CALIBRATION OF A NON-LINEAR BEAM POSITION MONITOR ELECTRONICS BY SWITCHING ELECTRODE SIGNALS

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Abstract

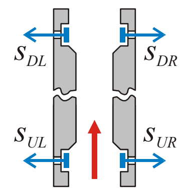
Button electrode signals from beam position monitors embedded into new LHC collimators will be individually processed with front-end electronics based on compensated diode detectors and digitized with 24-bit audio-range ADCs. This scheme allows sub-micrometre beam orbit resolution to be achieved with simple hardware and no external timing. As the diode detectors only operate in a linear regime with large amplitude signals, offset errors of the electronics cannot be calibrated in the classical way with no input. This paper describes the algorithms developed to calibrate the offset and gain asymmetry of these nonlinear electronic channels. Presented algorithm application examples are based on measurements performed with prototype diode orbit systems installed on the CERN SPS and LHC machines.

INTRODUCTION

In order to improve the quality of the LHC collimation system, new collimators will be equipped with embedded beam position monitors (BPMs) [1]. As shown schematically in Fig. 1, each collimator will have four button electrodes, one on each end of each jaw. This arrangement allows beam position measurement for the upstream and downstream electrode pairs as well as the tilt of each jaw, motorised independently on either side. The position and tilt will be used for precise and fast automatic positioning of the jaws symmetrically with respect to the beam [2].

Each electrode signal will be processed independently by one channel of Diode ORbit (DOR) front-end electronics [3]. The DOR system allows sub-micrometre resolution of beam orbit measurements, even with single proton bunches [3]. The resolution is achieved by employing compensated diode detectors, converting nanosecond beam pulses into slowly varying signals, which can be digitised with 24-bit ADCs, sampling at several kHz rate. The ADC samples are averaged in order to provide high resolution beam orbit data at a 25 Hz rate, used for controlling the motors of the collimator jaws. The position and tilt derivation as well as the compensation of the nonlinear characteristic of the button BPMs [2] will be fully implemented in the digital domain.

The most important application of the collimator BPM system is beam centring, so this system as well as DOR front-ends have been optimised for this application. However, collimator BPMs can be also used for regular beam orbit measurement and included in the LHC orbit feed-back system. This is why absolute beam orbit measurements are also considered.



upstream position $= f(s_{UL}, s_{UR})$
downstream position $= f(s_{DL}, s_{DR})$

left tilt $= f(s_{UL}, s_{DL})$
right tilt $= f(s_{UR}, s_{DR})$

Figure 1: Button electrode locations of the BPMs embedded into the jaws of an LHC collimator.

LHC collimators operate typically with jaw gaps in the order of 5 – 10 mm. As the button electrodes are placed some 10 mm below the jaw collimating surface, the collimator BPMs work with 25 –30 mm apertures. Since the expected beam centring accuracy is 10 µm, this requires that both DOR channels processing signals from each BPM electrode pair are symmetric at the 10^{-4} level. Such symmetry can be achieved only by careful calibration of the DOR electronics with beam signals.

The analogue processing scheme with compensated diode detectors is simple and allows achieving DC measurement resolution for nanosecond pulses, but the detectors operate in the linear regime only with signals of sufficient amplitudes, automatically maintained by dedicated programmable gain amplifiers. This architecture requires a special approach for calibrating the residual asymmetry of each DOR channel pair. The paper describes two algorithms based on measurements with beam signals, allowing such calibrations.

SCHEME WITH SWAPPING ELECTRODE SIGNALS

The principle of the first algorithm presented in this paper is shown in Fig. 2. Signals s_A and s_B from the opposing BPM electrodes A and B can be connected respectively either to the processing channels A and B (measurement 1, "straight"), or to channels B and A (measurement 2, "crossed"). Each processing channel, nonlinear for small input signals, can be considered as a linear system for operational input voltages and characterised by its gain g and offset o.

The two measurements result in four output values

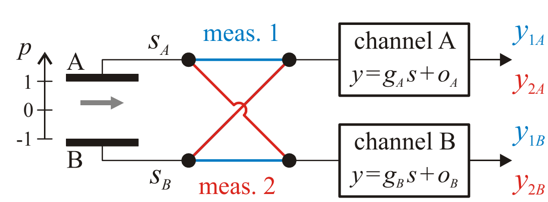


Figure 2: Calibration scheme with swapping BPM electrode signals between two processing channels.

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$$y_{1A} = g_A s_A + o_A \tag{1a}$$
$$y_{1B} = g_B s_B + o_B \tag{1b}$$
$$y_{2A} = g_A s_B + o_A \tag{1c}$$
$$y_{2B} = g_B s_A + o_B \tag{1d}$$

In this paper it is assumed that beam position p, normalised to the BPM aperture, can be calculated from BPM electrode signals s_A and s_B as

$$p = \frac{s_A - s_B}{s_A + s_B} \tag{2}$$

Therefore, p ranges from –1 to 1, as depicted in Fig. 1.

In the simplest case the processing channels of a BPM electrode pair are assumed identical. Then the electrode signals in (2) can be replaced by their corresponding output values, resulting in an approximate beam positions

$$p \cong p_1 = \frac{y_{1A} - y_{1B}}{y_{1A} + y_{1B}} \cong p_2 = \frac{y_{2B} - y_{2A}}{y_{2B} + y_{2A}} \tag{3}$$

A derivation of the procedure allowing calibration of the asymmetry of a processing channel pair as in (1) can be started by evaluating s_A and s_B from (1) and inserting them to (2). This allows a convenient calculation of the beam position from:

– the measurement 1 and 2 with channel A as

$$p_A = \frac{y_{1A} - y_{2A}}{y_{1A} + y_{2A}} = \frac{g_A (s_A - s_B)}{g_A (s_A + s_B) + 2 o_A} \tag{4a}$$

– the measurement 1 and 2 with channel B as

$$p_B = \frac{y_{2B} - y_{1B}}{y_{2B} + y_{1B}} = \frac{g_B (s_A - s_B)}{g_B (s_A + s_B) + 2 o_B} \tag{4b}$$

Since positions $p_A = 0$ and $p_B = 0$ for $s_A = s_B$, thus equations (4) allow ideal beam centring at the expense of switching the electrode signals, assuming a constant beam position during both measurements and identical switches. Positions (4) bear scaling errors caused by the offset terms in the denominators, however, in most cases, and for the collimator BPMs in particular, this is by far less important than a precise beam centring.

For low bandwidth systems as DOR, beam centring with continuous channel switching is not optimal, as it would cause many slow transients. In order to maintain 10^{-4} system accuracy, the switching transients must decay also below 10^{-4} level, which for DOR system with the bandwidth of 10 Hz it takes some 150 ms, introducing large gaps in the 25 Hz data stream. For that reason the switching will only be used to calibrate DOR channel pairs during a short dedicated period with forced stable beam conditions. Then the system will measure with no switching and continuous corrections using the previously obtained calibration parameters. The calibration with switching can be repeated when needed, depending on the system long-term stability and the required measurement accuracy.

Calibration of a DOR processing channel pair implies finding the relationship between the gains and offsets of the channels as in (1) using the four measured output values. Since electrode signals s_A in (1a) and (1d) are equal as well as s_B in (1b) and (1c), one can write a set of equations

$$\begin{cases} (y_{1A} - o_A)/g_A = (y_{2B} - o_B)/g_B & \text{(5a)} \\ (y_{2A} - o_A)/g_A = (y_{1B} - o_B)/g_B & \text{(5b)} \end{cases}$$

With two equations and four unknowns the solutions can be expressed as

$$\frac{g_B}{g_A} = \frac{y_{1B} - y_{2B}}{y_{1A} - y_{2A}} \tag{6a}$$

$$o_B = \frac{o_A (y_{1B} - y_{2B}) + y_{1A} y_{2B} - y_{1B} y_{2A}}{y_{1A} - y_{2A}} \tag{6b}$$

being the gain ratio and the relationship between the offsets, which nevertheless fully characterise the asymmetry between the processing channels.

Then it is convenient to assume that one channel is a follower

$$g_A = 1 \tag{7a}$$
$$o_A = 0 \tag{7b}$$

and calculate the parameters of the second channel as

$$g_B = \frac{y_{2B} - y_{1B}}{y_{1A} - y_{2A}} \tag{8a}$$

$$o_B = \frac{y_{1A} y_{2B} - y_{1B} y_{2A}}{y_{1A} - y_{2A}} \tag{8b}$$

For fairly symmetric channels also $g_B \approx 1$ and $o_B \approx 0$.

In practice it is convenient to express the above corrections as a linear transformation "reconstructing" the corrected output signals y_{c1A}, y_{c1B}, y_{c2A}, y_{c2B} from their corresponding "raw" equivalents y_{1A}, y_{1B}, y_{2A}, y_{2B}. This can be achieved by inserting equations (7) and (8) into (1) and calculating the corrected electrode signals s_{c1A}, s_{c1B}, s_{c2A}, s_{c2B}, which one would have if the processing channels were perfectly symmetric, i.e. they were both followers. Then the corrected output signals y_{c1A}, y_{c1B}, y_{c2A}, y_{c2B} are assumed to be equal to the reconstructed electrode signals and

$$y_{c1A} = y_{1A} \tag{9a}$$
$$y_{c1B} = 1/g_B \, y_{1B} - o_B/g_B = g_c \, y_{1B} + o_c \tag{9b}$$
$$y_{c2A} = y_{2A} \tag{9c}$$
$$y_{c2B} = 1/g_B \, y_{2B} - o_B/g_B = g_c \, y_{2B} + o_c \tag{9d}$$

where the calibration parameters are

$$g_c = 1/g_B = \frac{y_{1A} - y_{2A}}{y_{2B} - y_{1B}} \tag{10a}$$

$$o_c = -o_B/g_B = \frac{y_{2A} y_{2B} - y_{1A} y_{1B}}{y_{2B} - y_{1B}} \tag{10b}$$

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An application of the derived calibration procedure is shown on the following numerical example, with a summary listed in Table 1. It is assumed that a supposed beam has a normalised position P_0, which can result from normalised electrode signals S_A and S_B, satisfying (2). The supposed processing channels have gains G_A and G_B and offsets O_A and O_B, allowing calculation of the channel output signals Y_{1A}, Y_{1B} , Y_{2A} and Y_{2B}, according to (1). These output signals, which would be normally measured in a real BPM system, are used to calculate the calibration parameters G_c and O_c, according to (10), and two approximate positions P_1 and P_2 according to (3). For a better comparison, Table 1 lists only the position errors $\Delta P_1 = P_1 - P_0$ and $\Delta P_2 = P_2 - P_0$ caused by the channel asymmetry, which one would observe if the proposed calibration procedure is not used.

The obtained calibration parameters allow calculation of the corrected output signals Y_{c1A}, Y_{c1B}, Y_{c2A} and Y_{c2B} according to (9). These corrected values are then used to calculate beam positions P_{c1} and P_{c2} applying (3) and the corresponding errors $\Delta P_{c1} = P_{c1} - P_0$ and $\Delta P_{c2} = P_{c2} - P_0$, listed in the table.

Quantities explained above are listed in Table 1 for normalised positions P_0 of 0.1, 0.01, 0.001 and 0. Note that the calibration parameters G_c and O_c were evaluated only once from the values corresponding to the first pair of measurements for $P_0 = 0.1$. Then these parameters were used for correcting the electrode signals for the remaining cases summarised in the following table columns.

As listed in Table 1, positions calculated directly from the output signals have errors ΔP_1 and ΔP_2 in the order of 0.05, even for the centred beam. The corresponding errors ΔP_{c1} and ΔP_{c2} calculated using the output signals according to (9) with the calibration parameters (10) have much smaller errors, decreasing with the assumed beam position, down to 0 for the centred beam.

An example of the calibration procedure with swapping electrode signals from collimator BPMs is presented in Fig. 3. The measurements were done with the LHC collimator prototype tested on the SPS with a single bunch beam during a dedicated machine development

Table 1: Values of the Numerical Example with Signal Switching Assumed Only for the First Column ($P_0 = 0.1$)

channel param.: $G_A = 1.01$, $O_A = 0.01$, $G_B = 0.98$, $O_B = -0.02$				
calibration parameters $G_c = 1.03061$, $O_c = 0.03061$				
P_0	0.1	0.01	0.001	0
s_A	0.55	0.505	0.5005	0.5
s_B	0.45	0.495	0.4995	0.5
Y_{1A}=Y_{c1A}	0.56550	0.52005	0.51551	0.51500
Y_{1B}	0.42100	0.46510	0.46951	0.47000
Y_{2A}=Y_{c2A}	0.46450	0.50995	0.51450	0.51500
Y_{2B}	0.51900	0.47490	0.47049	0.47000
ΔP_1	0.04648	0.04578	0.04569	0.04569
ΔP_2	-0.04459	-0.04559	-0.04568	-0.04569
Y_{c1B}	0.46450	0.50995	0.51450	0.51500
Y_{c2B}	0.56550	0.52005	0.51551	0.51500
ΔP_{c1}	-0.00194	-0.00019	-0.00002	0.00000
ΔP_{c2}	-0.00194	-0.00019	-0.00002	0.00000

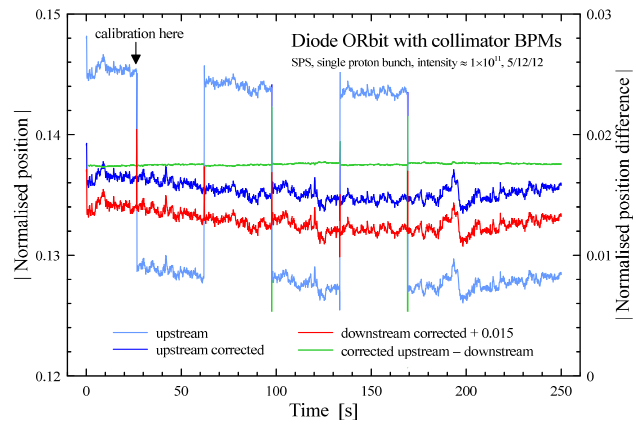

Figure 3: SPS measurement with swapping signals of the BPMs of the LHC collimator prototype.

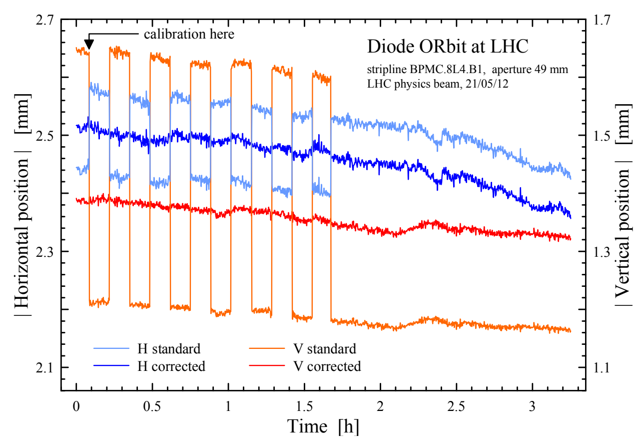

Figure 4: Measurement with swapping signals of an LHC BPM during a proton physics fill.

time. Signals from each BPM electrode pair were swapped by a coaxial mechanical relay and processed by two channels of a DOR front-end prototype.

As seen in Fig. 3, simple beam position (3) in the upstream BPM port (in light blue) suffers from artificial position jumps caused by the signal switching and the residual asymmetry of the DOR channel pair. From the first signal switching (indicated on the plot) one calculates the calibration parameters (10), which then are used to correct the whole measurement (in blue) according to (9). The calibration procedure makes the beam positions from the "straight" and "crossed" measurements equal, which is in fact the assumption of its derivation. In a similar way it is obtained the corrected position in the downstream BPM (shown in red). The jitter of the measurements from the upstream and downstream BPMs (spaced by about 1 m) is nicely correlated, indicating that it is dominated by beam noise. This is further illustrated by the smooth trace (in green), representing the difference between the upstream and downstream corrected positions.

The calibration procedure was also tested on an LHC stripline BPM with 49 mm aperture, whose signals were swapped by a mechanical switch and processed with a

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DOR front-end. Approximated beam positions (3) and their calibrated equivalents are shown in Fig. 4. Note that the calibration parameters were evaluated only from the first signal swapping. The subsequent switching confirms that the calibration parameters evaluated at the beginning of the record remain optimal.

SCHEME WITH A COMMON INPUT SIGNAL

In general evaluation of the calibration parameters (10) should be done with a significant beam offset, guarantying a reasonable signal changes caused by switching and defining the accuracy of the parameter evaluation. In the particular case of a centred beam, the calibration procedure based on swapping electrode signals cannot be used. Then an alternative is a calibration algorithm based on measurement with a common input signal using the scheme sketched in Fig. 5. In this case the inputs of the processing channel pair are connected to one of the BPM electrodes, forcing an equal input signal. If the channels are fully symmetric, the output signals should be equal as well. In the contrary case the output signal difference is a measure of the channel asymmetry and can be used to find a liner function describing the asymmetry and then used for its compensation. One of the simplest methods to find this relationship is a linear regression.

A demonstration of the effects of this method is shown in Fig. 6, summarising a laboratory measurement performed with four DOR channel pairs driven from one RF generator, simulating the electrode signals. Each channel pair was calibrated using parameters from a linear regression run on the DOR output samples averaged down to 0.1 Hz. Then beam positions were calculated according to (3), using both, the direct and calibrated DOR samples, and scaled to a stripline BPM with a 49 mm aperture. The plot shows that the beam positions calculated from the calibrated DOR samples drift by about an order of magnitude less that their equivalents calculated directly from the DOR samples.

In the example the calibration regression is performed on the whole signal record. In practice the calibration data set can be built successively by periodic switching to the calibration configuration only for a short period of time.

SUMMARY

Diode ORbit (DOR) front-end electronics will be used to process beam signals from BPMs embedded in the new LHC collimators. DOR technique is based on compensated diode detectors, which allow sub-micrometre resolution with simple hardware. The detectors operate in the linear regime only for large input signals, which implies using special calibration techniques to compensate for the residual asymmetry of each DOR channel pair. In this paper two such methods have been presented. First is based on measuring signals from each BPM electrode pair with a pair of DOR channels twice, with swapping the measured BPM signals for the second measurement. This allows calculation of calibration parameters, which make possible a compensation of the DOR channel asymmetry for all subsequent beam position measurements, when signal swapping is no longer necessary. The paper contains a derivation of the calibration parameters and three examples demonstrating the application of the technique.

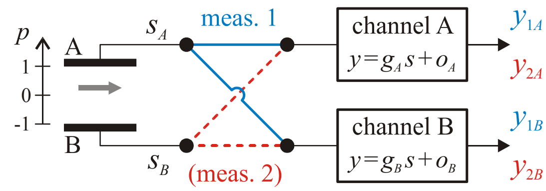

Figure 5: Calibration scheme with a common input signal.

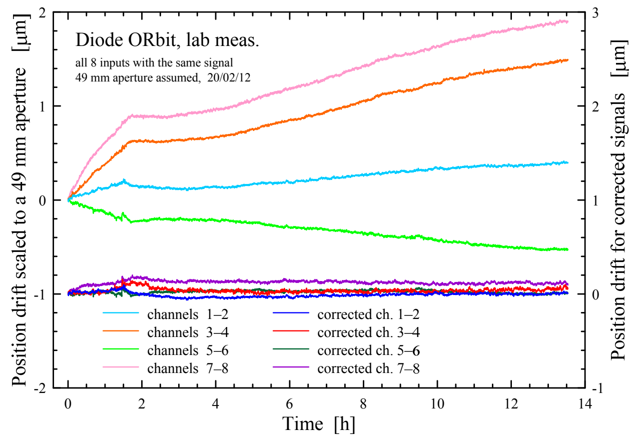

Figure 6: Comparison of beam position drifts calculated from the direct and calibrated DOR samples.

The second calibration technique is based on connecting both inputs of a DOR channel pair to one BPM electrode. The forced equal input signals allow a compensation of the DOR channel asymmetry with calibration parameters obtained from linear regression of the two DOR output signals. The effect of the procedure was shown on a lab measurement example.

The simplicity and performance of the presented methods may be interesting for other BPM systems requiring precise calibration and tolerating occasional switching of the input signals.

Each channel pair of the DOR front-end electronics will be equipped with GaAs switches, allowing both calibration configurations shown in Fig. 2 and 7. The calibration will be possible with beam and local signals generated for this purpose.

REFERENCES

[1] C. Boccard et al., “Embedded Collimator Beam Position Monitors”, DIPAC 2011, Hamburg.

[2] G. Valentino et al., “Successive Approximation Algorithm for BPM-Based LHC Collimator Alignment”, submitted to PRST-AB in September 2013.

[3] M. Gasior, J. Olexa, R. J. Steinhagen, “BPM Electronics Based on Compensated Diode Detectors (…)”, BIW 2012, MOPG010, with the references therein.

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