FIRST OPERATIONAL EXPERIENCE WITH EMBEDDED COLLIMATOR BPMs IN THE LHC

G. Valentino*, G. Baud, R. Bruce, M. Gasior, J. Olexa, S. Redaelli, A. Valloni, J. Wenninger
CERN, Geneva, Switzerland

Abstract

During Long Shutdown 1, 18 Large Hadron Collider (LHC) collimators were replaced with a new design, in which beam position monitor (BPM) pick-up buttons are embedded in the collimator jaws. The BPMs provide a direct measurement of the beam orbit at the collimators, and therefore can be used to align the collimators more quickly than using the standard technique which relies on feedback from beam losses. Online orbit measurements also mean that margins in the collimation hierarchy placed specifically to cater for unknown orbit drifts can be reduced, therefore increasing the beta-star and luminosity reach of the LHC. In this paper, the first operational results are presented, including a comparison with the standard alignment technique and a fill-to-fill analysis of the measured orbit in different machine modes in the first year of running after the shutdown.

INTRODUCTION

A multi-stage collimation system [1] is installed in the Large Hadron Collider (LHC) [2] to clean high-energy halo particles before they can reach the superconducting magnets. In order to maintain optimum cleaning performance, the two jaws of each collimator must be placed parallel to and equidistant from the beam at the desired number of beam σ units. The 108 collimators are positioned to form a four-stage hierarchy, with the primary collimators (TCP) closest to the beam, followed by the secondary collimators (TCSG) and absorbers (TCLA). Tertiary collimators (TCT) are installed to protect the experimental regions. Most of the collimators are installed in Insertion Region (IR) 3 and IR7 to clean particles with large off-momentum and betatron offsets respectively.

Following several feasibility studies with beam in the Super Proton Synchrotron (SPS) [3], the 16 TCTs in the experimental IRs and the 2 TCSGs in IR6 were replaced in Long Shutdown 1 (LS1) in 2013-2015, by new collimators with embedded BPM pick-ups (named TCTPs and TCSPs respectively) [4]. The pick-ups are installed on the upstream and downstream ends of the copper-based tapered region of each jaw [5], as shown in Fig. 1. They are retracted by 8.5 mm and 8.6 mm from the active surfaces of the TCSP and TCTP, respectively.

Two main reasons motivated the replacement. Embedded BPMs allow the possibility to perform the beam-based alignment faster, as already demonstrated in the SPS [6], and therefore to respond more quickly to configuration changes in the experimental IRs, such as crossing angle or β^* values. Secondly, a direct monitoring of the orbit at the collimator locations could allow to reduce the existing orbit margins in the TCSP-TCTP collimation hierarchy, which could lead to more room to push the β^* [7].

* gianluca.valentino@cern.ch

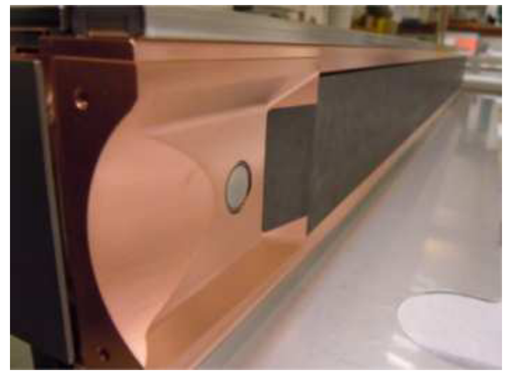

Figure 1: A TCTP collimator jaw showing the BPM pick-up embedded in the taper.

BPM-BASED COLLIMATOR ALIGNMENT

An upgrade of the collimator alignment software was performed during LS1 to allow the BPM collimators to be aligned in the LHC [8]. The BPM data acquisition is provided by the Diode ORbit and OScillation (DOROS) electronics [9]. The pick-up signals are sent to the *BPMCOL* Front-End Software Architecture (FESA) class, which converts them to beam positions in mm based on the distance between opposite electrodes (inferred from the collimator gap measurement) and jaw center offset provided by the *LHCCollAlign* FESA class. The latter also implements the successive approximation algorithm which was first tested with a prototype collimator in the SPS. The algorithm works by moving the so-called left and right jaws in steps across the beam, keeping the same gap, until the signals from the opposite upstream electrodes are equalized and the measured beam position relative to the collimator center is below 5 μm. As each jaw corner can be moved independently using a dedicated stepper motor, it then proceeds to move only the downstream jaw corners until the corresponding signals are also equalized. As a result of non-linearities due to the BPM geometry, 10-20 steps may be needed until the algorithm converges. An example of an alignment is shown in Fig. 2. The resulting tilts in the collimator jaws are a combination of misalignments of the collimator tank and of the actual beam angle. These tilts were confirmed by alignment of the individual

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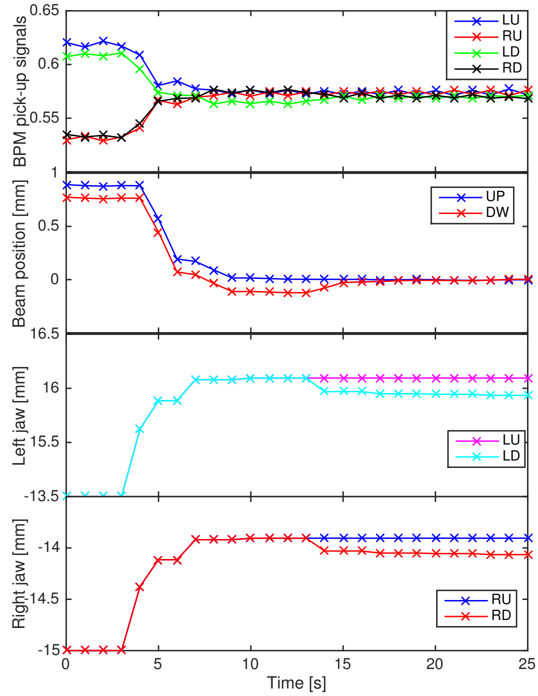

Figure 2: Example of a BPM-based alignment of the TCSP.A4R6.B1, showing the left-up (LU), left-down (LD), right-up (RU) and right-down (RD) jaw corner positions and electrode signals, as well as the upstream (UP) and downstream (DW) measured beam positions.

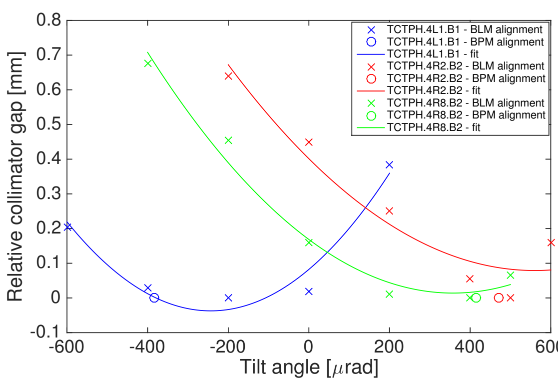

Figure 3: Measurements of tilts in three collimators from BPM-based and BLM-based alignment.

jaw corners to the beam with different tilt angles using the BLM-based technique, as shown in Fig. 3. The jaws are deemed to be parallel to the beam when the minimum jaw gap is achieved after touching the beam on either side with each jaw. Before each measurement, a gentle transverse beam excitation was done to repopulate the halo after the previous alignment, in which some beam is scraped away.

On the other hand, the alignment using feedback from Beam Loss Monitors (BLMs) is performed by moving in each jaw until the beam is touched on either side [10]. This is achieved when a characteristic loss spike is visible in the signal of a BLM placed directly downstream of the collimator. The beam center is then calculated as the average of the aligned jaw positions. This alignment procedure is time-consuming due to the distance that each jaw needs

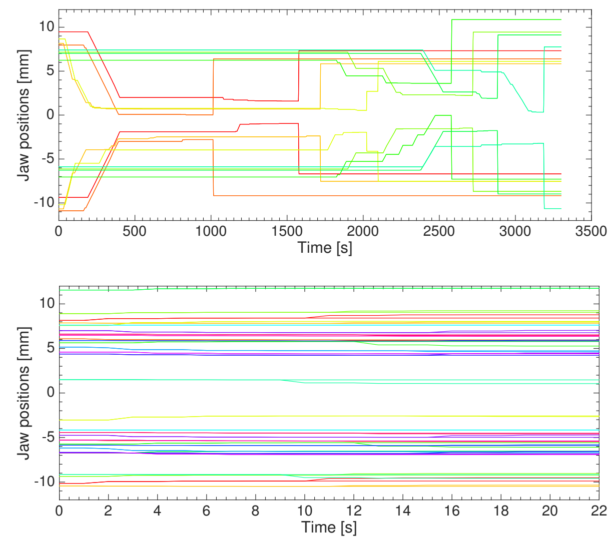

Figure 4: Time required to align the 8 TCTs in IR1 and IR5 in 2012 with the BLM-based technique (top) and all 16 TCTPs in 2015 with the BPM-based technique (bottom).

to travel, but however also provides a measurement of the beam size at the collimator location, which is not possible using the BPM-based technique. A comparison of the two techniques is shown in Fig. 4, with the BPM-based technique requiring a factor 150 less time to complete the alignment. The BPM-based technique also provides a more accurate measurement of the beam center and allows the possibility to align the collimators with unsafe beams at the large operational aperture, which is crucial for non-robust collimators.

FILL-TO-FILL PERFORMANCE

A fill-to-fill analysis was performed for the collimator BPM data acquired during several parts of the machine cycle in the standard p-p run in 2015, as shown in Fig. 5 for several TCTPs in different IRs, specifically ramp, squeeze and stable beams. None of the curves start from a zero beam position relative the collimator center, as during 2015 the collimator settings were based on measurements from the BLM-based alignment. The fill-to-fill reproducibility is good, and perhaps this could be exploited in the dynamic parts of the cycle (ramp and squeeze) by means of a feed-forward into the collimator functions. Plots of the beam positions measured at each pair of horizontal and vertical TCTPs in the same beam and side of each IR are shown in Fig. 6. This visualization allows for a better picture of the spreads in different IRs and planes over tens of fills.

BEAM INTERLOCKS

The direct monitoring of the orbit at the TCSPs and TCTPs would have to be interlocked if the orbit margins in the collimator settings are going to be reduced to push the β^* [11]. An interlock threshold scan was performed to determine the number of dumps that would have occurred during operation. A dataset of ∼50 fills with respect to an

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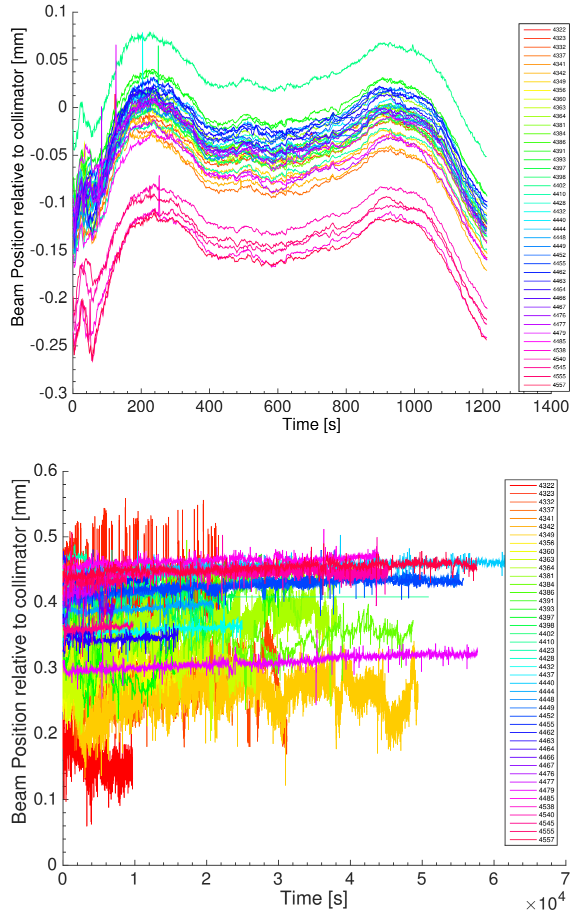

Figure 5: Beam positions measured relative to the centers of selected collimators during the ramp (top) and stable beams (bottom).

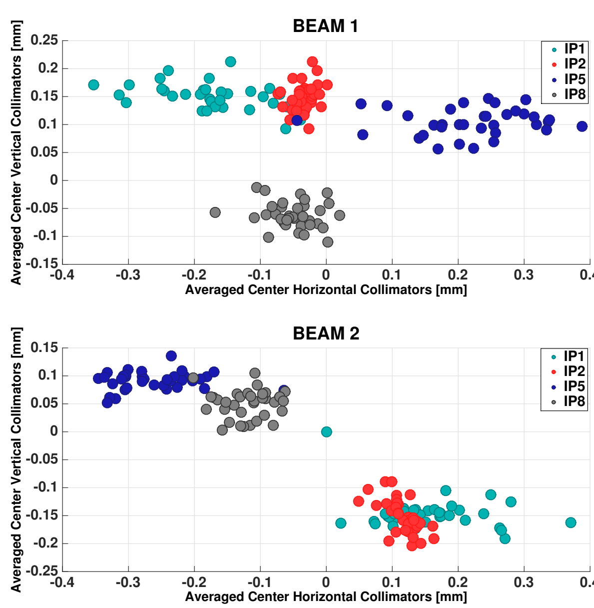

Figure 6: Beam positions at each pair of neighboring horizontal and vertical TCTPs in B1 (top) and B2 (bottom).

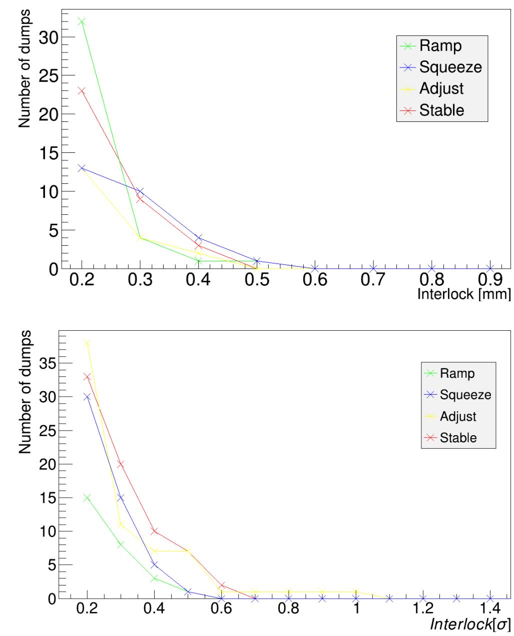

Figure 7: Number of predicted dumps for different BPM interlock thresholds for individual collimators (top) and a TCTP-TCSP combination (bottom).

initial reference fill was used. The analysis was done considering both individual interlocks, which would dump the beam if the relative orbit exceeds a given threshold at any collimator, and combined TCTP-TCSP interlocks, where instead the beam dump would be triggered based on the combined offsets at TCTPs and the upstream TCSPs, as shown in Fig. 7. Setting a conservative margin of $\sim 1\ \sigma$ for the combined interlock, which would not have caused any dumps in the selected fills, would already be an improvement compared to previously assumed margins based on Run 1 data.

CONCLUSIONS AND OUTLOOK

Beam position monitors embedded inside movable collimators can provide a direct measurement of the beam orbit, which can be used to center the jaws around the beam. A successful commissioning campaign was carried out to ensure the correct functionality of the BPMs and of the control software. The goal of significantly reducing the time needed to re-align the collimators for several frequent changes of machine configurations was achieved. The preliminary performance analysis from monitoring during stable beam conditions in p-p and Pb-Pb runs demonstrates the quality and reliability of the system, and together with the good reproducibility of the orbit and its dynamic behaviour during the ramp and squeeze, indicate that it would be possible to deploy beam interlocks in order to reduce the existing collimation hierarchy margins which account for orbit drifts. In addition, the orbit measured at the collimators can be also fed-forward into the collimator functions to ensure that the collimators are well-centred around the beam.

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