Do we really need 1001 shifts for energy calibration?

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Abstract

The dominant sources of uncertainty in the present evaluation of the LEP beam energy for high energy running are identified. The eight days worth of energy calibration measurements in 1998 are dissected, and the relation between each type of measurement and the energy uncertainty is examined. This allows an assessment of the repercussions of a drastic reduction of the time for calibration in future years. How to make most efficient use of calibration time is also discussed.

1 INTRODUCTION

The aim of this presentation is to explain the relationship between the several days worth of energy calibration measurements and the resulting systematic uncertainties [1]. The LEP spectrometer should allow an improvement in the beam energy uncertainty in 1999 [2], but until this new method is shown to work, the energy calibration will continue to rely on magnetic measurements to extrapolate from the precisely measured energies from resonant depolarisation (between 41 and 61 GeV beam energy) and the physics running energy (above 90 GeV). The minimum set of measurements needed for magnetic extrapolation is identified, and merged with the measurements needed for the spectrometer in an efficient way to give the total request for machine time in 1999.

2 REMINDER OF THE EXTRAPOLATION METHOD

The magnetic extrapolation method used to calibrate the centre-of-mass energy at LEP2 to date [1] relies on 16 NMR probes that 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 measured by resonant depolarisation in the region of 41 to 61 GeV. The fit is linear, with two free parameters: $E_{\rm pol} = a + bB_{\rm NMR}$. 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 operating energy above 90 GeV. Tests of this linearity assumption lead to the dominant systematic errors in the analysis of the 1997 data, as can be seen in Tab. 1

The largest uncertainty comes from a comparison 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, and a further systematic error from the variation of NMR calibrations from fill to fill through the year.

Source	Error [MeV]
Extrapolation from NMR–polarisation:	
NMR rms/$\sqrt{N}$ at physics energy	10
Different $E_{\rm pol}$ fills	5
Flux-loop test of extrapolation:	
NMR/FL difference at phys. energy	20
Field not measured by flux loop	5
Polarisation systematic	1
e^+e^- energy difference	2
Optics difference	4
Corrector effects	3
Tide	1
Initial dipole energy	2
Dipole rise modelling	1
IP specific corrections ($\delta E_{\rm CM}/2$):	
RF model	4
Dispersion	2
Total	25

Table 1: Error table for the beam energy measurement by magnetic extrapolation for 1997.

Other systematic uncertainties from the many other effects that influence the centre-of-mass energy are relatively small. They are also listed in Tab. 1, and more details can be found in [1].

Until the spectrometer method is proven, the energy calibration will rely on fitting the NMR probes to polarisation measurements over as long a lever arm as possible, and assuming that this normalisation is valid up to physics energy.

3 ENERGY CALIBRATION MEASUREMENTS IN 1998

The total time used for energy calibration in 1998 was 226.5 hours or about 9.5 days. The measurements made are listed in Tab. 2. The majority of this time was used to make measurements by the technique of resonant polarisation at several beam energies with the dedicated polarisation optics (60/60 optics). Some time was also needed to commission this optics, and to measure the offsets between beam pickups and quadrupole centres using k-modulation. The well known offsets also help to improve the quality of the orbit and the luminosity delivered in physics running. Resonant depolarisation measurements on the physics op-

Fill	From	To	MD	Hours	Comment
4665	14-06 06:00	15-06 14:30		8.5	60/60 commiss.
4666	14-06 14:30	15-06 11:00		20.5	60/60
4669	18-06 00:00	18-06 12:00	Y	12.0	102/90 cross cal.
4843	15-07 06:00	16-07 08:00	Y	26.0	60/60
5025	12-08 20:00	13-08 12:00		16.0	k-modulation on 60/60
5135-5137	05-09 14:00	06-09 14:00	Y	24.0	60/60
5141	07-09 06:30	08-09 10:00	Y	27.5	60/60
5214	20-09 06:00	21-09 08:00		26.0	60/60
5231-5232	29-09 11:30	30-09 08:00		20.5	102/90 cross cal.
5337	18-10 06:30	19-09 09:00	Y	26.5	60/60
5421-5422	02-11 17:00	03-11 12:00		19.0	102/90 Pol at 92 GeV

Table 2: Energy calibration measurements in 1998

Date	Fill	41 GeV	45 GeV	50 GeV	55 GeV	61 GeV	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

Table 3: The successful resonant depolarisation measurements at LEP2.

tics (102/90) were also made, to calibrate the small energy difference between the two optics, and also at the end of the year to search for polarisation close to physics energy. This last experiment is motivated by the hope that at very high energy, a new regime of polarisation buildup, with incoherent resonance crossing, is reached [3].

The gradual improvement in the programme to measure the beam energy with resonant depolarisation can be seen from the list of successful measurements between 1996 and 1998, given in Tab. 3. The first measurements away from the Z peak (around 45 GeV beam energy) were made in 1996. In 1997, the lever arm over which measurements were made was 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. The prospects for increasing this energy to 70 GeV by increasing Q_s while staying in the relatively well understood regime of polarisation buildup modelled by coherent resonance crossing are discussed in Ref. [3].

4 COMPARISON OF 1997 AND 1998 DATA QUALITY

The error table given above reflects the stability and consistency of the measurements made in 1997. Before making any request for machine time in 1999, it is useful to compare the data quality in 1997 and 1998. At this stage the 1998 data must be considered to be preliminary, in that some patching of logging errors still remains to be done.

4.1 Initial energy in each fill

The contribution to the initial beam energy in each fill from the main bend dipole fields is shown in Fig. 1 for all the high energy fills in 1997 and 1998. The fills generally show a small scatter with an rms of around 10 MeV, but with a

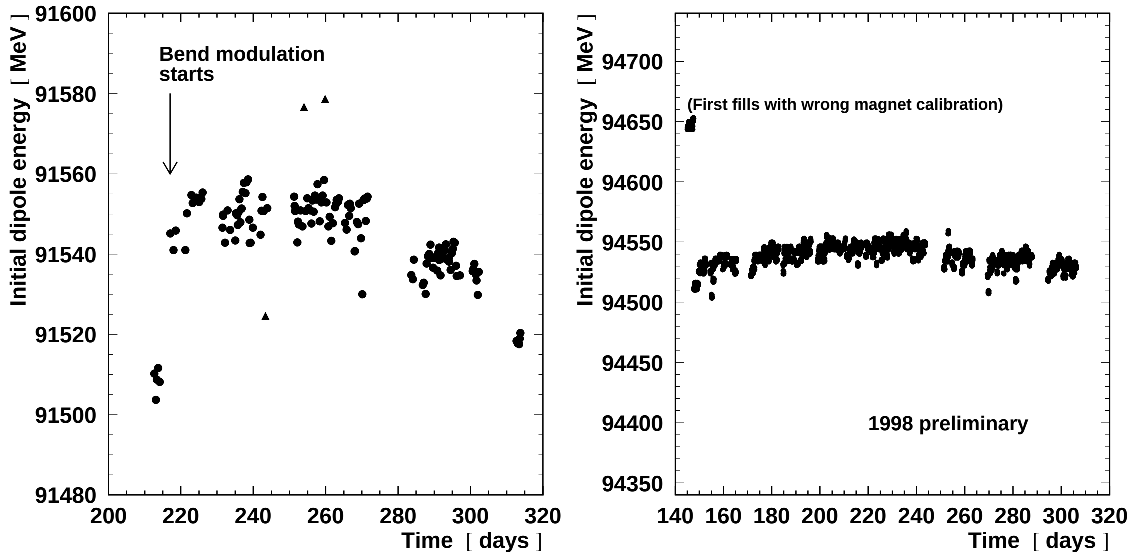

Figure 1: Initial dipole energy in a fill for 1997 (left) and 1998 (right).

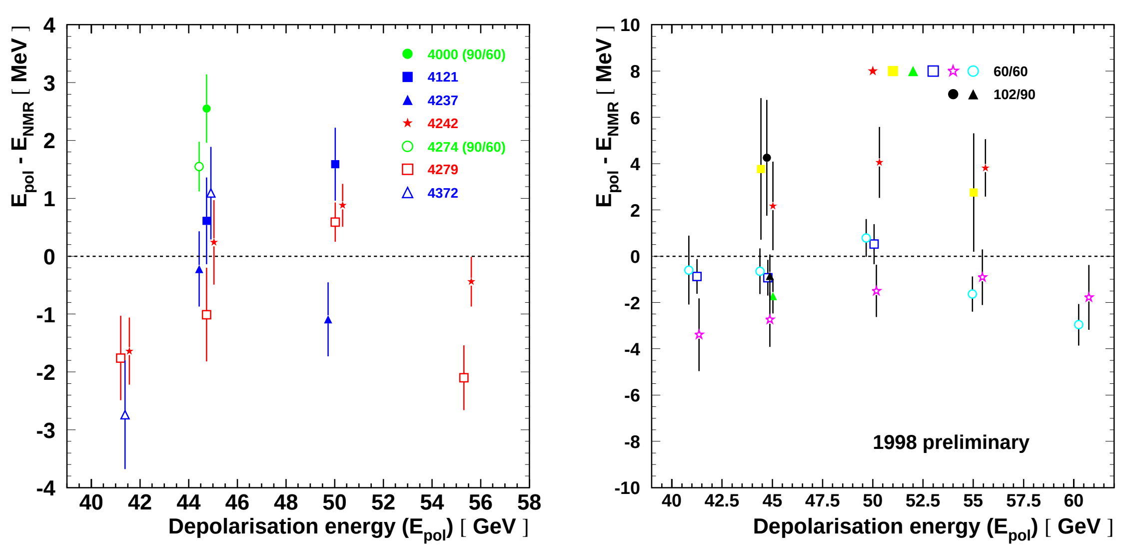

Figure 2: Residuals from the fits to all of the polarisation fills in 1997 (left) and 1998 (right).

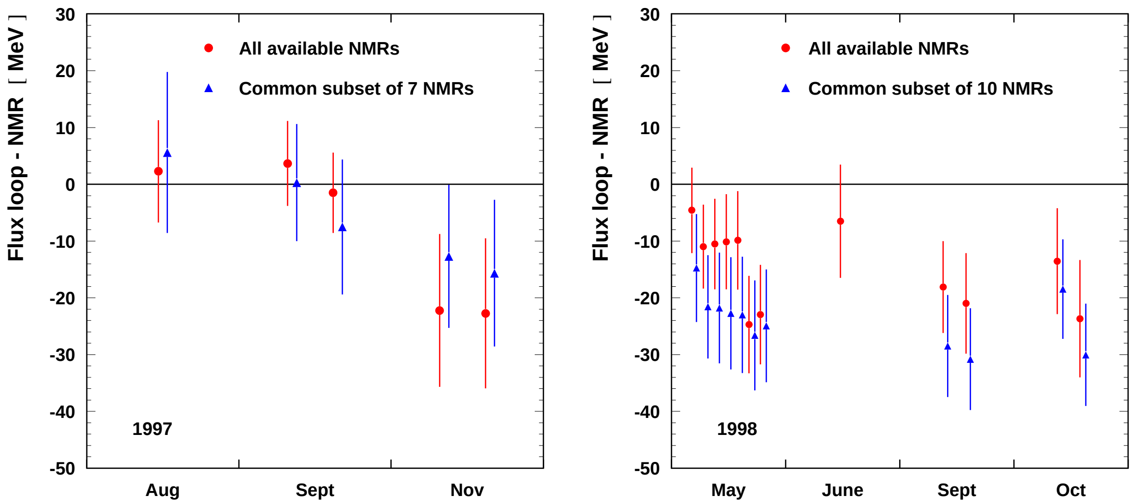

Figure 3: Residual difference between the flux-loop and NMR probes at physics energy in 1997 (left) and 1998 (right).

few anomalies. For example, at the beginning of 1998 there were a few fills before the correct magnet calibration curves were loaded, leading to an offset of more than 100 MeV. There are also occasional fills where there is a problem interpolating between the logged values around the start of a fill. The coils of the NMR probes gradually suffer radiation damage so that the probes fail to lock at lower energies. There is no apparent jump in the dipole fields after the NMR coils are replaced in the middle of a year. Even accounting for problem fills, the small scatter and the stable behaviour leads to a small uncertainty.

4.2 *Fits to all polarisation fills in a year*

The residuals from the straight line fits to the polarisation data are shown in Fig. 2. The error bars reflect the scatter over the working NMR probes at each measurement point. In 1997, these data lead to an error of 10 MeV from the scatter in predicted physics energy, plus in quadrature an uncertainty of 5 MeV from the variations from fill to fill. At this stage there is a larger scatter in the preliminary 1998 data. This may be improved once a complete check of the reliability of the probe measurements has been made, and bad measurements have been identified.

4.3 *Difference between flux loop and NMR probes*

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. The two devices are cross-calibrated in the range corresponding to the polarisation measurements, and the discrepancy seen at physics energy gave rise to the largest systematic uncertainty in the 1997 data. The differences for 1997 and 1998 are shown in Fig. 3. The discrepancy is of a similar size in the two years. Time variations during each year are not understood. There is also a lack of measurements in the middle of the year, when the NMR probes no longer functioned in the range of polarisation energies, although they could still be used in physics running to predict the energy.

4.4 *Study of non-linearities with five-point fills*

The validity of the linearity assumption can be tested by examining the residuals from the fits of NMR measurements to polarisation energies. The residuals from a fit to a single fill can be considered to be the most sensitive test, since any confusion from fill-to-fill scatter is avoided.

Fill 5214 in 1998 was exemplary, in that the full set of 16 NMR probes functioned at the five energy points between 41 and 61 GeV. The residuals to the straight line fit for this fill alone are shown in Fig. 4. The error bars are small, and any deviations are less than 1 MeV. However, larger residuals, with a characteristic banana shape have been observed in other fills.

If only those NMR probes that worked in the later fill 5337 are used in the fit to the fill 5214 data, then larger residuals are seen (Fig. 5). The deviations may therefore be explained as being due to the different characteristics of the local field as a function of excitation current of the particular set of magnets and positions that the NMR probes occupy. This observation extends back to 1997 - if only four energy points are used in the fit, and only the common probes, then the fill 5214 data can mimic the four-point fill 4242 from 1997 (Fig. 6).

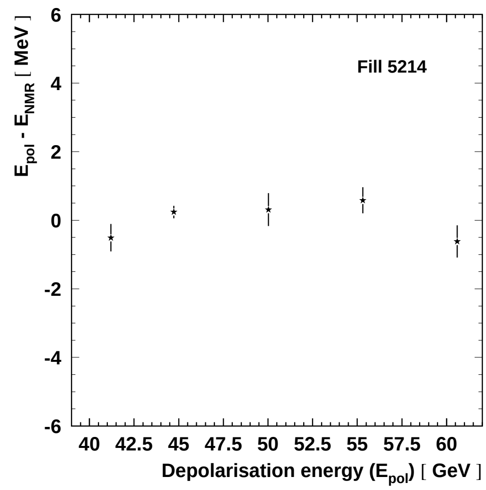

Figure 4: Residuals from a straight line fit to polarisation fill 5214, with five energy points and all NMR probes working.

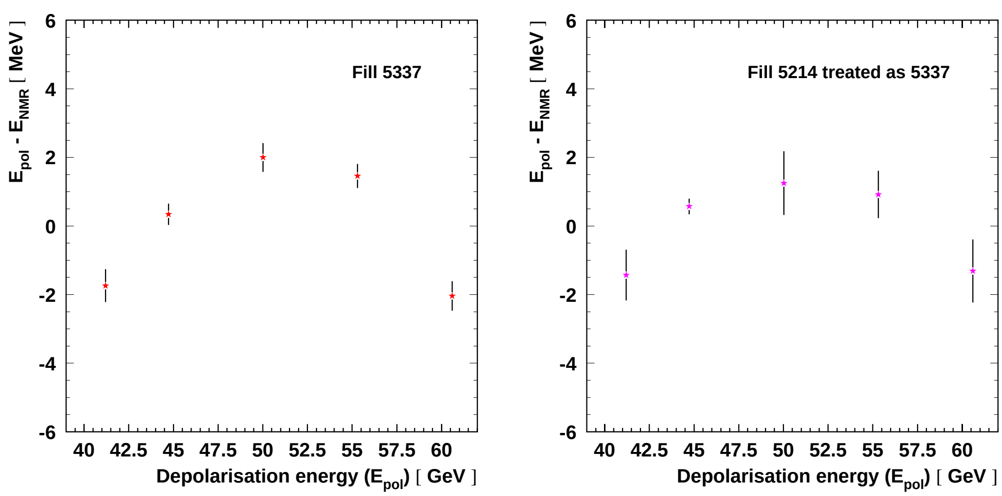

Figure 5: Comparison of residuals for fill 5337, and fill 5214, using only the common subset of probes.

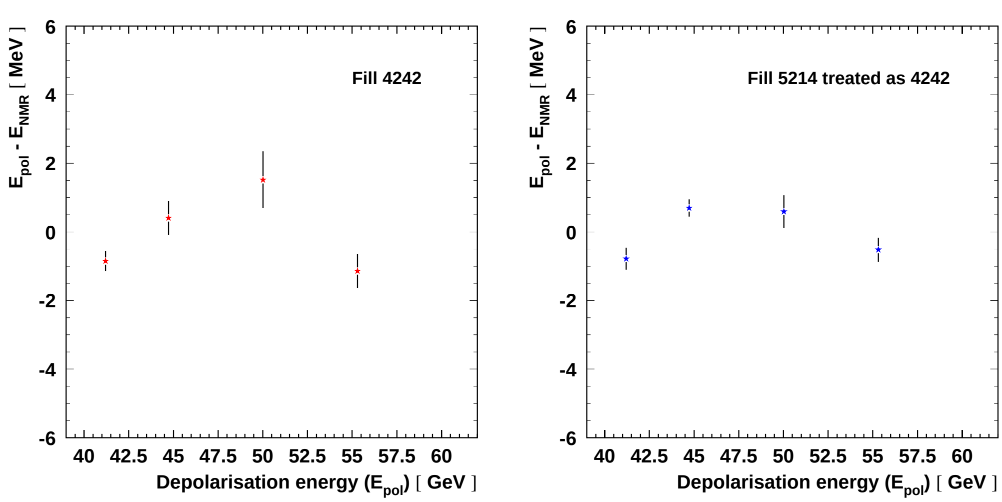

Figure 6: Comparison of residuals for fills 4242 and 5214, omitting the 61 GeV point, and only using the common probes.

5 W MASS ERRORS

The following oversimplified calculation is designed to be a pessimistic example that nonetheless shows an improvement in the overall error on the W mass if time is invested in energy calibration studies.

The W mass statistical error is proportional to $1/\sqrt{\mathcal{L}}$, and the statistical error for four LEP experiments combined, from 500pb^{-1} per experiment, is expected to be about 25 MeV. It is possible that the combined systematic error from experiments could eventually reach this level. To make the worst case for giving up luminosity to energy calibration time, this can also be assumed to rely on tests with the data, and to scale with $1/\sqrt{\mathcal{L}}$. The total experimental error would then be 35.4 MeV for 500pb^{-1}, and four experiments.

So far, energy calibration has taken significantly less than 10% of the running time each year at LEP2. As an overestimate, assume that 10% of the luminosity is used to improve the energy calibration error from 25 MeV to 10–15 MeV. This loss of luminosity increases the error from the experiments from 35.4 to 37.3 MeV. However, the total error on the W mass would be reduced from $35.4 \oplus 25 = 43.3$ MeV to between $37.3 \oplus 10 = 38.6$ and $37.3 \oplus 15 = 40.2$ MeV.

In general, and perhaps more importantly, it is highly undesirable to have the energy scale uncertainty as one of the larger systematic errors in the W mass, since it is common to all four experiments, and an easy target for criticism.

It is difficult to quantify this argument further. The energy calibration uncertainty is systematics limited, as will be seen, and depends on demonstrating that the measurements are stable with time. There is no simple relationship between time used and resulting uncertainty.

6 ENERGY CALIBRATION TIME REQUESTS FOR 1999

Until the spectrometer [2] has been demonstrated to work, the energy calibration at LEP2 will depend on the magnetic extrapolation method. The necessary measurements to repeat the analysis in 1999 are outlined in section 6.1. The spectrometer requests are given in section 6.2. These requests can be merged together to improve efficiency by using the same fill for several measurements. The resulting list and total time required is given in Tab. 4.

6.1 Extrapolation method errors and requirements

The "statistical" uncertainty of the extrapolation method is sensitive to the energy span of the polarisation points, and to the maximum energy measured by resonant depolarisation. However, it is not particularly reduced by having multipoint polarisation fills. For example, assuming a 2 MeV error per point, then measurements at:

- 45 plus 55 GeV give an error of 12.8 MeV at 95 GeV
- 40 plus 60 GeV give an error of 6.5 MeV at 95 GeV
- 40-45-50-55-60 GeV give an error of 5.8 MeV at 95 GeV

Just one fill with two energy points would then be enough to calibrate, but only if the system was known to be absolutely stable and linear. As has already been seen, there are additional uncertainties from the stability and reproducibility of the measurements, and the uncertainty in the linearity assumption.

The NMR calibration requires two fitted parameters, so having three points in a polarisation fill greatly reduces the chance of failing to notice a mistake at one of the energies by requiring that all three are consistent. It is also essential to have several fills during the year to check for stability, in particular if the NMR coils are replaced. It is vital to make flux-loop measurements throughout the year, to monitor and perhaps even understand the drifts that have been seen. Increasing the maximum energy at which a measurement by resonant depolarisation can be made would also reduce the flux-loop uncertainty, by decreasing the range in energy over which the flux-loop/NMR divergence would be applicable.

Taking into account these considerations and others gives the following list of measurements to be made:

- Take k-modulation data before trying polarisation at higher energies. (This is also needed to optimise performance in physics.)
- At least two polarisation measurements on 102/90 optics, 45 GeV, solenoids on. The difference in energy between physics and polarisation optics has to be measured, because the predicted value depends on imperfections.
- Four fills with at least three energy points per fill, spread through the year, with 60/60 optics, solenoids off, as many NMR probes locking as possible. The exact energy points depend on how well the NMR probes are locking. The optimal energies for minimising the error are 40-50-60 GeV, but 60 GeV is not reliable, so add at least one additional point, 45 or 55 GeV. At the end of these fills, if studies with high Q_s are promising, then continue up in energy to 70 GeV [3].
- At least one of these multipoint fills should be a five-point fill with all NMR probes working, to improve the understanding of the non-statistical non-linearities in the 41–61 GeV region.
- Flux loops after each polarisation MD, and in shadow of RF maintenance.
- Replace the NMR probes once or twice during the year.
- Look for polarisation above 90 GeV with 102/90 optics, solenoids off. This requires improved polarimeter shielding [3].
- Long term test of dipole rise effects (provoked by trains and temperature changes) at 45 GeV, 102/90 optics. (Eight hour extension of a cross-calibration fill.)

Hours	Measurement
On physics optics	
24	Dedicated k-modulation
4×16	Polarisation at 45 GeV and spectrometer measurement
8	Add rise test in one of the above four fills
16	Polarisation at 90+ GeV. If it works, rediscuss plan!
On 60/60 optics	
16	set up 60/60 optics
3×16	Three/four-point polarisation fills (+flux loop)
2×24	Five-point/higher energy polarisation fills (+flux loop)
	Could give back one of these if the first four are OK.
Total: 28 shifts, 9.3 days, INCLUDING spectrometer	

Table 4: Requests for energy calibration time in 1998

6.2 Spectrometer time requests

The aim of the spectrometer is to measure the difference between polarisation and physics energy much more precisely then by magnetic extrapolation. The device does not measure continuously in physics, but requires the NMR probes to transfer energy scale from the dedicated spectrometer measurement. However, the beam energy is measured directly from the bend angle in a dedicated, precisely mapped dipole magnet in the LEP lattice, both at a low energy, where it can be calibrated against a polarisation measurement, and again at physics energy. The NMR extrapolation is therefore only a small correction from spectrometer fills to physics fills, rather than a large extrapolation from polarisation to physics energies.

The spectrometer measurement must be performed on physics optics, so that a ramp up to physics energy is possible. (The 60/60 optics runs out of dynamic aperture below about 80 GeV.) To control the reproducibility and systematic uncertainties, four such fills are requested, with:

- Polarisation and angle measurement at 45 GeV
- Ramp
- Angle measurement at physics energy

requiring a total of 4×16 hours. These measurements must be scheduled such that the ramp to physics energy is at the right time of day to avoid train rise effects.

The spectrometer can also use multipoint polarisation fills for cross checks, and make short measurements at the end of physics fills.

When the spectrometer is shown to work, it should be possible to reduce the polarisation beam time requests for 2000.

7 IMPROVING THE EFFICIENCY OF ENERGY CALIBRATION MEASUREMENTS

Gathering together the requests in the previous section, and merging the spectrometer and extrapolation method measurements in the most efficient way possible, gives the total time listed in Tab. 4.

It has been clearly demonstrated that using the k-modulation data to correct for offsets increases the efficiency of polarisation measurements. These data also improve the performance in physics, and should be made near the beginning of the year.

Control and diagnostic software for polarisation and flux-loop measurements have also gradually been improved to help the efficiency. The online displays of probe readings used during a polarisation fill make it immediately obvious if the probes are locking, of if the beam energy might have jumped due to a train passing. The automatic procedure developed last year for the flux loop allows the shift crew to run a measurement any time there are a couple of hours without beam, without needing to call in an expert.

In general, the most efficient use of a fill needs the operations group and the experiments to be patient. If a measurement is going well, then extra time at the end can avoid the need for another fill later to make a dedicated experiment. By thoroughly preparing all working points in advance, then if there is an unexpected problem (for example with the LEP1 cryogenics) that will take a long time to recover, then there may be an opportunity to make a polarisation measurement at short notice. The 60/60 optics does not use the SC quads, and many of the polarisation measurements do not need the full RF to be available.

8 CONCLUSIONS

In the absence of a discovery of new physics, the W mass measurement would be the most significant result to come out of LEP2. The beam energy measurement is essential to measure the W mass. The energy calibration is systematics limited, and it is essential to have a minimum set of measurements to control the uncertainty. It is worth investing time in looking for polarisation at higher energy, because this would not only reduce the statistical uncertainty, but also the flux-loop/NMR divergence error, which dominates the uncertainty.

Time will be needed to establish the spectrometer. By combining measurements for the magnetic extrapolation method and for the spectrometer in the most efficient way, even with some contingency, all this can be accommodated in the same number of days as last year. Once the spectrometer analysis is established, it should be possible to reduce the requests for multi-point polarisation fills in 2000.

9 ACKNOWLEDGEMENTS

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10 REFERENCES

[1] LEP Energy Working Group, "Evaluation of the LEP centre-of-mass energy above the W-pair production threshold", CERN-EP/98-191, CERN-SL/98-073, December 1998, submitted to Eur. Phys. J. C.

[2] See the paper by Bernd Dehning in these proceedings.

[3] See the paper by Ralph Assmann in these proceedings.