AUTOMATIC COMPUTER ALGORITHMS FOR BEAM-BASED SETUP OF THE LHC COLLIMATORS*

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Abstract

Beam-based setup of the LHC collimators is necessary to establish the beam centers and beam sizes at the collimator locations and determine the operational settings during various stages of the LHC machine cycle. Automatic software algorithms have been successful in reducing the costly beam time required for the alignment, as well as significantly reducing human error. In this paper, the beam-based alignment procedure is described, and the design of algorithms such as a BLM feedback loop, parallel collimator alignment, pattern recognition of BLM loss spikes, automatic loss threshold selection and coarse BPM-interpolation guided alignment is explained. A comparison on the alignment results from the 2010 to the 2012 LHC runs is presented to illustrate the improvements achieved with the automatic algorithms.

INTRODUCTION

The Large Hadron Collider (LHC) located at CERN is designed to collide two counter-rotating particle beams with an energy of 7 TeV each [1]. Machine protection systems are installed to prevent damage to the LHC in the event of beam loss scenarios. The collimation system protects the collider against unavoidable losses, which may cause quenches in the superconducting magnets, damage to beam pipe equipment or cause electronics degradation as a result of radiation effects [2].

At present, the collimation system is made up of over 100 collimators which are arranged in four levels of retraction from the beam in the form of a hierarchy. The LHC consists of 8 arcs and 8 straight sections, called insertion regions (IRs). The collimators are located mainly in IR3 and IR7 to scatter and absorb particles with large momentum and betatron offsets respectively.

Each collimator providing cleaning of normal beam losses consists of two blocks, known as jaws, of graphite or tungsten. In order to ensure maximum cleaning efficiency and protection, the jaws must be positioned symmetrically around the beam with the correct gap in units of beam standard deviations (sigmas). The jaw positioning accuracy is 5 μm, and a three-tier control system allows the upstream and downstream edges of each jaw to be moved separately via four motors [3].

The beam centers and beam sizes at the collimator locations are determined from beam-based alignments. The setup procedure relies on feedback from beam loss monitors (BLMs) [4], which consist of ionization chambers placed downstream of the collimators. The BLMs capture beam loss showers caused by primary beam particles impacting on the collimators. A collimator jaw is aligned to the beam halo when a clear spike is observed in the BLM signal.

In 2010, the setups were performed ‘manually’, meaning that human feedback was required to determine when the jaw is aligned to the beam. This was achieved by observing the BLM signal on a screen following a jaw movement. A disadvantage of this method is the setup time required, which is data lost for the experiments and beam time for other users. Human error results in incorrect jaw movements, causing high losses and beam dumps, therefore contributing to the setup time. In order to speed up the collimator alignment and minimize the intervention required from the operator, a set of automatic algorithms has been implemented in the top-layer of the LHC software architecture in Java.

COLLIMATOR SETUP PROCEDURE

Each collimator is aligned in a four-step procedure, as established in [5]. The setup procedure is illustrated in Fig. 1. The first step is to align the left and right jaws of a reference collimator to form a reference cut in the beam halo. This collimator is taken to be the primary collimator (TCP) in the same plane (horizontal, vertical or skew) as the collimator to be aligned, called collimator *i*. As a particular jaw can be declared to be aligned only if it was the only jaw moving when the BLM signal spike occurs, the left and right jaws are moved towards the beam separately. After aligning the reference collimator, the same procedure is performed for the collimator *i* (2), and the reference collimator is aligned once again (3). The beam center can then be determined from the final measured left and right jaw positions $x_i^{L,m}$ and $x_i^{R,m}$ of collimator *i*:

$$\Delta x_i = \frac{x_i^{L,m} + x_i^{R,m}}{2} \quad (1)$$

A full derivation of the calculation for the inferred beam size at collimator *i* is available in [6], and can be calculated from the jaw half gap and the average cut n_1 in units of sigma at the reference collimator:

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$$\sigma_i^{inf} = \frac{x_i^{L,m} - x_i^{R,m}}{n_1^{k-1} + n_1^k} \tag{2}$$

where k is an index for the number of reference collimator alignments. The reference collimator is aligned both before and after the setup of collimator i to account for the halo that is scraped away. The final step is to set the left and right jaws of collimator i using the values obtained for the beam center and beam size to maintain the collimation hierarchy, where N_i is the half gap opening for a particular collimator family:

$$x_i^{L,set} = \Delta x_i + N_i \sigma_i^{inf} \tag{3}$$

$$x_i^{R,set} = \Delta x_i - N_i \sigma_i^{inf} \tag{4}$$

An alignment of all moveable 86 collimators is performed yearly during the beam re-commissioning phase. The beam centers and beam sizes must be known for various stages of the machine cycle. At 450 GeV (injection energy), all collimators are aligned. For the 4 TeV operational energy in 2012, 80 collimators are set up (the six injection protection collimators are excluded). The 16 tertiary collimators (TCTs) are aligned with both beams squeezed to the operational $\beta*$ in the experimental IPs, and are set up again when the orbit separation bumps are collapsed and the beams are brought into collisions. In addition, the tertiary collimators which protect the experimental regions are aligned following a change in the beam orbit to accommodate modifications for the experiments, such as a change in the crossing angle.

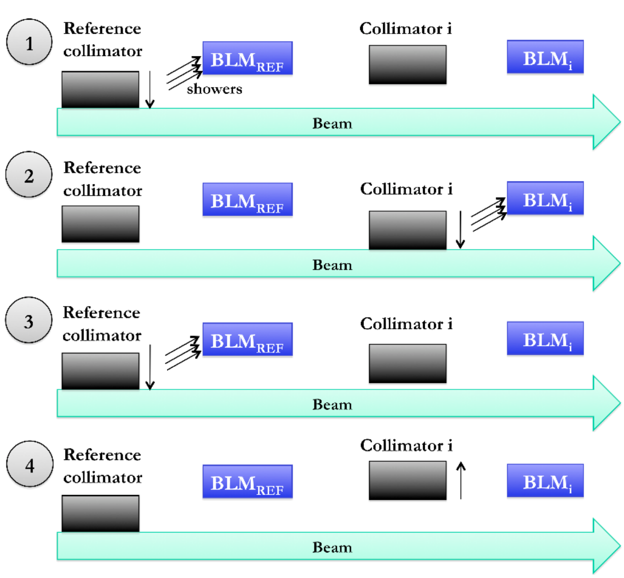

Figure 1: The four-stage beam-based alignment procedure for collimator i. The reference collimator is aligned to form a reference cut in the beam halo (1). Collimator i is aligned (2), followed by a re-alignment of the reference collimator (3). Finally, collimator i is opened to its position in the hierarchy (4).

BEAM LOSS FEEDBACK

The first algorithm developed to speed up and automate the alignment process makes use of a beam loss feedback loop [6]. A periodic jaw movement can be started from the top-level application, and before each jaw step the algorithm would ensure that the BLM signal is below a predefined threshold, which is several orders of magnitude lower than the beam dump loss threshold. The algorithm takes four inputs, consisting of the left and right jaw step sizes in μm, Δx_i^L and Δx_i^R, the BLM signal threshold S_i^{Thres} in Gy/s and the time interval between each step t_i^s in seconds. In the 2010 and 2011 LHC runs, the BLM data was acquired at a rate of 1 Hz, and following software upgrades as of 2012, the data is received at a rate of 12.5 Hz. The jaw moves at 2 mm/s, and steps can be sent at a rate of 1-8 Hz. When the jaw movement is stopped, human feedback is required to ascertain whether the jaw is touching the beam halo from the BLM loss spike displayed. Hence, the algorithm is semi-automatic. A flowchart of the algorithm is shown in Fig. 2.

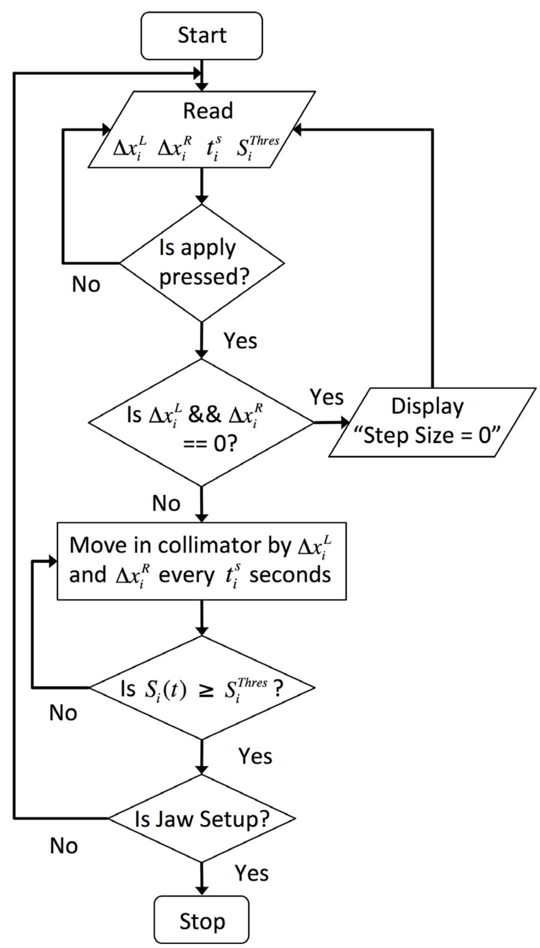

Figure 2: A flowchart of the beam loss feedback loop, which is used to align the collimator jaws in a semi-automatic manner. Human feedback is still required at the end to check whether the BLM signal is a clear loss spike, which would indicate that the jaw is aligned.

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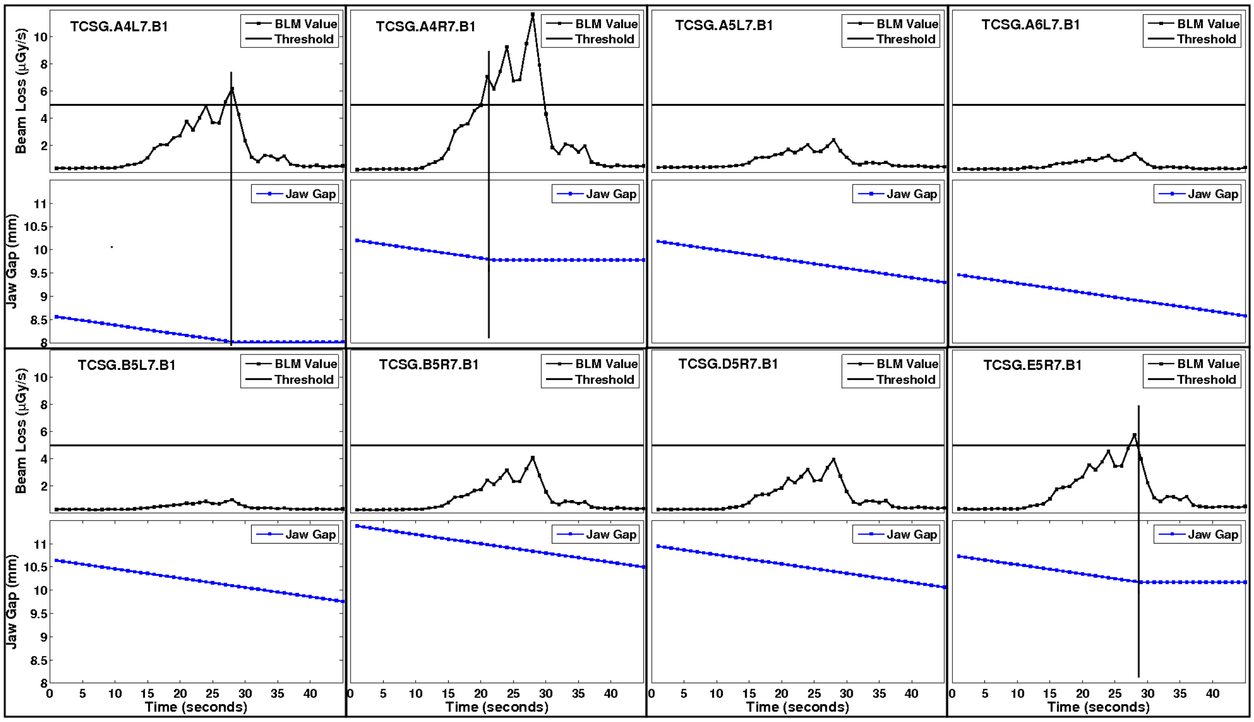

Figure 3: Both jaws of eight skew B1 collimators moving in parallel. The similarity of the BLM spike patterns and the simultaneous stopping of three collimators highlights the need to automatically identify which collimator jaw is actually aligned to the beam. The perpendicular lines indicate where the jaw stops when the losses exceed the threshold.

PARALLEL COLLIMATOR ALIGNMENT

A parallel alignment algorithm was developed to move all collimator jaws in steps towards the beam using the beam loss feedback loop, once the latter proved to be successful. It provides a coarse but quick way of positioning a set of collimator jaws around the beam, after which each jaw can be finely aligned in sequence. During initial tests of the algorithm, an expected cross-talk effect was observed, in which a loss pattern registered on the BLM of one particular collimator was also detected on on other collimator BLMs downstream. An example is illustrated in Fig. 3, where the BLM threshold was set to 5×10^{-6} Gy/s for all collimators. Three have stopped moving as the losses on their BLMs have exceeded the threshold. Cross-talk prevented the parallel setup method from functioning efficiently, and therefore the algorithm was designed to identify which collimator jaw is at the beam.

The parallel setup algorithm uses a timer task (CheckColls) to check whether any collimators have stopped moving. As soon as a collimator stops moving due to an exceeded BLM threshold, another timer task (CheckCollsT) is started to determine whether any other collimators also stop within a pre-defined time period T. If this is the case, all the other collimators moving in parallel are stopped so that the algorithm can concentrate on the collimators that stop within T. In case the BLM threshold S_i^{Thres} set during the previous movement is now below the background signal, an option allows the user to instruct the program to automatically increase the threshold in steps up to a maximum amount S_{max}^{Thres} . If the threshold is exceeded at the second step or thereafter, the jaw is declared to be aligned to the beam, and the algorithm terminates to allow the operator to start the sequential alignment.

BEAM LOSS SPIKE RECOGNITION

The alignment procedure can be automated further if a collimator expert is no longer required to visually judge whether a loss pattern is a clear indication that the jaw has touched the beam. An example of an optimal loss spike is shown in Fig. 4. The four pattern components include the steady-state losses before the spike, the loss spike, the temporal decay and the steady-state losses after the spike. Features inherent in the loss pattern were identified to discriminate between optimal and non-optimal loss spikes. A Gaussian fit can be applied to the loss spike component folded around the maximum value, while a power fit can be made to the temporal decay. Six features were considered:

- Maximum value
- Steady-state average
- Variance
- Gaussian fit correlation coefficient
- Power fit gradient
- Power fit correlation coefficient

The Support Vector Machines (SVM) algorithm is a supervised learning technique that can be used for classifica-

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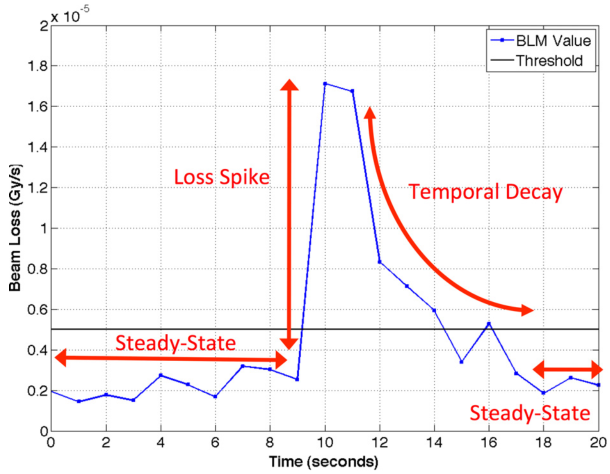

Figure 4: The components of a typical clear BLM signal when the collimator jaw touches the beam halo.

tion of data, and was used to classify the loss spikes [7]. It operates by maximizing the margin between the training data points and the decision boundary. The LIBSVM tool [8] was used for training and testing of the SVM model. The radial basis function kernel was chosen as it has less hyperparameters, and presents fewer numerical difficulties. A total of 444 samples were available from alignments in 2011 at 3.5 TeV. The sizes of the training and the testing datasets were chosen to be equal. An accuracy rate of 97.3% was achieved for the training data, while 82.4% of the test data were classified correctly, which gives an overall prediction rate of 89.9%.

AUTOMATIC THRESHOLD SELECTION

An algorithm that could automatically set the loss threshold at the start of each jaw movement would contribute greatly to automating the alignment procedure further. Samples of the steady-state BLM signal in 20 second intervals and the subsequent threshold set by the operator were collected. The exponentially weighted moving average of each sample was determined, with the larger weights assigned to the most recent values. If the thresholds set by the operator averages are plotted as a function of the logarithm of the averages, an exponential fit can be applied to the data as shown in Fig. 5. The threshold set by the algorithm during the alignment is therefore:

$$S_i^{Thres} = 0.53584e^{0.85916x} \quad (5)$$

The maximum threshold that can be set is 1×10^{-4}, which is an order of magnitude below the BLM dump thresholds.

BPM-INTERPOLATION GUIDED COLLIMATOR ALIGNMENT

An approximation to the beam centers at the collimators can be obtained from an interpolation of the orbit measured at specific locations by Beam Position Monitors (BPMs).

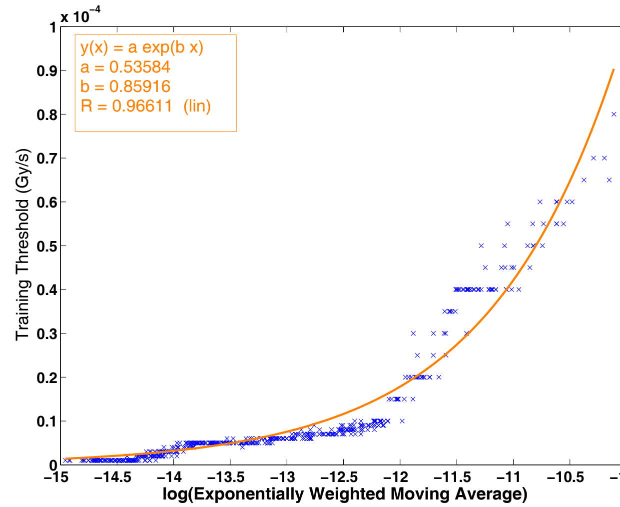

Figure 5: Loss thresholds applied before the start of a jaw movement as a function of the logarithm of the exponentially weighted moving average of the BLM signal. An exponential fit can be applied to the data.

The interpolation can be exploited to speed up the alignment process, if the errors between the interpolation and the beam-based measurements are not too large. Two datasets were built, one containing the beam-based alignment centers measured in 2011 and 2012, the other containing the interpolated orbit at each collimator at the time of alignment [9]. The average delta between the datasets is of $\sim$ 550μm, with maximum deltas of $\sim$ 3000μm for the tertiary collimators, where the interpolation reliability is known to be worse. The jaws can now be moved in one step at a rate of 2 mm/s from the initial positions to a safe margin around the beam based on the IR7 TCP cuts. A gain in time of a factor 200 can be achieved for this part of the alignment using this technique, instead of the standard 10 μm step every second. The left and right jaws are hence moved in to the following settings:

$$x_i^L = \Delta x_i^{int.} + (N_{TCP} + N_{margin}) \times \sigma_i^n + \frac{\Delta_{m,int.}}{2} \quad (6)$$

$$x_i^R = \Delta x_i^{int.} - (N_{TCP} + N_{margin}) \times \sigma_i^n - \frac{\Delta_{m,int.}}{2} \quad (7)$$

where $\Delta x_i^{int.}$ is the interpolated beam center at collimator i, N_{TCP} is the half-gap of the IR7 TCP in units of σ, σ_i^n is the nominal 1σ beam size and $\Delta_{m,int.}$ is the expected offset between the interpolated and the measured center from beam-based alignment, based on the empirical analysis. Once the IR7 TCP is aligned, typically at 3 - 4 σ, a further safety margin N_{margin} is applied (e.g. 2σ) over and above the TCP cut. In a LHC Machine Development (MD) study at 450 GeV [10], 27 collimators were positioned around the beam guided by the interpolated orbit, and were subsequently aligned using the parallel alignment algorithm. These collimators were aligned in 1.75

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hours, which if extrapolated to a full alignment of all 80 collimators at 4 TeV flat top results in a setup time of 5.5 hours. This is a factor 5 improvement over the setup time of 28 hours achieved with manual alignment at 3.5 TeV.

RESULTS

The time taken to set up collimators is the most important indicator of the efficiency of a setup algorithm. The total time required T_{setup} is defined as follows [6]:

$$T_{setup} = T_{beam} + d \times T_{turnaround} \quad (8)$$

where T_{beam} is the beam time used for setup, C is the number of collimators set up and d is the number of beam dumps caused by collimator setup. The turnaround time $T_{turnaround}$ is the time consumed from the point of beam dump until the machine is cycled back to the setup operating point, which can reach 3 hours for flat top. Figure 6 shows the evolution in T_{setup} and the average jaw step size for collimator alignments at injection and flat top from 2010 to 2012. A larger setup time was required for 2011 due to a phased change-over between manual and semi-automatic alignment and the use of a smaller average step size, which reduces the probability of dumping the beam and improves the alignment accuracy. The setup times achieved from 2011 onwards are more impressive when one considers that the average jaw step size was reduced by a factor 4, and hence the jaw takes longer to cover a given distance in mm. The setup times continued to improve in 2012 with a higher BLM data rate of 12.5 Hz allowing the jaws to be moved at the maximum rate of 8 Hz.

Figure 6: Evolution of the setup time for the collimator alignments and the average jaw step sizes used at injection and flat top from 2010 to 2012. The 1 hour 45 minutes required to setup 27 collimators during the 2012 MD is extrapolated to 5.5 hours for a full setup.

SUMMARY

The cleaning efficiency of the LHC collimation system is highly dependent on the careful positioning of all collimators. The positions are determined as a result of beam-based alignment. Due to the large number of collimators, the time to complete the alignment can reach over 20 hours in the absence of automatic algorithms, which results in reduced time for LHC physics operation. In this paper, several algorithms aimed at automating and speeding up the alignment procedure have been described. The algorithms have been successful in drastically reducing the need for operator intervention, and have decreased the set up time by a factor 5 at flat top.

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