 shows an example of this view; the x-axis represents the position of each monitor in the LHC ring and the y-axis shows the beam loss measured at each monitor normalized to the maximum measured beam loss. The insertion regions (IRs) are marked: the experimental insertions are IR1, IR2, IR5 and IR8; the main collimation locations are insertions IR3 (momentum cleaning) and IR7 (betatron cleaning); the acceleration with radio-frequency cavities (RF) are located

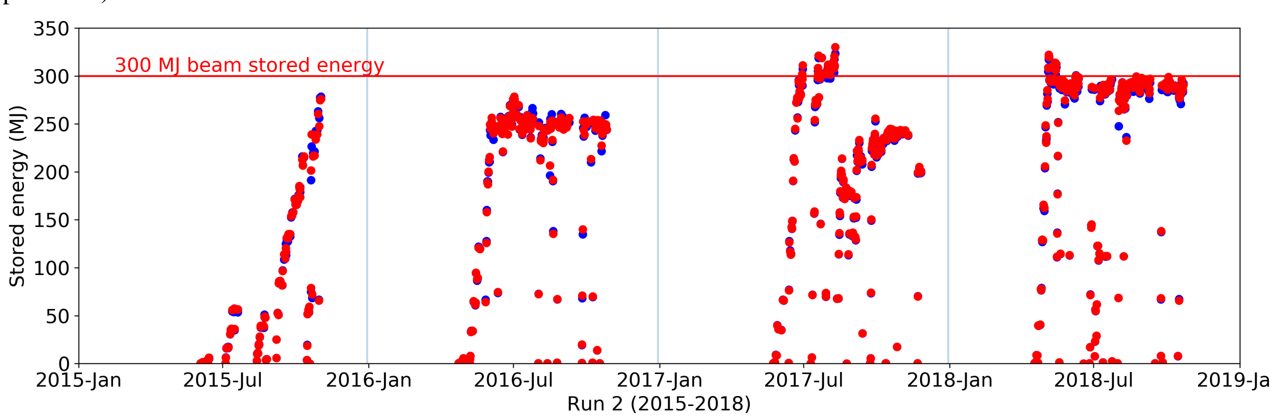

Figure 1: Maximum stored beam energy at the LHC over time during Run 2, each point represents one fill, for Beam 1 (blue points) and Beam 2 (red).

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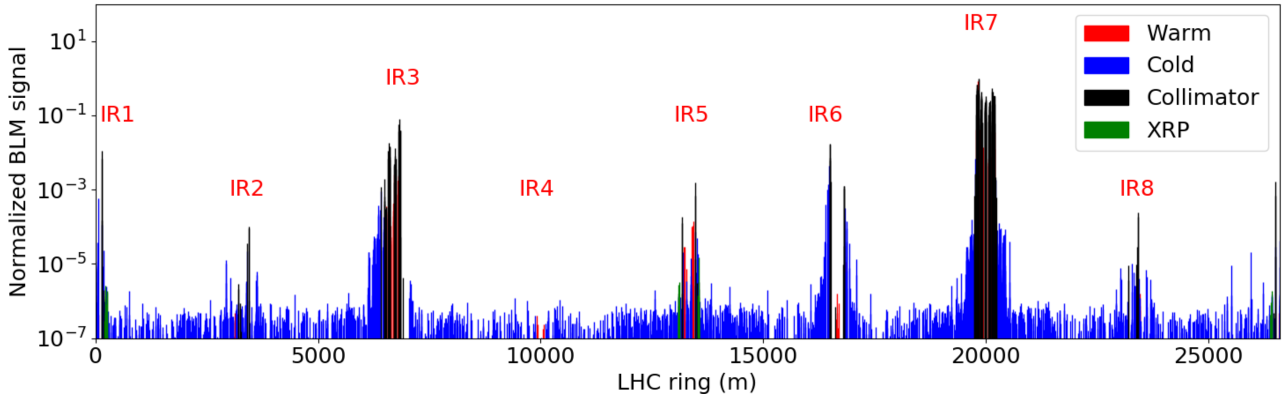

Figure 2: Normalized beam losses measured with ionization chambers along the LHC ring, each line corresponds to the measurement of one IC BLM.

in IR4; and the beam extraction to the dump channel is done in IR6.

Each IC BLM detector is made of a cylindrical tube of about 50 cm hosting parallel aluminum electrode plates separated by 0.5 cm holding a high-voltage of 1.5 kV. The tube is filled with about 1.5 L of nitrogen at 100 mbar over-pressure. Figure 3 shows a picture of an LHC IC type detector, with the metallic cover opened to display the interior.

The charges collected by the ionization chamber from the secondary particles created from lost protons is read-out using charge to frequency conversion with a dynamic range of 10^8, corresponding to currents from 10 pA to 1 mA. The measurement is provided in Gy/s in 12 different moving windows known as "Running Sums (RS)", ranging from 40 µs to 83.9 s. This allows the configuration of unique beam extraction thresholds as a function of the duration of the beam loss. Different beam abort thresholds as a function of the beam energy are also used.

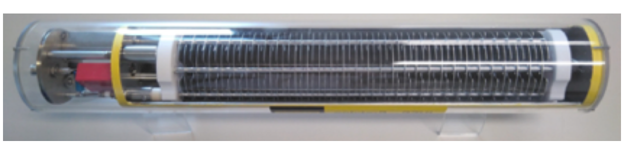

Figure 3: Picture of one IC BLM detector with the cylinder open in order to show the interior.

DIAMOND BEAM LOSS MONITORS

Complementary devices to the standard IC BLM chambers have also been installed in several locations [5,6]. These are diamond solid state detectors (dBLM) with an active volume of 10 mm × 10 mm × 0.5 mm. dBLM detectors have a linear response over a dynamic range of 10^9 with the advantage of providing fast time resolution data in a timescale of the order of a ns. As the minimum LHC bunch spacing is 25 ns, this means that the dBLM can provide bunch-by-bunch beam loss information.

Several dBLM units have been installed in the LHC during Run 2 covering:

- injection and extraction losses, one dBLM unit per beam (total 4),
- collimation betatron cleaning, three dBLM units per beam in IR7 and
- additional units in IR4 and in the injection transfer lines.

This contribution will focus on the signal of the dBLM detectors in IR7, as they provide the best measurements of circulating beam losses. Figure 4 shows a picture of the installation in one of the collimation areas in IR7.

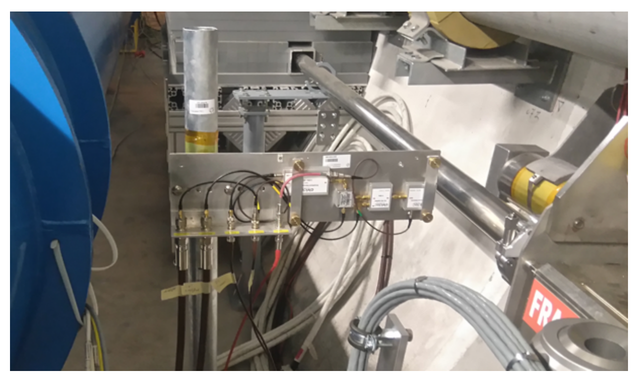

Figure 4: Picture of one Diamond BLM in the LHC tunnel in one of the collimation areas. Image credit: J.Kral.

The dBLM installed in IR7 are read-out using a 14-bit 600 MHz FMC ADC connected to a CERN Beam Instrumentation standard VME FMC carrier board (VFC-HD) [7]. The data processing from this system provides bunch-by-bunch losses in a counting histogram mode together with additional information such as the loss integral per bunch over a defined time period, the analysis of fast frequency losses and an internal trigger based on the signal shape of per-turn losses.

The so-called histogram mode or time-loss histogram provides an array of values corresponding to one LHC turn binned in slots of 1.6 ns. The measured signal is compared to a programmable threshold with a count registered in the corresponding bin if the signal is above the threshold. The counts are accumulated over a time period of 1 s. Figure 5 shows the concept of the time-loss histogram.

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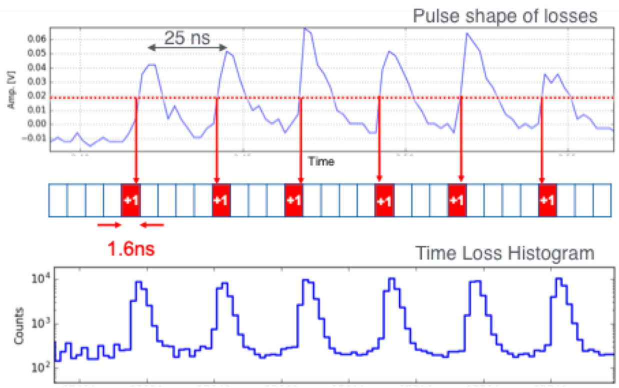

Figure 5: Raw amplitude signal as a function of time (top). Resulting histogram with bins of 1.6 ns with the accumulated counts on the y-axis (bottom). Image credit: Ch.Xu.

CALIBRATION OF BLM DETECTORS

DC current transformers (DC-BCT), measuring the average circulating beam current, are used to provide the absolute measurement of beam loss rate ($\mathrm{d}I/\mathrm{d}t$) or lifetime. However, at the LHC, this method requires the acquisition of the signal over several seconds. Figure 6 shows the measured signal of the LHC DC-BCT during standard stable beam collisions (left) and the estimation of the noise in the measurement (right). The DC-BCT can measure beam current of the order of $3 \cdot 10^{14}$ charges and its decay over time, with fluctuations at the 0.002% level for integration time of 1 second. For comparison, Figure 2 shows the loss map performed with IC BLM signals recorded for a beam loss of a few 10^9 protons in 1.3 s. This indicates that the IC BLM detectors are more suitable for the measurement of small loss transients as the signal-to-noise ratio is higher. However, since it is an indirect method of measuring the number of charges lost from the beam, they need to be calibrated to give absolute loss values in terms of number of protons.

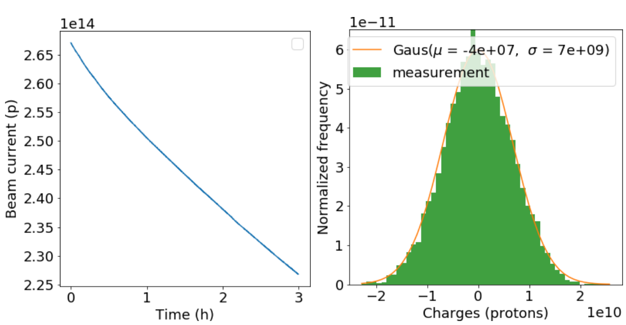

Figure 6: Beam current measurement at LHC during stable beams (left) and statistical noise analysis of the measured signal (b).

The following method used to calibrate IC BLM assumes that primary losses will always be initiated at the primary collimators. This is true for most of loss scenarios, except when local losses occur, such as dust particles falling into the vacuum chamber of certain magnets or local beam-gas interactions [8–10].

During LHC Run 1 (2010-2013), a calibration for individual IC BLM detectors was performed using two different types of input data:

- Dedicated beam scraping studies where a single collimator scrapes the beam in steps and both the BLM signal and the beam current are measured. A simple fit between the BLM signal and the total change of beam current gives the calibration [11].
- Analysis of regular beam losses during the LHC cycle. A fit to the BLM signal and the time derivative of the beam current is performed for different phases of the machine cycle. The advantage of this method is that no extra machine time is needed to calculate and validate the calibration [12].

A more sophisticated analysis was done in Run 2 including information from several monitors. There are about 100 collimators installed in the LHC and each one has a BLM downstream. Losses are initiated at the primary collimators, which have the smallest machine aperture, but the shower of particles will still travel on around the ring. Different loss patterns will be observed depending on the nature of the losses (horizontal, vertical or longitudinal). The signal of several BLM detector can therefore be linearly combined in order to provide a better measurement. In the next section specific calibrations depending on the final usage of the BLM data are explained.

BEAM LIFETIME

The beam lifetime (τ) is a parameter used to monitor the performance of the machine. It is defined as the time needed for the beam current (I) to decrease by a factor $1/e$:

$$I = I_0 e^{-\frac{t}{\tau}} \rightarrow \tau = -\frac{I}{\mathrm{d}I/\mathrm{d}t} \tag{1}$$

Fast drops of beam lifetime point to high and fast losses that risk to generate a quench, for this reason they need to be monitored continuously. For this specific case, one would like to measure the absolute number of protons lost per second ($\mathrm{d}I/\mathrm{d}t$) independently of the nature of the loss.

The solution proposed was to select 4 BLM detectors per beam that give similar signal for beam losses in different planes (horizontal or vertical). In this case the signal that is calibrated is the sum of the 4 monitors:

$$\frac{\mathrm{d}I}{\mathrm{d}t} = \alpha \cdot \sum_{i=1,4} S_i^{\mathrm{BLM}} \tag{2}$$

were α is the calibration factor and S_i^{BLM} is the BLM detector signal for monitor i of the selected BLMs.

This quantity was operationally implemented and is used regularly to provide on-line monitoring of the LHC beam lifetime. Figure 7 shows the reconstruction of the beam lifetime during beam scraping studies at the LHC. Lifetime drops occur every time the collimator touches the beam halo.

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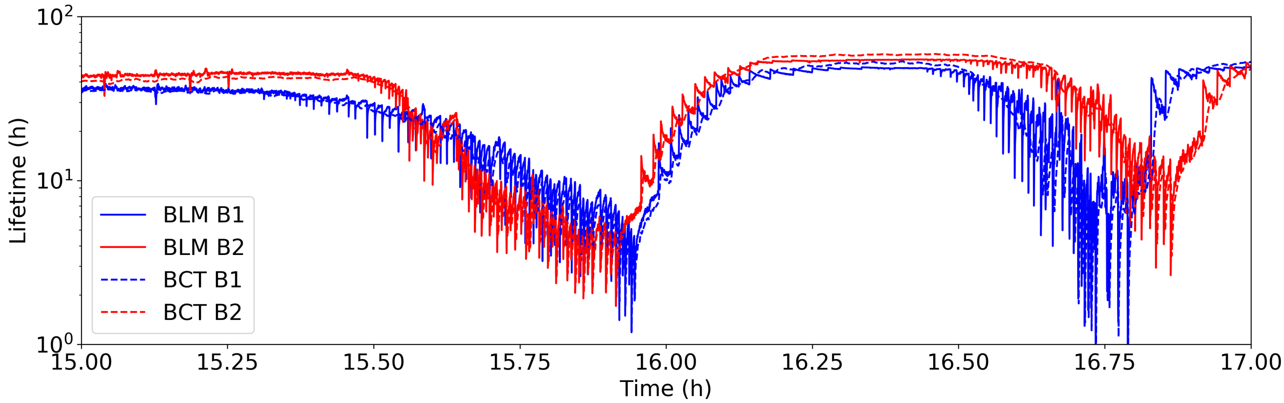

Figure 7: Beam lifetime during beam halo scraping at the LHC reconstructed with the combination of 4 BLM detectors per beam (solid lines) and the BCT (dashed lines).

The measurement is on average consistent with the beam current measurement, with the better response of the BLMs to fast losses clearly visible.

IDENTIFICATION OF BEAM LOSS PLANE

The identification of the orientation of the beam losses is also useful in order to understand how to optimize machine parameters. As an example, a better working point for the vertical tune was found when observing asymmetric beam losses between the horizontal and vertical plane.

The identification of the beam loss plane is possible because there are three primary collimators, one after the other in IR7 with three different rotational angles. The first primary collimator has the collimator jaws in the vertical plane, providing primary vertical halo cleaning. The second primary collimator is few meters downstream and provides horizontal halo cleaning, while the third primary collimator is set with an angle of 127.5 deg. Figure 8 shows a diagram of the position and orientation of these three primary collimators in IR7. The signal per proton lost measured by the BLM detectors depends on the origin of the losses. Beam losses initiated in the vertical collimator will give a signal in the BLM downstream the vertical collimator and an even larger signal in the BLMs further downstream. However, beam losses initiated at the horizontal collimator will only give a very small signal in the BLM of the vertical collimator. This is illustrated in Figure 9. The loss pattern in collimators further downstream will also depend on their angle.

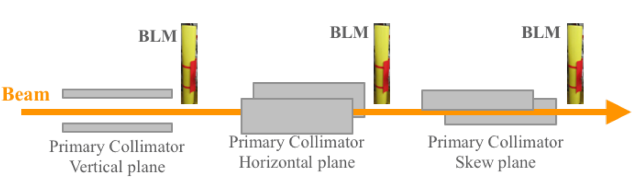

Figure 8: Diagram showing the position and orientation of the primary collimators in IR7.

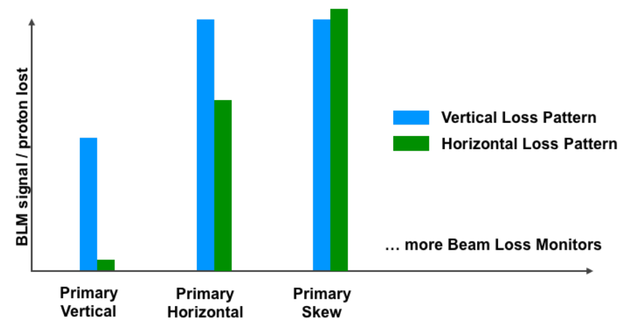

Figure 9: Diagram showing the signal of several BLM detector for different loss patterns.

The calibration factors are calculated using singular value decomposition (SVD) to provide the number of protons lost in the horizontal and vertical plane in IR7 and in the longitudinal plane (off-momentum losses) in IR3 [13]. In order to calculate the calibration matrix we need to generate beam losses in well-defined scenarios that can be used to calculate each matrix coefficient. This is achieved with beam halo scraping data in the different planes or with dedicated loss maps.

Loss maps are performed regularly at low beam intensity, less than $3 \cdot 10^{10}$ protons, in controlled configurations. Transverse losses are achieved by exciting the beam using white noise injected into the horizontal or vertical transverse damper system [14]. The effect of this excitation is to enlarge the beam transversely in a given orientation such that it is scraped at the collimators in the defined plane. Longitudinal losses are created by changing the frequency of the radio-frequency cavities. This shifts the beam orbit as a function of the machine dispersion, which is larger at the collimators in IR3. Figure 10 shows an example of loss maps done in the vertical plane for Beam 1 (top), horizontal plane for Beam 2 (middle) and longitudinal plane for both beams (bottom).

The result after calibration is a vector containing the number of protons lost in the different loss scenarios. This decomposition could be applied online on a subset of BLM signals. The sum of the decomposed loss for each beam should equal the total beam loss. Figure 11 shows an exam-

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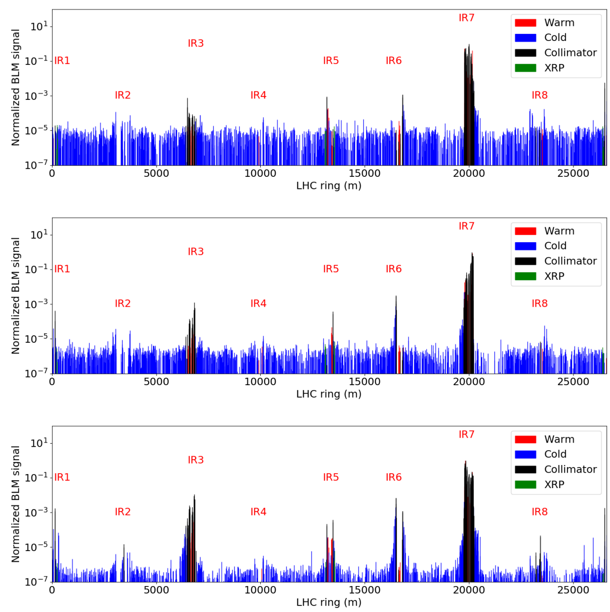

Figure 10: Loss maps for three different configurations: Beam 1 vertical losses (top), Beam 2 horizontal losses (middle) and both beams off-momentum losses (bottom).

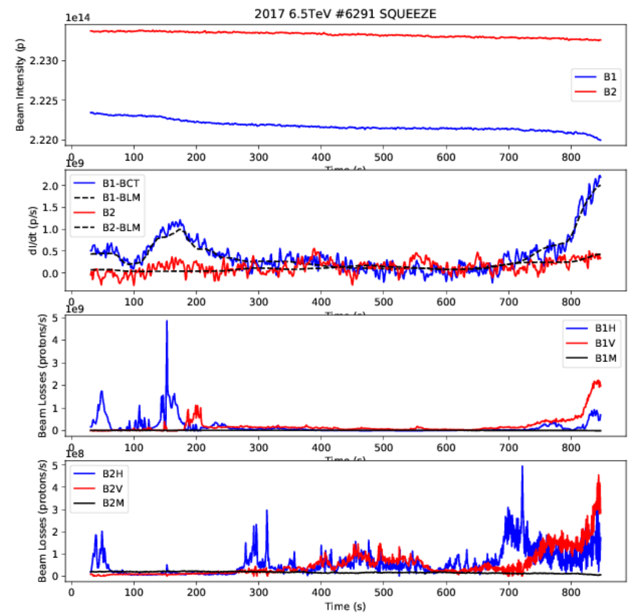

Figure 11: Example of beam loss decomposition. Stored beam current as function of time (top), beam loss rate as a function of time (middle), beam loss rate for each plane as function of time (bottom).

ple of this type of decomposition for Beam 1. The top plot shows the stored beam current measured by the BCT as a function of time. The middle plot shows the beam loss rate calculated from the BCT and from the BLM signal calibrated with the SVD coefficients (sum of all protons lost from the 3 different loss scenarios). And the bottom plots shows the beam loss rates in the horizontal, vertical and longitudinal planes. This data corresponds to a regular physics fill of the LHC in 2017 during the process of squeezing the beams in the experimental regions.

BUNCH-BY-BUNCH LOSS PATTERN

Diamond BLM detectors have better time resolution than the IC BLM detectors. This allows then to measure the bunch-by-bunch loss structure which serves to determine if losses come from aperture restrictions or from other mechanism such as instabilities or long range interactions. An example of these types of measurements is shown in Figure 12. The top plot shows the full time-loss histogram for the LHC, with x-axis representing one full turn of 89 µs and the y-axis the loss counts accumulated in each 1.6 ns during 1 s. In this particular case the machine is filled with a train of 12 bunches (as seen on the very left of the picture) and then with trains of 144 bunches. A zoom into the first bunches (middle plot of Figure 12) shows the structure of losses inside the beam trains. A qualitative analysis of the pattern already provides the following information:

- Higher losses in the first bunch of the second full train are found systematically. This could be due to the way the batches are formed in the injector chain.
- Losses increase smoothly from the head of a train towards the tail of a train. This is a typically indication of electron cloud formation.
- An increase of losses for the bunches in the middle of the train. This corresponds to bunches with more long-range beam-beam interactions.

The measurement and understanding of the loss pattern for different bunches can therefore help to improve the performance of the machine by applying appropriate mitigation measures.

OFF-MOMENTUM LOSS MAP FEEDBACK

The validation of the LHC configuration through the use of loss maps is done at every stage in the LHC cycle: at injection energy with injection protection collimators inserted and retracted, at the end of the energy ramp, at the end of the optics squeeze, and when the beams are colliding. Additional loss maps re performed for different beta-star settings and with the roman pots (very forward physics detectors) inserted and retracted. The off-momentum validation of a single configuration requires two dedicated fills (to probe both off-momentum sides), where the beams are completely lost on the IR3 collimators through an RF frequency change. With a minimum of 5 to 8 configurations to be validated this implies a significant loss of physics time, as re-injecting and ramping the beam after each loss-map takes at least 2 to 3 hours. In order to perform these off-momentum loss maps in a controlled way without losing the beam, a feedback based on the signal from beam loss monitors located downstream each collimator was developed.

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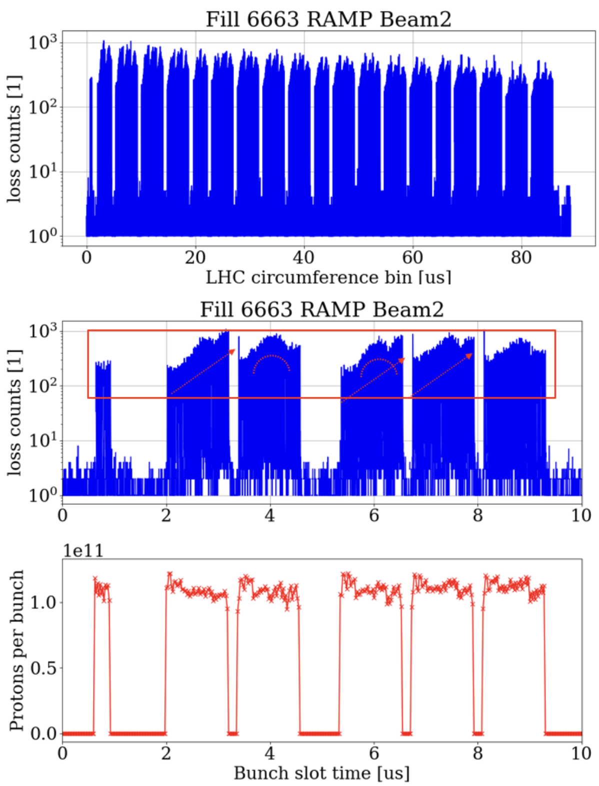

Figure 12: Loss count distribution from dBLM detectors as a function of bunch location (top) with its zoom (middle). Number of protons per bunch as a function of the zoomed area (bottom). Image credit: A.Gorzawski.

The IC BLM data is published every 1 Hz for each of the 12 moving average windows. A special, fast data stream of the 10.06 ms integration window was made available at the higher rate of 100 Hz. To perform the off-momentum loss maps using loss feedback, the RF frequency is changed in steps while losses in a subset of collimators are monitored via this fast data stream. The RF frequency change is reverted to the initial value when losses exceed a certain threshold or a particular combination of losses in different monitors occurs. Figure 13 shows the losses after a primary collimator in IR7 (blue) and a primary collimator in IR3 (red) together with the RF frequency shift (black) as function of time. With this technique the beam is not totally lost and several validations can be performed with the same beam within the same LHC cycle, saving a lot of time.

CONCLUSION

During Run 2 the additional use of existing beam loss measurement detectors has been explored for improving beam diagnostics by combining information from different devices and performing cross-calibration. In this way, beam loss monitors have been used to provide absolute measurements of the number of protons lost in the machine, as well as knowledge on whether they were lost horizontally, vertically or due to being off-momentum. They have also been successfully used in an active feedback to control off-momentum loss maps to gain considerable physics time. New fast, diamond BLMs have been used to measure the bunch-by-bunch beam loss structure, giving additional details on the origin of losses, and allowing mitigation measured to be put in place to further optimize machine performance. The cross-calibration of these detectors is also foreseen for the future.

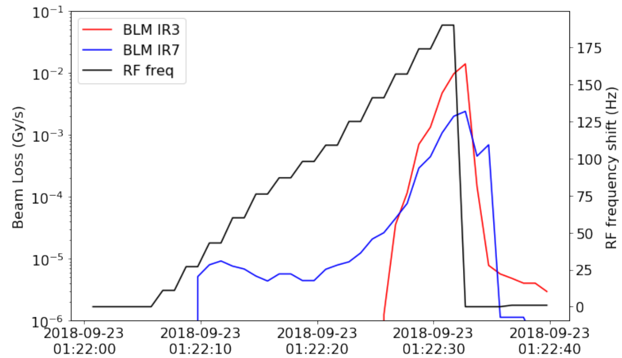

Figure 13: Distribution of beam losses after a primary collimator in IR3 (red) and in IR7 (blue) together with the change of RF frequency (black) as function of time.

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