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OPERATIONAL RESULTS OF LHC COLLIMATOR ALIGNMENT USING MACHINE LEARNING

G. Azzopardi*, University of Malta, CERN
A. Muscat, G. Valentino, University of Malta, Msida, Malta
S. Redaelli, B. Salvachua, CERN, Geneva, Switzerland

Abstract

A complex collimation system is installed in the Large Hadron Collider to protect sensitive equipment from unavoidable beam losses. The collimators are positioned close to the beam in the form of a hierarchy, which is guaranteed by precisely aligning each collimator with a precision of a few tens of micrometers. During past years, collimator alignments were performed semi-automatically, such that collimation experts had to be present to oversee and control the alignment. In 2018, machine learning was introduced to develop a new fully-automatic alignment tool, which was used for collimator alignments throughout the year. This paper discusses how machine learning was used to automate the alignment, whilst focusing on the operational results obtained when testing the new software in the LHC. Automatically aligning the collimators decreased the alignment time at injection by a factor of three whilst maintaining the accuracy of the results.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN is the largest particle accelerator in the world, used to accelerate and collide two counter-rotating beams, with an unprecendented center-of-mass energy of 13 TeV [1]. The LHC is susceptible to beam losses from normal and abnormal conditions, which can damage the superconducting magnets and other sensitive equipment [2]. Due to this, a robust collimation system is used to safely dispose of such beam losses by concentrating them in the collimation regions, with a 99.998% cleaning efficiency of all halo particles.

The LHC collimation system is made up of 100 collimators, which are mainly concentrated in two dedicated cleaning insertion regions; IR3 for momentum cleaning and IR7 for betatron cleaning. Collimators provide halo cleaning using a multi-stage hierarchy, which must be preserved by aligning the collimators with a precision of a few tens of μm. The majority of the collimators are aligned using the Beam Loss Monitoring (BLM) system. Each collimator has a dedicated BLM ionization chamber positioned outside the beam vacuum, immediately downstream. Such devices are used to detect beam losses generated when halo particles impact the collimator jaws. Recorded losses are proportional to the amount of beam intercepted by the collimator jaws and are measured in units of Gy/s.

Each year of LHC operation begins with a commissioning phase, which involves aligning all collimators and ensuring the correct operation to allow the LHC to achieve nominal operation [3]. Collimator alignment campaigns are performed at different machine states along the LHC generation cycle, i.e. injection at 450 GeV where 79 collimators are aligned, flat top at 6.5 TeV where 75 collimators are aligned, squeeze where 16 collimators are aligned and in collisions where 28 collimators are aligned. Such alignments are performed to determine the beam orbit and beam size at each collimator location, to establish the hierarchy and to generate continuous setting functions for the whole LHC cycle [4, 5].

ALIGNMENT PROCEDURE

Collimators aligned with BLM devices use a four-step beam-based alignment (BBA) procedure established in [6]. The standard sequence involves aligning a reference collimator in addition to the collimator in question (i), which is taken to be the primary collimator in the same plane as collimator i. This creates a "reference halo" that extends into the aperture of collimator i. The alignment of the collimators is beam-based as the collimators' jaws are moved towards the beam whilst observing the spikes in the beam loss signal of its respective BLM device. A jaw is classified as aligned when a signature spike pattern is detected in the losses.

Prior to the machine learning used in 2018, the software established in [7, 8] was used to align collimators using a semi-automatic algorithm. This procedure required the user to; select the collimator to be aligned, select the BLM threshold, start the alignment such that the collimator automatically moves towards the beam and stops when its losses exceed the BLM threshold, and finally the user must analyse the spikes in the BLM losses to check if the collimator is aligned. This approach is time consuming and requires collimation experts to be available for the entire duration of the alignments.

The cumulative net time required to align the collimators over the years during all machine states is displayed in Figure 1, excluding any operational overhead for configurations and setups. This diagram clearly indicates the consistent decrease in the alignment time each year. The initial alignment of the system in 2010 took 80 hours. Since then, several hardware and software upgrades were introduced to improve the alignment time and to reduce the complexity of the alignment procedure. In 2011-2012 the alignment software was semi-automated, in 2013-2015 collimators in the IRs where collimators are frequently reconfigured, were installed with beam position monitors [9] and in 2018 the fully-automated software was introduced. Initially, with the full-automation, the parallel alignment was not possible, as when a collimator

* gabriella.azzopardi@cern.ch

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touches the beam, beam losses are also measured in BLM detectors at nearby collimators, i.e. crosstalk. During commissioning the software did not yet cater for this, however one can still appreciate a decrease in the alignment time.

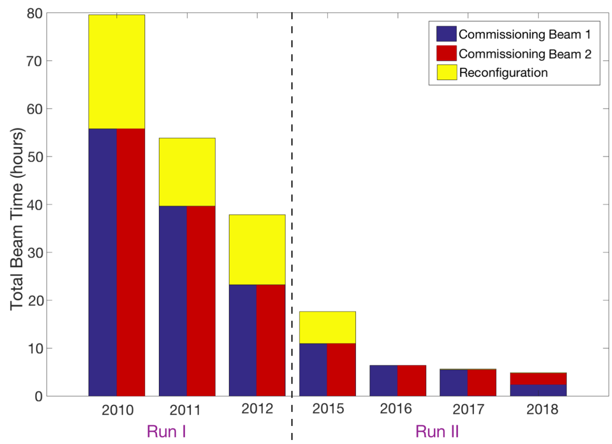


Figure 1: Time to align collimators in commissioning Run I and Run II. During 2010-2017 the collimators in the two beams were aligned in parallel (vertical bars), whereas in 2018 they were aligned one after the other (horizontal bars).

FULLY-AUTOMATIC ALIGNMENT SOFTWARE

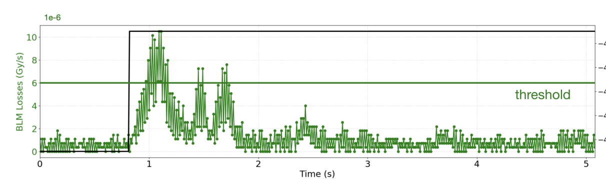
In 2018, the semi-automatic beam-based alignment was fully-automated by closing the loop between the collimator stopping its movement after its losses exceed the threshold, and resuming the alignment based on the BLM loss signal. This involved using the feedback from the BLMs in real-time, to replace the user tasks with dedicated algorithms.

Crosstalk Analysis for Parallel Selection

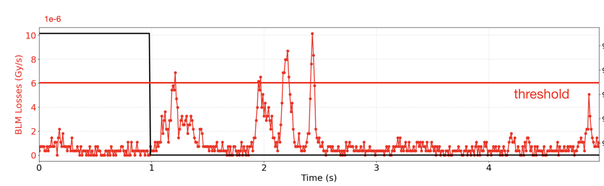
Aligning collimators in Beam 1 and Beam 2 in parallel depends on the crosstalk observed in the BLM signals. Alignments during commissioning 2018 were done sequentially, which provided a data set of BLM signals that were used to analyse the crosstalk caused by each collimator. A data set of 650 samples was generated, containing the BLM signals of the aligned collimators and all other collimator BLMs with losses larger than ten times the background losses. The collimators affected by crosstalk were identified by RMS-smoothing all BLM signals and if any BLM not attached to the moving collimator had a signal larger than 5% of the maximum loss at the aligned collimator BLM, then the collimator was labelled as having experienced crosstalk. The list of collimators affected by crosstalk was used as an initial model for automatically handling the parallel alignment of both beams.

Machine Learning for Spike Detection

The correct alignment of any collimator relies on being able to classify between alignment spikes and non-alignment spikes from the time-varying beam loss signal. This determines whether the collimator's jaws really touched the beam's reference halo, otherwise the collimator must continue moving towards the beam. Figure 2(a) shows an example of a clear alignment spike indicating that the collimator in question is aligned, whilst Figure 2(b) shows an example of non-alignment spikes which would usually arise due to beam instabilities or mechanical vibrations. The fully-automatic alignment software makes use of machine learning techniques to automatically classify between the two spike patterns in the BLM losses. A data set was assembled from previous alignment campaigns, from which fourteen manually engineered features were extracted and six machine learning models were trained, analyzed in-depth and thoroughly tested [10]. The suitability of using machine learning in LHC operation was confirmed during collimator alignments performed in 2018, where the machine learning models achieved a precision of over 95%.



(a) Alignment spike in 100 Hz data.



(b) Non-Alignment spikes in 100 Hz data.

Figure 2: Typical BLM signals, thresholds and jaw positions as a function of time, showing examples of (a) an alignment spike and (b) non-alignment spikes, after a collimator movement towards the beam.

Automatic Threshold Selection

The BBA involves moving the collimators towards the beam until their losses exceed a predefined threshold, which was selected by the user based on the current BLM signal. The ideal threshold must be: high enough to ignore any noisy spikes and touch the beam without interrupting the movement, and low enough to immediately stop the jaws and generate minimal losses when the collimator actually touches the beam. Based on this, the algorithm for automatic threshold selection applies an exponentially weighted moving root mean square on the latest BLM signal. The thresholds selected by users for alignments in 2016, were extracted to form a data set of 1778 samples, at injection and flat top. This data set was used to validate the algorithm, and the difference between the thresholds selected automatically and by the user were negligible ($\pm 25 \times 10^{-6}$ Gy/s) for over 90% of the cases.

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RESULTS WITH PROTON BEAMS

The fully-automatic BLM alignment software was used in LHC operation throughout 2018. The first version was used during commissioning to automatically align the collimators in the two beams sequentially, at injection and flat top. A machine development (MD) study was then scheduled to test the alignment of the two beams in parallel at injection. This section collects the results at injection to compare the two versions of the software.

Sequential Automatic Alignment

During commissioning at injection, the collimators in the two beams were aligned sequentially. The entire alignment campaign took 1.5 hours to align 79 collimators (i.e. 1 minute per collimator on average). The beam centres and beam sizes measured with BLM detectors at each collimator, are consistent with those from injection commissioning in 2017, evidently showing the reproducibility and stability of the LHC.

Parallel Automatic Alignment

During an MD at injection, a second version of the fully-automatic alignment software was tested [11]. This allowed for aligning the two beams in parallel, such that aligning 79 collimators took 50 minutes. This decreased the alignment time at injection by a factor of three, since 2017, as shown in Figure 3 and on average it took 1.5 minutes to align two collimators.

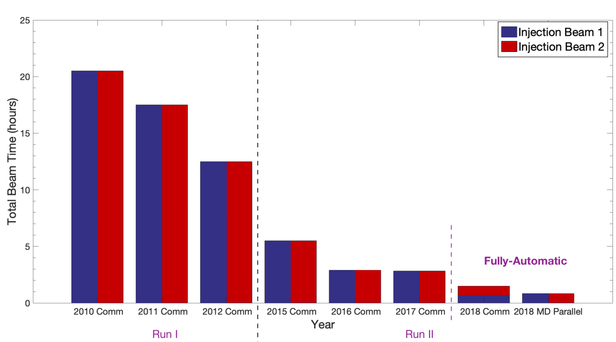

Figure 3: The time to align collimators at injection commissioning, compared to the 2018 parallel alignment MD.

The centers and beam sizes measured at each collimator are consistent with those from commissioning in 2018, as shown in Figure 4. This validates the new parallel alignment software, confirming that it can be used as a baseline for future parallel alignments at injection. Eventually it is planned for this software to be further upgraded based on more in-depth crosstalk analysis studies [12].

CONCLUSION

The LHC is protected by a complex collimation system, whereby collimators are aligned at tight gaps around the beam, enforcing precision and efficiency. During past years, BLM alignments have been performed semi-automatically,

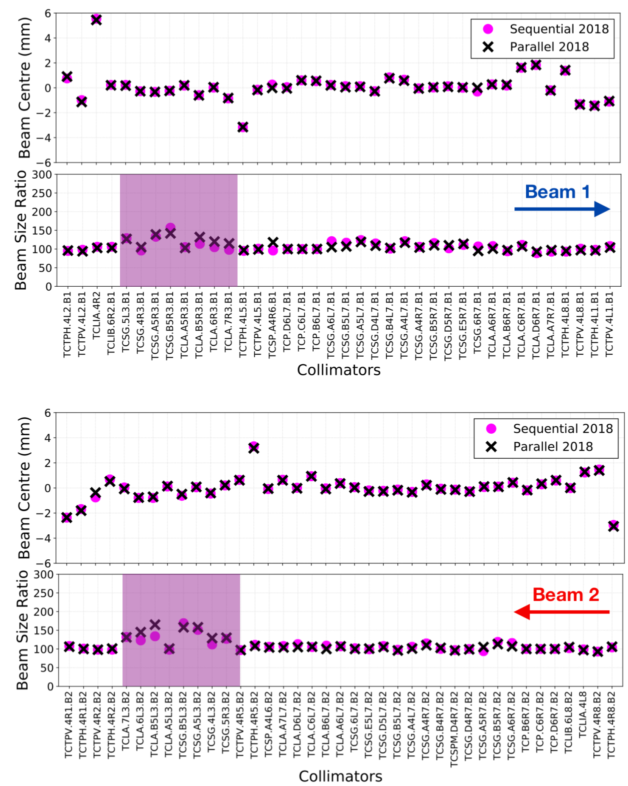

Figure 4: Beam 1 and Beam 2 result comparison of parallel and sequential alignments at injection, comparing the beam centres (top graph) and beam size ratios (bottom graph).

such that collimation experts were required to oversee and control the alignment. Recent work sought to apply machine learning and other algorithms based on BLM signal analysis, to transform the semi-automatic alignment into a fully-automated one. This new software was used in all collimator alignments throughout 2018, and this paper presents the results obtained. The first version was used during commissioning when the collimators in the two beams were automatically aligned sequentially, at injection and flat top. A few months later, an improved version of the software was used to align the collimators in the two beams in parallel at injection, by making use of a new crosstalk model. This successfully decreased the 2017 alignment time by a factor of three, at injection. Overall, the full-automation with the use of machine learning, has proven to be more efficient and able to generate reproducible results, therefore the plan is to use this as the default alignment software when starting the LHC in 2021.

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