Oxford University
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MEMO :

TO: The LEP Energy Group

FROM: Pete Renton

SUBJECT: The 1993 scan energies

Abstract

During the 1995 scan much was learnt about the behaviour of the LEP energy during fills. This was measured using depolarisation measurements carried out at the beginning and end of several fills. In addition, using NMR probes in two ring dipole magnets, the rises were continuously monitored during fills. A rise of several MeV per beam during a fill is typically observed.

The full extent of these rises was not taken into account in the analysis of the 1993 scan. In this note a preliminary investigation into the sizes of these variations is reported. The possible effect of the rises on the 1993 scan energies is assessed. The future work which is needed to obtain a better understanding of these effects, and a more reliable quantitative estimate of the shifts and the associated errors, is discussed.

1 Introduction

The precise determination of the 1993 LEP energy scale has been published by the LEP Energy Group [1]. The estimated precision on the beam energies at the offpeak energy points is 2.0 MeV at p-2 and 1.5 MeV at p+2. Together with the less precisely determined peak energy, these lead to errors on the Z mass and total width, from LEP alone, of 1.4 MeV and 1.5 MeV respectively.

During the course of the 1995 scan there were four physics fills with both beginning of fill (BOF) and end of fill (EOF) polarisation calibrations. These fills were 3022, 3029, 3030 and 3036; of which 3030 was at p-2 and the others at p+2. In addition there were two MD fills, 2929 and 3064, which have a series of polarisation measurements. Fill 2929 was at p-2 and 3064 at p+2. The NMR probe in octant 8 was not operational during fill 2929.

2 The 1993 and 1995 scans

The only NMR probe available for the 1993 scan was that outside the beam pipe in the reference magnet. This showed, at times, an erratic behaviour, with a series of jumps together with a general rise as a function of the time of the fill. The jumps, which were often equivalent to changes of several MeV in beam energy, were attributed to fluctuations in the main bend current. Indeed, an experiment was carried out in which an induced jump was “seen” by the beam. There was a single occurence where there were polarisation measurements before and after a jump. About one half of the NMR jump was “seen” by the beam. These pieces of evidence were used to attribute one-half of the NMR rise as real, and a systematic error of 100% of this rise was assigned.

As most of the new information on the change in beam energy with time comes from the 1995 scan, it is of interest to compare some basic quantities of the 1993 and 1995 scans. In Fig. 1 the relative luminosities, at p-2 and p+2, as a function of the time from the start of the fill are shown. In Fig. 2 the same information is shown for the 1995 scan. These plots are weighted by the luminosity of the fill, which is assumed to be constant in time throughout the fill.

In Figs. 3 and 4 the relative total luminosities delivered, at p-2 and p+2, in the 1993 and 1995 scans as a function of time of day are shown. It can be seen that there are significant differences between both the 1993 and 1995 scans and between the offpeak energy points. As the models discussed below use these two variables, these differences will need to be quantified as possible systematic errors. The peaks in the 1993 distributions are due to short fills with high luminosity.

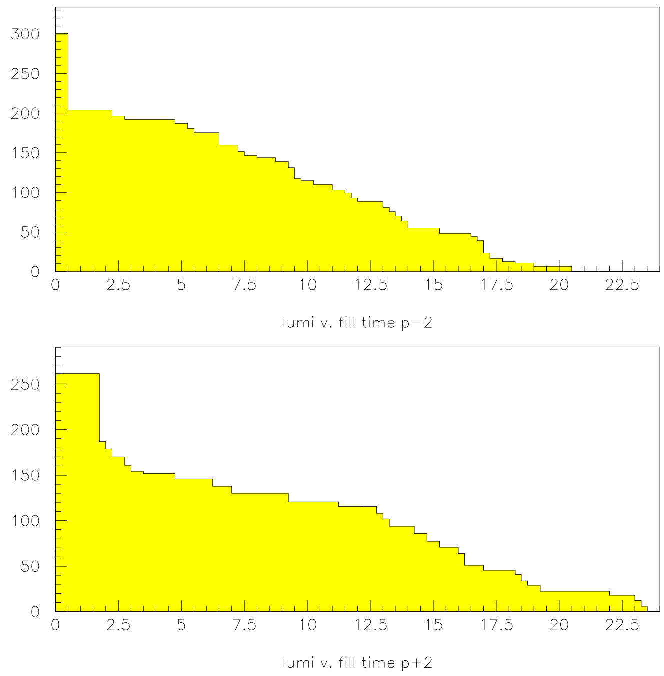

Figure 1: Relative luminosity versus time from start of fill (hours) for the 1993 scan.

3 The energy change during a fill

The NMR probes in octants 4 and 8 exhibited a considerable amount of noise during the 1995 scan, which showed a significant dependence on the time of day. In particular, the NMR probes were relatively quiet between midnight and about 5 am. By a lot of hard work it has been discovered [2] that a major component of this noise was due to earth currents from French trains, with these currents passing along the LEP beam pipe. The effects on the NMRs in the dipole magnets in octants 4 and 8 (called here NMR4 and NMR8) are, to some extent, anti-correlated. For this reason the combination

$$\mathrm{NMR48} = \frac{5}{8}\mathrm{NMR4} + \frac{3}{8}\mathrm{NMR8} \tag{1}$$

is used, where NMR4 and NMR8 are expressed in MeV using a scaling factor from their readings in gauss, chosen so that the values are close to the beam energy. This combination is less sensitive to the noise. These magnets are also equiped with temperature probes, with readings T4 and T8 for the octants 4

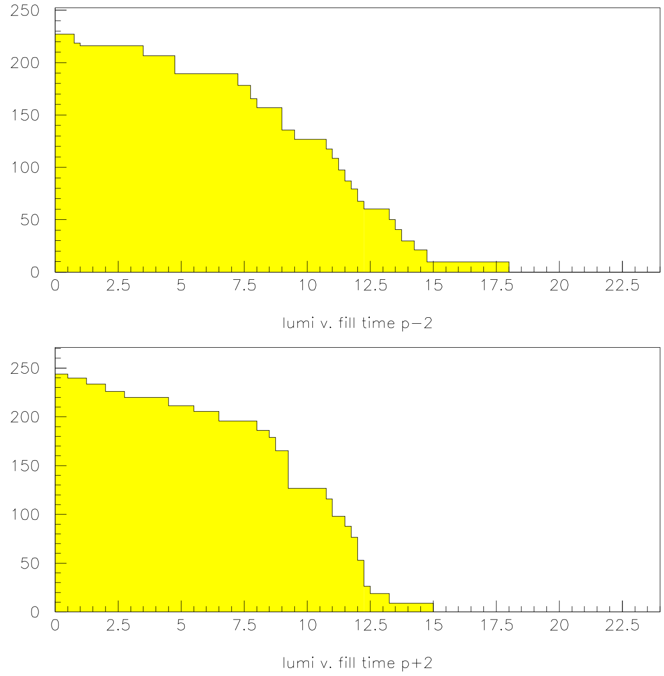

Figure 2: Relative luminosity versus time from start of fill (hours) for the 1995 scan.

and 8 respectively. The combination T48, with the same weighting factors as NMR48, is also used as is T34 which is the average temperature of the ring dipole magnets.

3.1 Parameterisation of the NMR data

The readings of NMR4 and NMR8 show a significant rise during the typical fill time of about 10 hours. Part of the observed rise is due to the change in temperature of the dipole magnets containing these NMR probes. As the local temperature T48 changes are often different to the average ring dipole temperature T34, these differences must be taken into account in order to establish the relationship between the change in the observed NMR48 readings and the changes in the LEP beam energy.

In order to try and quantify this relationship a fit was carried out to all the NMR data for all LEP energies which was logged during the 1995 scan. For each time-stamp the values of NMR4, NMR8, NMR48, T48 and T34 are used. About 4,900 such sets of data are used in the fit. A model is used in which three components of the LEP energy change are parameterised :-

1) energy rise per unit time as a function of time of day (t_{day}).

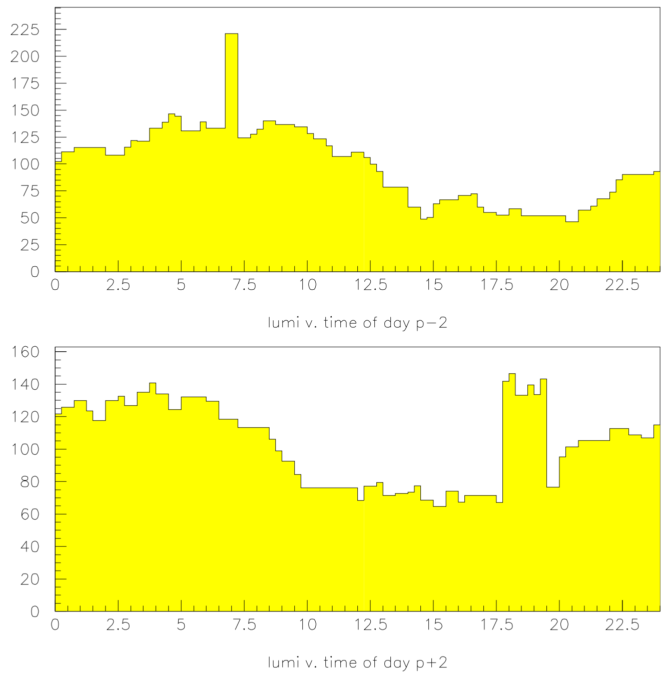

Figure 3: Relative luminosity versus time of day (hours) for the 1993 scan.

2) energy rise as a function of time from the start of fill ($\mathrm{t_{fill}}$).

3) energy rise from the difference between the local and average dipole temperatures, T34-T48.

The model used for the change in energy as a function of $\mathrm{t_{day}}$ and $\mathrm{t_{fill}}$ is as follows :

$$\Delta E_{model}(\mathrm{t_{fill}}) = \sum a_i(\mathrm{t_{day}}) + \Delta E_{fill}(\mathrm{t_{fill}}) + \sum cE_{beam}(\Delta \mathrm{T}_{48} - \Delta \mathrm{T}_{34}) \qquad (2)$$

where coefficients for the sum over the time of day are $\mathrm{a_1}$ for the period 0 to 5 hr. and $\mathrm{a_2}$ the period 5 to 24 hr. The units of these are MeV/hr. The coefficient c is a temperature coefficient for the difference in the behaviour of $\mathrm{T_{48}}$ and $\mathrm{T_{34}}$. For the term $\Delta E_{fill}(\mathrm{t_{fill}})$, corresponding to the change during the fill, several function forms were used. Those discussed here are using a *polynomial*

$$\Delta E^{poly}_{fill}(\mathrm{t_{fill}}) = \sum_{j=1}^{n} b_j \mathrm{t}^j_{\mathrm{fill}} \qquad (3)$$

or using an *exponential*

$$\Delta E^{exp}_{fill}(\mathrm{t_{fill}}) = d_1(1 - e^{-\sum_{j=2}^{m} d_j \mathrm{t}^{j-1}_{\mathrm{fill}}}) \qquad (4)$$

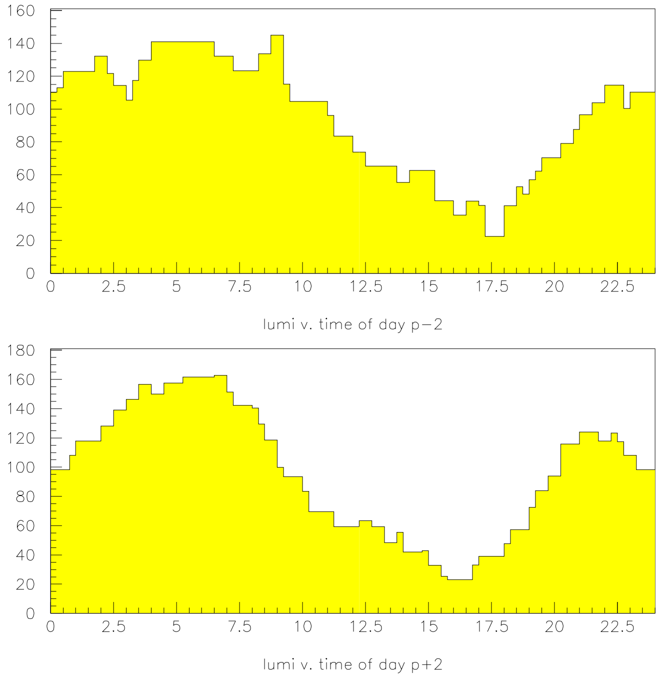

Figure 4: Relative luminosity versus time of day (hours) for the 1995 scan.

A χ^2 fit to the 1995 scan period NMR data was used to obtain the best values of the parameters a,b (or d) and c. An error of 2 MeV was taken for each value of NMR48 in order to obtain an acceptable minimum value of χ^2. This error is much larger than the precision of the NMR readings and reflects, to some extent, the scatter in the readings due to the "noise". However, as discussed below there are other contributing factors. For the polynomial form, the value of χ^2 decreased by about one in increasing the order from n=5 to 6. The value n=5 is used unless stated to the contrary. Likewise, for the exponential form, the value m=4 is used.

The fitted coefficients were then used to compute the changes in the 1993 scan energies, with respect to the values obtained using the published model [1] in which half of the reference magnet rise was used. The change in energy during a fill is estimated by appying the model in intervals of 15 minutes and computing the luminosity weighted average for each scan energy. The values of t_{day} and t_{fill} are used for this purpose. Note that there is no T_{48} term for this application. In addition there is a correction for the average dipole temperature T_{34}. However, this correction is the same for different models of the energy change. In computing the rms values of the model with respect to the measured EOF depolarisation measurements the dependence of T_{34} is taken into account using a temperature coefficient of $1.1\ 10^{-4}$.

3.2 Results for the 1993 beam energy shifts

The results for the shifts in the 1993 energies with respect to the values obtained using the published model are shown in Table 1 The different models considered are as follows :-

A) The standard 1993 model. The reference magnet NMR is used for the value at the start of fill and half of the rise of this NMR is assumed real.

B) As model A, but the initial energy used is that computed from the main bend current and rise is taken to be zero.

C) As model A, but the change during the fill is taken from the 1995 data where it is assumed that all the effects come from the time of day, with no term corresponding to the rise directly with $t_{\rm fill}$.

D) The initial energy is that computed from the main bend current. The change during the fill is from a fit to the 1995 data with a polynomial for the time of fill $t_{\rm fill}$, with n=5.

E) The initial energy is that computed from the reference magnet NMR. The change during the fill is from a fit to the 1995 data with a polynomial for the time of fill $t_{\rm fill}$, with n=5.

F) The initial energy is that computed from the reference magnet NMR. The change during the fill is from a fit to the 1995 data with an exponential form, with m=4.

G) As F), but with the coefficient $b_4 = 0$.

H) As F), but with the fit to the 1995 data restricted to those fills without a bend modulation. Fills with a bend modulation only after the end of physics or calibration were used.

I) As F), but with the fit to the 1995 data restricted to those fills without a "jump" in successive readings of NMR48 greater than 2 MeV.

J) As F), but with the fit to the 1995 data restricted to those fills with a χ^2 value for the fill less than 1.5 times the number of data points for that fill.

K) As F), but with separate fits to the 1995 data at p-2 and p+2, the results of which are applied to the corresponding energies in the 1993 scan.

L) As F), but only using NMR4 for the fits (i.e. NMR8 is not used)

M) As F), but only using NMR8 for the fits (i.e. NMR4 is not used)

It can be seen from Table 1 that all the models considered result in luminosity weighted energies which are lower than the "standard" values

model	peak -2		peak +2	
	rms (MeV)	ΔE_{cms} (MeV)	rms (MeV)	ΔE_{cms} (MeV)
A	6.8	-	2.9	-
B	6.5	-3.5	4.9	-0.2
C	7.7	-3.9	6.1	-6.0
D	7.4	-6.9	6.1	-4.3
E	7.7	-2.5	4.7	-3.1
F	7.8	-2.5	4.8	-3.1
G	7.8	-2.7	5.4	-3.9
H	7.8	-2.7	4.8	-3.5
I	7.6	-2.7	5.4	-4.1
J	7.7	-1.7	5.4	-2.7
K	7.5	-1.8	5.4	-4.6
L	7.0	-2.0	5.1	-3.9
M	8.3	-4.1	6.0	-5.7

Table 1: The values of the rms and energy shifts for p-2 and p+2 for the 1993 scan using different models. The models are described in the text. The shifts are defined with respect to model A, which is the standard 1993 model.

by a few MeV in the cms. It can also be seen that there is a significant difference for some models in the shifts for the two offpeak energies. Of course, not all of these models are equally plausible and that must be taken into account when an estimate is made of the systematic errors on the 1993 (and 1995) energies.

4 Comparison of the model with polarisation measurements

In the models described above it is implicitly assumed that the change in the values of the fields in the dipoles with NMR4 and NMR8, when corrected for local temperature effects, measure the change in the LEP beam energy. This, of course, need not strictly be so. Hence it is important to test the models against the variations in beam energy measured in fills with BOF and EOF calibrations.

Figs. 5, 6, 7 and 8 show the changes in energy during the fill, as a function of the time with respect to the start of either calibration or physics mode (whichever is first). The polarisation measurements are corrected from the standard reference values (T34 = 24 deg. C, tide=0, standard QFQD etc.) to the temperature T34 at the time of the measurement (but not for other effects). The changes are given so that zero corresponds essentially to the time of the first polarisation measurement. The NMR48 data are corrected for the difference between T48 and T34, using the temperature

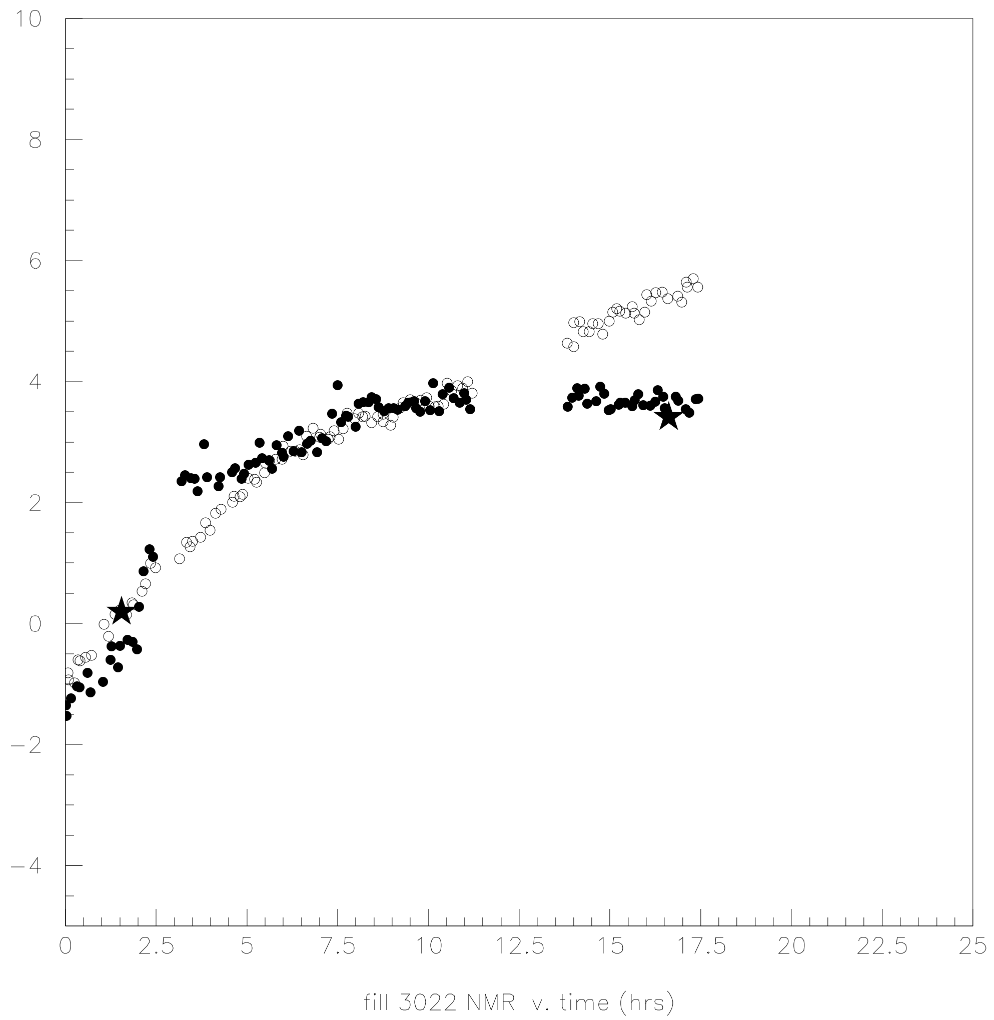

Figure 5: Variation in energy for fill 3022. The solid points show the NMR48 data, the open points the predictions of model F, and the stars the polarisation measurements.

coefficient determined from fit F. The model points are computed using the fitted coefficients from fit F. Thus all the points shown in these figures are corrected so that they correspond to the values expected at the average ring dipole temperature T34; and can thus be compared directly. Similar data are shown for the MD fill 3064 in Fig. 9.

It can be seen from these figures that the NMR48 data show considerable variation with respect to the polarisation measurements. The model

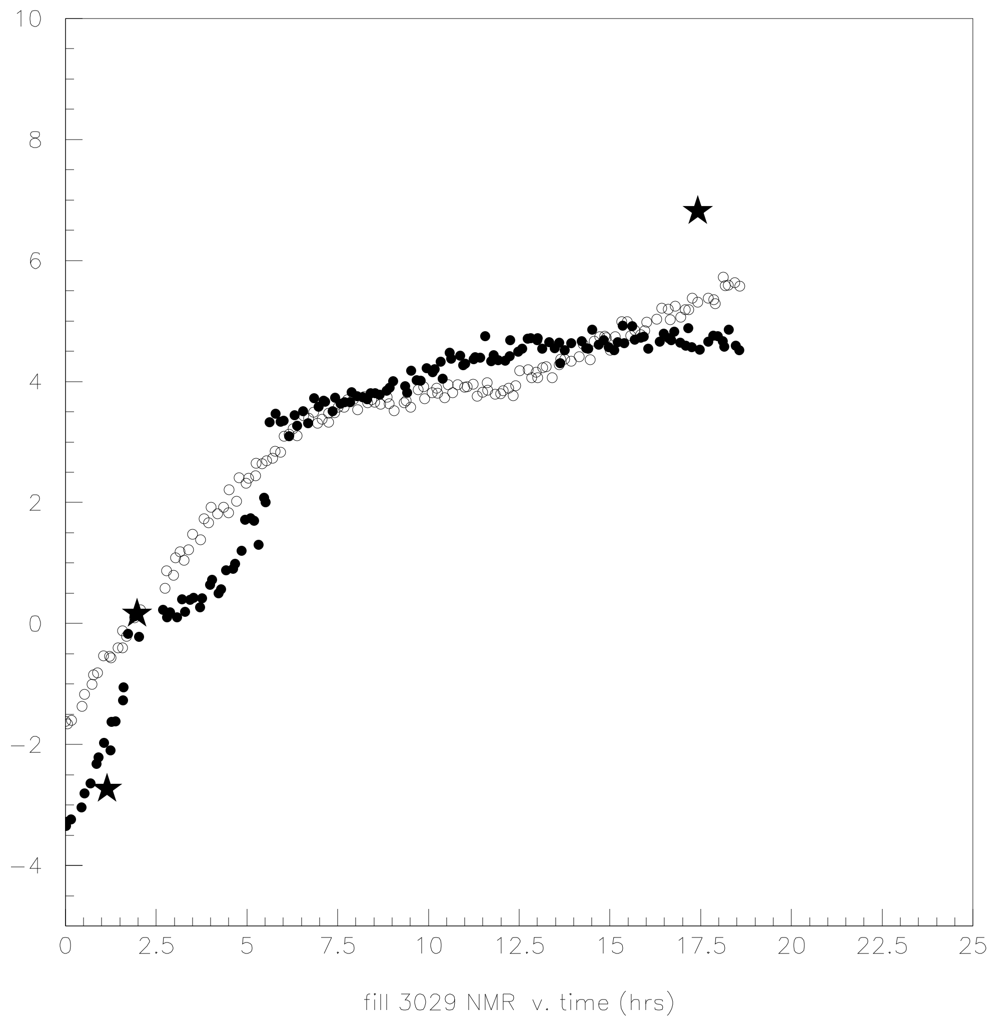

Figure 6: Variation in energy for fill 3029. The solid points show the NMR48 data, the open points the predictions of model F, and the stars the polarisation measurements.

predictions show a more regular behaviour with t_{fill} for the different fills; as is expected since the model is expressed in a rather limited number of parameters and these do not reproduce all the changes seen in NMR4 and NMR8. In particular, there are "jumps" in both NMR4 and 8. A study has been made of these and they show no pattern. The jumps can be classified as both increasing, one increasing the other decreasing, one increasing the other unchanged etc. Essentially all possible combinations

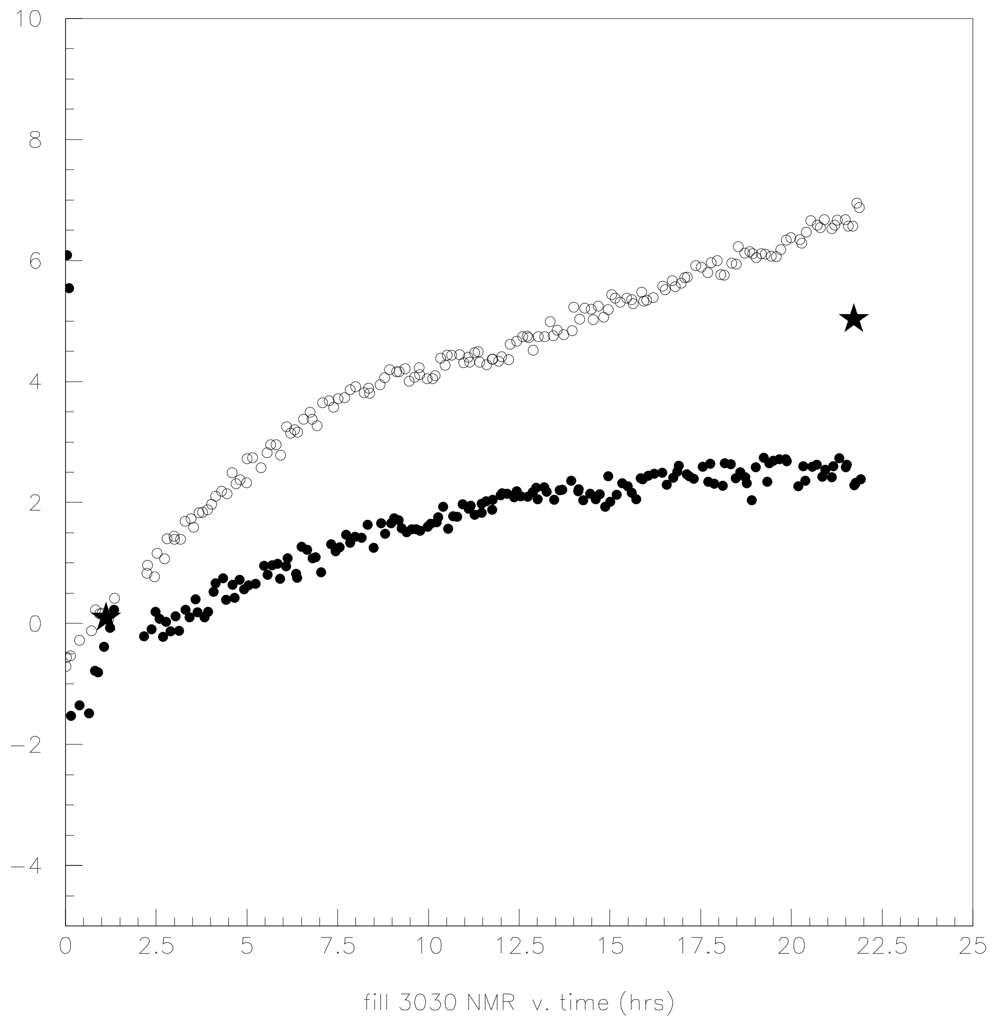

Figure 7: Variation in energy for fill 3030. The solid points show the NMR48 data, the open points the predictions of model F, and the stars the polarisation measurements.

are observed ! Further, it is found that the observation of a "jump" in the reference NMR is not a good estimator of jumps in NMR4/8. Hence there is insufficient information to treat these on an individual basis for the 1993 scan. If can further be seen from these figures that trends in NMR48 are not always followed by the polarisation measurements.

Some values of the averages over these fills for the differences between the start and end of fills are given in Table 2. It can be seen that there is

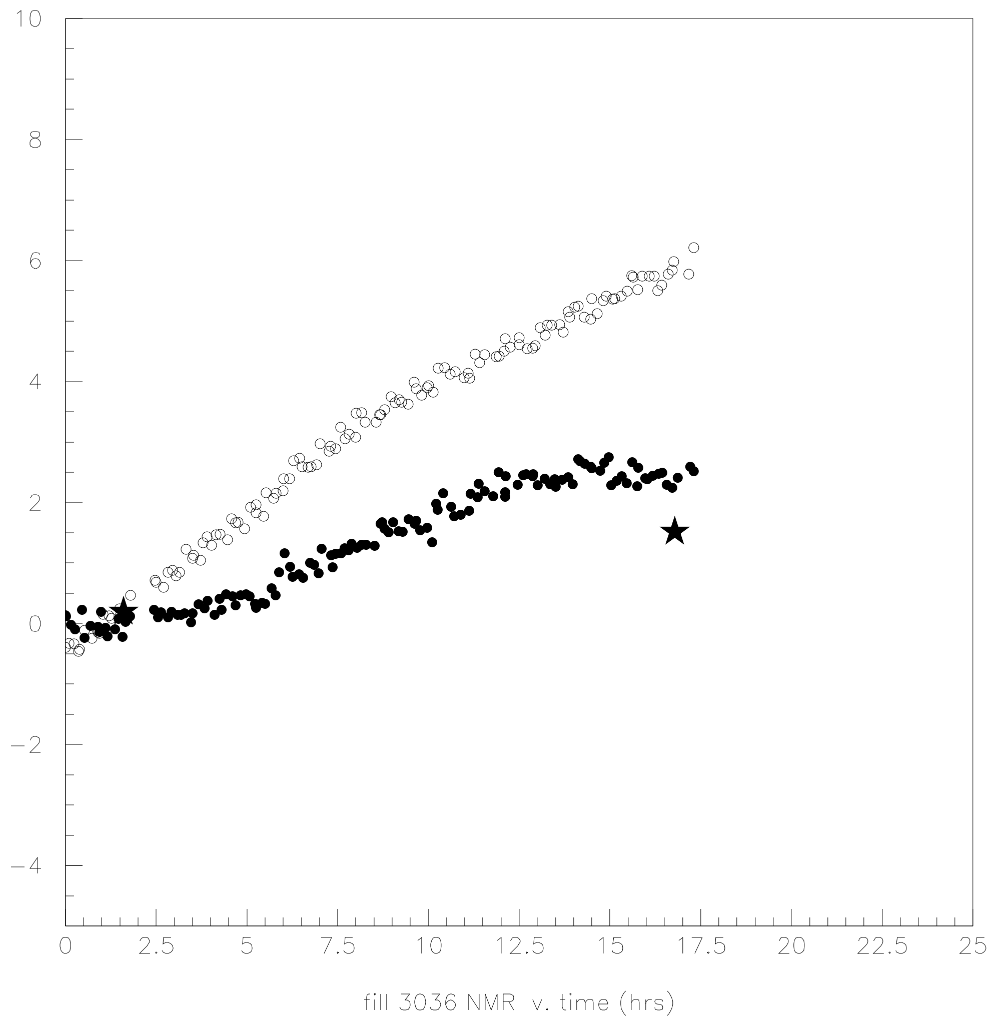

Figure 8: Variation in energy for fill 3036. The solid points show the NMR48 data, the open points the predictions of model F, and the stars the polarisation measurements.

a considerable rms spread in the change in the E_{pol} values. The direct NMR48 data and the model predictions reproduce these changes equally well (or badly!). Fig. 10 shows the changes from the end of fill compared to the start for the 1995 scan for the NMR48 data and for Model F for all fills during the scan. It can be seen that the NMR48 data exhibit a tail at large values which is not reproduced by the Model.

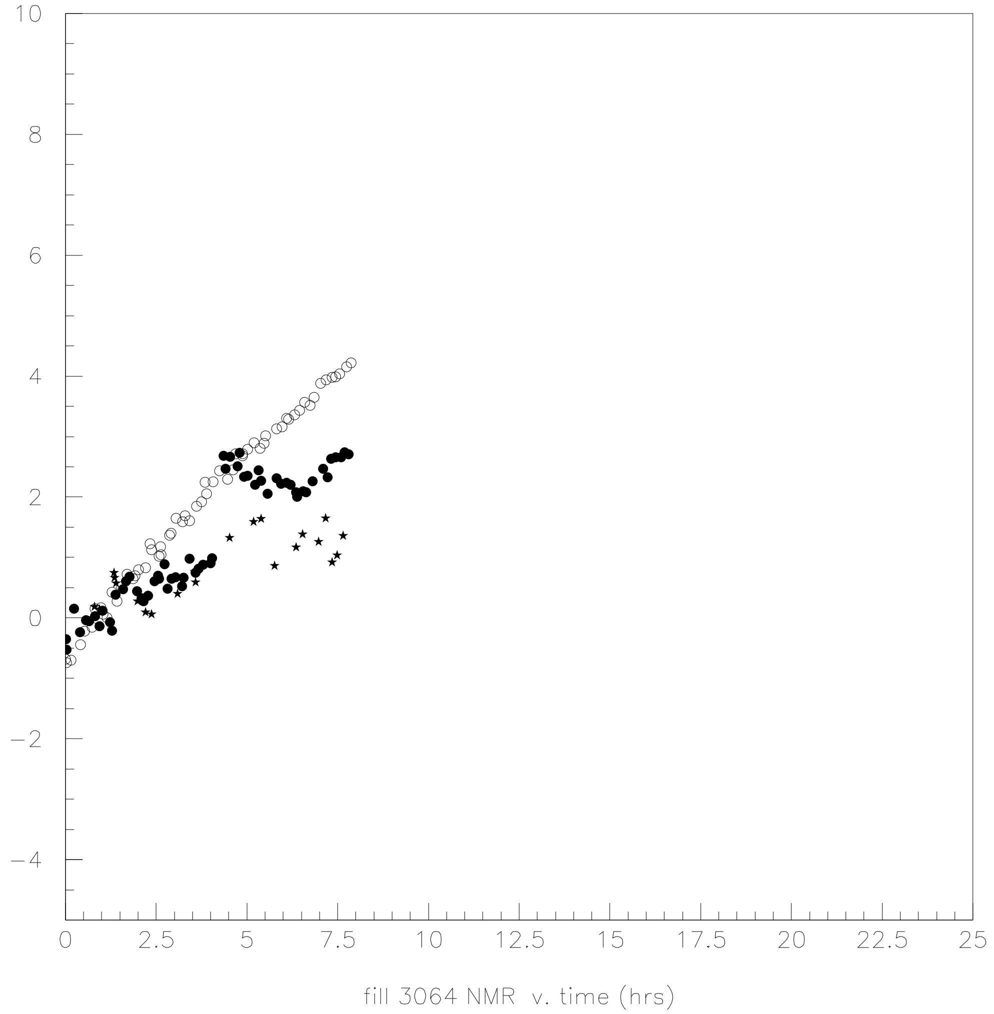

Figure 9: Variation in energy for fill 3064. The solid points show the NMR48 data, the open points the predictions of model F, and the stars the polarisation measurements.

5 Summary and future work

These studies, which are still in a preliminary state, confirm that the variation in the beam energy during a fill is significant and that this will entail a revision, in due course, of the 1993 scan energies. The indications of this study are that the mass of the Z will change by a few MeV (probably in the range 2 to 4 MeV). There will most probably be a modification which

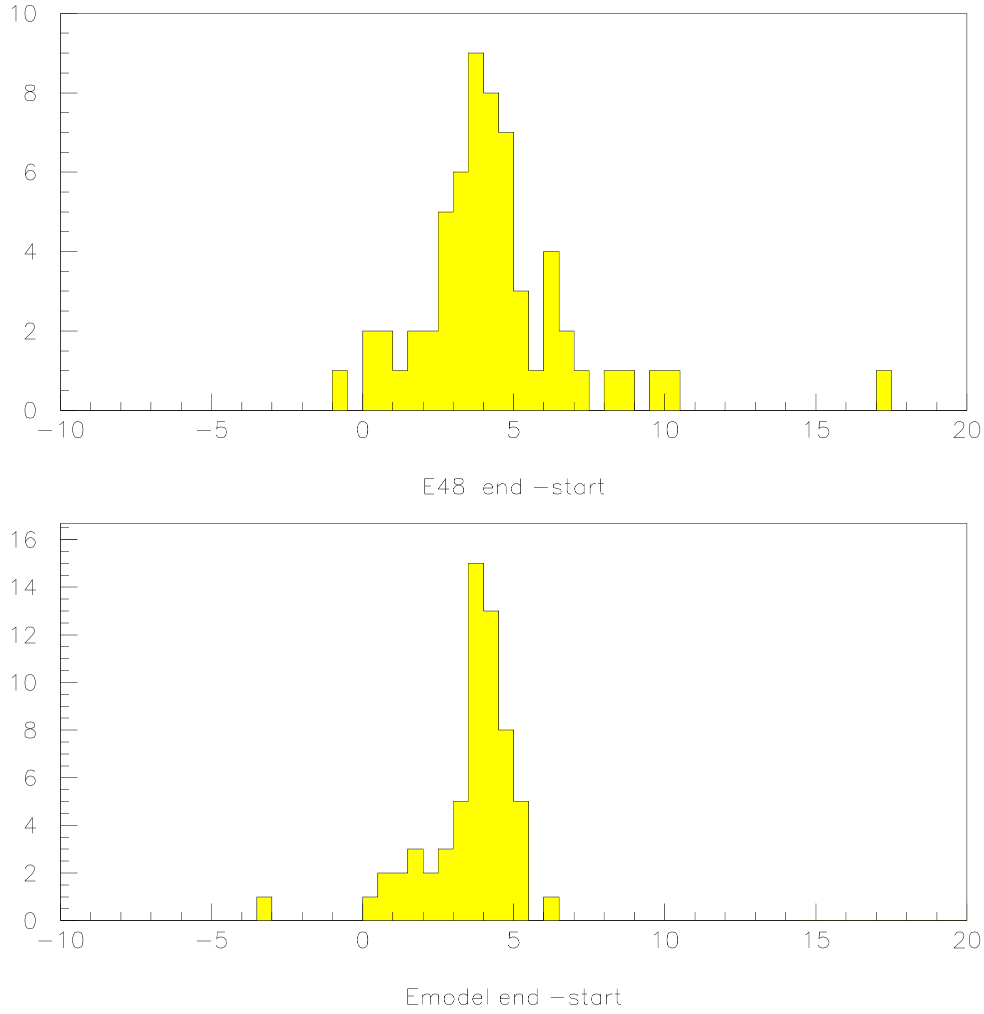

Figure 10: Difference between the EOF and BOF energy values for NMR48 and for Model F from the 1995 scan.

will change the Z total width, although this will probably be smaller in magnitude than the change in the Z mass.

More studies and measurements are needed before these effects can be better understood and quantified :-

- Better understanding is needed of the behaviour of NMR 4 and 8. Significant changes are seen which are beyond the scope of the parameterisation used here. A search for additional variables is desir-

rise in fill of	mean value (MeV)	rms (MeV)
NMR48	3.4 $\pm$ 0.4	1.0
model	4.1 $\pm$ 0.2	0.5
E_{pol}	3.8 $\pm$ 1.0	2.4
NMR48 - E_{pol}	-0.4 $\pm$ 0.8	1.9
model - E_{pol}	0.4 $\pm$ 1.0	2.3

Table 2: Mean and rms values of the estimated beam energy changes during a fill. The period of time is that between the BOF and EOF callibrations.

able.

- The study should be extended to use the various fills before 1995 which have multiple polarisation measurements (but not NMR4/8).
- The starting point of a fill used here is that of physics or calibration mode. There can be a considerable time between the ramp and this start time and this time maybe different at p-2 and p+2. These effects, which could be significant, require a quantitative study.
- A more detailed study of the similarities and differences between the 1993 and 1995 scanes is needed.
- A more detailed study of the similarities and differences between physics and calibration modes is needed.
- More polarisation measurements over a long period of time are needed, particularly at p-2. The LEP machine will have considerable changes in 1996 compared to 1995. However, since the main interest is on the changes in the energy as measured by polarisation, and monitored by the NMRs, these changes do not invalidate such measurements. More NMR probes functioning in the ring dipoles is highly desirable.
- Results from the test dipole magnets measurements need to be understood.
- A study of the systematic errors needs to be made, and the correlation between 1995 and 1993 determined.

In conclusion, there is much work remaining to be done. However, when the programme is completed it should still be possible to have very precise LEP energy results.

References

[1] R. Assmann *et al* , *Z.Phys. C* **66** (1995) 567.

[2] Minutes of the LEP Energy Group meetings, Aug. - Dec. 1995.