Measurement of the relative alignment between wirescanners and quadrupoles in the undulator section of VUV FEL

P. Castro

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Abstract

We have applied beam-based alignment techniques to correlate the position reference systems of quadrupoles and wirecanners in the undulator section of VUV FEL [1]. Procedure, error analysis and results obtained between October 8 and 11 are presented.

1 Introduction

There are six undulator segments [2] numbered from 1 to 6, each with a length of 4.5 m. Seven blocks are located between the undulator segments as well as upstream and downstream the undulator system. Each block contains a pair of quadrupoles, one beam position monitor (button type) and a pair of wirescanners (one horizontal and one vertical). A layout of the undulator section is shown in Fig. 1 indicating the name asigned to each component.

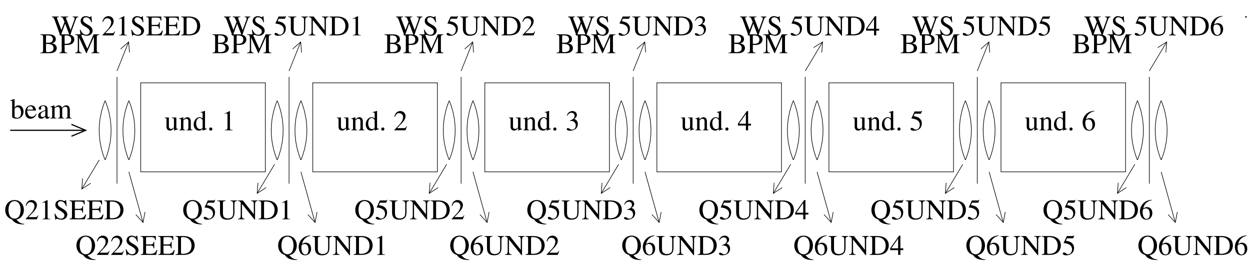

Figure 1: Schematic layout (not to scale) of the undulator system in VUV FEL. The electron beam enters from the left side. Quadrupole names begin with 'Q'. BPM stands for beam position monitor and WS means wirescanner.

All quadrupoles shown in Fig. 1 are of so-called type TQG[1]. Quadrupoles are mounted on micromovers which include a position referencing system. The position referencing system

[1]T stands for TTF or TESLA, Q for quadrupole.

of each quadrupole has been aligned during the survey of the accelerator components with a precision of a few hundreds of micrometers.

The FEL process requires a good overlap between the photon beam and the electron bunch along the entire undulator. To ensure the FEL process over the whole undulator, we need to minimize the trajectory kicks introduced by the quadrupoles located between undulator segments. The quadrupole kick is proportional to the distance between the quadrupole center and the beam. In order to get the distance between the beam and the quadrupole center, one needs to measure the position of the quadrupole and to measure the position of the beam. Additionally, we need to know the relative offset between the quadrupole reference system and reference position of the instrument used to measure the beam position.

Beam position monitors (BPM) measure the position of the beam with respect to the electric axis of the BPM defined by the geometry of the buttons. Alternatively, the position of the beam can be measured with wirescanners, which deliver the transverse beam profile in their own reference system. The position of the wires used in the wirescanners [3] is given by a precision system and is corrected by an offset value determined from mechanical measurements done in each specific diagnostics block [4].

We have applied beam-based alignment techniques to correlate the position reference systems of quadrupoles and wirecanners. The procedure used and the results obtained are presented in the following.

In this paper we use the sign convention that a positive value in the horizontal plane means an offset to the right looking downstream (in the direction of the beam) and that a positive value in the vertical plane means an offset upwards. The position readings from quadrupole and wirescanner reference systems delivered by the control system follow this convention since the September shutdown.

2 Experimental procedure

The trajectory kick α introduced by a quadrupole when the beam position has an offset x from the quadrupole center is (in thin lens approximation)

$$\alpha = e \cdot \frac{g \cdot L}{p} \cdot x \tag{1}$$

where g is the gradient and L is the effective length of the quadrupole and p is the beam momentum. The change in beam position observed with a downstream BPM depends on the transfer matrix element R_{12} which transforms position and angle from the quadrupole to the BPM.

$$\Delta x_{\mathrm{BPM}} = R_{12} \cdot \alpha = R_{12} \cdot e \cdot \frac{g \cdot L}{p} \cdot x \tag{2}$$

Extracting x from this equation requires a precise knowledge of all these parameters (g, L, p and R_{12}) and a good calibrated BPM. Independent from how precise the parameters g, L, p and R_{12} are known, it is possible to determine $x = 0$ by applying beam-based alignment techniques, for example, by scanning the position of the quadrupole and changing g.

The procedure applied here is explained in the following. Let us assume that the R_{12} between the quadrupole and the BPM is different from zero. We set two different values for the gradient of the quadrupole (a positive and a negative gradient are used in the example shown in Fig. 2). Plotting the beam position measured with the downstream BPM as function of the quadrupole position we obtain (ideally) two lines which slope depends on the quadrupole gradient. The point at which both lines cross each other marks the position of the quadrupole x_{q} for which $x = 0$, that is, the beam in centered at the quadrupole. At the same time the beam position is measured with an instrument adjacent to the quadrupole. The difference between x_{q} and the measured beam position at the quadrupole is the offset between quadrupole reference and the zero reference of the measurement instrument.

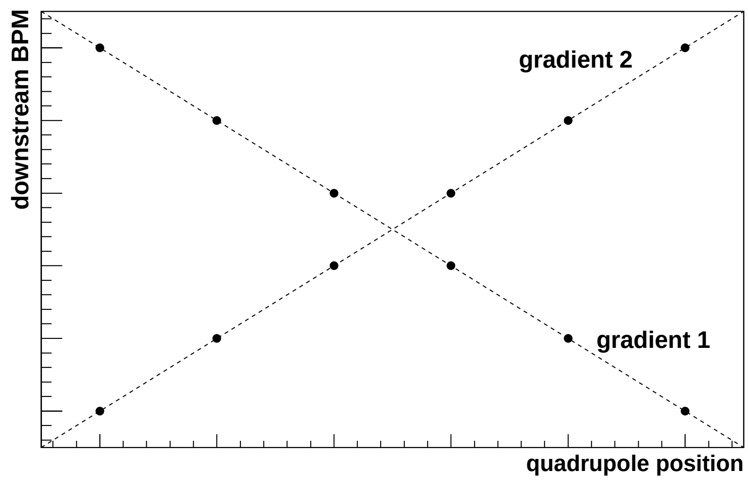

Figure 2: Change of beam position (ideally) as function of the quadrupole position for a positive and a negative quadrupole gradient.

The analysis of the data is explained in Sec. 3 and the results in Sec. 4.

3 Data analysis and error estimation

In order to increase the accuracy of the results we apply typically three or four different current values to the quadrupoles (sometimes up to six). For each applied current the quadrupole position is scanned over a large range to increase resolution. With a pulse repetition rate of 2 Hz, we have collected the readings of all BPMs in the undulator section and downstream. In the off-line analysis we have selected BPMs with a good resolution and a large R_{12}. All the plots used in the analysis can be found in [5].

In order to explain the analysis method applied, we have selected the measurements obtained for quadrupole Q21SEED in the vertical plane as an example. The quadrupole position has been scanned four times between ± 0.5 mm each time with a different quadrupole current. The duration of each scan is about 50 seconds in which the beam position is measured for each pulse resulting in about 100 points per scan. The beam position measured with six

BPMs downstream (5UND1, 5UND2, 5UND3, 5UND4, 5UND5 and 5UND6) is plotted in Fig. 3 as function of the quadrupole position.

The measurement points taken for the same quadrupole current are marked with the same color. A line is fitted to the measurement points taken in each scan and has the same color as the measurement points. We have reduced the limits of the fit in the case that the BPM presents some indication of saturation (for example, blue points taken with BPM 5UND1) or some defect (for example, blue points taken with BPM 5UND2). In the case of BPM 5UND4 and 5UND5 the four lines meet almost in the same point. In BPM 5UND1 and 5UND2 the intersection of the four fitted lines are spread over a range of about 0.1 mm. The R_{12} for BPM 5UND3 and 5UND6 is too small to provide a clear signal-to-noise ratio for the determination of the cross points.

In order to estimate the error in the determination of the cross between the fitted lines, we have collected all intersection points between each fitted line to another. With four fitted lines, we have six intersection points from which we have calculated the average, RMS and range. The average is marked with a full vertical line and the range is marked with two dashed lines in Fig. 3. All these values are shown for comparison in Fig. 4. The weighted average is $y_{\mathrm{q}} = 0.059 \pm 0.003$ mm, which means that if the quadrupole is positioned to 0.059 mm (in its reference system), then the beam center coincides with the quadrupole center and the kick introduced by the quadrupole field is zero.

Immediately after the quadrupole scan measurements, the vertical beam profile has been measured with wirescanner 21SEED and it is shown in Fig. 5. A Gaussian function is fitted to the measurements points. The center of the resulting Gaussian distribution is $y_{\mathrm{WS}} = -0.055$ mm. With this measurement, we obtain the offset $\Delta y_{\mathrm{ref}} = -0.114$ mm between the quadrupole reference system and the wirescanner reference system.

The measurement error of the beam position obtained from the transverse profile of the wirescan depends on a large number of factors, like its size, number of points, asymmetric tails, etc. In order to estimate the measurement error of wirescan profiles, we compare several profiles taken in the same conditions. For example, three wirescans taken with Q21SEED in a time interval of about one hour are compared in Fig. 6. The center of their respective Gaussian fits are -0.069, -0.055 and -0.023 mm. The RMS of these three values is 0.02 mm and it is a typical value for the reproducibility of the wirescanner results.

37 wirescans (taken in 15 locations and conditions) have been selected for the reproducibility test. For each location (or condition) the RMS of the centers of the Gaussian fits is calculated and shown in Fig. 7. The center of the beam profile is reproducible with an RMS of typically 0.02 mm in average. Only a few exceptions present larger deviations (up to an RMS of 0.15 mm) which correspond to beam profiles of a very large size and asymmetry. The RMS values are also shown in Fig. 8 as function of the size of the profile.

We conclude that an error of 0.02 mm in the beam position measurement is a conservative estimate based on the reproducibility tests shown above. Only in two locations (5UND3 and 5UND4) we have applied an error of 0.04 mm and 0.06 mm to the beam position measurements in the vertical plane (see Tab. 1).

4 Results

The results obtained using the analysis explained in Sec. 3 on the data taken between 8th and 11th of October are presented in Table 1.

quad name	x_{ws} **[mm]**	x_{cross} **[mm]**	Δx_{ref} **[mm]**
Q21SEED	-0.506 ± 0.020	-0.870 ± 0.003	0.364 ± 0.020
Q22SEED	-0.464 ± 0.020	-0.106 ± 0.003	-0.358 ± 0.020
Q5UND1	-0.344 ± 0.020	0.140 ± 0.030	-0.484 ± 0.040
Q6UND1	-0.431 ± 0.020	-0.546 ± 0.010	0.115 ± 0.021
Q5UND2	-0.127 ± 0.020	-0.445 ± 0.013	0.318 ± 0.024
Q6UND2	0.248 ± 0.020	-0.062 ± 0.025	0.310 ± 0.030
Q5UND3	0.332 ± 0.020	0.518 ± 0.020	-0.186 ± 0.030
Q6UND3	0.378 ± 0.020	-0.220 ± 0.002	0.598 ± 0.020
Q5UND4	0.324 ± 0.020	0.063 ± 0.010	0.261 ± 0.021
Q6UND4	0.520 ± 0.020	0.310 ± 0.020	0.210 ± 0.030
Q5UND5	0.464 ± 0.020	0.40 ± 0.05	0.06 ± 0.05
Q6UND5	-0.453 ± 0.020	-0.129 ± 0.012	-0.324 ± 0.021

quad name	y_{ws} **[mm]**	y_{cross} **[mm]**	Δy_{ref} **[mm]**
Q21SEED	-0.055 ± 0.020	0.059 ± 0.003	-0.114 ± 0.020
Q22SEED	-0.023 ± 0.020	0.144 ± 0.005	-0.167 ± 0.020
Q5UND1	-0.215 ± 0.020	-0.164 ± 0.006	-0.051 ± 0.020
Q6UND1	-0.217 ± 0.020	-0.153 ± 0.024	-0.064 ± 0.030
Q5UND2	-0.128 ± 0.020	0.020 ± 0.005	-0.148 ± 0.020
Q6UND2	-0.053 ± 0.020	0.063 ± 0.020	-0.116 ± 0.030
Q5UND3	0.20 ± 0.06	0.336 ± 0.010	-0.14 ± 0.06
Q6UND3	0.08 ± 0.06	0.210 ± 0.020	-0.13 ± 0.06
Q5UND4	-0.10 ± 0.04	0.014 ± 0.030	-0.11 ± 0.05
Q6UND4	-0.21 ± 0.04	-0.057 ± 0.015	-0.15 ± 0.04
Q5UND5	-0.199 ± 0.020	-0.19 ± 0.04	-0.01 ± 0.04
Q6UND5	-0.302 ± 0.020	-0.170 ± 0.013	-0.132 ± 0.024

Table 1: Summary of results obtained in the horizontal plane (top) and in the vertical plane (bottom). x_{ws} is the beam position measured with the wirescanner adjacent and x_{cross} is the beam position relative to the quadrupole reference. $\Delta x_{\mathrm{ref}} = x_{\mathrm{ws}} - x_{\mathrm{cross}}$ is the relative position between the wirescanner reference and the quadrupole reference.

The results are also shown in Fig. 9. The RMS of the offset between quadrupole reference system and the wirescanner reference system is 0.32 mm in the horizontal plane and is 0.045 mm in the vertical plane. The mean value of the vertical offsets is −0.11 mm.

The offsets between the quadrupole reference system and the wirescanner reference system are shown in Fig. 10 as function of the longitudinal quadrupole position z. It is important to note that in four diagnostics blocks (21SEED, 5UND1, 5UND3 and 5UND4) the position reference system of quadrupole doublets are horizontally misaligned with respect to each other by a distance of 0.4 mm up to 0.8 mm. An offset between the focusing quadrupole and the defocusing quadrupole of 0.8 mm deflects the beam trajectory by approx. 0.7 mrad for the nominal quadrupole settings and 445 MeV.

5 Conclusions

The position reference systems of quadrupoles and wirescanners have been correlated and an error analysis of the data is presented. The systematic error caused by a trajectory angle at the position of the wirescanner is not known. Since the longitudinal distance between the quadrupole and the wirescanner is about 20 cm, a systematic error up to 50 μm is very likely.

Some of the offsets have been measured previously [6]. In some cases, the differences between the measurements done in January and the measurements done in October are larger than the error bars. A reason for these differences has not been found.

6 Acknowledgments

We would like to thank the VUV FEL team and the members of the TESLA Collaboration. Specially we would like to express our gratitude to B. Faatz, O. Hensler and N. Baboi for their help in making these measurements so successful.

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[2] J. Pflüger, U. Hahn, B. Faatz, M. Tischer; Undulator system for the VUV FEL at the TESLA test facility phase-2, Nucl. Instr. Meth. A507 (2003) 228-233.

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[5] http://tesla.desy.de/TTFLOGBOOK/bba/plotsOct2005/index.html

[6] P. Castro, B. Faatz; Preliminary results from investigations of the relative alignment between the electron beam and quadrupoles in the undulator section of VUV FEL. DESY Technical Note 05-01, February 2004.

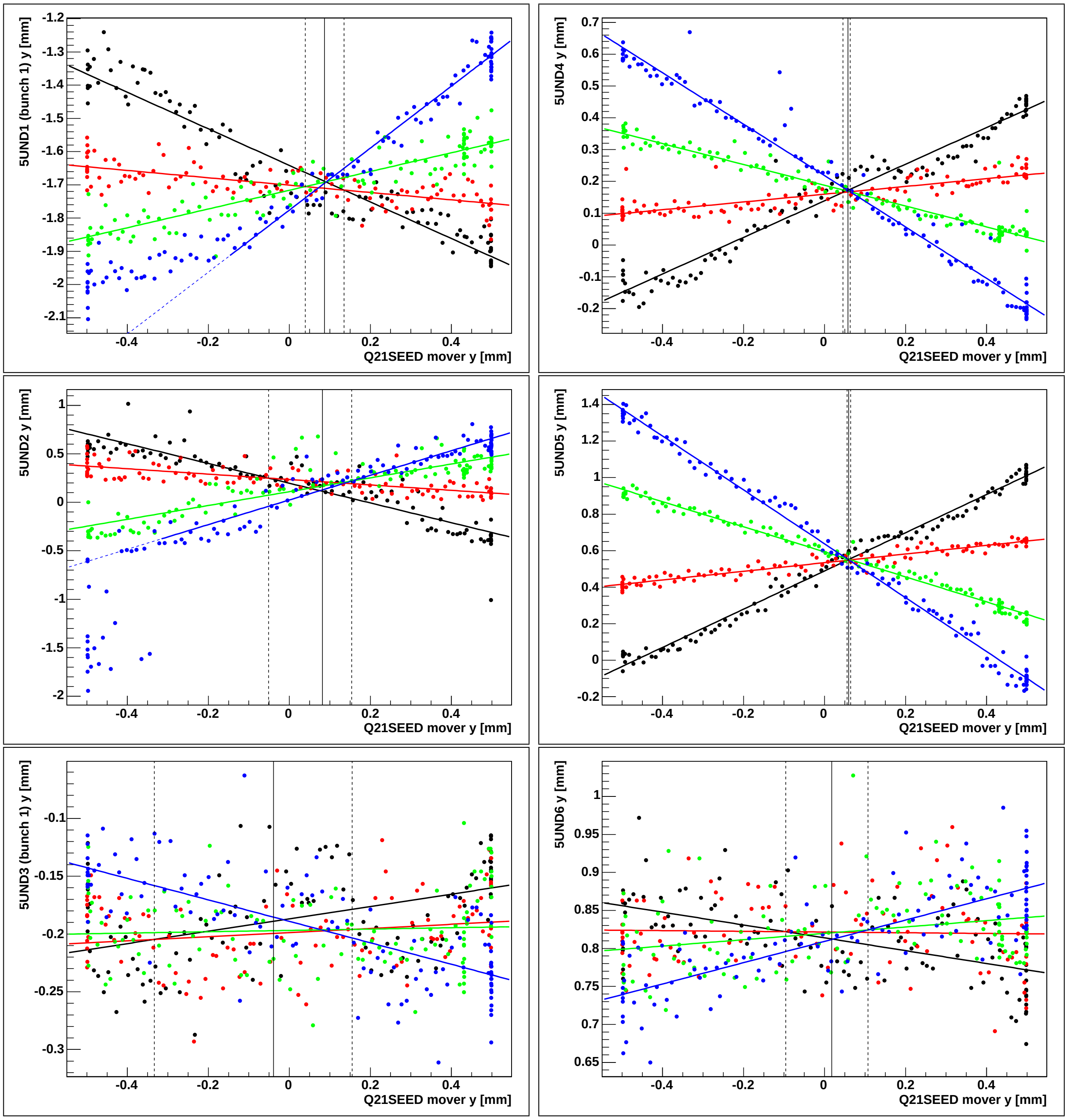

Figure 3: Beam position measured with six BPMs as function of quadrupole Q21SEED position for quadrupole current 0.6 A (black points), for −1.4 A (red points), for −3.4 A (green points) and for −5.4 A (blue points). The analysis of these data is explained in Sec. 3.

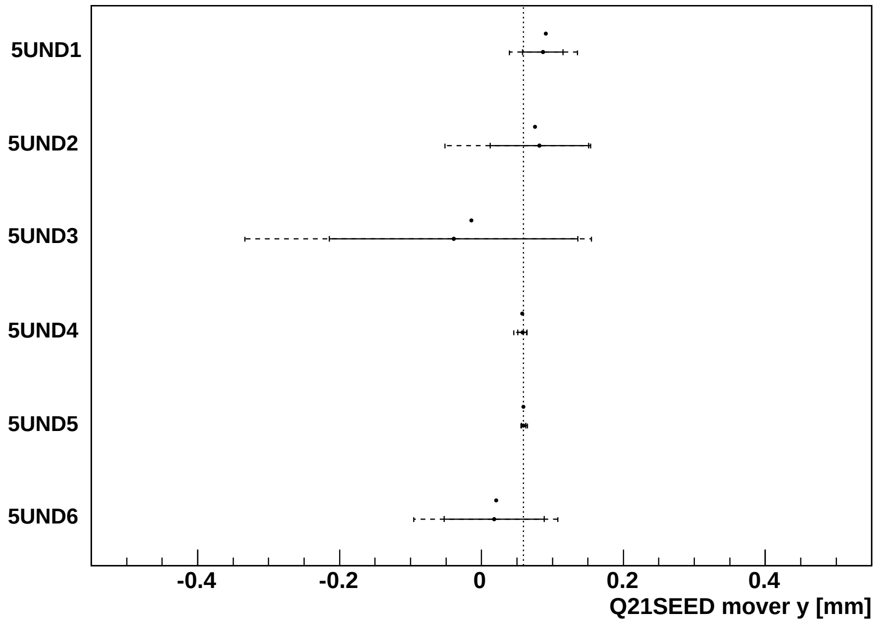

Figure 4: Average, RMS (full line error bars) and range (dashed line error bars) of the six interaction points determined by the fitted lines to the measurement points of each quadrupole scan.

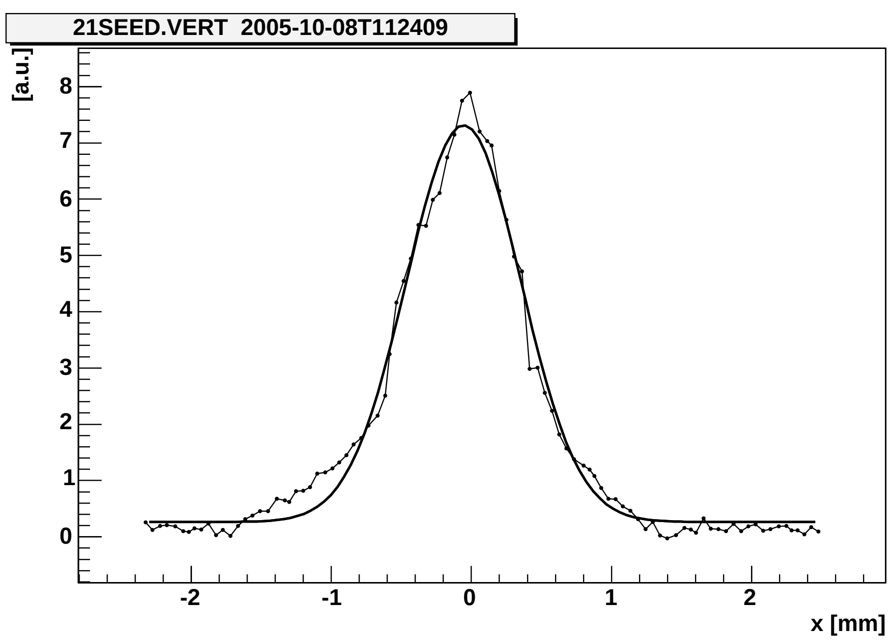

Figure 5: Transverse beam profile measured with the vertical wirescanner 21SEED at the Q21SEED quadrupole scan measurements. A Gaussian fit is applied.

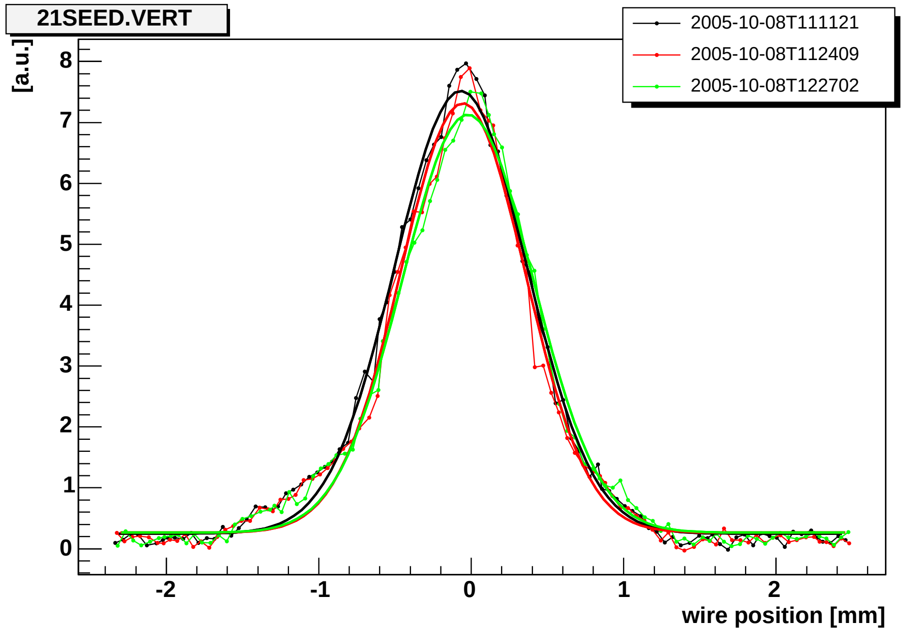

Figure 6: Three transverse beam profiles measured with the vertical wirescanner 21SEED during Q21SEED and Q22SEED quadrupole scan measurements. The time-stamp is shown in the legend.

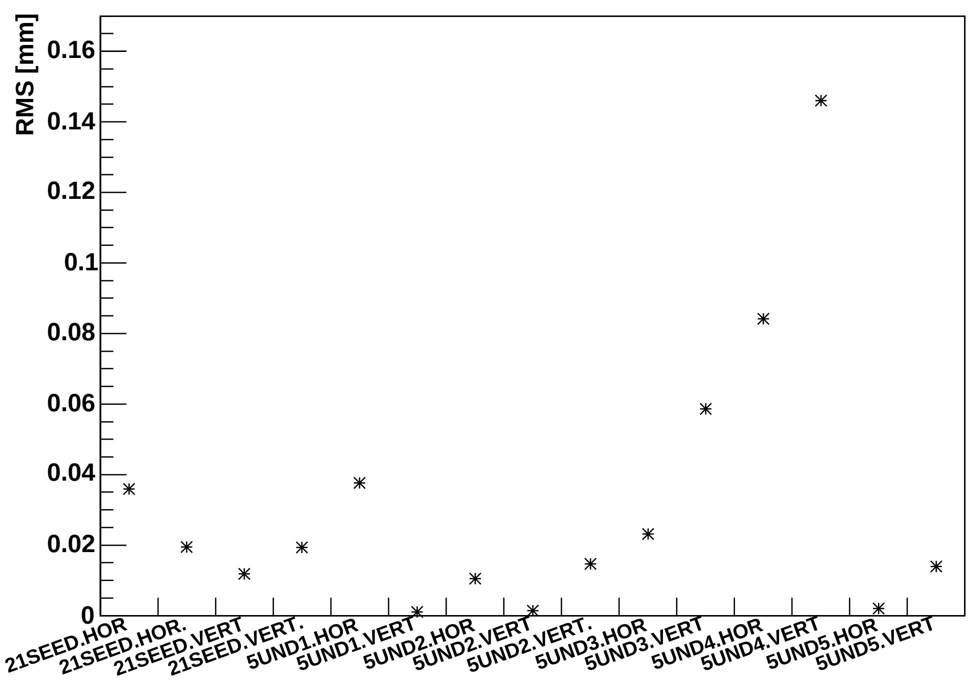

Figure 7: Reproducibility (RMS) of the center of the Gaussian fit for 12 locations (and for two different conditions for 21SEED.HOR, 21SEED.VERT and 5UND2.VERT).

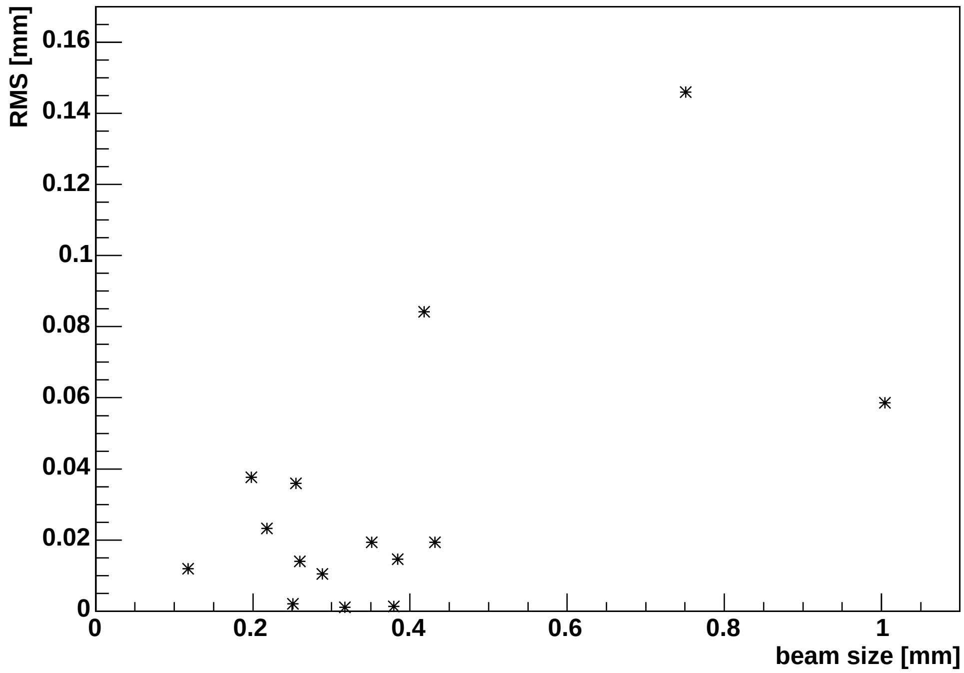

Figure 8: Reproducibility (RMS) of the center of the Gaussian fit for 12 locations (and for two different conditions for 21SEED.HOR, 21SEED.VERT and 5UND2.VERT).

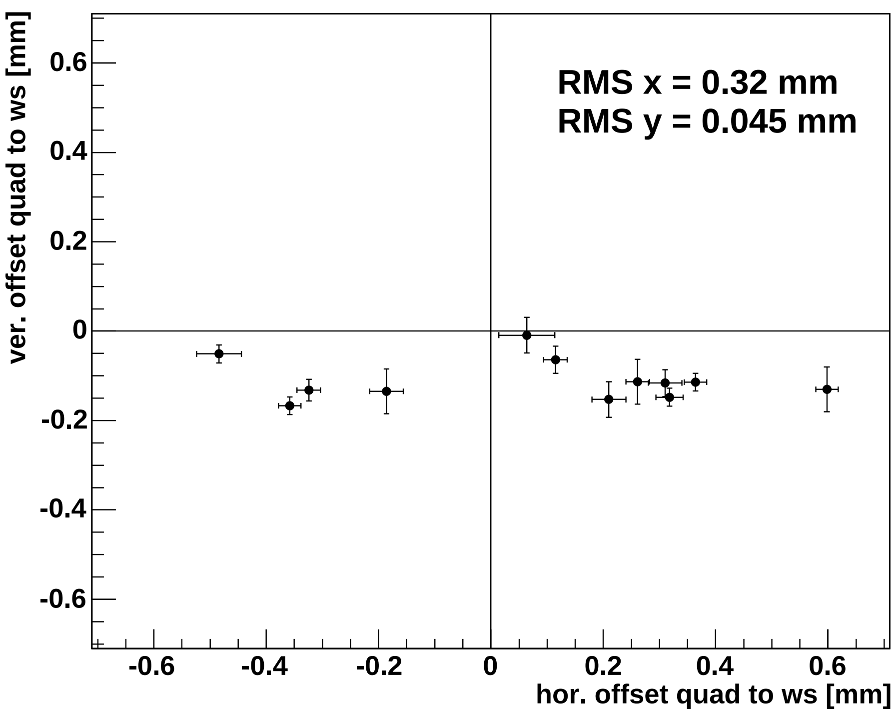

Figure 9: Horizontal and vertical offsets between the quadrupole reference system and the wirescanner reference system.

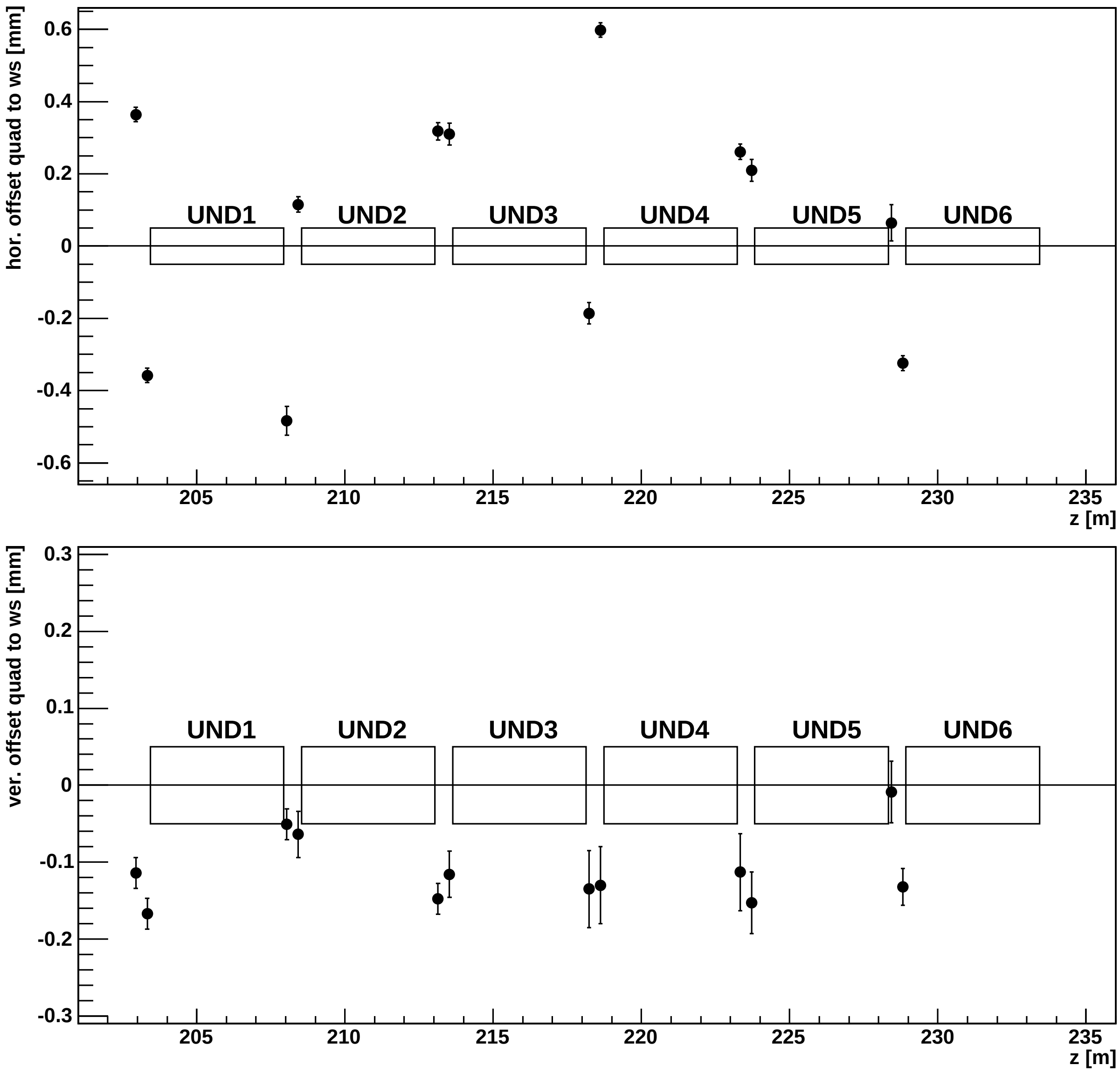

Figure 10: Horizontal (top) and vertical (bottom) offset between the quadrupole reference system and the wirescanner reference system. The beam enters from the left side.