LEP Energy Working Group 01/01
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Evaluation of the LEP centre-of-mass energy for data taken in 2000

The LEP Energy Working Group [1]

Abstract

The centre-of-mass energy at LEP2, above the W pair threshold, was evaluated in 1996–1999 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 2000 data are presented. The preliminary error on the beam energy in 2000 is determined to be 25 MeV. 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 1996–1999 data samples. This method is documented in Ref. [1, 2, 3]. In this note, the preliminary results of applying the same analysis techniques to the 2000 data are presented. The calculated energies and spreads have been distributed to the LEP experiments.

2 LEP operation in 2000

LEP operation during 2000 had two significant differences with respect to previous years, both of which were motivated by the aim of delivering luminosity at the highest possible collision energies.

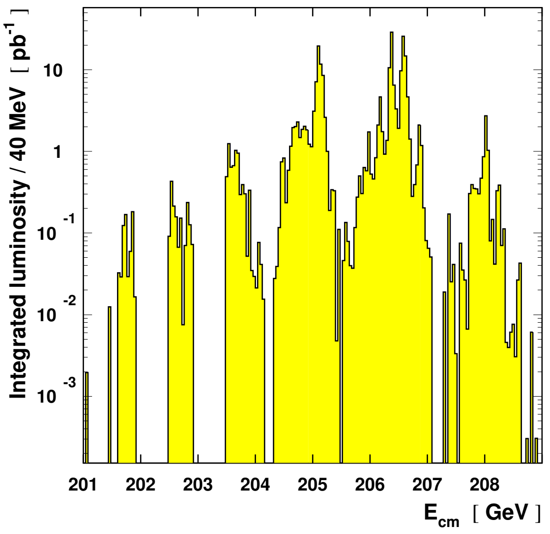
- **Miniramps** [4]
  Fills were started at a given beam energy safely within the capabilities of the RF system. When the beam currents had decayed significantly, typically after an hour, the dipoles were ramped and luminosity delivered at a higher energy. This procedure was repeated until the energy was at the limit of the RF, and data taken until the beam was lost through a klystron trip. These *miniramps* lasted less than a minute, and varied in step size with a mean value of 600 MeV. Hardware signals were used to flag the start and end of miniramps to the experiments, and this information was recorded with the logged triggers. The starting energy of fills, and the precise strategy of miniramping varied throughout the year, depending on the status of the RF system.

- **Bending Field Spreading (BFS)** [5, 6]
  Given a fixed RF acceleration voltage the synchrotron radiation power depends on how the bending field is distributed. During the 2000 run $\sim$ 100 previously unconnected corrector magnets were powered, in order to exploit this dependence to boost the beam energies by 0.18 GeV with respect to what would otherwise be possible. The BFS scheme was first enabled soon after the start of run, and increased in power for the final three months of operation.

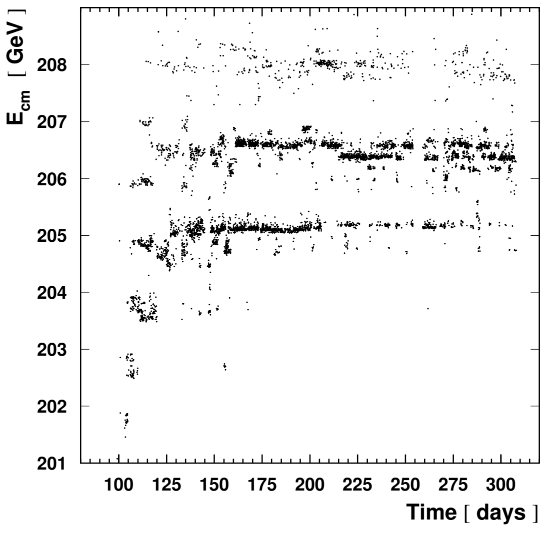
The luminosity collected in a single experiment as a function of E_{CM} is shown in figure 1(a), excluding the Z^0 calibration fills and some very limited running at 200 GeV. The mean energy was 205.9 GeV, with some running up to almost 209 GeV. The distribution of E_{CM} with time into the run is shown in figure 1(b).

3 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



(a)



(b)

Figure 1: Plot (a) shows the integrated luminosity in bins of $E_{\rm CM}$ for a single LEP experiment in 2000. Plot (b) shows the variation of $E_{\rm CM}$ against day of year; each entry corresponds to the mean energy for a data file of maximum length $\sim$ 30 minutes.

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, 1998 and 1999 data.

The largest uncertainty on the linearity assumption comes from flux loop measurements, 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: $B_{\rm FL} = c + dB_{\rm NMR}$. There is also a "statistical" contribution to the error from the scatter in the predicted physics energy over the probes.

Systematic uncertainties from the other effects that influence the centre-of-mass energy are relatively small. More details can be found in [1, 7].

4 Determining the energy scale in 2000

During 2000 RDP was successfully performed at 16 points spanning 41–55 GeV distributed through 7 fills, as listed in table 1. All measurements were performed with the dedicated 101/45 polarisation optics [8].

Following the same procedure as in previous years, calibration coefficients were determined for each NMR by fitting against the RDP data. The residuals of these fits averaged over all probes and all RDP measurements at a single energy point are shown in figure 2 for 2000. Also shown are the residuals for previous years, and for a global fit to all data. There is a small, but characteristic, non-linearity over the sampled energy range. The

Date	Fill	41 GeV	45 GeV	50 GeV	55 GeV
11/05/00	7129	•	•	•	
25/05/00	7251	•	•	•	
21/06/00	7519	•		•	
26/07/00	7929	•			
04/09/00	8368	•		•	•
11/09/00	8446	•			
25/09/00	8556		•	•	•

Table 1: The successful resonant depolarisation measurements in 2000. Energy points measured in a fill are marked •.

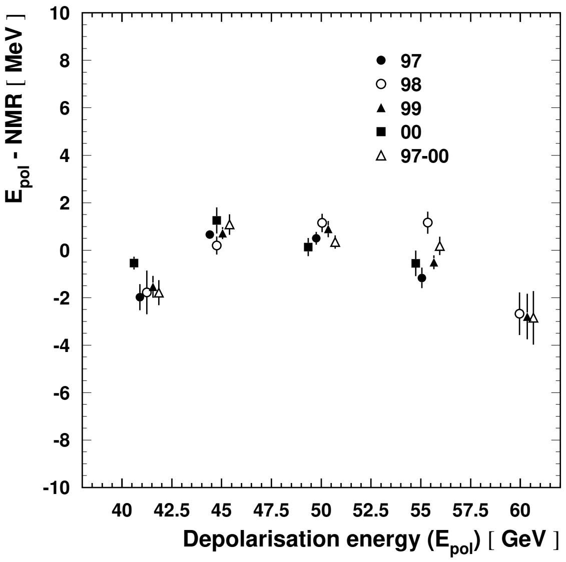


Figure 2: Residuals from the NMR fits to the RDP data of each year and a combined fit. The error bars indicate the statistical scatter over the measurements. (The position of each point on the horizontal scale has been adjusted for visibility.)

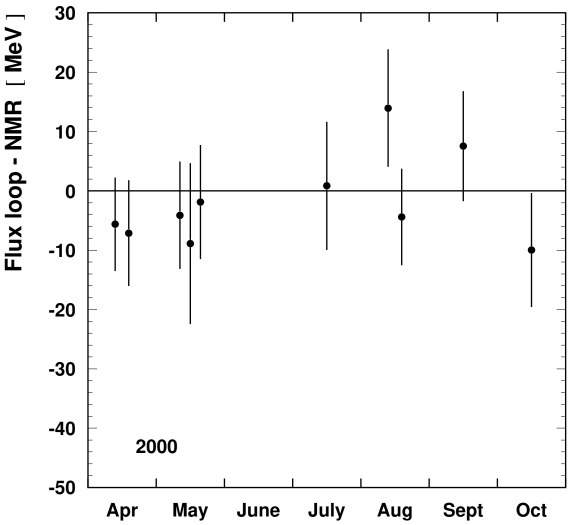


Figure 3: Residual difference between the flux loop and NMR probes at physics energy in 2000, for each cycle.

behaviour is remarkably similar year to year, indicating that the NMR calibration is very stable.

When applied in the physics regime the calibration coefficients predict a different energy, probe to probe. The mean of these predictions is taken as the raw dipole energy. The scatter throughout the 16 NMRs is 51 MeV, which is very similar to previous years.

As a cross-check the 2000 energy scale was re-evaluated with calibration coefficients from other years. Very stable results were seen, indicating that on average the magnet behaviour has been constant throughout LEP running. Those of 1999, for instance, shift the beam energy by less than 3 MeV.

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 corresponding to physics energy.

In 2000 a total of 10 flux loop cycles were recorded with usable data, evenly distributed throughout the year. The differences between flux loop and NMR prediction are shown in figure 3 for the analysed cycles. The mean and RMS value of this average offset is -2 ± 7 MeV. The distribution is compatible with those of previous years. There is no evidence of any significant non-linearity.

5 Systematic error evaluation

The preliminary estimate of the error breakdown for 2000 is given in table 2, together with the corresponding values for 1997, 1998 and 1999, and the correlation coefficients between 1999 and 2000. The 2000 errors concern only those data taken during stable operation, and are not applicable for the $\sim 1\%$ of integrated luminosity delivered during miniramps. For these an error of 300 MeV should be assumed.

The errors and correlations associated with the magnetic extrapolation have been assigned following the procedure of previous years, based on the observations presented in section 4. All other contributions are unchanged with respected to 1999, apart from the BFS and miniramp errors. These are briefly discussed below.

5.1 BFS error

The BFS boost was calibrated using the LEP spectrometer in two dedicated measurements. The beam was centred in the spectrometer and the bend angle measured. A nominal BFS boost of 300 MeV was applied and the bend angle observed to change. This energy boost was then compensated for by adjusting the RF frequency until the original bend angle was recovered. From the change of RF frequency the BFS boost was determined.

A preliminary analysis of the measurements gave consistent results in agreement with expectation. At present an error of 10 MeV per 300 MeV of BFS boost has been assigned. The mean boost throughout the run was 400 MeV [2], leading to an error of 13 MeV. This error supersedes that from corrector effects considered in previous years, and is essentially independent from these, as it is fixed from the precision of the two measurements.

5.2 Miniramps

From the signals received from LEP, experiments were able to flag any data taken during a miniramp accordingly. The synchronisation between these signals are very good compared with the duration of the miniramp. It is conceivable however, although very unlikely, that the miniramps had not finised when the ‘end of ramp’ signals were distributed. An upper limit of 30 seconds can be set on such time lags from the NMR looging. A systematic

[2]Note that the net gain in beam energy from the BFS is less than this, as the scheme requires operating the dipoles at slightly lower currents than would have been the case otherwise.

Source	Error [MeV]				Correlation
	1997	1998	1999	2000	
Extrapolation from NMR–polarisation:					
NMR rms/$\sqrt{N}$ at physics energy	10	8	11	13	100%
Variations from calibration procedure	5	4	3	3	0%
Flux-loop test of extrapolation:					
NMR flux-loop difference at physics energy	20	15	15	15	100%
Field not measured by flux loop	5	5	5	5	100%
Polarisation systematic	1	1	1	1	100%
e^+e^- energy difference	2	2	2	2	100%
Optics difference	4	6	4	4	50%
Corrector effects / BFS (2000)	3	4	2	13	0%
Tide	1	1	1	1	100%
Initial dipole energy / miniramps (2000)	2	1	1	2	0%
Dipole rise modelling	1	1	1	1	100%
IP specific corrections ($\delta E_{\mathrm{CM}}/2$):					
RF model	4	4	5	5	100%
Dispersion	1	1	1	1	50%
Total	25	20	21	25	82%

Table 2: Table of errors for 1997, 1998, 1999 and 2000 including the correlation coefficients between 1999 and 2000.

effect of this size would bias the energy determination in the periods of supposed stable operation by less than 2 MeV. Thus an error of this size has been conservatively assigned.

6 Energy uncertainty for Z running

On several occasions during the year luminosity was delivered at the Z resonance, in order to provide calibration data for the experiments. The uncertainty on E_b for these periods is estimated to be 6 MeV.

7 Errors and correlation matrix for different years, and future prospects

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 same assumption is made for the correlation between 1996 and 2000, with the caveat that the significant 2000 BFS error is clearly independent. The full correlations between these points are given in table 4.

Year	Nominal $E_{\rm CM}$	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
2000	206 GeV	25 MeV

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

E_{cm}	161	172	183	189	192	196	200	202	206
161	1.00	1.00	.91	.75	.76	.77	.77	.77	.81
172	1.00	1.00	.82	.67	.69	.69	.69	.69	.77
183	.91	.82	1.00	.75	.78	.78	.78	.78	.66
189	.75	.67	.75	1.00	.91	.91	.91	.91	.77
192	.76	.69	.78	.91	1.00	1.00	1.00	1.00	.82
196	.77	.69	.78	.91	1.00	1.00	1.00	1.00	.82
200	.77	.69	.78	.91	1.00	1.00	1.00	1.00	.82
202	.77	.69	.78	.91	1.00	1.00	1.00	1.00	.82
206	.81	.77	.66	.77	.82	.82	.82	.82	1.00

Table 4: The correlation matrix of the uncertainties on E_b for the energy points taken at LEP2, between 1996 and 2000.

During 2000 more data were taken with the LEP spectrometer, and additional Q_s vs $V_{\mathrm{R}F}$ scans were made (see [3] for a brief overview of these methods). When the analyses of these data are complete the central values and the error assignment for all LEP2 operation will be reviewed.

8 Energy Spreads

The luminosity weighted instantaneous centre-of-mass energy spreads have also been calculated for the 2000 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
2000	206 GeV	236 ± 12 MeV

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

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