View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by OAR@UM

Nuclear Instruments and Methods in Physics Research A 768 (2014) 62–68

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Beam feasibility study of a collimator with in-jaw beam position monitors

Daniel Wollmann [a,*], Andriy A. Nosych [a,b,c,1], Gianluca Valentino [a], Oliver Aberle [a], Ralph W. Aßmann [a,2], Alessandro Bertarelli [a], Christian Boccard [a], Roderik Bruce [a], Florian Burkart [a], Eva Calvo [a], Marija Cauchi [a], Alessandro Dallocchio [a], Daniel Deboy [a], Marek Gasior [a], Rhodri Jones [a], Verena Kain [a], Luisella Lari [a], Stefano Redaelli [a], Adriana Rossi [a]

[a] CERN, Geneva, Switzerland
[b] Cockcroft Institute, Daresbury, United Kingdom
[c] The University of Liverpool, Liverpool, United Kingdom

A R T I C L E I N F O

Article history:
Received 8 August 2014
Received in revised form
9 September 2014
Accepted 9 September 2014
Available online 19 September 2014

Keywords:
Circular collider
Collimation
Beam position monitor

A B S T R A C T

At present, the beam-based alignment of the LHC collimators is performed by touching the beam halo with both jaws of each collimator. This method requires dedicated fills at low intensities that are done infrequently and makes this procedure time consuming. This limits the operational flexibility, in particular in the case of changes of optics and orbit configuration in the experimental regions. The performance of the LHC collimation system relies on the machine reproducibility and regular loss maps to validate the settings of the collimator jaws. To overcome these limitations and to allow a continuous monitoring of the beam position at the collimators, a design with jaw-integrated Beam Position Monitors (BPMs) was proposed and successfully tested with a prototype (mock-up) collimator in the CERN SPS. Extensive beam experiments allowed to determine the achievable accuracy of the jaw alignment for single and multi-turn operation. In this paper, the results of these experiments are discussed. The non-linear response of the BPMs is compared to the predictions from electromagnetic simulations. Finally, the measured alignment accuracy is compared to the one achieved with the present collimators in the LHC.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

To intercept unavoidable losses of particles from the beam halo that would otherwise risk to hit the superconducting magnets, the Large Hadron Collider (LHC) has a powerful collimation system with 44 movable collimators per beam [1–3]. Most collimators consist of two jaws, which can be moved independently, with the beam passing through the center of the jaws. Each jaw is called 'left' or 'right' depending on its position with respect to the beam when viewed from the upstream side of the collimator. For optimal performance, the jaws have to be centered around the local orbit. This has so far been done using a beam-based alignment procedure for each collimator [4], where each jaw is moved separately towards the beam until it starts intercepting the halo particles. This is verified by monitoring the signal of a nearby downstream beam loss monitor (BLM), which registers the secondary shower particles created by impacts on the collimator. For machine protection reasons, the alignment procedure requires dedicated fills at low intensities that are done infrequently because the procedure is time consuming [5]. The introduction of a semi-automatic set-up procedure and constant improvements in the algorithms allowed to significantly reduce the set-up time in 2011 and 2012 compared to the first manual set-up in 2010 [6,7]. When all collimators have been centered around the beam, the cleaning performance is verified by provoked losses to create a so-called 'beam loss map'. In subsequent high-intensity fills, the collimators are driven back to the previously found positions, relying on the machine reproducibility. This implies strict requirements on the long-term orbit stability, as the time-consuming setups cannot be performed too frequently. The excellent performance of the LHC collimation system during run 1 has recently been discussed in [8].

To overcome these limitations, a new collimator design with in-jaw beam position monitors (BPMs) was proposed. Four BPM pickups are installed at the extremities of each jaw to provide a measurement of the beam orbit at the upstream and downstream sides of the collimator. Beam tests were successfully carried out

* Corresponding author. Tel.: +41 22 76 62479.
E-mail address: daniel.wollmann@cern.ch (D. Wollmann).
[1] Currently with ALBA CELLS, Barcelona, Spain.
[2] Currently with DESY, Hamburg, Germany.

http://dx.doi.org/10.1016/j.nima.2014.09.024
0168-9002/© 2014 Elsevier B.V. All rights reserved.

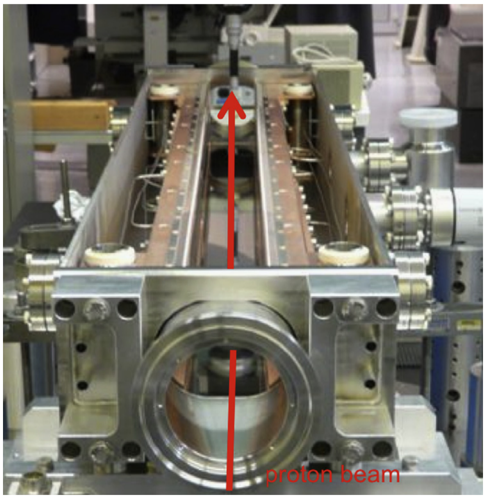

Fig. 1. Photograph of the prototype collimator from one end. The moveable jaws are centered around the beam path (red arrow) and enclosed by a 1.2 m long tank. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

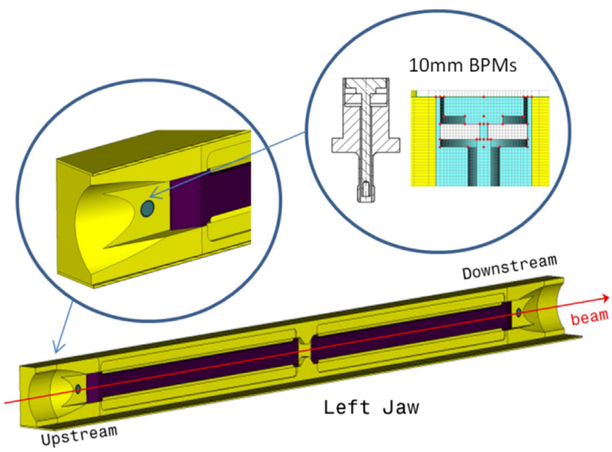

Fig. 2. A model of a single jaw of the prototype collimator with embedded BPM pick-ups at both ends.

with a mock-up collimator in the CERN Super Proton Synchrotron (SPS) [9,10]. Fig. 1 shows a photograph of the prototype collimator. The moveable jaws are centered around the beam path (red arrow) and enclosed by a 1.2 m long tank. A sketch of the mock-up jaw with the BPM pick-up buttons in the beginning (upstream) and end (downstream) of the jaw is depicted in Fig. 2. Fig. 3 shows a zoomed view of one BPM pick-up button in the upstream taper of the jaw during laboratory measurements of the button position with respect to the jaw surface.

A BPM-based alignment, where it is not necessary to touch the beam with the collimator jaws, would allow a fast and non-destructive beam-based collimator set-up, which would reduce the need for special fills with intensity constraints. In addition, it would allow to continuously monitor the beam offsets in the collimators with a much better resolution than is currently possible with the standard LHC BPMs, as the distance between the buttons and the beam would be much smaller and there would be no need to interpolate the orbit from the closest BPMs at the collimator location. The collimators could follow orbit drifts and therefore provide more flexibility for local orbit changes, which are regularly required around the experimental insertions. Measuring the beam offset at both ends of the collimator jaws will make it possible to position them fully parallel to the beam trajectory by introducing a longitudinal tilt angle to the jaws. For

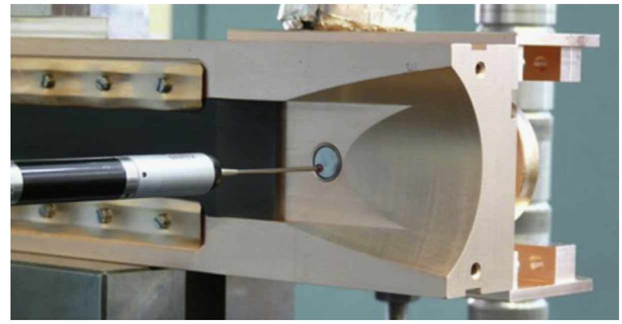

Fig. 3. Zoomed view of one BPM button in the upstream jaw taper during laboratory measurements of the button position with respect to the jaw surface [10].

the time being, the tilt angle of the jaws with respect to the beam can only be evaluated with long and detailed jaw scans and is hence only applied for the injection and dump protection collimators. Furthermore, the margins for orbit drifts between collimator families could possibly be reduced [11], which would eventually allow smaller beam sizes at the experimental interaction points (IPs) and lead to an increased luminosity of collisions.

This paper is structured as follows. Section 2 describes the BLM-based and BPM-based alignment techniques. This is followed by results from multi-turn and turn-by-turn beam measurements in Sections 3 and 4 respectively. Finally, the measurements are compared to simulations using an electromagnetic (EM) model in Section 5.

2. BEAM-based alignment

2.1. BLM-based alignment

The LHC collimators are currently aligned using feedback from the BLMs. Each jaw is moved separately to the beam on either side until the halo is touched, and the beam center is subsequently calculated as the average of the two aligned left and right jaw positions, J_L and J_R:

$$X_{beam} = \frac{J_L + J_R}{2} \tag{1}$$

Fig. 4 shows a typical BLM-based alignment with the mock-up collimator in the SPS. The jaws were moved in steps of 50 μm by means of two stepping motors installed at both extremities. The touching of the beam halo was recorded by a BLM installed about 50 cm downstream of the collimator. One jaw is considered to be aligned, if the signal of the BLM reaches $\sim 1 \times 10^{-6}$ Gy/s. This value may vary depending on the average losses without jaw movement, as a spike needs to be clearly distinguished from the background signal. This also defines the minimum step size. Note that in the LHC step sizes of 5–20 μm are used due to a better beam quality and higher particle energies. This technique unfortunately does not allow the alignment of the individual jaw corners.

2.2. BPM-based alignment

The mock-up collimator consists of two copper jaws and a 10 mm thick graphite layer on each jaw surface. The four stainless steel button electrodes of diameter 10.3 mm are placed at the upstream and downstream jaw extremities at 10.6 mm below the graphite surface. With such a setup, the total distance B between BPM electrodes, referred to as the *BPM aperture*, is $B = G + 2 \times 10.6$ mm, where G is the distance between the jaws in units of mm, referred to as the it jaw gap. According to [12], the coefficient of linear conversion

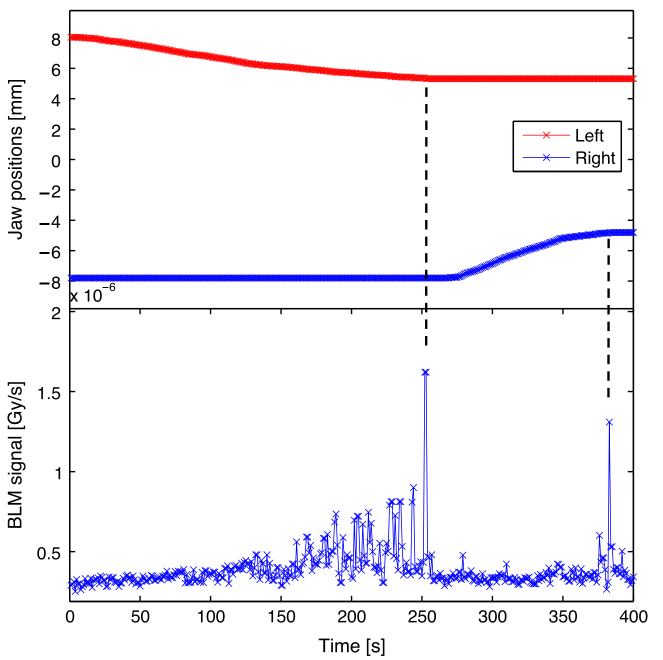

Fig. 4. Jaw positions and the BLM signal during BLM-based alignment. The jaws are aligned when a spike is observed in the BLM signal, as indicated by the dashed black lines.

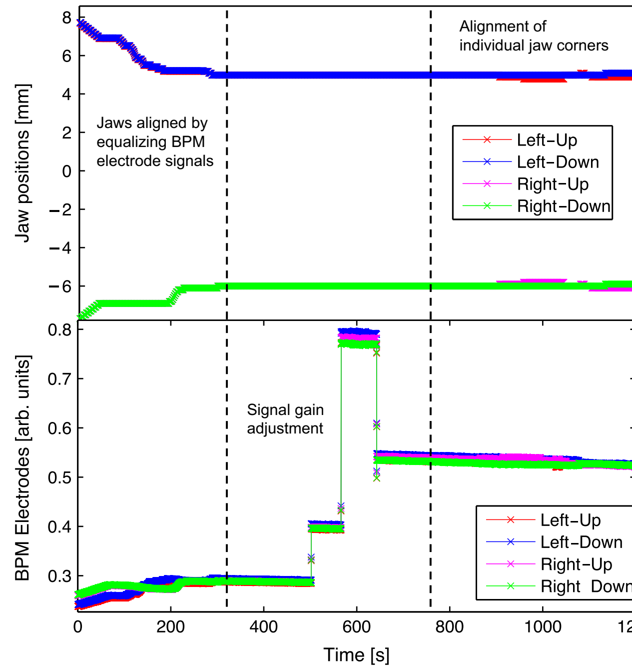

Fig. 5. Jaw positions and BPM electrode signals during BPM-based alignment. The electrode signal gain was changed to reduce the non-linearities in the electronics.

of raw position readings to millimeters amounts to $B/4$. The beam position can be then approximated by the linear expression:

$$X_{bpm} = \frac{B}{4} \times X_{raw} \approx X_{beam}. \quad (2)$$

Here, X_{bpm} is referred to as the *linearized* beam position, while X_{raw} is the normalized beam position, calculated from difference over sum of the measured peak voltages $V_{L,R}$ of the opposite electrodes on the left and right jaws:

$$X_{raw} = \frac{V_L - V_R}{V_L + V_R}. \quad (3)$$

The collimator is aligned when the electrode signals for each jaw corner are equalized. An example of BPM-based alignment is shown in Fig. 5. During the alignment, the gain of the BPM signals was changed as part of the beam test. At the end, the individual jaw corners are moved until the signals are equalised (or X_{raw} is approximately zero), and the beam center is calculated using Eq. (1).

The electrode signals are proportional to the distance between the beam and the jaw, as well as to the beam intensity, hence one can see a slight decrease in the signals over time.

3. Results of beam measurements with multi-turn BPM electronics

Experiments with a mock-up collimator with jaw-integrated BPM buttons were performed in the CERN SPS with stored beam at 120 GeV. The beam intensities were usually just below 1×10^{11} protons (longitudinal length of $4\sigma = 2$ ns), stored in one bunch. During the measurements presented below, the in-jaw BPMs were connected to the prototype of a high resolution diode-based orbit measurement system, which was developed at CERN for this application. This system was optimized for multi-turn applications. From measurements with BPMs installed in the LHC the achievable resolution with this system was estimated to be well below 1 μm [13].

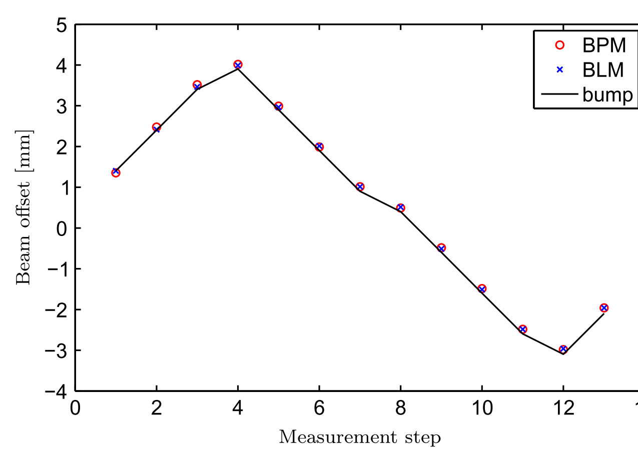

Fig. 6. Comparison of the orbit offset at the collimator given by the bump (black line) and the beam offsets measured with the in-jaw BPMs (red circles) and the BLM-based alignment method (blue crosses). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

3.1. Measurements with a four corrector closed orbit bump

To compare the accuracy of the BPM-based alignment method with the currently used BLM-based method, a four-corrector closed orbit bum p was created in the region of the mock-up collimator. The amplitude of this bump was changed in steps of 1 m. The values of X_{raw} are in the range of $[-1, 1]$ and are relative to the total voltage seen by both pickups. Fig. 6 shows changes of the beam offset during the measurement in 13 steps. The orbit offset at the collimator given by the bump (black line) is compared to the beam offsets measured with the in-jaw BPMs (red circles) and the BLM-based alignment method (blue crosses).

The correlation between the bump settings and the beam centers measured with the jaw-integrated BPMs (red) and the BLM-based method (blue) is depicted in Fig. 7. The discrepancy between settings and achieved orbit offset was estimated to be about 10% of the step

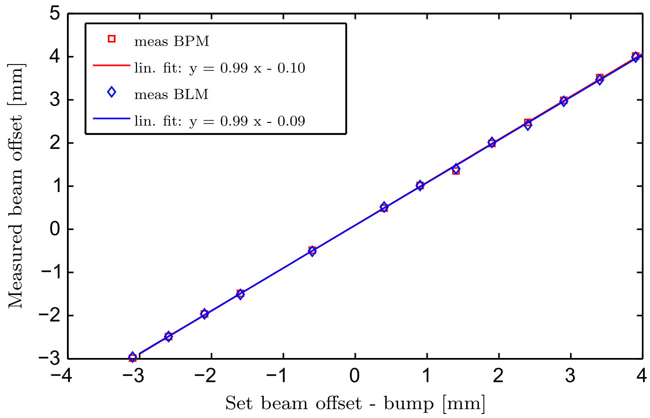

Fig. 7. Correlation between measured beam centers (BPMs – red, BLM-based method – blue) and the bump settings for the orbit offset at the collimator. The error in the bump settings was estimated to about 10% of the movement increment. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

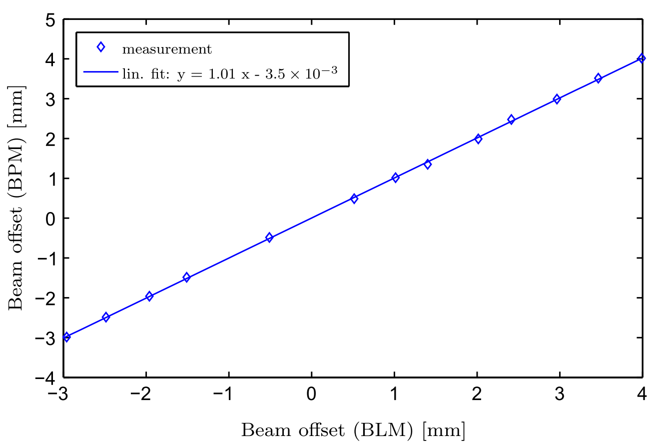

Fig. 8. Correlation between beam offsets measured with the BLM-based method and the jaw-integrated BPMs (blue diamonds). The blue line shows the linear fit of the measurement data. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

size, i.e. $\sim 100\ \mu m$. The deviations between the measured and set beam offsets are dominated by this uncertainty.

Fig. 8 shows the correlation between beam offsets measured with the BLM-based method and the jaw-integrated BPMs (blue diamonds). The linear fit of the measurement data (blue line) and the coefficients of the fit polynomial emphasize the good agreement between both methods.

Fig. 9 depicts the differences between the centers measured by the BPM and BLM-based methods (red circles), the differences between the bump set values and the centers measured by the BPMs (blue crosses), and by the BLM-based alignment (black diamonds). The deviations between the set and measured values for the beam offset can be found in the interval $[-50\ \mu m, +140\ \mu m]$ as indicated by the dashed black lines. The deviations between BPM and BLM method were within $[-50\ \mu m, +63\ \mu m]$ or between the red dotted lines.

The data indicate that the orbit drifted within the first 30 min of the measurement, i.e. between step one and four, by $\sim 100\ \mu m$, in addition to the closed orbit bump. The end of this orbit drift is indicated by the magenta dashed line. Excluding the data points before the end of this orbit drift (left of the magenta line), the deviations between the set and measured beam offset were $\leq \pm 40\ \mu m$. The black diamonds and blue crosses can be found between the upper red dotted line and the upper black dashed

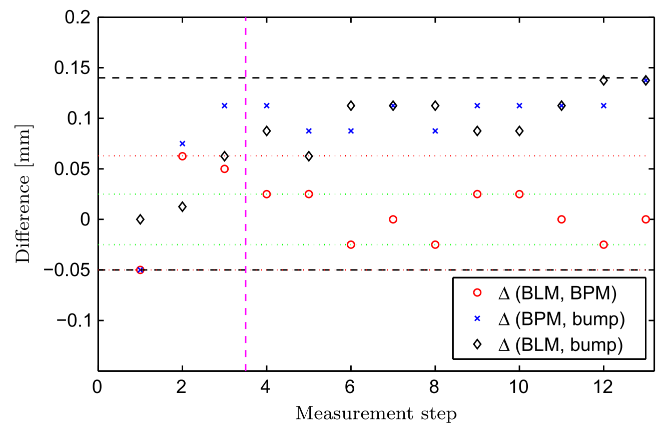

Fig. 9. Differences between bump settings and beam offsets measured with the in-jaw BPMs (blue crosses) and the BLM-based method (black diamonds) respectively. The differences of measured beam offsets between the BPM and BLM-based method are shown as red circles. The vertical magenta dashed line indicates the end of an additional external orbit drift during the first 30 min of the measurement. The horizontal dotted green lines indicate the maximum deviation between the beam offsets measured with the BPMs and the BLM-based methods, if the data during the orbit drift are not included. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

line. The differences between beam offsets measured by the BPM and the BLM method were $\leq \pm 25\ \mu m$, i.e. the red circles lie on or between the green dotted lines. It should be noted that the error when using the BLM-based method is given by the $50\ \mu m$ step size of the collimator jaw movement. Thus, the deviation between the BPM and BLM-based alignments is dominated by this.

3.2. Measurements with primary and secondary protons impacting on the jaw

One possible obstacle for the use of collimators with jaw-integrated BPM buttons could be a disturbance of the BPM signals due to particles impacting on the jaw. Therefore, several full beam scrapings with the maximum jaw movement speed of 2 m/s have been performed with the mock-up collimator. No disturbances of the BPM signals by primary protons impacting on the jaws have been observed with beam intensities up to $\sim 1.15 \times 10^{11}$ protons, i.e. a nominal LHC bunch. The BPM buttons, positioned in the taper at the beginning and end of the jaws, are retracted by 10.6 mm with respect to the jaw surface. This retraction is sufficient to avoid impacts of primary protons in the buttons.

To measure the possible impact of secondary protons on the BPM signals with the prototype collimator at a fixed position, an upstream SPS collimator was used to scrape the beam intensity down from 9.5×10^{10} p to 8.5×10^{10} p by reducing the gap in twelve steps from 15 mm to 2.75 mm. The out-scattered beam protons were then intercepted by the mock-up collimator, which was kept at a constant gap of 21 mm. Fig. 10 shows the beam offset in the BPM mock-up measured with the upstream (blue) and downstream (red) BPM button pairs versus the beam loss detected at a BLM downstream of the BPM-equipped collimator.

The measured beam offset stays well below $50\ \mu m$ with increasing beam losses. The outliers of $87\ \mu m$ for the upstream and respectively $108\ \mu m$ for the downstream BPM buttons are probably due to a drift of the beam orbit at the collimator. These orbit drifts can easily exceed $50\ \mu m$ in the SPS. This is an indication that the measurement of the beam offset is not affected by secondary protons impacting the jaws. The loss rate on a primary collimator (the one closest to the beam) in the LHC (5×10^8 p/s) [14] is well below the largest number of protons lost during a single step in the experiment (4×10^9 p in the last step).

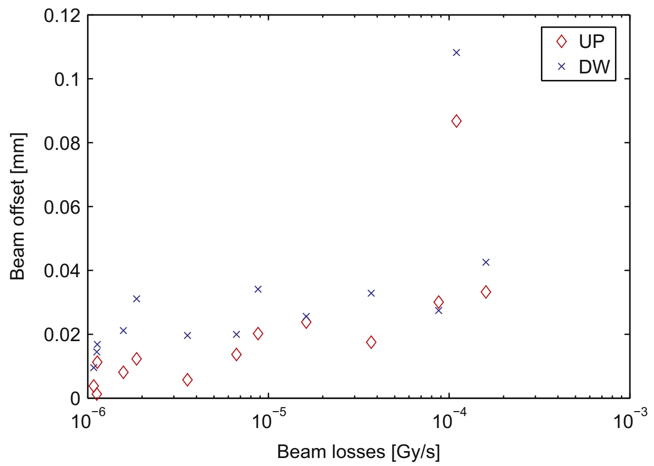

Fig. 10. Beam offset measured with the upstream (red) and downstream (blue) BPMs in the mock-up collimator versus the beam loss detected by a downstream BLM. The gap of the SPS collimators was closed in twelve steps from 15 mm to 2.75 mm, resulting in a loss of 1×10^{10}p. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

4. Results of turn-by-turn measurements with the LHC BPM electronics

The use of collimators with in-jaw BPM buttons may also be interesting in the transfer lines between the SPS and the LHC. In this case, the shot-by-shot or respectively the turn-by-turn reproducibility of the measured beam offset is the figure of merit.

The measurements presented below were performed with standard LHC BPM electronics connected to the in-jaw BPM buttons in single pass operation. The beam offset in the collimator was recorded in every turn for a total number of 300 turns before the jaws were moved again.

4.1. Collimator scans with constant gap

To measure the turn-by-turn reproducibility of the BPM signals for different beam offsets at constant gap the two collimator jaws were moved in parallel around the beam orbit with constant gap. This measurement was performed for four gaps: 14.75, 17.35, 20.35, and 24.75 mm. The asymmetry between the cables and the two electronics channels, which process the signals from one pair of BPMs, introduces gains and offsets in the measured data. Therefore, the BPM data were corrected by applying a linear fit of the form:

$$X_{bpm}^{corr} = B \times X_{raw} \times a - b \quad (4)$$

to the product $B \times X_{raw}$ to obtain values for the fit parameters a and b at each gap and beam offset.

Fig. 11 shows the corrected measured beam position at a gap of 20.35 mm and a beam offset of -0.025 mm over the 300 turns of the measurement. The turn-by-turn variation is partially due to injection oscillations and the limited accuracy of the used electronics. Fig. 12 depicts the averaged X_{bpm}^{corr} versus the set beam center at a gap of 20.35 mm. The plot shows that there is a good agreement between the set beam center and the corrected measured mean beam position for the up- and downstream BPMs.

The RMS of the measured turn-by-turn beam offsets is a measure for the expected shot-by-shot reproducibility of the BPMs with the standard LHC electronics. Fig. 13 shows the RMS of the beam offsets X_{bpm}^{corr} for turn-by-turn measurements during parallel scans with the jaws at gaps of 17.35 mm (upper) and 24.75 mm (lower). For the scan at a gap of 17.35 mm the RMS stays around 65 μm during the whole measurement. At a gap of 24.75 mm the

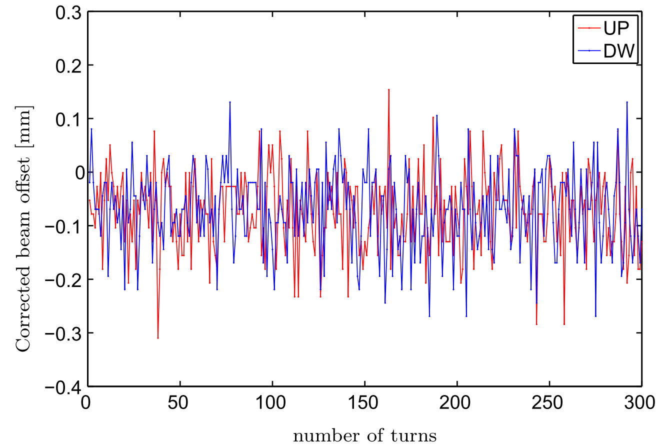

Fig. 11. Corrected measured beam offsets (upstream in red, downstream in blue) versus turn number. The jaw gap was 20.35 mm and the beam offset was -0.025 mm. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

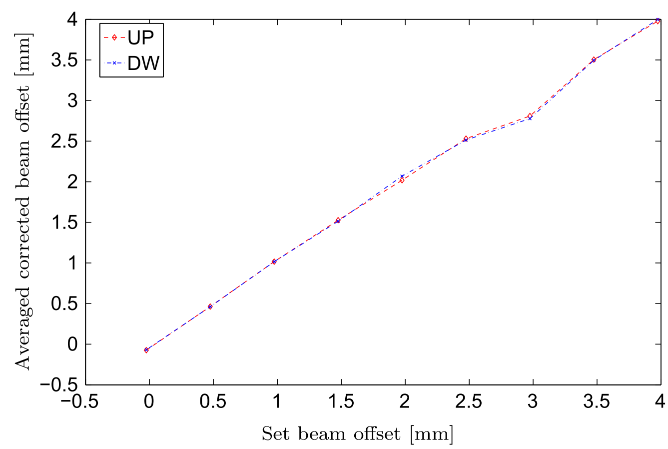

Fig. 12. Measured mean beam offsets for turn-by-turn measurements (300 turns) during collimator scans at gaps of 20.35 mm for the BPM buttons at the upstream (red) and downstream (blue) end of the collimator. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

RMS decreases with increasing beam offset. This effect may be explained by the non-linearity of the BPM buttons for big beam offsets. Note that the data have not been corrected for the non-linear response of the buttons. The maximum RMS of the measured beam offsets versus the collimator gap size is plotted in Fig. 14. As expected, the RMS increases with increasing gap, i.e. with longer distance between buttons and beam. The RMS stays below 90 μm even for gaps as large as 24.75 mm.

5. Simulation of in-jaw BPMs

5.1. Time-domain simulation of BPM response

Applying a method analogue to [15] the voltage response of the embedded BPMs in time domain has been simulated with CST Particle Studio [16]. The 3D model of the collimator mock-up consists of two 1 m long copper jaws with a 10 mm-thick graphite layer (resistivity $\rho = 13$ μΩm) as jaw surface material (Fig. 2). Four pick-up buttons with a diameter of 10.3 mm were placed at the jaw extremities 0.6 mm below the copper level, i.e. 10.6 mm below the graphite surface [10]. The bunch was modeled by a pencil-type Gaussian pulse ($\sigma_\tau = 75$ mm) of 17 nC charge, corresponding to the

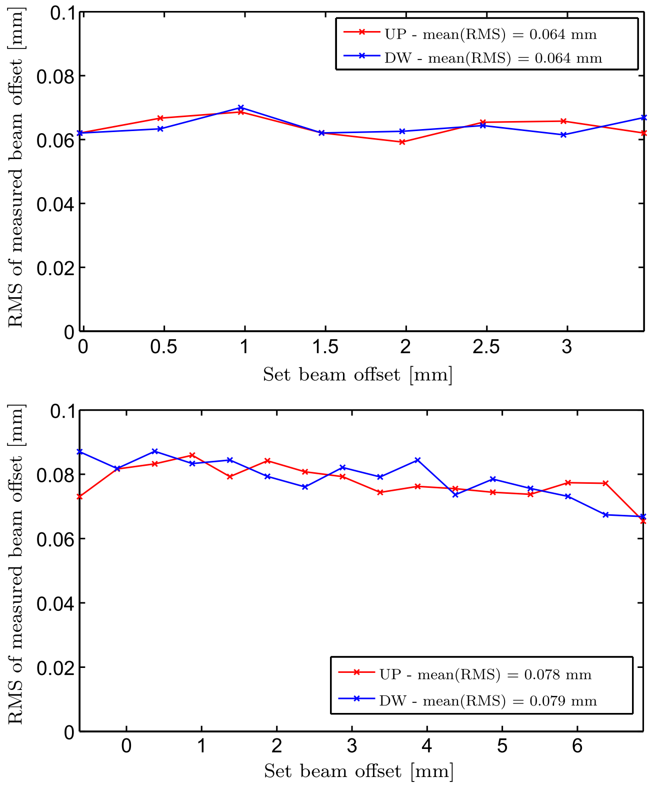

Fig. 13. RMS of the beam offsets for turn-by-turn measurements (300 turns) during collimator scans at gaps of 17.35 mm (upper) and 24.75 mm (lower) for the BPM buttons at the upstream (red) and downstream (blue) end of the collimator. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

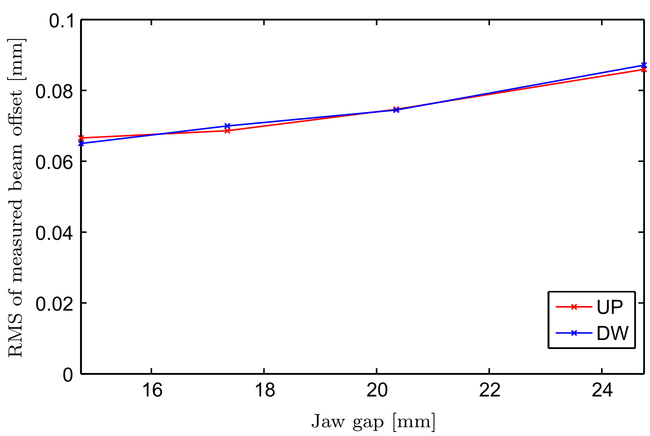

Fig. 14. Measured maximum RMS of the beam offset versus collimator gap for the BPM buttons at the upstream (red) and downstream (blue) end of the collimator. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

nominal LHC bunch of 1.15×10^{11} protons moving at the speed of light.

The studies focused on the linearity of the BPM response as a function of the jaw gap and the transverse offset of the beam. The sensitivity of the BPMs to beam displacement was studied by sweeping the simulated beam in the horizontal (H) plane at various jaw gaps [17]. A set of five fixed beam positions X_{beam} on the H-axis was simulated for jaw gaps G of 12, 16, 20, 24 and 28 mm. The beam positions included a centered beam and were equivalent to offsets of 0, 20%, 40%, 60% and 80% of the jaw half-gap ($G/2$). Fig. 15 shows schematically the simulation conditions for $G = 24$ mm and $G = 16$ mm.

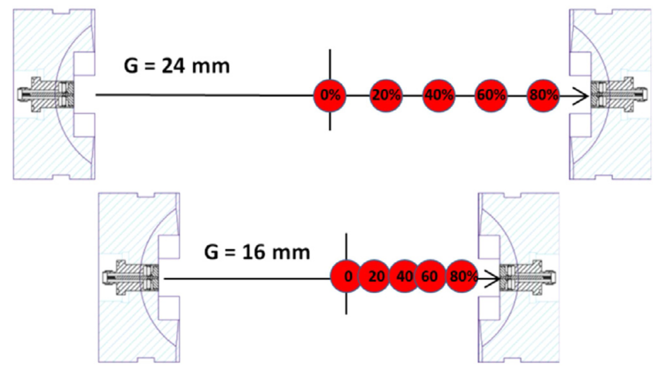

Fig. 15. Collimator schematic in the transverse plane showing the simulation conditions for beam sweeps along the *H*-axis for different jaw gaps and beam offsets (not to scale).

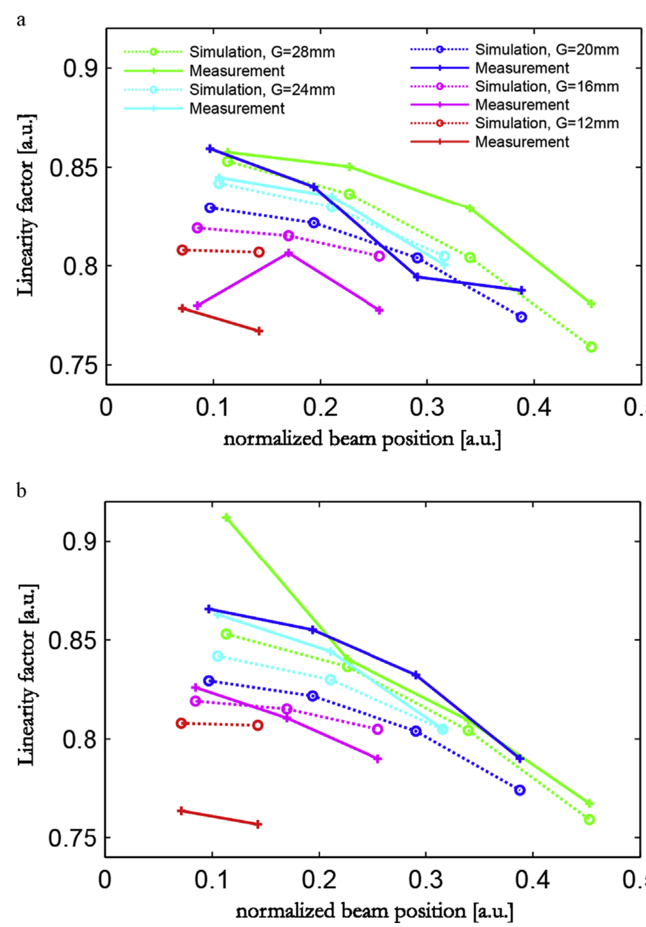

Fig. 16. Comparison of simulated and measured linearity factors of BPM characteristics, obtained with identical jaw gaps. (a) Upstream data and (b) downstream data.

5.2. Validation of simulated BPM response by measurements

To validate the simulations, an experiment was performed with the mock-up collimator and circulating beam in the SPS. The jaw gaps were chosen similar to the simulated ones. For each G the sets of 3–5 pre-defined beam offsets were measured. Note that for gaps below 16 mm, large beam offsets of over 60% of $G/2$ could not be achieved as these would have caused a scraping of the beam and therefore induced losses.

The *linearity parameter* L_f, which is a conversion coefficient between the linearized and the original beam positions, is calculated as

$$L_f = \frac{X_{bpm}}{X_{beam}} \quad (5)$$

and defines the mapping between the actual beam position and the measured position obtained from pickup signals.

The linearity factors of the measurements and simulations are compared in Fig. 16. The L_f curves are non-linear for each set of beam positions at one collimator gap. They quantify the slope of the BPM characteristic with respect to the linearized BPM position and the distance between pickups. The L_f is increasing with G and changes by less than 10% between the smallest and largest beam offset.

The estimated deviations between measured and simulated L_f are below 5%. The measurement of X_{beam} introduces systematic errors. The accuracy of the initial beam-based alignment was between 50 and 100 μm. With this method a small tilt of the collimator jaws with respect to the orbit cannot be excluded. These systematic uncertainties caused a difference of the readings between the up- and downstream BPMs of ~ 50 μm throughout all measurements. Furthermore, the beam orbit drifted slowly during the experiment, which increased the abovementioned alignment error of the jaws.

Nevertheless, this experiment showed that the geometrical non-linearity of the BPM readings can be well reproduced by simulations and therefore allows its correction for the full range of the jaw motion (2–60 mm).

6. Conclusions

Collimators with jaw-integrated BPMs promise a drastically reduced set-up time of the LHC collimation system – a few seconds per collimator compared to approximately five minutes achieved with BLM-based alignment – making the alignment less dependent on machine stability, as parasitic monitoring without dedicated fills will be possible. Furthermore, they allow to continuously monitor beam offsets at the collimators and thus improve the passive machine protection. They permit tighter collimator settings, could help improve the beam cleaning, and possibly allow for a higher luminosity in the experimental interaction points.

Experiments with a test collimator in the CERN SPS have shown excellent agreement between the novel BPM and the state-of-the-art BLM-based collimator alignment method, which was better than ± 25 μm. So far no disturbances in the BPM signals due to beam protons impacting on the collimator jaws have been observed. Experiments with an upstream collimator scattering protons onto the prototype collimator indicate that the accuracy of the BPM measurements is not affected by impacting secondary protons. The accuracy of in-jaw BPM buttons in single pass operation has been measured for the first time. The RMS of the measured beam offsets stayed below 90 μm even for gaps as large as 24.75 mm.

The non-linear response of the in-jaw BPM buttons has been simulated as a function of the gap width and the beam offset and compared to measurements with beam. A very good agreement was observed, showing that the discrepancy between simulation and measurement is within 5%. This discrepancy can eventually be accounted for in the signal processing.

Taking into account the results of laboratory measurements, the tests in the SPS, and the LHC collimation experience, it can be concluded that the accuracy of a BPM-based collimator set-up will be significantly better than the current BLM-based method. Furthermore, the measurements have shown that the accuracy of in-jaw BPMs in single pass operation is sufficient for the application in the transfer lines of the LHC. Therefore, the experience and results acquired from this feasibility study endorsed the installation of the new BPM-equipped collimators in the LHC.

Acknowledgments

This research was supported by EuCARD grant agreement no. 227579.

References

[1] R. Assmann, Collimators and beam absorbers for cleaning and machine protection, in: LHC Project Workshop—'Chamonix XIV', 2005, pp. 261–267.
[2] The LHC Design Report, vol. 1 Chapter 2, Technical Report, CERN (2004-003).
[3] The LHC Design Report, vol. 1 Chapter 18, Technical Report, CERN (2004-003).
[4] D. Wollmann, et al., First cleaning with LHC collimators, in: Proceedings of IPAC10 Kyoto, Japan, 2010.
[5] G. Valentino, et al., Comparison of the LHC collimation setups with manual and semi-automatic collimator alignment, in: Proceedings of IPAC2011, San Sebastian, Spain, 2011.
[6] G. Valentino, et al., Physical Review Special Topics Accelerators and Beams 15 (2012) 051002.
[7] G. Valentino, et al., Automatic computer algorithms for beam-based setup of LHC collimators, in: Proceedings of 11th International Computational Accelerator Physics Conference, Warnemuende, Germany, 2012.
[8] R. Bruce, et al., Physical Review ST Accelerators and Beams 17 (2014) 081004. http://dx.doi.org/10.1103/PhysRevSTAB.17.081004.
[9] D. Wollmann, et al., First beam results for a collimator with in-jaw beam position monitors, in: Proceedings of IPAC2011, San Sebastian, Spain, 2011.
[10] C. Boccard, et al., Embedded collimator beam position monitors, in: Proceedings of DIPAC2011, Hamburg, Germany, 2011.
[11] R. Bruce, et al., Calculation method for safe beta-star in the LHC, in: Proceedings of IPAC 2011.
[12] P. Piot, Evaluation and correction of nonlinear effects in FNPL beam position monitors, in: FNPL Notes, no. Beams-doc-1894-v1, 2005.
[13] M. Gasior, et al., BPM electronics based on compensated diode detectors—results from development systems, in: Proceedings of 2012 Beam Instrumentation Workshop, Newport News, VA, USA, 2012.
[14] R. Bruce, et al., Nuclear Instruments and Methods in Physics Research Section A 729 (0) (2013) 825. http://dx.doi.org/10.1016/j.nima.2013.08.058.
[15] G. Valentino, et al., Physical Review Special Topics Accelerators and Beams 17 (2014) 021005.
[16] CST Particle Studio, available at ⟨www.cst.com⟩.
[17] A. Nosych, et al., Electromagnetic simulations of BPMs embedded into collimator jaws, in: Proceedings of DIPAC2011, Hamburg, Germany, 2011.

View publication stats