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The energy of LEP in the 1995 scan - Dipole model

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Abstract

We present the analysis of the 1995 LEP energy on what affects the determination of the average energy of LEP. IP specific corrections are not discussed here. The present analysis has also consequences on the 1993 and 1994 calibrations which are also briefly discussed. Everything presented here is preliminary.

Contents

1 The 1995 scan

The 1995 LEP period saw a scan of the Z0 resonance. The energy points chosen were similar to the 1993 ones and the luminosities delivered were also similar. The analysis presented here is similar to the analysis performed in 1993 [1] in its concept. Due to the hardware improvements and experience gained from the 1993 run, the analysis is more refined.

We will be referring to the 1993 paper to some length and will emphasize only the differences of the new analysis with respect to the 1993 one.

1.1 Hardware differences from the 1993 scan

The hardware differences which have some impact on the LEP energy determination are the following:

1. Bunch train operation instead of using the Pretzel scheme: This new scheme gave rise to the possibility of large offsets to the mean colliding energy of the beams depending on their vertical collision offsets. The effect is discussed in a dedicated report.
2. Better temperature stability in the LEP ring. This modification has decreased the LEP uncertainty due to imprecise knowledge of temperature coefficients and gave a more stable machine
3. Introduction of two extra NMR probes fitted inside two of the LEP dipole magnets for better monitoring of the LEP dipole field in an attempt to better our model.

On top of these hardware improvements, it was decided to perform as many end of fill calibrations as possible, to reduce the uncertainty due to the fill to fill reproducibility of LEP.

1.2 The model

As discussed in the 1993 paper, the determination of the ECM energy of LEP at each experiment goes through the following stages:

1. Determination of the mean energy of LEP; Here we use a model that has two parts: (a) the dipole model and (b) the quadruple model. The accuracy of the model, as well as the overall normalisation factor, is determined from the very accurate depolarization measurements. The overall systematic error for this model would depend on the agreement with the depolarization measurements as well as the number of them.
2. Determination of IP-specific corrections: This in 1993 included only RF effects. In 1995 there is an extra correction having to do with OSVD.

2 Determination of the mean energy of LEP

Again, the overall strategy described on the 1993 paper is followed. Our uncertainty of the knowledge of the energy of LEP can be categorised in the following:

1. fill to fill behaviour
2. energy behaviour during a fill

Resonant depolarization measurements are a powerful method of determining any model biases, with one exception: Most of these measurements were performed at the end of physics fills, so although we have a very good handle to determine the energy at the end of a fill, our position is much weaker in determining the energy at the start. Depolarization measurements, therefore, are much better in determining (1) rather than (2). In 1993 the strategy adopted was to follow half of the rise seen by the reference magnet. It was assumed that this was representative of the true energy behaviour. In 1995 we have 6 dedicated experiments that measured the energy at start of physics. We shall use those measurements to evaluate our model, and, in contrast to 1993, we would not need to rely on assumptions for the mean fill rise (in at least what concerns the energy-point-independent rise).

The energy rise seen in these 6 measurements together with the energy rise recorded by the NMR in the reference magnet and in the tunnel are seen in table 1. This table will be discussed at a later section of this report, but it can clearly be seen that the NMR in the reference magnet tracks poorly the energy rise during a fill, whereas the information of the two NMRs in the tunnel is more precise.

2.1 Quadrupole part of the model

This comprises the energy corrections due to tides and due to the long term LEP circumference changes, monitored with the BOM system. There were no changes compared to 1993.

2.2 Dipole part of the model

Here significant changes have occurred from 1993, mainly to incorporate the extra information of the two new NMR probes.

2.2.1 The train effect

It was observed that the two NMR probes, one located close to IP4 and the other close to IP8, showed some anticorrelated noise during the day but were much quieter during the period from about midnight to 04:30.

This was finally traced to currents flowing through the beam pipe arising from leakage currents from trains passing though the Geneva-La Plaine line. The activity stops at night since there are no trains at this time, and has peaks during especially busy periods during the day (having to do with the TGV to Paris, for instance).

The noise in the NMRs per-se is of no consequence to the energy of LEP, however, the currents flowing though the beam pipe can upset the equilibrium of magnetic domains in the LEP dipole magnets that might have an effect on their energy. (The magnetic field induced by the beam pipe currents at the position of the beam is negligible).

In the limit of an infinitely long fill one expects that an equilibrium would be reached and any currents though the beam pipe would have no effect on the dipole magnetic field. What remains to be determined is the time constant and the magnitude involved in this process. Similarly, at times earlier than this characteristic time constant, one expects the energy change to be larger the larger the disturbance, i.e. a different behaviour according to the time of day.

The energy change can be parametrised as a function of (a) time of day and (b) time elapsed in a fill. The average energy change per hour as a function of these two quantities can be seen in figures 1 and 2. The characteristic time constant after which there is hardly any change in the dipole energy is about 12 hours, and the overall energy rise per hour is

0.42, 0.51 and 0.41MeV/h respectively for p-2, p and p+2 fills. The energy rise during the quiet period at night (midnight to 05:00) is 35% of the 24-hour averaged rise.

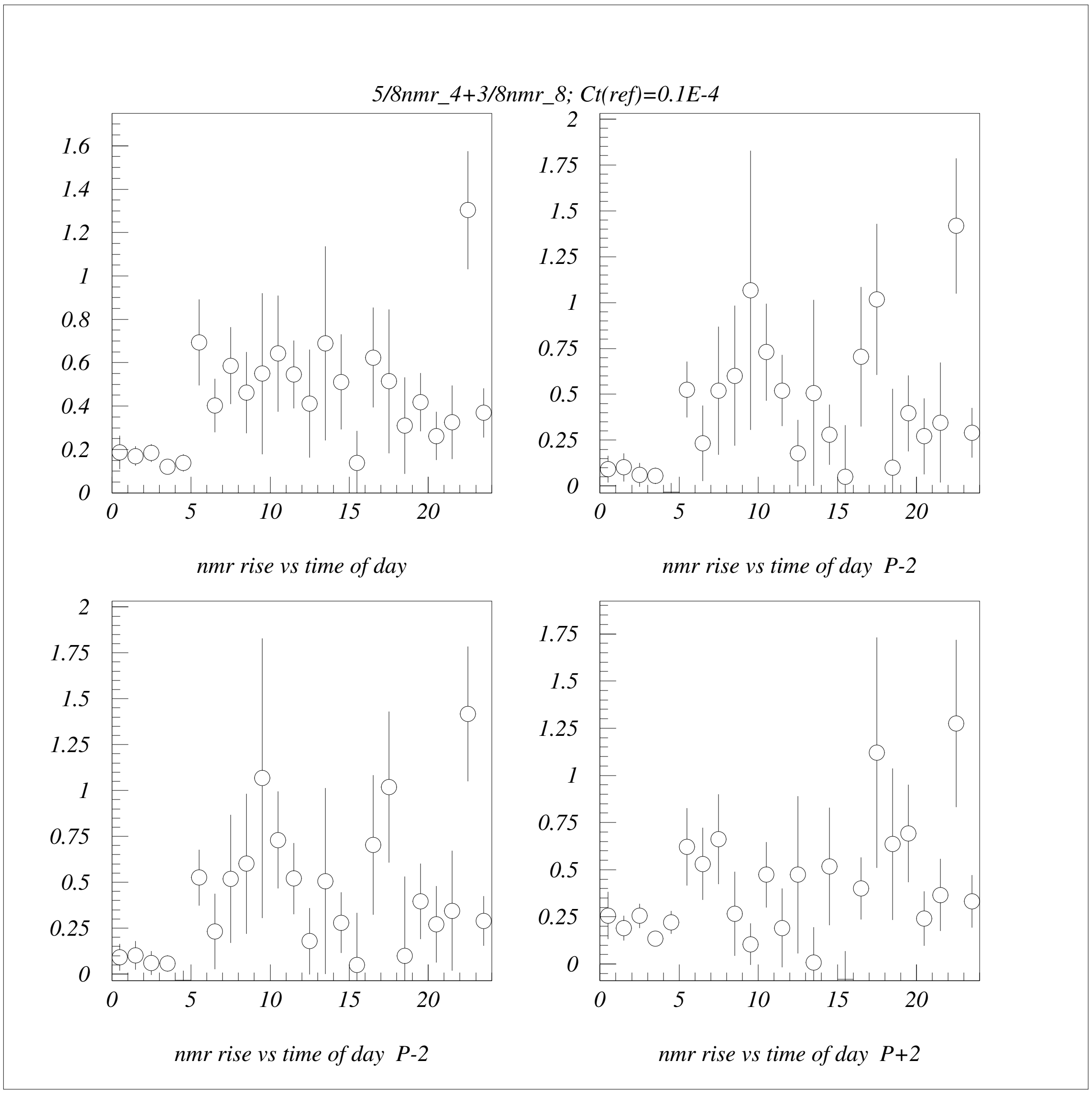

Figure 1: *This figure shows the mean energy rise per hour as a function of time of day Top left: all data top right: only P-2 bottom left: Peak bottom right: P+2 The rise in all energy points is similar.*

2.2.2 *Choice of the NMR average*

The two NMR probes in the ring sample two of the many (about 3000) dipole magnets and in the absence of other information the most unbiased determination of the field would be a straight average.

However, due to the fact that the rail tracks are not at diametrically opposite sides with respect to lep, more current passes through the beam pipe at IP4 rather than IP8 with an

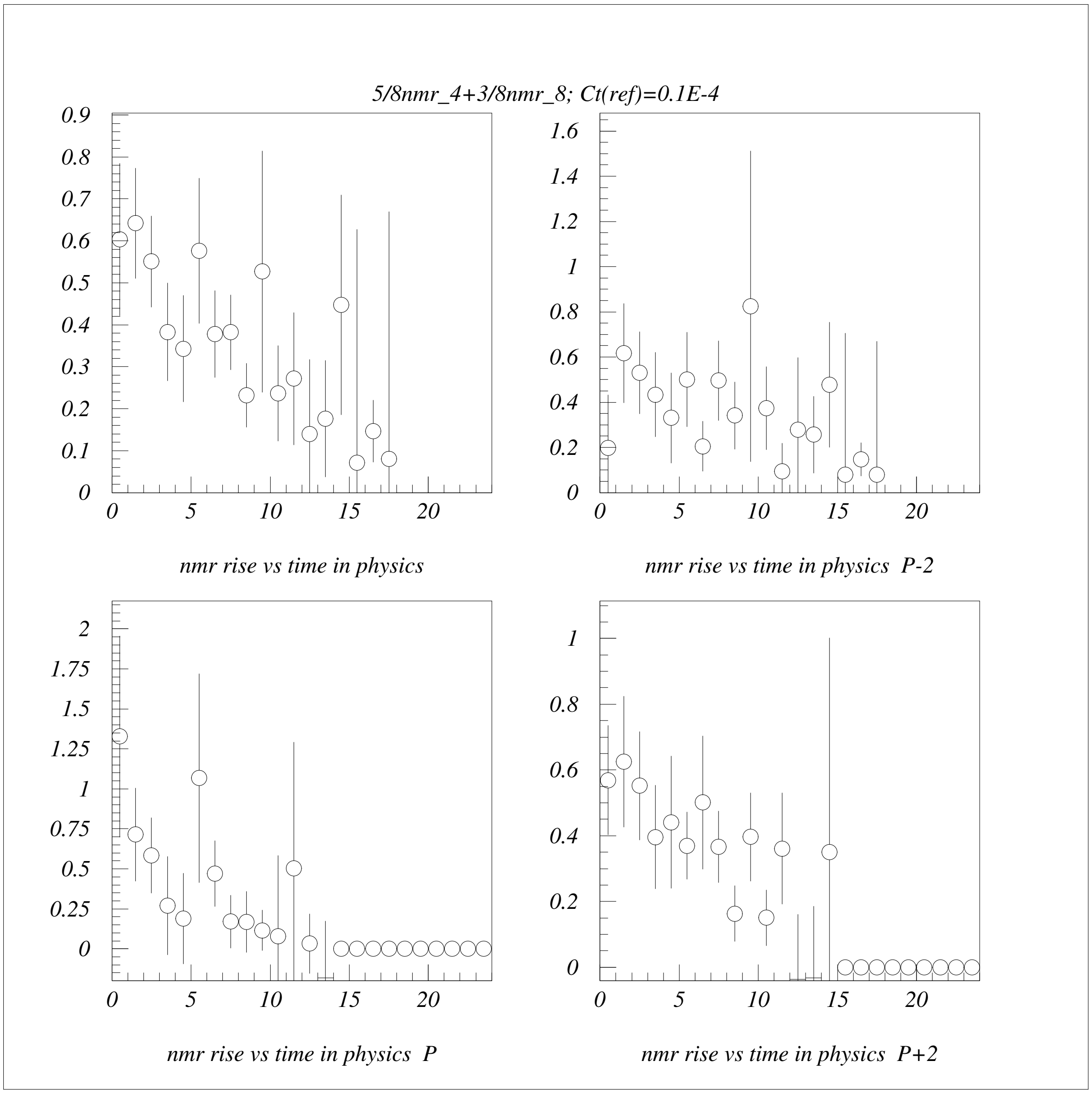

Figure 2: *This figure shows the mean energy rise per hour as a function of time elapsed during a fill. Time zero starts when physics is declared. Top left: all data top right: only P-2 bottom left: Peak bottom right: P+2 Again, data at different energy points look similar, as expected.*

approximate ratio of 5/8 to 3/8; The anticorrelated noise has also these coefficients. Therefore a sum of the NMRs with 5/8*nmr4 + 3/8*nmr8 has a much reduced noise component. Apart from this technical reason, however, there is also the fact that in a sense, NMR4 is 'representative' of a larger part of the ring than NMR8.

Therefore the 5/8;3/8 sum will be used in this analysis, with the differences that arise from a straight average appearing as a systematic error.

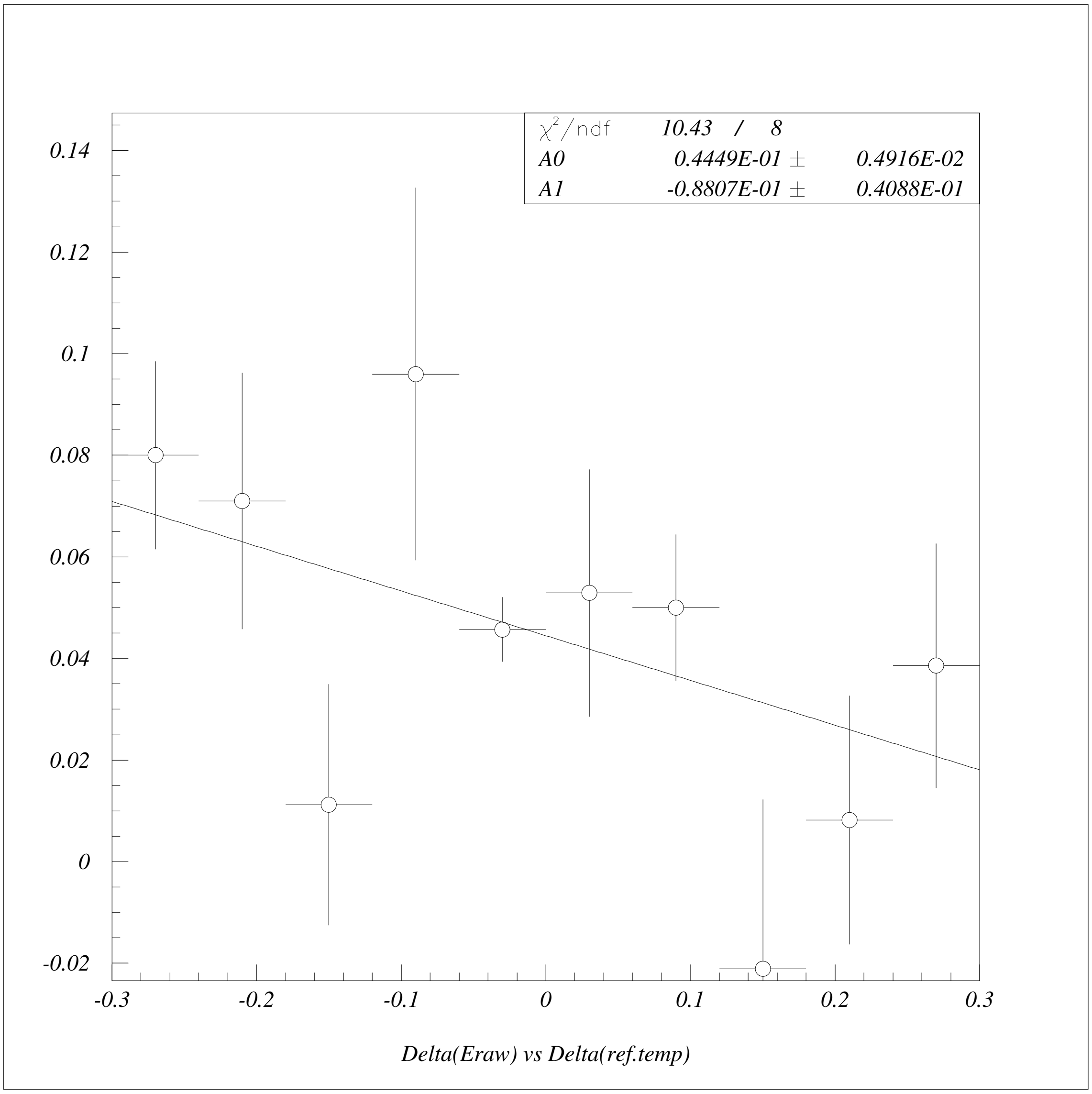

Figure 3: *We here use all the data from the 'quiet' period of 1995 (data taken between midnight and 05:00) and plot the difference between successive NMR readings (separated by 15 minutes) versus the tunnel NMR temperature correction, expressed in MeV for a temperature coefficient of 10-4. The fit, also shown, prefers much smaller values for the temperature coefficient, of the order* 10^-5 *The negative slope comes from the definition of the tunnel NMR temperature correction.*

2.2.3 The 'average behaviour' model

As we have seen, although there is an overall predominant trend for the energy behaviour during a fill, there is considerable scatter seen in individual fills. There is a case for using the average behaviour rather than the individual NMR behaviour since it is possible that the large number of dipole magnets in the ring act in such a way that it is the average

Table 1: *This is a list of the 6 BOF-EOF calibrations in 1995. The real rise in the dipole field seen, as measured with the depolarization technique, is compared with the rise seen by the tunnel NMRs (=5/8NMR4+3/8NMR4), the reference magnet NMR, and the model derived from the tunnel NMR data. 'diff' is the difference between the depolarization data and the relevant method. All data shown are MeV per beam.*

All BOF - EOF calibrations in 1995							
Fill	Edepol	tunnel NMR	diff	ref NMR	diff	Model	diff
2929	+0.92	2.04	-1.12	-0.62	1.54	2.04	-1.12
3022	4.15	4.48	-0.33	3.98	0.17	5.16	-1.01
3029	8.00	4.82	3.18	1.24	6.76	4.88	3.12
3030	5.00	2.82	2.18	2.04	2.96	5.24	-0.24
3036	4.04	2.55	1.49	0.28	3.76	5.15	-1.11
3064	1.22	2.83	-1.61	-0.08	1.30	3.03	-1.81
Mean	3.9-2.6		0.6-1.9		2.7-2.3		-0.4-1.8

behaviour of the magnets that dominates.

Such a model should give the same results when averaging over all fills with the model of using the individual NMR readings used to derive it, and could prove useful if it reduces the spread of the comparison with the energy calibrations.

A model of this type has been developed, correcting the dipole energy of LEP according to the time of day and the time since the beginning of fill, using the information of figures 2 and 1. No attempt is made to parametrize the data of these figures.

The extra bonus one gets from using this type of model, is that it can be applied to the 1993 scan where the NMRs in the tunnel were not available.

2.2.4 Determination of the temperature coefficient of the NMRs

Knowledge of the effective temperature coefficient of the sum of the two NMR probes is needed to interpret the average rise as seen, for instance, in figure 1 and figure 2. The temperature coefficient of various magnets was measured in 1992 resulting in an average value of about 1E-4, but with a considerable spread. In this analysis the temperature coefficient of the sum of the tunnel NMRs was directly measured using the data from the 'quiet period' of all physics fills (between midnight and 05:00) This is a delicate measurement, since we are trying to detect a small rise due to temperature on top of another, larger, rise in energy that happens when the magnet is still in metastable condition. To avoid bi-

Table 2: *This table shows the rms spreads of (a) the 'average behaviour' model and (b) the tunnel NMR model (=5/8NMR4+3/8NMR8) when compared to all EOF calibrations. All numbers given are in MeV in ECM. The last column shows the difference in the mean energy at all three points if one uses one or the other model, giving somehow the 'technical precision' of the 'average behaviour' model, since it is derived from model (a). The agreement between the two models is very good.*

Model - NMR comparisons			
Energy point	Model (a) spread	model (b) spread	difference in mean energy
p-2	4.5	6.8	0.48
P	-	-	3.12
P+2	2.6	4.6	0.20

ases, it is important to have readings when the temperature increases as well a decreases (since the other type of energy rise is believed to be monotonic).

The temperature coefficient derived from this analysis (figure 4) is smaller than the expected 1E-4, and it actually is closer to 1E-5. However, for 1995, changing the temperature coefficient for the tunnel NMRs from 0.1 to 1.0E-4 changes the mean energy by small amounts: 0.30MeV(ECM) at both P-2 and P+2.

2.2.5 Determination of the temperature coefficient of the ring

The average ring temperature in the 1995 scan was so stable, that is very difficult to determine a temperature coefficient with any precision using only 1995 data. (In other words, the temperature coefficient of the ring, even if known very poorly, does not increase the uncertainty of the lep energies by any significant amount.)

However, if one wants to determine the temperature coefficient for the LEP ring, one can look at the long experiment in 1993 (fill 1772) where over 22 hours the temperature changed by more than half a degree. Since no MNRs in the tunnel existed in 1993, the 'average behaviour' model was used to derive a temperature coefficient of 0.7E-4 (see figure 4)

Again, in 1995 the choice of the exact temperature coefficient is not very important; Varying the temperature coefficient from 0.7 to 1.1E-4 changes energies by: P-2 0.01MeV P+2 0.08; i.e. the error is completely negligible.

3 Checks of the model

3.1 Mean energy in 1995

The first check has to do with the fact that any model derived from certain data should yield the same results as the data it was derived from. And to justify using it instead of the original data, it has to provide reduced errors. The last column of table 2 shows the differ-

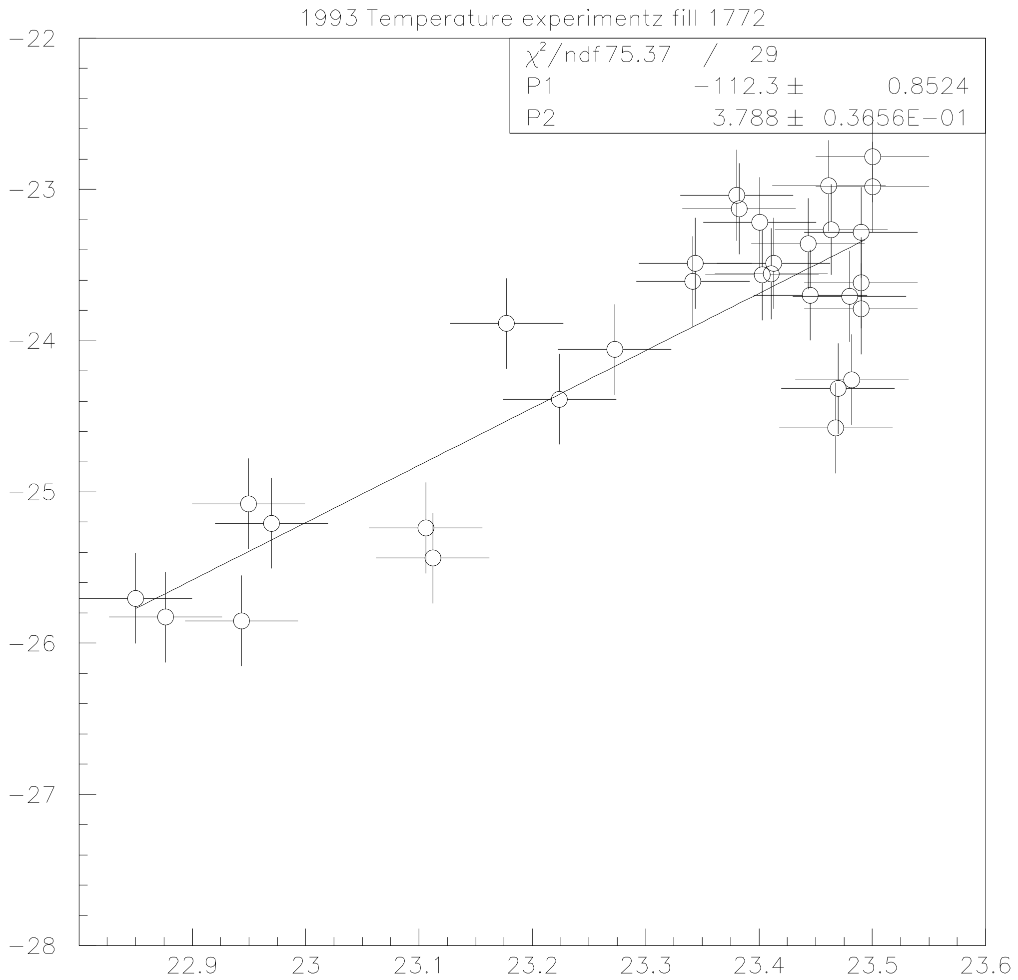

Figure 4: *This is a plot of the energy change (in MeV per beam) versus the temperature (in degrees) observed during the long 'temperature experiment' fill of 1993 (fill 1772). The temperature coefficient corresponding to the slope is 0.7E-4.*

ence in the luminosity weighted mean energy of LEP at the three energy points when using two different models: the 'average behaviour' model, or the sum of the two NMR probes which was used to derive the 'average behaviour' model in the first place. the agreement, some sort of 'technical precision' is very good. At the same time, the 'average behaviour' model provides reduced spreads when compared to the energy calibrations.

3.2 BOF calibrations in 1995

All information on the 6 BOF calibrations is shown in table 1. The tunnel NMR model and the 'average behaviour' model both show no significant bias in the determination of the mean energy rise, although the spread of their predictions is considerable. This, unfortunately, is the limiting factor in how much we can progress with our understanding of the 1995 energy rise during a fill. Both models have a spread of about 2MeV which, divided by the square root of the number of BOF calibrations gives about 0.8MeV of statistical accuracy on a quantity (the energy rise) that has a mean of 4MeV. This is a 20% precision with which we can determine the energy rise at each energy point from these 6 BOF calibrations.

4 Application of the model to the 1993 data

4.1 Why was the rise in a fill not seen in 1993?

During 1995 we have observed an average rise during a fill of the order of 4-5MeV per beam. This would modify the mean energy of LEP at each energy point by a similar amount, larger than the error quoted on the 1993 paper.

Due to the absence of NMRs in the tunnel, the sole means of observing this rise was though BOF calibrations or long term stability experiments. There was a series of long term experiments in 1993: three temperature experiments and two tide experiments.

Both tide experiments were performed after the end of a physics fill for efficiency reasons. The energy of LEP had reached its plateau and therefore no rise was present to be observed.

Two of the temperature experiments were short (one was over the quiet period between midnight and 5:00) and some of the rise observed was attributed to a temperature coefficient. The one long experiment in 1993 that showed the energy rise as we know it from 1995 was discarded because it was thought that it was not representative of typical running conditions

The two successive fills in 1992 when the tide behaviour was studied, had depolarisation measurements about 8 hours after the magnets were ramped to 45GeV. The extra rise one expects after 8 hours of running is an extra 1MeV, not enough to create a discrepancy. (there is only one measurement taken 4 hours after stable conditions were reached, which could move by about 2MeV, again not modifying the agreement either way).

4.2 Applying the 1995 model to 1993 data

As stated earlier, one of the advantages of using the 'average behaviour' model is that it can be applied to the 1993 data as well. One expects shifts which are of the order of 4-5MeV since this is the magnitude of the rise seen in 1995 whereas the rise seen in 1993 was much smaller. The difference in the mean energy of lep, luminosity weighted, when using the 1993 model or the 1995 model for the data of both years is seen in table 3.

5 LEP energy errors arising from the Dipole model

5.1 Fill to fill error

This is estimated in the same way as described in the 1993 paper. There were 22 P-2 fills out of which 14 were calibrated at the end of physics There were 14 Peak fills, out of which one was calibrated; And, finally there were 23 P+2 fills out of which 12 were calibrated.

Table 3: *This table shows the difference in the mean luminosity-averaged energy of LEP between the 1993 model (half the rise in the reference magnet, ring temperature coefficient of 1.1E-4) and the 1995 model ('average behaviour' model), correcting the energy according to the time of day and time spent in a fill, ring temperature coefficient of 0.7E-4). The mean energies of the 1995 model are always higher. the model differences appear to be similar for both years, indicating that the two years are indeed similar, as implicitly postulated by our model.*

Difference in mean CM Energy - luminosity weighted		
Energy point	1993 scan	1995 scan
p-2	5.0	4.8
P	7.4	5.2
P+2	4.8	5.5

The spread of the model when compared with the end of fill calibrations is 4.5MeV at P-2 and 2.6MeV at P+2. According to the formula used in 1993, the fill to fill error of LEP is therefore 0.7MeV for P-2 and 0.5MeV for P+2.

5.2 Error within a fill

Here we are limited by the imprecision of our model and the 6 BOF calibrations. According to table 1 over the 6 fills that were calibrated having an average rise of 3.9MeV per beam, our model showed a small bias (-0.4MeV) and a large spread of 1.8MeV. We can therefore determine the average rise with a statistical precision of 1.8/sqrt(6)=0.7MeV, or 20% of the average rise.

The average rise seen during a fill in 1995 is about 5MeV, therefore the fill to fill uncertainty is 1MeV(ECM).

5.2.1 Ring and NMR temperature coefficient uncertainties

These are negligible for 1995. Changing the ring temperature coefficient by 100% changes the mean energies by 0.0MeV and 0.3MeV (ECM) respectively for P-2 and P+2. Similarly, changing the NMR temperature coefficient by 100% changes the mean energies by 0.3MeV (ECM) for both P+2 and P-2.

5.2.2 Total error of LEP energy due to the dipole part of the model

A collection of the different uncertainties can be seen in table 4. For completeness, the Tide error is also shown. This is derived when changing the tide correction coefficient by 20% (in 1993 we assumed the tide coefficient to be known to 10%).

Table 4: *This table shows the errors associated to the dipole part of the 1995 LEP energy determination.*

Dipole model errors		
source	peak-2	peak+2
fill to fill error	0.7	0.5
Energy rise in a fill error	1	1
ring temperature error	0.0	0.3
NMR temperature error	0.3	0.3
Tide error	0.1	0.1
Total of above	1.3	1.2

References

[1] R. Assmann et al., The Energy Calibration of LEP in the 1993 Scan., CERN-PPE/95-10.