COMPARISON OF LHC COLLIMATOR BEAM-BASED ALIGNMENT TO BPM-INTERPOLATED CENTERS

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Abstract

The beam centers at the Large Hadron Collider collimators are determined by beam-based alignment, where both jaws of a collimator are moved in separately until a loss spike is detected on a Beam Loss Monitor downstream. Orbit drifts of more than a few hundred micrometers cannot be tolerated, as they would compromise the performance of the collimation system. Beam Position Monitors (BPMs) are installed at various locations around the LHC ring, and a linear interpolation of the orbit can be obtained at the collimator positions. In this paper, the results obtained from beam-based alignment are compared with the orbit interpolated from the BPM data throughout the 2011 and 2012 LHC proton runs.

INTRODUCTION

A collimation system protects the Large Hadron Collider (LHC) from quenches in the superconducting magnets, providing multi-stage hierarchical cleaning [1]. The collimators also protect against single-turn losses and radiation effects. Maximal cleaning efficiency can only be obtained if the beam centers are known, so that the jaws can be positioned symmetrically around the beam in units of σ.

In beam-based alignment, the collimator jaws are moved separately towards the beam from their initial positions in step sizes of 5 μm to 20 μm until a loss spike is observed on the Beam Loss Monitor (BLM) further downstream of the collimator. The beam center at each collimator location is calculated as the average of the two aligned jaw positions. The alignment precision depends on the jaw step size used to move the jaw. Through the use of a BLM feedback algorithm [2] which stops the repetitive jaw movement when the losses exceed a pre-defined threshold, the time required for a full alignment of all 86 LHC collimators has been reduced from ~29 hours in 2010 to ~17 hours in 2011.

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 [4]. These monitors are placed on each side of the warm quadrupoles, thus
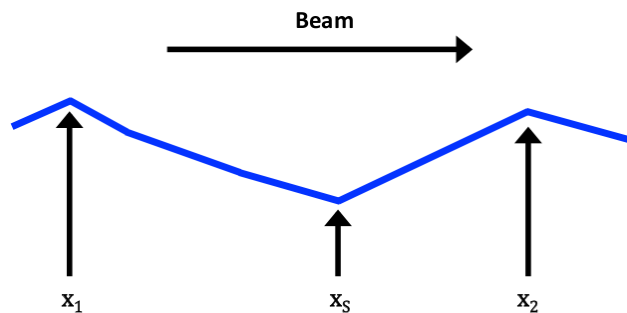
Figure 1: Example of the beam orbit through points 1, S and 2 (from [3]). With BPMs located at point 1 and 2, the objective of the interpolation is to find the orbit at point S.

providing the minimum configuration that allows a linear interpolation of the closed orbit, dispersion and β functions [5].

In a future implementation of the alignment software, the interpolated orbit could be acquired and exploited to speed up the alignment process, hence the motivation of this work. In the paper, the method used to calculate the interpolated orbit is explained, followed by a quantitative analysis of the differences between both sets of measurements.
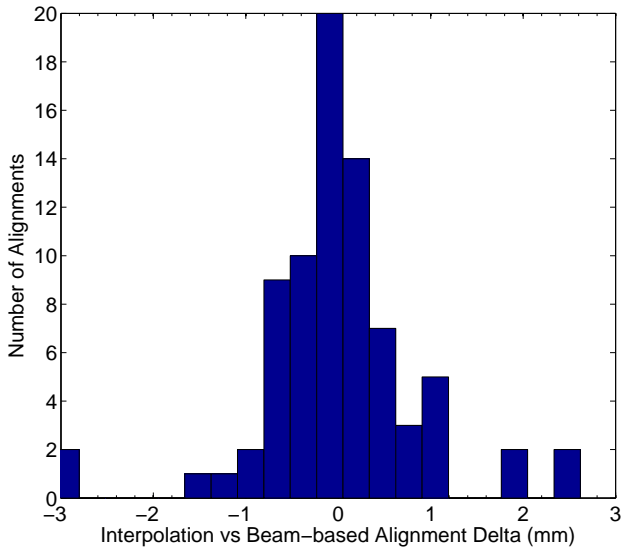
BPM-INTERPOLATED ORBIT

An example of the LHC beam orbit through various points in 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:
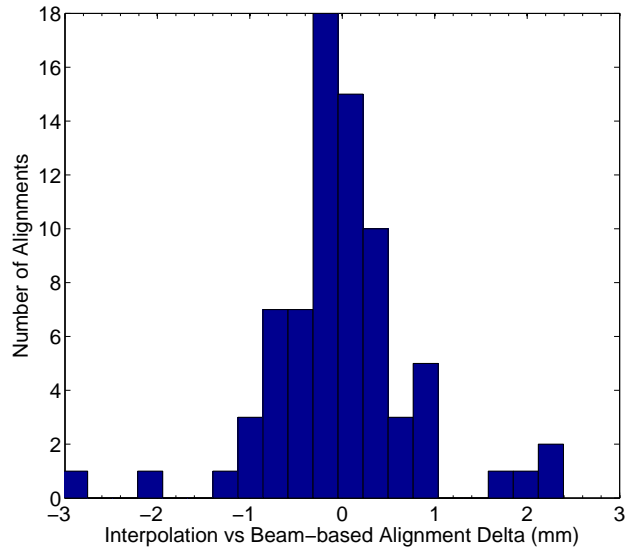
$$\begin{pmatrix} x_2 \\ x_2' \end{pmatrix} = M_{12} \begin{pmatrix} x_1 \\ x_1' \end{pmatrix} = \begin{pmatrix} C_{12} & S_{12} \\ C_{12}' & S_{12}' \end{pmatrix} \begin{pmatrix} x_1 \\ x_1' \end{pmatrix}$$

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

(a) Measurements at Injection (450 GeV)

(b) Measurements at Flat Top (3.5 TeV)

Figure 2: Delta between the BPM-interpolated and the beam-based centers at the LHC collimators in 2011.

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

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

$$S_{12} = \sqrt{\beta_1\beta_2}\sin\psi_{12} \qquad (3)$$

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

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:

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

The interpolated orbit is one of the features provided 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:

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

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

Table 1: BPM-interpolation and beam-based comparison statistics for 2011.

Dataset	Mean (mm)	R.M.S. (mm)	SD (mm)
Injection	0.553	0.849	0.854
Flat Top	0.536	0.811	0.817

from the calculation. The interpolation accuracy derives from the linearity of the BPM system (1% of the half radius, corresponding to $\sim$130μm for arc BPMs).

COMPARISON RESULTS

The interpolated orbit at each collimator was extracted for the same timestamp at which the collimator was aligned. Both datasets are acquired and logged at a rate of 1 Hz. Comparison results are presented for two stages in the LHC machine cycle when beam-based collimator alignment is performed, for data from the 2011 and 2012 runs.

Results in 2011

Comparison results for 2011 are shown as histograms in Fig. 2(a) and Fig. 2(b). The deltas generally lie within ± 1 mm, but large deltas can be observed for the tertiary collimators (TCTs). The large deltas at these locations are likely due to a poorer performance of the BPMs located in this region. The statistics for the 2011 run are presented in Table 1. The absolute average for the injection dataset corresponds to 0.553 mm, while for flat top the absolute average is 0.536 mm. The standard deviation is $\sim$0.840 mm.

Results in 2012

A similar analysis was performed for the collimator alignments in 2012 (see Fig. 3(a) and Fig. 3(b)). Once
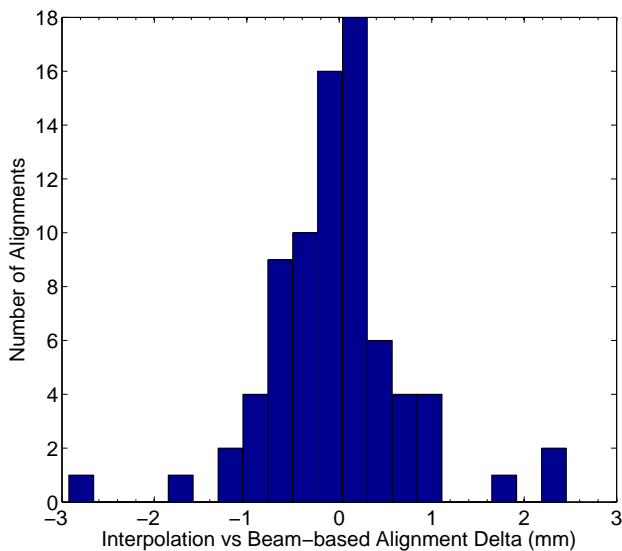
(a) Measurements at Injection (450 GeV)
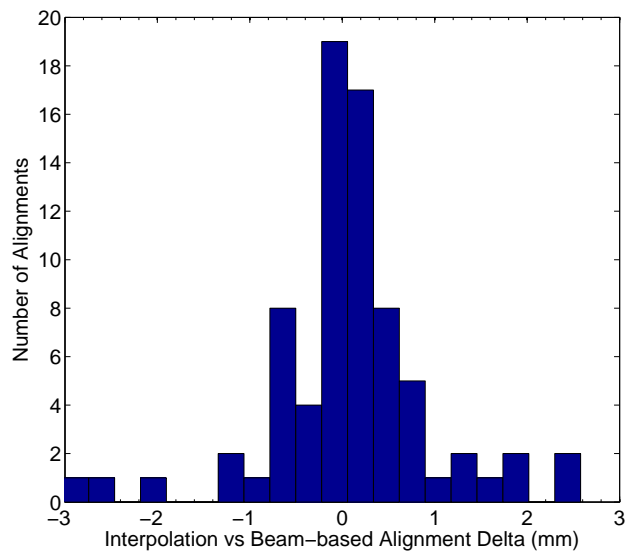
(b) Measurements at Flat Top (4 TeV)

Figure 3: Delta between the BPM-interpolated and the beam-based centers at the LHC collimators in 2012.

Table 2: BPM-interpolation and beam-based comparison statistics for 2012.

Dataset	Mean (mm)	R.M.S. (mm)	SD (mm)
Injection	0.501	0.758	0.762
Flat Top	0.564	0.883	0.885

again, large deltas were observed for the TCTs. The statistics for the 2012 run listed in Table 2 show an average of 0.501 mm and 0.564 mm for the injection and flat top datasets respectively. The standard deviation is ∼0.840 mm.

CONCLUSION

In this paper, a comparison between the beam centers at the LHC collimators obtained from beam-based alignment to the BPM-interpolated orbit at the collimators was presented. The analysis was performed for four collimator alignments at injection energy and flat top in 2011 and 2012. The average difference between the interpolated and the measured orbit is of ∼0.550 mm, with a maximum delta of 2.8 mm and a standard deviation of ∼0.840 mm. The study proves that beam-based collimator alignment is essential for the good performance of the system, as the collimators cannot be set deterministically from the orbit measurements without introducing large errors.

FUTURE WORK

The similarity between the two datasets can be exploited to speed up LHC collimator beam-based alignment, where all the jaws could be moved in a single step at a movement rate of 2 mm/s rather than 10 μm/s around the BPM-interpolated orbit. Another margin in mm could be placed to take into account the maximum possible difference between the interpolated and the measured beam center. Moving the jaws immediately to a safe half-gap margin of 5σ would provide a gain in setup time, as all collimators except the primary collimators are positioned from 6.3σ up to 26σ away from the beam.

ACKNOWLEDGMENTS

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