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The energy of LEP in 1993, 1994 and 1995 data taking periods - 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 stated. Everything presented here is preliminary. [This report is an update of the ”The energy of LEP in the 1995 scan - Dipole model”, presented to the LEP energy working group for the 1996 winter conferences. Changes are small and the main additions are the presentation of the long term experiments in 1993 and the corrector section.]

Contents

1 The 1995 scan

The 1995 LEP period saw a scan of the Z^0 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 emphasise 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, due to non-zero opposite sign vertical dispersion (OSVD). 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 Calibration statistics

The number of good physics fills and the number of end-of-fill (EOF) calibrations for the various years can be seen in table 1. Although the percentage of fills calibrated is not very different between 1993 and 1995, the percentage of luminosity taken in 1995 in calibrated fills is higher.

Table 1: *This table shows the number of good physics fills and the number of EOF calibrations for 1993, 1994 and 1995.*

	1993		1994		1995	
	fills	EOF calibs	fills	EOF calibs	fills	EOF calibs
p-2	38	13	-	-	22	14
P	57	1	167	11	14	1
P+2	31	11	-	-	23	12

1.3 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 quadrupole 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 for (2) 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 2. 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

In the 1993 paper this comprised the energy corrections due to tides (a rapid daily variation) and due to the long term LEP circumference changes, monitored with the BOM system. Another effect has been taken into account in this analysis: The effect of the dipole correctors, used for orbit manipulation.

2.1.1 Dipole correctors

Scattered around the LEP ring is a series of small dipole magnets that are used to correct the orbit in the horizontal and vertical planes. In 1993 the effect of these correctors on the LEP energy was considered negligible and did not contribute to any extra energy corrections or systematic errors. An analysis of the average settings of the correctors during an average physics run and during calibration has indicated some systematic differences. In the case that different corrector settings would mean different energy corrections, the introduction of an extra LEP energy correction due to the correctors is mandatory.

An in-depth analysis of the effect of correctors this year has indicated that there might be an LEP energy shift due to the horizontal dipole correctors, but the study has not yet been backed up by a dedicated experiment to demonstrate its validity. It is believed that the effect comes from the fact that the extra kicks that the electrons get from a corrector would cause them to enter the quadrupoles with an extra offset which would translate to an energy shift (hence the effect appears under the heading of the quadrupole model). The effect is then in nature similar to the tide or the BOM correction and should be seen by the BOM system, had its precision been adequate. One, therefore, should worry about double counting when correcting for the BOM information and the corrector information. The way that the BOM information was used in the past was to use one number per fill so as to follow the long term variation of the LEP ring circumference; This procedure is kept in the new analysis as well, and the extra corrector information is used additionally to allow for the difference between average physics conditions and calibrations.

Until the dedicated experiment to verify the theory is performed, it was decided to use 50% of the expected effect as an energy correction with an error of 50%. The, rather preliminary, effect of the correctors in 1993 and 1995 is shown in tables 8 and 9, together with the effect of other factors on the LEP energy.

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.

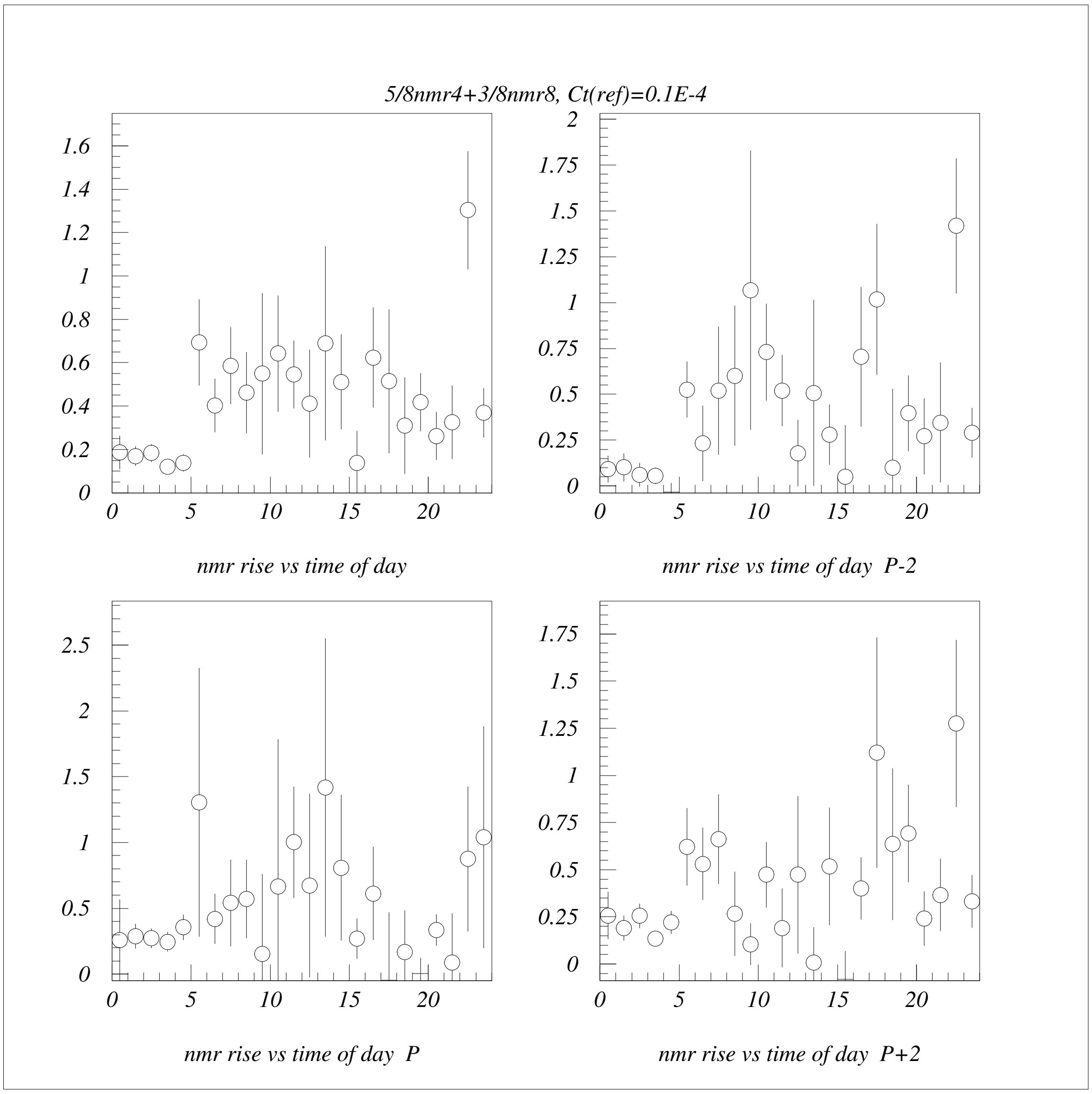

Figure 1: *This figure shows the mean energy rise per hour as a function of time of day Top left: all data top right: only P-2 bottom left: Peak bottom right: P+2 The rise in all energy points is similar.*

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 than at IP8 with an

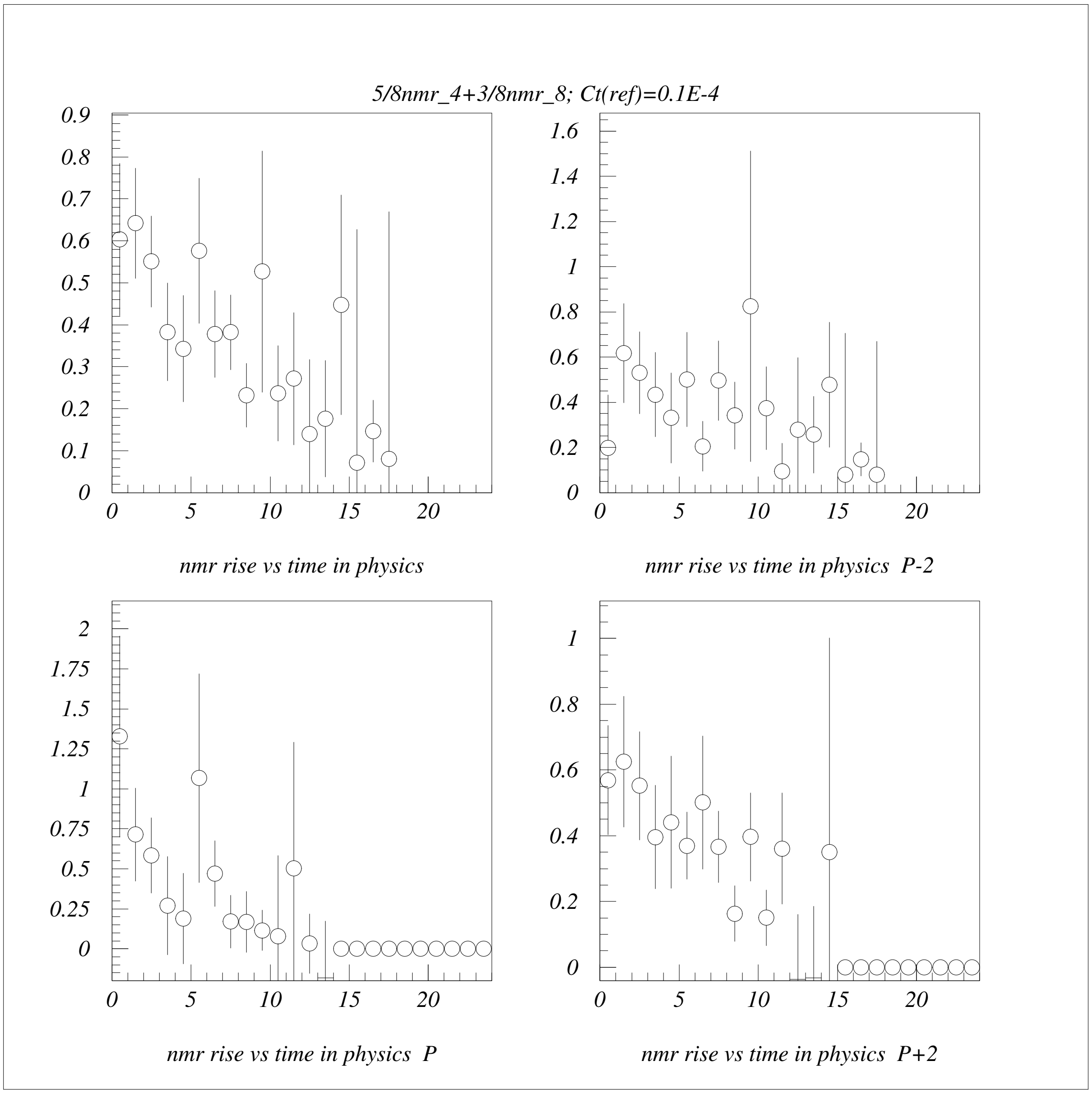

Figure 2: *This figure shows the mean energy rise per hour as a function of time elapsed during a fill. Time zero starts when physics is declared. Top left: all data; top right: only P-2; bottom left: Peak; bottom right: P+2. Again, data at different energy points look similar, as expected.*

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.

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

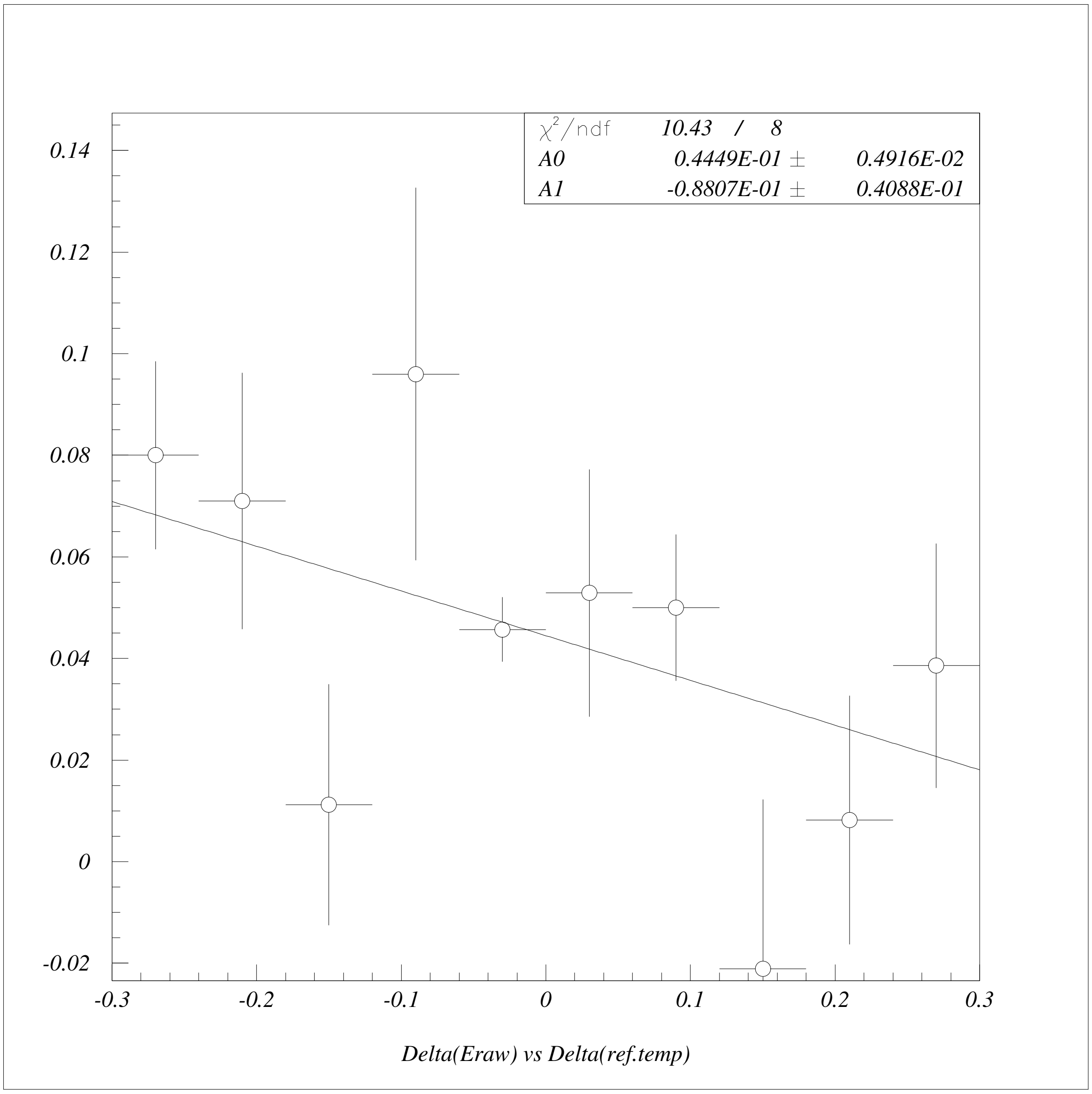

Figure 3: *We here use all the data from the 'quiet' period of 1995 (data taken between midnight and 05:00) and plot the difference between successive NMR readings (separated by 15 minutes) versus the tunnel NMR temperature correction, expressed in MeV for a temperature coefficient of* 10^{-4}*. The 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.*

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 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

Table 2: *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+3/8NMR8), 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	3.3±1.1	0.6±1.9	1.1±1.7	2.7±2.3	4.3±1.4	-0.4±1.8

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 parametrise 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 10^{-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 biases, 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 10^{-4}, and it actually is closer to 10^{-5}.

The value agreed to be used for the preliminary summer conferences 1996 data is $0.25 \pm 0.25 \times 10^{-4}$. My analysis yields values which are closer to $0.2 \pm 0.2 \times 10^{-4}$. Changing the temperature coefficients of the NMRs has a considerable effect on the mean energy of LEP when using the 'average behaviour' model for the energy rise. The reason for this is twofold: Firstly, with a large NMR temperature coefficient, one attributes a large part of the rise seen by the NMRs to temperature (and, therefore, not a 'real' rise seen by the whole of the ring). Secondly, when using a different NMR temperature coefficient one is effectively using a different model. There is a systematic error in the determination of this model. What we see when we change the temperature coefficient, is a measure of this systematic error. I believe that in this case the latter reason is stronger than the former.

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 in 1995.)

However, if one wants to determine the temperature coefficient of 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 0.9×10^{-4} (see figure 4). However, the systematic error of this measurement is considerable: The total energy rise in this experiment was about 7.5MeV; the energy rise expected from the model had the temperature been constant is about 5MeV. We know that we cannot predict the energy rise to better than 33% in 1993. Therefore, the systematic error of this measurement is very roughly about 60%.

What was decided to be used for the summer conferences 1996 data is $1.0 \pm 0.5 \times 10^{-4}$. The reason for the larger error compared to the 1993 paper is firstly due to the large systematic error of the direct measurement of the temperature coefficient of the ring as described above and also due to the fact that we are not ready yet to explain the difference between the temperature coefficients of the ring as a whole and individual magnets (we are not even sure if there is a difference). Various theories have been put forward to explain this difference. The simplest one says that there is a considerable spread in the temperature coefficients of these magnets; my personal preference is for the theory that assumes that the temperature affects the rise term of the magnets which macroscopically can be seen as a temperature coefficient of 10^{-4}. The 'real' temperature coefficient is, however, about an order of magnitude lower.

In conclusion, the question of the temperature coefficient of the LEP ring (and of the individual magnets) is a complicated one. It is hoped that the test bench currently running in the ISR tunnel will shed some light to this question. However, for 1995 the choice of the exact temperature coefficient is not very important; Varying the temperature coefficient from 0.7 to 1.1×10^{-4} changes energies by: P-2: 0.01MeV; P+2: 0.08MeV; i.e. the error is completely negligible.

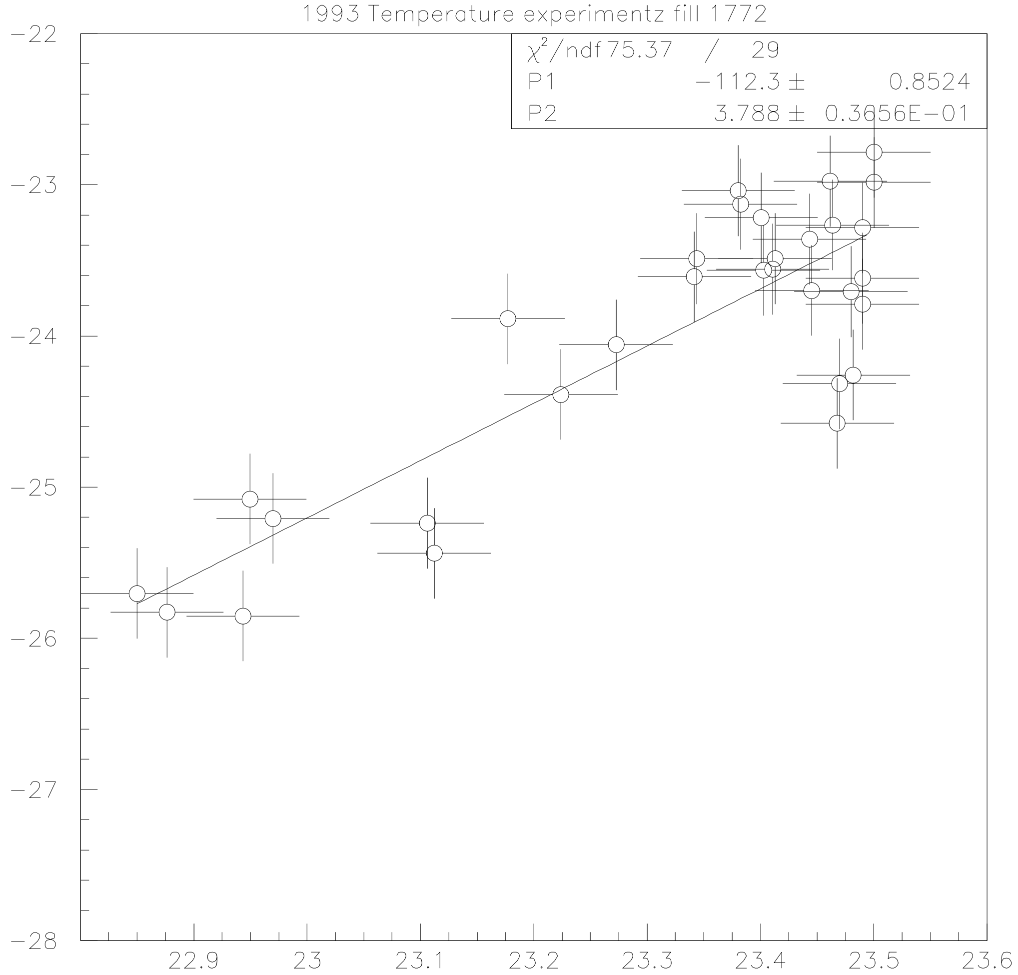

Figure 4: *This is a plot of the energy change (in MeV per beam) versus the temperature (in degrees) observed during the long 'temperature experiment' fill of 1993 (fill 1772). The temperature coefficient corresponding to the slope is* 0.7×10^{-4}.

2.3 Bending modulations

1995 saw another novelty compared to previous years: In an attempt to decrease the instability of dipoles and reduce the number and the magnitude of magnetic field jumps as well as the overall trend for the dipole field to increase during a fill, dipole magnet conditioning ('bending modulation') was performed at the beginning of a fill for about 50% of the data.

This magnet conditioning consisted of a series (about 10 in number) of current spikes deliberately fed to the powering circuit of the dipoles. The amplitude of the spikes was the equivalent of about 10MeV. After the conditioning, the magnetic field of the dipoles stabilised to a value higher by 2-3MeV. After the conditioning the probability for large magnetic field jumps was indeed reduced. Also, the average dipole field rise of the magnets for off-peak fills was reduced from 0.42MeV/h (no bending modulation) to 0.32MeV/h (after bending modulation).

The way that the bending modulation is taken into account in the model is the following: Two independent data sets are used, one for all data after a bending modulation and one for all data without, and the model parameters (rise as a function of time of day and time elapsed in a fill) determined separately. An extra dipole field rise of $2.5 \pm 1.0 MeV$ is added when a bending modulation is performed. The magnitude of the step was calculated from a dedicated experiment (fill 3029) where a calibration was performed before and after modulation. This value is in agreement with what the tunnel NMRs recorded before and after bending modulation for all the fills concerned. There is only one exception to the 2.5MeV step: Fill 3022 had a bending modulation performed after about 2 hours from reaching stable conditions; in such a case we do not expect a step as big as the step seen when a modulation is performed at the start of physics (as was the case for all other fills). For this fill a step of 1.0MeV was used, derived from the tunnel NMR information.

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. More checks can be performed by comparing the model with other models where one does not expect great differences. Table 4 shows how the model compares to the original NMR data used to derive it, as well as a simpler, one-dimensional model and two other models that use different assumptions for the temperature coefficient of the magnets that host the NMRs. As one can deduce from the table, the model is both consistent with the NMR data used to derive it and also stable with respect to changes in the modelling procedure that are expected to have a small effect. On top of that, using the model instead of the raw NMR information reduces the RMS spread of the EOF calibrations (a measure of the goodness of any model) by about 30%.

3.2 BOF calibrations in 1995

All information on the 6 BOF calibrations is shown in table 2. 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.

The latest model fit to those 6 BOF calibrations in 1995 and those of 1993 can be seen in table 3.

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 depolarization measurements about 8 hours after the magnets were ramped to 45Rev. 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 BOF calibrations in 1993

Close inspection of the 1993 data has actually revealed 7 'long term' calibrations (where long term is defined as longer than 2 hours). All these calibrations are used to check the model. However, the mean rise of those 7 calibrations is much lower than in 1995 and therefore the statistical accuracy of these checks in 1993 is not as strong. Here we can proceed in two ways: we can assume that any rise observed in 1993 should be similar to any rise seen in 1995. If we do so, we can combine the BOF experiments from both years and increase our statistical precision on our knowledge of the rise. This assumption is justified from the fact that the reason for the rise is believed to be independent of year: it is the magnets themselves (which have not been changed) and, to a smaller extend, the effect of trains in the Geneva region (whose schedule again has not changed over the last two years). A more conservative way of proceeding is to assume that the energy rise in the two years could be different, and treat each year independently. This conservative approach was decided to be followed for the summer 96 analysis.

As seen by table 3, the statistical accuracy of the rise in 1993 is 1.6/sqrt(7)MeV for a rise of 1.8MeV, i.e. 33%.

4.3 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 energy rise used for the 1993 paper 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 5.

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. In 1995, there were 22 P-2 fills out of which 14 were calibrated at the end of physics; 14 Peak fills, out of which one was calibrated; And, finally 23 P+2 fills out of which 12 were calibrated. In 1993, there were 38 P-2 fills out of which 13 were calibrated at the end of physics; 57 Peak fills, out of which one was calibrated; And, finally 31 P+2 fills out of which 11 were calibrated.

The spread of the model when compared with the end of fill calibrations is shown in Table 10. According to the formula used in 1993, the fill to fill error of LEP is therefore 0.7MeV for P-2 and 0.6MeV for P+2 in 1995 and 1.6MeV for P-2 and 1.0MeV for P+2 in 1993.

5.2 Error within a fill

Here we are limited by the imprecision of our model and the 6 BOF calibrations in 1995 and 7 in 1993. According to Table 3, over the 6 fills that were calibrated in 1995 having an average rise of 3.9MeV per beam, our model showed a small bias (-0.1MeV) and a large spread of 1.7MeV. We can therefore determine the average rise with a statistical precision of 1.7/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).

The equivalent values for 1993, if we treat it independently from 1995, are: We get a bias of 0.0MeV with a spread of 1.6MeV for an average rise of 1.8MeV. Therefore our statistical precision is 1.6/sqrt(7)=0.6MeV, or 33% (i.e. 1.5MeV).

5.2.1 Ring and NMR temperature coefficient uncertainties

Changing the ring temperature coefficient by 50% changes the mean energies by 0.0MeV and 0.1MeV (ECM) respectively for P-2 and P+2 in 1995. In 1993, the values are 0.2MeV for P-2 and 0.6 for P+2(ECM).

Similarly, changing the NMR temperature coefficient by 100% changes the mean energies by 0.4MeV (ECM) for P-2 and 1.0MeV for P+2 in 1995 and by 0.4MeV (ECM) for P-2 and 0.6MeV for P+2 in 1993.

6 Total error of the mean LEP energy

A collection of all the different uncertainties that contribute to the non-IP-sspecific LEP energy error can be seen in table 6. The correlations between the two energy points, essential for estimating the Z^0 mass and width errors, are not included in this table which is simply indicative of the magnitude of the errors.

The biggest contributions come from the uncertainty of the energy rise within a fill (due to the limited number of BOF calibrations and due to the fact that the two years are treated independently). The next important error is the error coming from the long term spread of the EOF calibrations, indicating the long term accuracy of our model. The next biggest error comes from the uncertainty of the NMR temperature coefficients, which is taken to be 100%. This is hoped to be decreased in the future.

7 Appendix

7.1 Differences between EOF calibrations and average conditions

For completeness, we include the differences between the (unweighted) average of all correction factors at various energy points for all end of fill calibrations compared to the (luminosity weighted) average of the same quantities during physics running. A difference of zero means that the EOF calibrations were completely representative of average running conditions and therefore the error associated with this correction factor completely vanishes. For a non-zero difference, the error comes by multiplying the difference (in MeV) by the uncertainty on the relevant quantity (for example, 10% in the case of the tide correction). Three tables are included: Table 7 shows the difference between EOF calibrations and average running conditions when using the tunnel NMR data for 1995. Table 8 shows the difference between EOF calibrations and average running conditions for 1993, using the 'average behaviour' model for the dipole field rise. Finally, table 9 shows the same difference but when using the model on the 1995 data (this is the model used to derive the LEP energies).

7.2 Model fill to fill accuracy

We also show the RMS spreads of the distributions of the difference between calibrations and model predictions for all EOF calibrations in 1993, 1994 and 1995. These are shown in table 10.

References

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

Table 3: *This is a list of all BOF-EOF and MD calibrations in 1993 and 1995. All fills with calibrations over the span of two hours or more are listed. The rise in the dipole field measured with the depolarization technique is compared to the rise given by the model derived from the tunnel NMR data. Time start is the elapsed time, in hours, between reaching stable conditions and the first calibration; the duration of the calibration is also given. 'diff' is the difference between the depolarization data and the model. All data shown are MeV per beam.*

All BOF - EOF calibrations in 1993 and 1995						
Fill	energy	time start	duration	Edepol	Model	diff
1636	P-2	2	4	1.11	3.12	-2.01
1734	P-2	2	4	2.23	2.16	0.07
1772	P-2	1.5	21.5	7.51	6.78	0.73
1811	P+2	21	5	-1.60	-0.04	-1.56
1849	P-2	13	11	3.21	0.37	2.84
1888	P+2	21	2.5	-0.19	0.03	-0.22
1892	P+2	21	2.5	0.57	0.45	0.12
Mean		11.6	7.2	1.8 ± 3.0	1.8 ± 2.5	-0.00 ± 1.6
2929	P-2	4.5	6	+0.92	1.87	-0.95
3022	P-2	1.5	15	4.35	5.60	-1.25
3029	P-2	2.5	15	8.00	5.58	2.42
3030	P-2	1.5	20	5.00	3.60	1.40
3036	P+2	1	15.5	4.04	4.07	-0.03
3064	P+2	3	6	1.18	3.28	-2.10
Mean		2.3	12.9	3.9 ± 2.6	4.0 ± 1.4	-0.09 ± 1.7

Table 4: *This table shows the consistency of the model when compared to (a) the NMR48 data used to derive it (b) A simpler one-dimensional model correcting only for time elapsed in a fill, for both 1993 and 1995. Also included are the differences of the model with two additional ones developed assuming temperature coefficients of MNR48 of of zero and* 0.5×10^{-4}*. Due to the fact that the temperature of NMR48 was rather stable, we expect changes of the order of 0.05MeV, so any change seen can be attributed to model systematics. All numbers are given per BEAM energy.*

model checks			
	difference		
source	Peak - 2	Peak	Peak + 2
Model - NMR48	0.16	-0.04	-0.06
Model - 1D Model 1995	-0.03	0.56	0.13
Model - 1D model 1993	-.25	-1.31	-0.06
Model - Model(0.0) 1995	-.21	-1.31	+0.29
Model - Model(5.0) 1995	.01	-1.31	+0.50

Table 5: *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* 1.1×10^{-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* 0.7×10^{-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

Table 6: *This table shows the errors associated to the magnetic (dipole and quadrupole) part of the 1993 and 1995 LEP energy determination. All numbers are given in ECM.*

Magnetic model errors				
source	1993 peak-2	1993 peak+2	1995 peak-2	1995 peak+2
fill to fill error	1.6	1.0	0.7	0.6
Energy rise in a fill error	1.5	1.5	1.0	1.0
ring temperature error	0.2	0.6	0.0	0.1
NMR temperature error	0.4	0.6	0.4	1.0
Bending modulation error	-	-	0.0	0.1
Tide error	0.0	0.4	0.1	0.1
BOM error	-	-	-	-
Total of above	2.2	2.0	1.3	1.5

Table 7: *This table shows the difference between the average running conditions and the conditions during an EOF calibration using the NMR data directly and not an 'average behaviour' model. The temperature coefficient for the 'reference' dipole field device (5/8NMR4+3/8NMR8) is taken to be* $0.2 \pm 0.2 \times 10^{-4}$*. The temperature coefficient for the ring is taken to be* $0.9 \pm 0.2 \times 10^{-4}$*. Both temperature corrections refer to a temperature of 24°C. The tide coefficient uncertainty is taken to be 10%. There is no error associated with the BOM correction, as in the 1993 paper; instead, any uncertainty is taken to have been absorbed in the model scatter. Difference (column 4) is defined as (average - EOF calib.). All numbers are given per BEAM energy.*

1995 model errors - using NMR data				
source	average	EOF calib.	difference	error
Peak - 2				
reference temperature (°C)	25.05	25.02	-0.03	
ref. temp. correction (MeV)	-0.94	-0.91	-0.03	0.03
ring temperature (°C)	24.56	24.56	0.00	
ring temp. correction (MeV)	2.26	2.27	-0.01	0.00
Tide correction (MeV)	0.60	0.90	-0.30	0.03
BOM correction (MeV)	-8.51	-9.17	1.02	-
QFQD correction (MeV)	-1.38	-1.38	0.00	0.00
Bending modulation step	-	-	-	-0.02
Peak + 2				
reference temperature (°C)	25.10	25.05	0.05	
ref. temp. correction (MeV)	-1.02	-0.98	0.04	0.04
ring temperature (°C)	24.61	24.58	0.03	
ring temp. correction (MeV)	2.55	2.42	0.13	0.03
Tide (MeV)	0.52	0.81	-0.29	0.03
BOM (MeV)	-9.49	-8.97	-0.52	-
QFQD (MeV)	-1.42	-1.42	0.00	0.00
Bending modulation step	-	-	-	-0.09

Table 8: *This table shows the difference between the average running conditions and the conditions during an EOF calibration. A 'reference' temperature correction does not exist per sè, since an 'Average behaviour' model is used for the energy rise. However, the model would predict a different rise if the temperature coefficient of the reference device (=5/8NMR4+3/8NMR8) would be different from the nominal* 0.25×10^{-4}*. Two further models were developed assuming an reference temperature coefficient of zero and* 0.5×10^{-4}*. The magnitude of the maximum difference that this makes to the average energy is what is shown in the last column of the ref. temp. correction. The temperature coefficient for the ring is taken to be* $1.0 \pm 0.25 \times 10^{-4}$*. The tide coefficient uncertainty is taken to be 10%. There is no error associated with the BOM correction, as in the 1993 paper; instead, any uncertainty is taken to have been absorbed in the model scatter. The uncertainty of the QFQD correction is taken to be 50%. All numbers are given per BEAM energy.*

1993 model errors - using the 2 dimensional model				
source	average	EOF calib.	difference	error
Peak - 2				
reference temperature (°C)	-	-	-	-
ref. temp correction (MeV)	-	-	-	0.19
ring temperature (°C)	23.76	23.81	-0.05	
ring temp. correction (MeV)	-0.96	-0.75	-0.21	0.05
Tide correction (MeV)	0.88	0.76	0.12	0.01
BOM correction (MeV)	-9.64	-9.48	-0.16	-
QFQD correction (MeV)	-1.60	-1.17	0.43	0.22
Corrector correction (MeV)			-0.40	-0.20
Peak + 2				
reference temperature (°C)	-	-	-	-
ref. temp correction (MeV)	-	-	-	0.27
ring temperature (°C)	23.83	23.97	-0.14	
ring temp. correction (MeV)	-0.70	-0.12	0.58	0.15
Tide correction (MeV)	0.84	-1.13	1.97	0.20
BOM correction (MeV)	-10.56	-10.15	-0.41	-
QFQD correction (MeV)	-1.68	-1.30	0.38	0.19
Corrector correction (MeV)			-0.25	-0.13

Table 9: *This table shows the difference between the average running conditions and the conditions during an EOF calibration. The model used was created using a temperature coefficient for (5/8NMR4+3/8NMR8) of* 0.25×10^{-4}*. Two more models were created with (5/8NMR4+3/8NMR8) coefficients of zero and* 0.5×10^{-4} *The temperature coefficient for the ring is taken to be* $1.0 \pm 0.25 \times 10^{-4}$*. Both temperature corrections refer to a temperature of 24°C. The tide coefficient uncertainty is taken to be 10%. There is no error associated with the BOM correction, as in the 1993 paper; instead, any uncertainty is taken to have been absorbed in the model scatter. The QFQD compensating loop was stable in 1995. The bending modulation step was taken to be* 2.5 ± 1.0 *MeV. Difference (column 4) is defined as (average - EOF calib.). All numbers are given per BEAM energy.*

1995 model errors - using the model				
source	average	EOF calib.	difference	error
Peak - 2				
reference temperature (°C)	-	-	-	
ref. temp. correction (MeV)	-	-	-	.21
ring temperature (°C)	24.56	24.56	0.00	
ring temp. correction (MeV)	2.50	2.53	-0.03	0.00
Tide correction (MeV)	0.59	0.90	-0.31	0.03
BOM correction (MeV)	-8.55	-9.17	0.98	-
QFQD correction (MeV)	-1.38	-1.38	0.00	0.00
Bending modulation step	-	-	-	-.02
Corrector correction (MeV)			0.19	0.10
Peak + 2				
reference temperature (°C)	-	-	-	
ref. temp. correction (MeV)	-	-	-	.50
ring temperature (°C)	24.61	24.58	0.03	
ring temp. correction (MeV)	2.83	2.69	0.14	0.03
Tide (MeV)	0.52	0.81	-0.29	0.03
BOM (MeV)	-9.54	-8.97	-0.57	-
QFQD (MeV)	-1.42	-1.42	0.00	0.00
Bending modulation step	-	-	-	.12
Corrector correction (MeV)			-0.64	-0.32

Table 10: *This table shows the spread of the distributions of (Emodel - Edepol) for all EOF calibrated fills for all years 1993 to 1995. All numbers are given per BEAM energy.*

Epol - Emodel spreads (MeV)			
year	Peak-2(calibs)	Peak (calibs)	Peak+2 (calibs)
1993	3.4 (13)	-	2.1 (11)
1994	-	3.0(11)	-
1995	2.2 (14)	-	1.5 (12)