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BPM TECHNOLOGIES FOR QUADRUPOLAR MOMENT MEASUREMENTS

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Abstract

Quadrupolar pick-ups (PU) have attracted particlular interest as candidates for non-intercepting beam size and emittance measurements. However, their application has been proven to be limited. Two fundamental factors make beam size measurements with quadrupolar PUs exceptionally challenging: first, the low quadrupolar sensitivity of PUs and second, the parasitic position signal incorporated into the measured quadrupolar quantity. In this paper, the basic concepts of the quadrupolar measurements are reviewed with a special focus on the challenging nature of the measurements. Additionally, the potential use of existing beam position monitor (BPM) technology is studied. Recent tests performed with BPMs in the Large Hadron Collider (LHC) are discussed. Preliminary measurements demonstrate promising results.

INTRODUCTION

Quadrupolar moment measurement based on electromagnetic pick-ups (PU), like beam position monitors (BPM), have been widely studied as non-intercepting diagnostics to determine the transverse beam size and emittance [1–7]. They are based on the extraction of the second-order moment of the PU signals which contains information about the beam size. In particular, the beam size signal is incorporated into the quantity ${\sigma_x}^2 - {\sigma_y}^2$, where σ_x and σ_y are the r.m.s. beam dimensions in the transverse plane. 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, 8].

Despite the simplicity of the concept, quadrupolar measurements are very challenging in reality. Two fundamental factors make beam size measurements with quadrupolar PUs a difficult task. The first factor is related to the fact that the quadrupolar moment constitutes only a very small part of the total PU signal which is dominated by the monopole (intensity) signal. As a consequence, the quadrupolar moment can be easily lost due to imperfections in the measurement system such as asymmetries and electronic noise. The second factor concerns the parasitic signal from beam position incorporated into the quadrupolar moment together with 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 quadrupolar measurement may be dominated by the beam position signal if the beam is significantly displaced.

In this work, we study the potential use of existing BPM technologies for quadrupolar measurements. To this end, a detailed review of the above mentioned limitation factors is first given in order to understand the challenges of the quadrupolar measurements. Several tests have been performed using some BPMs in the Large Hadron Collider (LHC). In order to efficiently cancel the parasitic effect of the beam position, an alignment technique based on movable PUs has been applied. Both absolute and differential measurements are discussed in terms of their performance and limitations. Preliminary measurements demonstrate the potentiality to use existing BPM technology as a basis for future quadrupolar measurement system.

MEASUREMENT APPROACH

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, [2, 9],

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

where i_b is the beam intensity, c_i are coefficients depending on the PU geometry and $D_{x/y}$, Q, and $M_{i\geq 3,x/y}$ 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 [9]:

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

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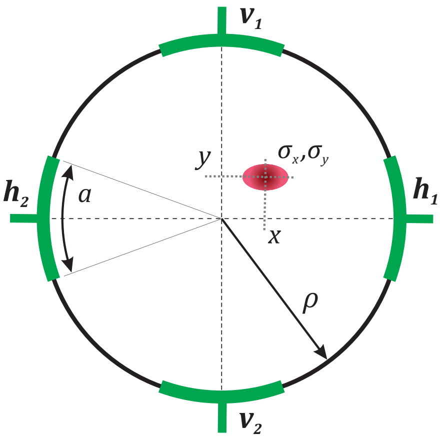

Figure 1: Crossection of a circular button Pick-Up (PU). The PU aperture is equal to $d = 2\rho$ and each electrode has an angular width a. An infinitely long beam at position (x, y) with respect to the pipe centre is considered.

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 [10]. What changes in every case is the form of the coefficients c_i which is a unique property of the PU geometry.

CHALLENGES

Despite the simplicity of the concept, quadrupolar measurements have been shown to be challenging in reality. There are, fundamentally, two limitation factors that make beam size measurements via quadrupolar PUs a difficult task: first, the low quadrupolar sensitivity, c_2/c_0, and second, the parasitic position signal, $x^2 - y^2$, incorporated into the quadrupolar term Q. Both factors may result in critical errors, as discussed in the following.

Low Quadrupolar Sensitivity

Considering the example of a 2D circular PU one can see from Eqs. (3) that each multipole moment M_i is inversely proportional to the factor ρ^i, i.e. $M_i \propto 1/\rho^i$. As a consequence, the contribution of the multipole terms to the electrode signals drops exponentially as the order i increases with a rate equal to $1/\rho$. In particular, the contribution of the quadrupole moment to the total signal can be approximated as

$$\frac{M_2}{M_0} = \frac{c_2}{c_0} Q \propto (\sigma/\rho)^2, \quad (6)$$

where σ represents an effective beam size which, for simplicity, can be approach by the dominant beam size component, e.g. σ_x for a horizontally flat beam. Under the assumption of relativistic beams, Eq. (6) is valid for a wide range of different PU designs, [10], and gives a qualitative rule of thump regarding the quadrupolar sensitivity.

In realistic cases, the factor $(\sigma/\rho)^2$ is significantly small due to the fact that PUs are normally designed with an aperture much larger than the nominal beam size in order to avoid particle losses. Therefore, the quadrupolar moment constitutes only a small part of the total PU electrode signal which is dominated by the monopole moment. As an example, the quadrupolar sensitivity of the LHC BPMs spans within the range $0.02 - 0.04\, dB/mm^2$ for PUs at locations where the beam size is expected to be in the order of $\sim 1\, mm$ at injection energy, i.e. at $450\, GeV$. It becomes, then, clear that the quadrupolar signal may be easily lost due to imperfections in the data acquisition process, like asymmetries or noise. As Fig. 2 demonstrates, even a slight cabling asymmetry between the PU channels in the order of few per milles leads to significant errors $\sim 20‰$.

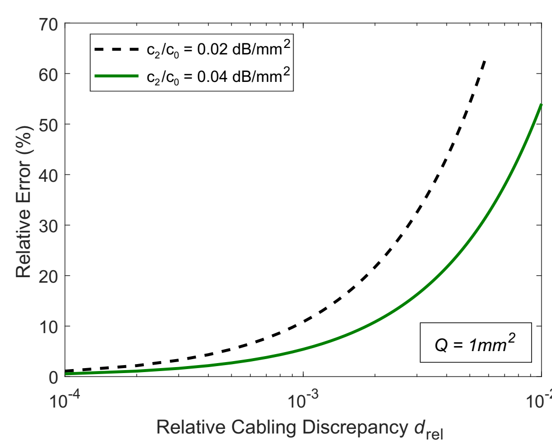

Figure 2: Relative error in quadrupolar measurement assuming a quadrupolar term $Q = 1mm^2$ and a slightly cabling asymmetry between the PU channels. In particular, three channels (e.g. h_1, v_1 and h_2) are considered to have a nominal cabling response g, i.e. $V_{\text{out}} = gV_{\text{in}}$, while the 4^{th} (e.g. h_2) has a relative cabling discrepancy d_{rel}, i.e. $V_{\text{out}} = (1 + d_{\text{rel}})gV_{\text{in}}$.

Parasitic Position Signal

Particle beams rarely traverse the center of a PU, adding parasitic position information to the quadrupolar moment. This parasitic signal, $Q_p = x^2 - y^2$, may remarkably deform the desired beam size information $Q_\sigma = {\sigma_x}^2 - {\sigma_y}^2$, even for small beam displacements, as shown in Fig. 3. To overcome this effect, the parasitic part, Q_p, can be subtracted from the total quadrupolar quantity Q by manipulating the PU as a normal BPM. In particular, by measuring the beam position, (x_m, y_m), the beam size part, Q_σ, can be evaluated as $Q_{\sigma,m} = Q - {x_m}^2 + {y_m}^2$.

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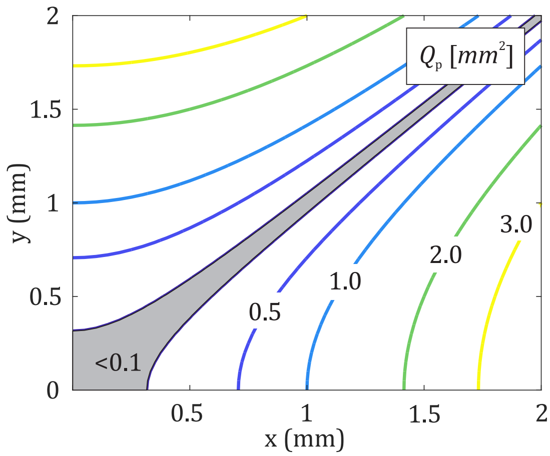

Figure 3: Parasitic position signal, Q_p for different beam displacements.

Although the above correction improves the measurement of Q_σ, a significant part of Q_p may remain under realistic conditions. Figure 4 depicts the expected error in Q_σ when some imperfections on the BPM system are considered. As can been seen, even for small errors in the position measurements, the error in Q_σ may be remarkably large for big beam displacements.

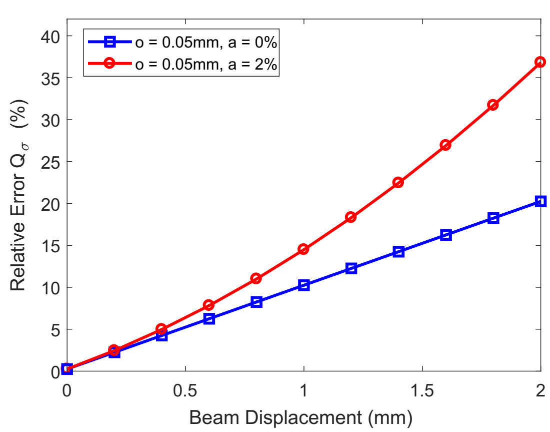

Figure 4: Relative error in Q_σ (beam size part), after the subtraction of Q_p (parasitic part) via position measurements. An offset o and a scaling factor a has been considered, i.e. $x_m = x + o + ax$. Only beam displacement in the horizontal plane has been taken into account.

MEASUREMENTS WITH EXISTING BPM TECHNOLOGY

BPMs constitute one of the most critical instrumentation system in particle accelerators. Their technology has been continuously advancing due to the need for precise position measurements for several kinds of beam configurations. Although BPMs design is optimized for position measurements the existing BPM technology can be potentially used as a basis for quadrupolar measurements.

In the context of LHC beam position measurement system several PUs are equipped with DOROS electronics, a diode-based acquisition system proved to provide stable and high resolution position measurements at some of the most critical LHC locations [11, 12]. Although these PUs are intended to work as BPMs, their signals are processed separately allowing us to perform quadrupolar measurements. Following, we present some tests we have performed using some of the existing LHC BPMs including collimator and circular button PUs.

Beam Centering via Movable PUs

As discussed in the previous Section, off-centered beams may result in crucial errors in quadrupolar measurements. Even if a direct subtraction via position measurements is applied, a significant part of the parasitic signal may remain under realistic conditions. To overcome this problem, the position signal can be efficiently cancelled by centering the beam via movable PUs, as demonstrated in a previous work [13]. In order to form 4-electrodes movable PUs we have used sets of horizontal and vertical collimators, as illustrated in Fig. 5. Profiting from the moving functionalities of collimators in both axes, these PUs can be aligned with the beam in order to remove the parasitic position part Q_p from the quadrupolar signal Q.

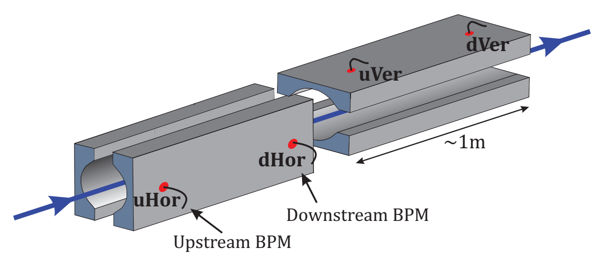

Figure 5: Schematic drawing of a Horizontal - Vertical collimator set in LHC with embedded BPMs. Two sets of BPMs are installed in each collimator forming in total four different combinations of 4-electrode PUs

The beam centering is perfromed within a two-step procedure. First, the PU is centred along the main axis (e.g. the Hor. axis for a Hor. collimator) using BPM position readings. However, this is not possible for the secondary axis (e.g. the Ver. axis for a Hor. collimator) since there are no electrodes to directly read the beam position. In this case, the center is detected through quadrupolar measurements by performing position scans along the secondary axis. In particular, as the PU moves away from the beam the quadrupolar moment changes quadratically according to Eq. (2). Therefore, the beam displacement is measured by detecting the extrema of the quadrupolar moment measurement, as shown in the xample of Fig. 6.

To get a deeper insight on our measurements, Fig. 7 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. Very good agreement between the measurements and the expected change due to the beam dis-

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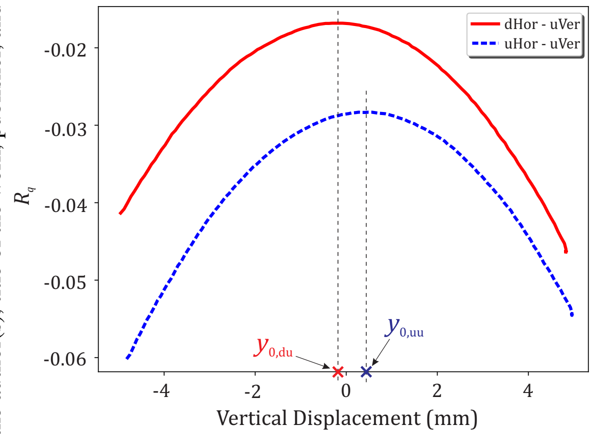

Figure 6: Normalized quantity R_q (see Eq. (4)) as measured during a vertical scan of a horizontal collimator. The collimator aperture is 33.2mm. The vertical displacement is measured by using a Linear Variable Differential Transformer (LVDT) system [11]

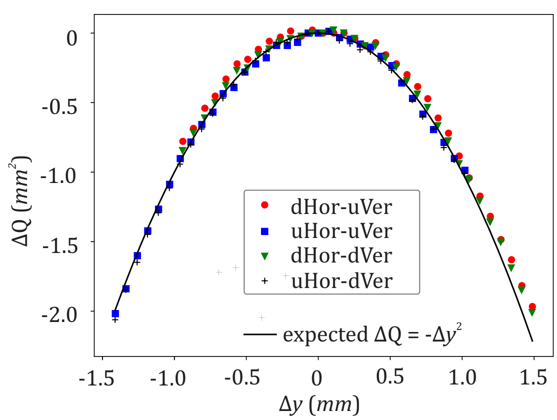

Figure 7: Change of the quadrupolar term, ΔQ, as measured during the vertical scan of the example of Fig. 6. The aperture of both horizontal and vertical PUs is 33.2mm. Coefficient q_f (see Eq. (5)) has been numerically derived via 3D electromagnetic simulations.

placement is shown for all the different PU combinations demonstrating a first valdation of our quadrupolar measurements.

Absolute and Differential Measurements

Looking carefully at the results obtained through the beam alignnemt process, we can extract some important information about the quality of the quadrupolar measurements. As observed in Fig. 6, the locations of the extrema during the vertical scan differ not only in the horizontal axis (information about the beam center) but also in the vertical one. In fact, the difference on the normalized quantity R_q can be directly translated into a difference in the absolute quadrupolar measurement since $Q = q_f R_q$. For the particular example of Fig. 6, this difference is $Q_{du} - Q_{uu} \sim 2.5mm^2$ which is significantly large contrary to the fact that the two BPM sets are placed one close to each other. On the other hand, differential measurements present a very good trend since all the BPM sets follow the expected behaviour as shown in Fig. 7.

To better understand the behaviour of the quadrupolar measurements we have performend some emittance scans, forced by the LHC transverse damper (ADT) system [14]. To ensure that the influence of the parasitic position signal is negligible we had first applied the beam centering procedure as previously described. Figure 8 illustrates results as obtained using a full set of four Hor.-Ver. collimator BPMs during a horizontal emittance blow-up. Looking at the absolute quadrupolar measurements (left side) we can clearly observe discrepancies between the four BPM sets. However, despite the large offsets, the measurements demonstrate a stable behaviour of the system. Taking out the offsets (right side) a nice agreement between all the different BPM sets is observed during the blow-up. As expected, the quadrupolar quantity increases in consistency with the emittance blow-up in the horizontal plane (a decrease would be expected in the case of a vertical blow-up).

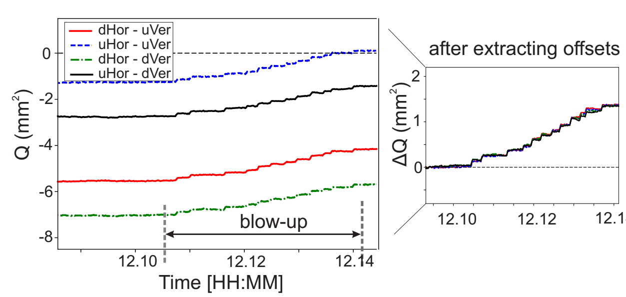

Figure 8: Quadrupolar measurements during an emittance blow-up forced by the LHC Transverse Damper system(ADT). A Hor.-Ver collimator BPM setup has been used. Left: Absolute mesurements. Right: Differential measurements (extracting all the offsets at the beginning of the blow-up).

Taking profit of the good differential measurements, we have also performed quadrupolar measurements during the LHC energy ramp. For these measurements, collimator BPMs are not suitable since the beam presents significant displacements during the ramp. Instead, we have preferred some circular button BPMs, fixed to the beam pipe, at locations with small beam position change during the ramp. Figure 9 illustrates the quadrupolar evolution as measured by the selected BPMs. The evolution is in consistency with the behaviour expected by the optics model and according to the lattice parameters given in Table 1. In particular, the quadrupolar signal increase when $\beta x < \beta y$ since $Q \approx {\sigma_x}^2 - {\sigma_y}^2 < 0$ and because the beam size shrinks during the ramp. In contrast, the opposite behaviour is expected when $\beta x > \beta y$. To validate even more the BPM measurements comparative values as obtained using Wire Scanners measurements are depicted. As can be seen, the BPM measurements are in very good agreement with the Wire Scanners ones during most of the ramp evolution time.

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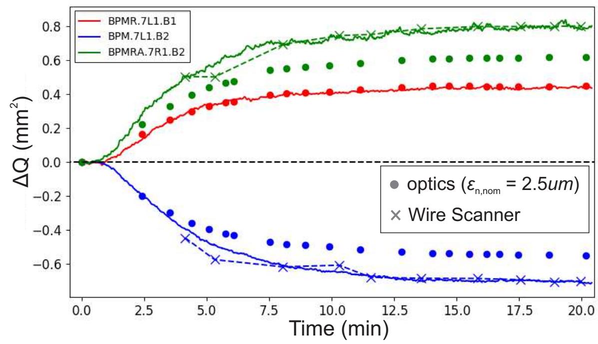

Figure 9: Differential quadrupolar measurement during an LHC energy ramp from 450 GeV to 6.5 TeV. Three circular button BPMs have been used. Results corresponding to the optics model (assuming nominal emittance) and to measurements from Wire Scanners are depicted as well.

Table 1: Lattice Parameters (β_x, β_y) $[m]$ at Start and End of LHC Ramp

	450 GeV	**6.5 TeV**
BPMR.7L1.B1	(48, 141)	(41, 143)
BPM.7L1.B2	(168, 56)	(140, 36)
BPMRA.7R1.B2	(62, 187)	(53, 138)

CONCLUSION

This paper reviewed the challenges of beam size measurements via quadrupolar PUs in connection with some recent beam measurements using existing BPM technology. Two limitation factors make beam size measurements with quadrupolar PUs a difficult task: first, the low quadrupolar sensitivity and second, the parasitic effect of beam position. To examine the possible use of existing BPM technology for quadrupolar measurements several tests have been performed in LHC. The parasitic position signal has been efficiently removed by using collimators with embedded BPMs which allow beam centering at the PU locations. Through several tests, it was demonstrated that differential measurements provide promising results and can be potentially used to measure the emittance evolution during the energy ramp. On the other hand, absolute measurements are dominated by large and systematic offsets. These can potentially come from small asymmetries between the four PU electrodes. To this end, new calibration schemes, able to take into the challenging nature of the quadrupolar measurements, are currently being ventured.

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