HLS-based Closed Orbit Feed-back at LEP

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Abstract

Hydrostatic Levelling Systems (HLS) measure the vertical positions at different locations around the four experimental interaction point of LEP. In particular, the positions of the strong low-beta insertion quadrupoles are of special importance. These magnets are the major source of vertical orbit drifts due to their strength, the large vertical beta function and their support. This presentation will cover the experience with the HLS and the applications of the measurements. A feed-back system uses the measured positions to calculate an orbit correction and prevents large orbit variations.

1. INTRODUCTION

A stable closed orbit is essential for the successful operation of a storage ring. A well corrected closed orbit assures small vertical beam sizes and hence a high luminosity, low background in the experimental detectors and a high degree of spin polarisation. The vertical orbit of LEP has been found to be drifting with time during operation. This required frequent orbit corrections by the operation crew to avoid a loss of luminosity.

The distribution of corrector magnets used for the corrections indicated that low-beta quadrupoles (QS0) were likely to be the source of the drifts. These quadrupoles are vertically focusing and have a quadrupole strength ($k = -0.16\ \mathrm{m}^{-2}$) 10 times larger than other magnets in LEP to achieve the small beam size at the four experimental interaction points. Their strength and the large vertical beta function at this location make the closed orbit very sensitive to any vertical mechanical displacement. In addition, the mounting of the magnets makes it possible that they can actually move.

Potentiometer-based position sensors and differential pressure systems were installed to measure the movements of the magnets continuously. After a first analysis of the observed movements and their correlation to orbit drifts [1], more precise hydrostatic levelling systems (HLS) were installed and used for the analysis. This led to a feed-back system which uses the mechanical measurements for a correction of the vertical closed orbit.

2. LAYOUT OF THE HLS

The schematic layout of one of the experimental interaction points (IP) is shown in Fig. 1. The low-beta quadrupoles are mounted in a cantilever support structure extending into the experimental

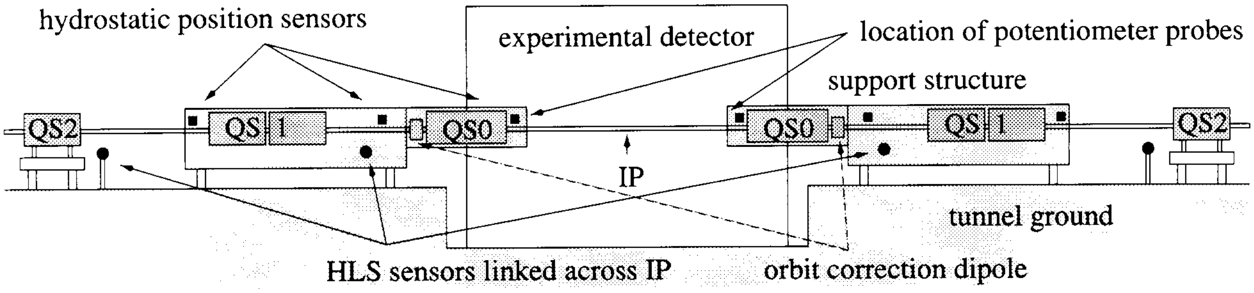

Figure 1: Schematic view of the low-beta insertion around one of the four experimental detectors. The QS0 are the superconducting low-beta quadrupole magnets. The layout of one IP (IP 2, housing the L3 detector) is slightly more complicated since the inner magnets (QS0, QS1) and the inner parts of the detector are mounted in a support tube (not shown).

detector. As the cantilever arm is about 5 m long and not supported on the inner side, the magnets can move with the structure. The Hydrostatic Levelling System used at LEP to measure these movements is a commercially available system [2]. The measurement vessels are installed at different locations on the support girder and the tunnel ground. The vessels are capacitance-based hydrostatic sensors with a measurement range of usually 5 mm. They are equipped with PT100 temperature sensors to compensate for variations in the density of the water with temperature. The individual vessels with their electronics are carefully calibrated. Polynomials of third or fourth order are applied to correct for nonlinearities. The measurement of the water level in the vessels reaches a resolution of the order of $0.2\,\mu$m over the measurement range.

The precision of the entire HLS is limited by thermally induced density differences of the water in the connecting tubes. The density gradient alters the hydrostatic pressure. The temperature is measured at some points of the circuit only. So all non-horizontal parts of the tubes introduce a measurement uncertainty Δz due to the unknown temperature difference ΔT (see Fig. 2). A vertical tube of height h with a difference in temperature of ΔT creates a water level difference Δz between points in the vessels A and B which are at the same height as (at $T = 20$°C)

$$\Delta z = 200\,\mu\mathrm{m} \cdot h[\mathrm{m}] \cdot \Delta T[^\circ\mathrm{C}]\,. \tag{1}$$

For $h = 10$ cm, one obtains already $\Delta z = 20\,\mu\mathrm{m}/^\circ\mathrm{C}$.

The HLS installation at LEP accounted for this error source and height variations were avoided where possible. The layout for the different interaction points is very similar. Two types of HLS installations are used (see Fig. 3).

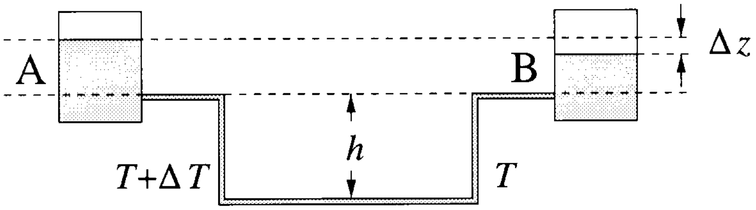

Figure 2: Measurement error Δz caused by temperature difference ΔT in the connecting circuit.

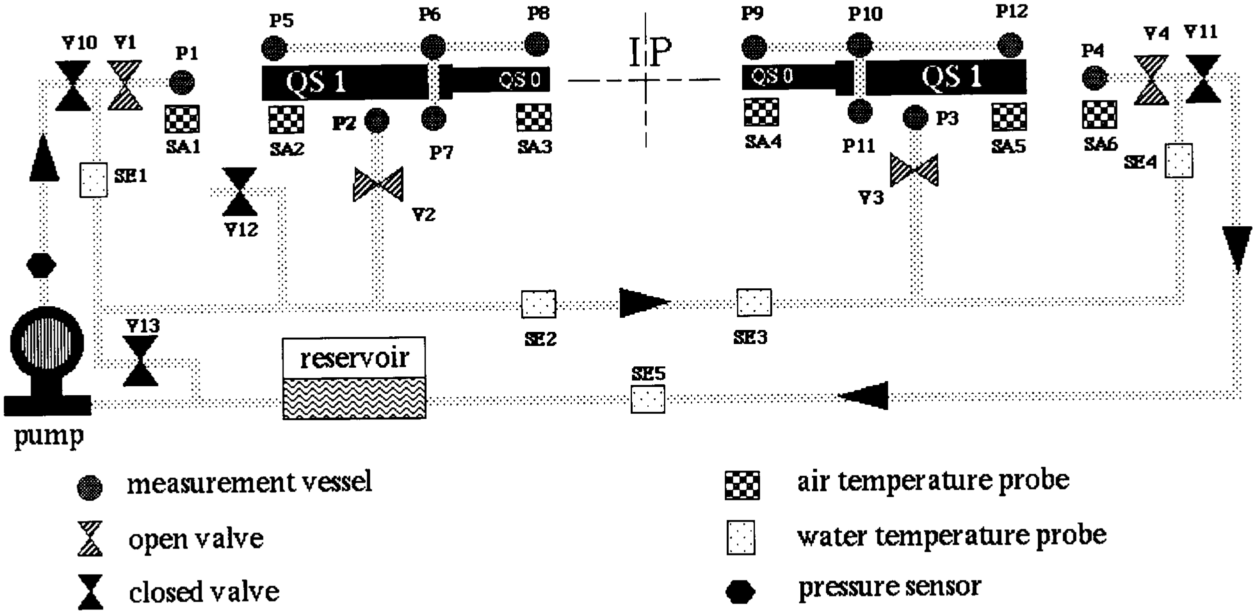

Figure 3: Schematic layout of the HLS installation at LEP.

- One system of four vessels (P5–P8 and P9–P12) connected by rigid horizontal tubes is installed on each support for the QS0 and the next closest magnets (QS1). The tubes are half filled with water with a fungicidal additive. Since the tubes are horizontal, local temperature differences do not introduce a measurement error.

- A different system of communicating vessels (P1–P4) is connecting the supports and the tunnel ground on both sides of a detector. It was not possible to install the tubes in a horizontal plane and the precision is limited by temperature effects. Valves in the connecting tubes can separate the vessels from the connecting tube network. Prior to a measurement, water from a large reservoir is circulated in the tubes until the water temperature is homogeneous. After stopping the water circulation, the valves are reopened. After a short waiting time, oscillations in the tubes are damped and measurements can be taken until the temperature differences become too important again. This type of system cannot be used for continuous measurements.

3. OBSERVED MOVEMENTS

The changes in the relative altitude between different points of the support structure which are fixed on the tunnel ground are small compared to movements of the part which supports the QS0 magnets. Fig. 4 shows a typical vertical movement of a low-beta quadrupole. The time pattern of the movement is very similar for all QS0 magnets. The movement is correlated with temperature variations of the support. The magnets start moving downwards with rising temperature. After a few hours, the magnet reaches an equilibrium position. The temperature changes are mainly caused by the operation cycle of LEP. The temperature starts rising after LEP has been ramped to higher energy from the higher current heating up the current feed-throughs which traverse the

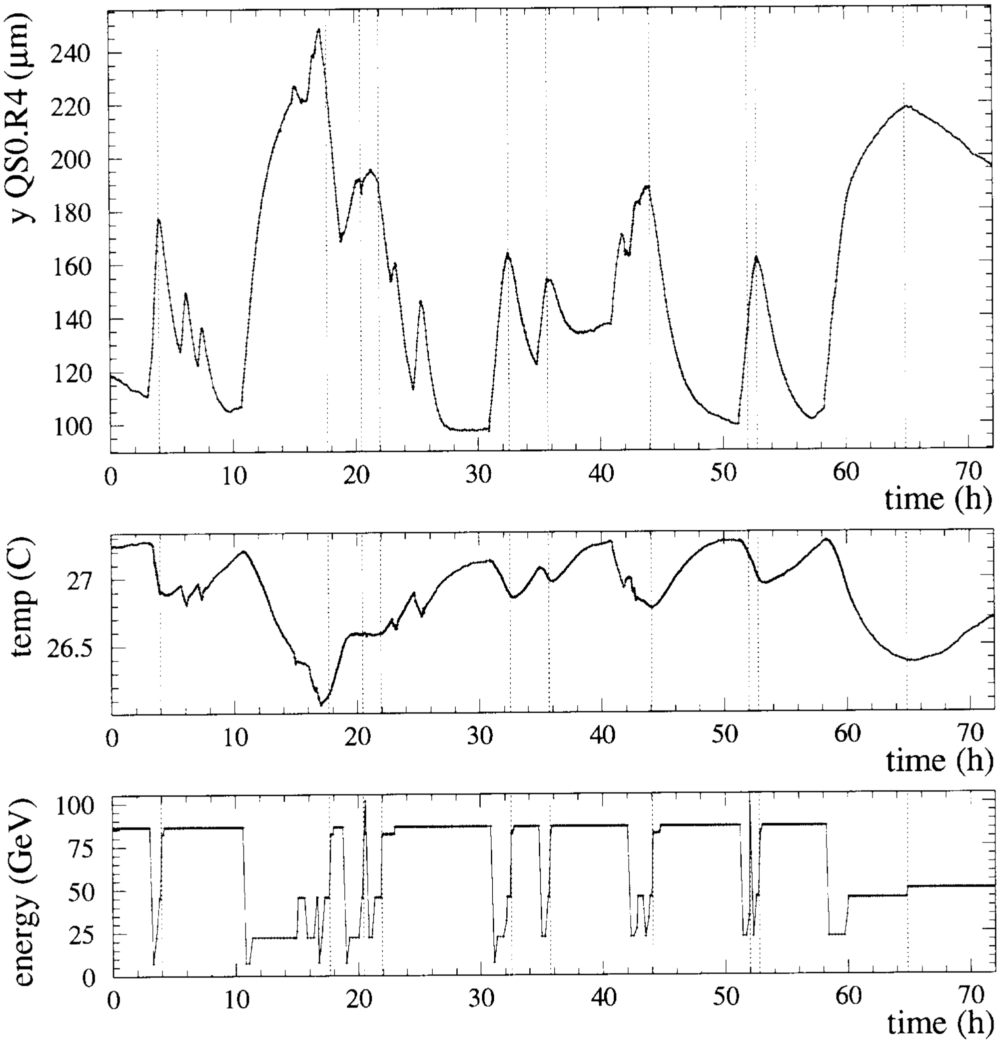

Figure 4: Movement of a low-beta quadrupole (QS0.R4, height difference between P9 and P11) for a period of three days (top), the temperature measured at vessel P10 (middle) and LEP beam energy (bottom). The vertical dashed lines indicate the end of the ramp to collision energy.

support. The time constant of the thermally driven movements is of the order of a few hours and a short refilling time keeps the amplitude of the movements smaller.

4. ORBIT ANALYSIS

The vertical orbit drifts were studied in detail to evaluate the contribution from the movements of the low-beta QS0 magnets. A movement Δy_Q of a quadrupole located at s_0 results in an angular kick $\Delta y'(s_0) = kl\Delta y_Q$. The closed orbit at any location s changes by $\Delta y(s)$ according to

$$\Delta y(s) = \frac{\sqrt{\beta(s)\beta(s_0)}\cos\left(|\mu(s) - \mu(s_0)| - \pi Q\right)}{2\,\sin(\pi Q)} \cdot \Delta y'(s_0). \qquad (2)$$

β, μ and Q are the betatron function, phase advance and tune, respectively. As both k and $\beta(s_0)$ are large for the QS0, the movement Δy_Q of a single QS0 causes a RMS change of the vertical closed orbit $\sigma_{\Delta y}$ 40 times larger than the mechanical movement. This enhancement factor is only 2 for a regular lattice quadrupole.

The beam optics configuration around the interaction point has yet an attenuating effect for the orbit movements. The QS0 pairs at the different interaction points tend to move in a similar way. The beta function is symmetric around the IP and the vertical betatron phase advance between the two QS0 magnets is nearly π. Eq. 2 shows that the effect on the orbit nearly cancels when both magnets move by the same amount in a common direction. A parallel movement of $\Delta y_Q = 10\mu$m for both QS0s creates a RMS orbit change of only $\sigma_{\Delta y} = 7\ \mu$m, nearly invisible in the noise of the orbit measurement. Eq. 2 also implies that the relative movement of the QS0 pair can be corrected with only one orbit corrector magnet (see Fig. 1) at each IP.

Closed orbits logged during physics data taking were used to calculate the *'bare orbit'*[1] from the orbit measurements y_{meas} by

$$y_{bare} = y_{meas} - \frac{\sqrt{\beta_{bpm}}}{2\sin(\pi Q)} \sum_{cor} \sqrt{\beta_{cor}} \cos\Big(|\mu_{cor} - \mu_{bpm}| - \pi Q\Big) \cdot \theta_{cor}\,. \tag{3}$$

The sum runs over all vertical correctors, θ_{cor} is the kick angle for the corrector, β_{cor} and μ_{cor} are beta function and phase at the corrector, β_{bpm} and μ_{bpm} at the beam position monitors, respectively. This procedure removes the effects of all corrector magnets. The difference of two bare orbits shows the orbit variations from other sources than corrector magnets and allows to localise the source of the changes.

The analysis was performed on a fill basis with a reference which was the first bare orbit after stable conditions for physics data taking have been declared. The bare orbit is calculated for all subsequent orbits in the fill, and the RMS of the difference $\sigma_{\Delta y}$ from the reference is computed. This is the movement of the orbit if no corrections had been made.

The difference orbit was corrected with only one orbit corrector magnet next to a QS0 per IP with the COCU package [3] using the MICADO algorithm [4]. This correction is very effective and takes away about 70–90% of the orbit drifts (Fig. 5). While the RMS orbit drifts in a fill reached often several millimetre, the residual after correction was usually below 300 μm. This proves that the low-beta magnets are indeed the dominant source of drifts.

5. CORRELATION ANALYSIS AND FEED-BACK

The calculated orbit correction kick $\Delta y'$ at each IP should be proportional to the differential movements of a QS0 pair. This correlation was studied for the different interaction points. No direct HLS connection exists between the two QS0 magnets at an IP. The relative height variations have to be calculated either including the less precise connecting HLS between both sides of the IP or under the assumption that certain reference points are stable. As a cross-check, this was compared to the height variations measured by position-sensitive potentiometer probes [5, 6] which measure the position of the QS0 relative to parts of the experimental detectors. An example for the movements during a day is shown in Fig. 6.

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[1] The closed orbit if all corrector magnets were switched off.

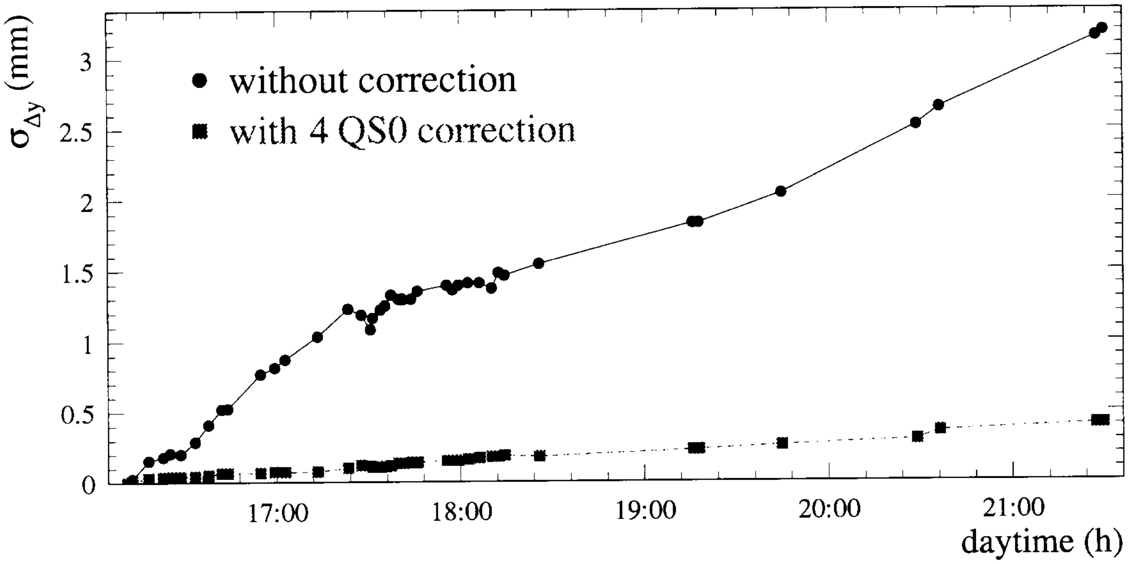


Figure 5: RMS of the difference of bare orbits relative to the first physics orbit before and after orbit correction with only 4 QS0 corrector magnets during a fill. A typical vertical orbit during data taking has a residual RMS of about 500 μm.

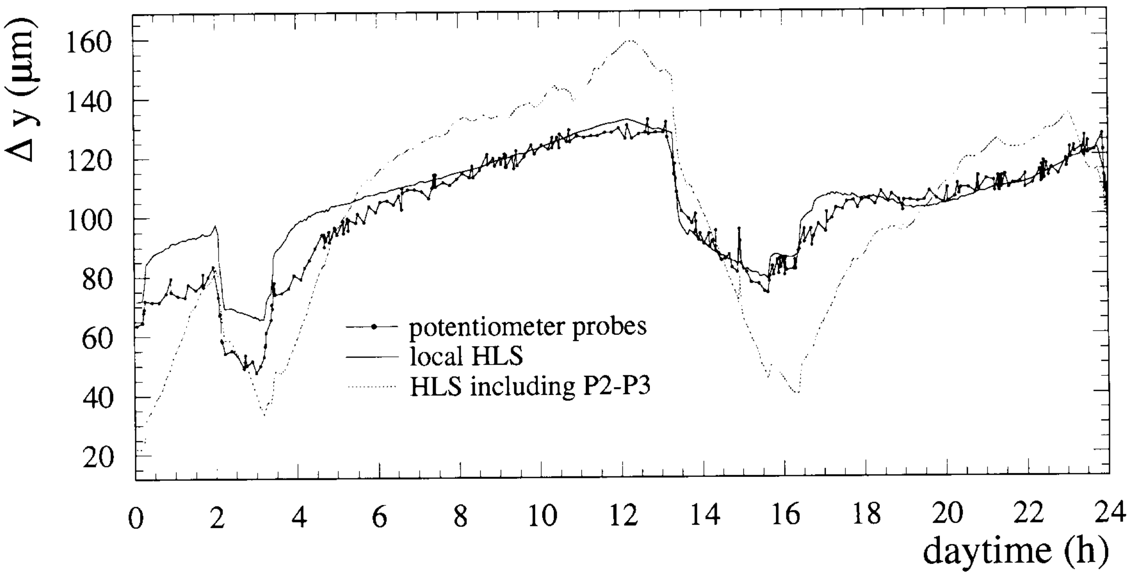


Figure 6: Comparison of the HLS and the potentiometer-based system for the differential movements of the QS0 quadrupole magnet pair at IP 4 during one day.

The measurements by the position-sensitive potentiometers is more noisy than the HLS data. The correlation between potentiometer and HLS data is not good when the difference $y_{\rm P2} - y_{\rm P3}$ between vessels P2 and P3 of the connecting HLS is included. This indicates that temperature variations in the vertical parts introduce a significant error. The precision of this system is limited to $\sim 10 - 30\,\mu$m.

Assuming that the support structures on the tunnel ground on both sides of the IP do not move relative to each other, the difference $y_{\rm P2} - y_{\rm P3}$ can be neglected. Only HLS vessels with horizontal connecting tubes are used which are not sensitive to the temperature variations. This results in a much better correlation. The remaining small deviations are due to the fact that the reference points for the HLS and potentiometers are not identical.

The correlation with the orbit correction kick was also significantly better in this case. For further analysis, only the HLS with horizontal connecting tubes on the supports were used. The best representation of the differential movement of a QS0 pair had to be found empirically. The differential movements of the vessels on the QS0 (P8 and P9) were studied relative to various reference points among the vessels P5 to P7 and P10 to P12, respectively. This movement was compared to the calculated correction kick $\Delta y'$. Fig. 7 shows an example.

The best correlation was usually obtained taking the vessels in the centre of the support (P6, P7 and P10, P11) as a reference. The proportionality factor between mechanical movement and correction kick was found nearly identical for different fills. The precision of the HLS could be estimated from the residual deviation from a straight line fit to be about 1–2 μm. Only at IP 2, where the the magnets are in a 32 m long support tube, the correlation was sometimes worse and the proportionality factor has a larger spread. This is clear from the fact that the reference points are not on the tunnel ground and can move with the support.

A software feed-back was developed which reads the mechanical position of the magnets and calculates the necessary correction kick from the differential movement and the proportionality factor. It operates during physics data taking. Whenever the correction kick exceeds a certain threshold, it is sent to the orbit corrector. The feed-back started running very successfully at the end of the 1996 operation period of LEP and is now used routinely. An example is given in Fig. 8. The feed-back was compensating well for the movements of the orbit and significantly reduced the number of orbit corrections that the operator had to make.

6. CORRECTOR RELOAD

Another application of the HLS measurements is the reload of a previously stored set of corrector excitations of an orbit which gave high luminosity and good background conditions. The different positions of the QS0 magnets at storage and reload time can lead to a large orbit kick and the reload bears a risk of beam loss. The HLS measurements allow to compare the position of the QS0 magnets at storage and reload time. The necessary orbit correction kick is computed and incorporated in the corrector excitation.

An experiment was performed where previously stored corrector setting of the preceding days were restored. Fig. 9 shows an example of the vertical closed orbit readings after reload. The orbit that would have resulted from the same corrector excitation without taking into account the

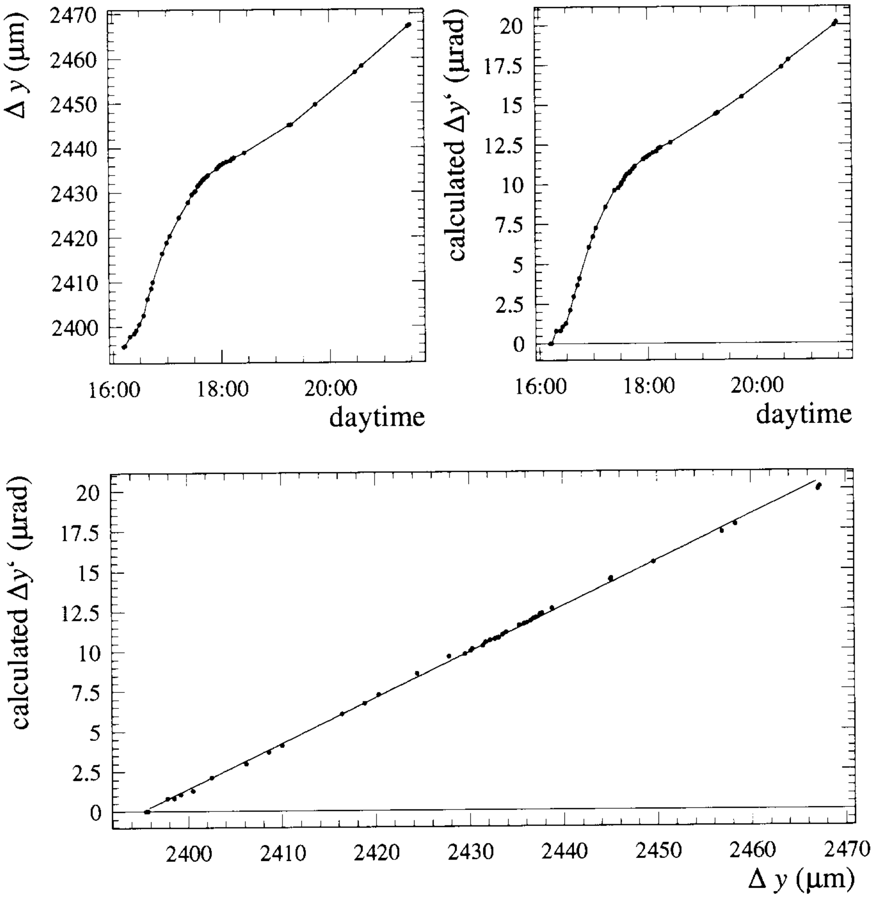


Figure 7: Example of the differential mechanical movement of a QS0 pair (top left), the calculated orbit correction kick (top right) and their correlation (bottom) at IP 4 during a fill with large quadrupole movements.

QS0 correction was simulated (Fig. 10). All orbits after reload showed reasonably small vertical excursions significantly lower than the result without incorporation of the QS0 position difference. This procedure reduces the risk of accidental beam loss when an old set of corrector settings is reloaded.

7. CONCLUSIONS

The superconducting low-beta quadrupoles are the major source of vertical orbit drifts at LEP. The movements originate in temperature variations of the cantilever support structure due to the LEP operation cycle.

The Hydrostatic Levelling Systems installed on magnets and supports measure the vertical movements of these magnets. In particular, the HLS with horizontal connecting tubes is very precise and reaches a precision of $\sim 1-2\ \mu$m. A HLS connecting both sides of an IP with vertical parts in the connecting tubes is limited by temperature effects and has a precision of $\sim 10-30\ \mu$m.

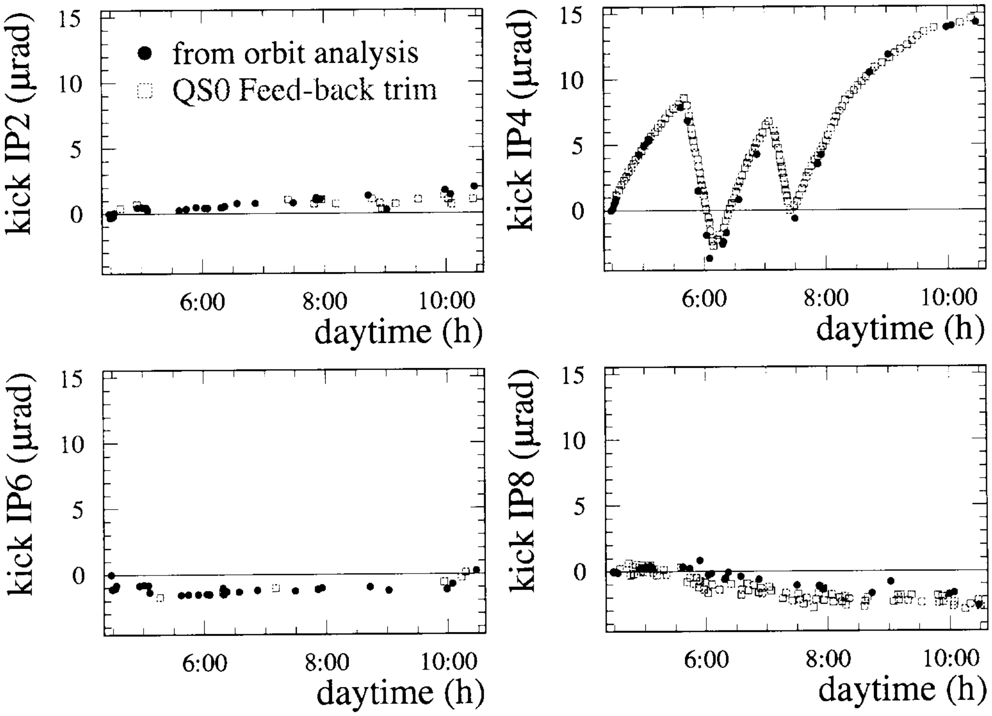
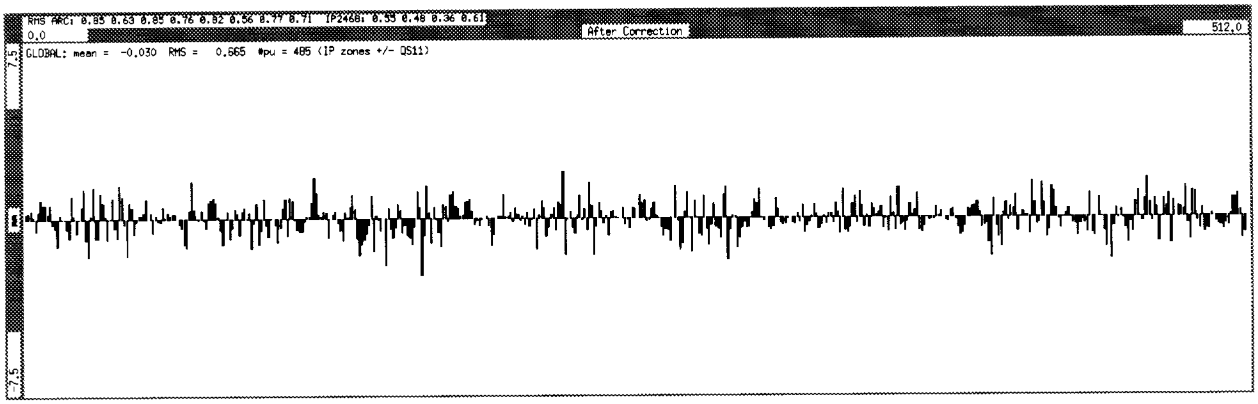


Figure 8: Example of the feed-back during one fill. The correction kicks sent by the feed-back are compared to the corrections calculated from the off-line orbit analysis. The potentiometer system used at that time at IP 8 is less precise than the HLS but still capable of tracking the movements.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RMS ARC: 0.85 0.63 0.85 0.76 0.82 0.56 0.77 0.71  IP2468: 0.55 0.48 0.36 0.61
GLOBAL: mean =  -0.030  RMS =   0.665  #pu = 485 (IP zones +/- QS11)
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Figure 9: BPM readings of the vertical closed orbit after reload of a set of corrector excitations including QS0 correction. The RMS is 0.67 mm.

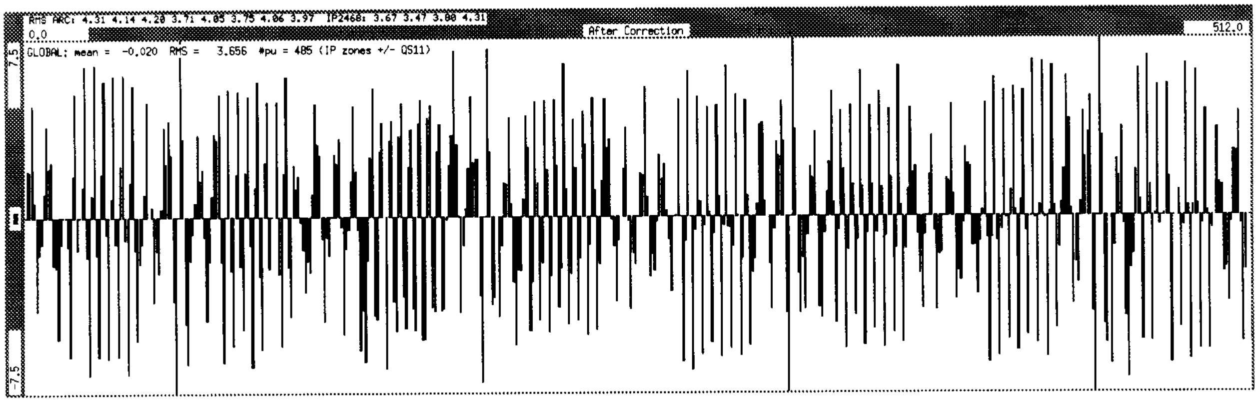

Figure 10: Simulated BPM readings of the vertical closed orbit after reload of a set of corrector excitations as in Fig. 9 but without QS0 correction. The RMS would be 3.66 mm in this example.

A software feed-back system based on the HLS measurements has been implemented. It calculates the necessary correction kick from the differential movements of the low-beta quadrupole pairs and acts on the orbit correctors. It successfully prevents large orbit variations during the physics data taking. Including the correction for QS0 movements in the reload of previously stored corrector settings results in smaller excursions of the orbit and avoids the risk of beam loss.

8. REFERENCES

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