ANOMALY DETECTION FOR BEAM LOSS MAPS IN THE LARGE HADRON COLLIDER

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Abstract

In the LHC, beam loss maps are used to validate collimator settings for cleaning and machine protection. This is done by monitoring the loss distribution in the ring during infrequent controlled loss map campaigns, as well as in standard operation. Due to the complexity of the system, consisting of more than 50 collimators per beam, it is difficult to identify small changes in the collimation hierarchy, which may be due to setting errors or beam orbit drifts with such methods. A technique based on Principal Component Analysis and Local Outlier Factor is presented to detect anomalies in the loss maps and therefore provide an automatic check of the collimation hierarchy.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN accelerates and collides two counter-rotating beams [1]. Proton beams are injected at an energy of 450 GeV, before being ramped to flat top (presently 6.5 TeV). The beams are then squeezed by reducing the β-function at the collision points, before bringing them into collisions. Throughout the machine cycle, the LHC machine is protected by a beam collimation system [2], which ensures that beam losses are absorbed before they can reach the machine aperture and possibly quench the superconducting magnets. The 108 LHC collimators form a multi-stage hierarchy, with the primary collimators (TCP) positioned closest to the beam, followed by the secondary collimators (TCSG), tertiary collimators (TCTP) and absorbers (TCLA). Most of the collimators are located in the betatron cleaning Insertion Region (IR7), with the remainder concentrated in IR3 for off-momentum particle cleaning and in front of the experiments.

In order to monitor beam losses, the LHC is equipped with a Beam Loss Monitoring (BLM) system [3], consisting of around 3600 ionization chambers (ICs). The beam orbit around the ring in the horizontal and vertical planes can be measured using approximately 1100 beam position monitors (BPMs) [4]. Although the TCTPs and IR6 secondary collimators are equipped with embedded BPMs following a recent upgrade [5], the rest of the collimators need to be aligned using a beam-based technique, in which each jaw is moved in steps of 5-20 μm towards the beam until a spike is observed in the BLM signal, indicating that the beam halo has been reached [6]. The beam center is computed as the average of the two aligned jaw positions.

The collimator jaw positions are then qualified by creating high losses and observing the resulting loss map, a snapshot of the BLM signals as a function of their longitudinal position in the ring. The IR7 betatron cleaning system is qualified by adding white noise to the beam using the transverse damper (ADT), to enhance diffusion [7]. The collimation hierarchy is deemed to be correctly set up when the highest losses in the ring occur at the IR7 TCPs, followed by the TCSGs and TCLAs, such that the collimation system cleaning inefficiency, defined as the ratio of the leakage of primary particles into the IR7 dispersion suppressor superconducting magnets to the losses at the primary collimator, is below $\sim 10^{-4}$ at 6.5 TeV.

Beam-based alignment and the qualification of the determined operational positions using loss maps needs to be performed at injection, flat top, at the end of the squeeze and in collisions, with functions to move the collimators during dynamic phases [8]. Thanks to the good reproducibility of the beam orbit, a yearly alignment campaign has been sufficient, however the system is re-qualified periodically, and the loss maps are qualitatively analysed. In this paper, an anomaly detection technique is proposed to detect minor changes in the loss maps over time due to collimator settings errors or orbit variations.

LOSS MAP OUTLIER ANALYSIS

The IR7 collimation hierarchy in betatron loss maps performed in 2015 and 2016 for proton beams was analyzed. A total of 12 loss maps were performed at injection (450 GeV), while 40 were performed at top energy (6.5 TeV), for both beams (B1 and B2) in the horizontal (H) and vertical (V) planes. The loss maps at top energy were done to qualify various configurations of the machine cycle (flat top, squeezed separated and colliding beams), however they can be accumulated into a single dataset as the hierarchy in IR7 is independent of the different stages which only affect the experimental regions.

A 'background' consisting of the BLM signals with beam in the machine without any excitation is first subtracted from the readings at the loss map timestamp, and the resulting values are normalized to the highest loss. From the 260 BLMs in the IR7 collimation region (19400 - 20600 m), 77 BLMs at the collimator locations in both beams, as well as empty collimator slots, were used as features for anomaly detection. In addition, all BPMs in the same region were considered. Principal Component Analysis (PCA) uses an orthogonal transformation to reduce the dimensions of a dataset by projecting it to a lower dimensional subspace. As the largest two eigenvalues account for 95% of all information in the loss map datasets [9], PCA was used to map the data to two dimensions to visualize the outliers. Local Out-

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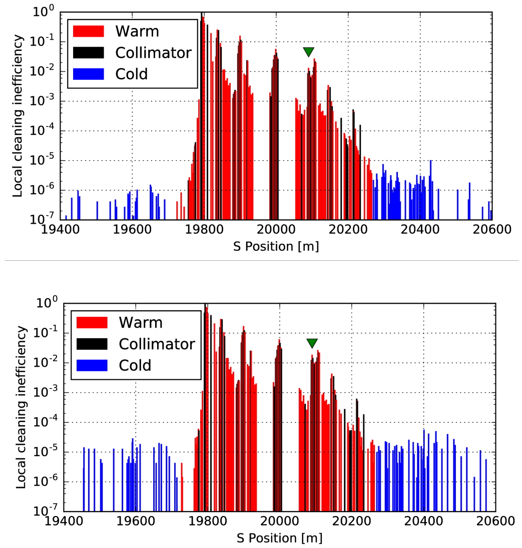

Figure 1: B1V loss maps at 450 GeV (IR7 zoom) for nominal collimator settings (top) and a 200 μm displacement in the TCLA.A6R7.B1 center (bottom).

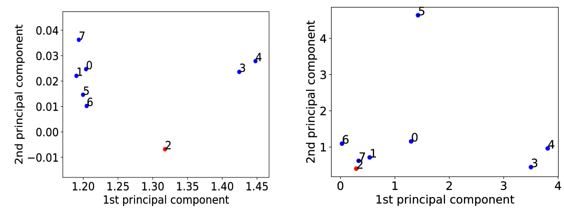

Figure 2: Principal Components Analysis of the BLM (left) and BPM (right) datasets for 450 GeV B1V loss maps.

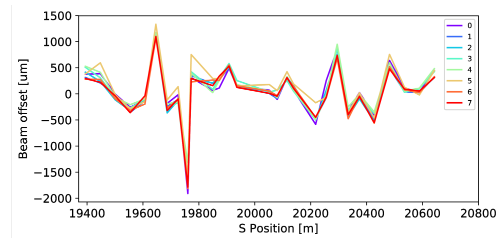

Figure 3: B1V BPM values in IR7 for 450 GeV loss maps.

lier Factor (LOF) [10] is an unsupervised learning technique which finds anomalous data points by measuring the local deviation of a given data point with respect to its neighbors. Therefore, LOF was used to compute a score for each loss map utilizing all features, with larger scores indicating a larger likelihood that the loss map is an outlier with respect to others.

RESULTS

Collimator Displacement Tests at 450 GeV

A dedicated test was performed in May 2015, in which a B1V loss map was performed at 450 GeV with the center of the TCLA.A6R7.B1 (vertical collimator) shifted by 200 μm with respect to the beam-based alignment center measured in beam commissioning a month earlier. The loss maps for these two cases are shown in Fig. 1, where the red and blue lines indicate BLMs in the warm and cold regions of the machine respectively, while the black lines indicate BLMs at collimators. A slight increase in the BLM signals of the loss map with center displacement is apparent at ~20100 m (indicated by the green marker). This loss map appears as an outlier with respect to other 450 GeV B1V loss maps in 2015 after performing PCA, shown in Fig. 2 (index 2 marked in red). The loss map indices are sorted chronologically. The BPM readings in IR7 B1V during the 8 loss maps performed at 450 GeV in 2015 are reported in Fig. 3, indicating a good reproducibility of the orbit throughout the period when the loss maps were done.

PCA analysis of the BPM readings shows that index 2 forms part of a cluster, therefore confirming that this particular loss map is different than the rest due to a collimator setting change rather than an orbit shift. Loss maps 3 and 4 were performed a few months afterwards, and from the BPM PCA an orbit shift is noted which is also reflected in the BLM PCA. Loss map 5 appears to be an outlier in the BPM PCA plot, however the deviation with respect to the other points is along the second principal component, which only represents ~10% of the information, and no corresponding difference is seen in the BLM PCA plot.

Hierarchy Limits Tests at 6.5 TeV

The objective of the hierarchy limits tests, held in July 2016, was to evaluate the IR7 collimation hierarchy with a tighter retraction of 1 σ between the TCPs (which are placed at 5.5 σ) and TCSGs, as opposed to the usual 2 σ, to be able to achieve a lower β^* [11]. First, loss maps were performed with the standard collimator settings. Then, the IR7 TCSGs were moved from 7.5 σ to 6.5 σ and another set of loss maps was taken, and following a beam-based alignment of all IR7 collimators, another two sets of loss maps were performed, first with the collimator gaps calculated using measured beam sizes determine from the procedure in [6], and then using nominal beam sizes ($1\sigma = \sqrt{\beta\epsilon}$).

Loss maps for B1H and B1V, performed with standard 2016 collimator settings, and with tighter settings during the test before beam-based alignment, are shown in Fig. 4 and Fig. 5. For B1H, the hierarchy appears to be maintained, however on closer inspection there is a slight increase in losses at ~20000 m (see green marker), which is expected as the TCSGs are now closer to the TCPs. This is reflected in the PCA analysis in Fig. 6, in which indices 10 and 12 marked in red correspond to the loss maps done with the TCSGs at 6.5 nominal σ before alignment, and with the TCSGs at the same position but with settings calculated using nominal beam sizes, respectively.

On the other hand, a clear hierarchy breakage is evident for B1V, which is also visible in the PCA analysis in Fig. 7 (index 10). Indices 10 and 12 appear as outliers in both cases due to a tilt in the collimator tank of the TCSG.D4L7.B1, causing its aperture to be tighter than foreseen using the

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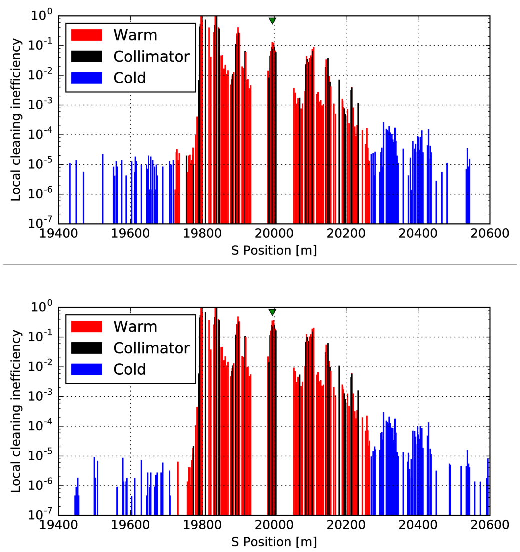

Figure 4: B1H loss maps at 6.5 TeV flat top (zoom in IR7) for standard collimator settings (top) and tight collimator settings during the hierarchy limits tests (bottom).

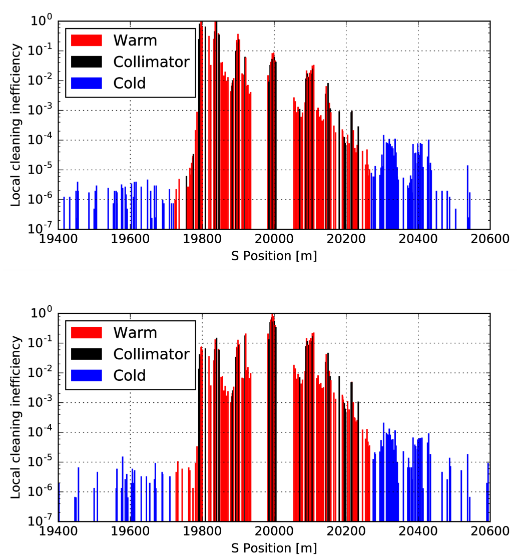

Figure 5: B1V loss maps at 6.5 TeV flat top (zoom in IR7) for nominal collimator settings (top) and tight collimator settings during the hierarchy limits tests (bottom).

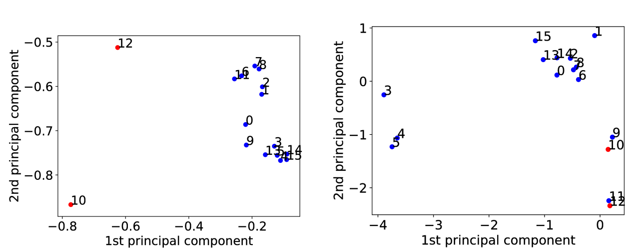

Figure 6: Principal Components Analysis of the BLM (left) and BPM (right) datasets for B1H loss maps at 6.5 TeV.

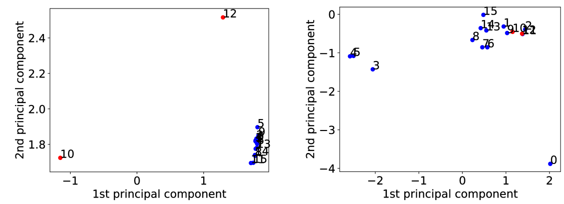

Figure 7: Principal Components Analysis of the BLM (left) and BPM (right) datasets for B1V loss maps at 6.5 TeV.

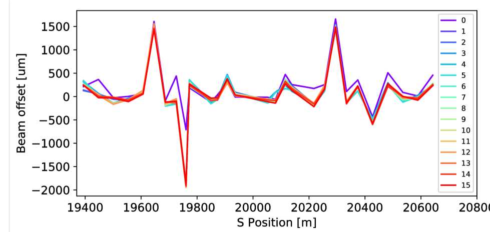

Figure 8: B1V BPM values in IR7 for loss maps at 6.5 TeV.

nominal σ. However, this issue disappears if the measured beam sizes are used (index 11), as the tilt error is reflected in the beam size and the resulting collimator gaps are now wider. The BPM readings during the B1V loss maps are reported in Fig. 8 for reference, where it can be seen that the readings in the first loss map are different from the rest. The LOF scores obtained for the BLM and BPM datasets for B1V loss maps at 6.5 TeV are shown in Fig. 9, where it can be seen that the same outliers as in the PCA analysis are obtained.

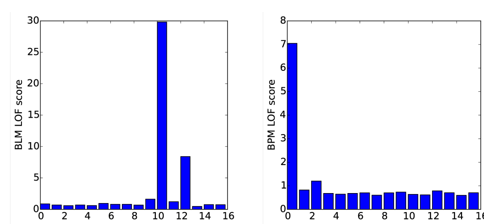

Figure 9: LOF scores obtained for BLM (left) and BPM (right) datasets for B1V loss maps at 6.5 TeV.

CONCLUSIONS AND OUTLOOK

The LHC collimation system is qualified for various points of the machine cycle at regular intervals via beam loss maps, and visual checks of the hierarchy of beam losses in IR7 is a good qualitative indicator of the correctness of the set up. In this paper, a quantitative method was proposed based on principal component analysis to reduce the problem to a two-dimensional space. In addition, a LOF model based on unsupervised learning was used in order to automatically identify anomalous loss maps based on the BLM and BPM measurements. This technique could also be extended to off-momentum loss maps, and to monitor losses during standard physics fills.

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