EXPERIMENTAL VERIFICATION FOR A COLLIMATOR WITH IN-JAW BEAM POSITION MONITORS

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Abstract

At present the beam based alignment of the LHC collimators is performed by touching the beam halo with the two jaws of each device. This method requires dedicated fills at low intensities that are done infrequently because the procedure is time consuming. This limits the operational flexibility in particular in the case of changes of optics and orbit configuration in the experimental regions. The system performance relies on the machine reproducibility and regular loss maps to validate the settings. To overcome these limitations and to allow a continuous monitoring of the beam position at the collimators, a design with in-jaw beam position monitors was proposed and successfully tested with a 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 measured alignment accuracy is compared to the accuracies achieved with the present collimators in the LHC.

INTRODUCTION

To intercept unavoidable losses of particles from the beam halo into the superconducting magnets the LHC has a powerful collimation system with 44 moveable collimators per beam [1, 2, 3]. The beam-based alignment of the LHC collimators is performed by touching the beam halo with the two jaws of each device and recording beam losses with the beam loss monitor (BLM) installed at the device [4]. This 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]. To guarantee the validity of the set-up and therefore a sufficient cleaning, strict requirements for long term orbit stability have to be fulfilled.

To overcome these limitations a new collimator design with in-jaw beam position monitors was proposed and preliminary beam tests were successfully carried out with a mock-up collimator in the CERN-SPS [8, 9]. A sketch of the mock-up jaw with the BPM buttons in the beginning (upstream) and end (downstream) of the jaw is depicted in Figure 1. Figure 2 shows one BPM button in the upstream taper of the jaw during laboratory measurements. 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 currently possible with the standard LHC BPMs, as the distance between buttons and beam would be much smaller and there would be no need for interpolating the orbit from the closest BPMs. The collimators could follow orbit drifts without overhead and give, therefore, more flexibility for local orbit changes, which are regularly required around the experimental insertions. Furthermore, the margins between collimator families could possibly be reduced, which would eventually allow smaller beam sizes at the experimental IPs, which means an increased luminosity.

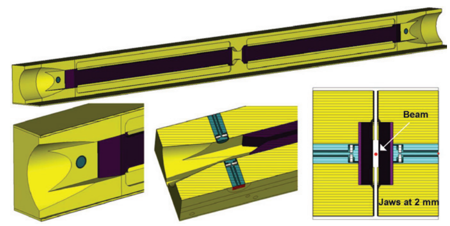

Figure 1: A view of a single jaw and cross-sections of the mock-up collimator with in-jaw BPM buttons [10].

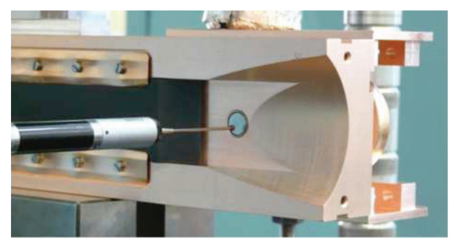

Figure 2: View of the BPM button in the taper at the beginning of the jaw during laboratory measurement of the button position [9].

Because of the promising results of the first beam tests in the SPS, presented in [8], an advanced mechanical design and a production prototype have been developed at CERN [11]. The first collimators with in-jaw beam position monitors will be installed in the period 2013-2014, when the LHC will not be operating because of upgrades and maintenance, into the experimental regions starting

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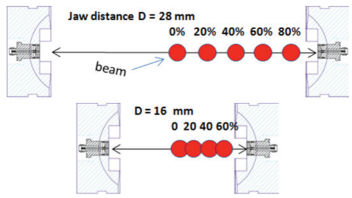

Figure 3: Simulation conditions for beam sweeps along the X axis for different jaw distances.

with ATLAS and CMS. These will replace the current tertiary collimators (TCTs). In addition the two secondary collimators (one per beam) installed in the dump region (IR6) will be replaced by collimators with jaw-integrated BPM buttons. Later also the TCTs around ALICE and LHCb will be replaced.

RESPONSE OF IN-JAW BPM BUTTONS

The CST Particle Studio Suite has been successfully used to simulate BPMs embedded into collimator jaws. Through EM simulation the jaw BPMs were characterized and studied for non-linearities of horizontal beam position dependence to the distance between jaws [10]. The particle beam was modelled by a single Gaussian-type bunch ($\sigma = 75\,\mathrm{mm}$) of 1.7×10^{-8} C, corresponding to the nominal intensity of a LHC bunch (1.1×10^{11} p). The collimator model, shown in Figure 1, consists of two copper jaw blocks ($84\,\mathrm{mm} \times 1194\,\mathrm{mm}$). The 50 mm homogeneous extrusions at both ends are needed to guarantee a smooth transition to the beam pipe. Graphite ($\rho = 13\,\mu\Omega\mathrm{m}$) was used as insert material on the jaw surfaces facing the beam. The four stainless steel (316L) pick-up buttons (diameter 10.3 mm), were placed at the jaw extremities 10 mm below the graphite surface [9]. The sensitivity of the embedded BPM signals was studied by simulating beam position sweeps in the hor. and ver. planes for several jaw distances and bunch lengths. For each jaw distance a set of 5 beam locations on the x axis was simulated (see Figure 3). All simulated beam positions were normalized to the button distance.

A *slope* parameter was introduced, which is a linear conversion coefficient between measured (x_{meas}) and actual simulated beam position (x_{act}) and is calculated as: $slopes = x_{meas}/x_{act}$. This quantity defines the mapping between the actual beam position and the measured position obtained from the BPM signals. Its values, calculated during the horizontal beam sweep simulations, are plotted in Figure 4. It can be seen that the slope value changes little for small button distances. However, even for the extreme case of the fully open jaws, the changes are $\leq 30\,\%$. The horizontal correction factor is non-linear with respect to the jaw gap, but the behaviour of real collimator BPM signals for various jaw gaps can be predicted through simulation. This leads to the conclusion, that the horizontal non-linearity correction factor - in the form of a cross-term polynomial - for the whole jaw motion range can be derived from slope values for several jaw gaps by building an inverse fit to the slope surface shown in Figure 4.

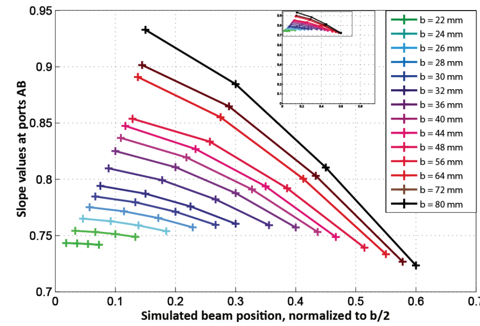

Figure 4: Simulated map of slopes vs. button distances, ranging from parked jaws to operational distance of 2 mm.

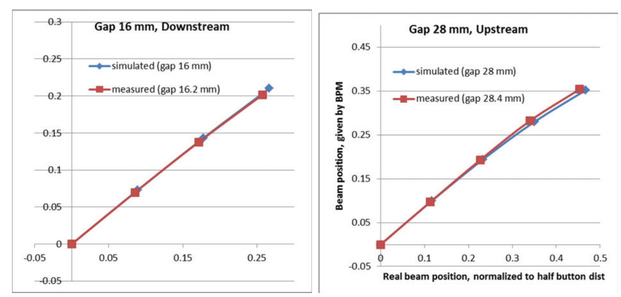

Figure 5: Comparison between simulated and measured a real beam position.

The simulation results were confirmed with corresponding beam measurements performed with the mock-up collimator installed in the CERN-SPS. Despite the presence of several imperfections in the experiment's conditions, a good agreement between simulation and measurement is observed (see Figure 5).

RESULTS OF BEAM MEASUREMENTS WITH MULTI-TURN BPM ELECTRONICS

The experiments with the mock-up collimator were performed in the CERN-SPS with stored beam at 120 GeV. The beam intensities were usually just below 1×10^{11} protons, 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 is 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 $1\,\mu\mathrm{m}$ [12].

Measurements with Primary and Secondary Protons Impacting on the Jaw

One major 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.

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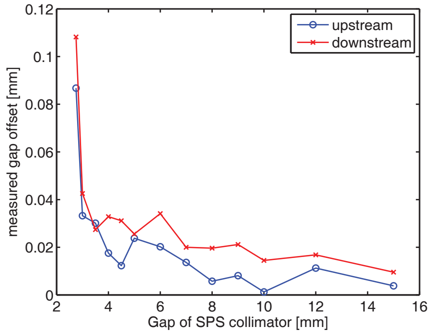

Figure 6: Beam offset measured with the upstream (blue) and downstream (red) BPMs in the mock-up collimator versus the gap of an upstream SPS collimator. The sharp increase of the BPM signal variation for smaller SPS collimator gaps is due to non-linearities in the BPM electronics at low beam intensities. The major part of the beam was already scraped away at that time.

Therefore several full beam scrapings with the maximum jaw movement speed of $2\,\mathrm{mm/s}$ 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 $10.6\,\mathrm{mm}$ with respect to the jaw surface. From the above results this retraction seems to be sufficient to avoid the impact of protons in the buttons.

To measure the possible impact of secondary protons on the BPM signals, an upstream SPS collimator was used to scrape the beam. The created secondary halo was then intercepted by the mock-up collimator, which was kept at a constant gap of 21 mm. Figure 6 shows the beam offset in the BPM mock-up measured with the upstream (blue) and downstream (red) BPM button pairs versus the gap of the upstream SPS collimator. Up to a SPS collimator gap of 3.5 mm the variation in the BPM signal was $\leq 35\,\mu m$ which is below the expected accuracy of the experimental set-up ($\sim 50\,\mu m$). The sharp increase of the variation for smaller SPS collimator gaps is due to non-linearities in the BPM electronics at low beam intensities. The major part of the beam was already scraped away at that time.

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 bump was created at the mock-up collimator. The amplitude of this bump was changed in steps of $1\,\mathrm{mm}$ starting with an initial beam offset of $0.4025\,\mathrm{mm}$. Figure7 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).

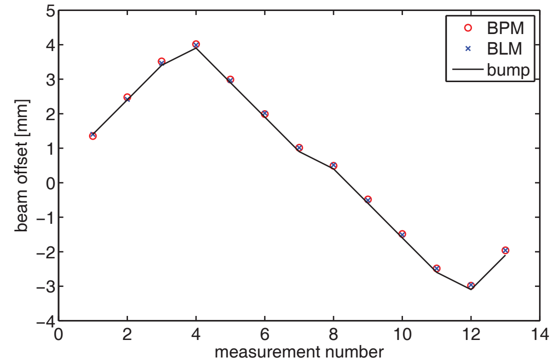

Figure 7: Comparison of the orbit offset at the collimator given by the bump (black line) and the beam offsets measured with the in-jaw BPMs (red circles) and the BLM-based alignment method (blue crosses).

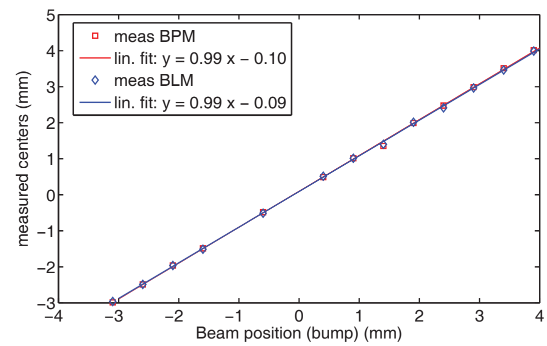

Figure 8: Correlation between measured beam centres (BPMs - red, BLM based method - blue) and the bump settings for the orbit offset at the collimator. The error in the bump settings was estimated to about 10% of the movement increment.

The correlation between the bump settings and the beam centres measured with the jaw-integrated BPMs (red) and the BLM based method (blue) are depicted in Figure 8. The discrepancy between settings and achieved orbit offset was estimated to about 10% of the step size, i.e. $\sim 100\,\mu m$. The deviations between measured and set beam offsets are dominated by this uncertainty.

Figure 9 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. Note that the BPMs allow an alignment within a couple of seconds, whereas the BLM-based method takes several minutes.

Figure 10 depicts the differences between the centres measured by the BPM and BLM-based methods (red circles), the differences between the bump set values and the

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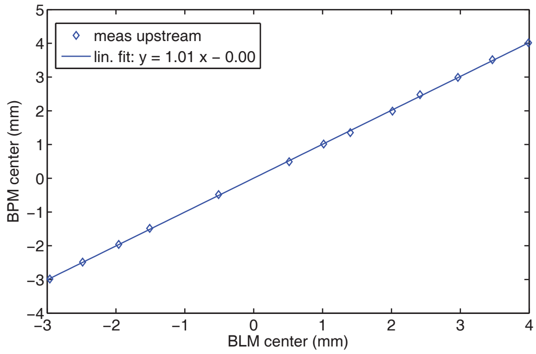

Figure 9: Correlation between beam offsets measured with the BLM based method and the jaw-integrated BPMs (blue diamonds). The blue line shows the linear fit of the measurement data.

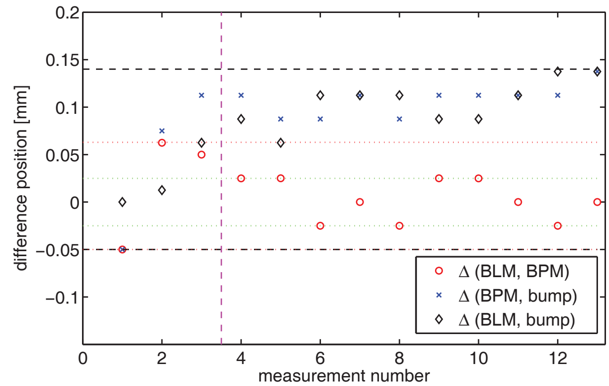

Figure 10: Differences between bump settings and beam offsets measured with the in-jaw BPMs (blue crosses) respectively the BLM-based method (black diamonds). The differences of measured beam offsets between the BPM and BLM based method are shown as red circles. The vertical purple line indicates the end of an additional external orbit drift during the first 30 mins 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.

centres 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 $[-50\,\mu\mathrm{m}, +140\,\mu\mathrm{m}]$ as indicated by the dashed black lines. The deviations between BPM and BLM method were within $[-50\,\mu\mathrm{m}, +63\,\mu\mathrm{m}]$ or between the red dotted lines.

The data indicate that the orbit drifted within the first 30 mins of the measurement, i.e. between step one and four, by $\sim 100\,\mu\mathrm{m}$, in addition to 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 $\leq \pm 40\,\mu\mathrm{m}$. I.e. the black diamonds and blue crosses can be found between the upper red dotted line and the upper black dashed line. The differences between beam offsets measured by the BPM and the BLM method were $\leq \pm 25\,\mu\mathrm{m}$, i.e. the red circles lye on or between the green dotted lines. Thereby does the $50\,\mu\mathrm{m}$ step size of the collimator jaw movement during the BLM-based alignment define the maximal error of this method. Thus, the deviation between the BPM and BLM-based alignments is dominated by this.

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. As this would be a single pass application 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 a 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.

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 scanned in parallel across the gap. This measurement performed at four gap widths: 14.75, 17.35, 20.35, and 24.75 mm.

Figure 11 shows the rms of the beam offsets 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 $65\,\mu\mathrm{m}$ during the whole measurement. At a gap of 24.75 mm the rms decreases with increasing beam offset. This effect may be explained by the non-linearity of the BPM buttons for big beam offsets. The non-linearity of the buttons has not been taken into account here. The maximum rms of the measured beam offsets versus the collimator gap size is plotted in Figure 12. As expected the rms increases with increasing gap, i.e. with longer distance between buttons and beam. The rms stays below $90\,\mu\mathrm{m}$ even for gaps as large as 24.75 mm.

CONCLUSION

Collimators with in-jaw BPMs promise a drastically reduced set-up time of the LHC collimation system - a few seconds per collimator compared to currently several minutes - and less strict requirements for the long-term orbit stability. Furthermore they allow to continuously monitor beam offsets at the collimators and therefore improve the passive machine protection. They would allow tighter col-

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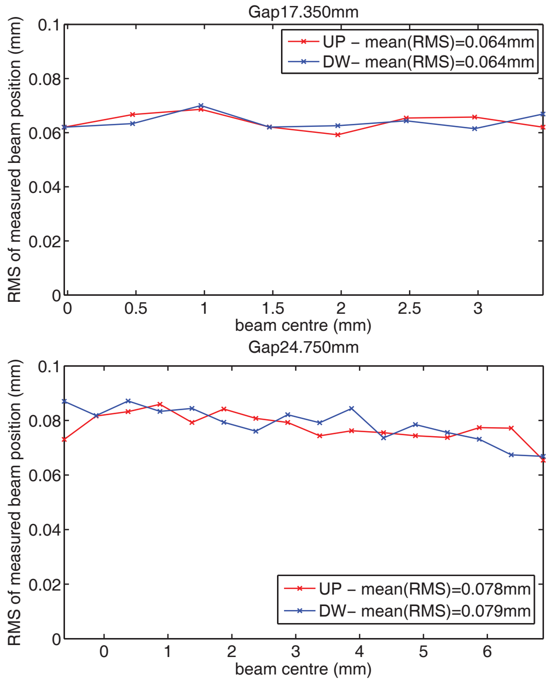

Figure 11: RMS of the beam offsets for turn-by-turn measurements (300 turns) during collimator scans at gaps of $17.35\,\mathrm{mm}$ (upper) and $24.75\,\mathrm{mm}$ (lower) for the BPM buttons at the upstream (red) and downstream (blue) end of the collimator.

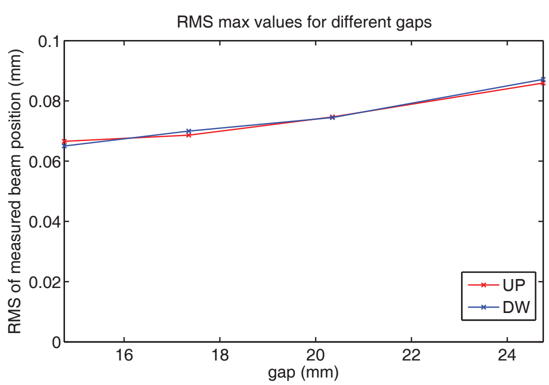

Figure 12: Measured maximum RMS of the beam offset versus collimator gap for the BPM buttons at the upstream (red) and downstream (blue) end of the collimator.

limator settings, thus, could help to improve the cleaning and possibly allow smaller beam sizes in the experimental IPs.

The non-linear beam response of the in-jaw BPM buttons depending on the gap width has been simulated and compared to measurements with beam. Despite the presence of several imperfections in the experiment conditions, a good agreement between simulation and measurement was observed. Experiments with a mock-up collimator in the CERN-SPS have shown an excellent agreement between the novel BPM and the state of the art BLM-based collimator alignment method, which was better than $25\,\mu\mathrm{m}$. So far no disturbances in the BPM signals due to primary or secondary particles impacting on the collimator jaws have been observed. 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 $90\,\mu\mathrm{m}$ even for gaps as large as $24.75\,\mathrm{mm}$. Taking into account the results of laboratory measurements, tests in the LHC and the LHC collimation set-up experience it can be concluded that the accuracy of BPM based collimator set-up will be better than the current state of the art BLM-based method. Furthermore the measurements showed that the accuracy of in-jaw BPMs in single pass operation is sufficient for the application in the transfer lines of the LHC.

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