Beam position determination at IP4 using LEP BOM data and QS0 position measurements

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Abstract

A comparison is presented of the beam spot position at IP4, as measured by the LEP wide-band BOM system and the ALEPH vertex detector, using data collected between 13 August and 11 September 1995. Discrepancies between the two methods are correlated to the measured movements of the low beta quadrupoles (QS0) located close to the interaction point. An estimate of the IP4 beam spot position obtained from the the LEP BOM data and the QS0 position measurements is shown to have a resolution of 7 μm in the vertical plane and 40 μm in the horizontal plane.

Foreword

The work described in this note has been carried out in the framework of the LEP2 workshop and presented and discussed in several meetings of the “Interaction Region” (IR) sub-group of the “Physics-Machine Interface” working group (WG4). This status report presents the current results rather than final conclusions; it is meant to be primarily a working document for the IR sub-group, summarizing the present knowledge on the subject. As decided by the IR sub-group, it will be used, together with similar notes from the other LEP experiments and from the SL division, as a supporting document for the written contribution to the final LEP2 workshop report.

1 Overview

One of the goals of the IR sub-group is to assess the possibility of using the BOM data to provide an accurate and reliable estimate of the beam spot position at the LEP interaction points during LEP2 operation. The study described in this document addresses the question of the precision of such an estimate in a real situation where the optics of the machine and the BOM calibration is not perfect. However, the uncertainty arising from the limited knowledge that one could have at LEP2 on the absolute position of the beam pickups relative to the experiment is not accounted for in this study.

Measurements of the IP beam position using LEP beam pickup electrodes has been pioneered by ALEPH for several years [1, 2, 3]. However, the need for a precision measurement based on BOM data was absent during LEP1, given that the physics requirements could be fully met with the use of vertex detectors. Therefore, although some of the systematic problems associated with the BOM measurements had been encountered a long time ago [4], it was not worth spending the effort to try to understand them.
At LEP2, the capability of the vertex detector to measure the beam spot position is reduced, due to the much lower rate of tracks emerging from the luminous region, and alternative ways of determining the beam position will play a bigger role. A Monte Carlo study [5] performed in ALEPH to assess the physics requirements on the beam position accuracy at LEP2, shows that an absolute precision of 20 (100) \( \mu \text{m} \) in the vertical (horizontal) plane would be desirable and sufficient. This conclusion is confirmed and supported by independent studies from other LEP experiments. Such precision can of course be achieved using tracks in the vertex detectors, but only at the expense of longer “integration” times, during which the beam spot could move. The advantage of the BOM based measurements is the quasi event-by-event frequency coupled with a very good intrinsic accuracy.

A study [6] performed on the BOM data collected by ALEPH in 1994 showed evidence for a systematic discrepancy of the BOM beam position interpolated at the IP and the vertex detector measurements taken as a reference. This discrepancy showed as an apparent vertical drift of the BOM beam position (typically of order 40 \( \mu \text{m} \)) during the first few hours of many different fills. It was postulated that these drifts were caused by motions of the QS0 quadrupoles. A coherent movement of these magnets can indeed create a closed bump around the IP which would be undetectable by the beam pickups located outside the bump.

During the 1994–1995 winter shutdown the QS0 quadrupoles were instrumented with position sensors to monitor their position relative to the ALEPH experiment. This setup and its performance are described in Sect. 2 below. The QS0 magnets are indeed observed to have the expected motions.

The BOM data used for the present study is described in Sect. 3 and the results are presented in Sect. 5. Using the vertex detector measurements as a reference, the LEP BOM extrapolations at IP4 are shown to give a better estimate of the beam position than an average time-independent assumption. The data also clearly show that the difference between the LEP BOM and the VDET measurements is correlated with the QS0 position measurements, at least in the vertical plane. This confirms last year’s working hypothesis about the drifts.

The extrapolated beam position is then corrected for the QS0 movements that are measured directly using the position sensors. The resulting determination of the beam spot position at the IP is shown to be in agreement with the ALEPH vertex detector (VDET) determination using tracks from \( Z^0 \) decays. The resolution of the measurements based on BOM and QS0 data is measured to be 7 \( \mu \text{m} \) in the vertical plane and 40 \( \mu \text{m} \) in the horizontal plane.

## 2 QS0 position monitors

### 2.1 Measuring devices

The position sensors installed in ALEPH to monitor the QS0 positions are the same as the ones used in DELPHI to monitor the position of their STIC luminometer. These devices have been manufactured by Techni Measure (UK) with the special requirement that no magnetic material should be used. Each device is made of a 32 mm long body traversed
by a metal pin which is spring loaded and mechanically connected to the variable voltage point of a 10 kΩ potentiometer integrated in the body. The end of the pin is arranged to touch a reference surface; any displacement of that surface with respect to the body of the device (along a direction parallel to the pin) will result in a longitudinal displacement of the pin inside the body, and therefore in a change of the resistance of the potentiometer. The total electrical stroke is approximately 11 mm, resulting in a change of order 1 Ω per μm displacement. The linearity of the response is at the 1% level according to the manufacturer’s specifications.

2.2 Installation

The probes have been installed on a horizontal bar rigidly fixed to the end of each QS0 girder, at approximately 38 cm from the end of the QS0 girder. These bars are square section aluminium tubes, of outer dimension 40 × 40 mm with 3 mm wall thickness. Their purpose is to transfer the position of the quadrupoles close to the LCAL detector (one of the ALEPH luminosity calorimeters) where the reference surfaces probed by the pins are attached. The assumption is that LCAL will not move with respect to the central tracking system, in particular the vertex detector. On each side, there are 3 reference surfaces, corresponding to orthogonal planes perpendicular and parallel to the beam line and the vertical direction. The entire setup is independent of the ALEPH end-caps and can be mechanically adjusted in its final operating configuration while the end-caps are open.

Only 6 probes where available at the time of the installation. These were distributed in the following way:

- 3 probes on side A, measuring all 3 coordinates;
- 1 additional probe on side A, providing a second (independent) measurement of the vertical coordinate;
- 2 probes on side B, measuring the 2 coordinates transverse to the beam line.

2.3 Readout

The readout of each probe is performed according to a circuit similar to the one sketched in Fig. 1. The 12 V power supplies and the 10 kΩ potentiometers allowing for the adjustment

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position sensor  12 V
10 kΩ            zero-adjustment screw
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Figure 1: Readout scheme for each individual QS0 position sensor.

of the 0 V output point have all been integrated in a single customized NIM module in the ALEPH BOM rack, in the C3 barrack. This module has been designed to handle a total
of 8 channels, allowing for a future upgrade of the system with 4 probes on each side. The “zero-adjustment” potentiometer allows a fixed voltage to be subtracted from the raw output of the position sensor, leading to an increased sensitivity around the operating point of the device. The resulting output voltage is digitized by a 10 bit ADC accepting a voltage in the range 0-1 V. One bit corresponds therefore to an approximate variation of the sensor resistance of approximately 1 Ω. The ADC card is located in the G64 crate labeled “ITC 87” in the C3 barrack, and the voltages arrive on connector SV2 at the back of the crate.

The readout of the ADC is performed by the ALEPH slow control system and the data written periodically as “slow control records” with the ALEPH raw data from beam interaction events.

2.4 Calibration

A calibration of each individual channel was performed on the 4th of April 1995, before the closing of the detector for the 1995 data taking period, using calibrated shims of thickness ranging from 50 to 500 μm. These shims were placed in turn between the references plates and the end of the pins. Figure 2 shows the voltage recorded by the slow control system as a function of the shim thickness. The response has been found to be linear for all channels and two calibration constants per channel (offset and slope) have been extracted from a straight line fit.

2.5 Online monitoring and general behaviour

In addition to being logged periodically with the events, the QS0 positions are also monitored online, by the means of time-charts available on a screen in the ALEPH control room.

Figure 3 shows the time dependence of these positions as recorded during an entire week in September 1995. A clear time structure is observed in all directions and on both sides. These movements are correlated with the machine activity; the quadrupoles typically move up as soon as their currents go to ~ 500 A (20 GeV setting) and then down when the currents are ramped to ~ 1000 A again (45 GeV setting). Due to the rather slow time constant associated to these movements (which suggests an explanation in terms of thermal effects), the magnets are usually still dropping by the time “stable beams” are declared. A similar behaviour is observed in the longitudinal direction (z coordinate). However, the position in the horizontal direction transverse to the beam (x coordinate), although also affected by the machine activity, does not seem to be subject to such long time constants.

As can be seen from Fig. 4, the amplitude of the vertical drop in the course of a fill is typically of order 30 μm on the left side (side A) and 60 μm on the right side (side B). Figure 5 shows an example of “anomalous” behaviour with movements not correlated with the current in the magnets.

Figure 6 shows the time-dependence of the average and the difference of the two independent measurements of the vertical position of the QS0 magnet on side A (left side). If the system were perfect, the difference would be constant with time. This is not the case and the variations of the difference (which stay within ±5–10 μm) seem to be a
reflexion of the variations in the position itself, pointing towards a small imperfection in the calibration, which has not been addressed so far.

3 Data sample used for this study

This study is based on data collected during fills in the range 2281–2975 between the 13th of August and the 11th of September 1995:

"on peak" fills: 2889, 2901, 2902, 2913, 2931, 2932, 2952, 2958, 2962 and 2973;

"off peak" fills: 2881, 2883, 2894, 2899, 2904, 2906, 2907, 2908, 2933, 2934, 2936, 2938, 2939, 2943, 2944, 2945, 2948, 2949, 2951, 2953, 2955, 2956, 2959, 2965, 2969, 2970 and 2975.

From the data collected by the ALEPH main DAQ system during these fills, a total of 2540 measurements of the beam spot position have been performed by the standard ALEPH reconstruction program using groups of approximately 400 selected tracks with vertex detector hits in chunks of consecutive events (VDET chunks). The average duration of a VDET chunk was 3.7 (9.0) minutes in an on-peak (off-peak) fill. As shown on Fig. 7 the average error on a VDET measurement is 10.5 \( \mu \text{m} \) vertically and 16.7 \( \mu \text{m} \) horizontally, whereas the distribution of the VDET measurements themselves has a RMS of 29 (75) \( \mu \text{m} \) in the vertical (horizontal) plane. After quadratic subtraction of the average error, this width becomes 27 (74) \( \mu \text{m} \) and constitute a measure of the stability of the beam spot during the period under study.

The QS0 positions were logged every two minutes. For each VDET chunk, all QS0 measurements recorded between the first and the last hadronic event in the chunk have been averaged. On side A, the comparison between the two independent measurements of the vertical coordinate of the QS0 can give an idea of the spread (\( \sim \) systematic error) associated to the QS0 position measurement in each chunk; as shown on Fig. 8 the RMS spread is 2.1 \( \mu \text{m} \) only.

The beam spot positions using data from the LEP beam pickups located near the QS0 and QS4 quadrupoles (wide-band BOM system) have been calculated by the TURBOIP program [7]. The orbit corrections applied by the dipole magnets between QS0 and QS4, as well as the bunch train bumps applied by the electrostatic separators, are taken into account in the calculation. The \( x-y \) coupling introduced by the magnetic field of the ALEPH coil is also accounted for. Each TURBOIP calculation consists of 4 independent estimates of the beam spot position, both in the vertical and the horizontal plane: the estimate using the electron data from the right side of the IP, the estimate using the positron data from the right side of the IP, and the corresponding estimates using the data from the left side of the IP. These estimates were available on average every 2 minutes, except for fills 2895 and 2948. They have been processed in the following way:

- for each VDET chunk, the average of all the measurements taken between the first and the last hadronic event of the chunk has been calculated; if no TURBOIP measurement has been done within this time interval, then the measurement closest in time is used if the time difference is less than 1 minute (this margin corresponds to a possible time difference between the ALEPH and LEP clocks);
• the data from fill 2938 has been rejected because the LEP BOM data showed obvious inconsistencies;

• the electron and positron beam positions at the IP have been averaged.

After the above treatment, a total of 2384 VDET chunks remained with valid LEP BOM data.

4 Notations

In this section, we define notations that will be useful for the rest of this document.

• Constants:
  \( \sigma_x = 10.5 \, \mu m = \) mean error on the VDET measurement of the vertical position of the beam spot at IP4 (see Fig. 7)
  \( \sigma_z = 16.7 \, \mu m = \) mean error on the VDET measurement of the horizontal position of the beam spot at IP4 (see Fig. 7)
  \( \sigma_q = 2.1 \, \mu m = \) RMS of the distribution shown in Fig. 8, interpreted as the error on any of the QS0 position sensor measurement

• VDET measurements:
  \( y^{VDET} = \) VDET measurement of the vertical beam position at IP4
  \( x^{VDET} = \) VDET measurement of the horizontal beam position at IP4

• BOM and QS0 measurements, averaged over VDET chunks as described in Sect. 3:
  \( y^BOM_L = \) BOM measurement of the vertical beam position at IP4 based on the data from the pickups on the left side of IP4
  \( y^BOM_R = \) BOM measurement of the vertical beam position at IP4 based on the data from the pickups on the right side of IP4
  \( y^{BOM} = \frac{1}{2}(y^BOM_L + y^BOM_R) \)
  \( y^{QS0} = \) measurement of the vertical position of the QS0 magnet on the left side of IP4
  \( y^S = \) measurement of the vertical position of the QS0 magnet on the right side of IP4
  \( y^{QS0} = \frac{1}{2}(y^{QS0}_L + y^{QS0}_R) \)
  \( y^{BQ}(\alpha) = y^{BOM} + \alpha y^{QS0} \)
  \( y^{BQ}(\alpha) = y^{BQ} + \alpha y^{QS0} \)
  \( y^{BQ}(\alpha) = \frac{1}{2}(y^{BQ}_L(\alpha) + y^{BQ}_R(\alpha)) = y^{BOM} + \alpha y^{QS0} \)
  \( \ldots \) and similarly for \( x^{BOM}, x^{BOM}, x^{BOM}, x^{QS0}, x^{QS0}, x^{QS0}, x^{BQ}(\alpha), x^{BQ}(\alpha) \) and \( x^{BQ}(\alpha) \), where \( \alpha \) is a real number (note that \( y^{BQ}_L(0) = y^{BOM}_L \), for example).

5 Results of the study

5.1 Correlation between VDET and BOM measurements

The left-hand side plots of Fig. 11 show the distributions of \( y^{VDET} - y^{BOM} \) and \( x^{VDET} - x^{BOM} \). The RMS of these distributions are 18 \( \mu m \) and 45 \( \mu m \) respectively, showing a clear improvement compared to the RMS of the VDET measurements alone (see Fig. 7), and
indicating that the BOM measurement is a better estimate of the beam position than a constant assumption. After subtraction (in quadrature) of the average VDET error, these RMS become 14 and 42 μm respectively and quantify the resolutions of the BOM measurements.

5.2 Correlation between VDET–BOM and QS0 measurements

Figure 9 shows that the difference \( y^{VDET} - y^{BOM}_L \) (\( y^{VDET} - y^{BOM}_R \)) is clearly correlated with \( y^{QS0}_L \) (\( y^{QS0}_R \)). Assuming a linear relationship between these two quantities, the slope is found to be 1.46 (0.83) for the left (right) side. If an average between the two sides is used both for the BOM extrapolation and for the QS0 measurements, the slope is \( \alpha = 1.06 \). One can therefore improve the BOM estimate of the vertical beam spot position, \( y^{BOM} \), by adding to it \( \alpha \) times the measured QS0 position:

\[
y^{BOM} \rightarrow y^{BQ}(\alpha) = y^{BOM} + \alpha y^{QS0}
\]

where \( \alpha \) will be called the "QS0 correction factor". The expected value for \( \alpha \) is 1.4 [8], i.e. vertical movements of the quadrupoles are amplified by a factor 1.4 at the IP. The upper right-hand plot of Fig. 11 shows the distribution of \( y^{VDET} - y^{BQ}(\alpha) \), with \( \alpha = 1.06 \). Its RMS of 12.5 μm is significantly lower than the RMS one would obtain with no QS0 correction, namely 18 μm. After quadratic subtraction of the vertical VDET error, one gets an error of 7 μm on \( y^{BQ}(1.06) \).

In the horizontal plane, the correlation between \( x^{VDET} - x^{BOM} \) and \( x^{QS0} \) is less clear (see Fig. 10); the fitted slopes have opposite signs on the left and right sides, with an average of \(-0.81\). As shown on the lower plots of Fig. 11, the RMS of \( y^{VDET} - x^{BQ}(-0.81) \) is practically equal to the RMS of \( x^{VDET} - x^{BQ}(0) \), showing that no significant improvement can be achieved with a QS0 correction in the horizontal plane.

5.3 Correlation between the left-right differences of BOM and QS0 measurements

An alternative approach, illustrated in the lower right-hand sides plots of Figs 9 and 10, is to apply a QS0 correction such as to optimize the agreement between the left and right BOM+QS0 measurements, rather than optimizing the agreement between the VDET measurements and the BOM+QS0 measurements. Ideally, the QS0 correction factor is expected to be the same as before. A fitted slope of 0.78 is obtained in the vertical plane, to be compared with the previous result of 1.06. As before, things don't look very convincing in the horizontal plane (no obvious correlation between \( x^{BOM}_L - x^{BOM}_R \) and \( x^{QS0}_R - x^{QS0}_L \)).

5.4 Study of the QS0 corrected estimates of the BOM beam spot position as function of the QS0 correction factor

The first plot of Fig. 12 shows the RMS of the quantities \( y^{VDET} - y^{BQ}_L(\alpha) \), \( y^{VDET} - y^{BQ}_R(\alpha) \), \( y^{VDET} - y^{BQ}(\alpha) \), and \( y^{BQ}_L(\alpha) - y^{BQ}_L(\alpha) \) as a function of \( \alpha \). Also shown are two reference levels given by \( \sigma_y \) and the RMS of \( y^{VDET} \). Any value of \( \alpha \) for which the curve is below RMS\((y^{VDET})\) improves the beam spot position estimate. The constant \( \sigma_y \) represents the
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<td>Constant assumption</td>
<td>27 μm</td>
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<td>BOM measurement</td>
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<td>BOM measurement corrected for QS0 movements</td>
<td>7 μm</td>
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Table 1: Summary valid for the period 13/08/95–11/09/95

smallest RMS that one could imagine to achieve in this context. All 4 curves are ideally expected to have their minimum at the same value of the QS0 correction factor.

The second plot of Fig. 12 shows the error on the BOM+QS0 estimate of the vertical beam spot position extracted from each of the above quantities and normalized to a single side. In this plot, all 4 curves are ideally expected to have the same value at their minimum (and have their minimum at the same value of the QS0 correction factor).

Figure 13 shows the situation in the horizontal plane. The minima of the various curves are much shallower, due to the fact that the QS0 don’t have larger motions in x during physics. A striking feature is that the RMS of $x_{L}^{BQ}(\alpha)$ exceeds the RMS of $x_{L}^{VDET}$ for all values of $\alpha$. This indicates that the BOM data on the left side provides a worse estimate of the horizontal beam spot position than a constant assumption.

6 Conclusion

We have established that vertical movements of the QS0 quadrupoles affect the beam spot position in IP4, and cause a bias on the BOM measurements of this position. These movements are believed to have thermal origin (see Appendix below) and depend on the activity of the machine. Their precise and direct measurement with respect to the experiment is feasible using position sensors. The data from these sensors can then be used to apply a correction to the BOM measurements. The effect of such a correction is illustrated in Figs 14 and 15.

The magnitude of the vertical correction is found to be 1.06 times the measured displacement of the quadrupoles. The uncertainty on that number is quite large given the fact that its determination on the left and right sides are 1.46 and 0.83 respectively (or else the two sides are really different). From machine optics, one would expect the IP4 beam position to move by 1.4 times the vertical displacement of the quadrupoles [8]; assuming that this expectation is valid for movements of the center of the magnets, the measured displacements would be 1.4/1.06 ≈ 1.3 times the displacement of the center of the magnets. Given the fact that the QS0 girders holding the magnets are cantilevered with a fulcrum on the tunnel floor, this would favor the hypothesis of a rotation of the QS0 girder around that point.

The situation in the horizontal plane is less clear, but also less critical since the requirements from LEP2 physics are much looser.

Quantitative conclusions are summarized in Table 1, for the average between the left and right sides. The LEP BOM measurements are providing a beam spot position which is
more accurate (by a factor of approximately 2) compared to a constant assumption equal to the average position over the studied period. Applying a correction for the movements of the QS0 quadrupoles further improves the accuracy by another factor 2 in the vertical plane, but does not help in the horizontal plane.

A detailed study of the left and right BOM data shows that there is a problem with the left side data in the horizontal plane.

**Appendix**

Fill 2872 is interesting from the point of view of the QS0 movements. On the 10th of August 1995, there was an air-conditioning failure in the pit around 6 pm, in the middle of this fill. The left QS0 magnet quickly started to move up (see Fig. 16) and orbit instabilities were observed by the LEP operators. The situation came back to normal a few hours later. This is the first clear indication that the QS0 movements are caused by temperature effects. Unfortunately, the LEP BOM system was not working during fill 2872. However, the ALEPH BOM data could be used to reconstruct the beam spot position, and indeed, a correction for the QS0 movements brings the VDET and BOM measurements in better agreement (see Fig. 17).

**Acknowledgments**

It is a pleasure to thank Tiziano Camporesi who provided us with the position sensors (spare DELPHI units), and Mike Lamont and Jörg Wenninger who developed TURBOIP for the needs of the LEP experiments. Valuable discussions with Joe Rothberg, Georg von Holtey and Jörg Wenninger are gratefully acknowledged, as well as the work of Marie Jacquet who looked at the ALEPH BOM data and QS0 data of the first part of the 1995 year.

**References**


Figure 2: Calibration of the ALEPH QS0 position probes. The two parameters of the straight line fit, the offset $P1$ and the slope $P2$, are defined by $t = P1 + P2 \times V$, where $t$ is the shim thickness in microns and $V$ is the output voltage in volts.
Figure 3: Online time-charts showing the time-dependence of the QS0 positions during an entire week of running (4–11 September 1995). The horizontal axis is the date. The left (right) column of plots refers to the QS0 quadrupole on the left (right) side of the IP when looking from the center of LEP. The first 3 rows show the $x$, $y$, and $z$ coordinates in microns with an arbitrary offset ($z$ horizontal pointing towards the center of LEP; $y$ pointing up and $z$ along the $e^-$ beam direction). No $z$ measurement is available on the right side. The last row shows the currents in the QS0 magnets in amps; 500 (1000) A corresponds roughly to the setting for a beam energy of 20 (45) GeV.
Figure 4: Online time-charts showing the time-dependence of QS0 positions during fill 2907. Horizontal axes are in hours. See caption of Fig. 3 for more details.
Figure 5: Online time-charts showing the time-dependence of QS0 positions during fill 2949. Horizontal axes are in hours. See caption of Fig. 3 for more details.
Figure 6: Online time-charts showing the time-dependence of the average (top plot) and difference (bottom plot) of the two independent measurements of the vertical position of the QS0 quadrupole on the left side of the IP. Units are days on the horizontal axes and microns on the vertical axes.
Figure 7: VDET measurements and their errors.

Figure 8: Distribution of the difference (divided by $\sqrt{2}$) between the readings of the two vertical QS0 position sensors on side A.
Figure 9:  
a) difference between the vertical positions measured by VDET and by the left side of the LEP BOM system as a function of the measured position of the QS0 magnet on the left side;

b) same, but using measurements on the right side;

c) same, but using the average of the measurements on the left and right sides;

d) difference between the vertical positions measured by the LEP BOM system on the left and right sides as a function of the difference between the measured vertical positions of the QS0 magnets on the right and left sides.
Figure 10:  

a) difference between the horizontal positions measured by VDET and by the left side of the LEP BOM system as a function of the measured position of the QS0 magnet on the left side;

b) same, but using measurements on the right side;

c) same, but using the average of the measurements on the left and right sides;

d) difference between the horizontal positions measured by the LEP BOM system on the left and right sides as a function of the difference between the measured horizontal positions of the QS0 magnets on the right and left sides.
Figure 11: Residual distributions. See Sect. 4 for the definition of the quantities that are histogrammed in these plots.
Figure 12: Left plot: RMS of the quantities $y^{\text{VDET}} - y^{BQ}_L(\alpha)$ (squares), $y^{\text{VDET}} - y^{BQ}_R(\alpha)$ (triangles), $y^{\text{VDET}} - y^{BQ}(\alpha)$ (circles), and $y^{BQ}_R(\alpha) - y^{BQ}_L(\alpha)$ (diamonds) as a function of $\alpha$, the “QS0 correction factor”. Right plot: error on the BOM+QS0 estimate of the vertical beam spot position extracted from each of the quantities shown in the left plot, normalized to a single side. More specifically, the squares have been computed as $\sqrt{\text{RMS}(y^{\text{VDET}} - y^{BQ}_L(\alpha))^2 - \sigma_y^2 - \alpha^2 \sigma_q^2}$, the triangles as $\sqrt{\text{RMS}(y^{\text{VDET}} - y^{BQ}_R(\alpha))^2 - \sigma_y^2 - \alpha^2 \sigma_q^2}$, the circles as $\sqrt{2 \text{RMS}(y^{\text{VDET}} - y^{BQ}(\alpha))^2 - 2\sigma_y^2 - \alpha^2 \sigma_q^2}$, and the diamonds as $\sqrt{\frac{1}{2} \text{RMS}(y^{BQ}_R(\alpha) - y^{BQ}_L(\alpha))^2 - \alpha^2 \sigma_q^2}$. 

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Figure 13: Similar to Fig. 12, but for quantities in the horizontal plane. See caption of Fig. 12 for details.
Figure 14: Time-dependence of the vertical beam spot position during fill 2907. The errors bars are the VDET measurements. The open symbols are the LEP BOM extrapolations from the left side (circles) and the right side (squares). The plain symbols are the same BOM measurements corrected for the QS0 movements with a factor $\alpha = 1.06$. The time dependence of the QS0 positions during this fill is displayed in Fig. 4. In all cases, the measurements have been shifted by a constant amount to provide the best match with the VDET data. The corresponding offsets, $\chi^2$ values and $\chi^2$ probabilities are shown in the table at the top of the plot. It is interesting to note that the agreement at the beginning of the fill, where the QS0 movements have the biggest amplitude, is improved significantly by the correction.
Figure 15: Time-dependence of the vertical beam spot position during fill 2949. See caption of Fig. 14 for details. The time-dependence of the QS0 positions during this fill is displayed in Fig. 5.
Figure 16: Online time-charts showing the time-dependence of QS0 positions during fill 2872. Horizontal axes indicate the time in hours. The large vertical excursion of the left QS0 quadrupole between 6 and 9 pm was due to an identified air-conditioning fault. See caption of Fig. 3 for more details.
Figure 17: Time-dependence of the vertical beam spot position during fill 2872. The errors bars are the VDET measurements. The open symbols are the ALEPH BOM interpolations. The plain symbols are the ALEPH BOM measurements corrected for the QS0 movements with a factor $\alpha = 1.1$. The time dependence of the QS0 positions are displayed in Fig. 16. In all cases, the measurements have been shifted by a constant amount to provide the best match with the VDET data. It is interesting to note that the agreement with the VDET data improves significantly after the correction.