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PS Booster Orbit Correction

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Abstract

At the end of the 2007 run, orbit measurements were carried out in the 4 rings of the PS Booster (PSB) for different working points and beam energies. The aim of these measurements was to provide the necessary input data for a PSB realignment campaign during the 2007/2008 shutdown. Currently, only very few corrector magnets can be operated reliably in the PSB; therefore the orbit correction has to be achieved by displacing (horizontally and vertically) and/or tilting some of the defocusing quadrupoles (QDs).
In this report we first describe the orbit measurements, followed by a detailed explanation of the orbit correction strategy. Results and conclusions are presented in the last section.

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1 Introduction and background

In the last few years it has been observed that the vertical and horizontal orbits of the four PS Booster rings were larger than expected and gradually deteriorating. Possible reasons are the following:

- In 1996 the tilts of all the quadrupoles in the ring have been realigned incorrectly due to a misunderstanding or loss of information[1].
- In 2003 the vertical tune of the machine has been lowered by one integer and changed to 4.23 at extraction to reduce the effect of resonances [1].

To measure the orbit of the PS Booster, one pickup (PU) is available per section (16 in total) and it can measure in either plane (H or V). The PUs are installed in between the first focussing quadrupole (QF) and the defocussing quadrupole (QD) with the basic optics cell of the Booster being bending1-QF1-QD-QF2-bending2 (QDs have double integrated length than the QFs).
Table 1 shows the peak-to-peak orbit values, averaged over all 4 Booster rings and 10 orbit measurements, after injection (*c=301*, *c* being a cursor that defines the timing along the PSB cycle) for the four different working points, after capture (*c=500*) and before extraction (*c=790*). It can be seen that the vertical orbit is worse than the horizontal one. The largest orbit excursions are obviously obtained close to the integer resonances.

Table 1: Summary of the peak-to-peak rms orbits for the different working points and energies.

c (ms)	**E$_{kin}$ (MeV)**	**Q$_h$**	**orbit$_h$ (mm)**	**Q$_v$**	**orbit$_v$ (mm)**
301	63	4.08	±8.6	4.13	±10.6
		4.17	±5.2	4.23	±6.7
		4.21	±4.7	4.30	±5.5
		4.28	±4.3	4.58	±4.6
500	403	4.16	±6.1	4.23	±7.5
790	1377	4.17	±6.8	4.23	±7.3

An example for the average of 10 orbit measurements at *c=301* and Q_h=4.17, Q_v=4.23 ring-by-ring is shown is figure 1.

For Q_v around 4.23, vertical orbit excursions amount to about ±7 mm. The vertical acceptance A_v at injection can be calculated by $A_v = r^2/\beta_v$. With a limiting vertical radius of 29.5 mm (at the end of bending1 and the start of bending2) and a β_v of 6.07 m this yields a vertical acceptance A_v of about 143 πmmmrad. An orbit of ±7 mm reduces this acceptance to 83 πmm·mrad. The situation gets even worse approaching the integer resonances. It should be mentioned that at Booster injection energies space charge has to be considered as well as it leads to an important tune spread.
Based on these arguments, an orbit correction campaign has been proposed for the 2007/2008 machine shutdown period [2] in order to minimize losses, which are particularly severe for high intensity beams.

2 Orbit measurements at the PSB

An orbit correction for the PS Booster is quite critical and complicated due to several reasons:

- The number of PUs to measure the orbit is limited ($< 4\times$the tune, whereas it is often said that it should be $\approx 6 \times Q$), but however this number is quite standard for most of the machines (e. g., SPS, RHIC, HERA-P).

[1] It has to be noted that a movement of each quadrupole affects the four superposed rings of the Booster as there are no individual quadrupoles per ring.

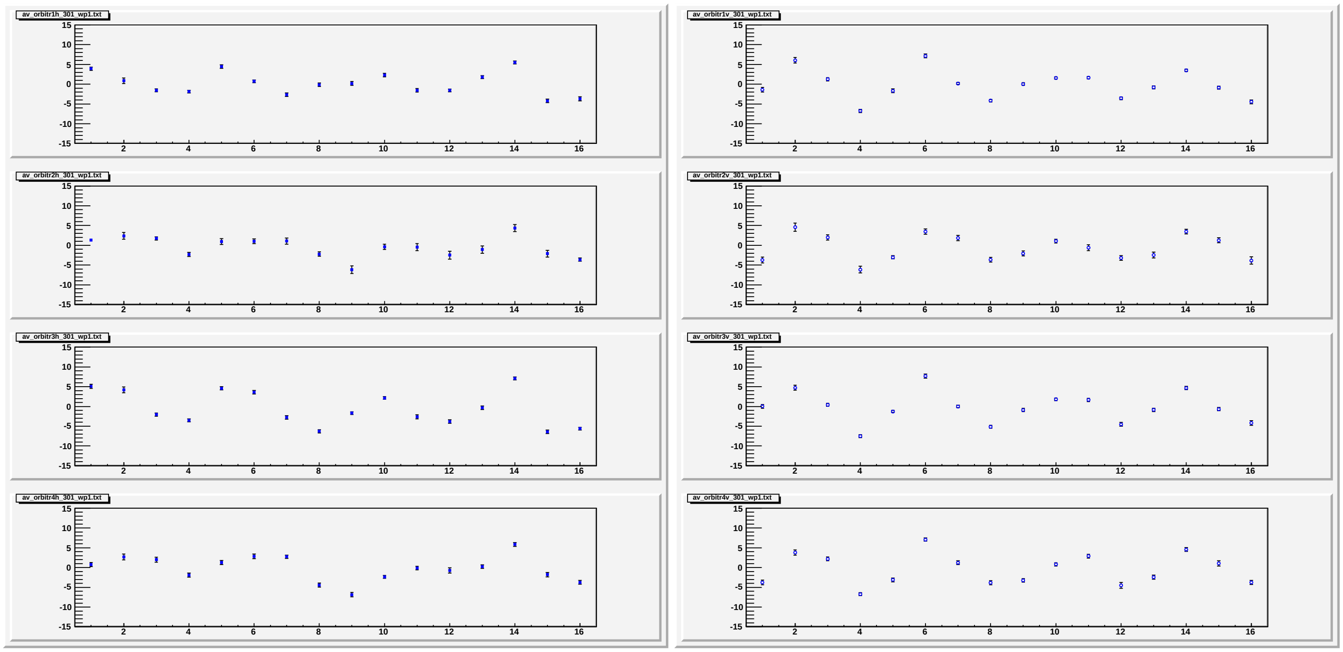

Figure 1: Average of 10 orbit measurements along the 16 sections of the PS Booster. The left plot shows the data for the horizontal plane, the right one for the vertical plane. Ring 1 is shown on top, followed by the other 3 rings (inverse to the actual situation). The y-axis is in units of mm.

- The system with the orbit correctors is complicated, and unreliable, because the power supplies need to be connected through the patch panel. For this reason the system was not used in operation for long periods[2].
- Due to the previous point an orbit correction requires the displacement of quadrupoles, but as explained before each displacement affects all 4 Booster rings. Vertical and horizontal movements of the quadrupoles should act equally on all rings, but a tilt will introduce different kicks for each ring. We will consider tilts only in the radial plane.
- The precision for alignment is limited to about 0.3 mm for the horizontal plane, 0.2 mm for the vertical plane and 0.2 mrad for the tilt (measurement precision is around 0.1 mm); the principal reason is the fact that the quadrupoles are much taller than wide.

Moreover, the original position of the quadrupoles has to be measured beforehand. As the last complete PS Booster measurement campaign dates back to the year 1996, it was decided to carry out a new survey of the whole machine [3].

2.1 Orbit pickup studies

Reliable beam position measurements in both planes are mandatory for beam based re-alignment. As it was discovered that the noise of the PUs was unacceptably high, the normalizer modules were exchanged (using the old PS modules) at the beginning of 2007, which improved the situation. Systematic studies were then performed with all the 16 PUs and a new calibration was made. The noise of the PUs can be checked using calibration pulses (corresponding to no displacement or $\pm$50 mm offsets); position variations were mostly within the $\pm$0.1 mm range, which is acceptable. The highest noise was seen for PU2 ($\pm$0.3 mm) as the electronics for this PU is located in a crate with other electronics modules leading to additional noise; PU10 showed $\approx \pm$0.2 mm variations.
Another test consisted in disconnecting all delta-signals, which should lead to a measured position of

[2] The power supplies and controls for these correctors will be replaced in the framework of the LHC injector consolidation project and should be available in 2010 (see http://ab-div.web.cern.ch/ab-div/Meetings/APC/2007/apc070706/minutes_070706.html)

zero mm. This was the case for all PUs; with an envelope usually around ±0.2 mm and maximum excursions of 0.5 mm.
A last check consisted in displacing voluntarily the mean radial position (MRP) of the beam by a few mm and compare the resulting orbit. Also this test passed to our satisfaction as the orbit showed the same offset as the MRP. It should nevertheless be mentioned that this test is of limited significance, as the MRP is an average position calculated from the measured values of 4 of the 16 orbit PUs (PUs 4, 6, 12 and 14).

2.2 2007 Orbit data for orbit correction

For the orbit measurements a modified version of the 'NORMHRS' beam was used (i. e. , the beam used for ISOLDE operation on the HRS target, see [4]). First of all, the intensity of this beam was reduced to about 5×10^{11} protons by reducing the number of injection turns and by using the sieve (a mechanical intercepting device with uniformly distributed apertures). This reduces the charge density and minimizes space charge effects; therefore the tune spread is kept as small as possible and the programmed tune should not differ too much from the actual tune (also the Q-strips that are used to correct the quadrupole field ring-by-ring were set to zero).
Moreover the vertical corrector dipoles used during 2007 operation were set to zero for a proper vertical orbit measurement.
In addition, care was taken to program flat RF functions for the cavities C02 and C04 in proximity of the measurement region to avoid possible influence of the longitudinal bunch shape.
The orbit measurement was performed in the low gain regime and more than 20 ms after injection (to guarantee that the feedback loop of the PUs is fully efficient yielding stable orbits).

As mentioned already in the introduction, measurements were taken at 3 different beam energies (see table 1), 10 measurements per point. The first measurement point close to injection (at cycle timing c=301 ms; PSB injection takes place at c=275 ms) was investigated in more detail for four different working points (WP) as the injection region is more critical due to the larger beam size combined with the tune spread: WP1 (Q_h=4.17, Q_v=4.23), WP2 (Q_h=4.08, Q_v=4.13), WP3 (Q_h=4.21, Q_v=4.30) and WP4 (Q_h=4.28, Q_v=4.58). The measurement point at c=790 ms corresponds to a time in the cycle after synchronization with the PS and before the extraction bump becomes active. The tunes were measured for each energy and WP for one ring and showed good correspondence to the programmed tunes.

The resulting peak-to-peak and rms variations of the horizontal and vertical orbit (averaged over 10 measurements each time) are visualized for each ring in figure 2. For the horizontal data, rings 1 and 4 show similar values. Surprisingly, ring 3 (which is the only ring that is vertically in the same plane as the injection and extraction line) shows the largest orbit excursions and is much worse than ring 2 (which is, in turn, worse than rings 1 and 4). This is not yet understood, as all the bendings and quadrupoles of rings 2 and 3 are powered in series. As some unknown effect seems to be causing the bad orbit of ring 3, it was decided to exclude the ring 3 data from the global correction analysis.

3 PSB Orbit correction

The orbit data described in the previous section were the necessary input for the partial PSB realignment strategy. Briefly, the procedure required that a correction scheme be calculated for the measured orbits assuming to use the horizontal displacements and tilts of the 16 QDs for the correction of the horizontal orbit, and the vertical displacements of the QDs for the correction of the vertical orbit. These corrections were then applied to the machine during the 2007/2008 winter shutdown. The resulting orbit was remeasured during the first week of the 2008 machine startup and determined whether a second iteration would be necessary.

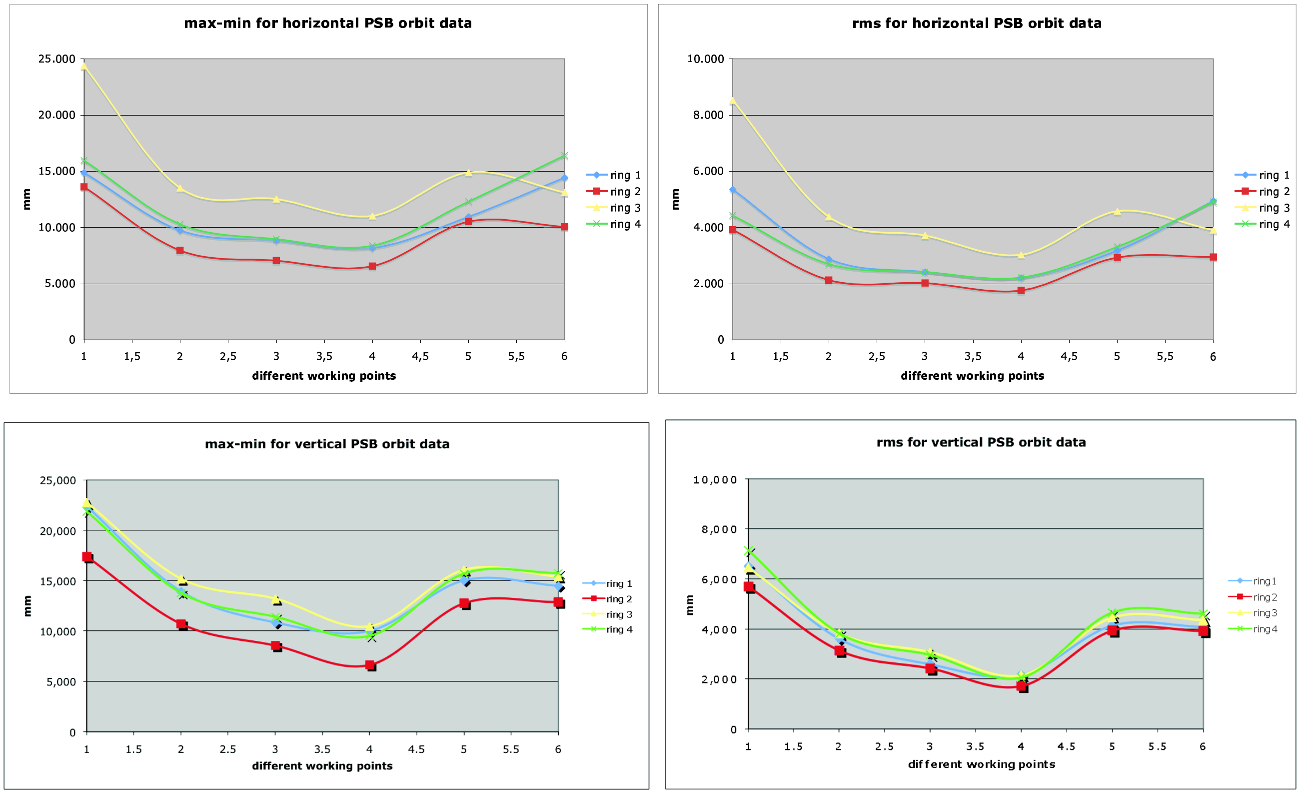

Figure 2: Peak-to-peak (left) and rms (right) orbit values (average over 10 measurements) in mm for different energies and working points (data for the horizontal plane is shown on top and for the vertical plane below). The first four points correspond to measurements done at c=301 (in the order of WP2/WP1/WP3/WP4), data for point 5 was taken at c=500 and point 6 at c=790.

3.1 General description of the orbit correction procedure

The closed orbit correction procedure is based on the ideal response matrix $\bar{\mathbf{R}}$, which relates the orbit change at the PUs $(\vec{\Delta x}_o, \vec{\Delta y}_o)$ with the horizontal and vertical displacements of the QDs $(\vec{\Delta x}, \vec{\Delta y})$ (orbit response to unit QD displacements). Therefore, the 32 readings (16 horizontal + 16 vertical) from a given measurement set at the PUs of only one of the four PSB rings can be written as

$$\begin{pmatrix} \vec{\Delta x}_o \\ \vec{\Delta y}_o \end{pmatrix} = \bar{\mathbf{R}} \cdot \begin{pmatrix} \vec{\Delta x} \\ \vec{\Delta y} \end{pmatrix} \tag{1}$$

If the QD displacements could be separately assigned ring by ring and assuming that the 4 rings of the PSB are identical, this equation can be generalized to:

$$\begin{pmatrix} \vec{\Delta x}_{o1} \\ \vec{\Delta y}_{o1} \\ \vec{\Delta x}_{o2} \\ \vec{\Delta y}_{o2} \\ \vec{\Delta x}_{o3} \\ \vec{\Delta y}_{o3} \\ \vec{\Delta x}_{o4} \\ \vec{\Delta y}_{o4} \end{pmatrix} = \begin{pmatrix} \bar{\mathbf{R}} & \bar{\mathbf{0}} & \bar{\mathbf{0}} & \bar{\mathbf{0}} \\ \bar{\mathbf{0}} & \bar{\mathbf{R}} & \bar{\mathbf{0}} & \bar{\mathbf{0}} \\ \bar{\mathbf{0}} & \bar{\mathbf{0}} & \bar{\mathbf{R}} & \bar{\mathbf{0}} \\ \bar{\mathbf{0}} & \bar{\mathbf{0}} & \bar{\mathbf{0}} & \bar{\mathbf{R}} \end{pmatrix} \cdot \begin{pmatrix} \vec{\Delta x}_1 \\ \vec{\Delta y}_1 \\ \vec{\Delta x}_2 \\ \vec{\Delta y}_2 \\ \vec{\Delta x}_3 \\ \vec{\Delta y}_3 \\ \vec{\Delta x}_4 \\ \vec{\Delta y}_4 \end{pmatrix} = \bar{\mathcal{R}} \cdot \begin{pmatrix} \vec{\Delta x}_1 \\ \vec{\Delta y}_1 \\ \vec{\Delta x}_2 \\ \vec{\Delta y}_2 \\ \vec{\Delta x}_3 \\ \vec{\Delta y}_3 \\ \vec{\Delta x}_4 \\ \vec{\Delta y}_4 \end{pmatrix} \tag{2}$$

Unfortunately, the QDs share the same physical support for all four rings, and therefore the elements of the vectors of the ring-by-ring displacements, $(\vec{D}_{xi}, \vec{D}_{yi})_{i=1,2,3,4}$, are not independent. In fact, they depend linearly on three sets of parameters, which are the displacements and tilt angles of the QD supports, $(\vec{\alpha}, \vec{D}_x, \vec{D}_y)$. Assuming that the QD supports can be tilted around Ring 1 and with ΔL being the vertical distance between two rings (=0.36 m), the vector of the ring-by-ring displacements can be written as:

$$\begin{pmatrix} \vec{\Delta x}_1 \\ \vec{\Delta y}_1 \\ \vec{\Delta x}_2 \\ \vec{\Delta y}_2 \\ \vec{\Delta x}_3 \\ \vec{\Delta y}_3 \\ \vec{\Delta x}_4 \\ \vec{\Delta y}_4 \end{pmatrix} = \begin{pmatrix} \bar{\mathbf{0}} & \bar{\mathbf{I}} & \bar{\mathbf{0}} \\ \bar{\mathbf{0}} & \bar{\mathbf{0}} & \bar{\mathbf{I}} \\ \bar{\mathbf{I}} & \bar{\mathbf{I}} & \bar{\mathbf{0}} \\ \bar{\mathbf{0}} & \bar{\mathbf{0}} & \bar{\mathbf{I}} \\ 2\bar{\mathbf{I}} & \bar{\mathbf{I}} & \bar{\mathbf{0}} \\ \bar{\mathbf{0}} & \bar{\mathbf{0}} & \bar{\mathbf{I}} \\ 3\bar{\mathbf{I}} & \bar{\mathbf{I}} & \bar{\mathbf{0}} \\ \bar{\mathbf{0}} & \bar{\mathbf{0}} & \bar{\mathbf{I}} \end{pmatrix} \cdot \begin{pmatrix} \Delta L \cdot \vec{\alpha} \\ \vec{\Delta x} \\ \vec{\Delta y} \end{pmatrix} = \bar{\mathbf{K}} \cdot \begin{pmatrix} \Delta L \cdot \vec{\alpha} \\ \vec{\Delta x} \\ \vec{\Delta y} \end{pmatrix} \tag{3}$$

Finally, combining Eqs. (2) and (3) and using the general inverse, the vector of the required corrections will be given by

$$\begin{pmatrix} \Delta L \cdot \vec{\alpha} \\ \vec{\Delta x} \\ \vec{\Delta y} \end{pmatrix} = -\left(\bar{\mathcal{R}} \cdot \bar{\mathbf{K}}\right)^{-1} \cdot \begin{pmatrix} \vec{\Delta x}_{o1} \\ \vec{\Delta y}_{o1} \\ \vec{\Delta x}_{o2} \\ \vec{\Delta y}_{o2} \\ \vec{\Delta x}_{o3} \\ \vec{\Delta y}_{o3} \\ \vec{\Delta x}_{o4} \\ \vec{\Delta y}_{o4} \end{pmatrix} \tag{4}$$

The generalized inversion of the matrix $\bar{\mathcal{R}} \cdot \bar{\mathbf{K}}$ (which is not square) is carried out using the Singular Value Decomposition technique and applying a singular value cut of 1%. This parameter can be handily set to a different value in the correction routine. Figure 3 shows, for instance, all the singular values of the $\bar{\mathcal{R}} \cdot \bar{\mathbf{K}}$ matrix, corresponding to two out of the 6 PSB measurement sets described in the previous section. It is evident that a cut at 1% of the maximum value allows including basically all the singular values except the very last two ones, very close to zero. Different choices could be made and a cut of 0.1, or even higher, could be applied, which would correspond to cutting at any of the other "jumps" among the singular values (hardly visible on the logarithmic scale).

The energy error must be first determined from each of the measured horizontal orbits and its contribution must be then subtracted in the orbits used for the correction algorithm. In particular, considering one horizontal orbit (i.e. working point, energy, ring fixed), the following quantity has to be minimized,

$$S = \sum_{i \in PUs} \left(\Delta x_{oi} - D_i \cdot \delta\right)^2 \quad , \tag{5}$$

which yields

$$\delta = \frac{\sum\limits_{i \in PUs} \Delta x_{oi}}{\sum\limits_{i \in PUs} D_i} \quad . \tag{6}$$

This expression reduces to

$$\delta = \frac{\langle \Delta x_{oi} \rangle}{D} \quad , \tag{7}$$

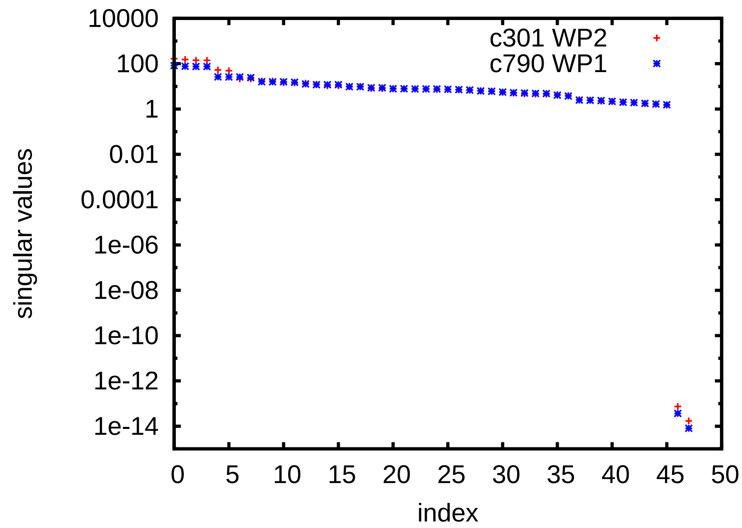

Figure 3: Singular values plotted in decreasing order for two of the 6 PSB measurement sets described in the previous section.

because in the PSB the dispersion function has the same value at the location of all the PUs; $(D_i)_{i \in PUs} = D$. This translates to "cleaning" all the horizontal orbits from their average values.

The routines that were developed for the orbit correction calculation easily allow for the removal of data from bad PUs as well as for a reduction of the number of correctors. For this purpose, a scanning MICADO-like [5] algorithm has been implemented to test the individual efficiency of each corrector and to minimize the number of correctors to be used. The correctors are tested one by one first, then by pairs, triplets, and so on up to the desired number, keeping always the strongest correctors from all previous iterations and probing the remaining ones at each new iteration. The criterion that defines the new strongest corrector at each iteration consists of choosing the one that, in combination with those selected from previous iterations, minimizes the orbit residual (i.e. the rms value of the estimated orbit after correction).
More details on the software package can be found in [6].

3.2 Orbit correction based on 2007 PSB orbit measurements

The procedure detailed in the previous section has been applied to the PSB. The orbit data collected at the end of 2007 and described in Section 2.2 was used as input. With these data, the readings from PU5 have been systematically removed as they seemed to be doubtful in most cases (especially for ring 1 in the horizontal plane, where values exhibited very large fluctuations). However, it should be mentioned that there did not appear to be much difference in the final required corrections, whether the data from this PU was taken out or not.
Another important point is that for each measurement set the lattice was matched to the measured tunes.

3.2.1 Global orbit correction

As first step, all the QDs were taken as correctors and the required displacements and tilt angles calculated for each measurement set. Figures 4 show the overall needed corrections averaged over the 6 available sets of data. The error bars represent the rms spreads over the measurement sets. It turned out that horizontal displacements up to >1 mm were required, whereas the needed vertical displacements are below 0.5 mm. The tilt angles were all below 1 mrad, except for QD9, which seemed to need tilting by about 2.5 mrad (this particular quadrupole was voluntarily tilted in 1996; see [7]).

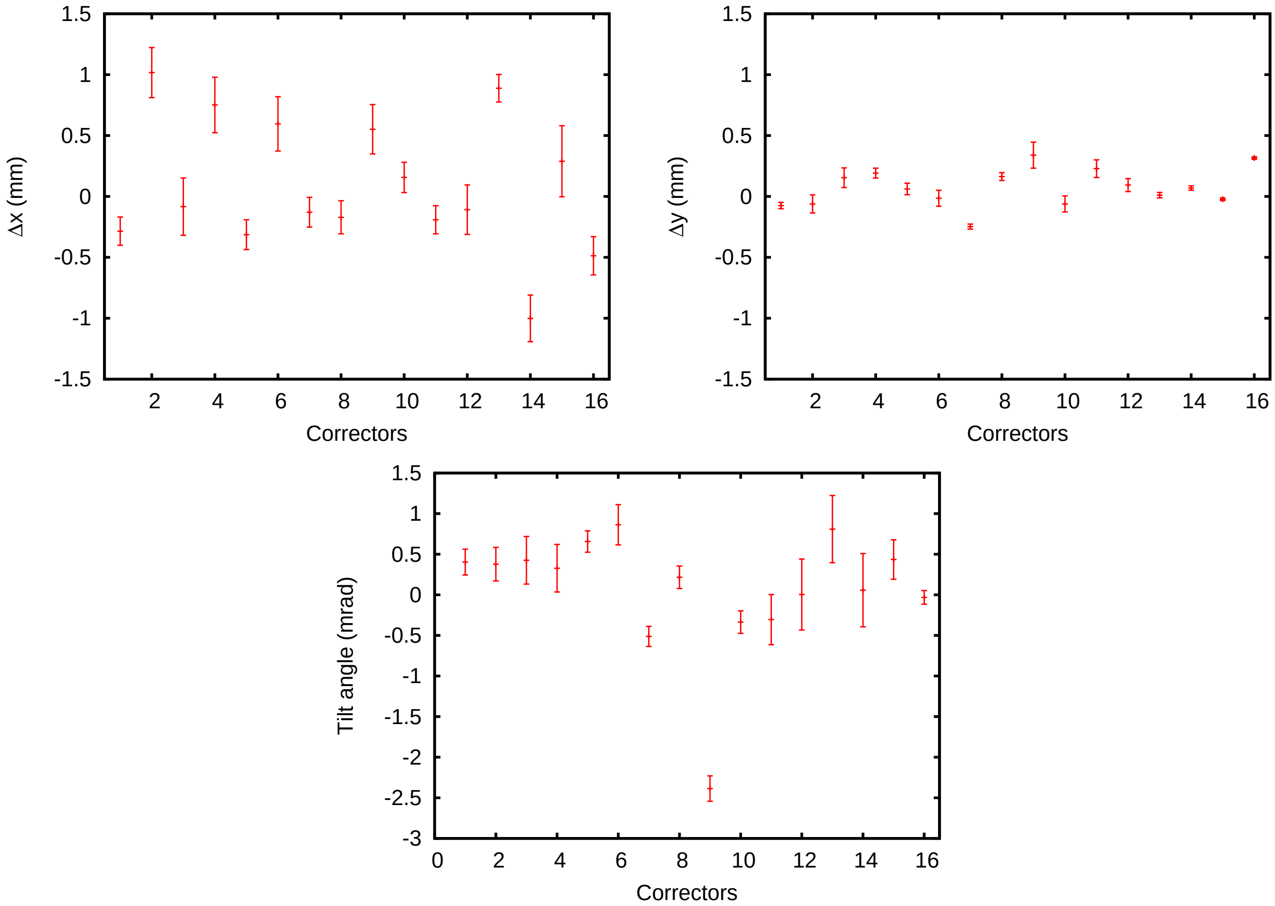

Figure 4: Corrections calculated (for the horizontal plane top left, for the vertical plane top right, for the tilt bottom) using all 16 QDs as correctors. Data from all rings were included in this analysis.

Due to the observed worse orbits in ring 3 (see Section 2), which were suspected to point to some localized error present in ring 3 alone, the analysis above was repeated discarding data from ring 3. Results are displayed in Figs. 5. While hardly any difference can be spotted in the required vertical displacements, significantly more correction around QD9 (i.e. QD8 and QD10) seemed to be demanded in terms of both horizontal displacement and tilt angle.

The next step was the attempt to minimize the number of QDs to be used for the correction. The residuals of the correction were calculated using different quantities of correctors for each working point. The results are plotted in Fig. 6. It shows that 6 QDs are sufficient to produce reasonably well corrected orbits for all cases.

However, it turns out that the subset of 6 strongest correctors needed for the best correction is not the same for all data sets. Only two correctors (QD2 and QD13) are present for all measurement sets, whereas 6 of them never appear in the list (QD1, QD3, QD4, QD5, QD6, QD11). All the others appear with a certain frequency, as summarized in the occurrence plot of Fig. 7. Looking at this graph, it can be seen that the 6 strongest correctors are QD2, QD7, QD8, QD9, QD10 and QD13. Among these, we chose to use only QD2, QD9, QD10 and QD13, because the phase advances between QD7 and QD9, and between QD8 and QD10, are about 180^o.

The horizontal and vertical displacements, as well as the tilt angles of the four correctors, are plotted in Figs. 8. The residuals for all measurement sets are summarized together with the rms orbits in Table 2.

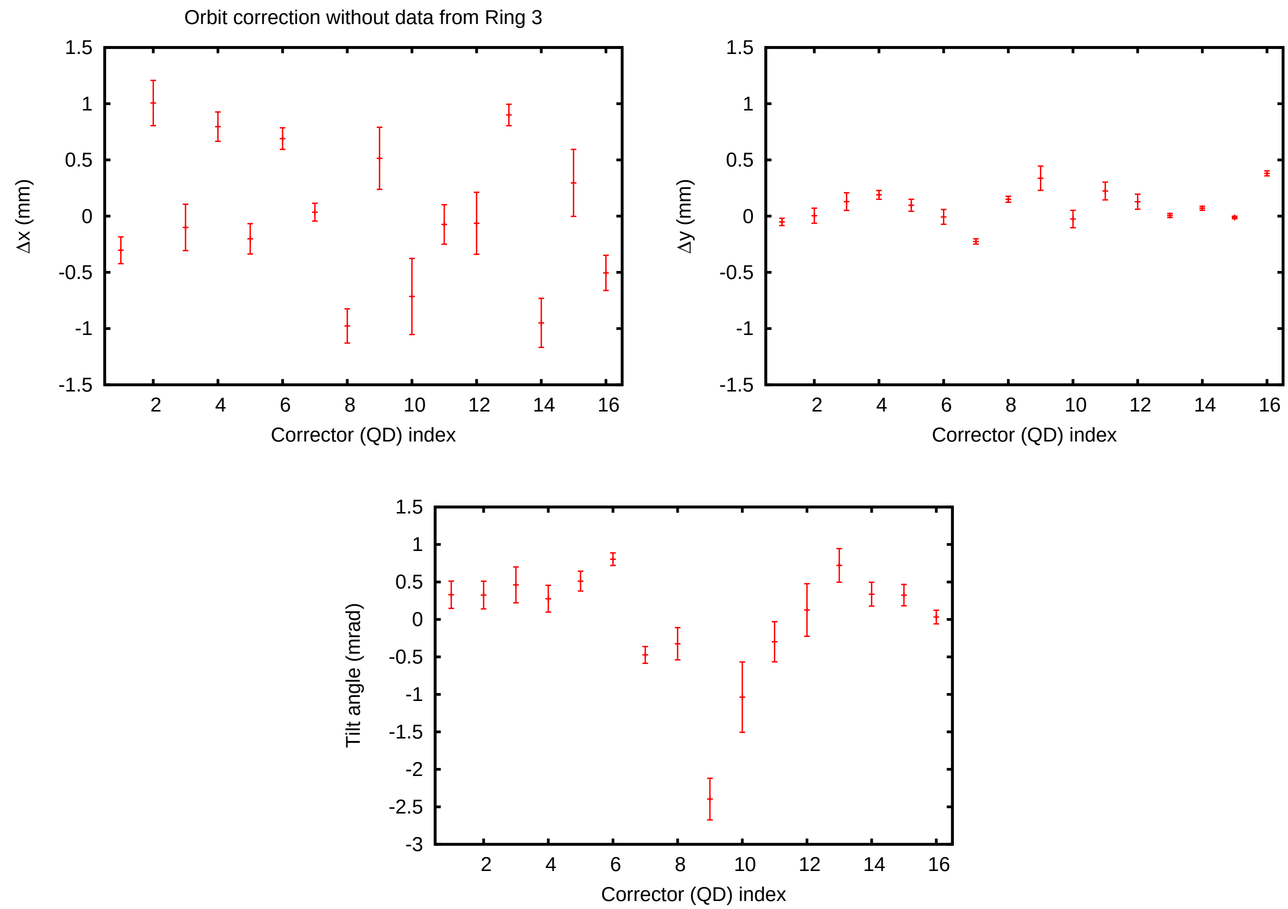

Figure 5: Corrections calculated (for the horizontal plane top left, for the vertical plane top right, for the tilt bottom) using all 16 QDs as correctors. Data from ring 3 were not considered in this analysis.

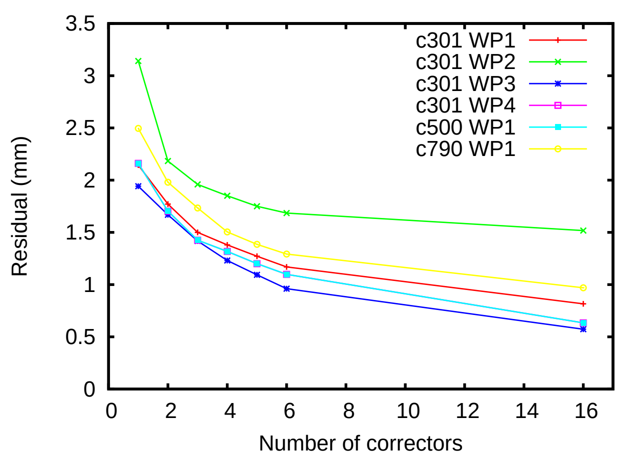

Figure 6: Residual as a function of the number of QDs as correctors for the different measurement sets.

3.2.2 Separating the orbit correction for horizontal and vertical plane

As alternative approach, the correction algorithm can be separately applied to the horizontal and the vertical planes. We can find two distinct sets of best correctors by correcting the horizontal orbits first, and then the vertical ones. Similarly to what was done in the case of global correction, the Micado-like procedure to determine the strongest correctors was used for the two planes. Figure 9 shows the occurrences of each corrector while separately correcting the horizontal and vertical orbits. The residuals

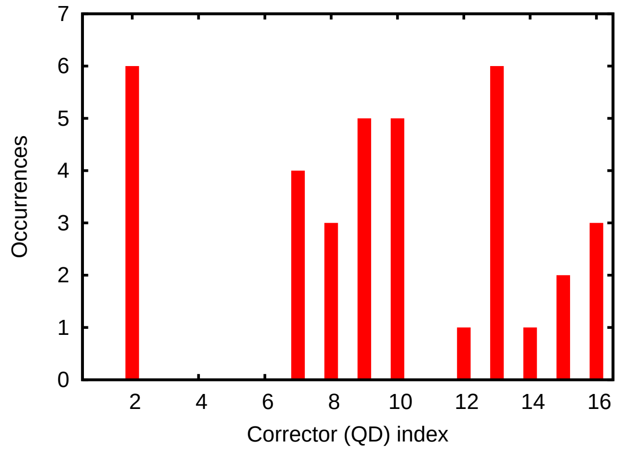

Figure 7: Number of times that each corrector appears in the list of best correctors per measurement set (6 measurement sets in total), when limiting the number of required correctors to 6.

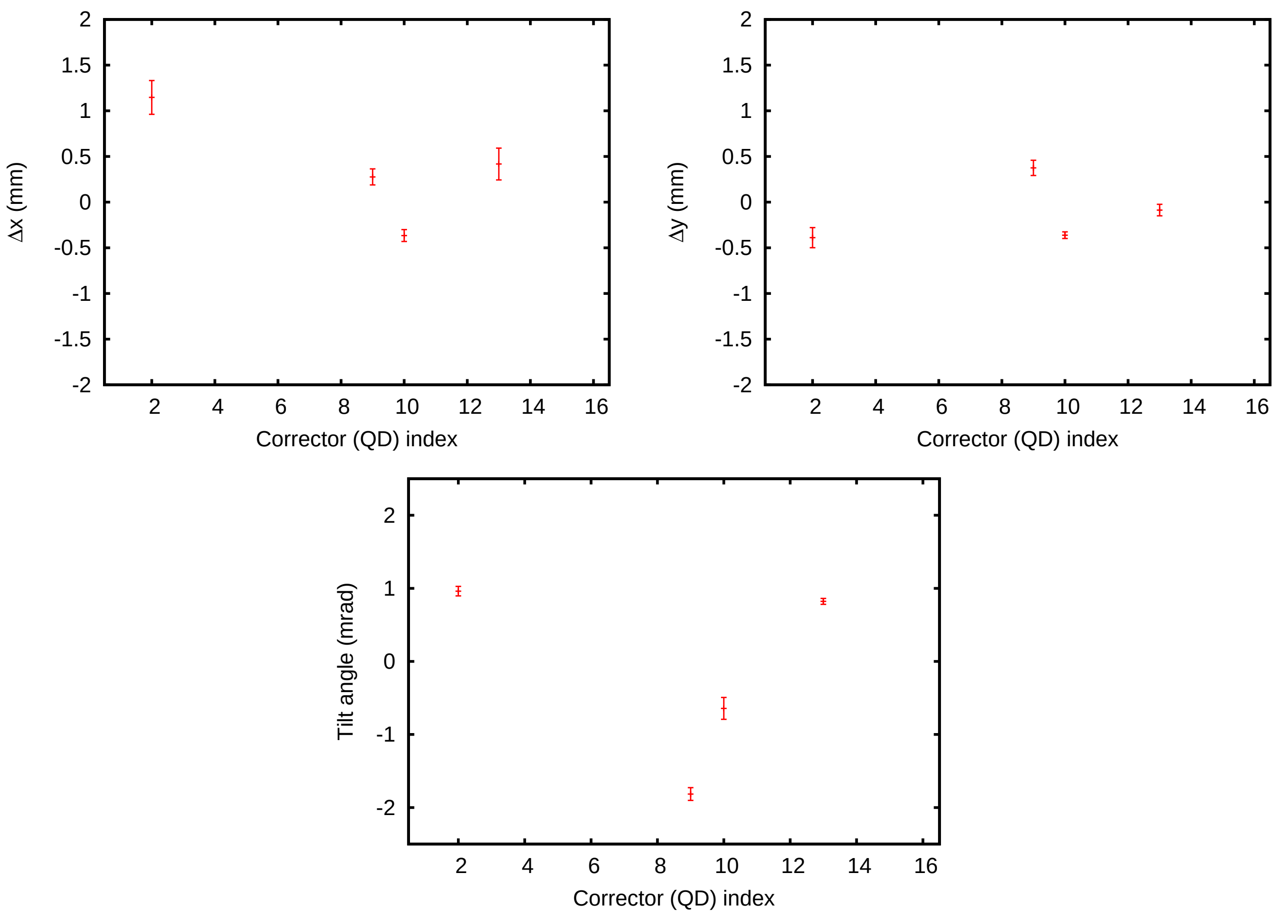

Figure 8: Corrections calculated using only the 4 strongest correctors. Data from ring 3 were not considered in this analysis.

after each correction (and also the initial rms orbits, corresponding to the case of zero correctors) are displayed in Fig. 10. It turned out that the subset of correctors that would be best to correct the horizontal orbits (QD2, QD9, QD10, QD13) had no overlap with the subset for the correction of the vertical orbits (QD4, QD7, QD8, QD16). However, as it was expected, the occurrences found in the global case consist of a mixture of both, even if the global correction appears to be dominated by the correction of

Table 2: Residuals from orbit correction with 4 QDs.

Data set	Rms orbit (mm)	Residual (mm)
c301 WP1	3.216	1.367
c301 WP2	5.715	1.819
c301 WP3	2.608	1.242
c301 WP4	2.169	1.321
c500 WP1	3.825	1.287
c790 WP1	4.322	1.484

the horizontal orbits. An explanation of this behaviour will be given further below.

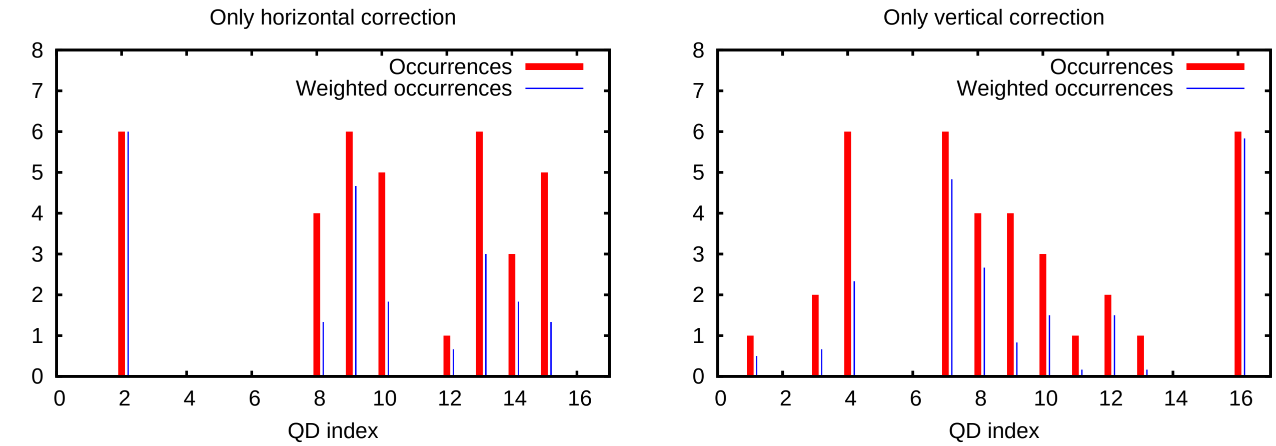

Figure 9: Occurrence of each corrector in the list of best correctors per measurement set (6 measurement sets in total), when limiting the number of required correctors to 6. The weighted occurrences also take into account the order in which the correctors appear (strongest, second strongest and so on).

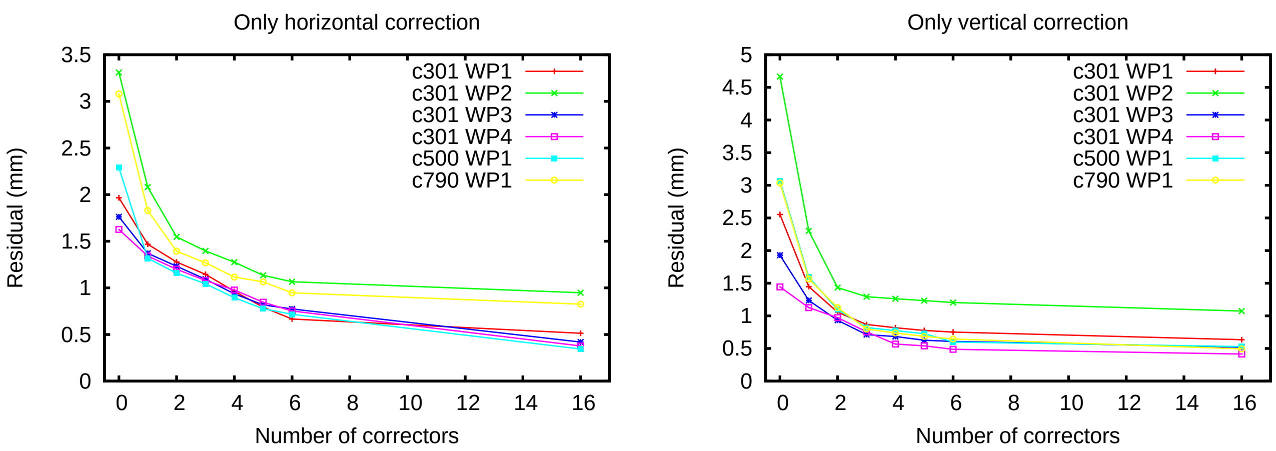

Figure 10: Residual as a function of the number of QDs as correctors for the different measurement sets (left: horizontal correction, right: vertical correction).

As a first attempt, 4 correctors were used to calculate the correction of the horizontal orbit and 3 for the correction of the vertical orbit. The horizontal and vertical displacements of the 4+3 correctors are plotted in the first of Figs. 11. The resulting tilt angles of the four correctors in the horizontal plane are plotted in the second of Figs. 11. It is evident that the horizontal displacements as well as the tilt angles are basically the same as those calculated for the global correction. The vertical displacements of the 3 best correctors in the vertical plane are also consistent with what was obtained before, taking into account that the pair QD9-QD10 is here replaced by the pair QD7-QD8, situated 180^o apart in phase advance. Similarly, the correction given now by QD16 was before given by QD2. Magnitude and sign of the new corrections are consistent with those calculated when doing the global correction. The reason why the global analysis of the orbits gives results very close to those from the horizontal plane alone could lie in the fact that, while the choice of correctors is more critical in the horizontal plane to have a good correction (probably due to the tilt angle), the correction in the vertical plane can still be efficiently made by using different subsets of correctors.

By carrying out separate corrections in the horizontal and vertical planes with the same 4 correctors that were used for the global correction scheme, it was found that the residuals after the vertical correction were about 10–20% higher in the global scheme than those attainable with the separated horizontal and vertical correction scheme. This lead us to prefer the latter one to the global correction scheme, even if it would imply moving 7 quadrupoles instead of 4.

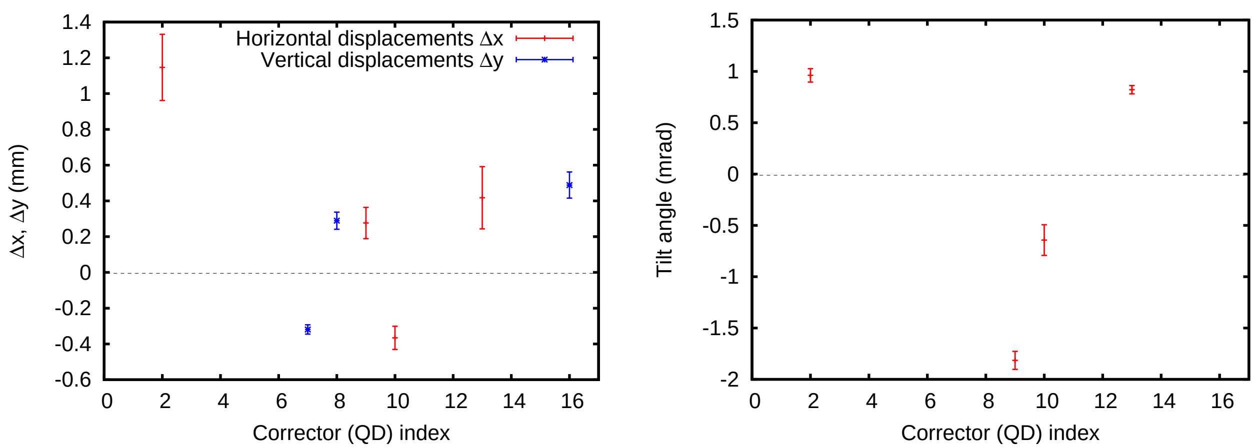

Figure 11: Corrections calculated using only the 4 strongest correctors for the horizontal correction and the 3 strongest correctors for the vertical correction. Data from ring 3 were not considered in this analysis.

Another correction option, which would still require moving 7 correctors in total, is to use 6 correctors in the horizontal plane (QD2, QD8, QD9, QD10, QD13, QD15) and 3 in the vertical plane, two of which are in common with the horizontal plane (QD8, QD9, QD16). This should allow to have a better correction in the horizontal plane (the slope of the residuals as a function of the number of correctors, Fig. 10, seems to suggest that more than 4 correctors should yield a significantly better correction in the horizontal plane), while losing only few % in the vertical plane with respect to the optimum scheme. The plots of the requested corrections under this scheme are plotted in Figs. 12.

As a result of the vertical alignment survey in the PSB, it was noticed that the three PUs PU7, PU10 and PU15 exhibited a large offset (by about 1–1.5 mm) relatively to the close-by elements. It was therefore decided to correct the orbit data by this amount and re-calculate the strongest correctors and the optimum correction in the vertical plane using the corrected PU data. The difference in the occurrence of the correctors is plotted in the first one of Figs. 13. It is clear that, while QD16 and QD7 remain the strongest correctors to achieve a good vertical orbit correction, QD6 appears to be the third strongest, basically replacing Q8 and Q10. The best 3 correctors become therefore QD6, QD7 and QD16, which

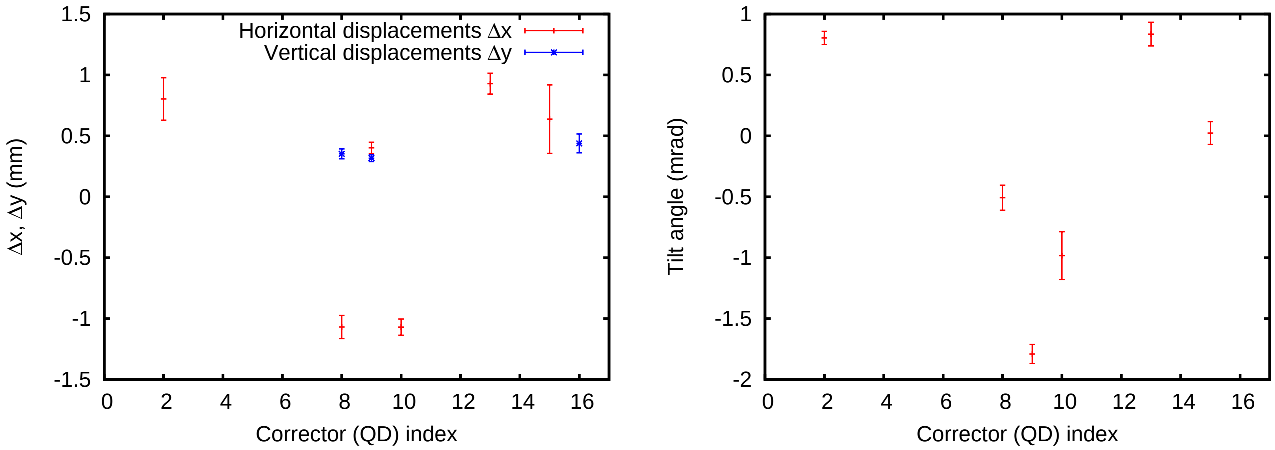

Figure 12: Corrections calculated using the 6 strongest correctors for the horizontal correction and 3 correctors for the vertical correction (two strongest ones and a third common to the horizontal plane). Data from ring 3 were not considered in this analysis.

can yield residuals up to 20–30% better than the three correctors proposed in the previous scheme and allow gaining nearly up to 1 mm in the peak-to-peak orbit. The required corrections for these three correctors are plotted in the second of Figs. 13.

The final decision on the PSB orbit correction was therefore to use these last corrections for the vertical plane and leave unchanged those previously established for the horizontal plane.

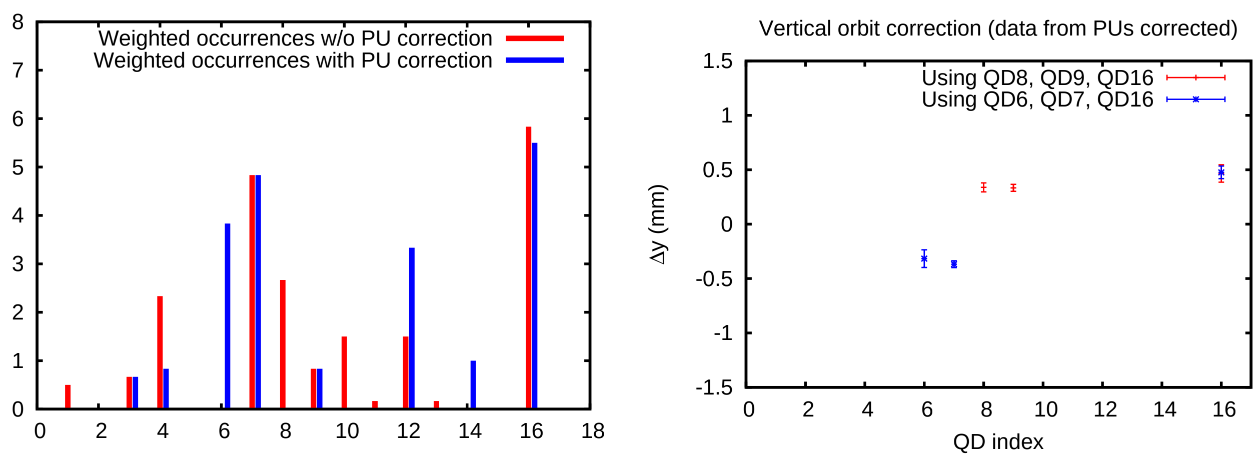

Figure 13: Weighted occurrences of the QDs as vertical correctors using data with and without the correction to the misaligned PU readings (left plot). Proposed QDE displacements using the three best correctors coming from the analysis with and without the PU alignment corrections (right plot).

3.3 Results of the orbit correction (first iteration)

During the 2007/2008 machine shutdown the requested horizontal and vertical displacements and tilt angles were applied to the selected QDEs. To summarize, the requested horizontal displacements and tilt angles are those given in Fig. 12 and the vertical displacements are the blue points in Fig. 13.

For a correct interpretation of the proposed corrections, a remark should be added about sign conventions. The MAD-X convention for the PSB assigns positive Δx values towards the inside of the

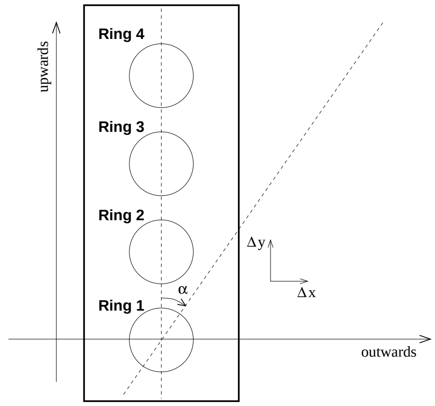

Figure 14: Sign convention for the calculated corrections.

ring (the beam in the PSB turns counter-clockwise) and positive Δy values upwards. The PU data from the PSB keep the same convention in the vertical plane, whereas in the horizontal plane positive values correspond to outward offsets and negative offsets have to be understood being towards the inside of the machine. As a consequence, while the calculated vertical corrections can be taken with their signs using the MAD-X convention, the calculated horizontal corrections and tilt angles need to be interpreted with the opposite convention with respect to MAD-X. In addition, for our calculations ring 1 (the lowest PSB ring) is the reference ring for the tilt (pivot point). In summary, conventions for the signs of the resulting corrections are displayed in Fig. 14.

To complicate things, the surveyors also work with their proper sign conventions: positive Δx values always point to the left (seen going with the beam), i.e. for the PSB towards the inside of the ring. A positive tilt angle for the surveyors means that the equipment is leaned towards the inside of the PSB as well, but the pivot point for the tilt is ring 3 in this case. Positive Δy values point upwards.

Table 3 gives a summary of the requested QD movements (horizontal, vertical and tilt) for both conventions (calculated values and values for surveyors).

Table 3: Summary of the requested QD magnet displacements to correct the PSB orbits.

	Δ_h **(calc.) [mm]**	Δ_h **(surv.) [mm]**	Δ_{tilt} **(calc.) [mrad]**	Δ_{tilt} **(surv.) [mrad]**	Δ_v **[mm]**
QD2	+0.80	-1.38	+0.80	-0.80	
QD6					-0.32
QD7					-0.37
QD8	-1.07	+1.43	-0.50	+0.50	
QD9	+0.40	+0.89	-1.79	+1.79	
QD10	-1.07	+1.78	-0.98	+0.98	
QD13	+0.93	-1.53	+0.84	-0.84	
QD15	+0.64	-0.64			
QD16					+0.48

Alignment data after the voluntary displacements showed that, while the movements in the vertical plane appeared to be within the expected tolerances, those applied in the horizontal plane exhibited large discrepancies with respect to the requested values. Orbit measurements were carried out soon after the PSB startup, on the 28 April 2008. The same working points and energies as in November 2007 were chosen and 10 horizontal and vertical orbits were measured for each point in order to quantify the improvement compared to the past year and to obtain input data for a possible second iteration of orbit correction. The measurements performed in April 2008 confirmed that a clear improvement was obtained in the vertical orbits (by up to a factor of 3–4) for all working points and energies both in rms and peak-to-peak values. However, the horizontal orbits did not seem to have improved from 2007, and it was also clear that Ring 3 remained the worst performing of the four PSB rings, having larger horizontal orbits for all working points and energies. The results of this first iteration of orbit correction are displayed in Fig. 15.

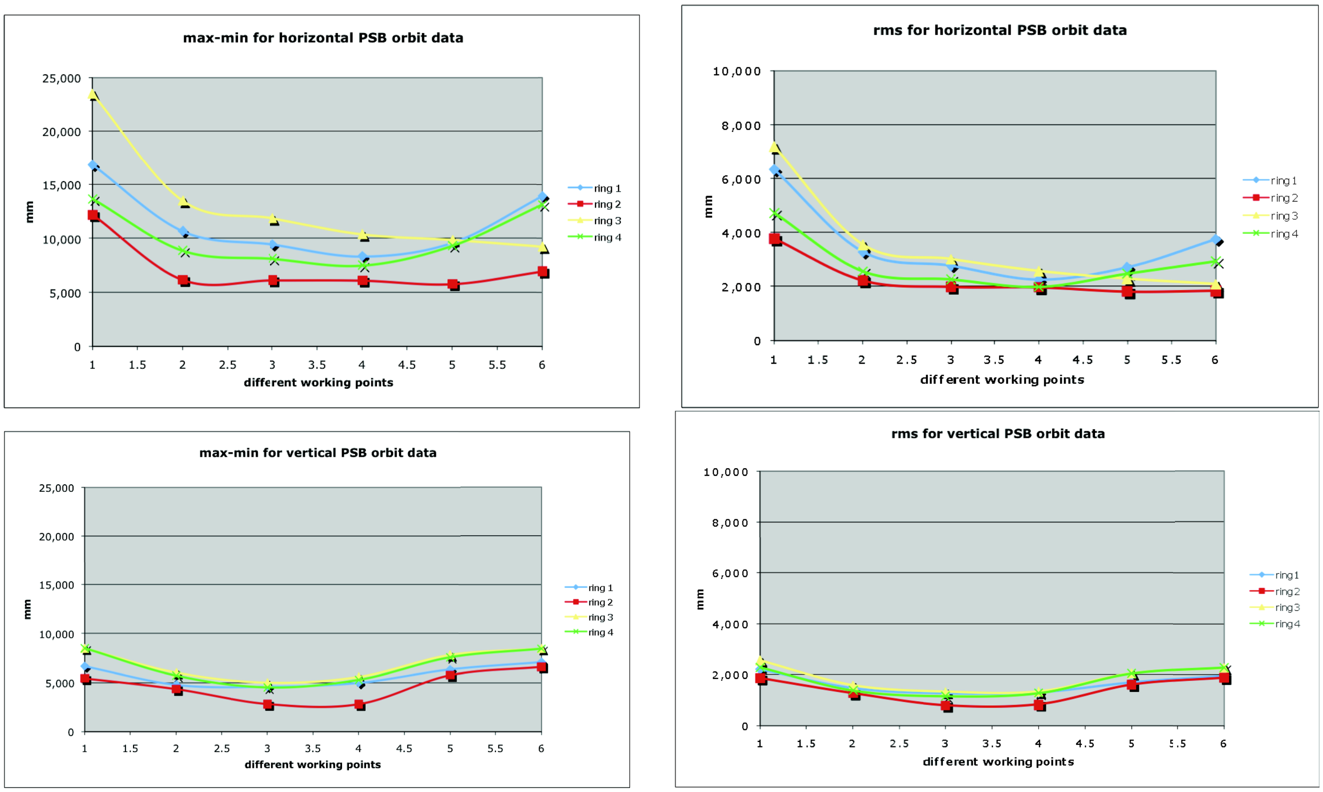

Figure 15: Peak-to-peak (left) and rms (right) orbit values (average over 10 measurements) in mm for different energies and working points (data for the horizontal plane is shown on top and for the vertical plane below). These measurements represent the situation after the first orbit correction campaign.

3.4 Second iteration of the PSB orbit correction with 2008 data

Even if it was evident from the beginning of the 2008 run that the achieved improvement in the vertical orbit had a direct positive impact on the machine performances (the highest beam currents could be easily injected and accelerated without requiring too much fine tuning), a rapid calculation for a possible second iteration of orbit correction was run using the new data. It was decided to go for a selection of the best QD correctors over all the measurement sets, and choose only the two best ones in both planes due to time constraints for the intervention. As could be expected, the two best correctors in the vertical plane would only need very small vertical displacements (within the tolerances of the surveyors), which confirmed that the first iteration had been successful and whatever further improvement could in fact only be marginal. On the contrary, in the horizontal plane the displacement and tilt of two QDs turned out to be potentially effective to improve both the horizontal rms and peak-to-peak orbits by a factor 1.5–2. The required displacements and tilt angles are summarized in Fig. 16 and Table 4. It was also proven that about the same orbit improvement could be achieved both relying on the raw or on the corrected data from the horizontal PUs[3].

[3]For the second orbit correction iteration we also had the radial alignment data of the PUs available.

Table 4: Summary of the requested QD magnet displacements to correct the PSB orbits (2nd iteration).

	Δ_h (calc.) [mm]	Δ_h (surv.) [mm]	Δ_{tilt} (calc.) [mrad]	Δ_{tilt} (surv.) [mrad]
QD5	+0.64	-0.82	+0.25	-0.25
QD12	+0.80	-0.50	-0.41	+0.41

Therefore it was decided to have a further attempt to correct the horizontal orbit and ask for another machine intervention to apply the newly calculated corrections. The displacements (horizontal and tilt) were carried out on April 30^{th} and the orbits were remeasured after the intervention. The final result was that the vertical orbits did not change with respect to the previous 2008 measurements (as we expected, because we had not requested any vertical movement of the QDEs), but the horizontal orbits were improved by the predicted factor of 1.5–2 (see fig. 17). Furthermore, the performance of Ring 3 was equalized to that of the other three rings.

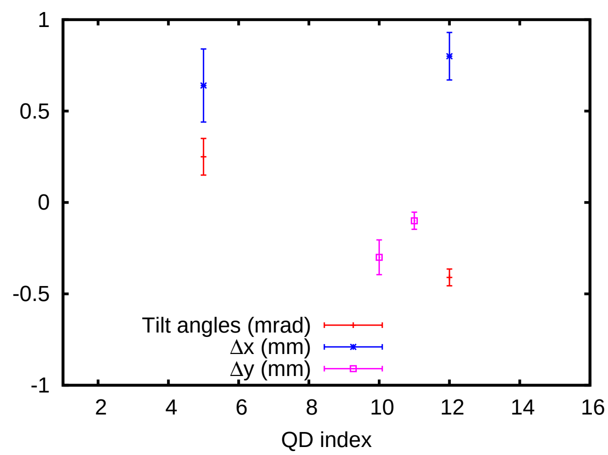

Figure 16: Corrections calculated using the 2 strongest correctors both for the horizontal and for the vertical correction, after the orbit measurements in April 2008.

4 Summary of the results and conclusions

An orbit correction has been carried out for the PS Booster in two iterations during the 2007/2008 machine shutdown and at the start of the 2008 run. New software has been developed to take into account the special layout of the Booster with four coupled rings with respect to the defocusing quadrupoles that have to be moved. Corrections were calculated for the horizontal, vertical and tilt displacements of these QD magnets.

Orbit measurements after the two iterations show that the horizontal and vertical PSB orbits could be improved by the respective factors predicted from the calculations. The peak-to-peak (rms) orbit variations decreased in average from about 14 (4) to 7 (2) mm for the horizontal plane and from about 14 (4) to 6 (1.5) mm for the vertical plane. Another important side effect of the orbit correction was that the performance of ring 3 could be recovered as its orbit had deteriorated with the years.

The orbit correction proved to be very beneficial for the 2008 machine operation and was also useful for the transverse emittance blow up through resonance excitation, since the orbit correction reduced the width of the integer resonance stop-band, making it possible to approach it more than ever before.

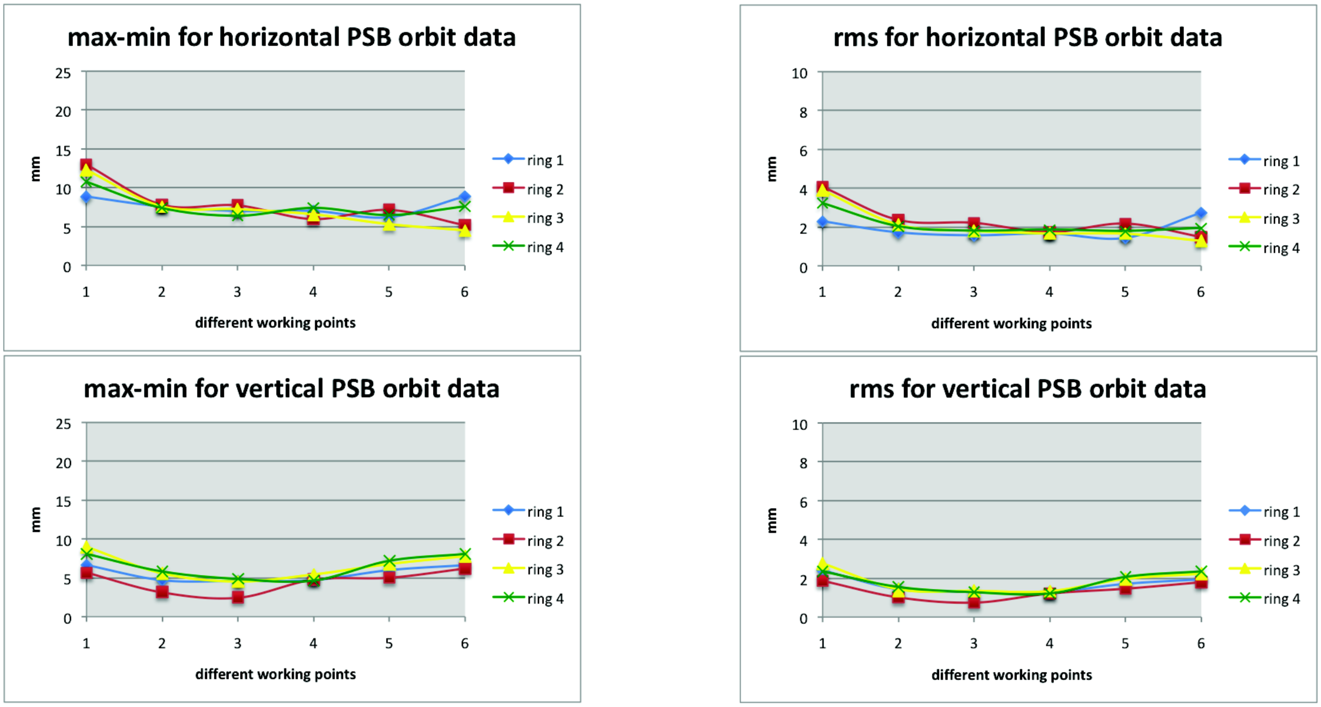

Figure 17: Peak-to-peak (left) and rms (right) orbit values (average over 10 measurements) in mm for different energies and working points (data for the horizontal plane is shown on top and for the vertical plane below). These measurements represent the situation after the 2 orbit correction campaigns.

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