LEP Energy Working Group 00/01
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Evaluation of the LEP centre-of-mass energy for data taken in 1999

The LEP Energy Working Group [1]

Abstract

The centre-of-mass energy at LEP2, above the W pair threshold, was evaluated in 1996, 1997 and 1998 using a magnetic extrapolation method. The average beam energy is measured precisely in the range 41–61 GeV by the method of resonant depolarisation. The beam energy for physics running is inferred from measurements of the magnetic field in several LEP main bend dipole magnets made by NMR probes, both during the resonant depolarisation measurements and during physics fills. The dominant systematic uncertainty comes from a comparison of the total bending field measured by a flux-loop with the fields measured by the NMR probes. Small corrections are applied to account for magnets other than the main bend dipoles, and for the beam energy variation around the ring, to derive the centre-of-mass energy at each interaction point. In this short note the results of applying this method to the 1999 data are presented. The preliminary error on the beam energy in 1999 is determined to be 21 MeV. The status of two alternative methods of energy determination, the LEP spectrometer and a fit of the total RF voltage to the synchrotron tune, are discussed. The spreads of the centre-of-mass energies are also given.

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1 Introduction

The centre-of-mass energy (E_{cm}) of LEP above the W-pair production threshold has been determined by the method of magnetic extrapolation for the 1996, 1997 and 1998 data samples. This method is documented in Ref. [1, 2]. In this note, the preliminary results of applying the same analysis techniques to the 1999 data are presented, where luminosity was delivered at nominal centre-of-mass energies of 192 GeV, 196 GeV, 200 GeV and 202 GeV [2]. The calculated energies and spreads have been distributed to the LEP experiments.

During 1999 significant progress was made on the LEP spectrometer project and in the analysis of the RF voltage dependence of the synchrotron tune. These are two complementary methods of determing the centre-of-mass energy which are being used to cross-check the magnetic extrapolation approach, and will eventually be considered in the error assignment. In the present note their status is briefly summarised.

2 Reminder of the extrapolation method

The magnetic extrapolation method used to calibrate the centre-of-mass energy at LEP2 to date [1, 2] relies on 16 NMR probes that continually measure the local magnetic field in several of the LEP main bend dipole magnets. The field readings of the probes are fit to the beam energy (E_b) measured by resonant depolarisation (RDP) in the region of 41 to 61 GeV. The fit is linear, with two free parameters: $E_{\mathrm{pol}} = a + bB_{\mathrm{NMR}}$. From this fit, the beam energy in physics can then be predicted from the average field measured by the probes in physics runs. The relationship between beam energy and measured magnetic field is assumed to be linear between the region calibrated by polarisation and the physics regime. Tests of this linearity assumption lead to the dominant systematic errors in the analysis of the 1997 and 1998 data.

The largest uncertainty on the linearity assumption is assigned with the flux loop, where in dedicated cycles the ring is ramped and a comparison made of the total bending field measured by the flux loop and the predicted total bending field from the average over the NMR probes: $B_{\mathrm{FL}} = c + dB_{\mathrm{NMR}}$. There is also a "statistical" contribution to the error from the scatter in the predicted physics energy over the probes, and a further systematic error from the variation of NMR calibrations from fill to fill through the year.

Systematic uncertainties from the other effects that influence the centre-of-mass energy are relatively small. More details can be found in [1, 3].

3 Resonant depolarisation measurements in 1999

Table 1 lists the successful RDP measurements made so far at LEP2. The first measurements away from the Z peak (around 45 GeV beam energy) were made in 1996. In 1997, a dedicated polarisation optics (60/60) was commissioned. This enabled the lever arm over which measurements were made to be extended down to 41 GeV (the lowest energy at which the NMR probes lock reliably) and up to 55 GeV. In 1998 the highest energy with a sufficient level of transverse polarisation to make a measurement increased to 61 GeV. In

[2]Note that LEP operated with an RF frequency offset which reduced the centre-of-mass energy by ~ 400 MeV below these nominal values.

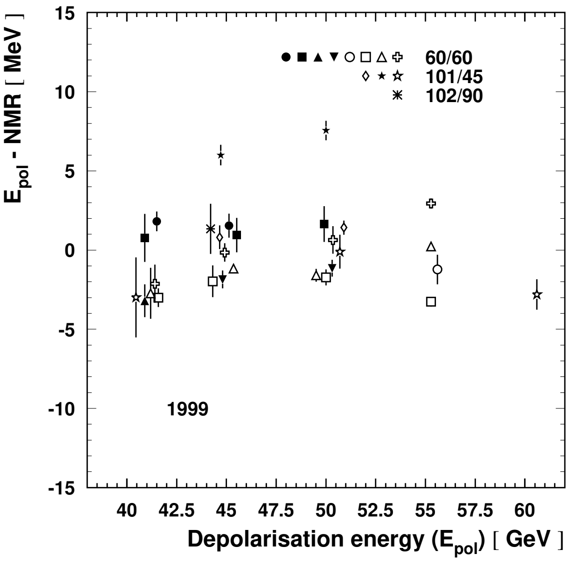

Figure 1: Residuals from the NMR fits to the RDP data in 1999. The error bars indicate the statistical scatter over the probes. The optics of each measurement are indicated. (The position of each point on the horizontal scale has been adjusted for visibility.)

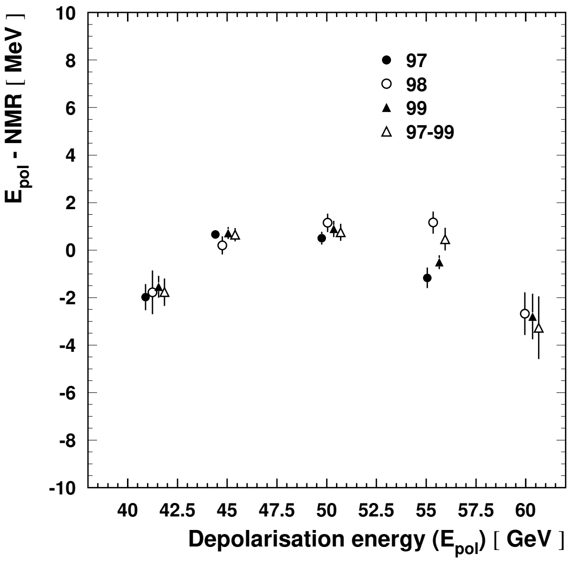

Figure 2: Residuals from the NMR fits to the RDP data for 1997, 1998, 1999, and a combined fit to all data. The error bars indicate the statistical scatter over the measurements. (The position of each point on the horizontal scale has been adjusted for visibility.)

1999 measurements were made at the same energies, some with a new polarisation optics (101/45) [4]. A benefit of this new optics is that, in contrast to 60/60 operation, the beam may be ramped to high energy, which is necessary for spectrometer measurements.

Following the same procedure as in previous years, calibration coefficients were determined for each NMR by fitting against the RDP data. Because of radiation damage it was necessary to replace each probe up to 4 times during the run. However care was taken to place the probes in the same position in the magnets, and no feature in the data can be correlated with these replacements. The residuals of these fits for each RDP measurement, averaged over all probes, is shown in figure 1.

Figure 2 shows the same residuals averaged over all RDP points, plotted for separate fits to the 1997, 1998 and 1999 data, and a global fit to all data. There is a small, but characteristic, non-linearity over the sampled energy range. The behaviour is extremely similar year to year, indicating that the NMR calibration is very stable. A further test of this stability has been performed by using the calibration coefficients obtained with one year's RDP data to determine the physics energy scale in another year. This exercise results in shifts which are always less than 4 MeV with respect to the correct procedure.

4 Flux loop / NMR comparison in 1999

The difference between the total field measured by the flux loop and predicted by the average over the NMR probes can be converted into an energy difference, and used to assess the validity of the NMR extrapolation. The two devices are cross-calibrated in the range corresponding to the polarisation measurements, and then compared at a field

Date	Fill	41 GeV	45 GeV	50 GeV	55 GeV	61 GeV	HE ramp	Optics
19/08/96	3599			•				90/60
31/10/96	3702		•					90/60
03/11/96	3719		•	•				90/60
17/08/97	4000		•					90/60
06/09/97	4121		•	•				60/60
30/09/97	4237		•	•				60/60
02/10/97	4242	•	•	•	•			60/60
10/10/97	4274		•					90/60
11/10/97	4279	•	•	•	•			60/60
29/10/97	4372	•	•					60/60
14/06/98	4666		•	•	•			60/60
18/06/98	4669		•					102/90
15/07/98	4843		•		•			60/60
06/09/98	5137		•					60/60
07/09/98	5141	•	•	•				60/60
20/09/98	5214	•	•	•	•	•		60/60
29/09/98	5232		•					102/90
18/10/98	5337	•	•	•	•	•		60/60
07/06/99	5670	•	•					60/60
25/06/99	5799	•	•	•				60/60
22/07/99	5969	•						60/60
22/07/99	5971		•	•				60/60
08/08/99	6087				•			60/60
09/09/99	6302	•	•	•	•			60/60
20/09/99	6371	•	•	•	•			60/60
25/09/99	6397		•	•			○	101/45
26/09/99	6404	•	•	•	•			60/60
29/09/99	6432		•	•			○	101/45
09/10/99	6509	•		•		•		101/45
27/10/99	6627		•				○	102/90

Table 1: The successful resonant RDP measurements at LEP2. Energy points measured in a fill are marked •. Fills with 'HE ramp' marked by ○ are where the beam was ramped to high energy and useful spectrometer data recorded. The 60/60 and 101/45 optics were devised specifically for RDP measurements, whereas the 90/60 and 102/90 optics were also used for physics operation.

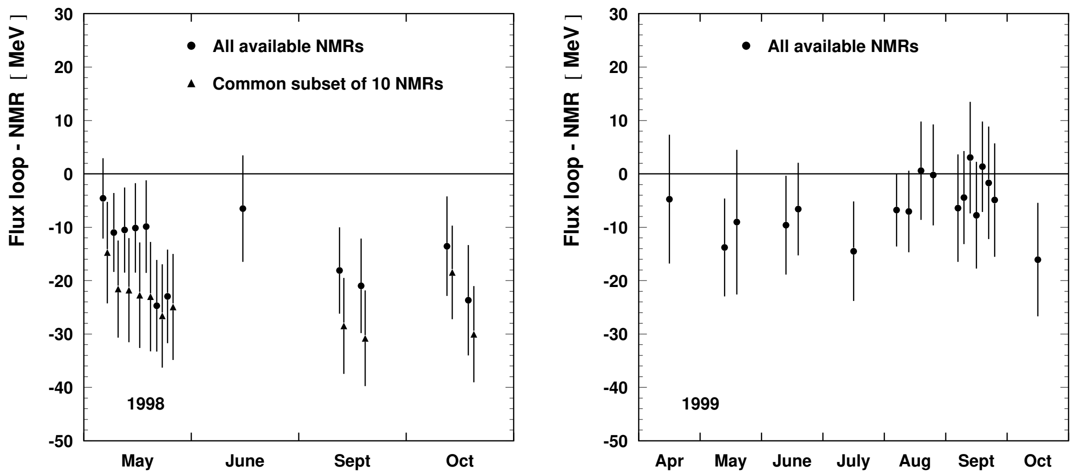

Figure 3: Residual difference between the flux loop and NMR probes at physics energy in 1998 (left) and 1999 (right), for each cycle.

corresponding to physics energy.

In 1999 a total of 17 flux loop cycles were recorded with usable data, evenly distributed throughout the year. The differences between flux loop and NMR prediction for 1998 and 1999 are shown in Fig. 3 for the analysed cycles. The 1999 behaviour is very similar to that seen in previous years. Few cycles have a full complement of 16 NMRs working, due to radiation damage, and this accounts for some of the observed fluctuation. The most meaninful way to quantify any offset is to determine a mean offset for each probe for the flux loops with data, and then to average these offset over all the probes. The mean value of this average offset is -6 ± 8 MeV, slightly smaller than that observed in 1998 (-11 ± 8 MeV). There is no evidence of any significant non-linearity.

The flux loop provides data octant by octant. Because of radiation damage some octants do not always provide useful data in a cycle. This problem was quite serious in 1999, where the mean number of octants per cycle was 4.6, although with variations in the identities of the live octants. For this reason the different between flux loop and NMR was studied for each flux loop octant averaged over all the available cycles. The result can be seen in figure 4, for both 1998 and 1999. It can be seen that in general the octants exhibit very similar offsets, and that these offsets are stable year to year.

5 Systematic error evaluation

The preliminary estimate of the error breakdown for 1999 is given in table 2, together with the corresponding values for 1997 and 1998, and the correlation coefficients between 1999 and 1998. These assignments are briefly discussed in the following sections.

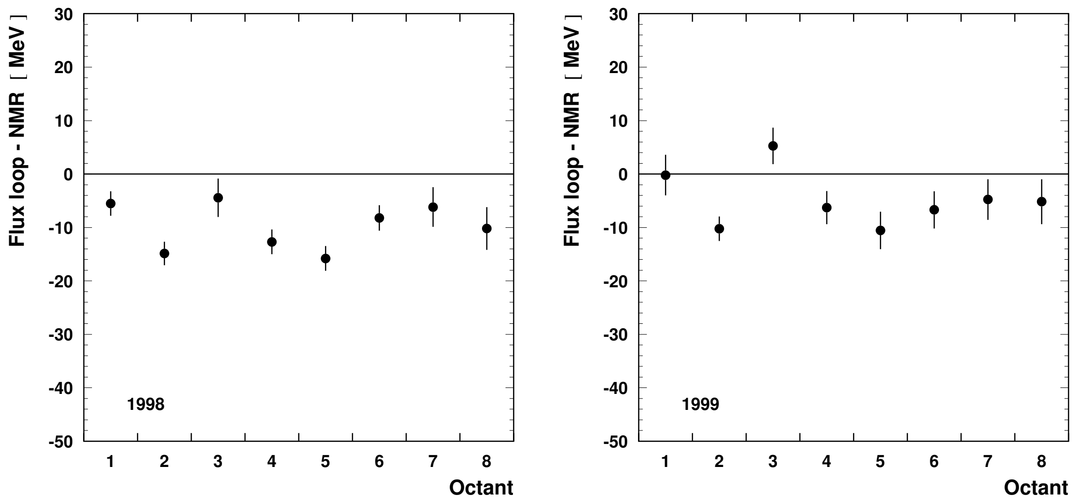

Figure 4: Residual difference between the flux loop and NMR probes at physics energy in 1998 (left) and 1999 (right), for each flux loop octant, averaged over all cycles.

5.1 Scatter in predicted physics energy over NMR's

The rms scatter of the average initial energy per NMR in physics runs for the 1999 data is 45 MeV, compared to 41 MeV and 33 MeV in 1997 and 1998 respectively. This implies an uncertainty on the mean initial energy of 11 MeV.

There is a strong correlation in the initial dipole energy per NMR between the years. This is understood to mean that the scatter reflects the intrinsic properties of the magnets in the positions measured by the NMR's, and is therefore preserved when the probes are exchanged.

5.2 Variations from calibration procedure

Two separate analyses exist for calibrating the NMR probes against the polarisation fills. These analyses differ in how they deal with short term fluctuations of the NMR data, and the reference point at which they choose to perform the calibration. The analyses agree on the physics energy scale to within 3 MeV.

In previous years a systematic uncertainty has been assigned from this consideration, but also to account for anomalous polarisation fills and NMR behaviour. All data in 1999 appear to be very compatible. One fill (6397), visible on figure 1, has residuals of > 5 MeV, most likely arising from uncertainties in the ring deformation correction, which for this fill is very large. The fill, however, has little weight in the calibration, and is anyway considered below in the evaluation of the optics difference error. The uncertainty is taken to be uncorrelated between the years.

5.3 Flux-loop/NMR difference at physics energy

The results of the flux-loop/NMR comparison in 1999 are very similar to those obtained in 1998, and so the same error of 15 MeV is assigned, with 100% correlation. This is the

Source	Error [MeV]			Correlation
	1997	1998	1999	
Extrapolation from NMR–polarisation:				
NMR rms/$\sqrt{N}$ at physics energy	10	8	11	100%
Variations from calibration procedure	5	4	3	0%
Flux-loop test of extrapolation:				
NMR flux-loop difference at physics energy	20	15	15	100%
Field not measured by flux loop	5	5	5	100%
Polarisation systematic	1	1	1	100%
e^+e^- energy difference	2	2	2	100%
Optics difference	4	6	4	50%
Corrector effects	3	4	2	50%
Tide	1	1	1	100%
Initial dipole energy	2	1	1	0%
Dipole rise modelling	1	1	1	100%
IP specific corrections ($\delta E_{\mathrm{CM}}/2$):				
RF model	4	4	5	100%
Dispersion	1	1	1	50%
Total	25	20	21	91%

Table 2: Table of errors for 1997, 1998 and 1999 including the correlation coefficients between 1998 and 1999.

dominant systematic uncertainty in the analysis.

The field outside the flux loop is assumed to be the the same for all years, and therefore the error assigned is identical and fully correlated.

5.4 Polarisation and e^+e^- energy difference

These small uncertainties are the same in each year, and fully correlated between years.

5.5 Optics difference

The NMR-polarisation residuals of the 60/60 optics, used for the majority of the polarisation measurements, and the 102/90 physics optics (and 101/45 optics) are very similar, indicating no significant energy dependence. However an error of 4 MeV has been assigned by comparing the average of these residuals and multiplying this difference by two, to account for the expected scaling of any difference with energy.

The optics dependence has some systematic uncertainties in common between the years, but is driven by imperfections, so a 50% correlation coefficient has been chosen.

5.6 Corrector effects

Recent calculations and measurement have improved the understanding of the interplay between horizontal correctors and central frequency measurements [5]. Furthermore the magnitude of the average horizonal corrector energy shift in 1999 is very small, at $\sim$ 1 MeV. Consequently the assigned error from this source has been reduced to 2 MeV, with a 50% correlation between the years.

The improved studies have also resulted in a calculation of the central frequency which shows reduced fill-to-fill scatter compared with previous determinations. These values have been used in the present analysis.

5.7 Tide, initial dipole energy, and dipole energy rise

The uncertainty from all of these sources is at a negligible level. Following tradition, an entry remains in the table with a 1 MeV assignment. The initial dipole energy contribution comes from the scatter fill-to-fill, and therefore is uncorrelated between years.

5.8 RF and dispersion effects

The evaluation of these uncertainties uses the same criteria as in previous years. The RF uncertainty is found to be 4 MeV for the 192 GeV running, 5 MeV for the other energy points, and is taken to be fully correlated between the years. The dispersion error remains the same at 1 MeV, with a 50% year-to-year correlation. (In previous publications and notes this had been incorrectly given as 2 MeV.)

6 Errors and correlation matrix for different years

Year	Nominal E_{cm}	Error in E_b
1996	161 GeV	27 MeV
1996	172 GeV	30 MeV
1997	183 GeV	25 MeV
1998	189 GeV	20 MeV
1999	192 GeV	21 MeV
1999	196 GeV	21 MeV
1999	200 GeV	21 MeV
1999	202 GeV	21 MeV

Table 3: The uncertainty in the beam energy for the LEP2 data.

The total systematic errors on E_b for the main LEP2 energy points to date are given in table 3. The errors on E_{cm} are merely twice these. The total errors from 1997–1999 are assumed to be fully correlated with the 1996 data points. This approximation is adequate, given the lower statistics at the lower energy points. The full correlations between these points are given in table 4.

E_{cm}	161	172	183	189	192	196	200	202
161	1.00	1.00	.91	.75	.76	.77	.77	.77
172	1.00	1.00	.82	.67	.69	.69	.69	.69
183	.91	.82	1.00	.75	.78	.78	.78	.78
189	.75	.67	.75	1.00	.91	.91	.91	.91
192	.76	.69	.78	.91	1.00	1.00	1.00	1.00
196	.77	.69	.78	.91	1.00	1.00	1.00	1.00
200	.77	.69	.78	.91	1.00	1.00	1.00	1.00
202	.77	.69	.78	.91	1.00	1.00	1.00	1.00

Table 4: The correlation matrix of the uncertainties on E_b for the energy points taken at LEP2, between 1996 and 1999.

The dominant contribution in the error assignment comes from the uncertainty in the extrapolation, at present assigned from the flux loop comparison. Two alternative methods, the spectrometer project and a fit to the RF voltage dependence of the synchrotron tune, have been proposed to perform independent measurements of E_b in the physics regime, and therefore improve confidence in the extrapolation. The status of two methods is briefly described.

7 The LEP Spectrometer

A project was initiated in 1997 to install an in-line energy spectrometer into the LEP ring. By replacing an existing concrete LEP dipole with a precisely mapped steel dipole, and installing triplets of high precision beam position monitors (BPMs) on either side, the local beam energy can be measured in the ratio of the dipole bending field and the deflection angle as $E_b = \frac{1}{\Theta}\int B \cdot dl$. A schematic of the spectrometer assembly is shown in figure 5. While measuring the absolute deflection angle Θ to the desired relative precision of 10^{-4} is impossible, a high precision relative measurement can be performed by using RDP at lower energy to calibrate the spectrometer bend angle, and then using the change in the bend angle together with the change in the dipole field to monitor the beam energy as LEP is ramped to full physics energy.

With a triplet lever arm of roughly 10 meters, the BPMs must have a precision of 1 μm in the bending plane, and be stable against mechanical and electronic drifts at this level. As the spectrometer is to be calibrated with RDP, however, this stability is only needed for the few hours necessary to make a calibration and ramp the beams to full energy.

7.1 Mechanical Design

To ensure the desired mechanical stability of the spectrometer BPMs, custom shielding has been designed to shadow the BPM pickup blocks from the intense synchrotron radiation present in the LEP environment. As the synchrotron power emitted by the beam increases as E_b^4, and the mechanical deformation of the BPM blocks at the BPM button radius is

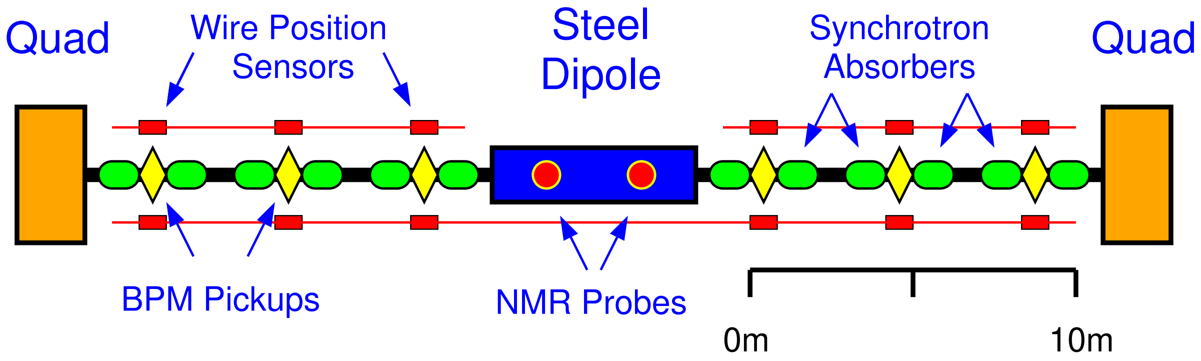

Figure 5: A schematic of the LEP spectrometer.

approximately $1\mu m/°C$, this extra shielding is critical to keep the BPM system stable as the beam is ramped from RD energies to physics energies. Independent temperature regulation of the BPM pickup blocks is used to maintain a temperature variation of less than 0.2°C, and independent capacitive wire position sensors capable of a few hundred nanometer resolution are also used to verify the stability of the spectrometer components.

7.2 Beam Position Measurements

To achieve the desired 1 micron resolution and stability on the beam position measurement, custom BPM readout cards were developed based on a design first used in Synchrotron light source storage rings [6]. In the BPM electronics, the four analogue button signals from each BPM station are multiplexed into a common amplifier chain to reduce the effects of gain drifts on the measured beam position. The spectrometer BPM system, therefore, is not capable of turn-by-turn orbit measurements, but rather provides an integrated mean beam position with a frequency response of around 100 Hz. Additional filtering is added to reduce noise and lower the overall frequency response to below 1 Hz.

During the 1999 LEP run, a technique for performing *in situ* calibrations of the spectrometer BPM system was commissioned. By comparing the measured beam position in the six BPM pickups during a series of beam translations and rotations in the spectrometer bending plane, the relative gain of each BPM station is determined. Repeated calibrations during individual spectrometer measurements indicates a relative gain accuracy of $\simeq 0.2\%$. To avoid additional large systematics from BPM non-linearities and residual gain errors, the beam position within the spectrometer is kept constant to better than ± 200 microns over the course of a measurement using local orbit corrections.

7.3 Magnetic Mapping

The remaining critical component of the LEP spectrometer project is the calibrated steel dipole used to provide the deflection of the beam. As this dipole is energized and ramped along with the other magnets in the LEP ring, it is important to understand the total bending field provided by this dipole at any LEP setting. Four NMR probes are mounted locally in the spectrometer dipole to measure a reference field value B_{Ref}, and the total integral bending field has been determined as a function of B_{Ref} with an extensive magnetic mapping campaign.

Using a precision motor stage instrumented with an independent NMR probe mounted to a carbon fiber mapping arm, the core magnetic field of this dipole was measured with an intrinsic relative precision of 10^{-6} for a variety of excitation currents and environmental conditions. In the end field region the mapping NMR probe will no longer lock, and temperature-stabilized Hall probes also mounted to the movable arm were used to complete the field mapping. While these devices have an intrinsic relative precision of only 10^{-4}, the end field represents about 10% of the total dipole bending field, and thus a relative precision per map of 10^{-5} is achieved.

In addition, since this mapping was performed in a magnetic test lab and not in the tunnel where the spectrometer operates, an additional *in situ* field mapping technique was developed using an NMR probe and miniature flux coil which could be inserted into the LEP beam pipe. The precision of this technique is quite comparable to the magnetic test stand itself, and maps made with this technique in the LEP tunnel after dipole installation show consistent results. While the analysis of this mapping data is still ongoing, consistency of the field maps taken over several months indicates a relative accuracy of the mapping technique better than 5×10^{-5}.

7.4 Preliminary Spectrometer Results

While a single arm prototype was installed in LEP for the 1998 run to test the mechanical design, the final spectrometer assembly was only completed towards the end of the 1999 LEP run. Two techniques have been used during the spectrometer commissioning to verify the performance of the device.

First, during small RF frequency shifts the change in beam energy, dE_b^{spect}, as determined from the spectrometer is compared to the expected energy change, dE_b, using the relations:

$$dE_b^{\mathrm{spect}}/E_b^{\mathrm{spect}} \;=\; -d\Theta/\Theta, \qquad dE_b/E_b \;=\; -\alpha_c^{-1}\, df_{\mathrm{RF}}/f_{\mathrm{RF}},$$

where $d\Theta$ is the observed change in bend angle, df_{RF} is the size of the frequency shift and α_c is the momentum compaction factor. This technique can also be used to calibrate the absolute gain of the spectrometer BPMs, and limit residual non-linearities of the system. Overall, good agreement with the expected behavior is seen after the *in situ* gain calibrations are performed.

Second, the beam energy observed by the spectrometer is compared to the beam energy determined by RDP during multi-point polarization fills. This provides a direct check of the spectrometer energy measurement over the range from 40 – 60 GeV. The data from five multi-point fills (starting with 6371) have been analyzed during the time when the spectrometer was fully operational, and no bias is observed between the spectrometer and RDP results. From the variance of the observed differences between the spectrometer and RDP techniques, a systematic uncertainty of 15 MeV on the beam energy measurement at 95 GeV is expected. While this number is slightly higher than the design goal of 10 MeV, improvements to the calibration procedure and better beam alignment during the spectrometer measurements are expected to reduce this uncertainty during the 2000 LEP run.

Finally, three fills have been used to perform a direct beam energy measurement using the spectrometer at physics energies. Each of these fills was first calibrated using RDP at lower energy, then ramped directly to high energy. The details of these fills are given in table 1. Figure 6 shows the difference observed between the beam energy measured directly by the spectrometer and the value predicted by the LEP NMR readings. No bias is observed, and the scatter of the data seen at high energy is quite consistent with the 15 MeV uncertainty expected from the multi-point cross check.

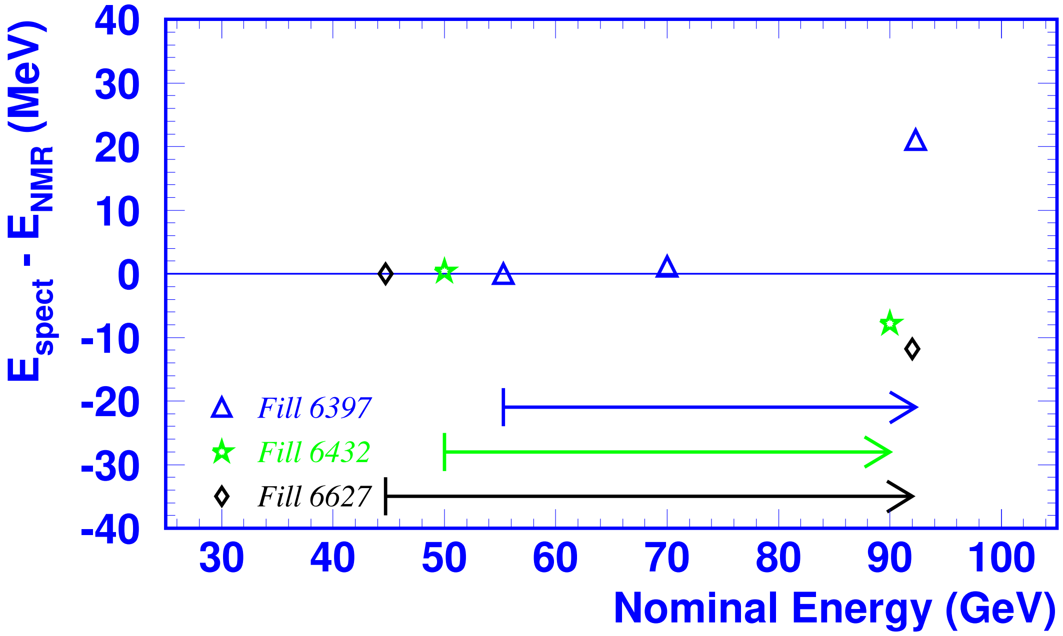

Figure 6: Spectrometer energy measurements in 1999. The beam energy measured by the spectrometer at high energy is compared to the prediction from the LEP NMR readings for three fills in 1999. In each fill, a RDP measurement was performed at the indicated low energy point to calibrate the overall spectrometer energy scale. In fill 6397 a spectrometer measurement was also made at an intermediate energy.

These results are encouraging, but firm conclusions await the collection of more data during the 2000 run.

8 Energy from the synchrotron tune Q_s

Since the energy loss per turn, U_0, increases with the fourth power of energy

$$U_0 = \left(\frac{C_\gamma}{\rho}\right) \; E_b^4, \tag{1}$$

where C_γ is a constant depending on the particle type and ρ is the average bending radius, observables sensitive to the energy loss per turn can be used to determine the beam energy, provided they can be measured and understood with sufficient precision. The synchrotron tune of the beam, Q_s, is such an observable. It has a dependence on the total effective accelerating voltage, V_{RF} and the energy loss as follows

$$Q_s^2 \;=\; \left(\frac{\alpha_c h}{2\pi E_b}\right)\sqrt{e^2V_{RF}^2 \;+\; bV_{RF}^4 \;-\; (U_0+K)^2}, \tag{2}$$

with α_c the optics dependent momentum compaction factor, and h the harmonic number (ratio between RF frequency and revolution frequency). This expression differs from more naive formulations of the dependence in having a term in V_{RF}^4, which accounts for the inhomogenous distribution of the accelerating voltage around the ring, and a contribution K, which represents energy loss from sources other than synchrotron radiation in the dipole magnets. These include losses from synchrotron radiation caused by position offsets and finite beam sizes in quadrupole magnets, from synchrotron radiation in corrector magnets used for beam steering and from parasitic mode losses caused by the resistive part of the longitudinal impedance.

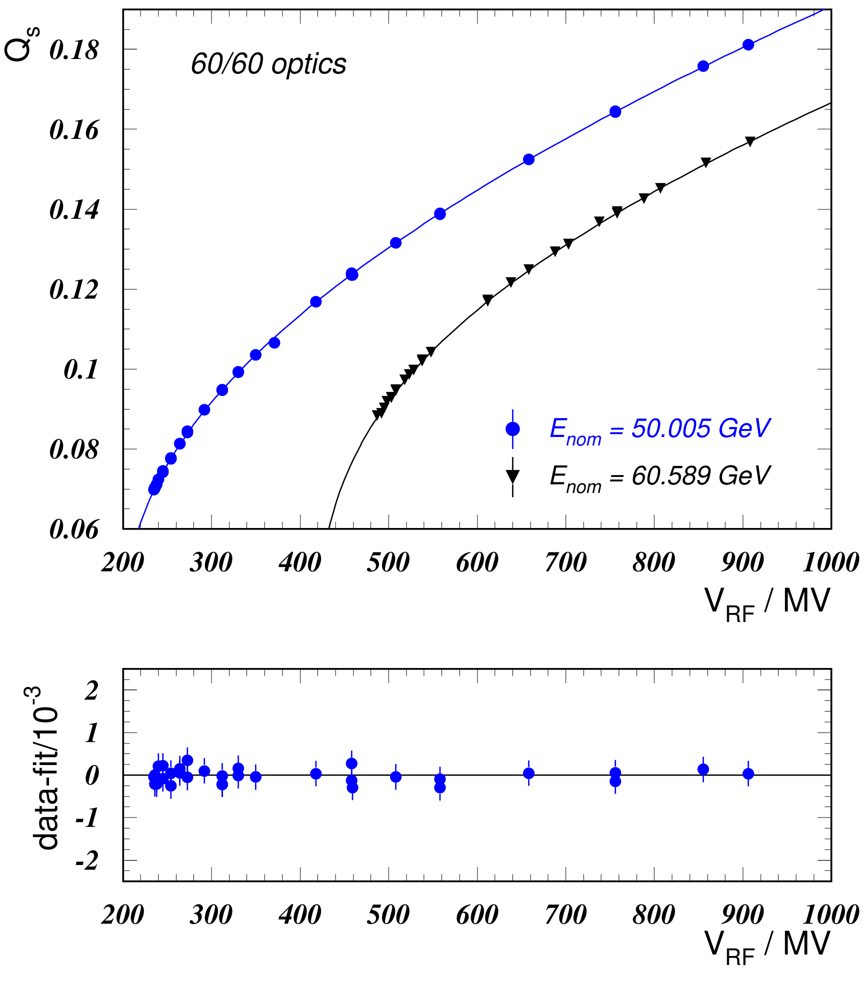

Figure 7: Measurements of Q_s as function of total RF voltage with the 60/60 optics. The curves are the results of the fits according to expression 2 (top). Fit residuals for the 50.005 GeV data (bottom).

Measurements of Q_s as function of V_{RF} are used to extract the beam energy with a fit to this expression. The actual measurement of Q_s is based on a harmonic analysis of the measured phase difference between the bunch and RF signals. In a given experiment voltage scans are first made at low energy and the comparison to the NMR model is used to fix a voltage calibration factor; a voltage scan at higher energy is then made for the measurement itself. The correction terms in the expression are determined both from dedicated measurements and from model calculations and simulations. Figure 7 shows such measurements for beam energies of 50.005 and 60.589 GeV. The curves are fits using expression 2. The bottom plot shows the residuals for the fit to the 50.005 GeV data. It can be seen that the model describes the measurements well.

The uncertainty on the beam energy is about 20–25 MeV and essentially energy independent. This has a statistical component which comes from the error in the fit, and systematic contributions which arise mainly from the modelling of the total additional energy loss K, from the determination of the voltage calibration and from the machine parameters (the momentum compaction factor α_c and effective bending radius ρ). There is hope to improve the understanding of these parameters.

E_b has been measured using this method at the high energy points of 80 GeV (twice in 1999) and 90 GeV (once in 1998). The comparison between the obtained values and the prediction of the NMR model is shown in figure 8. It can be seen that the agreement is good. Further measurements are planned for the 2000 run.

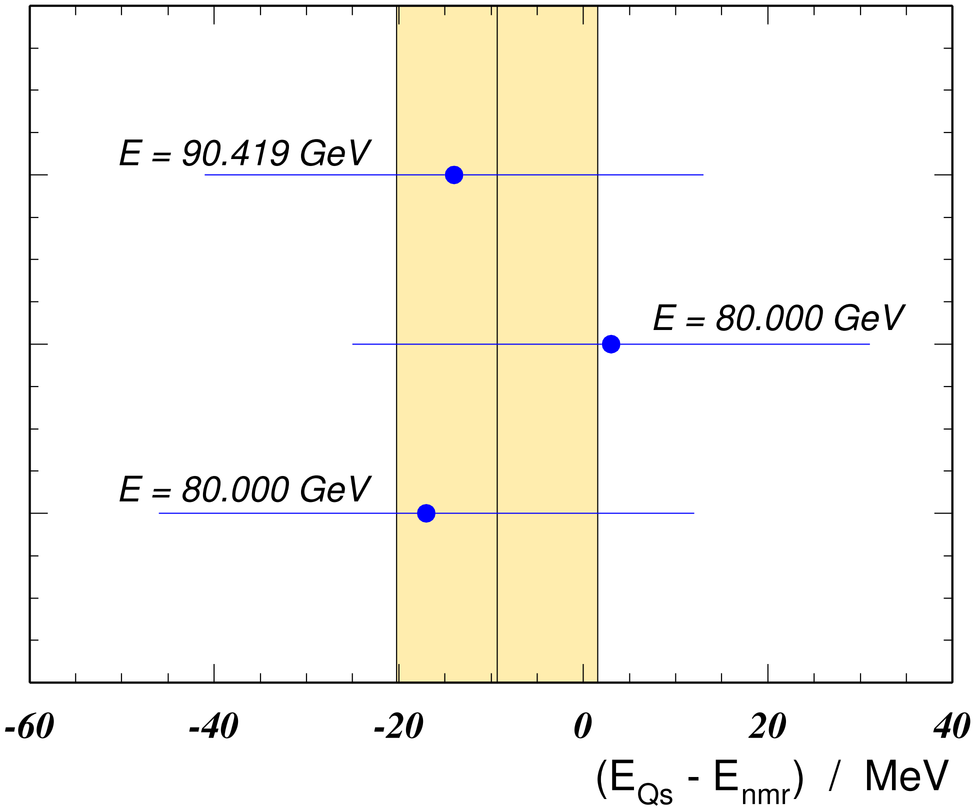

Figure 8: Q_s energy measurements in 1998 and 1999. The difference is shown between the Q_s measurements of E_b and that coming from the NMR model. The error on each measurement is shown. The average value and statistical scatter of the measurements is indicated by the vertical line and band.

9 Energy Spreads

The luminosity weighted instantaneous centre-of-mass energy spreads have also been calculated for the 1999 data samples, following the same procedure as in [1]. The energy spreads are listed in table 5 for the main LEP2 data samples, each with a 5% assigned error. The fact that the spreads do not always increase with energy arises from different mean offsets in the RF frequency.

Year	Nominal E_{cm}	E_{cm} spread
1996	161 GeV	144 ± 7 MeV
1996	172 GeV	165 ± 8 MeV
1997	183 GeV	219 ± 11 MeV
1998	189 GeV	237 ± 12 MeV
1999	192 GeV	254 ± 13 MeV
1999	196 GeV	266 ± 13 MeV
1999	200 GeV	265 ± 13 MeV
1999	202 GeV	253 ± 13 MeV

Table 5: The luminosity weighted centre-of-mass energy spread for LEP2 data.

References

[1] LEP Energy Working Group, "Evaluation of the LEP centre-of-mass energy above the W-pair production threshold", Eur. Phys. J. C 11 4 573-585, 1999.

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