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LEP Center-of-Mass Energies in Presence of Opposite Sign Vertical Dispersion in Bunch-Train Operation

The LEP Energy Working Group

Abstract

The presence of opposite sign vertical dispersion at the IPs in the bunch-train mode of operation of LEP leads to possible shifts in the center-of-mass energy. A collision offset of 1 micron leads to a shift of 1 to 3 MeV. A strategy to control these shifts is presented, based on the fact that the energy shifts are minimized when luminosity is maximized. In practice, this condition can be ensured quantitatively by regular vernier scans. A special procedure was developed to perform vernier scans automatically. Results on the statistical and systematic precision of vernier scans, as well as on their reproducibility and stability in time are now available from more than 100 scans performed in june 1995. For a given electrostatic configuration of LEP, the stability of the offsets seems to be better than a micron. Vernier scans also provide measurements of the separation between bunches in the trains and of the beam size at the IPs. The opposite sign vertical dispersion at the IPs was also measured by performing vernier scans at different RF frequencies. Combining these results, a running strategy is proposed that ensures an additional systematic error on the center-of-mass energy coming from bunch-train side-effects of less than 0.7 MeV for any LEP experiment. This leads to upper limits of 0.4 MeV additional error on the Z width, and 0.5 MeV on the Z mass.

Contents

1 Motivation

With the existence of opposite sign vertical dispersion due to bunch-train bumps, the center-of-mass energy can be shifted by an amount proportional to the beam-beam mis-crossing [1]:

$$E_{cm} = E(e^{+}) + E(e^{-}) + \Delta E_{cm} \tag{1}$$

$$\Delta E_{cm} = -\frac{\delta_v}{\sigma_y} \cdot \frac{\frac{(D_{e^+} - D_{e^-})}{2} \cdot \frac{\sigma_E}{E}}{\sigma_y} \cdot \sigma_E. \tag{2}$$

Where δ_v, the collision offset, is the distance between the center of the positron bunch and the electron bunch in collision at the IP, σ_y the individual beam size, $\frac{(D_{e^+} - D_{e^-})}{2}$ the opposite sign vertical dispersion (OSVD), and σ_E the beam energy spread. In the case of one bunch, it is obvious that the maximum of the luminosity coincides with zero energy offset. This result can be generalized to a situation with many bunches with different collision offsets. Although the center-of-mass energy for each of the colliding bunch combinations can be different by tens of MeV, it can be demonstrated [1] that the overall energy shift averages to zero if one considers the luminosity-weighted average over the bunches. The demonstration makes no other assumption than a gaussian particle distribution within the bunches and equal OSVD for the various bunch combinations.

Although the energy shifts are not directly measurable, all ingredients in formula 2 are accessible to measurement. Beam energy spread can be predicted reliably and verified experimentally with the z distribution of annihilation events in the LEP detectors. The collision offset can be measured and adjusted to zero by vernier scans which also provide direct measurements of the vertical beam size. The opposite sign vertical dispersion at the IPs can be measured by performing vernier scans at different RF frequencies. Vernier scans are therefore an essential tool of investigation and monitoring.

This note is organized as follows. First the results of theoretical calculations are described. They are used as a guideline to define the strategy, but not in the actual derivation of the energies or for systematic error estimates. A description of the vernier scan procedure, and of the statistical and systematic errors on individual vernier measurements, follows. Statistics on the available vernier scans are then analysed to derive their stability. Results of dispersion measurements, train shapes and beam sizes are then given, and compared to predictions. These results are used to determine systematic errors on the center-of-mass energy and energy spread. Based on this experience, a running scheme is proposed for off-peak points, that ensures good control of the offsets and, ultimately, small systematic errors from this source on the Z mass and width.

Further improvements to the procedure were suggested by this experience and will be implemented. Means for tracking the offsets between vernier scans are being developed. At the end, provided logging of the relevant machine parameters is carefully maintained, is it is likely that the errors given here, estimated using present results, will be further reduced.

2 Theoretical results

Calculations of offsets and vertical dispersion of individual bunches in bunch train running mode are difficult to perform in a truly self-consistent way [2]. Much hope is placed in the new code by F.C.Iselin [3]. The most important results of new calculations [4] using this code, for equal beam currents of 300 μA per bunch and maximum bump amplitude are as follows:

1. Collision offsets differ between bunches by amounts of the order of 3,1,0 microns, for trains of 4, 3, and 2 bunches. These collision offsets are symmetric within the trains, being equal for bunches (a and d) and bunches (b and c) in the case of 4 bunches, for bunches (a and c) in the case of 3 bunches. These collision offsets were calculated for equal bunch currents, and arise from parasitic encounters.

2. Opposite sign vertical dispersions are calculated for perfect electrostatic bumps to be 1.95 mm in point 2 and 6, -0.95 mm in point 4 and -0.5 mm in point 8. The largest source of OSVD is the LEP electrostatic separation system itself, and is the same for all bunches. Parasitic encounters produce additional OSVDs that are different between the bunches, but they are calculated to be less than 0.1 mm.

In real life, bunch currents are not equal and electrostatic bumps are not perfect, so substantial deviations from these estimates are expected. Measurements of these quantities are presented in the following sections.

The energy shifts resulting from these collision offsets and OSVDs are calculated bunch by bunch in [4]. They amount to up to 7 MeV. It is found however [5] that the overall energy shift indeed vanishes to better than 0.2 MeV when the overall luminosity is maximized, confirming the prediction of [1].

A good order of magnitude estimate is obtained by applying these values to formula 2. For a typical beam size of $\sigma_y = 5$ μm, an OSVD of 2 mm and an energy spread of 8.10^{-4}, an energy shift of 2.3 MeV is found for a collision offset of 1 micron.

3 Vernier Scans

Given the considerable importance of vernier scans in bunch train operation, an automatic procedure was created [6]. It acts on the voltages in the electrostatic separators ZL2 and ZL4 to vary the beam separation at one of the IPs in steps of tunable size. The vernier coordinate is twice the vertical movement of the positron beam. After each step, the luminosity, measured in the LEP luminosity monitors, was integrated over periods of 20 seconds and recorded once or several times for each bunch family.

Figure 1 shows the luminosity and beam sizes, as a function of vernier setting for a scan performed after four hours of physics in fill 2778. Beam currents were around 200 μA per bunch. The dashed or/and dotted lines are the result of a gaussian fit to the individual bunch luminosities, the full line is a fit to the total luminosity. The box show the results of a gaussian fit to the total luminosity, giving the maximum luminosity, (P1), the vernier setting where luminosity is maximum $Y^{\max}_{\text{vernier}}$ [1] (P2), and the width of the distribution (P3).

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[1] The value of $Y^{\max}_{\text{vernier}}$ is equal in magnitude and opposite in sign to the value of the collision offset for $Y_{\text{vernier}} = 0$. It was realized during the preparation of this document that, since the polarity of the separators in L3 and OPAL is negative, the vernier scale was reversed in these points. This sign error has been corrected for the results presented in the rest of this note.

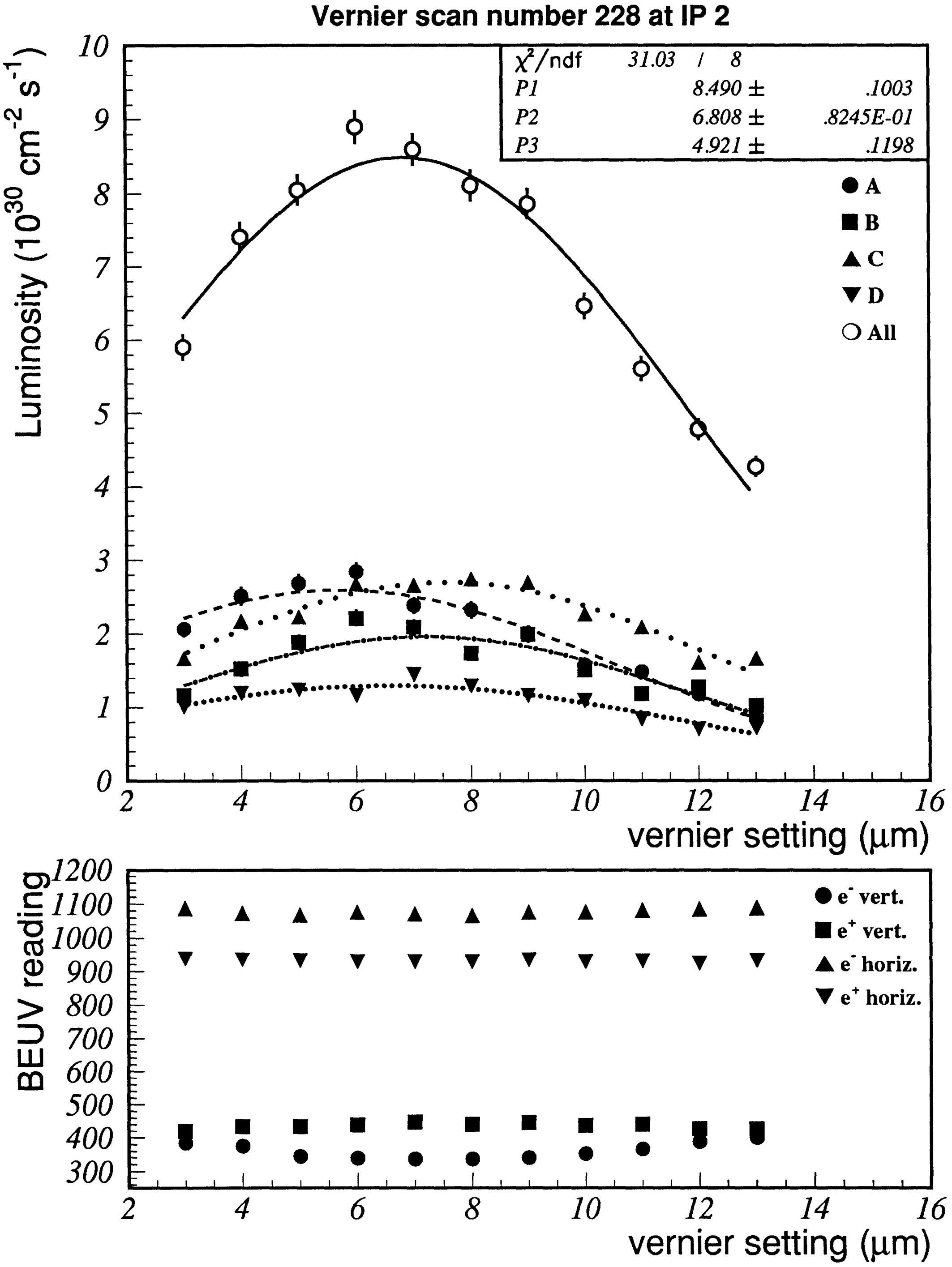

Figure 1: *Results of a vernier scan in point 2, on 24-06-95.*
Top plot: luminosity as a function of the vertical vernier steps.
Bottom plot: BEUV readings during the vernier scan, averaged over families.

The width of the distribution is related to the beam size by the formula:

$$\sigma_y^{\text{vernier}} = \sqrt{\sigma_y^2(e^+) + \sigma_y^2(e^-)} \tag{3}$$

The differences in the collision offsets between families is clearly visible. Empirical optimization earlier in the fill had led to adjust the vernier at 8 microns.

In the bottom plot, vertical and horizontal BEUV images sizes are plotted as a function of vernier setting. Given that an image size of around 240 microns corresponds to an infinitely small beam size [7], the vertical emittance of the electrons was varying quite strongly.

3.1 Statistical precision on vernier scans

The statistical precision on luminosity measurements is estimated from the number of recorded coincidences, taking into account the background subtraction. Typical errors on luminosity are 0.2 10^{30}/cm^2/s for an exposure of 20 seconds. The resulting error on the luminosity maximum depends on the number of points in the vernier scan, on the number of luminosity samples recorded, and, importantly, on the span of the scan with respect to the width and maximum of the distribution.

The following typical statistical errors are obtained for the presently preset vernier scans, beam size of 5 microns, beam currents of 200μA:
" micro-scan": 11 steps of 1 micron : $\Delta(\delta_v) = 0.16\mu\text{m}$
" midi-scan" : 5 steps of 3 microns: $\Delta(\delta_v) = 0.12\mu\text{m}$
" mega-scan" : 7 steps of 3 microns: $\Delta(\delta_v) = 0.09\mu\text{m}$
Errors for individual families are typically twice larger. At present, the time needed to perform a vernier scan is around one minute per step. A vernier scan lasts typically 5 to 10 minutes per interaction point. More optimized operational procedures will be implemented.

These errors assume the typical background and noise conditions. They were occasionally larger for point 6 where the LEP luminosity monitors suffered recurrent noise problems. This problem has now been cured. It is possible to have even better precision, if needed, by increasing the number of luminosity samplings at each step, or the span of the scan. A statistical precision of 0.05 microns on the separations has been achieved on special occasions [9]. The errors can become considerably larger and the scan inconclusive if the span is smaller than the beam size, or if the scan is too badly centered around the luminosity maximum. A quasi-online fit programme will be available after the technical stop of july 1995. This will allow quick verification of the quality of the results, so that the vernier scan can be repeated with better parameters if needed.

3.2 Systematic errors on vernier scans

The main source of systematic error on vernier scan results is well known: as the beams pass through each other, the beam-beam forces vary and the beam size changes rapidly. Increase in beam size causes loss of luminosity, quite apart of the collision offset. This can in principle be corrected using the measurements from the LEP Beam Emittance UV monitors (BEUV), after suitable calibration [7]. It has been shown that BEUV and luminosity are well correlated [8]), at least on a short time basis. This makes it possible to correct the fitted luminosity profile by the variable beam size:

$$\mathcal{L}(y_v) = e^{-\frac{1}{2}\frac{(Y_v - Y_0)^2}{\sigma_y^2(e^+)+\sigma_y^2(e^-)}} \frac{I^+.I^-}{2q_e^2.f_{rev}.\pi\sqrt{(\sigma_y^2(e^+) + \sigma_y^2(e^-))(\sigma_x^2(e^+) + \sigma_x^2(e^-))}} \tag{4}$$

for single bunch crossing, where the beam sizes are varied proportionally to the measured beam sizes in the BEUV, q_e is the charge of the electron, f_{rev} the revolution frequency, I^+, I^- the positron and electron bunch currents.

For data taken until end of june 1995, only the average beam sizes were recorded, and not the individual beam sizes of all bunches. Correction for beam size could not be done rigorously. In cases with the 4×2 configuration where the two bunches were not offset, and with rather equal bunch currents between the families, the goodness of the fits could be significantly improved [9].

To assess the systematic error from this source, the results of fits performed with and without correction for the average beam size to the total (summed over bunches and trains) luminosity were compared. The result is a difference of $-0.05 \pm 0.035\mu\mathrm{m}$ with an r.m.s. spread of 0.350 $\mu\mathrm{m}$ for 102 vernier scans. This indicates that there is no obvious systematic bias on the average, but that, for the moment, an additional systematic error of around $0.350\mu\mathrm{m}$ should be added from this source on the result of each individual fit. In the following, the results of gaussian fits will be shown, bearing in mind this additional systematic error. After the technical stop, the beam sizes of all bunches in LEP will be recorded, both during vernier scans and during normal data taking. A more complete correction will then be possible, and this error should be much reduced.

It was noted that the quality of either type of fit is sometimes very poor. In particular, when several luminosity measurements were taken at each vernier step, the spread of the results was larger than the estimated errors by a factor of around 1.5. There are several possible origins of this fact, among which: i) inadequacy of the assumption of random background for the LEP luminosity monitors; ii) timing errors; iii) varying beam size. Although some of the bad readings could be attributed clearly to one of these causes, no unique systematic trend could be found. Improvements of points ii) and iii) are being pursued. Meanwhile the errors on vernier scan results have been enlarged by a factor 1.5.

3.3 Reproducibility and stability of collision offsets

The 102 vernier scans of the first period were performed under considerably varying conditions. The bunch train bump amplitudes were often varied, in particular for considerations of backgrounds to the experiments. The number of bunches per train and the currents were also highly variable. Nevertheless the r.m.s. of the scan results, excluding those taken for dispersion measurements, are of the order of 2-3 microns over the whole period, table 1. It was found that the result of the fit to the vernier scans was typically within 1-2 microns of the optimum found empirically by the operator.

A more telling statistics come from the last period of the run, june 23-25, were three long consecutive fills were taken, with almost unchanged bunch train bump amplitude, 100% in all IPs except in OPAL where the bump amplitude was changed from 100% to 80%. The statistics are shown in table 2.

Table 1: *Statistics of vernier scans performed june 4 to june 25. Vernier scans used for dispersion measurements are not included.*

All bump amplitude and train configurations			
IP	scans	average($Y^{\mathrm{max}}_{\mathrm{vernier}}$)($\mu$m)	r.m.s.($Y^{\mathrm{max}}_{\mathrm{vernier}}$)($\mu$m)
L3	24	-4.2	2.5
ALEPH	23	-3.8	1.8
OPAL	23	-6.5	3.8
DELPHI	22	6.0	1.4

Table 2: *Statistics of vernier scans performed with 4x4 bunch train running from june 23 to june 25. BT bump amplitudes where 100% in all points, except in OPAL where the bump amplitude was lowered to 80% on june 24 at 23:00.*

4X4 bunch train running			
IP	scans	average ($Y^{\mathrm{max}}_{\mathrm{vernier}}$)($\mu$m)	r.m.s.($Y^{\mathrm{max}}_{\mathrm{vernier}}$)($\mu$m)
L3 all	7	-6.92	1.1
100% amplitude in OPAL	3	-7.72	0.8
80% amplitude in OPAL	4	-6.33	0.9
ALEPH	5	-3.9	0.5
100% amplitude in OPAL	2	-4.8	0.3
80% amplitude in OPAL	3	-3.5	0.1
OPAL	8	-8.7	2.2
100% amplitude in OPAL	4	-11.25	0.6
80% amplitude in OPAL	4	-6.46	0.8
DELPHI	5	5.7	0.5
100% amplitude in OPAL	2	5.3	0.1
80% amplitude in OPAL	3	5.9	0.5

The effect of changing the bump amplitude is very visible on the OPAL collision offset which varied by four microns. It is less clear on the other interaction points. The fluctuations on the offsets in the previous period could be largely correlated to such bump amplitude changes, when those were recorded.

We conclude that, once the electrostatic structure of LEP was stable, a stability of the collision offsets within an r.m.s. of better than 1 micron was observed.

3.4 Sources of variation of collision offsets

Table 3: *Vertical separation (in microns) between e^+ and e^- trains due to parasitic beam beam kicks in the four IPs (From [4], table 2), and resulting r.m.s. variation in $Y^{\max}_{\text{vernier}}$ when current decreases from 300 to 150μA.*

Variation of collision offsets with bunch current		
IP	average separation between e^+ and e^- trains $I_{\text{bunch}} = 300\mu$A	resulting r.m.s. variation during a fill $I_{\text{bunch}} = 300\mu$A to $I_{\text{bunch}} \simeq 150\mu$A
L3	+1.46	0.20
ALEPH	-4.68	0.68
OPAL	+1.94	0.27
DELPHI	-2.43	0.35

Collision offsets are not expected to be stable, even in a perfectly stable configuration of LEP. The following sources of variations are known.

1. *Variation of the LEP beam energy.*

   Because of the OSVD, variations of the LEP beam energy cause an opposite movement of the electron and positron beams.

$$\Delta Y^{\max}_{\text{vernier}} = -(\Delta Y(e^+) - \Delta Y(e^-)) = -(D_y(e^+) - D_y(e^-))\frac{\Delta E}{E} \qquad (5)$$

   It is well known [10] that terrestrial tides change the beam energy by up to $\Delta E/E = 2.\ 10^{-4}$ in 8 hours on high tide days. This corresponds to a full swing of 0.8 microns on the vernier offset within a fill. This effect can easily be corrected for if the dispersion is known. If uncorrected it contributes about 0.3 microns to the r.m.s. spread of the results. Other sources of changes of the beam energy due to the geometrical deformation of LEP are probably much slower. Deliberate changes in beam energy via RF frequency changes can be used to measure the OSVD, see below.

2. *Variation of the beam currents.*

   The bunch train shape is expected [4] to scale in proportion to the beam currents, and so does the global offset. The average separation between e^+ande^- trains is calculated in [4] and reproduced in table 3. If the current decreases during a physics fill from 300 to 150 μA, one expects a variation of the point of maximum luminosity by half this offset, leading to the r.m.s. variations shown in the same table.

3. *Variations in the magnetic configuration of LEP*
   are expected to produce very similar effects on $e^+$and e^- beams. They should induce variations in the collision offsets only to second order, because of saw-toothing. This has not been studied so far.
4. *Variations in the electrostatic configuration of LEP*
   are definitely expected to modify the electron and positron orbits differently. The jump in the offset shown in table 2 upon variation of the bump amplitude is revealing. The change in bump amplitude should not really cause such an effect, this points to the fact that the BT bump in point 6 was not well closed. Both from the points of view of center-of-mass energy determination and for good luminosity, large changes in the electrostatic configuration should either be avoided, or trigger vernier scans to be performed. Empirical optimization of the vernier setting to improve luminosity naturally converges to the luminosity maximum, and, since the vernier settings are logged, can be corrected for off-line if needed. Even for a stable configuration, drift in the field of the electrostatic separators could occur at the level of 0.4 microns [11], leading to an additional spread of 0.15 microns.

In summary, for a stable electrostatic configuration of LEP, the variation of collision offsets from the considered sources is around 0.7 microns r.m.s. or less. The observed variations (table 2) are consistent with this order of magnitude estimate.

4 Measurements of Bunch train properties

Vernier scans give access to three important quantities: OSVD, offset splitting within the trains and vertical beam size.

4.1 Measurements of Opposite Sign Vertical Dispersion

By comparing collision offsets measured by vernier scans performed with different LEP RF frequencies f_1 and f_2, it is possible to derive the OSVD:

$$\frac{(D_{e^+} - D_{e^-})}{2} = \frac{1}{2} \frac{Y^{\mathrm{max}}_{\mathrm{vernier}}(f_1) - Y^{\mathrm{max}}_{\mathrm{vernier}}(f_2)}{f_1 - f_2} \cdot \alpha \frac{f_1 + f_2}{2} \qquad (6)$$

where $\alpha = 1.85\ 10^{-4}$ is the momentum compaction factor, $Y^{\mathrm{max}}_{\mathrm{vernier}}(f_1)$ (resp. f_2) is the vernier position of the luminosity maximum for RF frequency f_1 (resp. f_2). This experiment was performed on two occasions. On June 17 the machine set-up was 4x2 trains with BT bump amplitudes of (80%, 64%,80%, 64%). On june 25, the set-up was 4x4 trains with BT bump amplitudes of (100% in IP 2,4,8, 80% in IP6), with better vernier scan parameters and luminosity monitor noise conditions. The results for the average over families is shown in table 4. The dispersion for each of the families was also measured [12]. They were found to be consistent within the present statistical and systematic errors. The expected differences between bunches are of the order of 0.1 mm, and not accessible to measurements at this point.

Table 4: *Measured Opposite Sign Vertical Dispersion (in millimeters) compared with the predicted values from [4]. The first errors come from the statistical precision of the measurements, the second ones from estimated systematic uncertainties.*

Opposite Sign Vertical Dispersion (mm)			
BT bumps	Measured on June 17 (80%, 64%,80%, 64%)	Measured on June 25 (100%, 100%,80%,100%)	Predicted (4 x 100%)
L3	+1.38 ±0.13±0.15	+1.37 ±0.09±0.15	+1.95
ALEPH	-0.05 ±0.18±0.15	-0.66 ±0.08±0.15	-0.94
OPAL	+1.59 ±0.23±0.15	+1.70 ±0.11±0.15	+2.01
DELPHI	-0.46 ±0.20±0.15	-0.26 ±0.08±0.15	-0.50

Table 5: *Measured Opposite Sign Vertical Dispersion (in millimeters) for the four families on june 25. The first errors comes from the statistical precision of the measurements, the second ones from estimated systematic uncertainties.*

Opposite Sign Vertical Dispersion per Family (mm)				
IP	family a	family b	family c	family d
L3	+1.37 ±0.22±0.15	+1.34 ±0.24±0.15	+1.30 ±0.19±0.15	+1.47 ±0.40±0.15
ALEPH	-0.78 ±0.22±0.15	-0.51 ±0.23±0.15	-0.71 ±0.20±0.15	-0.62 ±0.23±0.15
OPAL	+1.52 ±0.23±0.15	+1.40 ±0.25±0.15	+1.66 ±0.27±0.15	+2.19 ±0.32±0.15
DELPHI	-0.45 ±0.22±0.15	-0.25 ±0.23±0.15	-0.06 ±0.20±0.15	-0.29 ±0.23±0.15

4.2 Collision offsets per family

The vernier scans performed in the 4x2 mode revealed that families a and c had the same collision offset [9]. This was in contradiction with the theoretical predictions at the time [2], but in good agreement with the new calculations [4].

The deviations of the individual family offsets with respect to the overall train offset are shown in table 6 for the vernier scans performed in the 4x4 mode.

Table 6: *Deviations of the individual families collision offsets from the average of the train, for the vernier scans taken from june 23 to june 25 in 4x4 mode. The errors shown are calculated from the r.m.s. of the results. The prediction from [4], table 2, is scaled down to a current of 140μA. It is calculated for equal bunch currents and predicts equal deviations for bunches (a and d) or (b and c), equal to the average of (a and d) minus the average of (b and c) noted "(a+d-b-c)/2".*

Collision offsets per family (μm)						
IP	family a	family b	family c	family d	(a+d-b-c)/2	prediction
L3	+1.40 ±0.16	-0.56 ±0.06	-0.78 ±0.07	+0.05±0.10	+1.39 ±0.10	+1.66
ALEPH	-0.34±0.16	+0.64 ±0.20	+0.28 ±0.07	-1.18 ±0.40	-1.22 ±0.27	-1.40
OPAL	+0.89 ±0.35	-0.93 ±0.50	-1.11 ±0.50	+0.92±0.45	+1.92 ±0.45	+1.66
DELPHI	-1.30 ±0.17	+0.92 ±0.08	+0.97 ±0.14	-0.75±0.20	-1.97 ±0.17	-1.85

4.3 Vertical beam sizes at the interaction points

The fitted width of a vernier scan is related to the beam size by the formula 3. Table 7 shows the resulting beam sizes per family for the 4x4 vernier scans. The difference between IPs could point to differences either in the optics or in the calibration of the vernier scale. However, a close look at formula 2 leads to the conclusion that, since the collision offset and OSVD are both normalized to the beam size, all being measured in the same units by vernier scans, the vernier scale drops out in the estimate of energy shifts.

5 Systematic errors on beam energies

The systematic error on the average center-of-mass energy for data taken at one of the off-peak points could be estimated as follows:

- Error from the uncertainty in the collision offset. Let us assume that N_{verniers} are performed with a reproducibility of 1 micron. Using the measured OSVDs and beam sizes for all four IPs, the largest of the resulting center-of-mass errors is 2.4 MeV$/\sqrt{N_{\text{verniers}}}$. If 15 fills are taken and two vernier scans are performed per fill, the error on the average center-of-mass energy is therefore less than 0.5 MeV.

Table 7: *Beam sizes at the Interaction Point calculated from gaussian fits to the vernier scans performed from june 23 to june 25 in 4x4 mode. The statistical error on these numbers is about 0.2. The systematic uncertainties have not been calculated.*

Beam sizes per family (μm)					
IP	family a	family b	family c	family d	all families
L3	3.81	3.85	3.98	3.88	3.95
ALEPH	4.80	5.10	4.56	5.50	4.91
OPAL	4.76	5.10	5.25	5.69	5.37
DELPHI	4.07	4.06	3.93	4.46	4.15

- Error from the unequal dispersions between bunches. Formula 2 is only valid if one assumes equal dispersions for all bunches. If one takes the measurements of dispersion of table 5, and the bunch offsets and sizes of tables 6 and 7, one can calculate by how much the average center of mass energy would be shifted when the overall collision offset is zero. The result is consistent with zero, with uncertainties coming from the measurement errors adding up to 0.3 MeV.
- Error from the dispersion and beam size in case the average collision offset is non zero. If a correction has to be made to the data for a systematic non-zero collision offset, the uncertainty on the dispersion and beam size has to be propagated. Assuming that the largest difference between the measured dispersion and its prediction gives an order of magnitude of the unpredictability of the OSVD, e.g. 0.6 mm, and an offset correction of 0.3 microns, an error of 0.34 MeV results. The predictability of dispersion should rather come from a few measurements of this quantity, from which the spread could be assessed more reliably. If a number N_{disp} measurements of OSVD can be performed, the error will be reduced accordingly. Assuming that measurements of dispersion are performed every two weeks, four measurements at least should be available, giving an uncertainty of less than 0.2 MeV.
- Systematic bias on the vernier scan procedure. The above mentioned bias of 0.05 ± 0.035 leads to an error estimate of less than 0.3 MeV.

Summing these uncertainties in quadrature leads to a total error estimate of less than 0.7 MeV for each scan point and all experiments. Correlations between energy points and experiments have to be considered. Since many sources of variation of offsets and dispersion are common to all energies and experiments, it is likely that these correlations (or even anti-correlations for the experiments) will not be negligible. Taking an estimate of 50% correlation between experiments and energy points, an error estimate of 0.4 MeV on the Z width and 0.5 MeV on the Z mass is obtained.

6 Center-of-mass energy spread

Table 8: *Monochromatization and shift on the Z width resulting from OSVD in the four IPs. These numbers were calculated using the measured OSVDs and collision offsets per family.*

Monochromatization		
IP	Monochromatization(%)	$\delta\Gamma_z$(MeV)
L3	3.9±1.1	0.39± 0.11
ALEPH	1.3±0.5	0.13± 0.05
OPAL	5.8±1.5	0.58± 0.15
DELPHI	0.4±0.2	0.03± 0.02

Independently of the collision offsets, OSVD causes a reduction of the center-of-mass energy spread (monochromatization). This reduction results in a shift of the measured value of the Z width. For an center-of-mass energy spread of 55 MeV, a 1% change results in a shift of 0.1 MeV on the Z width. Using the measured offsets and dispersions, one obtains the monochromatizations and shifts given in table 8. The resulting systematic error on Γ_z is less than 0.2 MeV for all experiments.

7 Tracing the collision offsets

It would be of great interest to be able to interpolate the collision offsets between vernier scans, to allow i)better precision on the collision offsets, ii)to maximize luminosity. Three proposals have been made in this direction and are being actively pursued.

1. Direct determination of the point of maximum luminosity using for each family the measured luminosities, the recorded BEUV sizes and the individual currents. (Asymmetry method). It is clear from figure 1 that the relative luminosities of the different bunches are quite sensitive to a variation of the vernier setting. Formula 4 can be fit using these input data to give the point of maximum luminosity without having to perform a vernier scan, provided the separation between bunches in the train is known and large enough. The good agreement between data and the predictions gives confidence that the internal offsets could be determined reliably from bunch currents. A precision of better than 0.3 microns could be in principle obtained every four minutes. This method can be tested off-line immediately after the technical stop and implemented on-line soon after.
2. Variation of the extrapolation of the individual bunch trajectories to the interaction point using the WB beam pick-ups [13]. This method could provide a fast measurement of the collision offsets at the IP in a relative manner. Tests will be needed to check that normalization to vernier scans is possible and that the result is stable and precise enough.
3. An other possibility [14] would be to explore continuously the collision offsets by varying the vernier setting at regular intervals, and provoking movements towards the point of maximum luminosity. Simulations made for one collision point show good

convergence to the actual luminosity maximum, with a precision of 0.2 microns [15]. The actual programming for four experiments and the interference with other machine optimizations remain to be understood.

The advantage of all three methods is to provide control of the offsets also at the beginning of fills, where conditions are still unstable, and vernier scans potentially hazardous. The first two methods are entirely passive, and could lead to a "collision offset monitor" (COM) providing on-line information to the operator. Their efficiency will be re-assessed after a week of running after the technical stop. If one of these methods is successful, one would obtain a substantial reduction of the final errors, and considerable operational advantages. They have not been used yet in the assessment of systematic errors shown in this document which can therefore be considered as upper limits.

8 Proposed strategy

It has been shown that the errors on the center-of-mass energies stemming from the opposite sign vertical dispersion in the bunch train mode of LEP operation can be reduced to a small number thanks to the precision and reproducibility of the vernier scans.

The following strategy for the line shape scan, based on vernier scans [16], is proposed. This strategy applies to **off-peak** energies only.

1. Vernier scans should be performed routinely twice per fill, once as early as possible in the fill during the first half, and once during the second half of the fill.
2. Vernier scans should be performed before and after every modification of the electrostatic set-up of LEP. It would be preferable to run with stable electrostatic conditions.
3. Dispersion measurements should be performed at regular intervals, at least every two weeks.
4. Logging of beam sizes and luminosities for each family of bunches is necessary at regular intervals (say 4 minutes) and at every step of the vernier scans, and will be done [17].
5. The LEP experiments can continue taking data during vernier scans. Provision is made [18] to allow them to tag events taken during vernier scans and follow changes in the vernier settings, during and outside of vernier scans.
6. The results of vernier scans will be made available in the LEP control room within a short delay (few minutes).

This strategy will ensure systematic uncertainties as above. The necessary logging and improved procedures will be tested during the first week of running after the technical stop. The integrated luminosity loss due to vernier scans is less than 2%. Data taken during vernier scans will represent 5% of the total off-peak luminosity.

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