ENERGY CALIBRATION: STATUS AND PROSPECTS

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Abstract

The requirements of the W mass measurement on the knowledge of the LEP beam energy is stated, and three complementary methods of beam energy determination are presented. The status of these methods and their prospects in the final year of LEP operation are discussed, and the demands on machine time summarised.

1 PHYSICS GOALS AND METHODS OF ENERGY CALIBRATION

The measurement of the W boson mass, $\mathrm{m_W}$, is one of the main goals of the LEP2 programme. The experiments reconstruct the decay of the W^+W^- pair, using a kinematic fit which takes the beam energy, $\mathrm{E_b}$ as a constraint. Therefore the fractional error on $\mathrm{E_b}$ enters directly as a fractional error on $\mathrm{m_W}$. The projected statistical and combined experimental uncertainty on $\mathrm{m_W}$ for the complete LEP2 data set is ≈ 36 MeV [1]. It is highly desirable to know $\mathrm{E_b}$ with a precision of $10 - 15$ MeV so as not to inflate the $\mathrm{m_W}$ error, and to ensure that this common systematic is not a significant component. The run in 2000 offers the final opportunity of making measurements to achieve this aim.

The method of resonant depolarisation (RDP), used to great success at LEP1 [2], cannot be used to directly measure $\mathrm{E_b}$ at the W scale. Polarisation has only been observed up to energies of 60 GeV. Instead, three alternative and complementary methods are being exploited, all of which offer interesting precision:

- **NMR-extrapolation method**
  Here the local fields, as measured by NMR probes in several dipoles around the ring, are calibrated against RDP in the energy interval $41 - 60$ GeV. This calibration is applied to give the energy in the physics regime, and a 'non-linearity' error assigned through a comparison to the flux loop. This method has been used since the start of LEP2.

- **Spectrometer**
  Here the bend angle of the beam is measured by beam pickup monitors (BPM's) in a dipole of known integrated field, and thereby $\mathrm{E_b}$ determined. This provides a direct measurement of $\mathrm{E_b}$ in the physics regime, but the result is normalised to a low energy measurement, which is cross-calibrated against RDP, in order to reduce systematic unknowns. The spectrometer has been operational since autumn 1999.

- $\mathrm{Q_s}$ **vs** $\mathrm{V_{RF}}$
  In dedicated fills the RF voltage, $\mathrm{V_{RF}}$, is varied and the synchrotron tune, $\mathrm{Q_s}$, measured. The dependence of $\mathrm{Q_s}$ on $\mathrm{V_{RF}}$ involves the energy loss, and thereby $\mathrm{E_b}$. A model has been developed which fits the data sufficiently well for a fit to be made and $\mathrm{E_b}$ extracted with confidence. Such measurements have been made since 1998.

These methods will be discussed in more detail, their status reviewed and their prospects and requirements in the forthcoming run assessed.

2 STATUS AND PROSPECTS

2.1 Depolarisation measurements in 1999

Despite the absence of polarisation at high energy, RDP measurements still play a vital role in the energy calibration, which all the methods exploit to a greater or lesser extent. Here the goals and achievements of the 1999 depolarisation campaign are briefly reviewed.

At the 1999 LEP performance workshop a proposal was presented which requested 9 days of machine time for RDP measurements [3]. This time was to be devoted to the following studies:

- Commissioning of 60/60 polarisation optics and k-modulation measurements;

- Fills with 3–5 energy points measured ('multi-points') for calibrating the extrapolation-NMR method, cross-checking non-linearity systematics and commissioning the spectrometer;

- Fills with a single energy point, and then ramp to high energy, for spectrometer measurements;

- A search for evidence of polarisation above 90 GeV and an attempt to enhance polarisation levels in the intermediate regime with high $\mathrm{Q_s}$ operation, as proposed in [4].

In practice, the total time spent on both RDP measurements and on related energy calibration studies was 14 days. There was however very little interference with physics operation, as the majority of the measurements were performed during periods of cryogenic maintenance, RF interventions and SPS MDs. On only three occasions was calibration work scheduled as an alternative to high energy physics running.

The main goals of the calibration programme were successfully realised. Table 1 summarises the successful measurements. It can be seen that 29 points were calibrated (compared with 21 in 1998), spanning an energy interval of 41-60 GeV (as in 1998), including several multi-points.

Many of these RDP's were performed after the spectrometer became operational, and four of these fills were ramped to high energy.

Table 1: Summary of polarisation measurements in 1999, showing the date, fill number and energy points calibrated (in GeV). 'R' indicates whether the fill was then ramped to high energy. The spectrometer was operational for fills after and including 6302.

			Depol energy [GeV]					
Date	Fill	Optics	41	45	50	55	60	R
7/6	5670	60/60	Y	Y				
25/6	5799	60/60	Y	Y	Y			
22/7	5969	60/60	Y					
22/7	5971	60/60		Y	Y			
8/8	6087	60/60				Y		
9/9	6302	60/60	Y	Y	Y	Y		
20/9	6371	60/60	Y	Y	Y	Y		
25/9	6397	101/45		Y	Y			Y
26/9	6404	60/60	Y	Y	Y	Y		
29/9	6432	101/45		Y	Y			Y
9/10	6509	101/45	Y		Y		Y	Y
27/10	6627	102/90		Y				Y

Time constraints, and worries about the effects of the resulting short bunch lengths, meant that the high Q_s operation was not explored. No significant polarisation was found at $\sim$ 90 GeV. A beneficial by-product of this search was the development of an alternative calibration optics, 101/45 [5]. In comparison with the established 60/60 optics, this offers similar, if not higher, polarisation levels and allows the beam to be ramped to high energy. This last feature therefore makes the optics ideal for spectrometer operation.

2.2 *NMR-extrapolation method*

Status The depolarisation campaigns at LEP2, notably in 1997, 1998 and 1999, have yielded 70 RDP points. This is a sufficiently large sample to make general studies of the behaviour and stability of NMR calibration, year to year.

Figure 1 shows the residuals between the RDP measurements and NMR fits, for all three years, and a global fit to the complete dataset. Each point is averaged over the 16 NMRs, and over all RDP measurements at that point. The error bars are assigned based on the statistical scatter. In all years there is a characteristic 'banana', which is evidence of non-linearity in this region. However the magnitude of the banana is very small – about 2 MeV over a lever arm of 20 GeV. The shape of the banana is very reproducible between years, indicating that the global NMR calibration is extremely stable. Such a conclusion cannot be reached by studying individual probes, as these exhibit more scatter. This is to be expected, as radiation damage has required that the probes be repaired and reinserted at the start of each run, and indeed several times throughout a run (3 to 4 times per probe in 1999). Care has been taken to ensure that that the probes be repositioned exactly as before, so that the same field be sampled, but small differences are inevitable. However, averaged over the full ensemble of NMRs the global behaviour remains invariant.

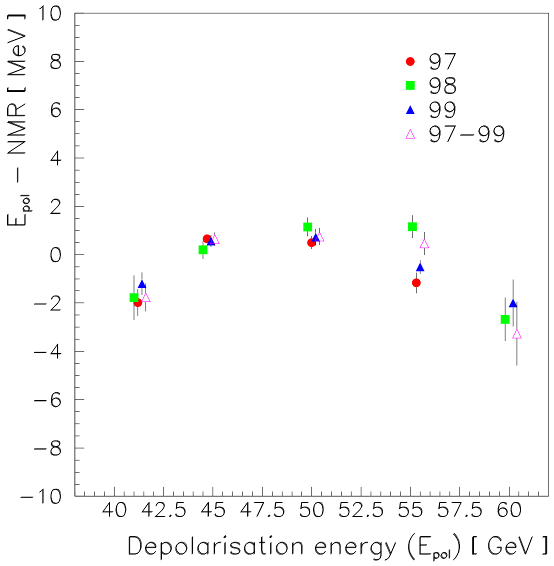

Figure 1: Residuals of NMR fits to RDP points, for 1997, 1998, 1999, and a global fit to all three years. Each point is averaged over all probes and all RDP measurements.

As is to be expected from figure 1, the NMR-extrapolation method's determination of the physics energy scale is also very stable, year to year. This can be demonstrated by applying the calibration coefficients determined in one year to the physics operation of another year. Such exercises give shifts in E_b at the $\sim 2 \times 10^{-5}$ level.

The challenge of the NMR-extrapolation method lies in the error assignment. Figure 1 shows evidence of some small non-linearity for the 16 magnets sampled in the $40 - 60$ GeV range, but says nothing about what happens for the ring as a whole at 100 GeV. This error is assigned by comparing the NMRs to the flux loop in a manner directly analogous to the RDP-NMR procedure. Flux loop cycles are performed periodically throughout the year, and the NMRs fitted to the integrated field points in the $40 - 60$ GeV range. The results of this fit are then used to predict the field high energy, and the prediction compared with the actual flux loop reading. This field residual, expressed in energy, is shown for the 1999 cycles in figure 2 against the day of the year. The average of the NMR sample has an offset, but one which is small at ~ -10 MeV. This behaviour is also very similar to what was observed in previous years. Taking the flux loop to be representative of the ring as a whole, an error on E_b is assigned. In 1998 this was 20 MeV. (This uncertainty is dominated by the flux loop comparison, but receives other contributions, as is explained in [6, 7].) The analysis has yet to be finalised for 1999, but is expected to have a similar uncertainty.

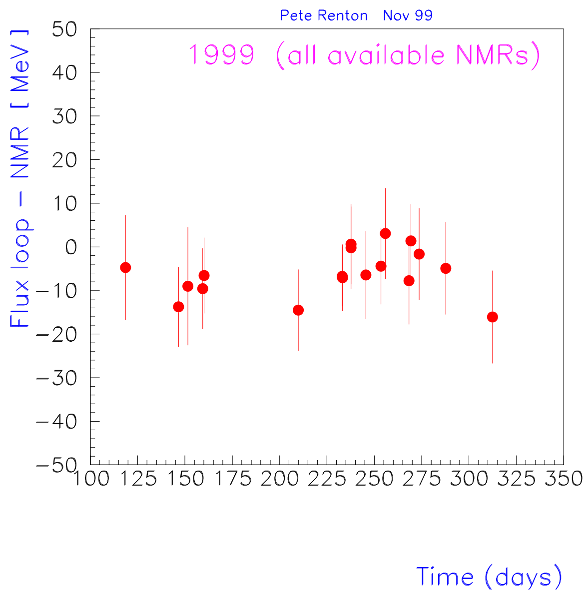

Figure 2: Residuals of NMR fits to the 1999 flux loop cycles points, as a function of time. The residuals are evaluated at fields corresponding to $E_b = 196\,\mathrm{GeV}$.

Prospects and plans The data accumulated to date exhibit a remarkable consistency over the years of LEP2 operation. For this reason it is not necessary to schedule further RDP measurements for the NMR-extrapolation method alone; in particular long multi-point MDs are not required. The RDP points which will be recorded for spectrometer studies will be sufficient to cross-check the NMR calibration. When possible, flux loop cycles should be performed to monitor the stability of the extrapolation error. Periodic interventions will be necessary to replace radiation damaged probes, and to maintain the flux loop.

Unfortunately, the reproducibility of the results also means that, in the absence of fresh insight, the error assignment on E_b from the extrapolation method will not significantly decrease. The present uncertainty is not adequate for the physics goals. Moreover the assignment relies on certain assumptions, which though weak, are nonetheless unavoidable. For this reason alternative methods have been devised to directly measure E_b at high energy, in particular the spectrometer.

2.3 *The spectrometer*

Components and performance 1999 saw the first data taken with the fully operational LEP spectrometer. The spectrometer determines E_b by measuring the bend angle of the beam in a lattice dipole of known integrated field.

The spectrometer is shown schematically in figure 3. The bend angle is measured by a triplet of BPMs either side of the dipole. The stability of these triplets is monitored by stretched wire position monitors. In order to minimise temperature coefficients, inhomogenities, and ageing, the dipole is a specially built steel magnet, similar to those used in the injection region. Inserted in the dipole are 4 NMR probes to monitor the local field. Synchrotron absorbers around the BPMs and shielding around the position sensors protect against the effects of synchrotron radiation. The temperature of the spectrometer is carefully regulated, and monitored at many points. In 1998 a prototype of the spectrometer had been installed, involving a conventional dipole and one instrumented arm, in order to learn about the operating environment [8].

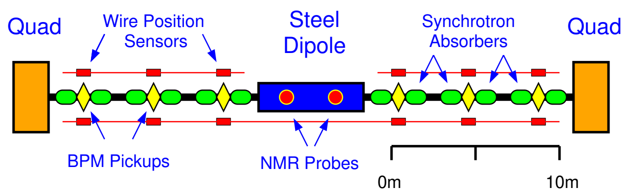

Figure 3: Schematic of the LEP spectrometer.

By the early autumn of 1999 all components of the spectrometer were installed and sufficiently understood for meaningful measurements to be attempted. To arrive at the completely functioning instrument, only 2 years after the concept was first proposed, has required huge efforts. Selected examples of this work in the past year have included a dedicated field mapping of the dipole, which has enabled the field integral to be related to the NMR readings with a precision of a few 10^{-5}, and the installation and commissioning of BPM electronics which give a relative position resolution of $\sim$ μm. These are the design specifications and are necessary for achieving the desired 10^{-4} precision on E_b.

Operation Although in principle the bend angle and field integral alone provides a direct measurement of E_b at a given energy, in practice it is necessary to perform a relative measurement in which the spectrometer result is compared at two energies, where the scale of the lower energy is cross-calibrated by RDP. In this manner systematics, such as knowledge of absolute position in the BPMs, are suppressed. It is desirable that these two energies are taken close in time, and in the same fill, as this ensures that the BPM response is the same, and the operating conditions stable. Because the 60/60 optics cannot be ramped to high energy, it is unsuitable for these measurements, and hence the physics optics or, better still, new 101/45 optics must be used.

In order to measure the bend angle the gains of the BPMs must be known. These gains can conceivably vary with time and depend on factors such as beam current. Therefore they are determined in situ for each energy point. This is achieved by a sequence of beam bumps and rotations, which enable the relative gains in the triplets to be determined. This gain calibration takes $\sim$ 1 hour, but may be optimised for the coming run.

Preliminary results The performance of the spectrometer can be assessed with multi-point RDP fills. In these fills the energy intervals measured by RDP can be compared with those measured by the spectrometers. From the autumn multi-point fills, 10 energy steps are available with trustworthy BPM data. Figure 4 shows the difference between the energy step estimate of the spectrometer and that of RDP, plotted against the energy of the second (or subsequent) step, and the projection of this distribution. The distribution shows no evidence of bias, and has a width of 8 MeV indicating that the spectrometer is reliably tracking the energy change.

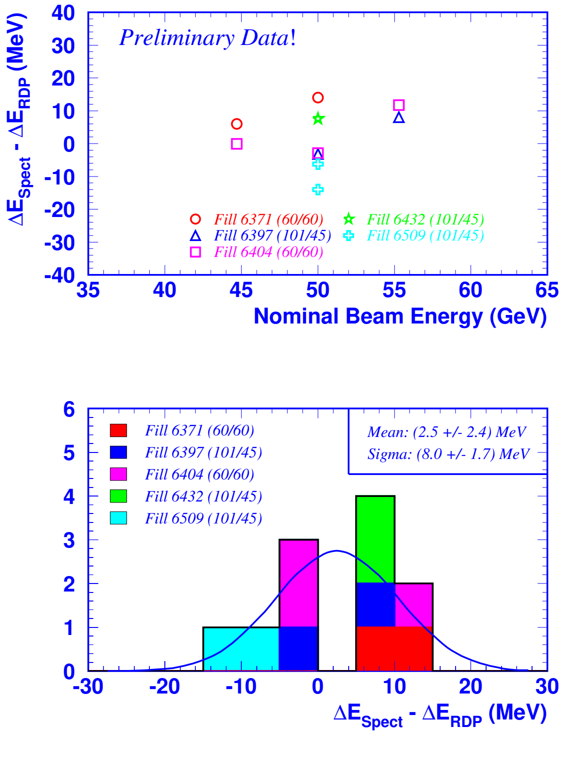

Figure 4: Preliminary comparison of energy intervals as measured by RDP, and the spectrometer, for the second (and subsequent) energies in muti-point fills.

Reassured by this, three RDP fills which ended in a ramp to $\sim 90\,\mathrm{GeV}$ can be used to measure $\mathrm{E_b}$ at high energy (a fourth fill with ramp can not be analysed because of unstable BPM data). This result can then be compared with that predicted by the NMR-extrapolation model, as shown in figure 5. The difference of the spectrometer and NMR energy determinations at high energy is $0 \pm 11\,\mathrm{MeV}$. The analysis is preliminary, and the statistics limited, but this is a first indication that the spectrometer confirms the NMR-extrapolation method.

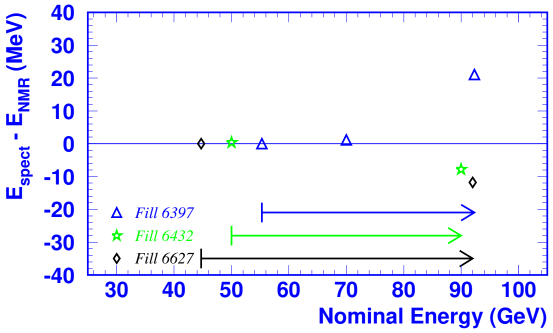

Figure 5: Preliminary comparison of the energy as determined by the spectrometer and the NMR extrapolation method, in three fills where the beam was ramped to 90 GeV. (Note that in fill 6397 an intermediate measurement at 70 GeV was also made.)

Prospects The preliminary results from the spectrometer are most encouraging. To ensure that it is properly exploited, the operations in 2000 need to be carefully planned. The following measurements are proposed:

- **Multi-point fills for error control**
  Comparisons such as that shown in figure 4 will be important in quantifying and controlling systematic errors. Therefore multi-point RDP measurements are necessary. There is no need, however, to record the long duration 4 and 5 point fills which the extrapolation method required in the past. Several two point fills should suffice, with some three point fills scheduled later in the run when polarisation has been established at each energy point. 6 and 2 fills respectively are proposed, giving a total of 10 energy intervals.

- **Gold-plated spectrometer measurements at the physics scale**
  Assuming that each of the RDP fills can be concluded with a ramp to high energy, then 8 measurements in the physics regime will be possible.

- **Additional spectrometer measurements without RDP**
  As explained, spectrometer measurements require that a low energy point be cross-calibrated. This cross-calibration is best performed using RDP. However, at low energy the NMR model is known to be very reliable (see [2]), and therefore the model may be used for the cross-calibration. Therefore ($\sim$ 6) additional measurements of $\mathrm{E_b}$ *without* RDP are envisaged, in order to augment the statistics. These measurements will be quick ($3-4$ hours) and not require that the experiments lower their solenoids.

In addition the procedure will be improved and optimised, in order to minimise systematics and reduce operation time, and a fast analysis performed, to ensure a rapid response to problems. 2000 is the last opportunity for spectrometer measurements, and these measurements may have consequences not only for the 1999-2000 energies, but for the complete LEP2 dataset.

2.4 Q_s *vs* V_{RF}

The synchrotron tune, Q_s, is related to the total RF voltage V_{RF} in the following manner:

$$Q_s^2 = \left(\frac{\alpha_c\, h}{2\pi E_b}\right) \sqrt{(e^2\, V_{RF}^2 \, - \, U_0^2)} \tag{1}$$

where α_c is the momentum compaction factor, and U_0 the total energy loss (itself a function of E_b). Therefore, as proposed in [9], a measurement of the dependency of Q_s with V_{RF} and a fit to expression 1 allows E_b to be extracted.

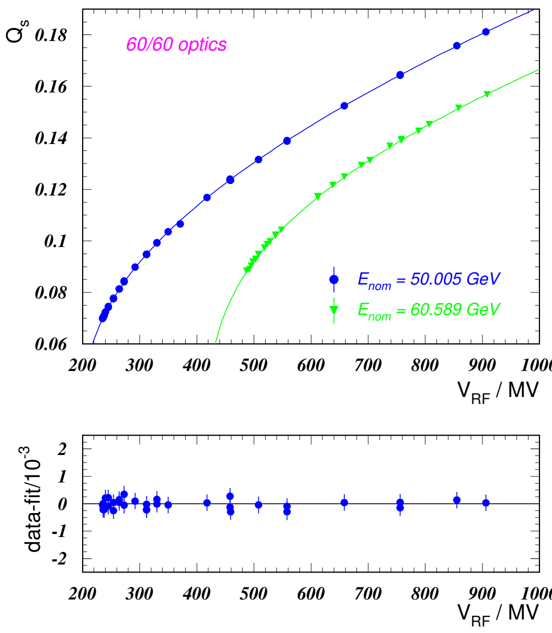

Figure 6: The data and superimposed fits of two Q_s vs V_{RF} scans, and the residuals for one fit. The data are at low energy, but similar agreement is obtained in high energy measurements.

To adequately fit the data, however, requires that expression 1 be refined. It is necessary to scale V_{RF} from its nominal value, and carefully account for all mechanisms of energy loss in U_0. When this is done excellent fits result, as is seen from figure 6. From these fits E_b can be extracted with a precision of $\sim 25\,\mathrm{MeV}$, virtually independent of the energy at which the measurements were performed. Existing measurements are in agreement with the NMR model. The error has several components involving the modelling of the machine energy loss, and there is clear scope for reducing these with additional work and measurements (see [10] for a review).

In the coming run 30 hours of machine time are envisaged for making Q_s vs V_{RF} scans, and for associated measurements.

3 SUMMARY OF MACHINE REQUESTS

The summary of machine time required for energy calibration work in 2000 is given below. The main aspects have been discussed, but additional commissioning and measurements are included, such as the requirement to determine the energy boost provided by the horizontal corrector field spreading scheme [11]:

- **Optics commissioning** – 8 hours.
- **k modulation** – 16 hours (only if needed).
- **Spectrometer polarisation measurements** – 6 $\times$ 12 hours + 2 $\times$ 16 hours.
- **Spectrometer measurements without polarisation** – 5 $\times$ 4 hours with physics optics and solenoids on.
- **Horizontal corrector energy boost measurement** – 3 hours.
- Q_s vs V_{RF} **measurements** – 2 $\times$ 8 hours, 1 $\times$ 4 hours and 1 $\times$ 10 hours.
- **Flux loop measurements** – cycles to be taken throughout year when no physics is possible.

In total this amounts to 181 hours, or 7.5 days. This is less than has been requested in previous years. Furthermore, as no long multi-point fills are envisaged, and it is expected to perform almost all measurements with a single optics, it may be considered a robust programme. It is hoped that as in 1999, many of these measurements can be performed when no high energy physics operation is possible, but it should be noted that the experiments have placed a high priority on a successful energy calibration programme [12].

4 CONCLUSIONS

Three methods of determining E_b at high energy have been considered. The NMR-extrapolation method is rather well-understood, and stable; unfortunately there is limited scope for reducing the assigned uncertainty of $\sim$ 20 MeV. The spectrometer project is progressing in a very promising manner; the preliminary indications from 1999 support the NMR determined energy scale, and suggest that with a carefully excecuted programme of measurements in 2000 the design precision of $10 - 15$ MeV is attainable. The Q_s vs V_{RF} method is an attractive and complementary approach, where an error of $< 20\,\mathrm{MeV}$ is feasible. There is every reason to remain optimistic that the uncertainty on

E_b will contribute a negligible uncertainty to the LEP m_W measurement.

Acknowledgements

The results presented here are the work of the LEP ECAL group. Many people, both members of the group and others, are to be congratulated and thanked for the enormous efforts which led to the successful installation and commissioning of the LEP spectrometer.

5 REFERENCES

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[12] Meeting between the LEP coordinator and representatives of the experiments, January 2000. See: http://alephwww.cern.ch/ janot/LEPCO/.