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LEP Energy Calibration in 1996

The LEP energy working group

Abstract

The methods developed to measure the LEP1 beam energies in previous years have been extended to allow the determination of beam energies in 1996. At LEP2 the average energy can no longer be measured by the technique of resonant depolarization at physics energy. In 1996 the energy was measured at two lower energy points using resonant depolarization, and the energy scale at physics energy was inferred by extrapolation using magnetic measurements with a number of NMR probes in LEP dipole magnets, and the flux-loop measurement of the integrated LEP dipole field. The mean beam energy for 1996 has been determined with a precision of about 30 MeV.

1 Overview

The LEP running in 1996 at centre-of-mass energies of 161 and 172 GeV marked the start of the LEP2 physics program. Data samples of about 10pb^{-1} were recorded by the experiments at each of the two energies. The initial choice of 108/60 optics proved too difficult to operate, and the 161 GeV data were delivered during July and August with the 90/60 optics in bunch-train mode, at first with trains of one bunchlet, and later with trains of two bunchlets. There was then a technical stop during which additional superconducting RF cavities were installed. Data taking resumed in October at 172 GeV, again with the 90/60 optics and almost all fills with trains of one bunchlet. After a three-day stop to recable the sextupoles at the beginning of November, the last week of 172 GeV running was with the 108/90 optics.

With the 1996 data alone, the anticipated precision on the W mass is about 150 MeV, so a beam energy precision of less than 50 MeV is quite adequate. With the desired full LEP2 sample of 500 pb^{-1}, the experimental errors on the W mass should be less than 40 MeV, requiring a beam energy uncertainty of at most 15 MeV.

The method used to calibrate the beam energy in 1996 was an extension of that used for the scans of the Z lineshape [1, 2], which can be summarised as:

- Determine the absolute energy scale by resonant depolarization.
- Model the variation of the average beam energy with time from effects such as earth tides and the rise in dipole field during a fill due to temperature and parasitic train currents.
- Calculate corrections specific to each interaction point (IP) due to the RF configuration and vertical collision offsets.

However, the determination of the absolute energy scale is made more complicated at LEP2 because no polarization measurement is likely to be possible at the physics energy. The energy scale in 1996 was established from three fills during which the beam energy was determined by resonant depolarization at a beam energy of 45 or 50 GeV. This energy estimate was carried over to the physics fills by the 16 NMR probes installed in dipole magnets in the tunnel: there is at least one probe in each octant, and in octants 1 and 5 there are strings of 5 probes in adjacent dipoles. The uncertainty in the extrapolation of the energy scale was determined from comparisons of the NMR probes, the flux-loop magnetic field measurements and the resonant depolarization measurements at 45 and 50 GeV, relying heavily on a single fill in which both energies were measured.

The determination of the time dependent variation of the average energy was simplified by having at least one NMR probe per octant, whereas in 1995 only two octants were equipped. Also in contrast to 1995, no magnet conditioning ("bend modulation") was performed at the start of physics fills in 1996.

In section 2, the determination of the absolute energy scale from resonant depolarization and magnetic measurements is described. In the following section, the derivation of the time dependent variation of the average energy over the ring is explained. The IP-specific corrections are presented in section 4. The systematic uncertainties in the beam energy estimate are listed in section 5 and the paper concludes with a discussion of future prospects for energy calibration.

2 Absolute energy scale

2.1 Polarization measurements

During 1996, attempts were made to measure the beam energy by the technique of resonant depolarization [3] at energies around 45 GeV, where the procedure was well established in previous years, and at higher energies. The maximum energy at which a depolarization measurement was achieved was 50 GeV. This fixes the lever arm over which the extrapolation of magnetic measurements can be tested to 5 GeV. The distance of extrapolation to the physics beam energies of 80.5 and 86 GeV is also determined by the maximum polarized energy, so that the measured extrapolation uncertainties must be scaled by 30.5/5 and 36/5 for the two running periods.

Several depolarization measurement during the first running period were rejected after close examination revealed that not all mirror resonances or side-band resonances had been excluded by cross-checks during the energy measurement. The unambiguous measurements are listed in Table 1, where they have been corrected to give just the dipole contribution to the energy (i.e. corrected for RF frequency, tide and xarc effects). These can then be compared directly to the predicted energy from the NMR probes using the energy model that is described below (sections 2.5 and 3). Each row in the table corresponds to an average over several depolarizations.

Fill	Date	E^{depol}	E^{model}
3599	19/08	50012.0	50021.4
3702	31/10	44707.0	44706.9
3719	03/11	44710.8	44710.3
3719	03/11	50010.9	50008.0
3719	04/11	50010.5	50008.2

Table 1: *Polarization measurements in 1996. The value E^{depol} is the energy from resonant depolarization, corrected for RF frequency, tide and xarc. The value E^{model} is calculated from the calibrated NMR probes.*

Only one of these measurements is from the first running period, in fill 3599 at 50 GeV, and even this measurement is not of the best quality. As can be seen, the energy measured in this fill is in relatively poor agreement with the prediction from the model based on NMR data. Keeping in mind possible problems with this measurement, it is nontheless retained as a check of the first data-taking period at 161 GeV.

Two fills were calibrated in the second running period, including calibrations made at two different energies in fill 3719. This fill is used to assess the linearity of the energy extrapolation, as discussed in section 2.2. The first measurement at 50 GeV in this fill was with a polarization level of 5%, while the second was made after applying harmonic spin matching to increase this level to 12%, as shown in Figure 1.

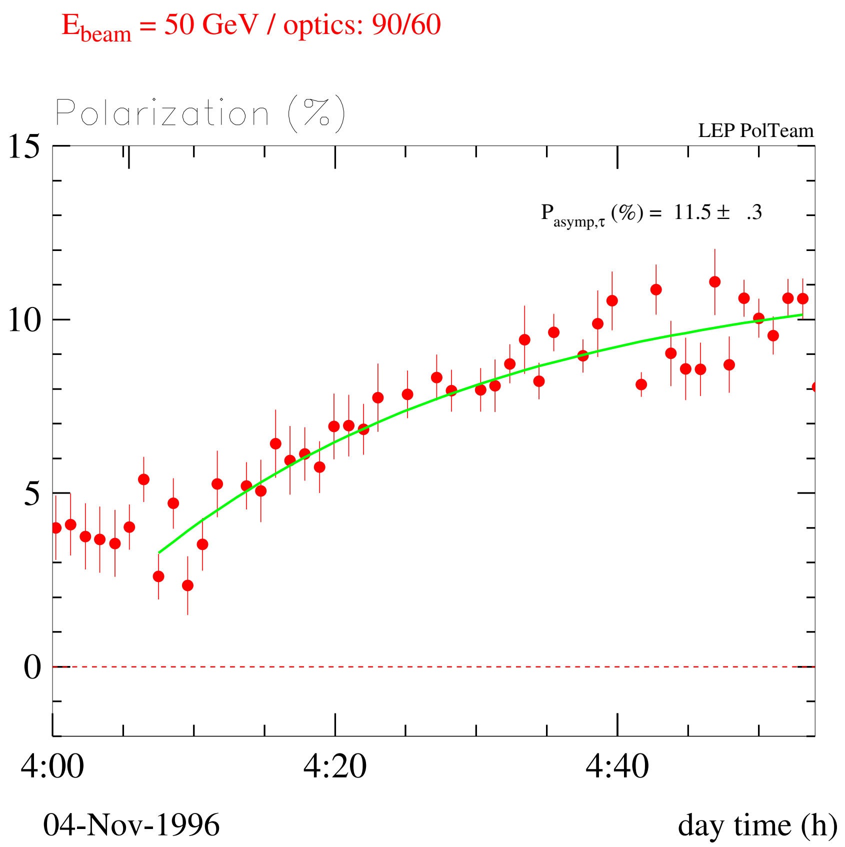

Figure 1: *The level of polarization achieved at 50 GeV with harmonic spin matching.*

2.2 Comparison of polarization and NMR's

The NMR probes in the LEP tunnel provide information throughout a physics fill on the magnetic field in a sample of LEP dipole magnets. In section 2.5, the determination of the energy scale for 1996 using all the polarized fills is described. In this section, the linearity of the energy calibration derived from the NMR probes is discussed. This uses the single fill (fill 3719) with beam energy measurements by resonant depolarization at both 45 GeV and 50 GeV. Since the depolarization measurements in a single fill share the same magnetic and thermal history, they should be less susceptible to systematic fill-to-fill differences, and allow a more precise check of the linearity of the energy extrapolation.

As a result of synchrotron radiation damage, only 11 of the 16 tunnel probes provided readings in fill 3719 for the five depolarizations at 45 GeV and the six depolarizations at 50 GeV. Each 45 GeV depolarization j was used to calibrate all the NMR probes individually, and these calibration factors were then used to calculate an extrapolated energy $E_{jk}^{\mathrm{ext},i}$ at 50 GeV, to be compared to each 50 GeV depolarization measurement k. The difference between extrapolated and depolarization energies at 50 GeV was formed as:

$$\Delta E_{jk}^{i} = E_{jk}^{\mathrm{ext},i} - E_{k}^{\mathrm{depol}} = \frac{E_{j}^{\mathrm{depol}}}{B_{j}^{i}} B_{k}^{i} - E_{k}^{\mathrm{depol}}, \qquad (1)$$

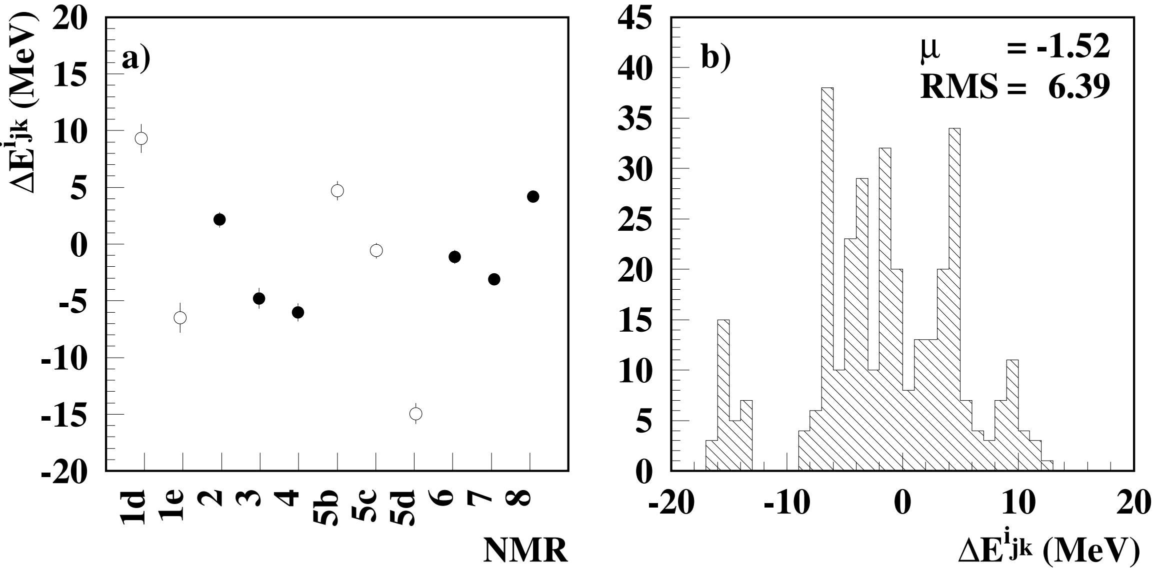

Figure 2: *The comparison of NMR calibrations at 45 and 50 GeV: a) the mean and RMS ΔE^i_{jk} for each NMR probe used – the hollow points show octants with more than one probe (labelled a,b,c...), and the solid points show single-probe octants; b) one entry per ΔE^i_{jk} for all NMR probes and all calibrations.*

where B^i_j (B^i_k) is the NMR i field reading at the time of depolarization j (k).

Figure 2 shows the values of ΔE^i_{jk} for each of the 11 available probes, and all possible jk extrapolations. The mean of the distribution is -1.5 MeV and is taken as an estimate of the average NMR non-linearity from 45 to 50 GeV. The RMS spread amongst the individual probes is 6.4 MeV and is used as an estimate of the sampling error on this mean non-linearity. The mean non-linearity is almost identical when the probes in octants 1 and 5 are averaged together to form a single device for each octant. When scaled for an extrapolation to 80.5 GeV (86 GeV) the resulting energy difference is -8.8 ± 11.6 MeV (-10.3 ± 13.7 MeV). Since this is consistent with zero, no explicit correction was applied to the NMR calibrations in extrapolating to physics energies. The normalization procedure (section 2.5) uses both depolarization energies and therefore absorbs part of the difference into a single calibration coefficient assigned to each probe.

The non-linearities of the three probes within octant 5 are systematically different, ranging from -15.0 MeV to $+4.7$ MeV over the interval from 45 to 50 GeV. A similar range is seen for octant 1. In both cases the range within an octant is larger than the range of the other 6 single-probe octants. Since the environment and beampipe current were similar for all dipoles within an octant, the observed variation can be attributed to inherent variability amongst the dipoles themselves. Under this assumption, the most conservative error evaluation comes from treating the 11 available NMR probes as independent samples from the total number of dipoles, rather than to average devices in octants 1 and 5, which would reduce the total spread due to cancellation of the most non-linear of the devices.

2.3 Flux-Loop Calibrations

All the 3280 standard LEP dipoles are equipped with individual "flux-loops". Each flux-loop is made of thin wires embedded in grooves machined in the lower poles of the magnets [4]. At the time of the calibration prior to installation in the tunnel, the magnetic properties of each dipole were determined on test benches. The field measurements were compared to the induced voltage in the flux-loop to provide a calibration of the effective area of each flux-loop. The typical area is 1.3 m^2. In LEP the flux-loops of all dipoles in one octant are connected in series. The signal of each octant is digitised by high-precision integrators. The average field for each octant can then be reconstructed using the knowledge of the flux-loop areas.

During a full flux-loop calibration, the main dipoles were first cycled through the standard degauss cycle from 300 A up to 4480 A and back to 300 A. Then the power converters were switched off and the polarity was inverted. The current was ramped to −4480 A before being brought back to 300 A with the nominal polarity. This procedure

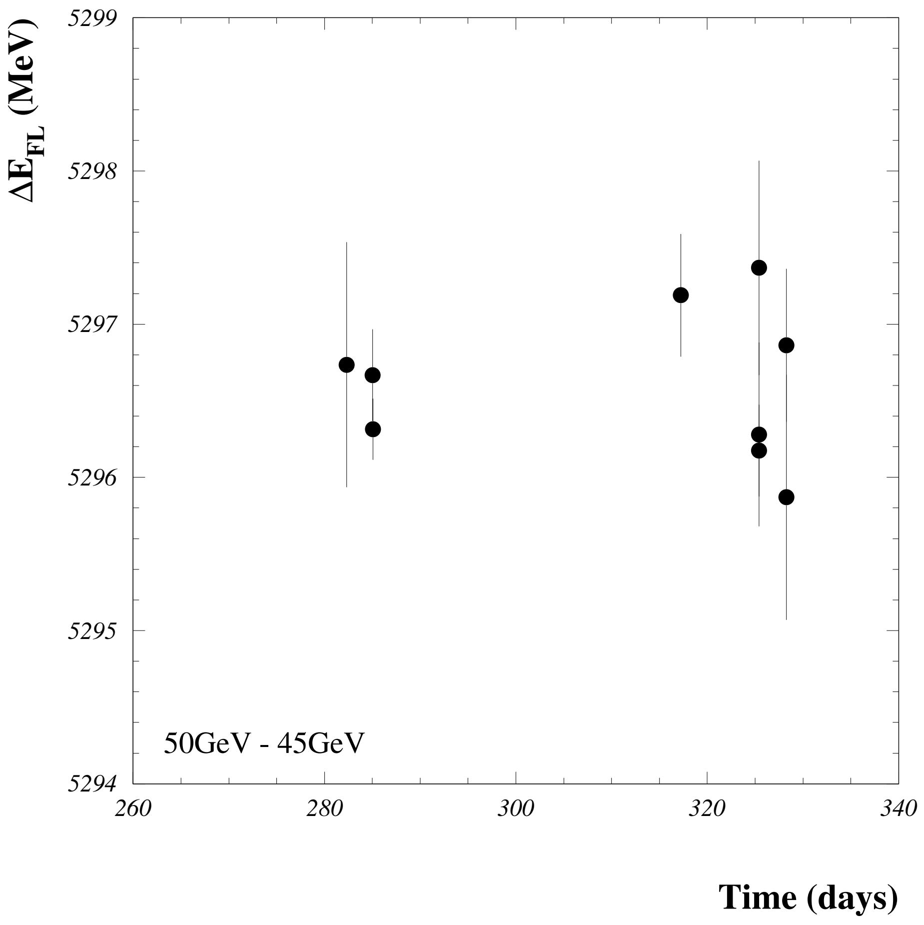

Figure 3: *Energy difference between the 45 and 50 GeV LEP settings measured by the flux-loop as function of time. The mean value is 5296.6 MeV with an RMS spread of 0.6 MeV.*

provides an absolute calibration of the field, but it provokes a strong perturbation of the magnetic cycle of the dipoles, requiring many degauss cycle to restore the initial magnet behaviour. To avoid such unpleasant side effects, most flux-loop calibrations performed in 1996 used only the normal degauss cycle (without change of polarity), which provides a relative field calibration, sufficient to interpolate the beam energies.

To compare the flux-loop results with beam energies measured by resonant depolarization, the fields must be converted into a beam energy on the central orbit using the knowledge the effective length of the dipoles (19.19 km). The relative contributions of the 24 double-field injection dipole cores (1.44%) and of the 32 weak dipole cores at the end of the arcs (0.19%) have also to be taken into account because their contributions are not measured with the flux-loop. An attempt to compare the "pure dipole" part of the beam energy extracted from the resonant depolarization with flux loop results indicates a difference of 3 ± 2 MeV for the difference between the 45 and 50 GeV settings. The error of 2 MeV on the 5 GeV lever arm leads to an error of 12 to 15 MeV at 80.5 and 86 GeV for a linear scaling. Figure 3 shows the stability of the flux-loop measurements over a period of 3 months.

2.4 Comparison of flux-loop and NMR measurements

Three experiments were performed during 1996 to compare NMR and flux-loop measurements. During these dedicated experiments the dipole magnets were ramped from 80 to 900 Gauss. At nine field values above the NMR threshold of 450 G, the ramp was interrupted for 5 min in order to allow the NMRs to sample the field a sufficient number of times. At each step the change in the magnetic field was also measured by the flux-loop system.

For each experiment and for each NMR probe, a linear fit was made to the field measured by the probe as a function of flux-loop field change. The average fit parameters from the three experiments were then computed for each individual probe, and the residuals of the NMR readings with respect to this average fit were calculated for each probe at each of the nine steps and for each experiment.

In Figure 4, the mean and RMS of the residuals for the 16 probes are shown for two of the experiments that were separated in time by one month. The flux-loop measurements are relative to the initial field at 80 G. In the figure, linear fits to the residuals as a function of flux-loop setting are also shown, to illustrate the difference between the two experiments. The different constant term for the two experiments can be attributed to fluctuations in the initial field in the dipoles and is not significant. The non-zero slopes allow an estimate of the relative change of linearity of the flux-loop and NMR measurements, although the cause of the slope cannot be unambiguously determined. The difference in slopes corresponds to about 10 MeV at the highest energy. The RMS scatter at each point corresponds to about 3 MeV, and is dominated by the non-reproducibility of the magnets. The pattern in the scatter of the points around the fitted line arises from the systematic differences in the hysteresis curve of the dipole subset equipped with NMR probes respect to the whole ring as seen by the flux-loop. In conclusion, the flux-loop and NMR energy measurements agree to about 10 MeV at the physics energy, and show similar linear extrapolation properties.

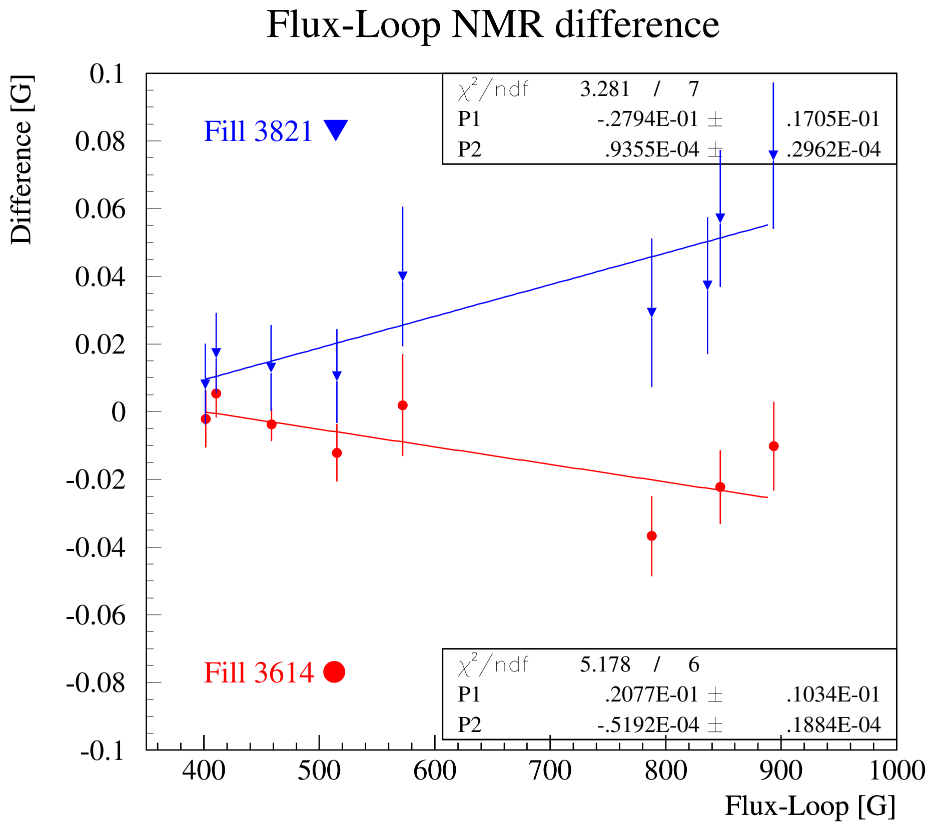

Figure 4: *Mean and RMS of residuals of the NMR readings from a linear fit to NMR readings as a function of the change in field measured by the flux-loop. Two separate experiments are shown, which were separated by one month.*

2.5 Normalization of beam energies for 1996 data

In the determination of the energies for each fill, the starting value of the dipole field was taken from a mean of the energies of each octant, as estimated from the NMR probes. This required a calibration of each NMR to relate the field reading to the mean beam energy.

The calibration was performed using the four averaged depolarization measurements at 45 GeV and 50 GeV, in the three fills 3599, 3702 and 3719. (All the 50 GeV depolarizations in fill 3719 were averaged together for this purpose, so that there are only four combined measurements to be considered.) For each probe, at each depolarization, a single calibration coefficient k_i was determined:

$$E^{\,\mathrm{depol}} = k_i B^i(t=0) + \Delta E^{\mathrm{dipole}}_{\mathrm{ring}} + \Delta E^{\,\mathrm{tide}} + \Delta E^{\,\mathrm{xarc}} \tag{2}$$

where $E^{\,\mathrm{depol}}$ is the mean beam energy as measured by the depolarization, $B^i(t=0)$ is the reading of the NMR at the start of fill, $\Delta E^{\mathrm{dipole}}_{\mathrm{ring}}$ is the mean rise in dipole field seen over the entire ring between start of fill and the measurement, $\Delta E^{\,\mathrm{tide}}$ is the calculated correction to the energy at time of polarization from the earth tides, and $\Delta E^{\,\mathrm{xarc}}$ the xarc correction for this fill. These corrections are discussed in section 3.

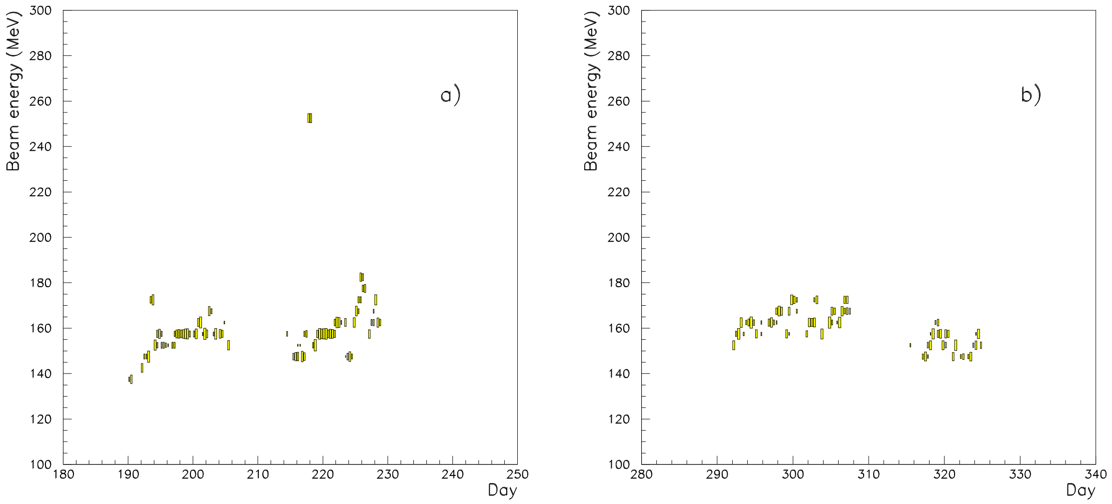

Figure 5: *Energy at the start of physics fills after calibration of the dipole field measured by the NMRs, for first (a) and second (b) periods of running, against day of year. The energies have had* $80,500$ *and* $86,000$ *MeV subtracted, respectively. The anomalous energy around day* 220 *in plot a) is caused by a high setting of the bending current.*

Note that $\Delta E_{\rm ring}^{\rm dipole}$ is taken from the mean rise of all NMRs. It is known from observation that the dipole field evolves differently in each magnet, thus it is more correct to take the field rise averaged over the ring to relate a specific NMR to the value of the depolarization energy.

For each NMR, the k_i coefficients were averaged over the 4 depolarizations to find a single value best suiting that ensemble of data. For certain probes in certain fills, readings were absent at the time of depolarization. However there were sufficient data to obtain calibration coefficients for each octant. The probes in octant 4 and 8 were replaced between the 161 GeV and 172 GeV running; the calibration coefficients for these octants were fixed wholly by depolarizations occuring in the latter period.

This calibration procedure fits a linear dependence between NMR reading and beam energy at 45 GeV and 50 GeV, passing through the origin. The uncertainty on the assumption of linearity is discussed in section 2.2.

After calibration, the ring energy according to the model of equation (2) was recalculated for the 4 depolarizations, but averaged over all the NMRs in all octants. The distribution of $E^{\rm depol} - E^{\rm model}$ was centred on zero with an RMS scatter of less than 5 MeV, with the largest pull coming from fill 3599.

Using this calibration, the initial energies for physics fills can be calculated. Figure 5 shows the distribution of initial energy plotted against the day of year for both the 161 GeV and 172 GeV running. The initial energies have an RMS scatter of 9 MeV and 7 MeV for the 161 and 172 running respectively.

The systematic uncertainty in this calibration and modelling procedure was assigned by repeating the NMR calibration, with slight variations in procedures. Subsets of the depolarizations were used, and different criteria of data quality were applied in treating the

NMR measurements. It was established that the exclusion of the potentially anomalous fill 3599 had little effect. The bias induced in the 161 GeV analysis by using calibration coefficients for octants 4 and 8 taken from the second period was studied. Errors of 10 MeV and 5 MeV in the beam energy were sufficient to account for the variations in mean energy observed at 161 GeV and 172 GeV respectively. These assignments include any uncertainty arising from the scatter in initial energy, fill-to-fill.

After the release of the energies to the experiments, continued analysis yielded improved understanding of the NMR calibration. In particular, the RMS scatter in initial energy for the 161 GeV running was originally larger, and improved by a factor of 2 to the value presented here. The agreement in mean energy between the released and revised analyses was good, and well within the assigned normalization errors.

3 Energy variation in the fill

3.1 Rise in dipole field

During the 1995 scan of the Z peak it was discovered that the dipole field rises significantly during a fill. This was seen in the data of NMR probes installed in two LEP dipoles. Several long-term depolarization experiments confirmed that this change in dipole field induces a rise in beam energy. This energy rise, typically of $\sim$ 0.5 MeV per hour at Z energies, was understood to be driven by the excitation of parasitic currents on the beam pipe, and by a complex response of the magnets to temperature variation. The dipole field rise is discussed in [2, 5].

This dipole field rise was also observed during the high energy running of 1996. Figure 6 shows the equivalent change in beam energy as inferred by the NMR probes as a function of length of fill, for both the 161 and 172 GeV running. It can be seen that the energy change is sizable: up to 20 MeV for a 10-hour fill. As a fractional energy rise this is consistent with that seen in 1995, when account is taken of the more extreme temperature excursions of the magnet cores and the absence of magnet conditioning ("bend modulation") before physics.

The NMR data themselves were used to include the dipole field rise in the determination of the beam energy. The energy rise of the beam at a given moment with respect to the start of fill was estimated by calculating the mean field rise of the 8 octants in that fill, as given by the NMRs. It was assumed that with the 16 NMR probes, a sufficient number of magnets are sampled around LEP to be representative of the mean ring behaviour. Note in this case there is no need to attempt to separate the temperature and the beampipe current components of the energy rise. This assumption could not be made with the 2 NMR probes in 1995.

Alternative procedures for modelling the energy rise were developed as cross-checks. "Average behaviour" models, identical in concept to that described in [2], were constructed from the 161 GeV and 172 GeV NMR data. Both average behaviour models were applied to each data set in turn. The change in mean beam energy observed for the various models was used to assign a systematic error of 2 MeV.

In future years it will be essential to ensure that all the NMRs remain fully operational. Long-term depolarization experiments will be important to verify that the energy rise as experienced by the beam is in good agreement with that expected from the NMR data.

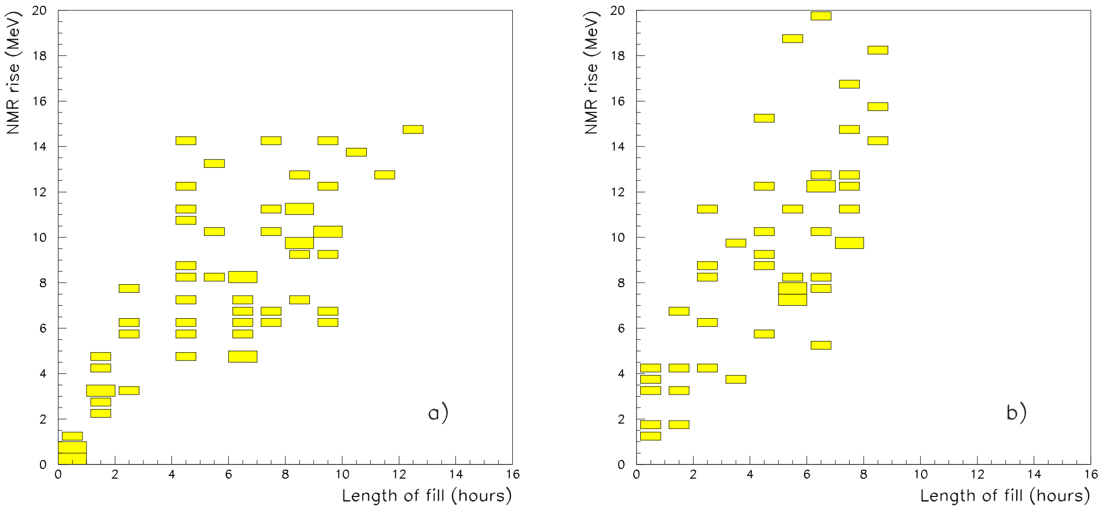

Figure 6: *Average dipole field rise, expressed in beam energy, as seen by NMR probes during 161 GeV (a) and 172 GeV (b) running, against length of fill.*

3.2 Tides

The tide correction as a function of time is calculated as in previous years [2].

3.3 Central frequency

Changes of the LEP ring circumference can be tracked accurately using beam position data from the LEP Beam Orbit Monitor (BOM) system . For the energy scans of the Z resonance, BOM data was used to track relative changes of the beam position with respect to the average centre of the quadrupoles. To compare flux-loop calibrations with resonant depolarization data, the knowledge of the absolute position of the beam is important to disentangle the various contributions to the beam energy. For this reason, the BOM data were cross-calibrated in 1996 with central frequency measurements [6] which provide an absolute measurement of the orbit length. When the LEP RF frequency coincides with the central frequency the average contribution of the quadrupoles to the beam energy vanishes.

In 1996, 9 central frequency measurements were made at end of physics or during machine development time. The calibration of the BOM data with respect to central frequency was stable within about $\pm$ 2 Hz which is adequate for the present time. Figure 7 shows the evolution of the central frequency in 1996. These measurements were translated into an average xarc energy correction for each fill.

3.4 Orbit correctors

During 1996, a model for the effect of horizontal orbit corrections on the LEP beam energy was developed and checked with resonant depolarization measurements [7]. The corrections for the 1996 data were small and give rise to a negligible uncertainty.

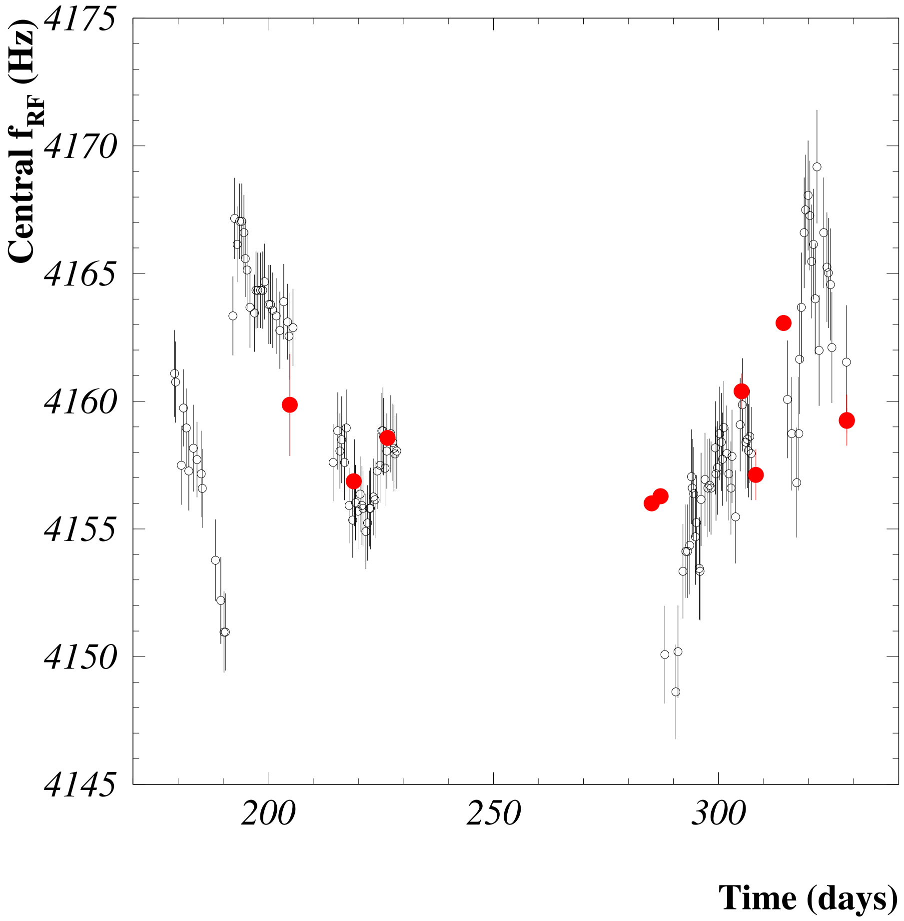

Figure 7: *Evolution of the central frequency (minus 352 MHz) as a function of time in 1996. The actual central frequency measurements are indicated by the large solid points. The small points correspond to BOM measurements that were calibrated with the central frequency data.*

4 Interaction point corrections

4.1 Collision energy corrections from the RF system

Since the beam energy loss due to synchrotron radiation is proportional to E^4_{beam}, operation of LEP2 requires a large amount of RF acceleration to maintain stable beam orbits. To provide this acceleration, new super-conducting (SC) RF cavities have been installed around all of the experiments in LEP. This implies that, contrary to past years, the exact anti-correlation of RF effects on the beam energy at IP4 and IP8 is no longer guaranteed, and that large local shifts in the beam energy can occur at any of the IPs. Corrections to the average beam energy must therefore be calculated for each IP, taking into account the local energy loss/gain of the circulating beams.

4.1.1 Determining the corrections

As in past years [1, 8], the modelling of the corrections is carried out by the iterative calculation of the stable RF phase angle ϕ_s which proceeds by setting the total energy gain of the beams as they travel around the machine equal to all of the known energy losses. In the past, the measured value of the synchrotron tune Q_s was compared to the value calculated from the model, and modifications were made to the model in order to achieve better agreement between the two Q_s values. The energy offset between the two beams as they enter and leave each IP is measured in the LEP arcs by measuring the distance between the two beams; this quantity can also be calculated in the model and provides a sensitive check of the cavity phasing. In addition, longitudinal shifts of the collision point in the IPs could also be traced to changes in the RF configuration, and hence could be predicted from the model. A comparison of these predicted and measured shifts provides another way of cross-checking the model's validity.

As mentioned above, running conditions in 1996 consisted mostly of single-bunch operation, but there were a substantial number of fills with two bunches in each train. The corrections for each bunch are calculated independently, and the average correction is provided. Another notable feature of LEP2 operation is that, effectively, all of the RF cavities are needed to provide the necessary acceleration for compensating the energy loss. This simplifies the analysis considerably since the model is no longer sensitive to the detailed assumptions of the physics underlying the beam-cavity interaction in unused cavities. An additional advantage is that the monitoring of the cavities has become critical to the stable operation of LEP, which has resulted in a vast improvement of the quality of the logged data and eliminated any uncertainties due to missing records.

4.1.2 The 1996 Model-Tuning Strategy

The analysis of the available measurements relevant to the 1996 RF model has revealed several mismeasured or miscalibrated quantities that render impossible the complete modelling of the RF system. The fundamental problem lies with the time-dependence of the phases of the individual units in the system. If all of the unit phases were always close to optimal, this would not be an issue; however, each of the SC cavities has been tuned away from the optimal phase to prevent ponderomotive oscillations induced by the passage of the beam. Thus each unit operates with a non-zero phase error. In principle, given the beam current, the klystron forward and reflected power, and the unit voltage, one can calculate the phase of the unit. Unfortunately, the calibrations of the forward and reflected power, while sufficiently accurate for safe operation of the RF, are too coarse to allow a reliable calculation of the unit phase. This leaves the 22 (24) SC unit phases for the 161 (172) GeV running essentially unconstrained, except that the total RF voltage must be such that the observed Q_s values are correct.

In order to assess the size of the possible misphasings, the overall voltage scale correction which must be applied to the RF voltage calibration is fixed at a value of 1.02, which is the same as 1993, 1994, and 1995[1]. With this assumption, the calculated Q_s values from the RF model are approximately 5% too high, which implies a net phase error of approximately 4° in the RF system. Since the "correct" distribution of this error around

[1]The RF voltages have been calibrated at injection energy with small bunch currents each year; the overall scale factor is not then expected to change for 1996.

the LEP ring is unknown, the central values of the RF corrections have been calculated assuming *no* phase errors. The variation of the corrections when this misphasing is included is taken as the systematic error, as is a 4% variation of the voltage scale factor. The distributions comparing calculated and measured Q_s are shown in Figure 8 for the 1996 running. These figures also display the stability of the RF system during high-energy running. Although the agreement between calculated and measured Q_s is not as good as in past analyses, it is sufficient for us to concluded that there are no gross problems with the RF model calculations.

The average corrections for the 1996 running are shown in Table 2. The bunchlet-to-bunchlet variation in corrections is negligible.

LEP IP	$\Delta E_{\rm CM}$ 161	$\Delta E_{\rm CM}$ 172
2	19.7	18.8
4	–5.5	–5.8
6	20.2	19.5
8	–9.3	–8.0

Table 2: *The corrections (in MeV) to $E_{\rm CM}$ for each LEP IP and each energy point for the 1996 RF model.*

4.1.3 Evaluation of Errors for the RF Corrections

The constituent errors on the 1996 analysis are discussed below. In order to keep the error estimate as conservative as possible, all errors should be considered 100% correlated between IPs and energy points. In all cases of variation, the maximum shift in the RF corrections at any one IP is assumed as the error for all IPs.

The difference between the Q_s measured for electrons and positrons is -4×10^{-4} (8×10^{-5}) for the 161 (172) GeV running, which is consistent with the size of phase errors expected on the RF cavities. This difference in the RF model output is much smaller since no phase errors have been assumed for the central values. The errors due to this effect are absorbed in the RF phasing error.

As mentioned above, the voltages obtained from the database were scaled upwards by an overall factor of 2% in order to agree with the calibration factors determined in earlier years. The full variation on the voltage scale factor is taken as the difference between what it would be if we assumed no phasing errors (0.975) up to the value assumed in this analysis, 1.02. The maximum shift in corrections, 2 MeV, was taken as the error.

A comparison of the calculated and measured positions of the collision point along the beam axis reveals no significant discrepancies between the model and the data.

An analysis of the orbit data show that phase errors must be more or less evenly distributed around the LEP ring, as no IP has energy offsets that differ substantially from the average. In order to estimate the effects of an unknown phase error, we assume as a worst case that the entire error occurs at one side of one IP (in which case the total misphasing of the cavities is $\sim 30^\circ$) and take the maximum variation of the corrections

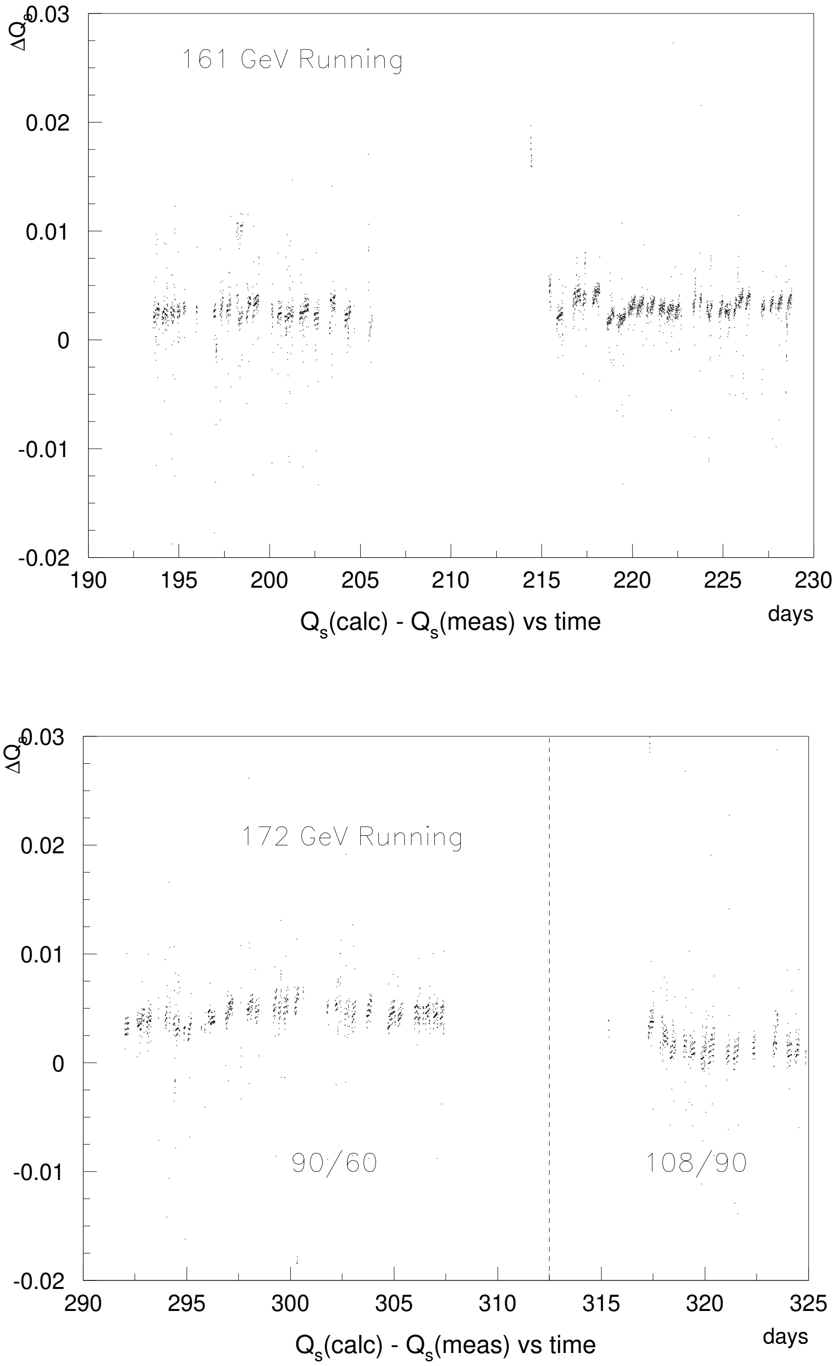

Figure 8: *The difference between the measured value of Q_s and that calculated from the RF model as a function of time for the 161 GeV (top) and 172 (bottom) running. The mean difference in Q_s is 0.0028 (0.0034) for the 161 (172) GeV running, with a corresponding RMS of 0.0023 (0.0026). The vertical line in the lower plot divides the running period into the times when the 90/60 or 108/90 lattice was used in LEP. The shift in ΔQ_s between the two optics is not understood. Note that the RF system is essentially stable, a necessary condition for smooth running at LEP2.*

over the 8 possible positions as the error. A maximum shift of 4 MeV is seen. As this procedure is entirely arbitrary, we conservatively take twice this value as the error, which leads to an 8 MeV error on E_{CM} due to the unknown phases.

For 1996, the effects of the cavity misalignments are estimated for the copper and SC cavities independently, and added to obtain the total error. The uncertainty on the copper cavity alignment was taken to be ± 1 mm and was estimated in the same manner as past years[8]. Measurements performed in October 1996 to cross check the alignment constants of the SC cavities have reduced somewhat the uncertainties in the SC cavity positions[9]. The systematic error due to SC misalignment is calculated by shifting the cavity positions to those measured in October and adding a supplementary 1mm uncertainty which is the RMS of the difference between the new and previously measured positions. This results in a maximum shift of 3 MeV, which is taken as the error. Note that the the uncertainty in the alignment measurements is the same as an uncertainty on possible length differences in the LEP octants between the four IPs, so that these two previously separate effects are now combined.

Other effects on the corrections, such as an uncertainty on the momentum compaction factor, are negligible in comparison to the above errors, as they contribute at most 1 MeV, to be added in quadrature.

The total error on E_{CM} from the RF corrections is merely the sum in quadrature of the phasing, alignment, and voltage calibration errors, which is 10 MeV for each IP.

4.2 Collision energy corrections from dispersion

As pointed out earlier, opposite-sign dispersion ($\Delta D_y = D_y^+ - D_y^-$) of the electron and positron beams may lead to shifts of the centre-of-mass energy (E_{CM}), if vertical collision offsets (δ_y) are present[10, 11]. The energy offset can be calculated as follows:

$$\Delta E_{\mathrm{CM}} = -\frac{1}{2}\frac{\sigma_E^2}{E}\frac{\Delta D_y}{\sigma_y^2} \times \delta_y, \tag{3}$$

where E denotes the beam energy, σ_E the beam energy spread, and σ_y the vertical beam size.

			$D_y^{\pm}$ (mm)				
Energy (GeV)	Optics	Bump setting (%)	IP2	IP4	IP6	IP8	σ_E (MeV)
80.6	90/60	70/70/70/70	1.0	–0.0	1.1	–0.0	102
80.6	90/60	50/70/50/70	0.5	–0.3	0.6	–0.3	102
86.2	90/60	50/70/50/70	0.5	–0.3	0.5	–0.3	116
86.2	90/60	50/50/50/50	0.7	–0.0	0.7	–0.0	116
86.2	108/90	50/50/50/50	0.6	–0.1	0.6	–0.1	116

Table 3: *Dispersion ($D_y^{\pm}$) and energy spread σ_E for the different LEP settings and interaction points as calculated by MAD. The energy spread is the same for all interaction points.*

LEP IP	$\langle \Delta E_{\mathrm{CM}} \rangle$ (MeV)	$\langle \sigma\Delta E_{\mathrm{CM}} \rangle$ (MeV)
2	0.8	1.5
4	–0.1	0.2
6	0.8	1.4
8	0.1	0.2

Table 4: *Average correction to the centre-of-mass energy,* ΔE_{CM}*, and the average error on this correction,* $\sigma\Delta E_{\mathrm{CM}}$.

	Typical error
$\Delta\sigma_y/\sigma_y$	0.06
$\Delta\sigma_E/\sigma_E$	0.02
$\Delta\delta_y$ [μm]	0.3
$\Delta D_y^{\pm}$ [mm]	0.4

Table 5: *Typical errors in the quantities used to calculate the dispersion effect.*

In 1996 no dedicated dispersion measurements were made, and the only knowledge of the dispersion comes from a simulation of the LEP machine using MAD [12]. During 1995, there was good agreement between this simulation and the measured dispersion. The predicted dispersions for the various 1996 configurations can be found in Table 3. Large dispersion effects can only be expected in IP2 and IP6, while the effect can be neglected in IP4 and IP8. The energy spread has also been calculated using the MAD simulation of LEP and is in good agreement with the results obtained from measurements of the bunch length by the experiments (see Table 3).

The beam size and the best vertical offset "Vernier" settings for head-on collisions (y_{best}) were determined by "Vernier Scans" using the beam deflection angle [13]. The collision offset δ_y was then determined by comparing y_{best} with the actual setting of the machine y. The difference was time averaged over a fill to determine the size of the dispersion effects:

$$\delta_y = \langle y_{\mathrm{best}} - y \rangle_{\text{fill average}} . \tag{4}$$

The average correction to E_{CM} and its error can be seen in Figure 9 and Table 4. The error on this correction is derived from the errors on σ_y, y_{best}, σ_E and $D_y^{\pm}$, which are given in Table 5. Effects due to the evolution of beam size and y_{best} during a fill have been neglected.

In summary, for the high energy running of LEP2 in 1996 the beams show some dispersion at IP2 and IP6. However, collision offsets were minimised using Vernier scans, resulting in negligible effects on the energy due to dispersion.

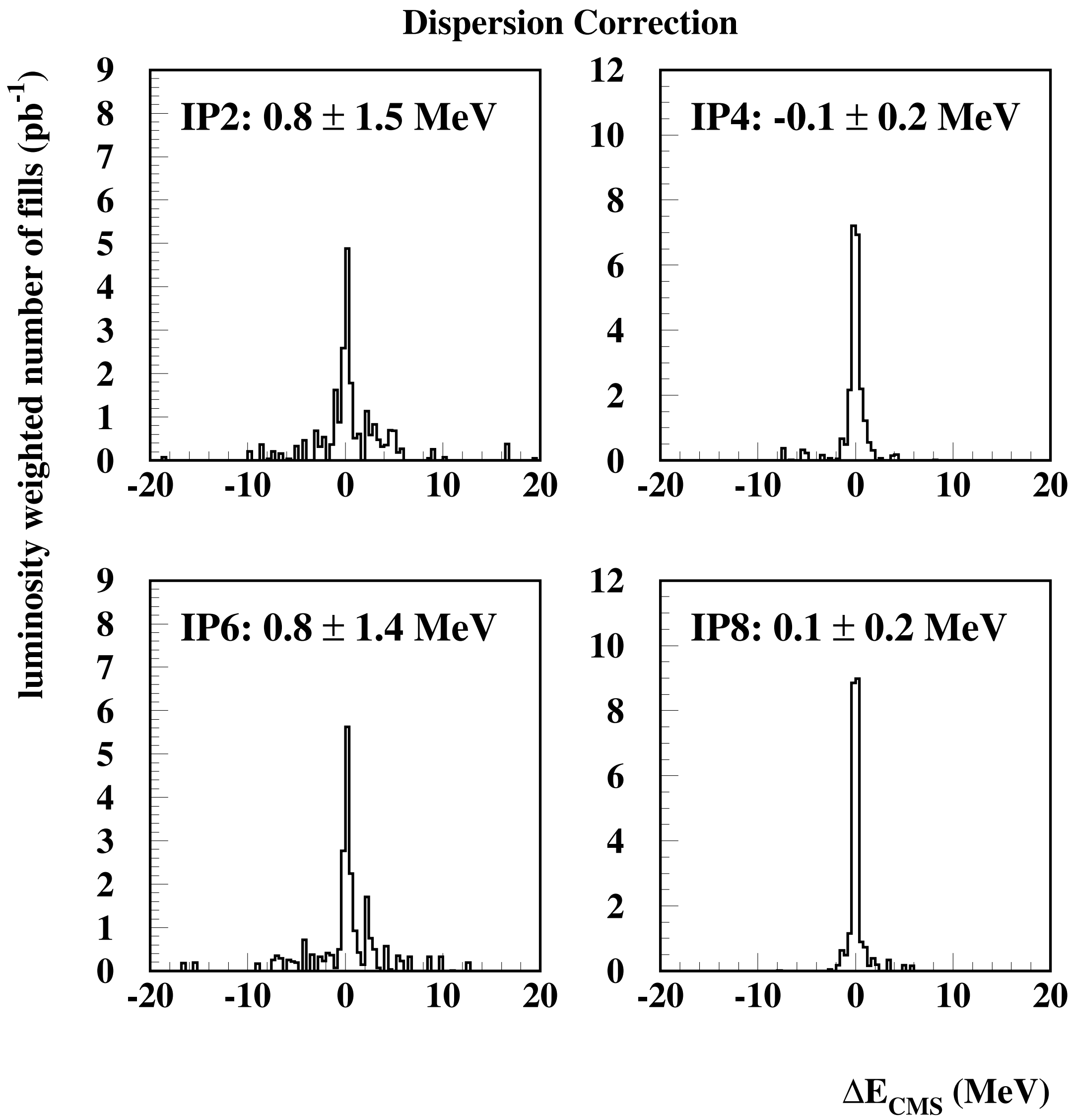

Figure 9: *Dispersion correction for the different interaction points (IP). Plotted is the luminosity weighted correction to the centre-of-mass Energy (ΔE_{CM}). The numbers given for the 4 IP's are the average correction and the average error on the individual corrections.*

5 Systematic uncertainties on the beam energies

The uncertainties in the beam energy estimate for the two running periods with beam energies of 80.5 GeV and 86 GeV are listed in Table 6. Those errors not discussed in previous sections have been determined as in previous years [2]. The assignment of the extrapolation uncertainty needs further explanation.

The extrapolation error estimates from NMR and flux-loop data are typically 10 to 12 MeV. However these rely heavily on a single fill (3719) in which resonant depolarization measurements were made at two different energies. The reproducibility of this extrapolation has not been tested. If the extrapolation uncertainty for the NMR probes is assessed in the same way as in section 2.2, but using all fills, including fill 3599 where the consistency between polarization and NMR data is worst, the error would be about 25 MeV. However, this estimate includes some component from the fill-to-fill scatter. Using the flux-loop absolute energy scale would give a deviation of about 20 MeV compared to the energy derived from a linear extrapolation of the polarization points.

With only two different polarized energies, it is also difficult to constrain the linearity of the extrapolation, which is only partly tested by the NMR/flux-loop comparison. Possible systematic uncertainties come from the magnet fringe fields and the short, stronger dipoles in the injection region.

In view of these considerations, we conservatively assign the extrapolation errors given in the table. The errors are proportional to the difference between the physics energy and 50 GeV, the maximum energy at which the extrapolation could be checked. They are fully correlated between the two energies and for all experiments.

$\sigma(E_{\mathrm{beam}})$ [MeV] at	80.5 GeV	86 GeV
Energy Scale Errors:		
Polarization systematic	1	1
e^+e^- energy difference	2	2
Fill-by-fill normalization	10	5
Extrapolation	24	29
Orbit correctors	1	1
Variation within a fill:		
Tide model	1	1
NMR/temperature model	2	2
IP specific:		
Dispersion	1	1
RF	5	5
Total	27	30

Table 6: *The errors on the beam energy in MeV.*

6 Summary and outlook

For future years, with an increased beam energy, the present study would give a beam energy uncertainty of about 40 MeV. In order to reduce the error, in particular from extrapolation, to the desired precision of less than 15 MeV in the beam energy, the requests for measurements in 1997 include:

- End-of-fill polarization calibration during Z running at beginning of the year (to check the energy scale as early as possible, as well as to debug the polarimeter and other associated equipment).
- At least 6 fills with $\geq 2E_{\mathrm{depol}}$ energies measured. These 6 fills should *include* at least 2 fills with $\geq 3E_{\mathrm{depol}}$ energies measured.
- Increase the maximum energy at which depolarization measurements are possible.
- Install k-modulation in those arcs not already equipped to increase $E^{\mathrm{max}}_{\mathrm{depol}}$ and in general speed up the polarization measurements.
- Investigate the possibilities of a dedicated polarization optics.
- Continue to maintain the NMRs, and try to reduce their sensitivity to radiation damage.
- Continue regular flux-loop measurements.
- Calibrate RF forward and reflected power, and make further RF alignment cross checks.
- Measure the opposite sign vertical dispersion
- Check the efficacity of magnet conditioning (bend modulation) at the ISR test setup. If this is expected to reduce significantly the rise in the dipole field during a high energy fill due to parasitic currents on the beam pipe (train effect), perform bend modulation at the start of each physics fill.

The estimated time for all the depolarization calibration measurements is approximately 8 days total. These measurements should allow tests of the reproducibility of the extrapolation using NMRs. Increasing the maximum energy at which a depolarization measurement can be performed is also essential; the final error scales up with the difference between the physics energy and the maximum depolarized energy, and down with the lever arm over which the extrapolation can be tested. Although the present measurements lead to the assignment of a relatively large beam energy uncertainty, there is no indication of serious problems with the energy calibration strategy, and we can hope to achieve a much smaller error in future years.

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