A TOOL BASED ON THE BPM-INTERPOLATED ORBIT FOR SPEEDING UP LHC COLLIMATOR ALIGNMENT

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Abstract

Beam-based alignment of the LHC collimators is required in order to measure the orbit center and beam size at the collimator locations. During an alignment campaign in March 2012, 80 collimators were aligned at injection energy (450 GeV) using automatic alignment algorithms in 7.5 hours, the fastest setup time achieved since the start of LHC operation in 2008. Reducing the alignment time even further would allow for more frequent alignments, providing more time for physics operation. The proposed tool makes use of the BPM-interpolated orbit to obtain an estimation of the beam centers at the collimators, which can be exploited to quickly move the collimator jaws from the initial parking positions to tighter settings before beam-based alignment commences.

INTRODUCTION

In the CERN Large Hadron Collider (LHC), collimators are in place to intercept halo particles before they are deposited in the super-conducting magnets, potentially causing quenches [1]. A collimator consists of two blocks of material (jaws) that have to be positioned symmetrically on either side of the beam for optimum halo cleaning. There are four collimator families for ring cleaning: primary (TCP), secondary (TCSG), tertiary (TCT) collimators and absorbers (TCLA). During operation, each collimator family is positioned at a number of beam sigmas from the beam trajectory, such that all the LHC collimators form a four-stage hierarchy. The collimators are mainly located in two insertion regions (IRs), with off-momentum cleaning performed in IR3 and betatron cleaning done in IR7. The TCTs protect the experimental insertions, while as from the 2012 LHC run the TCLs in IR1 and IR5 capture luminosity debris.

Beam-based alignment of the LHC collimators is required to calculate the settings of all collimators throughout the operational cycle and establish the correct collimator hierarchy for machine protection and maximal cleaning efficiency. The alignment is necessary because, due to small beam σ values, the required accuracy to respect the hierarchy is not compatible with typical errors in the orbit, BPM readings, optics and design tolerances. A semi-automatic algorithm [2] allows the jaws to be automatically moved in small steps of 5 μm to 20 μm towards the beam until the signal of a Beam Loss Monitor (BLM) positioned downstream of the collimator exceeds a pre-defined threshold. The beam center at the collimator is then determined as the average of the two aligned jaw positions. It is sufficient to perform the alignment of all collimators once a year, except for selected TCTs in the event of an optics or orbit change in the experimental IPs.

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). A BPM consists of four button electrode feedthroughs mounted orthogonally in the beam pipe [3]. These monitors are placed on each side of the warm quadrupoles, providing the minimum configuration that allows a linear interpolation of the closed orbit, dispersion and β functions [4].

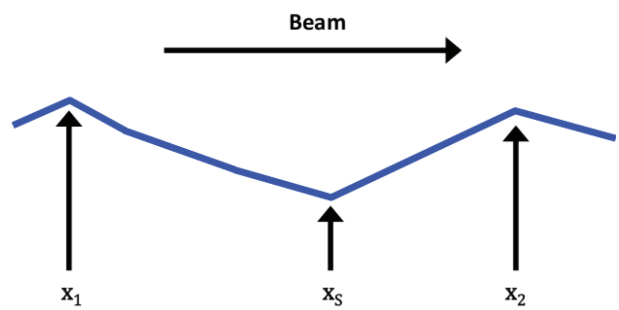

Figure 1: Example of the beam orbit through points 1, S and 2 (from [5]). With BPMs located at point 1 and 2, the objective of the interpolation is to find the orbit at point S.

BPM-INTERPOLATED ORBIT

An illustrative schema of the LHC beam orbit through various points in a section of the machine is shown in Fig. 1. With BPMs located at point 1 and 2, the orbit at an intermediate point S can be calculated using linear transfer matrices. The interpolation is done per plane and per segment, which is defined as the region between two BPMs. The angle can be calculated from the orbit transfer matrix between a pair of adjacent BPMs. The orbit at point 2 can be established from point 1 using a transfer matrix:

$$\begin{pmatrix} x_2 \\ x_2' \end{pmatrix} = M_{12} \begin{pmatrix} x_1 \\ x_1' \end{pmatrix} = \begin{pmatrix} C_{12} & S_{12} \\ C_{12}' & S_{12}' \end{pmatrix} \begin{pmatrix} x_1 \\ x_1' \end{pmatrix}$$

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where M_{12} is the transfer matrix between point 1 and 2 with elements:

$$C_{12} = \sqrt{\frac{\beta_2}{\beta_1}}(\cos\psi_{12} + \alpha_1 \sin\psi_{12}) \tag{1}$$

$$C'_{12} = \frac{\alpha_1 - \alpha_2}{\sqrt{\beta_1\beta_2}}\cos\psi_{12} - \frac{1+\alpha_1\alpha_2}{\sqrt{\beta_1\beta_2}}\sin\psi_{12} \tag{2}$$

$$S_{12} = \sqrt{\beta_1\beta_2}\sin\psi_{12} \tag{3}$$

$$S'_{12} = \sqrt{\frac{\beta_1}{\beta_2}}(\cos\psi_{12} - \alpha_2 \sin\psi_{12}) \tag{4}$$

Similarly for the orbit from point 1 to S:

$$\begin{pmatrix} x_S \\ x'_S \end{pmatrix} = M_{1S}\begin{pmatrix} x_1 \\ x'_1 \end{pmatrix}$$

The interpolated orbit at point S can hence be expressed as:

$$x_S = C_{1S}x_1 + S_{1S}\frac{x_2 - C_{12}x_1}{S_{12}} \tag{5}$$

At the LHC, the interpolated orbit is provided online by the LHC Aperture Meter [6], an application which provides the operators with real-time information on the current machine bottlenecks. Finally, in order to compare to the beam centers found from beam-based collimator alignment, the interpolated orbit needs to be transformed to the collimator co-ordinate system:

$$\Delta_i^{int} = x_S^{hor}\cos\theta_i + x_S^{ver}\sin\theta_i \tag{6}$$

where θ_i is the azimuthal tilt angle of the collimator i in the transverse plane. For beam 2 collimators, the sign of the horizontal component is inverted. The interpolation is highly dependent on the BPMs selected, and invalid monitors which give erroneous readings need to be removed from the calculation. The interpolation accuracy derives from the linearity of the BPM system (1% of the half radius, corresponding to ∼130 μm for arc BPMs).

BPM-INTERPOLATION GUIDED COLLIMATOR ALIGNMENT TOOL

To compare the proximity between the measured and the interpolated centers, 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 [7]. The average delta between the datasets is of ∼550 μm, with maximum deltas of ∼3000 μm for the tertiary collimators, where the BPM signal reliability is known to be worse due to systematic offsets in regions with a common beam pipe.

This reproducible correlation can be exploited during the alignment by moving in the jaws in one step at a rate of 2 mm/s from the initial positions to a safe margin around

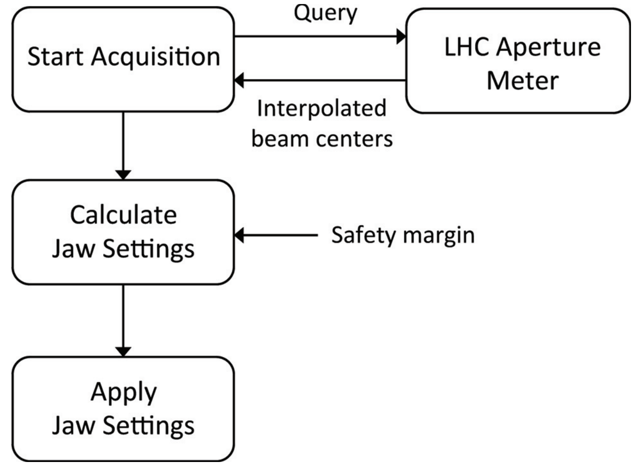

Figure 2: Flowchart of how the tool acquires the interpolated BPM readings and applies the tighter jaw settings based on a safety margin defined by the user.

the beam without scraping any beam, instead of using the semi-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. Based on these parameters and the nominal 1σ beam size, the left and right jaws are moved to the settings:

$$x_i^L = x_i^{int.} + (N_{TCP} + N_{margin}) \times \sigma_i^n + \frac{\Delta_i^{m,int.}}{2} \tag{7}$$

$$x_i^R = x_i^{int.} - (N_{TCP} + N_{margin}) \times \sigma_i^n - \frac{\Delta_i^{m,int.}}{2} \tag{8}$$

where $x_i^{int.}$ 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 at collimator i and $\Delta_i^{m,int.}$ is the expected average offset between the interpolated and the measured center from beam-based alignment per collimator, based on the empirical analysis. Once the IR7 TCPs in both beams are aligned, at a half gap usually between 3 and 4 σ, then a further safety margin N_{margin} is applied (e.g. 2 σ) over and above the cut made by the TCP.

The software tool was written in Java, and was integrated into the top-level collimator control application [8]. When the user starts the tool, a query is made to the LHC Aperture Meter, which returns the interpolated beam centers updated at a rate of 1 Hz. Once a safety margin is selected, the tool calculates the new tighter settings which will be sent to the hardware (see flowchart of the operation in Fig. 2). A screenshot of the GUI used to move in the collimators based on these values is given in Fig. 3. The checkboxes on the right-hand side allow the user to prevent the tool from moving the jaws if they are not selected.

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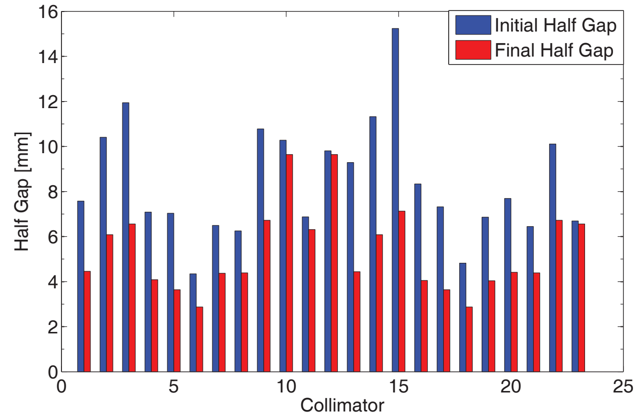
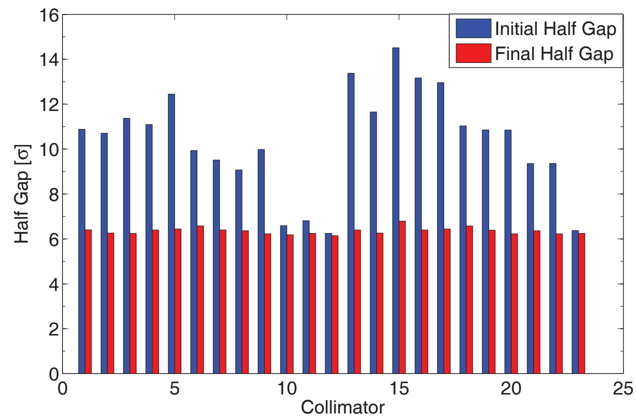
Figure 3: Screenshot of the GUI used to set the collimator jaws around the BPM-interpolated orbit.



(a) Initial and final jaw half gaps in mm



(b) Initial and final jaw half gaps in σ

Figure 4: Comparison of the initial parking positions and the tighter half gaps after the tool was executed, in units of mm (left) and σ (right). Note the large change for collimators initially positioned with a half gap of more than 10 σ.

EXPERIMENTAL RESULTS

The tool was tested during a LHC Machine Development (MD) study performed at 450 GeV in April 2012. In the study, 23 horizontal collimators in IR3 and IR7 in both beams were moved from the initial parking positions to tighter settings around the interpolated orbit. The TCTs were not aligned during this feasibility study, as the interpolation is known to be worse at these collimator locations due to a less reliable BPM signal. The TCP cut was made at 4.2 σ, and safety margin was set to 2 σ to give an overall half gap of 6.2 σ. The initial and final jaw positions in mm and beam σ are shown in Fig. 4(a) and Fig. 4(b).

If these collimators were to reach the tighter settings using the semi-automatic setup tool, the elapsed time would be much larger. Typically, if a step of 5 μm is made every 1 s, the time taken for all 23 collimators aligned during the MD to reach the tighter settings would be 27 minutes. In this case, therefore, the tool provided a speed-up by a factor 1620. The semi-automatic setup tool was then used to move the jaws further inwards until they touched the beam halo and the alignment was completed. Considering also the beam-based alignment of the IR3 TCPs (for the momentum halo cut) and the IR7 TCPs (to define the betatron halo for alignment), the setup for a total of 27 collimators including the BPM-interpolation guided initialization lasted 1 hour 45 minutes. If this time is scaled with the total number of collimators (86), an extrapolated setup time of 5.5 hours is reached, which is 2 hours less than the previous best time achieved.

The time gain is more than the expected 27 minutes, as the time spent by the algorithm resuming the alignment after BLM signal crosstalk during the semi-automatic setup [2] is greatly minimized. The crosstalk in the BLM signal occurs when one collimator out of a group of simultaneously moving collimators touches the beam edge, and the resulting loss spike is detected also on the BLMs immediately downstream of the other collimators. At the start of the alignment, some collimators may already be close to the beam, and each time crosstalk occurs, the stepwise movement of other collimators much further from the beam is halted as the algorithm sequentially re-aligns each stopped collimator to identify which one is touching the beam.

SUMMARY AND OUTLOOK

This paper presents a software tool conceived to speed up the alignment of the LHC collimators. The reproducible correlation between the BPM-interpolated orbit and the measured beam centers at the collimator positions is ex-

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ploited to quickly move in the collimator jaws from the initial parking positions to tighter settings before the start of beam-based alignment. It was tested during a LHC beam study, where 23 collimators were moved in to 6.2 σ, after which beam-based alignment was performed. The collimators were aligned in 1.75 hours, which can be extrapolated to 5.5 hours for an alignment of all LHC collimators, a gain of 2 hours over the previous best setup time. The tool will be integrated into the standard alignment software to be used for all future collimator setups.

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