DECOMPOSITION OF BEAM LOSSES AT LHC

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Abstract

The LHC collimation system provides betatron cleaning and off-momentum cleaning in two different locations of the LHC ring. In the betatron cleaning area, three primary collimators cut the primary halo in horizontal, vertical and skew planes. The beam loss monitors located downstream each of these collimators can be used to diagnose the main plane of loss. We present here a method to identify these beam losses at the LHC and decompose them as a linear combination of loss scenarios using singular value decomposition to calculate Moore-Penrose pseudoinverse of the scenario matrix. This matrix has been used to evaluate the type of beam losses in different stages of the LHC cycle.

INTRODUCTION

Due to unprecedented beam energies in the LHC (close to 360 MJ per beam) it is vital to control and understand beam losses. At the LHC, halo beam cleaning and passive machine protection is provided by a complex collimation system with 108 movable collimators [1]. The collimators are installed in horizontal, vertical and skew planes to cover the full phase space. Primary, secondary and absorber collimators are distributed in two main warm insertion regions: IR3 for off-momentum cleaning and IR7 for betatron cleaning.

In addition, the four interaction regions are also equipped with tertiary collimators for triplet magnet protection. Physics debris cleaning is provided in IR1 and IR5 where the high luminosity experiments, ATLAS and CMS, are located.

Beam losses are measured by more than 3900 Beam Loss Monitors (BLM) that are distributed around the ring [1, 2]. Losses are constantly monitored and if one single monitor has a measured signal above a defined threshold the beam is quickly extracted from the machine.

Each collimator is equipped at least with one BLM. Because collimators are the smallest aperture of the machine in all scenarios for high-intensity operation primary losses will be at the collimator locations. The BLMs located downstream the collimators are the most sensitive to losses and could be used to get information about the type of loss [3].

DECOMPOSITION OF LOSSES

The BLMs are the perfect devices to measure beam losses at the LHC, however, as they are ionization chambers, their signal is provided in Gy/s. In Run I a calibration of the signal to protons/s from a single BLM downstream a primary collimator in IR7 was calculated. This was done through (a) dedicated beam scraping studies where the beam was progressively cut by a primary collimator and the BLM signal calibrated with the measurement of the beam current [4] and (b) through the analysis of all the regular fills in 2012 by fitting the BLM signal during the machine cycle to the derivative of the beam current measurement [5]. Both analyses proved to be very useful. A further improvement is proposed to use BLM patterns to identify the plane of losses in addition to the total amount of losses.

Instead of calibrating one single beam loss monitor we propose here to use a selected number of monitors and build a decomposition of the losses as a linear combination of well defined controlled loss scenarios. The result of this decomposition will be the number of protons lost due to each loss scenario.

LOSS SCENARIOS

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 validate the collimation cleaning.

The six basic loss scenarios are:

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

Longitudinal losses are created by shifting the RF frequency by typically ±500 Hz. This is done in order to create losses from off-momentum particles. Transversal losses (horizontal and vertical) are created by adding white noise to the beam with the LHC Transverse damper (ADT) [6]. Figure 1 shows an example of Beam 1 horizontal betatronic losses along the LHC ring normalized to the maximum loss while Figure 2 shows an example of Beam 1 and Beam 2 off-momentum losses. In these cases one can distinguish easily the different loss patterns for the two scenarios, in Figure 1 the losses are mainly in IR7 (located between 19400 and 20600 m) and in Figure 2 the losses are distributed both in IR7 and in IR3 (located between 6100 and 7300 m). The distribution of losses for each beam are also very different. One can observe the decreasing BLM signal in the beam direction. Figure 3 shows Beam 1 vertical betatronic losses, where the beam goes from left to right. Figure 4 shows Beam 2 vertical betatronic losses, where the beam goes from right to left, both zoomed in IR7. The identification of the loss plane, vertical vs horizontal, is more subtle. It relies on the information from the ratio of losses measured downstream of the horizontal and vertical collimators.

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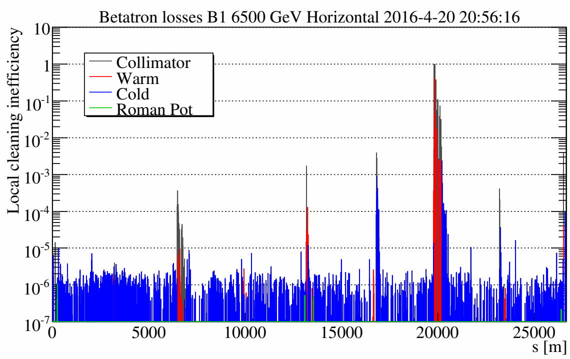

Figure 1: Distribution of beam losses in the LHC ring for Beam 1 horizontal betatronic losses. The loss signal for each BLM is normalized to the maximum loss.

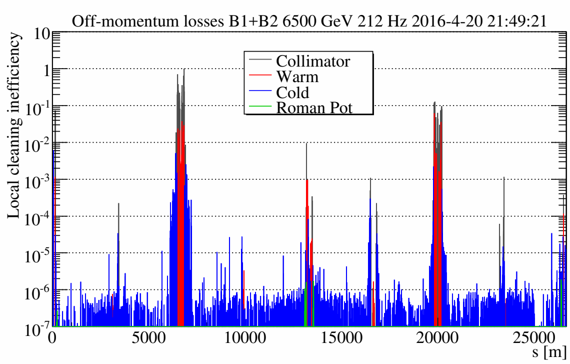

Figure 2: Distribution of beam losses in the LHC ring for Beam 1 and Beam 2 off-momentum losses. The loss signal for each BLM is normalized to the maximum loss.

ALGORITHM

Because the LHC is equipped in IR7 with 3 primary collimators, each of them with different orientation (horizontal, vertical and skew), the signal from BLMs downstream IR7 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.

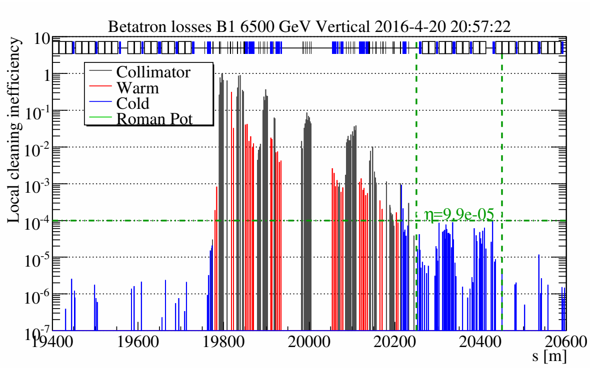

Figure 3: Distribution of beam losses in the LHC ring zoomed in IR7 for Beam 1 vertical betatronic losses. The loss signal for each BLM is normalized to the maximum loss.

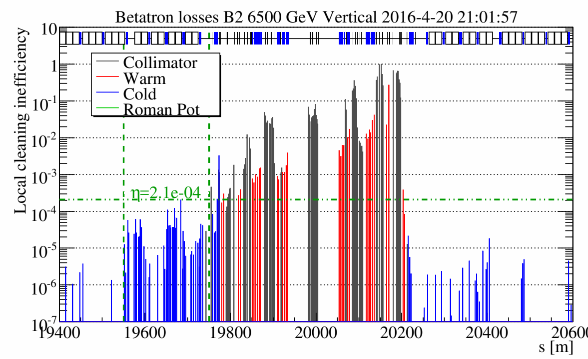

Figure 4: Distribution of beam losses in the LHC ring zoomed in IR7 for Beam 2 vertical betatronic losses. The loss signal for each BLM is normalized to the maximum loss.

The signals read from a selection of monitors can be used to built a vector and the vector can be decomposed as linear combination of the loss scenarios presented above. A singular value decomposition has been applied to the scenario matrix and its Moore-Penrose pseudoinverse has been calculated. This enabled the determination of the contributions from different loss scenarios.

Instead of using the information of all BLMs a subselection of only 6 BLMs per beam is used for the decomposition. The use of more BLMs did not improve the result of the decomposition significantly. Table 1 shows the list of collimators that were used in this analysis.

The measurement of the beam current is used to normalize the result of the decomposition in order to get the number of protons lost in each scenario.

Table 1: Collimator Name and Orientation

Beam 1	Beam 2	orientation
TCP.C6L7.B1	TCP.C6R7.B2	horizontal
TCLA.D6R7.B1	TCLA.D6L7.B2	horizontal
TCLA.A7R7.B1	TCLA.A7L7.B2	horizontal
TCP.D6L7.B1	TCP.D6R7.B2	vertical
TCLA.C6R7.B1	TCLA.C6L7.B2	vertical
TCP.6L3.B1	TCP.6R3.B2	horizontal

VALIDATION

The decomposition matrix was applied to a second set of reference loss maps, different from the initial ones used for the calculation of the matrix. Table 2 shows the result expressed as percentage of the contribution from each loss scenario. In general, the loss maps are well decomposed. In the worst case analyzed a Beam 2 vertical loss map was found to have 93 % of Beam 2 vertical losses instead of 100 %. This error might not be due to the algorithm itself but also to the nature of the beam, it is possible that, for example, a vertical betatron loss map has a small contribution of hor-

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izontal losses if the beam has been blown-up horizontally previously. Another source of losses for the second plane could be coupling. In the case of the off-momentum losses analyzed, the loss map contains losses from both beams but depending on the beam intensity and the emittance for each beam the ratios could be different, this is reflected in the percentages of 63 % for Beam 1 and 26 % for Beam 2.

Table 2: Contribution in Percentage from each Loss Scenario Computed for a Periodic Loss Map Using the Decomposition Established for a Reference Loss Map (H: Horizontal, V: Vertical, L: Longitudinal).

Loss type	Beam 1 [%]			Beam 2 [%]		
	H	V	L	H	V	L
B1H	100	0	0	0	0	0
B1V	3	97	0	0	0	0
B2H	0	0	0	100	0	0
B2V	0	0	0	7	93	0
Off-momentum	1	1	63	6	1	26

LOSSES DURING THE LHC CYCLE

The built matrix has been used to estimate the total number of protons lost during two LHC machine modes. Squeeze: when the beam size in the colliding IRs is being reduced and Adjust when the beams are set into collisions.

Figure 5 shows the time evolution of losses and the beam intensity during a random fill (number 4896) in Adjust for Beam 1. A clear correlation between identified losses and the slope of the beam intensity is visible.

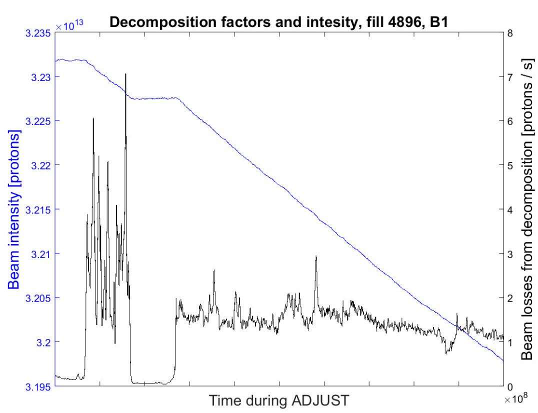

Figure 5: Beam intensity (blue) and losses from decomposition (black).

The decomposed losses during squeeze and adjust are shown in Figures 6 and 7 respectively. The total number of protons lost due to a particular scenario is shown as percentage of the initial intensity in the corresponding beam mode. In general, in 2016 LHC operation there were very small losses, well below 2 % of the beam was lost in either of the two beam modes analyzed. Beam 1 shows systematically more losses than Beam 2. In all cases they are mainly in the transverse planes (horizontally and vertically equally distributed).

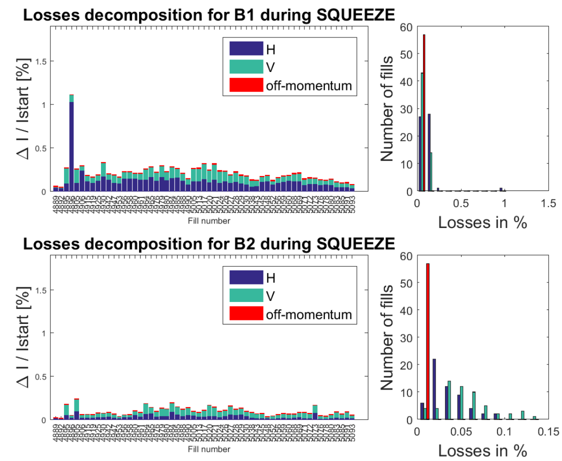

Figure 6: Decomposition of beam losses during squeeze.

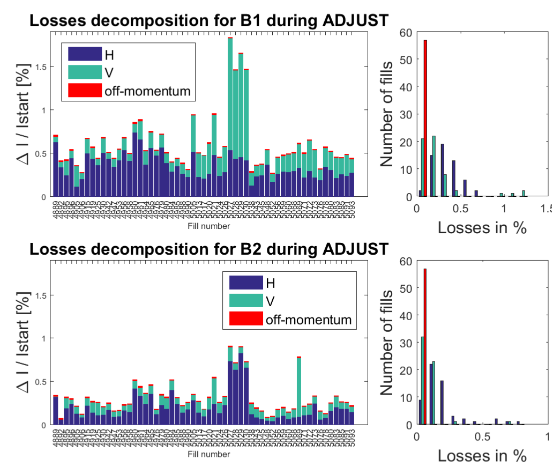

Figure 7: Decomposition of beam losses during adjust.

CONCLUSION

The loss maps used for the validation of the collimation system provide pure horizontal, vertical and off-momentum losses. An algorithm that decomposes the beam losses as linear combination of these well defined loss scenarios has been presented here. The algorithm can be used both online and offline to provide the total number of protons lost calculated from the BLM signals as well as the main loss plane. Losses during squeeze and adjust were analyzed, remaining in both cases well below 2 %. In both cases the plane of loss is mainly betatronic, either horizontal of vertical, equally distributed along the fills. This algorithm has been used at the LHC to identify specific losses that were traced to instability in specific planes.

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