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BEAM SIZE MEASUREMENTS BASED ON MOVABLE QUADRUPOLAR PICK-UPS

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Abstract

Quadrupolar pick-ups (PU) have been widely studied as candidates for non-intercepting beam size and emittance measurements. However, their application has been proven to be limited. Two fundamental factors make quadrupolar measurements exceptionally challenging: first, the low quadrupolar sensitivity of PUs and second, the parasitic position signal incorporated into the measured quadrupolar measurement. In this paper, an alignment technique, based on movable PUs, is proposed to efficiently cancel the parasitic position signal. Tests have been performed using PUs embedded in collimators in the Large Hadron Collider. Beam measurements demonstrate promising results.

INTRODUCTION

Quadrupolar moment measurements based on electromagnetic pick-ups (PU) have attracted particular interest as non-intercepting diagnostics to determine the transverse beam size [1–6]. They are based on the extraction of the second-order moment of the PU signals which contains information about the beam size incorporated into the quantity ${\sigma_x}^2 - {\sigma_y}^2$. Here, σ_x and σ_y are the r.m.s. beam dimensions in the transverse plane. Then, using at least two PUs at locations with different lattice parameters, the r.m.s. beam size and emittance can be evaluated by solving a linear system of equations [1, 7].

Despite the simplicity of the concept, quadrupolar measurements have always been challenging in practice. There are two fundamental factors that make such beam size measurements a difficult task. The first concerns the fact that the quadrupolar moment constitutes only a very small part of the PU signal, which is dominated by the contributions of beam intensity and position. As a consequence, the quadrupole signal can be easily lost due to imperfections in the measurement system such as electronic noise, assymetries, or even due to mechanical uncertainties. The second factor concerns the parasitic signal from beam position attached to the second-order moment in addition to the desirable beam size information as ${\sigma_x}^2 - {\sigma_y}^2 + x^2 - y^2$, where (x, y) is the beam centroid. As a consequence, the beam size measurement may be dominated by the beam position if the beam is significantly displaced.

This work focuses on the effect of the position signal on quadrupolar measurements and how it can be minimized by using movable PUs. The use of movable PUs has been suggested by some authors as a means to improve the calibration of quadrupolar measurement systems [8]. Here, we present a beam-based procedure, using movable PUs, able to efficiently cancel the parasitic position signal. As opposed to other approaches based on logarithmic amplifiers [9, 10], the proposed technique can be applied to many data acquisition architectures. Preliminary measurements, using movable collimators with embedded button PUs in the Large Hadron Collider (LHC) at CERN, have demonstrated promising results.

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BACKGROUND

In order to understand the principle of quadrupolar measurements, one can start by studying the 2D case of an electrostatic Pick-Up (PU) in a circular beam pipe, as illustrated in Fig. 1. Assuming a relativistic beam, sufficiently longer than the PU buttons, the signal induced on the electrodes can be analytically approximated by the following multipole expansion, [5, 10],

$$U_{h1} = i_b(c_0 + c_1 D_x + c_2 Q + c_3 M_{3,x} + \ldots) \quad (1a)$$
$$U_{h2} = i_b(c_0 - c_1 D_x + c_2 Q - c_3 M_{3,x} + \ldots) \quad (1b)$$
$$U_{v1} = i_b(c_0 + c_1 D_y - c_2 Q + c_3 M_{3,y} + \ldots) \quad (1c)$$
$$U_{v2} = i_b(c_0 - c_1 D_y - c_2 Q - \underbrace{c_3 M_{3,y} + \ldots}_{\text{High Order Moments}}), \quad (1d)$$

where i_b is the beam intensity, c_i are coefficients depending on the PU geometry and $D_{x/y}$, Q, and $M_{i\geq3,x/y}$ are quantities which contain information about the beam position and size. In particular, the dipole terms, $D_{x/y}$, are directly connected to the beam position, i.e. $D_x = x$ and $D_y = y$. On the other hand, the second-order quadrupolar term, Q, contains information about both beam position and size and it is given by the following equation:

$$Q = \sigma_x^2 - \sigma_y^2 + x^2 - y^2. \quad (2)$$

Higher order terms can be neglected since they contribute much less to the total signal. The coefficients c_i are given as a function of the PU aperture radius, ρ, and the angular size of the buttons, a, according to the following equations [10]:

$$c_0 = \frac{a}{2\pi} \quad (3a)$$
$$c_1 = \frac{1}{\rho}\frac{2\sin(a/2)}{\pi} \quad (3b)$$
$$c_2 = \frac{1}{\rho^2}\frac{\sin(a)}{\pi} \quad (3c)$$
$$c_3 = \frac{1}{\rho^3}\frac{2\sin(3a/2)}{3\pi}. \quad (3d)$$

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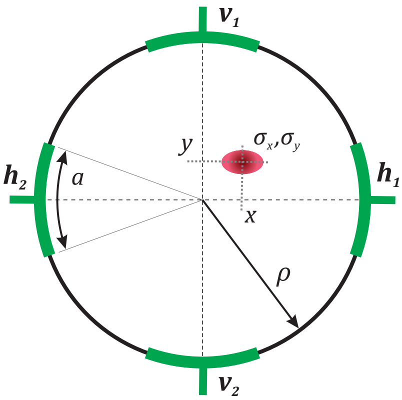

Figure 1: Crossection of a circular button Pick-Up (PU). The PU aperture is equal to $d = 2\rho$ and each electrode has an angular width a. An infinitely long beam at position (x, y) with respect to the pipe centre is considered.

Looking at Eqs.1, the monopole and dipole terms can be cancelled by subtracting the sum of the signals on each plane: $\Sigma_{hor} - \Sigma_{ver} = (U_{h1} + U_{h2}) - (U_{v1} + U_{v2})$. Then, using the following normalized quantity,

$$R_q = \frac{U_{h1} + U_{h2} - U_{v1} - U_{v2}}{U_{h1} + U_{h2} + U_{v1} + U_{v2}}, \quad (4)$$

one can get the quadrupole term as

$$Q = q_f R_q, \quad (5)$$

where $q_f = c_0/c_2$.

The previous analysis is not restricted only to the simplistic example of a 2D circular PU but can be extended to any family of capacitive PUs with different aperture shapes [11]. What changes in every case is the form of the coefficients c_i which is a unique property of the PU geometry.

POSITION SIGNAL SUBTRACTION

Particle beams rarely traverse the centre of a PU, adding parasitic position information to the quadrupolar term. In order to cancel the position terms from the quadrupolar quantity Q, the PU can be manipulated as a beam position monitor (BPM) by applying the so-called difference over sum rule for each plane, i.e. $\Delta_p/\Sigma_p = (U_{p1} - U_{p2})/(U_{p1} + U_{p2})$, where the index p corresponds to the horizontal (h) or to the vertical (v) plane. The beam size part of the quadrupolar moment, $Q_\sigma = {\sigma_x}^2 - {\sigma_y}^2$, can then be estimated by subtracting the measured position, (x_m, y_m), from the total quadrupole term:

$$Q_{\sigma,m} = Q - x_m^2 + y_m^2. \quad (6)$$

Although the above correction improves the measurement of Q_σ, small errors in the position measurement system can result in large errors in Q_σ when the beam displacement is big. In particular, assuming an error in the horizontal position measurement, $\Delta x = x - x_m$, the remaining parasitic signal after the position subtraction from the quadrupolar moment is equal to

$$Q_{rem,x} = x^2 - x_m^2 \approx 2x\Delta x. \quad (7)$$

It becomes clear that big displacements may lead to significant remainders Q_{rem}, even if the position measurement error, Δx, is small.

This fact raises the importance of having reasonably centred beams in order to correct the quadrupolar measurement from the parasitic position signal. This can be achieved by using a PU that can independently move in both horizontal and vertical directions. The position signal from the PU can be used to centre the PU around the beam in both planes. The remaining signal then reduces drastically to $Q'_{rem,x} \approx -2\Delta x^2$ and becomes independent of the actual beam displacement, as demonstrated in Fig. 2.

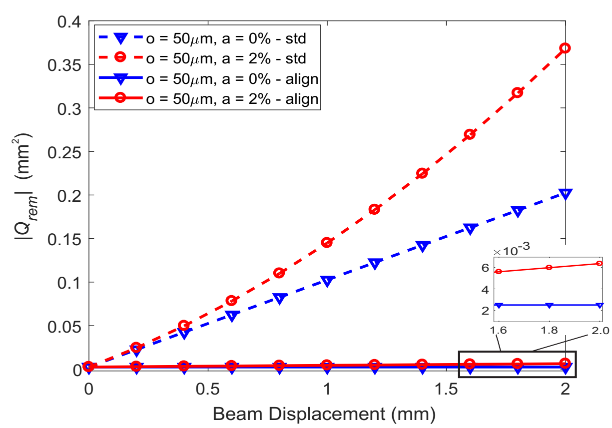

Figure 2: Remaining parasitic position signal, $Q_{rem,x}$, after a) standard correction with fixed PU ('std',dashed line) and b) alignment correction with moveable PU ('align',solid line). An offset o and a scaling error a has been considered, i.e. $x_m = x + o + ax$. Only beam displacement in the horizontal plane has been taken into account.

EXPERIMENTAL SETUP

In the context of the LHC collimation system, several collimators have been equipped with button PUs in order to achieve a fast and reliable alignment with the beam [12]. A representative example of a collimator jaw with embedded button is given in Fig.3a. Profiting of the moveable nature of such collimators, these PUs can form a quadrupolar system able to move in both transverse directions. Their signals are processed by DOROS electronics, a diode-based system proved to provide stable and high resolution position measurements in some of the most critical LHC locations [13]. Although collimator PUs are intended to work as BPMs, their electrode signals are processed separately allowing us to perform quadrupolar measurements.

For our test measurements, we have selected a pair of horizontal and vertical collimators, placed one next to the other. Both collimators are equipped with two PUs, embedded in the upstream and downstream locations of their jaws. It should be underlined that each PU is equipped with electrodes only along the main axis of the collimator, as Fig. 3b depicts. However, the horizontal PUs of one collimator can

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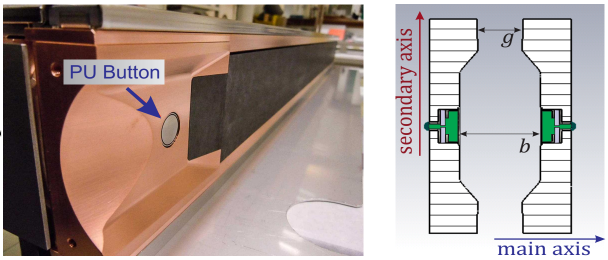


(a) (b)

Figure 3: a) Example of a collimator jaw with embedded PU button in LHC. b) Crossection of the collimator PUs under study.

collimator can be combined with the vertical PUs of the adjacent collimator to form a 4-electrode PU. For the considered setup, the ex-pected Q_σ under normal LHC conditions is $Q_\sigma \approx 0.43mm^2$ at injection energy and $Q_\sigma \approx 0.13mm^2$ at top energy, as Table 1 shows. For a static BPM, even knowing the position of the electrical centre of the PU to $50um$, a typical beam offset of 1mm quickly leads to a 25% error in Q_σ (see Fig.2). By centring the PU on beam the parasitic position signal can be decreased to the range of $\sim 1\% - 2\%$.

As a first test, we have performed a beam based alignment of the PUs under study. Along the main axis of each collimator, the PU is centred using the BPM position readings. However, this is not possible for the secondary axis since there are only electrodes on the main axis. Here, the beam center can be detected through quadrupolar measurements by performing position scans along the secondary axis. As the PU moves away from the beam the quadrupolar moment changes quadratically according to Eq. (2). Therefore, the beam displacement can be measured by detecting the extrema of the quadrupolar moment measurement.

Figure 4 shows measurements of the normalized quantity R_q during a vertical scan of the horizontal collimator. As expected, R_q follows a quadratic behaviour as the PU moves vertically. The beam displacement y_0 for each PU set is measured by detecting the locations of the corresponding maxima. To get a deeper insight on our quadrupolar measurements, Fig.5 illustrates the absolute change on the quadrupolar term, $\Delta Q = Q - Q_0$, as the PUs move away from the measured beam location y_0. Two examples, corresponding to scans of horizontal and vertical collimators with differenct apertures, are shown. In both cases, the measured quantity ΔQ is in very good agreement with the expected change of quadrupolar moment due to the beam displacement demonstrating a first validation of our test setup.

Table 1: Nominal Beam Values at the Experimental Setup

	(β_x, β_y) $[m]$	(σ_x, σ_x) $[mm]$	Q_σ $[mm^2]$
450 GeV	(164, 81)	(0.93, 0.65)	0.43
6.5 Tev	(716, 359)	(0.51, 0.36)	0.13

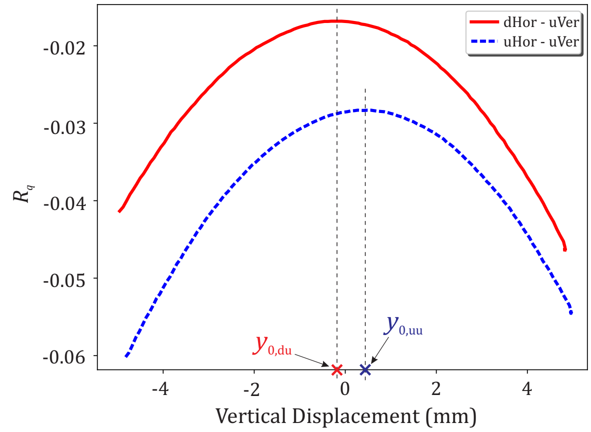
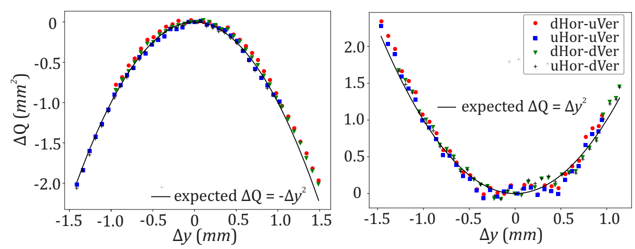


Figure 4: Normalized quantity R_q (see Eq. (4)) as measured during a vertical scan of the selected horizontal collimator. The indices 'd' and 'u' correspond to the downstream and upstream PUs, respectively. The vertical displacement is measured by using a Linear Variable Differential Transformer (LVDT) system [12].



(a) (b)

Figure 5: Change of the quadrupole term, ΔQ, as measured during displacement scans along the secondary collimator axis. a) Horizontal collimator scan with PU aperture $b = 33.2mm$. b) Vertical collimator scan with $b = 37mm$. Coefficient q_f (see Eq. (2)) has been numerically derived via 3D electromagnetic simulations.

CONCLUSION

The parasitic effect of beam position on quadrupolar pickup measurements was studied in this paper. Although the position signal can be subtracted from the quadrupolar moment via position measurements, it was demonstrated that a significant error remains under realistic measurement conditions. To overcome this, an alignment technique based on movable PUs was presented. Through analytical examples, it was shown that the proposed approach eliminates the position signal even for large beam displacements. We have tested the presented technique using collimator PUs in LHC. Both position and quadrupolar measurements have been performed during alignment of the main and the secondary PU axes, respectively. Differential quadrupolar measurements were in very good agreement with theory demonstrating a first validation of the experimental setup. This method will now be applied to quadrupolar measurements aimed at extracting the beam size during normal LHC operation.

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