FAST AUTOMATIC BEAM-BASED ALIGNMENT OF THE LHC COLLIMATION SYSTEM*

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Abstract

Maximum beam cleaning efficiency and LHC machine protection is provided when the collimator jaws are properly adjusted at well-defined distances from the circulating beams. The required settings for different locations around the 27 km long LHC rings are determined through beam-based collimator alignment, which uses feedback from the Beam Loss Monitoring (BLM) system. After the first experience with beam, a systematic automation of the alignment procedure was performed. This paper gives an overview of the algorithms developed to speed up the alignment and reduce human errors. The experience accumulated in four years of operation, from 2010 to 2013 is reviewed.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN is the world's highest energy particle accelerator. Proton beams circulate at a nominal beam energy of 7 TeV, and particle losses of only 7.6×10^6 ps^{-1}m^{-1} (2.5×10^{-6}% of the circulating beam) are sufficient to quench the superconducting magnets [1]. A multi-stage, multi-turn collimation system [2] is installed to clean the halo particles and protect the machine from damage.

The primary collimator (TCP) jaws are placed tightest around the beam, followed by the secondary collimators (TCSG), tertiary collimators (TCT) and absorbers (TCLA). The LHC consists of 8 arcs and 8 straight sections, called insertion regions (IRs). The collimators are located mainly in IR3 and IR7 for momentum and betatron cleaning respectively. An LHC collimator consists of two parallel blocks, or jaws, of carbon, tungsten or copper material. Each of the 86 collimators is oriented azimuthally to clean in the horizontal, vertical or skew planes. The four jaw corners can be moved individually by dedicated stepping motors with a minimum step size of 5 μm.

ALIGNMENT PROCEDURE

Maximum beam cleaning efficiency and LHC machine protection are provided when the collimator jaws are properly adjusted at well-defined distances from the circulating

beams, therefore respecting a pre-defined collimation hierarchy [3]. The required settings for different locations around the LHC rings are determined through beam-based collimator alignment. Alignments are performed during beam commissioning at the start of each year of LHC operation. They are also performed throughout the year whenever the orbit and optics configuration parameters at the experimental regions are changed, such as the beam crossing angles and β-functions at the interaction points (known as the β^*), as well as for dedicated beam studies.

Each collimator is aligned in a four-step procedure, which was established in [4]. A jaw is aligned when a sharp increase followed by a slow exponential decrease appears in the signal read out from a Beam Loss Monitoring (BLM) detector [5] placed downstream of the collimator. As from January 2012, a new BLM data buffer was implemented to allow for automatic and faster collimator alignment [6]. The BLM data is now transmitted to the collimation software application in the form of User Datagram Protocol (UDP) packets at a rate of 12.5 Hz, instead of the previous 1 Hz.

The alignment sequence, involving the reference collimator and the collimator i to be aligned, is shown in Fig. 1. The collimator jaw of a reference collimator is moved in steps towards the beam to form a reference cut in the beam halo (step 1 in Fig. 1). The reference collimator is taken to be the primary collimator in the same plane (horizontal, vertical or skew) as the collimator i. A BLM signal spike can be attributed to a particular jaw movement if only that jaw was moving when the spike occurs. Therefore, the left and right jaws are aligned separately. After aligning both jaws of 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 aligned jaw positions of collimator i:

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

where $x_i^{L,m}$ and $x_i^{R,m}$ are the measured left and right jaw setup positions. The inferred beam size is expressed as a function of the half gap, with n_1 being the cut of the reference collimator in units of nominal σ (with nominal beam emittance $\epsilon = 3.5$ μm):

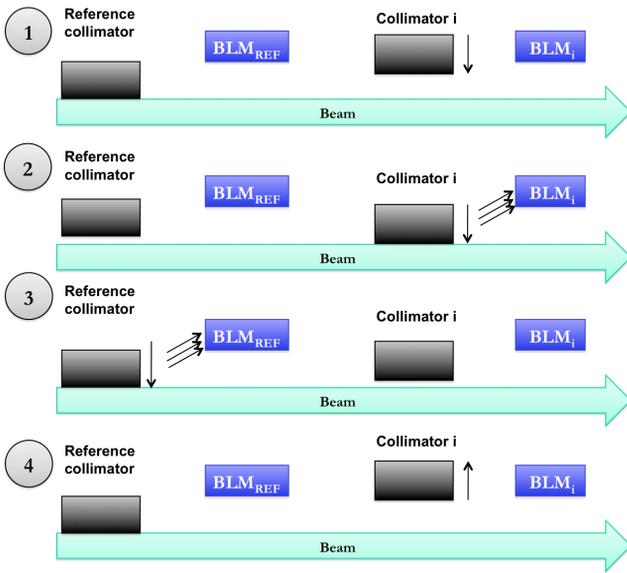$$\sigma_i^{inf} = \frac{x_i^{L,m} - x_i^{R,m}}{2n_1} \qquad (2)$$

Figure 1: The four-stage beam-based alignment procedure for collimator i, using a primary collimator as a reference. Only one jaw is shown for simplicity.

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 (4):

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

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

where N_i is the half gap opening specific to a collimator family.

## ALIGNMENT ALGORITHMS

BLM Feedback

A BLM feedback loop allows for individual or parallelized movement of collimator jaws in steps towards the beam, until the losses exceed a pre-defined BLM stopping threshold [7]. The thresholds were initially input manually by the operator. This provided a lot of training data which was exploited to set the threshold automatically. The set threshold were found to increase linearly with the exponentially weighted moving average [8].

Loss Spike Recognition

Before the implementation of a loss spike classification algorithm, a collimator expert was required to visually judge if a loss pattern is a clear indication that the jaw has touched the beam during the setup process. This is carried out when the jaws stop moving after the pre-defined beam loss threshold is exceeded. An example of an optimal loss spike is illustrated in Fig. 2(a), while a non-optimal loss

spike is presented in Fig. 2(b). If the loss spike was non-optimal, then the expert was required to manually repeat the movement until the spike was of satisfactory quality.

The beam loss signal that is observed when a jaw touches the beam is the product of two physical processes. The first part of the signal is the loss spike. This sharp increase in the beam losses registered by the BLM detector is due to the scraping of particles from the beam halo. The secondary particles formed as a result of the scraping are scattered into the BLM detector, and ionize the chamber to produce the spike. After the spike, the losses gradually decay to a steady-state signal. Any other pattern which does not have this structure is referred to as a non-optimal spike. This type of loss pattern can arise due to beam instabili-
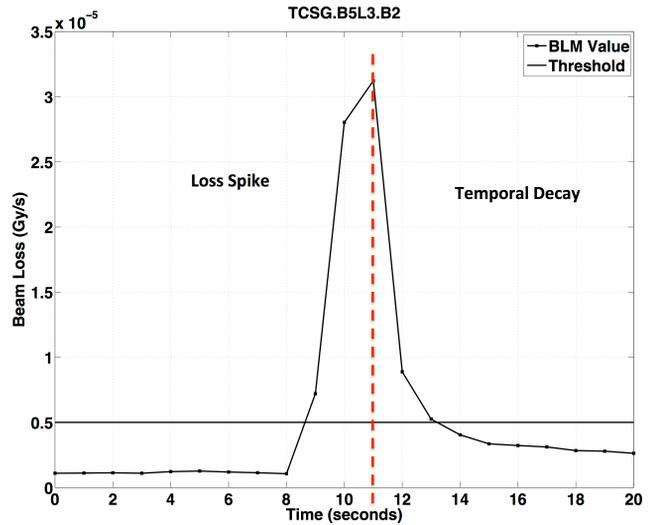
(a) Optimal loss spike
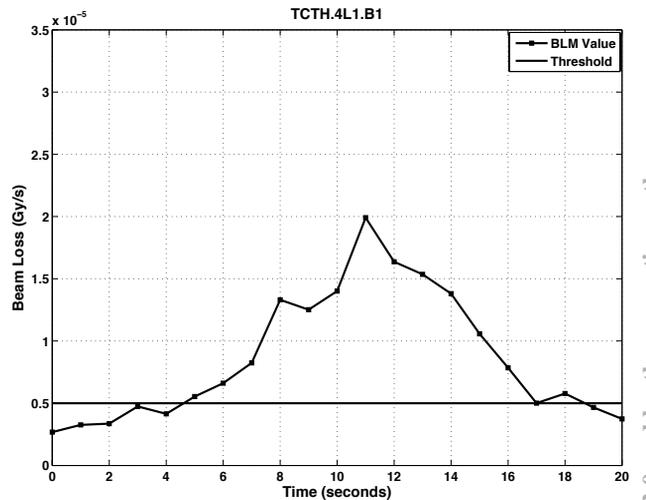
(b) Non-optimal loss spike

Figure 2: Optimal beam loss spike generated by the TCSG.B5L3.B2 collimator (left) and non-optimal beam loss spike generated by the TCTH.4L1.B1 collimator (right). A BLM threshold of 5×10^{-6} Gy/s was set in each case.

ties or mechanical vibrations of the opposite jaw which is close to the beam. A classification model based on Support Vector Machines (SVM) was built from alignment training data [9]. An accuracy rate of 97.3% was achieved for the training data, while 82.4% of the test data points were classified correctly. This gives an overall prediction rate of 89.9%.

BPM Interpolation

An approximation to the beam centers at the collimators can be obtained from an interpolation of the orbit measured at specific locations by BPMs. The interpolated orbit is one of the features provided by the LHC Aperture Meter [10], an application which provides the operators with real-time information on the current machine bottlenecks. The interpolation is highly dependent on the BPMs selected, and invalid monitors which give erroneous readings need to be removed from the calculation.

The reproducible correlation between the measured and interpolated centers can be exploited during the alignment [11]. This is done by moving in the jaws in one step at a speed of 2 mm/s from the initial positions to a safe margin around the beam without scraping any beam, instead of using the automatic setup tool with small step sizes. As it is not possible to accurately measure the beam size at the collimators without aligning them, the jaws can be opened to a half gap which considers the initial cut made by a reference collimator (IR7 TCP) and a safety margin (the maximum recorded shift on a collimator-by-collimator basis).

ALIGNMENT RESULTS

The time taken to set up collimators is the most important indicator of the efficiency of a setup algorithm. The average time per collimator T_{average} and the total time required T_{setup} are defined as follows:

$$T_{\text{average}} = \frac{T_{\text{beam}}}{C} \qquad (5)$$

$$T_{\text{setup}} = T_{\text{beam}} + d \times T_{\text{turnaround}} \qquad (6)$$

where T_{beam} is the beam time used for setup, C is the number of collimators and d is the number of beam dumps caused by collimator setup. The turnaround time $T_{\text{turnaround}}$ is the time consumed from the point of beam dump until the machine is cycled back to the setup operating point. The average LHC turnaround times used for this analysis vary from 3 hours to reach injection to 4.48 hours to reach collisions in 2011. The evolution of the alignment times achieved at top energy is shown in Fig. 3. Thanks to the algorithms, the alignment time has decreased from 30 hours in 2010 to almost 4 hours in 2012. A superimposed timeline illustrates the phased introduction of the alignment algorithms. The last two points are extrapolated from an alignment of half the collimation system in IR6 and IR7 (40 collimators). A similar plot was generated for the

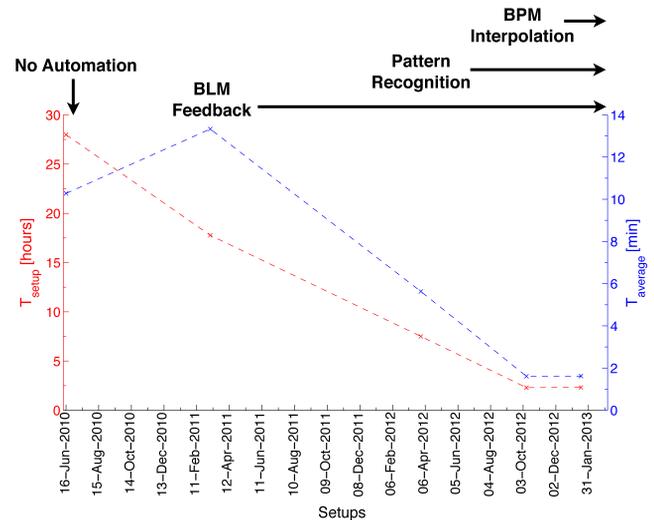Figure 3: Evolution of T_{setup} and T_{average} for full alignments at flat top over the 2010-2013 LHC run.
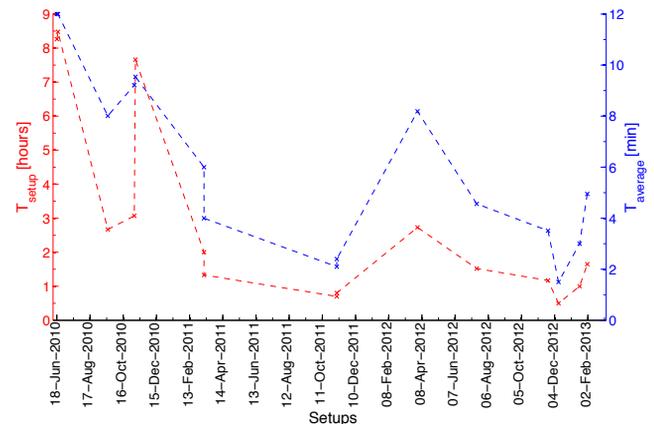

Figure 4: Evolution of T_{setup} and T_{average} for TCT alignments with squeezed separated and colliding beams over the 2010-2013 LHC run.

evolution of the TCT alignment times (see Fig. 4), where the setup time decreased from ∼8 hours in 2010 to under 2 hours in 2013.

An overview of the collimator setup performance gain with automatic setup is illustrated in Fig. 5. The number of aligned collimators increased over the years due to frequent changes in the optics and crossing angles (see Fig. 5(b)). The 2013 run lasted for only 1 month, which explains the reduced number of alignments. The time used for setup decreased by over 40 hours, as shown in Fig. 5(a). The reduction in the alignment time is one of the contributors to the increase in machine availability for physics production, which increased from 16% in 2010 to 36.5% in 2012 [12]. Figure 5(c) indicates an improvement in the accuracy of beam-based alignment by a factor 8, as well as in its safety (see Fig. 5(d)) as there were no beam dumps during alignment at top energy.
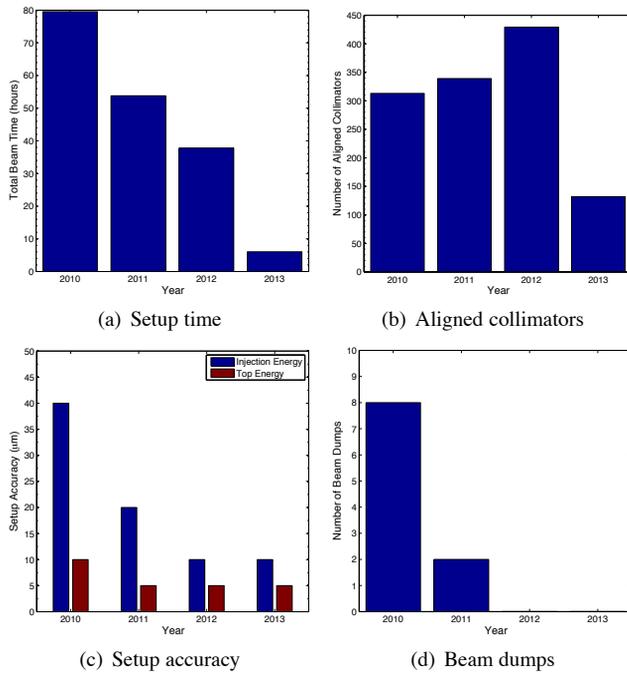
(a) Setup time

(b) Aligned collimators

(c) Setup accuracy

(d) Beam dumps

Figure 5: Summary of the performance gains with automatic alignment.

CONCLUSION

The performance of the LHC collimation system is highly dependent upon the jaw position settings, which can only be determined by beam-based collimator alignment. An array of algorithms has been developed to automate and speed up the beam-based alignment of the LHC collimators. These algorithms have achieved the right balance between obtaining optimal BLM signal spikes, ensuring that the losses remain below beam dump thresholds, and aligning collimators in the fastest time possible and with the greatest accuracy available (5 μm jaw step size).

The time for a full alignment of the whole collimation system has been reduced from 30 hours in the 2010 LHC run, to almost 4 hours in 2012 without triggering any beam dumps. More and more alignment campaigns were carried out over the years, despite the fact that the total time consumed by collimator alignment has decreased year after year. The LHC operation has relied a lot on the faster alignment, which allowed the possibility for more flexible and frequent changes of machine configuration.

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