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Preliminary LEP energy calibration for 1997 data

The LEP Energy Working Group

Abstract

The analysis of 1997 beam energy measurements by resonant depolarisation at low energy and of magnetic measurements used to extrapolate the energy scale to physics energy is described. The results of this analysis have been used to prepare preliminary beam energies for the 1997 data. The associated systematic uncertainties are also discussed.

1 Introduction

The LEP beam energy at LEP2 is the absolute calibration used to set the scale for the measurement of the W boson mass. The aim is for a total experimental uncertainty $\sigma(M_W) \approx 30$ MeV, setting the target of 10–15 MeV for $\sigma(E_{\rm beam})$. This contrasts with LEP1, where the Z mass and width were measured with uncertainties $\sigma(M_Z)$, $\sigma(\Gamma_Z)$ of about 2 MeV, corresponding to beam energy uncertainties of $\lesssim 1$ MeV

At LEP1, the average energy around the LEP ring at a moment in time was measured very precisely using resonant depolarisation (RDP). Due to broadening resonances, this cannot be used at LEP2 physics energies, and the use of magnetic measurements to extend the calibration to top energy becomes the largest source of uncertainty. This resulted in $\sigma(E_{\rm beam}) = \sigma(M_W) = 30$ MeV for the 1996 data [1]. The extrapolation to physics energy depends on a comparison of the measured RDP energies, $E_{\rm pol}$, with the magnetic fields measured by NMR probes in the LEP dipoles, and on the relationship between the NMR fields and the total bending field measured by the flux loop. At present, the method proceeds as follows:

- Calibrate the NMR's using RDP measurements at low energy.
- Infer the energy for physics running by a linear extrapolation of this calibration. The NMR's record the field for all RDP measurements and for physics running.
- The NMR's sample a small fraction of the field while the flux loop measures nearly all the bending field. Cross-calibrate NMR's and flux loop over the full range from RDP to physics energies and check the consistency. If the measured field from the NMR's can predict the increase in total bending field between RDP and physics energies, then it is a good assumption that they also predict the difference in energy.
- Propagate the uncertainty from the precision of all consistency checks to the uncertainty in the physics energy. Also assign errors from any discrepencies observed, and to account for the contributions to the field outside the flux loop.

Having fixed the overall normalisation, the energy must be corrected for variations as a function of time, due to earth tides, temperature effects, leakage currents from neighbourhood electric trains and so on. There are also corrections to relate the average energy to the collision energy at each interaction point, in particular due to the exact accelerating RF configuration. All of these effects have been rather well understood at LEP1 [2], and contribute a total additional uncertainty below 10 MeV.

2 Reprise of 1996 analysis

The analysis of the 1996 data lead to an uncertainty of 30 MeV in E_{beam} at 86 GeV [1]. This was largely based on a single fill with RDP measurements at 45 and 50 GeV. The apparent consistency of the flux-loop and NMR data compared to RDP data was about 2 MeV over this 5 GeV interval, i.e. a relative error 4×10^{-4}, which using a naive linear extrapolation would give an uncertainty of 15 MeV at 86 GeV. This was inflated to 30 MeV by the following considerations:

- There was no test of the reproducibility from fill to fill.
- There were no fills with more than two RDP energy points with which to check the non-linearity.
- No work was done on the possible precision for the 3.5% of bending field outside the flux loop.

With no improvements, the uncertainty in 1997, at $E_{\text{beam}} = 91.5$ GeV would be about 35 MeV.

3 Measurements in 1997

3.1 Magnetic measurements

The LEP dipole fields are monitored in two ways. There are 16 NMR probes positioned inside some selected main bend dipoles, see figure 1. Each octant has at least one NMR, and octants 1 and 5 have NMR's in several adjacent dipoles (and in one instance two probes in the same dipole). The NMR's measure the local field with a precision of $\sim 1 \times 10^{-6}$, and can be read out essentially continuously (typically every 30 seconds), but each probe only samples the B-field in a small region of one out of 3200 dipoles. The probes are read out during RDP measurements and during physics runs.

In contrast, the flux loop measures 96.5% of the total B-field, including 98% of the main bend dipole field. It is also shown schematically in figure 1. It measures the change in B field during a dedicated demagnetisation cycle, outside physics running. Only a handful of flux-loop measurements were made in 1997. These measurements included a pause at several intermediate field values, so as to allow time for the NMR's to lock and be read out. These special flux-loop measurements are referred to by an adjacent LEP fill number.

Missing from the flux loop are the "10%" dipoles at the ends of the arcs, the special injection dipoles, fringe fields of the main dipoles, and any bending field from other magnets such as quadrupoles or horizontal orbit correctors.

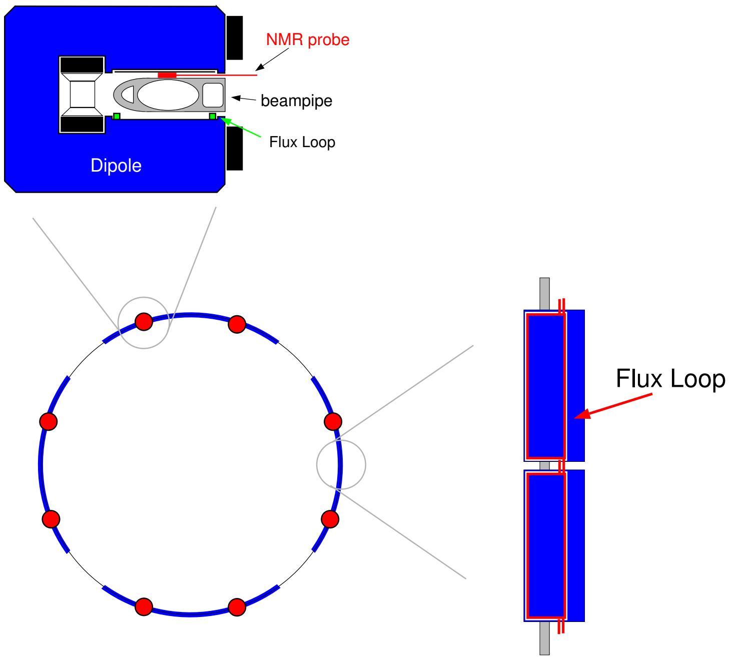

Figure 1: The two systems for monitoring the LEP magnetic field.

3.2 Polarisation measurements in 1997

The need for more RDP measurements motivated the k-modulation programme and the development of a dedicated polarisation optics [3]. The successful RDP experiments are listed in table 1. There are 5 fills with more than one energy point, and 2 fills with 4 energy points which allow a linearity check. The lever arm over which the agreement can be tested has increased from 5 to 14 GeV, and the maximum RDP calibrated energy has increased from 50 to 55 GeV, promising a much more reliable magnetic extrapolation analysis.

Date	Fill	41 GeV	44 GeV	50 GeV	55 GeV	Optics
17/08/97	4000		yes			90/60
06/09/97	4121		yes	yes		60/60
30/09/97	4237		yes	yes		60/60
02/10/97	4242	yes	yes	yes	yes	60/60
10/10/97	4274		yes			90/60
11/10/97	4279	yes	yes	yes	yes	60/60
29/10/97	4372	yes	yes			60/60

Table 1: Fills with successful polarisation measurements.

4 Normalisation of 1997 data

4.1 Optics difference

The development of a dedicated polarisation optics implied that a cross-calibration of polarisation and physics optics was necessary. The measured average energy difference between RDP measurements with the two optics is:

$$E(90/60) - E(60/60) = -4 \text{ MeV at } 45 \text{ GeV}. \tag{1}$$

The predicted shift from the different phase advance (QFQD effect) and the different horizontal corrector settings used in practice is:

$$E(90/60) - E(60/60) = -6 \pm 1 \text{ MeV at } 45 \text{ GeV}. \tag{2}$$

The predicted difference between the optics from known effects is expected to scale with beam energy. Assigning an uncertainty of 2 MeV at 45 GeV from the discrepency, the optics correction to be applied at LEP2 physics energy is:

$$E(90/60) - E(60/60) = -8 \pm 4 \text{ MeV at } 91.5 \text{ GeV}. \tag{3}$$

4.2 NMR/Polarisation Comparison

A fit of the form

$$E_{\rm pol} = a^i + b^i B^i_{\rm NMR} \tag{4}$$

has been made to the RDP data for each NMR $i = 1, 16$. The RDP energy is corrected for quadrupole effects before fitting. Fitting a slope plus an offset requires two or more $E_{\rm pol}$ values in the same fill. Using $E^i_{\rm NMR} = a^i + b^i B^i_{\rm NMR}$, the residuals $E_{\rm pol} - E^i_{\rm NMR}$ are examined for each NMR. Four examples are shown in figure 2. Different probes show different behaviour, but this behaviour is reproduced from fill to fill.

If the residuals are averaged over all NMR's, a characteristic shape can be seen which is a measure of the non-linearity in the energy range 41–55 GeV. This is shown in figure 3, where the error bars are the rms of the residuals over the NMR's. This illustrates the interest in further increasing $E^{\rm max}_{\rm pol}$ to $\gtrsim 60$ GeV in future.

The average field measured by each NMR during physics running at a nominal energy of 91.5 GeV can be used to derive the NMR prediction of the physics energy from the fits to the RDP measurements: $E^i_{\rm NMR} = a^i + b^i B^i_{\rm NMR}$. The distributions of predicted energies from two separate fits to each of the two fills with four RDP measurements are shown in figure 4. The best estimate of the energies is derived from a simultaneous fit to all the available fills with two or more RDP measurements. The rms scatter over the NMR's of the predicted energy is about 40 MeV using any combination of RDP fills. This contributes $40/\sqrt{(16)} = 10$ MeV to the systematic uncertainty from the normalisation procedure.

In 1996, the RDP measurements were fitted to a line passing through the origin, $E_{\rm pol} = p^i B^i_{\rm NMR}$. If this is tried for the 1997 data, the rms scatter increases to 60 MeV.

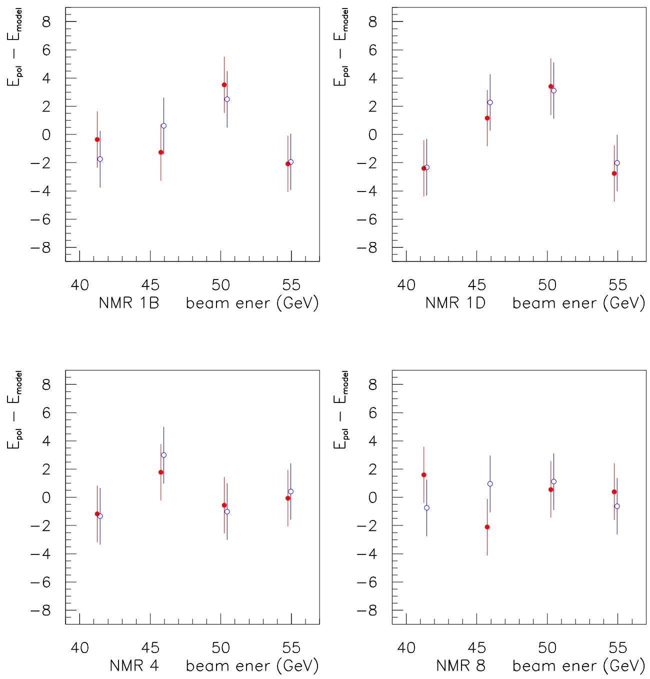

Figure 2: Example residuals for 4 NMR's fitting the two fills with four RDP measurements. The open and closed points correspond to the different fills.

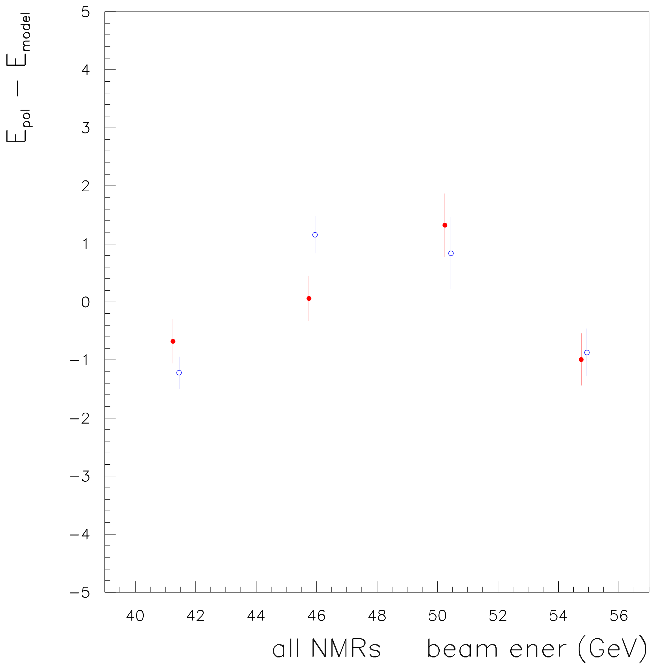

Figure 3: Average residuals over all NMR's for the two fills with four RDP measurements. The open and closed points correspond to the different fills.

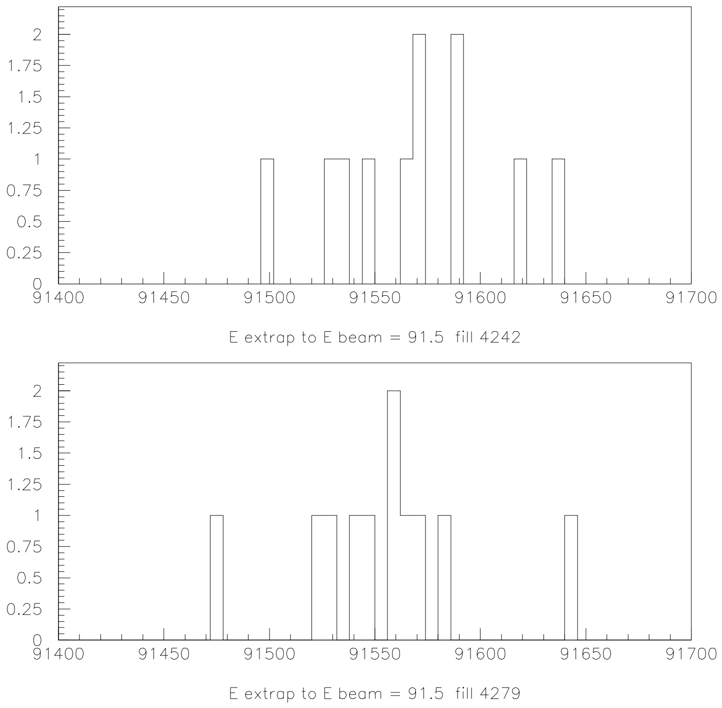

Figure 4: Distribution of predicted physics energy for each working NMR, using each of the four point RDP fills.

4.3 NMR/flux-loop comparisons

The NMR magnetic field as a function of the change of field measured by the flux loop can also be fitted to a line with a slope and offset for each NMR

$$B^i_{\mathrm{NMR}} = c^i + d^i B_{\mathrm{FL}}. \tag{5}$$

Examples of the residuals from this line as a function of ΔB_{FL} are shown in figure 5. From octant-to-octant and magnet-to-magnet the probes show different behaviour. The slopes are not constant with energy. However, the behaviour is reproduced from fill-to-fill.

If the RDP measured energies, E_{pol}, are proportional to the total bending field measured by the flux loop, B_{FL}, then one would expect a strong correlation between the fitted slopes if the NMR/flux-loop fit is restricted to the range corresponding to 40–55 GeV. The slopes β and d for each NMR, from fits to the lines:

$$\begin{aligned} B^i_{\mathrm{NMR}} &= \alpha^i + \beta^i E_{\mathrm{pol}} \\ B^i_{\mathrm{NMR}} &= c^i + d^i B_{\mathrm{FL}} \end{aligned} \tag{6}$$

are shown in figure 6. A good correlation is seen within the errors, which reflect the fill-to-fill scatter.

Having established this correlation, the flux loop can now be used to test the extrapolation method. From the fit in the 40–55 GeV region, the NMR's can be used to predict the increase in B_{FL} at physics energy, and this prediction can be compared with the flux loop measured B_{FL}. An example is shown in figure 7 for a single flux-loop measurement. The mean and rms over NMR's can be calculated for each excitation current (where

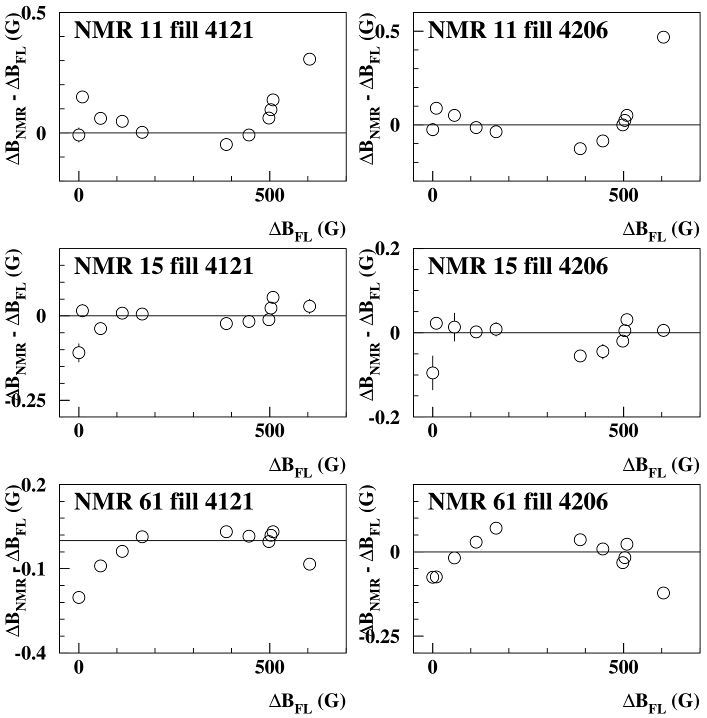

Figure 5: Residuals from the fit of B_{NMR} to B_{FL} for three probes and two different flux-loop measurements. The plot is shown as a function of ΔB_{FL}, defined to be 0 G at 41 GeV and about 500 G at physics energy.

4000 A corresponds to physics energy), and used as an estimate of the bias and error in the extrapolation method. This has been done for each flux-loop measurement, and the results are shown in figure 8. The bias at physics energy is in the range -10 to $+20$ MeV, with an rms of 30–40 MeV. The bias tends to increase during the year. However, this increase in the bias can be partially understood as being due to the smaller sample of NMR's available in the latter part of the year. If this smaller subset of NMR's is used for earlier fills, then a larger bias is also seen for these fills. Changing the quality cuts used to select which NMR's to include can cause changes of order 10 MeV in the measured bias.

4.4 Choice of normalisation in 1997

The preliminary central values of the energies for 1997 are based on two parameter fits for each NMR probe to all the polarisation fills with two or more RDP energies. Using different subsets of polarisation fills leads to an uncertainty of 5 MeV, to be combined with the uncertainty of 10 MeV from the scatter over the NMR's.

The tests with the flux loop are not used to correct the NMR calibration from polarisation data, but allow an independent estimate of the precision of the method. The difference between the NMR and flux-loop measured field increase is taken to assign a systematic uncertainty of 20 MeV. Although the rms over the NMR's is correlated with the NMR scatter of the polarisation calibration, it is retained as an additional uncertainty.

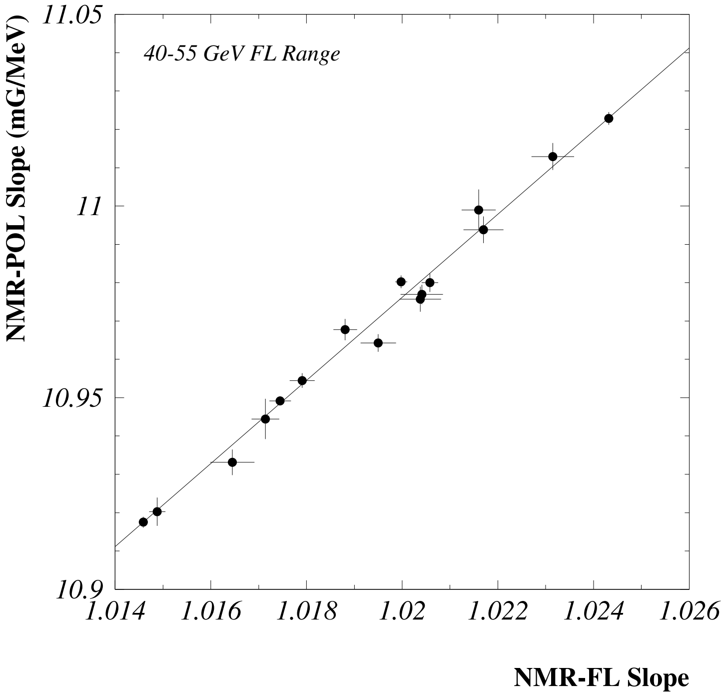

Figure 6: Comparison of the fitted slopes in the 40–55 GeV range for NMR vs E_{pol} and NMR vs B_{FL}. There is one point per NMR.

5 Time dependent effects

5.1 Horizontal orbit correctors and other geometrical effects

The difference in energies measured with RDP using the standard physics optics (90/60) and the dedicated polarisation optics (60/60) has already been taken into account. This includes a contribution from the different horizontal orbit corrector settings used with these two optics for polarisation studies. However, there are also different settings to achieve a good orbit for physics running with the 90/60 optics, compared with the orbit for polarisation.

The effective orbit length increase due to the horizontal orbit correctors is shown in figure 9. The change in orbit length is related to the change in energy by:

$$\frac{\Delta E_{\mathrm{beam}}}{E_{\mathrm{beam}}} = -0.2\Delta L[\mathrm{m}] \tag{7}$$

The size of the effect is much larger than in previous years, and corresponds to 11 MeV at high energy for a significant portion of the data (after day 250). However, the orbit lengthening due to orbit correctors can also be used to predict the corresponding change in central rf frequency, from:

$$\frac{\Delta f}{f} = -\frac{\Delta L}{L} \tag{8}$$

This change can also be inferred from the change in radius measured by the beam orbit monitors. The central frequency is also occasionally measured directly, as shown in figure 10. These two measures of the central frequency agree rather well with the value

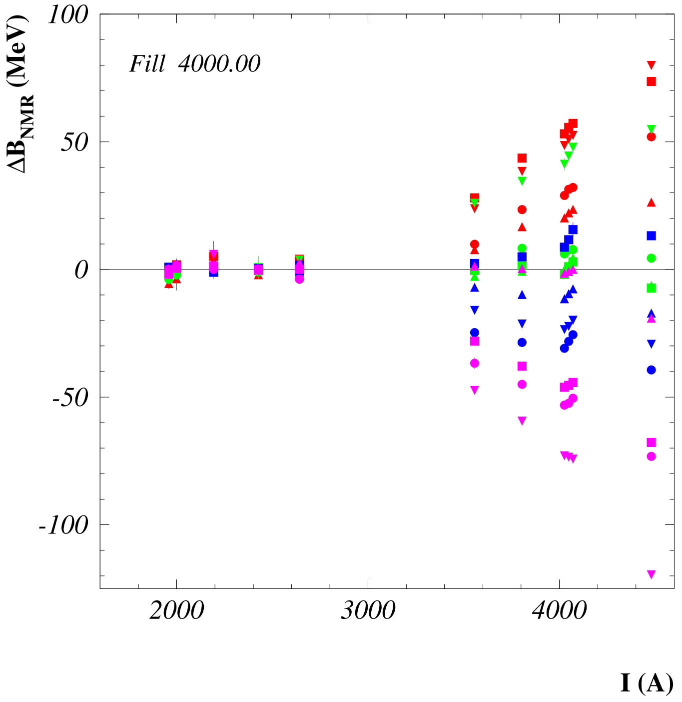

Figure 7: The difference between NMR-predicted and flux-loop-measured increase in $B_{\rm FL}$ between 45 GeV and higher energies. The difference is plotted here against excitation current: 2000 A corresponds to 45 GeV, 4000 A to the 1997 physics energy. The difference in B field has been given in units of equivalent energy shift in MeV. There is one symbol per NMR.

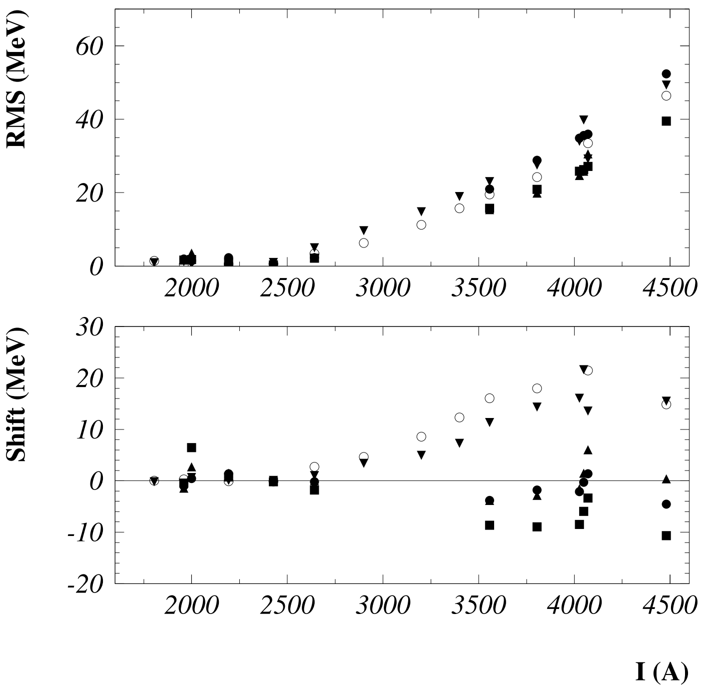

Figure 8: The rms spread and average bias derived from the NMR/flux-loop comparison.

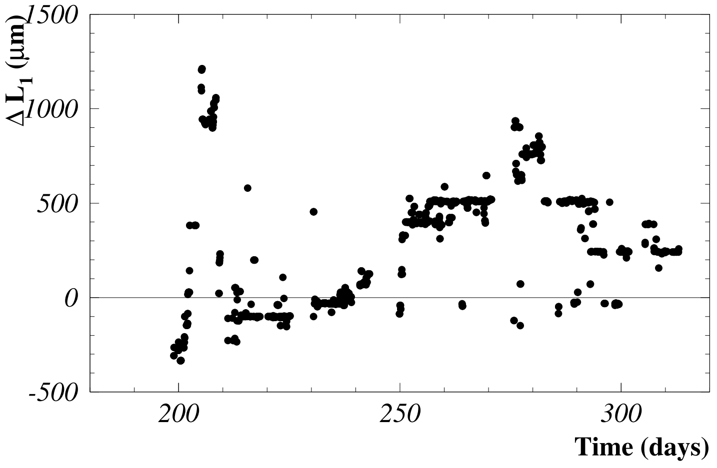

Figure 9: The orbit lengthening inferred from the horizontal orbit corrector settings. The Z calibration running is up to day 210, and the LEP1.5 running occupies a block from day 276 to day 283.

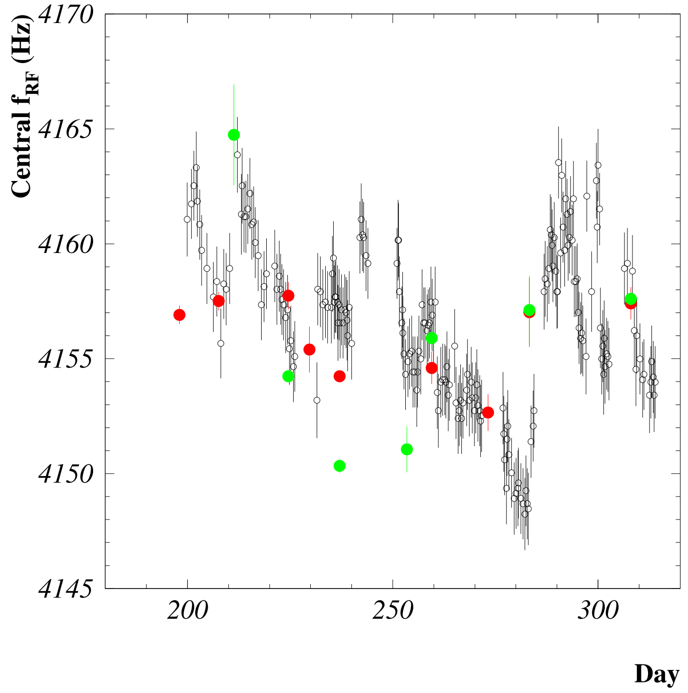

Figure 10: The central rf frequency as measured directly (large points) and inferred from BOM data (smaller, open points).

predicted by the orbit lengthening from the horizontal orbit correctors, but they should also account for any large scale ground motion that changes the size of the LEP ring. A correction for the central frequency as measured by the orbit radius is applied, so if this is the entire effect, an additional correction for the horizontal orbit correctors is not needed. This is consistent with the procedure in previous years, where the orbit radius correction was used to normalise each fill, but horizontal orbit corrector *changes* during a fill were taken into account.

An error of half the effect (i.e. ± 6 MeV) is assigned at this stage, pending further simulation studies. More information about the effect of the central rf frequency and the orbit correctors on the beam energy can be found in reference [2].

The offsets in the Z running for calibration at the beginning of the year were varying rapidly, as can be seen in figure 9, and in the LEP1.5 running the increase in length was typically larger than in the high energy running. However, the resulting correction in MeV is proportional to the beam energy, and therefore turns out to be of about the same size as the correction at high energy. An uncertainty of ± 6 MeV is therefore also appropriate for the lower energy data in 1997.

The model of earth tides is well understood from LEP1. It should be noted that the amplitude of the tide effect is proportional to energy, and so is larger at LEP2.

5.2 Effects from the main bend dipoles

The average of the NMR's is used to take into account changes is energy due to temperature and parasitic currents. Bend modulation was routinely carried out at the start of each fill from 5 August (fill 3948), so the rise in dipole field during a fill was smaller than in 1996: the total dipole rise effect on the average beam energy was only 3.5 MeV. From experience at LEP1, and the fact that the 16 NMR's give a good sampling of the whole ring, it is safe to assign 25% of this effect, i.e. 1 MeV, as the uncertainty due to the dipole rise.

For one or two fills, there was an error in the bend modulation sequence such that it terminated at the wrong excitation current, leading to a slightly different initial bending field. Also, a small drift in the dipole excitation current for the same nominal setting was observed during the year. For example, these effects lead to an rms of 13.5 MeV for the 153 fills with a nominal beam energy of 91.5 GeV. Since this effect is tracked by the NMR's in determining the initial field, no additional uncertainty is assigned.

5.3 RF frequency shifts

For the first time in 1997, the RF frequency was routinely increased from the nominal value to change the horizontal damping partition number. This is a useful technique at high energy, causing the beam to be squeezed more in the horizontal plane, and increases the specificy luminosity. However, side effects of this are that the beam energy changes, and that slightly more RF accelerating voltage is needed to keep the beam circulating. A frequency shift of +100 Hz gives an energy decrease of about 150 MeV.

Occasionally, when an RF unit tripped off, the operators would temporarily decrease the RF frequency to keep the beam lifetime high. However, the energy values are at present only calculated every 15 minutes. This course sampling could lead to a shift in the mean beam energy over the year. A conservative 3 MeV uncertainty has been assigned at this stage. In future, this effect can be treated exactly by updating the energy to be used by the experiments every time the RF frequency changes. This uncertainty is not relevant at lower energy where beam-beam effects dominate and the RF frequency shift is not applied.

6 IP specific corrections

6.1 RF

Considerations for determining the IP-specific corrections to the beam energy are similar in 1997 to the 1996 LEP2 running[1]. 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. The measured value of the synchrotron tune Q_s and the energy offsets between the beams as they enter and leave the experimental IPs are used to constrain energy variations due to overall RF voltage scale and RF phase errors. In particular, the phase error at each IP is set using the size of the energy sawtooth measured by the LEP BOM system compared with the total RF voltage at that IP. This extra constraint on potential phasing errors was not used in the 1996 analysis.

The average corrections for the 1997 running are shown in Table 2. The bunchlet-to-bunchlet variation in corrections is negligible.

	ΔE_{CM} (MeV)			
LEP IP	$E_{\mathrm{CM}} = 91$ GeV	$E_{\mathrm{CM}} = 130$ GeV	$E_{\mathrm{CM}} = 136$ GeV	$E_{\mathrm{CM}} = 183$ GeV
2	1.3	–1.2	–3.0	8.1
4	–1.2	–3.4	–3.3	-10.8
6	2.1	3.0	–2.1	5.9
8	–3.0	–4.1	–5.1	–13.3

Table 2: The average corrections (in MeV) to E_{CM} for each LEP IP and each energy point for the 1997 RF model.

The errors on the 1997 analysis were evaluated in exactly the same manner as 1996 [1], with the exception that the more precise phasing information from the orbit measurements has reduced the uncertainty from unknown phase errors. The most important contributions to the error on E_{CM} from the RF corrections are from the phasing, alignment, and voltage calibration errors, which gives 6 MeV (3 MeV per beam). In order to keep the error estimate as conservative as possible, this error should be considered 100% correlated between IPs and energy points.

6.2 Opposite sign vertical dispersion

In the bunch train configuration, beam offsets at the collision point can cause a shift in the centre-of-mass energy due to opposite sign dispersion [4]. The change in energy is evaluated from the calculated dispersion and the measured beam offsets from beam-beam deflections scans.

The dispersions have been calculated using MAD for all the configurations in 1997. They agree to within about 50% with the measured values, and this is the largest cause of uncertainty in the possible error correction. Beam offsets have been controlled to within a few microns by beam-beam deflection scans. The resulting luminosity weighted correction to the centre of mass energies are typically 1 to 2 MeV, with an error of about 2 MeV. No corrections has been applied to the 1997 energies for this effect, and an uncertainty of 2 MeV has been assigned.

7 Preliminary error summary

The contributions from each source of uncertainty described above are summarised in table 3.

The first errors concern the polarisation measurement, including the possible difference in energy between electrons and positrons, and the difference between optics.

The next groups describe the uncertainty in the normalisation derived from NMR-polarisation comparisons, NMR-flux-loop tests and the part of the bending field not measured by the flux-loop. A rather conservative 1% relative uncertainty is assigned for this last effect, pending further study. There is some double counting here, since the flux-loop and polarisation slopes in fits to NMR fields are rather well correlated.

Additional uncertainties from time variations in a fill, and IP specific corrections are each under control at the $\lesssim 6$ MeV level.

8 Conclusions

The method of energy calibration by magnetic extrapolation of resonant depolarisation measurements at lower energy has made substantial progress with the 1997 data. The huge improvements in establishing polarisation above the Z have allowed a much more robust application of the method. The mutual consistency of the RDP, NMR and flux-loop data has been established at the 20–30 MeV level at physics energy.

Before providing final numbers for the 1997 data, more work remains to be done, including:

- Implementing an exact treatment of RF frequency shifts.
- Improving the systematic understanding of the flux loop from the ISR test set up, to be backed up by tests with the full LEP ring at the end of April or in May.
- A more thorough evaluation of systematic uncertainties on parts of the bending field outside the flux loop.
- Further simulation of the interplay between horizontal orbit corrector and central frequency effects.

Source	Error [MeV]		
	Hi E	LEP1.5	Z
Polarisation systematic	1	1	1
e^+e^- energy difference	2	2	2
Optics difference	4	3	2
Extrapolation from NMR–polarisation			
NMR rms for two parameter fit	10	5	0
Different E_{pol} fills	5	3	2
Flux-loop test of extrapolation			
NMR flux-loop difference per fill	20	10	0
NMR scatter	10	5	0
3.5 % of field not measured by FL			
with 1 % uncertainty over 55 to 90 GeV	12	6	0
Corrector effects	6	6	6
Tide	1	1	1
Dipole rise modelling	1	1	2
RF frequency shift (15 min sampling)	3	0	0
IP specific corrections ($\sigma(E_{\mathrm{CM}})/2$)			
RF model	3	3	3
Dispersion	2	2	2
Total	29	16	8

Table 3: Summary of contributions to the beam energy uncertainty. The uncertainties for high energy (Hi E), LEP 1.5, and Z calibration running are given separately.

References

[1] "LEP Energy Calibration in 1996", The working group on LEP energy Note 97/01.

[2] "Calibration of centre-of-mass energies at LEP1 for precise measurements of Z properties", paper in preparation by the LEP Energy Working Group, and references therein.

[3] See the talk by Bernd Dehning in the proceedings of the LEP performance workshop in Chamonix, 1998.

[4] Talk by Alfons Weber at the 145th Energy Calibration Meeting held on 5 December 1997.