Analysis of quadrupolar measurements for beam size determination in the LHC

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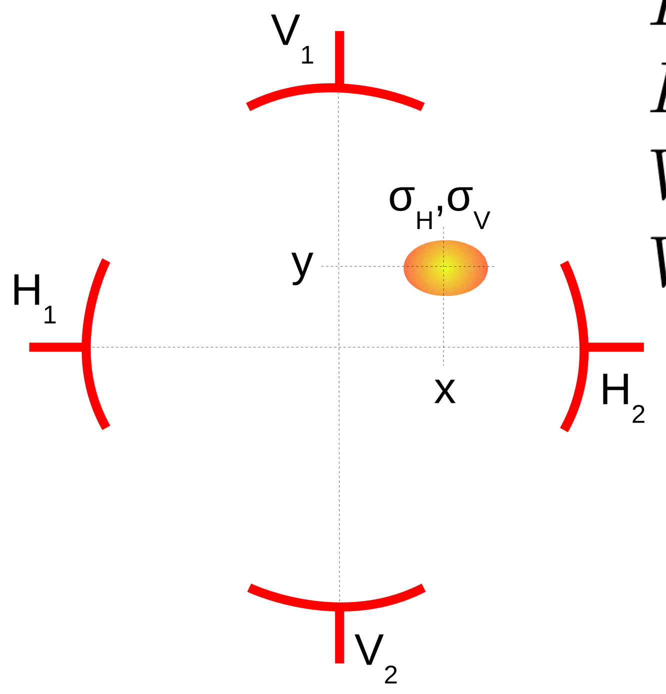
Abstract: Due to limitations with non-invasive beam size diagnostics in the LHC, particularly during the energy ramp, there has been an interest to explore quadrupolar-based measurements for estimating the transverse beam size, and hence determining the transverse emittance. This technique is especially attractive as it is completely passive and can use the existing beam position instrumentation. In this work, we perform an analysis of this method and present recent measurements taken during energy ramps. Quadrupolar-based measurements are compared with wire-scanner measurements and a calibration strategy is proposed to overcome present limitations.

BPM electrode amplitudes



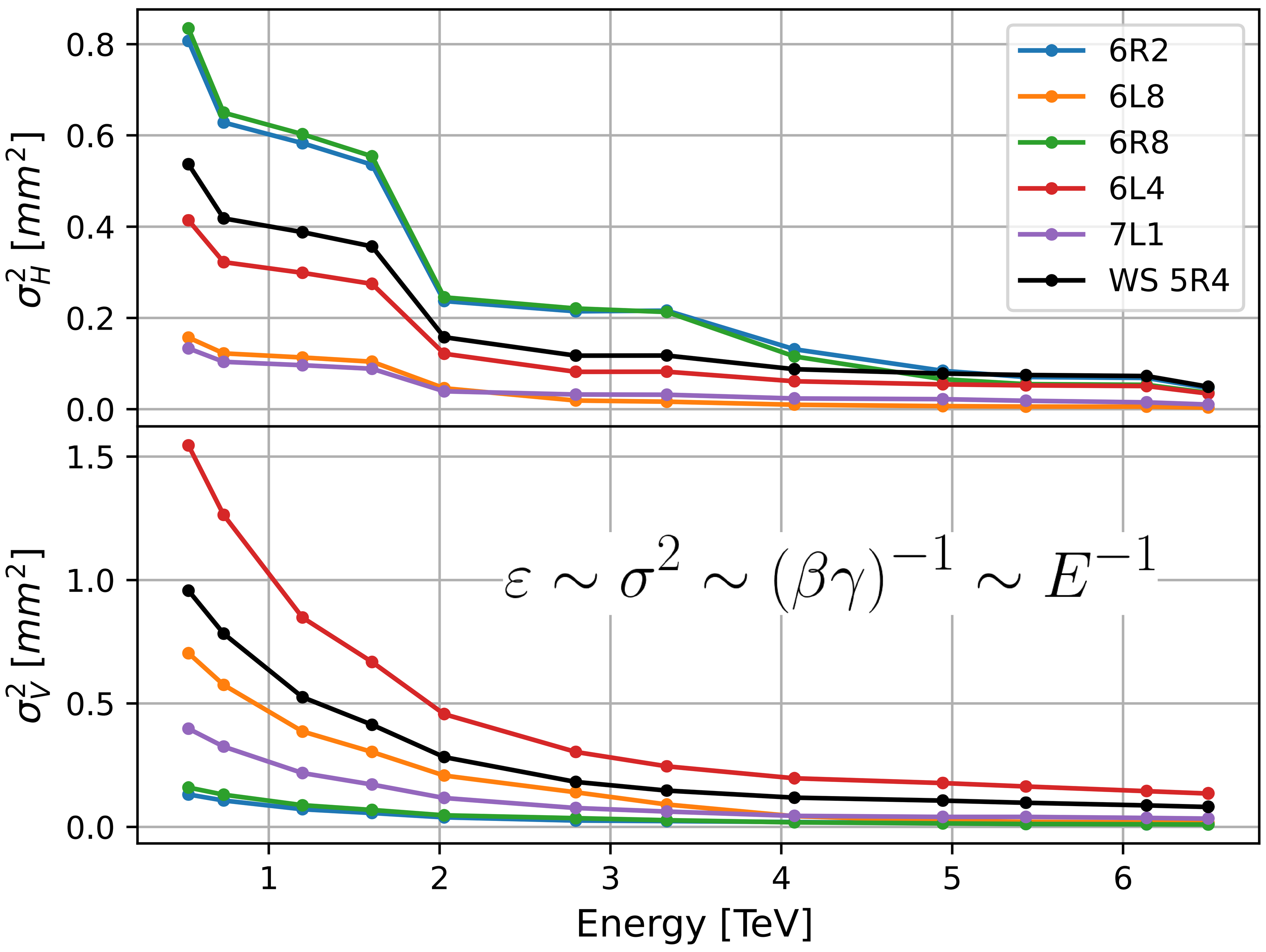
$$H_1 = h_1 I\left(c_{0h} + c_{1h}x + c_{2h}Q + \ldots\right) + k_1$$
$$H_2 = h_2 I\left(c_{0h} - c_{1h}x + c_{2h}Q + \ldots\right) + k_2$$
$$V_1 = v_1 I\left(c_{0v} + c_{1v}y - c_{2v}Q + \ldots\right) + w_1$$
$$V_2 = v_2 I\left(c_{0v} - c_{1v}y - c_{2v}Q + \ldots\right) + w_2$$

- *I*: beam intensity
- *h,v*: individual channel gains
- *k,w*: individual channel offsets
- *c*: pick-up geometric constants

Quadrupolar moment

$$Q = Q_\sigma + Q_r = (\sigma_H^2 - \sigma_V^2) + (x^2 - y^2)$$

Wire scans during energy ramp



The WS-based beam size estimations are projected to the positions of the BPMs

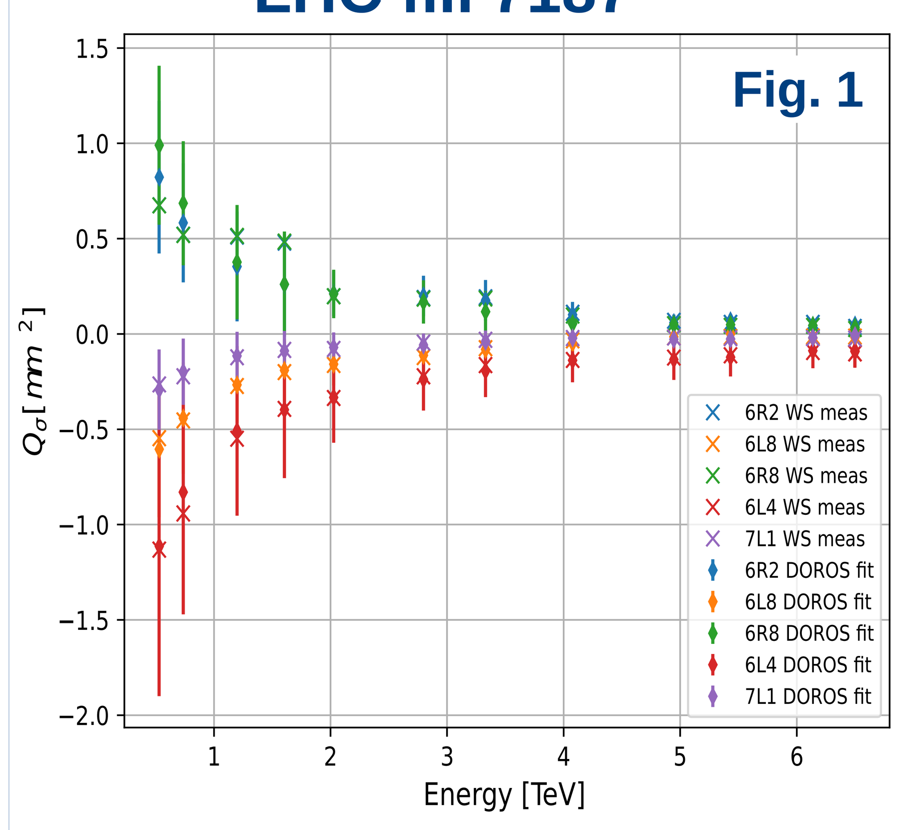
$$\begin{cases} \sigma^2_{H,BPM} = \dfrac{\beta_{H,BPM}}{\beta_{H,WS}}\sigma^2_{H,WS} \\ \sigma^2_{V,BPM} = \dfrac{\beta_{V,BPM}}{\beta_{V,WS}}\sigma^2_{V,WS} \end{cases}$$

Calculate calib. parameters *m* and *b*

Linear regression

$$Q_\sigma = m\underbrace{\frac{\Sigma_H - \Sigma_V}{\Sigma_H + \Sigma_V}}_{R} + b - Q_r \quad (1)$$

LHC fill 7187



LHC fill 7220

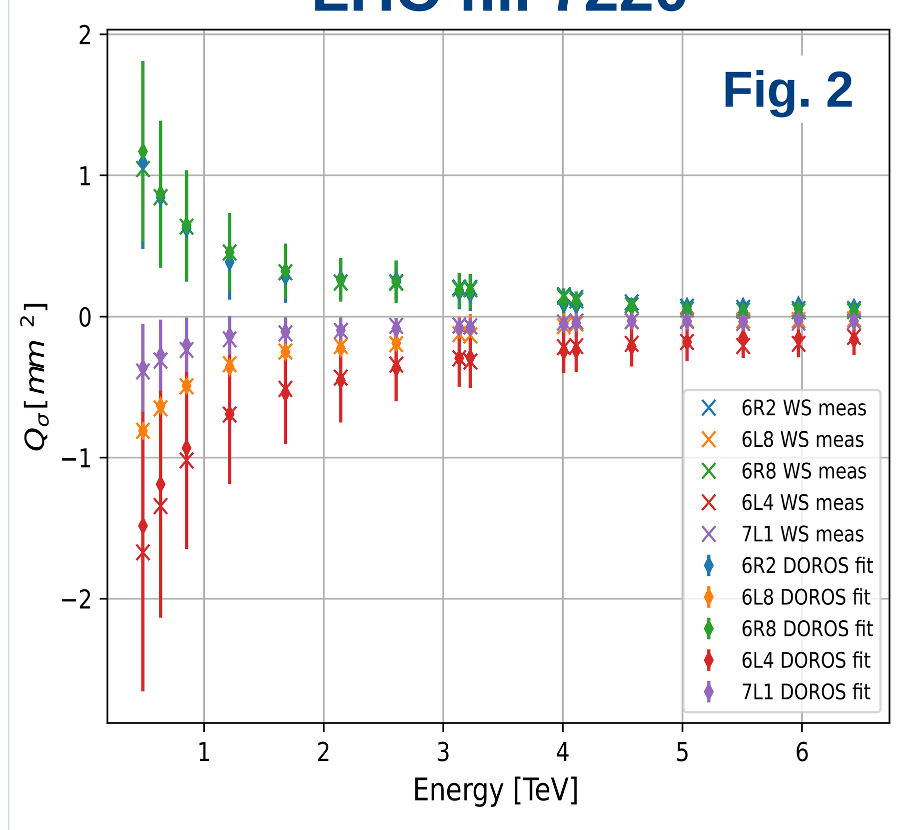


Table 1

BPM	m	$\frac{\sigma_m}{m}$	b	$\frac{\sigma_b}{b}$
6R2	248.11	0.11	-0.79	-0.12
6L8	239.24	0.06	0.2	0.05
6R8	320.77	0.11	0.71	0.10
6L4	371.46	0.05	-0.22	-0.02
7L1	270.22	0.08	-0.2	-0.07

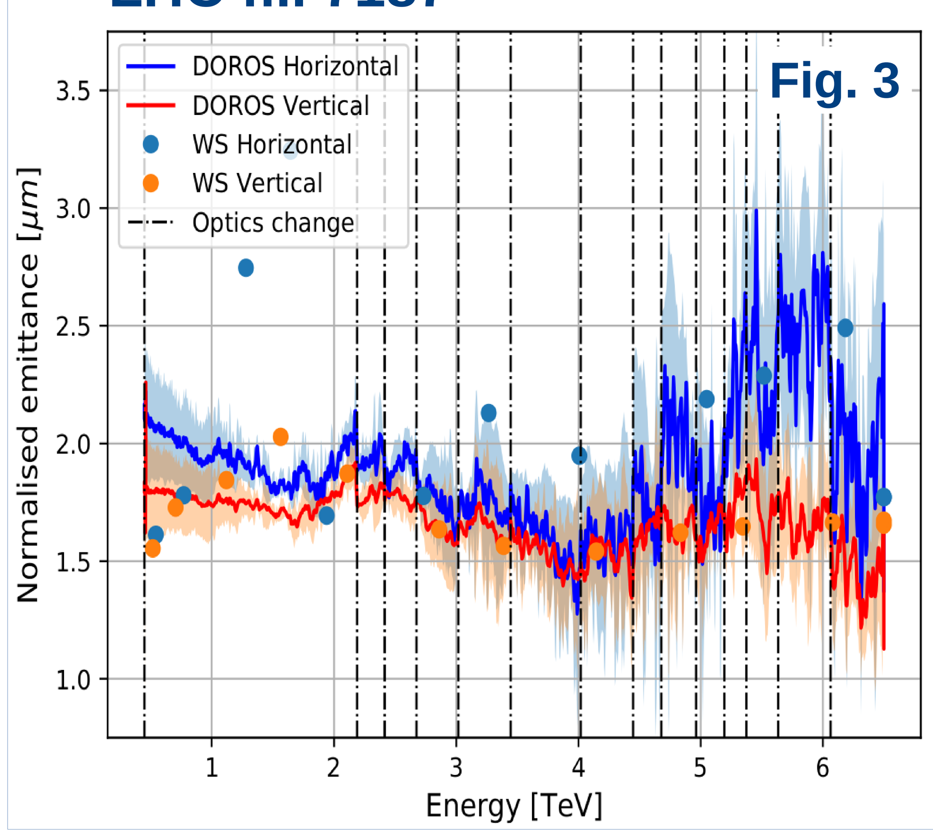
Table 2

BPM	m	$\frac{\sigma_m}{m}$	b	$\frac{\sigma_b}{b}$
6R2	439.15	0.11	-2.1	-0.11
6L8	442.64	0.07	-0.87	-0.08
6R8	437.95	0.03	-0.094	-0.07
6L4	647.10	0.07	-0.99	-0.05
7L1	444.99	0.08	-1.2	-0.07

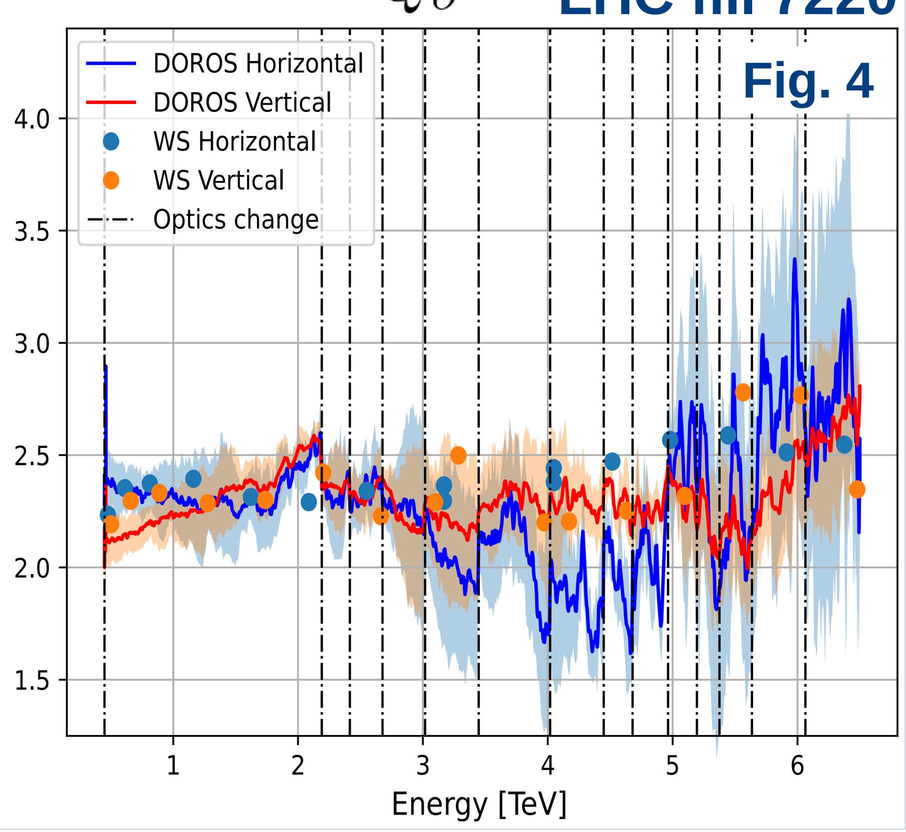
Emittance calculation – least squares

$$\begin{bmatrix} \beta_{1,H} & -\beta_{1,V} \\ \vdots & \vdots \\ \beta_{n,H} & -\beta_{n,V} \end{bmatrix} \begin{bmatrix} \varepsilon_H \\ \varepsilon_V \end{bmatrix} = \underbrace{\begin{bmatrix} \overbrace{m_1 R_1 + b_1}^{Q} - \overbrace{(x_1^2 - y_1^2)}^{Q_r} \\ \vdots \\ m_n R_n + b_n - (x_n^2 - y_n^2) \end{bmatrix}}_{Q_\sigma}$$

LHC fill 7187



LHC fill 7220



Conclusions

As observed in Figs. 1 and 2, Eq. 1 seems to describe well the $Q_\sigma(R)$ relationship. One should keep in mind that some horizontal scans performed during the ramp of fill 7187 provided biased estimations of the normalised emittance. Since the horizontal and vertical scans are not simultaneous, there is a deterioration of the accuracy of the WS-based Q_σ estimations, thus making the times at which matching samples are selected from the BPM electrode amplitudes an average between the time of the two scans.

It is interesting to note, from Table 2, that all BPMs except 6L4 have similar *m* values. This is consistent with the fact that 6L4 has different apperture and button sizes. We also notice that the *m* values for the same BPMs in both tables differ by a factor of ≈ 1.7. Assuming that the offset term *b* is fairly random from BPM to BPM, then this difference can only be explained by differences in the discrepancies between the horizontal and vertical gains and geometric constants.

The final calculations of the normalised emittances, as shown in Figs. 3 and 4, reveal a good agreement in the vertical plane and a poorer agreement in the horizontal plane. The abrupt jumps in the traces at the time of optics changes can indicate changes in the uncertainty of the beta functions as it is unlikely that the emittance itself could change that fast. Using the calibration procedure described herein in low intensity beams with similar peak bunch intensity and for different filling patterns, we hope to be able to use this method to provide reliable emittance measurements during the LHC ramps of standard high intensity physics fills.

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