INTERACTION REGIONS

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1 Beam Induced Particle Backgrounds

From the two main types of beam induced particle backgrounds to the LEP experiments—off-energy electrons and synchrotron radiation (SR) photons—only the latter is expected to increase with beam energy. The rate of off-energy electrons produced by beam-gas Bremsstrahlung is to first order independent of beam energy. The second source for off-energy particles, scattering of beam particles from thermal photons, is energy dependent but does not add to the off-energy background to the experiments. The number of radiated SR-photons in magnetic quadrupolar fields, as well as the critical energy of the spectra, increases sharply with beam energy and would lead to unacceptably high photon background levels at 90 GeV [1]. To cope with this situation, the background protection system had to be upgraded for LEP2 by adding collimators, enlarged vacuum chambers, photon absorbers and in particular synchrotron radiation masks close to the IPs [2]. All these additional elements will be in place for 1996 [3].

The SR-photon background rate is difficult to calculate as it is strongly dependent on several optics and beam parameters, which are not all known. The estimates given below must therefore be used with great caution. Apart from the beam energy, the most sensitive parameter is the beam size in the horizontal plane and the particle density distribution far into the horizontal tails. The photon rate at the detectors increases typically by a factor of ten when the beam distribution is changed from a gaussian to an exponential density distribution with constant RMS beam size (see Fig. 1). For small emittances and high energies this factor can be as large as 40. It is this effect, the build-up of non-gaussian tails with high currents near the beam-beam limit, that can make the SR-photon background increase faster than linear with beam current.

The exponential increase of the photon rate with increasing beam emittance, mainly due to small angle back scattering, made the introduction of SR-masks for LEP2 necessary, as the nominal horizontal beam emittance for LEP2 is $\epsilon_x = 50\,\mathrm{nm}$ (for the 90^o optics). The effect of the SR-masks is seen in the simulation results of Fig. 1b, where the sharp exponential rise of the photon rate is much reduced for emittances larger than 35 nm. However, in spite of the

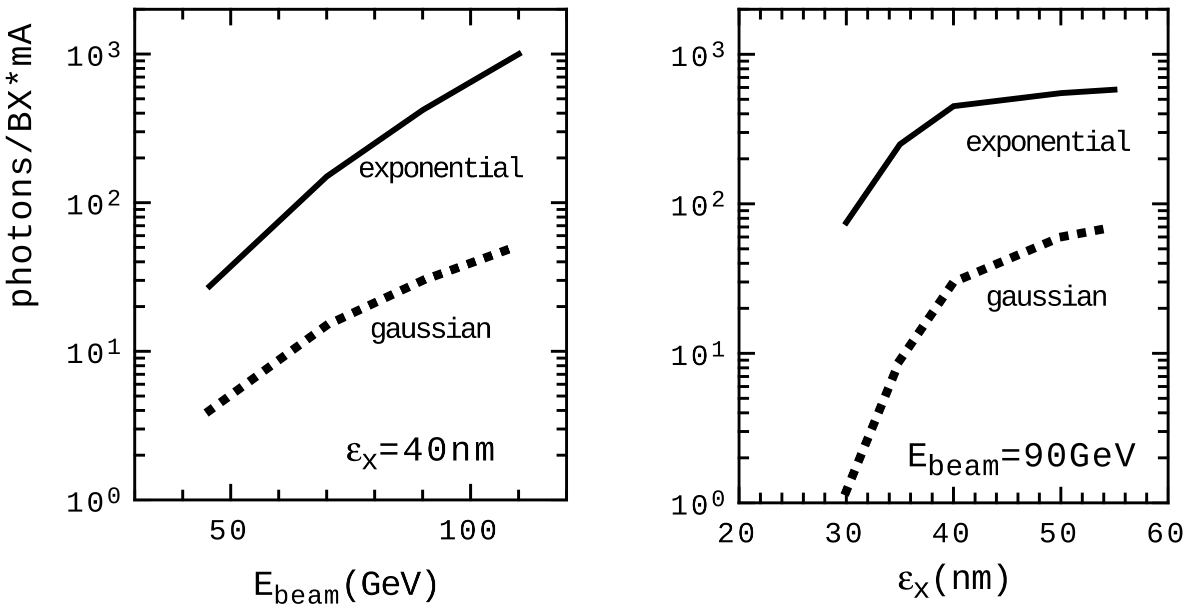

Figure 1: Simulated photon background rates as a function of the beam energy (a) and the horizontal beam emittance (b). The results are valid for IP6, equipped with all additional LEP2 background protection elements, including SR-masks.

protection by masks, the expected rate still rises by a factor of more than 10 if the emittance is increased from 30 nm (108^o optics) to 50 nm (90^o optics).

With constant emittance the SR-photon rate at the detectors is expected to increase by about a factor of ten when doubling the beam energy from 45 to 90 GeV (Fig. 1a). This factor can be compensated for if, as it is now planned, the 108^o optics is used at LEP2.

The above arguments hold strictly only for a machine without bunch trains. The vertical separation bumps needed for bunch trains are a source of additional particle backgrounds [4]. However, with reduced beam-beam effects at high energy, smaller separation can be tolerated, thus keeping the separation bump amplitudes well below the threshold value above which the photon background rate has been seen to rise very rapidly. The main effect of bunch trains on the background situation at LEP2 is therefore to increase the sensitivity of the machine to beam instabilities, which lead to blow-up of the beam size, and consequently to increased background rates.

The expected SR-photon background rate, per unit beam current, at the W-pair energy is more than one order of magnitude higher than at 45 GeV with the 90^o optics and about the same if the low emittance 108^o optics can be used. Therefore the expected particle background is a strong argument in favour of the 108^o optics. Running LEP at the energy limit (corresponding to zero 'missing cavities') may produce unstable beam conditions with small beam lifetimes and occasional significant beam losses with the consequence of large beam backgrounds in the detectors.

2 Luminosity Lifetimes at LEP2 Energies

Beam lifetimes in LEP1 are well understood, they are limited by beam-beam collisions [5]. For single or separated beams the dominant lifetime limitation is due to scattering on thermal photons and only in second place due to beam-gas scattering.

Losses from scattering on thermal photons will increase with beam energy. The black body photon radiation is effectively boosted twice by the Lorentz factor gamma of order 10^5 in the Compton scattering process. The mean energy loss induced by this process increases from 1.1% at LEP1 to 2.2% at LEP2, thus resulting in a shorter lifetime [6].

Beam lifetimes reduce significantly when beams are brought into collision. The dominant process for beam lifetimes is Bhabha scattering with very small scattering angle but non-negligible energy loss by radiation of a photon in the initial state. The process of radiative Bhabha scattering as lifetime limitation is often referred to as beam-beam Bremsstrahlung. The full kinematics of the process and the introduction of a cutoff parameter corresponding to the mean half-distance between particles in the bunch is discussed in [7]. The cross section for LEP is approximately independent of energy and about 0.21 barn.

For fixed beam sizes, luminosity increases quadratically with beam currents. Above a certain current per bunch, beam sizes will start to increase by the beam-beam effect. This corresponds to operation at the beam-beam limit, characterized by a constant beam-beam tuneshift and a linear increase of luminosity with current. The relative strength of the beam-beam effect decreases with beam energy, therefore more collisions should be possible at higher energies for the same beam current. This results in lower lifetime from collisions at the IPs at higher energies. The typical contribution to beam lifetimes for LEP1 and LEP2 is given in Table 1.

Table 1: Contributions to the beam lifetime at LEP1 and LEP2

Process	LEP1	LEP2
Thermal photons	88 h	50 h
Beam gas	200 h	200 h
B.B.Bremsstrahlung	25 h	12.5 h
Total	17 h	9.5 h

Beam lifetime and luminosity lifetime are equal for operation in the beam-beam limit. This was the case for LEP1. At high energies, the beam-beam limit will be at higher bunch currents and the luminosity lifetime is expected to become 1/2 of the current lifetime towards the end of coasts.

The optimum time in coast has been studied with a program that simulates beam lifetimes and the beam-beam effect for various single beam sizes [7]. The result is typically a 6 hour coast for LEP2, compared with 10–12 hours for LEP1. However the maximum is rather flat and the integrated luminosity decreases only slowly if coasts are kept longer.

3 Beam Spot Position Measurements

A knowledge of the transverse position of the LEP luminous region (beam spot) at the interaction points is useful in identifying long lived particles (primarily b quarks) that decay some distance from their production point. At LEP1, the high rate of tracks from Z^0 decay allows the beam spot position to be determined with high accuracy ($\sigma_x \sim 20\,\mu$m, $\sigma_y \sim 10\,\mu$m) typically every few minutes. Movements of up to $100\,\mu$m or more are observed during the course of some fills.

At LEP2, the event rate will be much lower, and such an accurate beamspot determination will not be possible using tracks. The track rate will be dominated by two-photon ($\gamma\gamma$) events, which will provide a limited beamspot measurement. However the LEP beam orbit monitor (BOM) system [9], [10] provides an alternative method to monitor short term movements, and this has been extensively tested using LEP1 data. Unfortunately, displacements of the superconducting low-beta quadrapole magnets (QS0s) either side of each interaction point can cause movement of the beam spot not seen by the BOM system, so the QS0 positions must also be monitored to produce an accurate measurement.

3.1 Beam Spot Position Requirements

Tagging of b quarks at LEP2 is primarily required in the search for $H \to b\bar{b}$. The primary vertex position is constrained by the beam spot, but the size of the luminous region (approximately $150\,\mu$m in x and $5\,\mu$m in y) must also be taken into account. Thus an accurate beam spot position is much more important in the vertical (y) than the horizontal (x) direction. Knowledge of the beam spot position improves the performance (efficiency *vs.* purity) of b-tagging algorithms, and translates into an increased Higgs sensitivity for a given integrated luminosity.

The requirements have been studied in detail by the LEP experiments. The ALEPH study [11] simulated the process $e^+e^- \to H\nu\bar{\nu}$, $H \to b\bar{b}$ together with appropriate backgrounds. An impact parameter based b-tag was used together with appropriate kinematic cuts. The beam spot position resolution was varied between $10\,\mu$m and 1 cm. A resolution of $100\,\mu$m in x and y was found to give a 10% reduction in the integrated luminosity needed to discover an 80 GeV Higgs at $\sqrt{s} = 175$ GeV, compared to the situation with no beam spot measurements. Improving the beam spot resolution below $100\,\mu$m brought little further gain in integrated luminosity.

A similar study performed by L3 [12], found that the absence of beam spot information would lead to a 20% increase in the integrated luminosity required to discover an 80 GeV Higgs at $\sqrt{s} = 190\,\mathrm{GeV}$. Full b-tagging performance was achieved with a resolution of $150\,\mu$m in x and $50\,\mu$m in y. In DELPHI [13], the effect of removing the beam spot information in $Z \rightarrow b\bar{b}$ events was found to reduce the event tagging efficiency by 10%, and no improvement was found for resolutions below $20\,\mu$m.

These studies show that extremely accurate beam spot measurements are not required, and the gain in b-tagging power is not very large. However, being conservative, and bearing in mind the likely small number of candidate events, a target of $100\,\mu$m in x and $20\,\mu$m in y has been set and agreed upon by all the experiments.

3.2 Measurement from Two-Photon Events

The cross section for $\gamma\gamma$ events at LEP2 is much higher than at LEP1, and is the dominant source of tracks, which can be used for measuring the beam spot position. If the rate is high enough, they may be used to follow movements during a fill, otherwise they will be useful in providing an absolute position measurement on a fill by fill basis.

The tracks from $\gamma\gamma$ events have an angular distribution peaked in the forward direction, and a steeply falling momentum spectrum. Hence the rate seen in detectors depends critically on the acceptance and trigger momentum thresholds. In ALEPH [14], $\gamma\gamma$ events were simulated at $\sqrt{s} = 175\,\mathrm{GeV}$, and the beam spot determined using all events with at least one track with momentum greater than 0.3 GeV in the vertex detector. Chunks of $3.6\,\mathrm{nb}^{-1}$ gave a beam spot position accurate to $42\,\mu$m in x and $32\,\mu$m in y, corresponding to a 1% loss in effective luminosity in the Higgs search. Chunks of $60\,\mathrm{nb}^{-1}$ gave a measurement accurate to around $10\,\mu$m in x and y, corresponding to around 30 minutes running at a luminosity of $3 \times 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The Monte Carlo was cross-checked with $\gamma\gamma$ data taken at $\sqrt{s} = 89.4\,\mathrm{GeV}$, and found to be in reasonable agreement [15].

In OPAL, simulated $\gamma\gamma$ events tagged in the forward and luminosity calorimeters were studied [16], using a more restrictive event selection requiring at least 2 charged tracks with $p_T > 0.25\,\mathrm{GeV}$ in the central jet chamber acceptance. This yielded a measurement of $15\,\mu$m in x and $10\,\mu$m in y for $1\,\mathrm{pb}^{-1}$ (a 9 hour fill at $3 \times 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$). Using untagged $\gamma\gamma$ events and a $p_T > 1\,\mathrm{GeV}$ requirement on the tracks gave a similar resolution for just $150\,\mathrm{nb}^{-1}$ [17]. This is similar to the ALEPH result taking into account the tighter tracking cuts used.

These results show that a reasonable beam spot measurement should be possible from $\gamma\gamma$ events, tracking movements over the time scale of 1 hour to better than the required accuracy. However, the event selection may be vulnerable to background contamination, and the beam moves around on shorter time scales, so it is worth using the BOMs to improve the accuracy of the beam spot measurements.

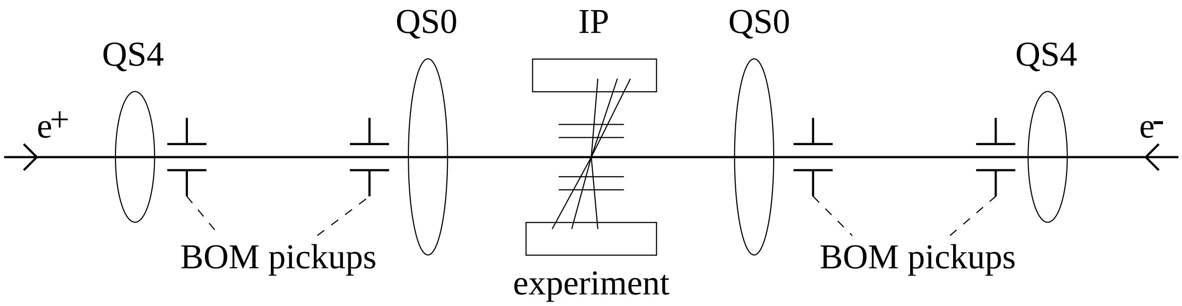

Figure 2: Schematic showing the positions of BOM pickups and QS0 magnets relative to the interaction point.

3.3 Measurement using BOM pickups and QS0 monitoring

Several sets of wide band BOM pickups, measuring the beam x and y positions, are installed on each side of each interaction point (see Fig. 2). Knowledge of the LEP beam optics and corrector magnet strengths allows the beam positions to be extrapolated to the interaction points themselves [18]. These extrapolations were performed for a few selected fills in 1994 data, and the results compared with beam spots measured from tracks by the four LEP experiments [13], [16], [19], [20]. While it was found that the BOM system had the potential to perform a measurement to the required accuracy, there were severe systematic problems associated with movements of the QS0 magnets over time. If the QS0s on either side of the IP move symmetrically, a 'π-bump' is created in the machine which changes the IP beam spot position, but is not seen by the BOMs which are outside the QS0s.

Two major improvements were implemented in 1995. Firstly, the BOM extrapolation was implemented online, with the results being stored in a database accessible to the experiments [23]. This calculation was active for the majority of the 1995 Z^0 scan period. Four independent measurements of each coordinate were calculated, using BOM data for the incoming and outgoing beam on each side of the experiment. Secondly, the QS0 magnets at IP2 and IP8 were instrumented with hydrostatic level measuring equipment, and ALEPH and DELPHI also installed their own monitoring of the QS0 positions relative to the experiments.

The hydrostatic level systems consist of capacitative liquid level measuring sensors mounted on the tunnel floor, the QS0 support girders and the magnets themselves [24]. These are currently installed in IP2 and IP8, and will be installed in the other two interaction regions during the 1995-1996 shutdown. The DELPHI luminosity calorimeter (STIC) is attached to their QS0 support structures and movements relative to the main detector are measured by several pin potentiometer probes [22]. This system was installed in 1994, and has an intrinsic resolution of a few microns. For the 1995 run, a similar system was installed in ALEPH, monitoring movements of the QS0 supports relative to reference surfaces attached to their main detector [21].

Movements of the order of $50\,\mu$m in the QS0 vertical position have been seen in all these systems, and correlated with the currents in the QS0 magnets. Slow drifts are observed when the currents are changed, consistent with thermal effects due to the currents in the QS0s and bus bars. Sudden jumps and movements in the horizontal direction are also observed, and are not yet fully understood.

Consideration of the LEP beam optics shows that the beam spot position at the IP y_{IP} can be estimated from the BOM extrapolation from the left side of the IP, $y_{BOM,L}$, and from the position of the left QS0, $y_{Q,L}$:

$$y_{IP} = y_{BOM,L} + \alpha y_{Q,L} \quad (1)$$

and similarly on the right side. The best estimate is obtained by averaging the BOM (y_{BOM}) and QS0 (y_Q) data on both sides:

$$y_{IP} = y_{BOM} + \alpha y_Q \quad (2)$$

Thus asymmetric movement of the QS0s has no effect at the IP, whilst symmetric motion causes the largest effect. The parameter α is expected to have the value 1.4 [18].

The correlations between beam spot measurements from tracks, those from the improved BOM extrapolations and QS0 movements were studied by ALEPH [21] and DELPHI [22]. In the ALEPH study, the data were normalised by assuming a constant offset between the vertex and BOM measurements throughout the 1 month data taking period. The RMS of the difference between vertex and BOM measurements was then taken as a measure of the BOM measurement resolution, after subtracting off the component from the vertex beam spot resolution. Using BOMs alone gave a resolution of $42\,\mu$m in x and $14\,\mu$m in y, a clear improvement on the $74\,\mu$m and $27\,\mu$m obtained assuming a constant beam spot position instead of the BOM measurements. Correcting the BOM measurements using the measured QS0 displacements improves the resolution in y. The QS0 movements on each side contribute to the improvement in a consistent manner and the best resolution of $7\,\mu$m is obtained using both sides with $\alpha = 1.06$. The potentiometers actually measure movements at the end of a cantilevered structure which may magnify the QS0 movements, so this measured value is not incompatible with the expected 1.4. A typical example fill is shown in Fig. 3, clearly showing the agreement between both sides and the improvement that can be gained in the vertical plane using the QS0 information. During the first few hours of this fill, the QS0s on either side of ALEPH moved by 40 and $70\,\mu$m respectively. Movements in the horizontal plane are less well understood, and no significant improvement was obtained when applying a QS0 correction.

The DELPHI study considered movements of the beam spot during fills, the data being normalised to the difference in average BOM and vertex detector beam spots in each fill. Using the STIC probes to correct the BOM measurements, an improvement was seen in the y direction, the BOM resolution being reduced from 8 to $6\,\mu$m with $\alpha = 1.4$. A similar improvement was also found using the hydrostatic level measuring system to monitor the QS0 positions. The beam spot movement within a fill has an RMS of $9\,\mu$m in y, so the improvement using BOMs and QS0 monitoring appears modest. However, vertex movements not seen by the BOMs of up to $80\,\mu$m have been seen in some fills, and these are nicely tracked by the QS0 monitoring. A nice example using the STIC probe monitoring is shown in Fig. 4. The beam spot movement

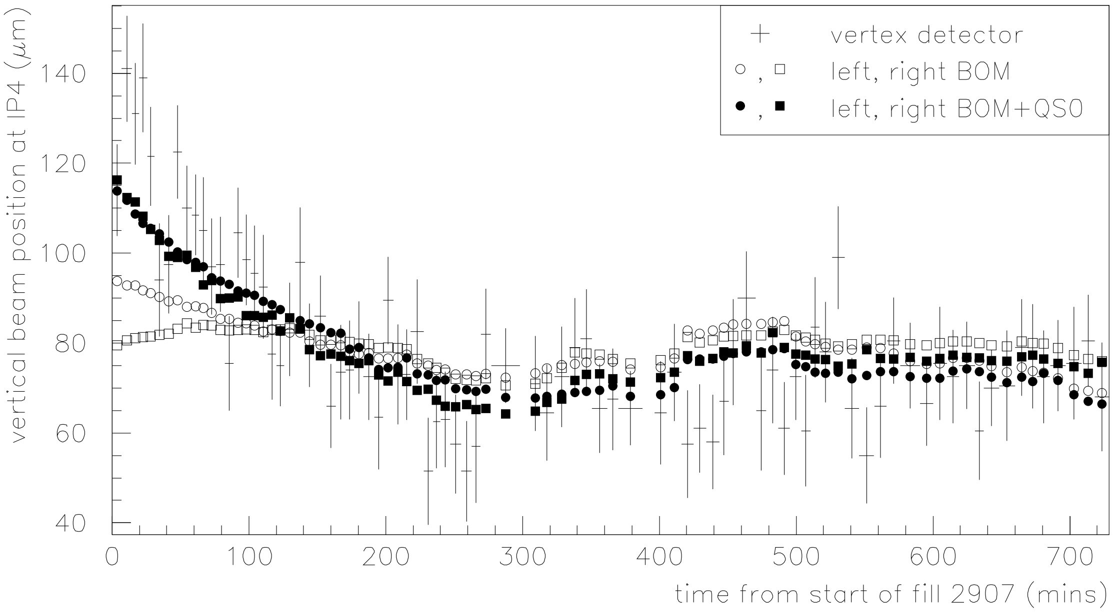

Figure 3: Beam spot measurements for fill 2907 in ALEPH: vertex detector (error bars), BOM (open symbols), BOM corrected by QS0 measurements (filled symbols). Left side measurements are circles and right side squares.

in x within fills has an RMS of $25\,\mu$m, and this was not improved by using BOM and QS0 measurements.

In OPAL, measurements of the QS0 position were not available from either hydrostatic or potentiometer systems. An analysis was therefore performed using BOM information alone, giving a beam spot resolution of $19\,\mu$m in x and $6\,\mu$m in y [17], again normalising the average positions from BOMs and vertex detector measurements in each fill. This resolution is similar to that obtained by DELPHI after correcting for QS0 motion, and suggests that the latter effect is much smaller in OPAL. Examining the residual differences between vertex and BOM measurements shows some evidence for systematic effects attributable to QS0 movements, but only on a scale of 10–$15\,\mu$m, smaller than those seen in ALEPH and DELPHI. The reason for this smaller effect is not yet understood.

The OPAL analysis also considered the problem of establishing the absolute calibration between the BOM coordinate system and the detector. This was done using the fill averaged beam spot measured from tracks. By accurately determining the latter quantity using all the tracks from Z^0 events, the fill to fill variation in BOM to vertex detector offsets was studied, and is shown for some of the BOMs in Fig. 5. Variations of up to $100\,\mu$m in individual BOM offsets were observed. Since no QS0 corrections were applied, most of these variations may be explained by QS0 current cycling between fills. An appropriate fraction of the Z^0 event tracks was then used to simulate the lower track rate from $\gamma\gamma$ events expected at LEP2. By combining compatible offsets from adjacent runs, a resolution of $23\,\mu$m in x and $9\,\mu$m in y was achieved, not much worse than that obtained by removing fill to fill offsets. Hence the effects from BOM

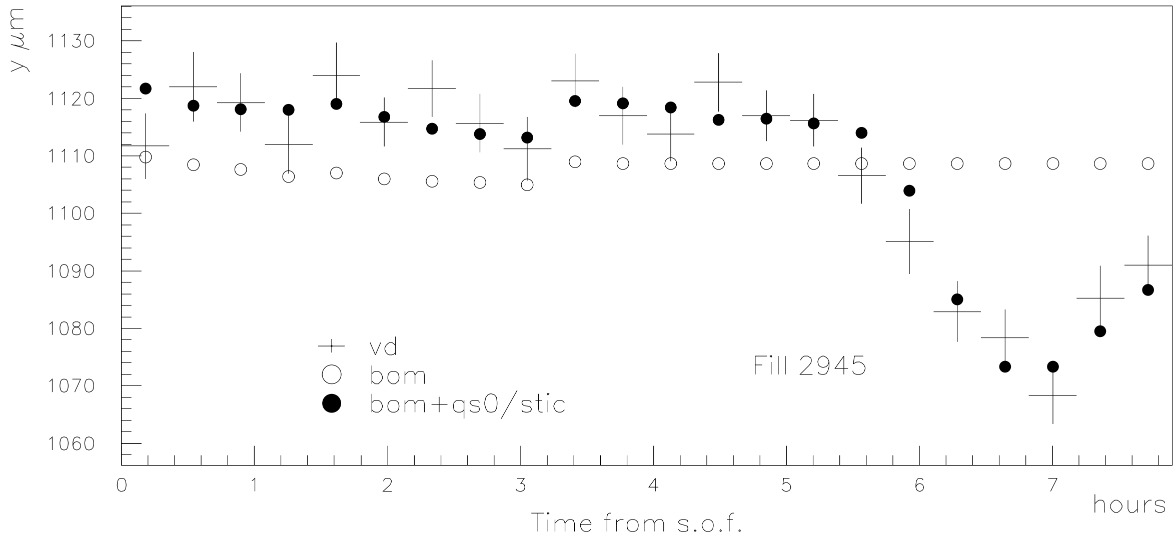

Figure 4: Beam spot measurements for fill 2945 in DELPHI: vertex detector (error bars), BOM (open circles), BOM corrected by STIC QS0 measurements (filled circles)

offset changes (probably due to QS0 movement) can be partially compensated for.

The resolutions in x and y measured by the experiments in 1995 LEP1 data under various conditions are summarised in Table 2, showing that the target resolution of $100\,\mu$ in x and $20\,\mu$m in y can be met. Large movements are seen in the beam spot positions during a data taking period, though less so during the course of individual fills. These movements can be tracked using the BOM system corrected by QS0 position monitoring, which follow both the in-fill and fill to fill variations well. It should be stressed that large deviations due to QS0 movement are sometimes seen, and that these are expected to be more important at the higher magnet currents required for LEP2. Hence it will be important to monitor the QS0 positions continuously during machine operation.

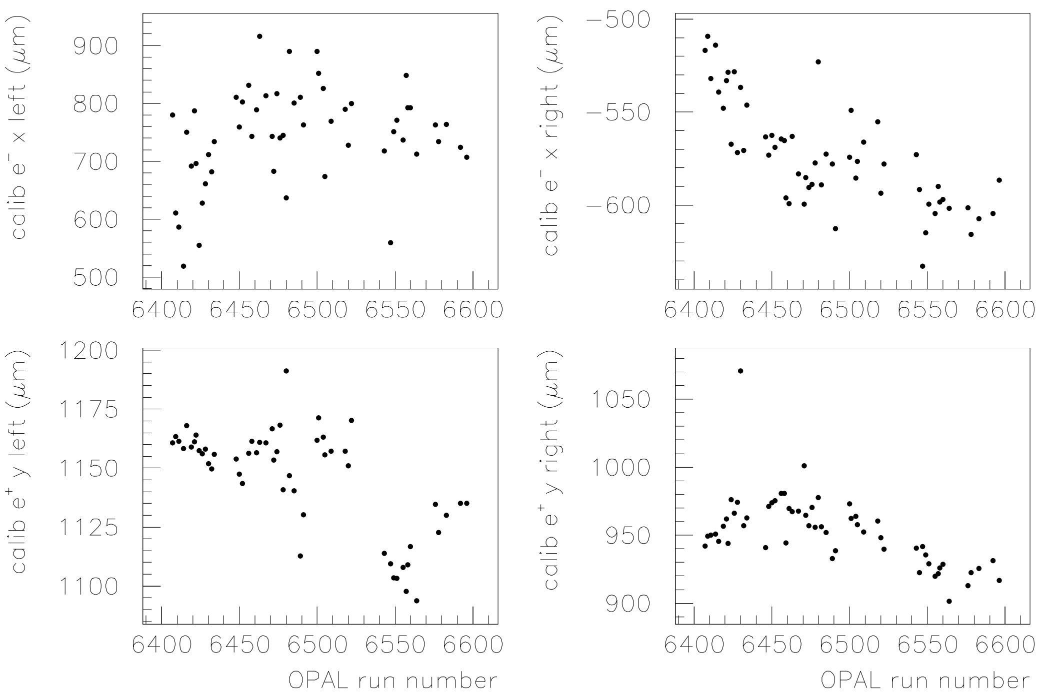

Figure 5: BOM measurement offsets with respect to vertex position measurements vs fill in 1995 OPAL data.

Table 2: Summary of beamspot requirements and resolutions measured by the experiments (see text)

Experiment	Measurement	Offset per fill	Resolution x (μm)	Resolution y (μm)
All	Requirement	–	100	20
ALEPH	Constant assumption	no	74	27
ALEPH	BOM	no	42	14
ALEPH	BOM+QS0	no	41	7
DELPHI	Constant assumption	yes	25	9
DELPHI	BOM	yes	27	8
DELPHI	BOM+QS0	yes	27	6
OPAL	Constant assumption	no	79	32
OPAL	Constant assumption	yes	26	10
OPAL	BOM	yes	19	6
OPAL	BOM	sim $\gamma\gamma$	23	9

3.4 Conclusion

The beam spot position requirements for LEP2 and methods of meeting them have been extensively studied. A knowledge of the beam spot position helps in b-tagging, which has been evaluated in the context of the $H \to b\bar{b}$ search. A position resolution of $100\,\mu$m in x and $20\,\mu$m in y is adequate, and higher precisions do not bring significant gains in physics performance.

Measuring the beam spot position from both $\gamma\gamma$ events and the BOM system has been studied. The former may provide enough resolution by itself to monitor slow variations, and the latter should do considerably better than the requirements when corrected for the movements of the QS0 magnets. Hence the physics requirements should be met. It is also worth emphasising that the BOM measurements are very useful for understanding the behaviour of the LEP machine itself.

4 Acknowledgements

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