The DELTA Beam-Based BPM Calibration System

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Abstract. A third-generation synchrotron light source like DELTA[1] (1) requires a measuring system to determine the beam position with high resolution and great accuracy with respect to the center of the quadrupole magnets. This paper presents the beam-based BPM calibration system developed for DELTA, providing a calibration accuracy of about 150 µm. We describe the basic idea of the measurements, the installed hardware, and present the results of an initial calibration of the closed-orbit measuring system (2).

INTRODUCTION

The conventional approach for calibrating a closed-orbit measuring system (CO system) requires several steps carried out one after the other. The first step is to measure each BPM on a test bench to obtain a calibration with respect to the center of the BPM. Possible offsets of the BPM electronics and the influence of varying damping factors of the measuring cables have then to be taken into account. This procedure is very time consuming and has to be performed with great accuracy. It is also very difficult to repeat this calibration after the final installation of the BPMs, cables, and electronics. Since most of the BPMs are normally mounted in or close to quadrupole magnets, the last step of calibration is to determine the position of the BPMs with respect to the axis of the quadrupoles.

The DELTA BPMs are assembled to the quadrupoles in two different ways. The heads for one half of the BPMs fit to the aperture of the quadrupole magnets with an accuracy of 70 µm ("fixed" BPMs). The other half of the BPMs have no mechanical connection to the quadrupole and can move to avoid any stress to the quadrupoles resulting from thermal movements of the vacuum chamber ("floating" BPMs). There is

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an uncertainty of the position of the floating BPMs with reference to the quadrupole axis of approximately 1 mm.

For these reasons, it was decided to install a system for beam-based calibration of the CO system.

BASIC IDEA OF BEAM-BASED CALIBRATION MEASUREMENTS

An electron beam passing through a quadrupole magnet (length l) displaced by Δx_Q with respect to the magnetic axis gains an orbit kick with angle $\vartheta_Q = l \cdot \Delta k \cdot \Delta x_Q$ if the focusing strength is changed by Δk (3). In linear approximation, this leads to a closed-orbit distortion of

$$\Delta x_i(\Delta k, \Delta x_Q) = \frac{\sqrt{\beta(s_Q)\beta(s_i)}}{2\sin(\pi Q_x)} \cos(\pi Q_x - |\psi(s_i) - \psi(s_Q)|) \cdot \vartheta_Q \qquad (1)$$

where Δx_i is the orbit displacement in the i-th BPM and the usual nomenclature has been used. For a beam passing along the axis, this orbit deviation vanishes and therefore the magnetic center of the quadrupole can be determined as follows.The strength of the quadrupole magnet whose BPM is to be calibrated is varied by Δk and the resulting average quadratic orbit distortion

$$\overline{\Delta x^2(x_Q)} = \frac{1}{N} \sum_{i=1}^{N} \Delta x_i^2(\Delta k, \Delta x_Q) \quad \propto \quad \Delta x_Q^2 \qquad (2)$$
$$N = \text{ number of BPMs}$$

is measured as a function of the measured beam position x_Q in the selected quadrupole. By steering the beam across the quadrupole and fitting a parabola

$$p(x_Q) = a \cdot (x_Q + b)^2 + c \qquad (3)$$

to the measured data points the position of the center of the quadrupole can be determined from the position b of the vertex of the parabola (see Fig. 2). The parameter c takes into account the noise of the BPM system and should be the same for all calibration measurements.

HARDWARE OF THE BEAM-BASED CALIBRATION SYSTEM

The Closed-Orbit Measuring System

The DELTA closed-orbit measuring system consists of a total number of 44 BPMs, 40 of which are mounted in quadrupole magnets. They are made out of blocks of stainless steel with an inner geometry identical to the cross-section of the vacuum chamber. Each of them houses four capacitive pick-up electrodes (ESRF type) and is connected to the BPM electronics via double-shielded RG223U coaxial cables. The BPM-electronics have been fabricated by the French company BERGOZ (4) and allow for a resolution of less than 1 µm and a long-term stability (measured in the laboratory with a signal source and power divider over a period of 240 h) of better than 3 µm. Due to the control system connection, using CAN-bus modules with 12-bit accuracy, the present resolution of orbit measurements is limited to ≈10 µm. The maximum repetition rate for a complete orbit measurement is about 1 Hz.

Additional Cabling of Quadrupole Magnets

Since none of the DELTA quadrupole magnets has its own power supply, additional hardware had to be installed to change the *k*-value of individual quadrupoles. In order to obtain the most flexible solution and to avoid a distributed system which is difficult to maintain, it was decided to install an additional cabling for all quadrupoles. Therefore, we connected each quadrupole to one of a pair of 19" racks, each rack accommodating one half of the DELTA ring, with an extra cable ($2\times 4\text{mm}^2$).

For calibrating the CO system, it would have been sufficient to install additional cables only for these quadrupoles where BPMs are mounted. Nevertheless we decided to connect all quadrupoles because the beam-based calibration system also provides the possibility of determining the local beta-functions by measuring the betatron tune shift as a function of the quadrupole strength. This allows us to compare the theoretical optics with those of the real machine and to detect deviations from the fourfold symmetry of the DELTA lattice.

Selection of the Quadrupole Magnets

To select a specific quadrupole, a relay cascade is used for both half rings (see Fig. 1). This setup allows using of one DC-power supply to add an additional current to the quadrupole to cause a change of strength. The main advantage of the design of the relays cascade is the inherent protection against short circuits between different quadrupole circuits. For a later extension, a second input port will be used to operate the system with two different power supplies. For a 1.5 GeV beam, the excitation currents of the strongest quadrupoles are in the order of 60 A. Together with a resistance of the quadrupole coils of 0.7 Ω this corresponds to a maximum voltage drop of 42V per quadrupole. Therefore, a voltage controlled DC current source with potential free output of 70V–10A was chosen as the additional power supply.

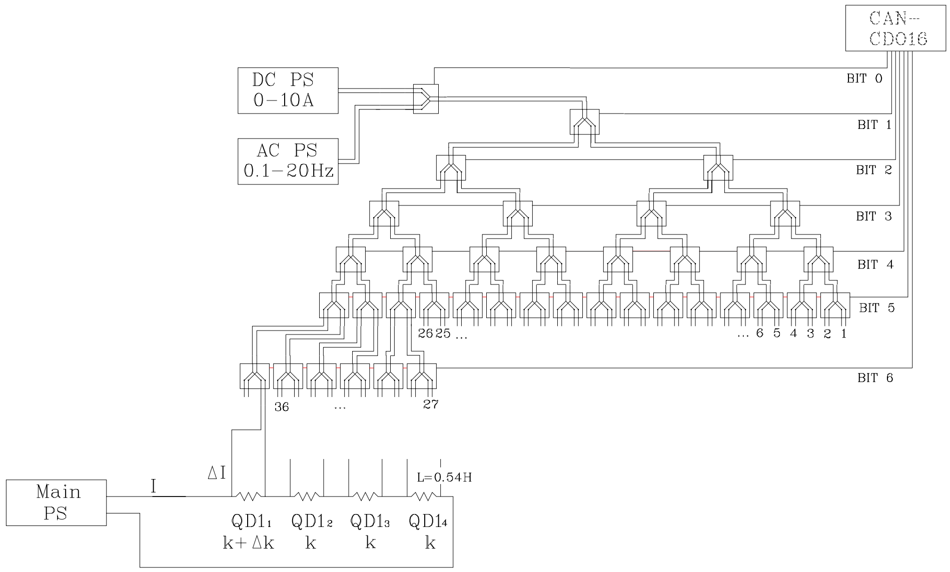

FIGURE 1. Sketch of the hardware installation for beam-based calibration measurements.

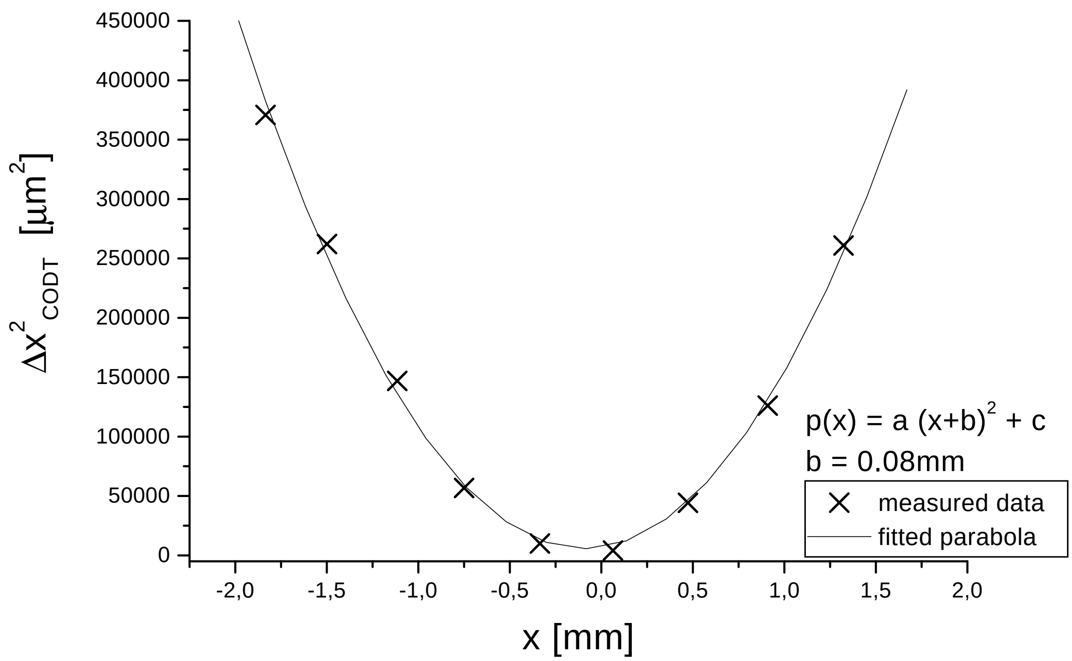

FIGURE 2. An example of the calibration measurement of BPM No. 35, Quadrupole QF5-4 (k=-2.62 m^{-2}, Δk=5%, β=18.7 m).

RESULTS OF THE INITIAL CALIBRATION OF THE CO SYSTEM

The first step of the calibration measurements is to correct the orbit using the uncalibrated CO system. This results in an orbit with position uncertainties with respect to the center of the quadrupole magnets of about 1 mm. Nevertheless this is a good starting point for further measurements. In the next step, an adequate *k*-variation of the selected quadrupole has to be calculated according to the present *k*-value and the local beta-function (see equation No. 1). This *k*-variation should be strong enough to measure a significant closed-orbit distortion, but should not disturb the operation of the storage ring. It turned out that for most of the quadrupole magnets $\Delta k \approx 5\%$ is a useful value.

In the last step, where the beam is steered in equidistant steps across the quadrupole, the variation of the *k*-value by Δk and the measurement of the average quadratic closed-orbit distortion $\overline{\Delta x^2(x_Q)}$ as a function of the beam position (see Fig. 2) is performed. The measurement is done automatically by a program written in Tcl/Tk (5). This program selects the corresponding quadrupole for the BPM which is to be calibrated via the relay cascade, calculates the necessary current the extra power supply must add to the quadrupole, and steers the beam with a local 3-magnet bump around the quadrupole. For each BPM we measure a total range of ±2 mm in steps of ~0.5 mm for the horizontal and vertical directions separately. At the moment, the calibration of one BPM in both directions requires four minutes; therefore a complete calibration of the CO system lasts four hours.

To determine the offsets automatically, it is necessary to have a quantitative measurement for the goodness-of-fit which allows one to determine bad data without plotting them. The incomplete gamma function $Q(\nu/2, x^2/2)$, where ν is the difference between the number of measured data points and the number of parameters to fit and x^2 is calculated as a result of the fitting routine, seems to be a promising candidate (6). For values of *Q* between 0.2 and 1, the fitted data is well represented by the parabola.

Figure 3 shows the results of the first complete calibration of the DELTA closed-orbit measuring system for both directions. The values of the average absolute offsets are:

$$\left|\overline{x_{offset}}\right| = 0.52\text{mm}$$

$$\left|\overline{z_{offset}}\right| = 0.63\text{mm}$$

These values show the necessity of the calibration measurements. It is astonishing that there is no significant difference between the offsets of the “fixed” and the “floating” BPMs. Naturally, we expected that the average absolute offsets of the fixed BPMs should be smaller than those of the floating BPMs. The calibration measurements, however, show that there is no difference. This is a hint that there are unknown uncertainties to be studied in the future.

By calibrating a BPM more than once, the accuracy of the calibration procedure is estimated to be on the order of 150 µm. This value can be decreased by repeating the complete calibration after an orbit correction which takes into account the first measured offsets. This will reduce the effect originated by a beam passing diagonally across the quadrupole. For a longitudinal distance of 120 mm between the pick-ups and the middle of the quadrupole, a beam passing under an angle of 1 mrad results in a deviation of the beam position of 120 µm. This can be reduced by a better orbit correction that brings the

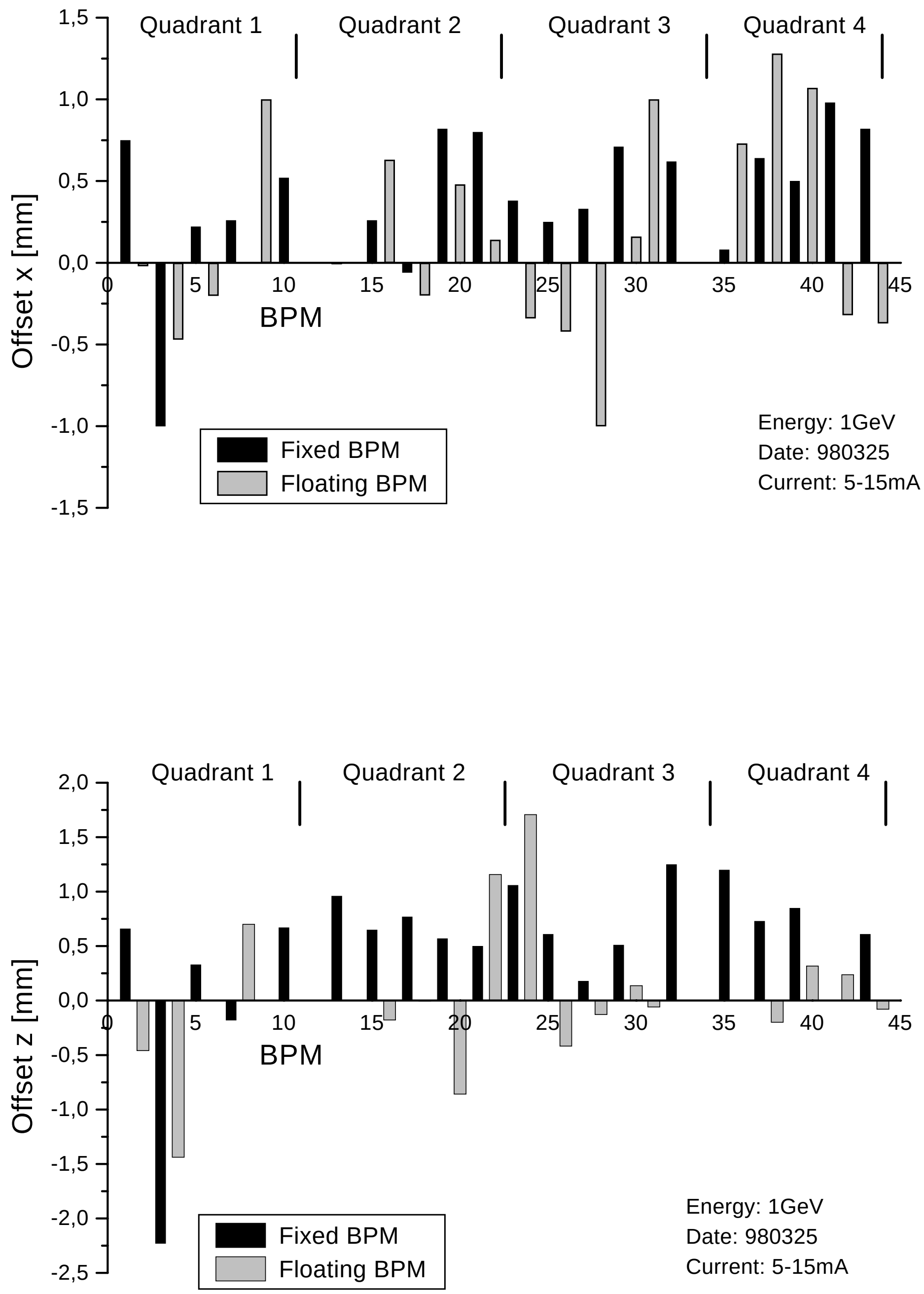

FIGURE 3. Results of the initial calibration of the closed-orbit measuring system. The diagram shows the offset of the CO system with respect to the quadrupole axis.

beam nearer to the center of the quadrupole magnets.

From the parameter c (Eq. (3)) of the fitted parabola, it is possible to estimate the noise figure of the BPM system. From all calibration measurements, we obtained an average value for the noise figure of 10 μm, which is in good agreement with the predicted value for the DELTA CO system.

FUTURE PLANS

Future work will deal with detailed studies of the performance of the calibration system. In particular, we will investigate the influence of the beam-based calibration on such beam parameters as emittance, lifetime, and orbit stability.

To study possible thermal movements of the BPMs when the vacuum chamber heated is by synchrotron radiation and to isolate them from real orbit drifts, we want to speed up the measuring time to less than 1 minute for both directions.

A better accuracy of the beam-based calibration should be possible by performing a harmonic modulation of the quadrupole strength (7) with the frequency f:

$$\Delta k(t) = \Delta k_0 \cdot \sin(2\pi \cdot f \cdot t) \tag{4}$$

This leads to an harmonic closed-orbit oscillation:

$$\Delta x_i(\Delta k_0, \Delta x_q, t) \;\propto\; \Delta k_0 \cdot \Delta x_q \cdot \sin(2\pi \cdot f \cdot t) \tag{5}$$

which can be detected in the frequency domain.

By measuring $\Delta x_i(\Delta k_0, \Delta x_Q, f)$ at a BPM with a suitable betatron phase advance as a function of the beam position in the selected quadrupole, the BPM offset can be determined. We will install a second AC power supply for the harmonic excitation of the quadrupole and connect an FFT analyser to a Bergoz BPM processor, which has a bandwidth of 2 kHz for such measurements. By using a lock-in amplifier, the sensitivity of this measurement can be drastically increased and a better accuracy or a lower value of quadrupole k-modulation is possible.

To increase the performance of the beam-based calibration and the closed-orbit measuring system, we have begun the development of a fast 16-Bit ADC interface board based on the CAN-protocol. This board will have a measuring speed of 6 kHz and, by the use of an integrated micro controller, averaging capabilities. Together with the higher resolution of the ADC, it is possible to reach a resolution of the orbit measurements of <1 μm. This will benefit the performance of the closed-orbit measurements and also the beam-based calibration system.

ACKNOWLEDGMENTS

Many thanks to the DELTA crew for spending some not-scheduled shifts in the DELTA control room and for making this initial calibration measurement possible before the workshop starts.

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