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The Energy Calibration of LEP in 1992

The working group on LEP energy

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Abstract

This paper summarizes the procedure followed to provide the absolute energy calibration of LEP for 1992 data. An overall average correction to the *field display energy* is obtained with a procedure similar to the one used for 1991 calibration. In the paper we discuss temperature corrections, RF effects, and the calibrations by resonant depolarization. The result is a calibration of the centre-of-mass energy with a precision of 18 MeV. The centre-of-mass energy spread is also discussed.

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1 Introduction

This report summarizes the measurements and effects which are taken into account for the 1992 LEP energy calibration. The calibration is estimated following a procedure similar to the one adopted in 1991 [1].

Section 2, on temperature effects, starts by demonstrating that the average of 16 temperature measurements represents the temperature variations of the LEP main ring magnets. Since the average temperatures during physics and during the calibrations are not quite the same, a small correction factor is evaluated. Section 3 on R.F. effects gives a reminder of the underlying problem, and goes on to compare measured and computed values of the synchrotron frequency in order to see how well the model and data logging works, and to evaluate errors on the energy corrections.

The results of the 1992 resonant depolarization calibrations are described in the following section. The calibrations made in early 1992 are not strictly relevant since they were made on the 60^0 optics, and transporting them to the 90^0 physics optics introduces a large error. Three sets of accurate measurements were made on the physics optics, but a difference of 34 MeV was observed on the centre-of-mass energy between the first and the last measurements. This difference is not understood and contributes the dominant error. Section 5 calculates the absolute energy from magnetic measurements alone and compares the result with that from resonant depolarization.

A further property of interest is the beam energy spread, which is dealt with in section 6. Finally section 7 summarizes the results for the energy calibration.

2 Temperature effects

Temperature data are available, in the LEP database, from week 31 (July 23rd) for 16 magnets. The behaviour of these dipoles was studied during a 20 day period in October and the results are given in table 1. One LEP and one SPS MD are included in this timeslot. The second column ($< \Delta T >$) is the average difference between the temperature of an individual magnet and the average of all 16. Since the spread of this difference is small (column 3), we assume that the average of the 16 temperature measurements represents temperature variations of all the LEP magnets.

Magnet name	$< \Delta T >$ [°C]	RMS ΔT [°C]
MT_137	0.58	0.17
MT_237	1.38	0.15
MT_337	-0.65	0.15
MT_437	-1.36	0.16
MT_537	-0.05	0.08
MT_637	2.26	0.24
MT_737	0.24	0.17
MT_837	-1.28	0.19
MT_163	0.74	0.23
MT_263	0.92	0.14
MT_363	-2.37	0.16
MT_463	-1.19	0.21
MT_563	0.10	0.11
MT_663	1.26	0.12
MT_763	-0.47	0.16
MT_863	-1.01	0.20

Table 1: Temperature data for October 1st to 20th, 1992. The second column refers to the average difference between the temperature of an individual magnet and the average of all 16 and the third one refers to the spread of these differences.

The temperature increases during a fill. In stable running conditions it increases by typically 0.2°C. However at a start up (for instance during the first fill after a technical stop), the difference between the temperature at the beginning and at the end of a fill can be as large as 2.8°C.

The whole data sample has an average temperature of 24.01°C, with a maximum value of 24.6°C and a minimum of 21.7°C. The rms of the distribution is 0.38°C.

Weighting the temperature with the luminosity, the average value becomes 23.98°C and the rms becomes 0.40°C, corresponding to ± 3.6 MeV on the centre-of-mass energy. The mean value of the temperature during the 7 calibration runs on the 90/60 optics is $T_{ref} = 23.8°C$.

The correction for temperature effects is then

$$\Delta E_{CM}^{temp} = 2E_{FD}(< T_{16} >_{phys} - T_{ref})\alpha_{temp} \tag{1}$$

where [1]

$$\alpha_{temp} = (1.0 \pm 0.25) \times 10^{-4} \quad \text{per} \quad ^\circ C \quad \text{at} \quad 45 \text{ GeV}.$$

This corresponds to a correction of

$$\Delta E_{CM}^{temp} = (1.6 \pm 0.4) \quad \text{MeV} \tag{2}$$

3 RF effects

Further understanding of the shifts in centre-of-mass energy due to the alignment of the radio-frequency cavities was achieved by using RF and LEP parameters logged at the end of 1992 [2]. All RF voltages, the measured Q_s for electrons and positrons, the wiggler currents and the bunch currents were available for the last weeks of running in 1992 and were used to test and improve the modelling of RF effects by comparing the measured and the computed values of Q_s. The model to compute changes of the centre-of-mass energies has been described in [1]. This was extended by taking into account the following effects:

- 12 of the 208 dipoles in octants 1 and 8 are shorter than the standard ones, but have twice the bending strength; this results in slightly higher synchrotron losses per turn.
- The emittance wigglers in points 5 were used in 1992 to control the bunch length; this led to additional energy losses per turn. Variations of Q_s with wiggler current were observed and are well described by the model.
- Q_s is also sensitive to the bunch current, because the effective voltage seen by the particles depends on the amount of energy taken out of the RF system by the bunches. A clear variation of Q_s with bunch current was observed and could be described by the model.

After all corrections, the r.m.s spread of the difference between the computed and the measured Q_s was found to be about 1% of the average Q_s value. In order to obtain agreement between the mean values of the measured and the

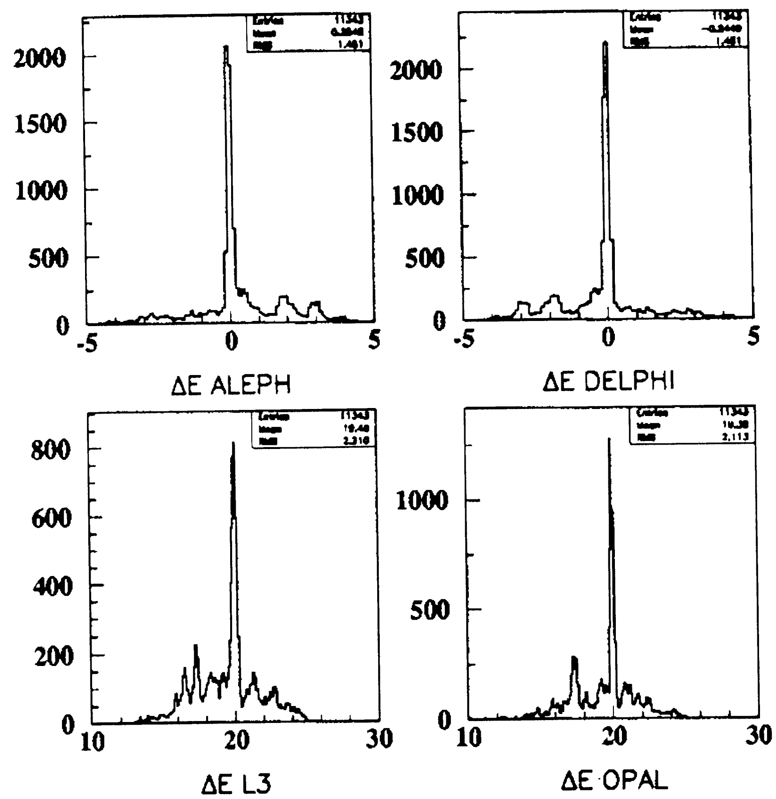

Figure 1: Distribution of corrections on the centre-of-mass energy (in MeV) for the four experiments, computed from RF voltages logged in 1992 [2].

computed Q_s distributions, the RF voltages had to be scaled up by 2.5%, with an estimated uncertainty of $\pm 1\%$.

The average 1992 energy correction for each interaction point was then computed from **all** voltages logged during 1992. The resulting distributions of the energy shift at each interaction point are shown in figure 1. Systematic errors in the determination of the 1992 RF correction for points 2 and 6 arise dominantly from the uncertainty on the scaling factor for the RF voltages (± 0.2 MeV on E_{CM}), from the relative precision of $\pm 5\%$ with which the momentum compaction factor is known (± 1 MeV on E_{CM}), from an observed difference between the values of Q_s for electrons and positrons (± 0.5 MeV on E_{CM}), and from uncertainties in the geometrical alignment of the RF cavities of ± 1 mm (± 0.4 MeV on E_{CM}). The uncertainty for points 4 and 8 comes mainly from a possible difference in the lengths of the LEP arcs, which have been measured to be equal to within ± 5 mm (± 1 MeV on E_{CM}). The average RF corrections for 1992 and their errors are given in table 2. The errors are fully anti-correlated between points 4 and 8 and only partially anti-correlated between points 2 and 6.

	ΔE_{CM} [MeV]			
	L3	ALEPH	OPAL	DELPHI
RF corr. from 1992 voltages	19.5±1.2	0.25±1.1	19.4±1.2	-0.25±1.1

Table 2: Correction on the centre-of-mass energy (in MeV) for the four interaction points.

4 Calibration by resonant depolarization

The results of the calibrations performed in 1992 are shown in figure 2. They have been corrected to tide = 0 to take into account the effect of the earth-tides caused by the Moon and the Sun changing the diameter of LEP [3]. The calibrations performed on 60/60 optics, corrected for tide effects, show a difference $E_{pol} - E_{FD}$ of -38 MeV in agreement with 1991 results. The calibrations performed on 90/60 optics show a decrease with time. The first calibrations (week 45) give a value of -32 MeV for $E_{pol} - E_{FD}$. By the tide-experiment (week 46) this difference had decreased to -42 MeV while at the end of the year (week 47) it was -49 MeV. The reason for this drift has not been found. It has been checked that there is no correlation between this decreasing trend and various other variables, including instabilities in the RF cavities or variations of the level of the water in the Geneva lake or, finally, changes of the water pressure on the tunnel walls.

It has been found that the humidity changed by ±20% in region 3/4 during the period immediately after 1st of November (week 44), due to the fact that the equipment to stabilize the humidity in that region was switched off. Since the influence of the humidity on LEP dipoles is not well known, no conclusion can be derived from this fact.

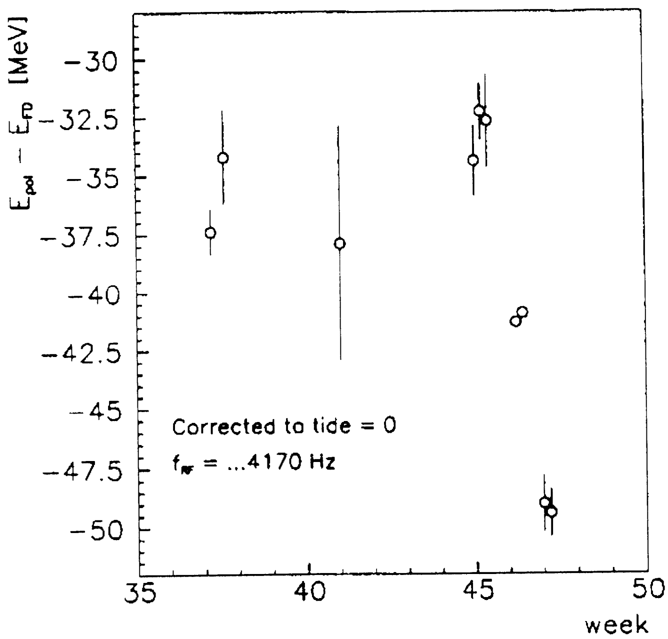

Figure 2: Polarization results. The first three points refer to 60/60 optics. The others to 90/60 optics. The calibration of week 41 (done at "-2" setting) has been corrected for non linearity. An overall uncertainty of ±5 MeV must be introduced when transporting the calibrations from 60/60 to 90/60 optics.

The flux loop data collected in November, the period in which all the polarization runs are concentrated, do not reflect the variation of the energy. To take into account this not understood variation, the correction factor has been fixed in the middle of this variation interval with an error covering the whole spread of data

$$\Delta E_{CM}^{pol} = E_{CM}^{pol} - 2E_{FD} = (-81 \pm 17) \quad \text{MeV}. \tag{3}$$

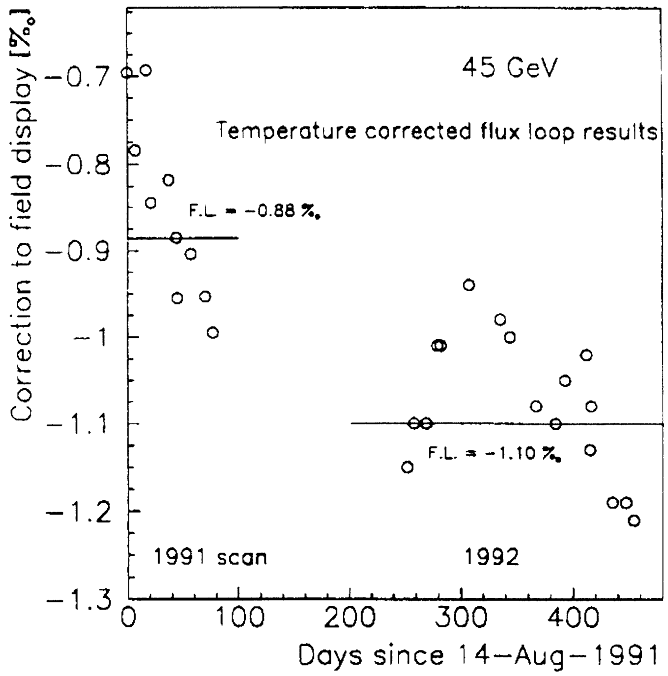

Figure 3: Flux loop calibrations results corrected to $T_{ref} = 22.25°C$. The horizontal lines are the luminosity weighted average of the flux loop results.

4.1 1992 calibration

The centre-of-mass energy is evaluated from the field display system corrected for the effects described above (see appendix A).

The polarization runs were performed at the "+2" setting. The non-linearity effect has to be taken into account to transport the calibration to the peak. The correction factor is

$$\Delta E_{CM}^{non-lin} = (2E_{FD} - 93.0\ GeV)\alpha_{non-lin} \tag{4}$$

where, as for 1991

$$\alpha_{non-lin} = (-2.0 \pm 1.5) \times 10^{-3}.$$

Taking $2E_{FD} = 91.3$ GeV the numerical value of the correction factor is:

$$\Delta E_{CM}^{non-lin} = (3.4 \pm 2.5) \quad \text{MeV}. \tag{5}$$

An additional correction is needed to transport the calibration in time, taking into account the behaviour of the flux loop calibrations during all the year (see figure 3). The luminosity weighted average of the flux loop calibrations corrected for temperature effects $((E_{flux-loop} - E_{FD})/E_{FD})$ is $-1.10‰$. For the data collected in November only, this average value is $-1.20‰$. This difference leads to a correction

$$\Delta E_{CM}^{flux-loop} = (9 \pm 5) \quad \text{MeV} \tag{6}$$

The error has been calculated from the rms of the flux loop data distribution.

The final formula for the centre-of-mass energy taking into account all the corrections evaluated above is

$$E_{CM} = 2E_{FD}^{fill} + \Delta E_{CM}^{temp} + \Delta E_{CM}^{pol} + \Delta E_{CM}^{non-lin} + \Delta E_{CM}^{flux-loop}. \tag{7}$$

This formula leads to a total shift in the centre-of-mass energy of

$$\Delta E_{CM} = (-67 \pm 18) \quad \text{MeV}. \tag{8}$$

1992 Calibration	-81	±	17	MeV
Flux Loop	9		5	
Temperature Correction	1.6		0.4	
Non linearity	3.4		2.5	
Net Correction to CM energy	-67	±	18	MeV

Table 3: Calibration with resonant depolarization in 1992.

5 Comparison of the polarization calibrations with magnetic measurements and with the 1991 calibration.

5.1 Comparison with magnetic measurements.

The flux loop calibrations can be used to estimate the absolute energy of the circulating beams. There are several corrections to the raw data to take into account :

- the shielding effect of the nickel layer on the vacuum tube,
- the flux loop ageing before the first measurements in the tunnel were made,
- the effect of the earths magnetic field and of the LEP correctors,
- the uncertainty on the central orbit frequency,
- the temperature difference between the physics runs and the flux loop measurements.

Taking the luminosity weighted value for the flux loop measurements, we find the results of table 4. We have taken an uncertainty of $\pm 2.5\ 10^{-4}$ on the absolute flux loop calibration. The resulting correction to the centre of mass energy is thus -61 ± 34 MeV which agrees very well with the resonant depolarization result of -67 ± 18 MeV.

Flux Loop	-100	±	23	MeV
Nickel	- 2		12	
FL ageing	+27		9	
Earths Field	- 1.8			
Correctors	0.0		4.6	
Central orbit correction (±15Hz)	0.0		20.4	
Temp Correction.	16.0		1.2	
Net Correction to CM energy	-61	±	34	MeV

Table 4: Lep energy calibration by magnetic measurements.

5.2 Comparison with the 1991 calibration.

The 1991 energy calibration can be transported to the 1992 run using the *relative* flux loop measurements. Since the effects of shielding of the nickel, the ageing before the first measurements were made in the LEP tunnel and the contribution of the Earth's magnetic field remain constant, the precision of the measurement is not degraded by these effects. Furthermore, the relative precision of the flux loop measurements is estimated to be $\pm 1\ 10^{-4}$, as compared to the absolute accuracy of $\pm 2.5\ 10^{-4}$. The central orbit uncertainty is reduced by a factor 2 because it scales with the difference between the inverse of the momentum compaction factors.

$$\frac{\Delta E}{E} = \frac{\Delta f}{f} \left| \frac{1}{\alpha_c^{60/60}} - \frac{1}{\alpha_c^{90/60}} \right| . \tag{9}$$

The 0.5°C error on the temperature (in table 5) reflects the fact that the set of thermometers used to measure the average temperature during 1991 polarization runs and 1992 data taking were not the same.

The central value of this correction (-68 MeV) to the centre of mass energy agrees very well with the 1992 resonant depolarization result (-66 MeV) and the two errors are comparable. However the extrapolation of the 1991 calibration to 1992 has been computed with the assumption that the length of the central orbit was stable. The comparison between the resonant depolarization results and the flux loop calibrations done in November 1992 suggests that the length of the central orbit was not stable. We should then add another error to the extrapolation of the 1991 calibration to 1992 to take into account this effect. This extra error would be totally correlated with the error on the 1992 resonant depolarization result. Hence we have decided not to average the two results.

1991 Calibration	-68	±	4	MeV
Flux Loop 1991 to 1992	-20		9	
Central orbit correction (±15Hz)	0.0		10	
Temperature Correction	16		4	
Error on temperature (0.5°C)	0		8	
Non linearity	3.6		2.8	
Net Correction to CM energy	-68	±	17	MeV

Table 5: Transporting the 1991 calibration to 1992.

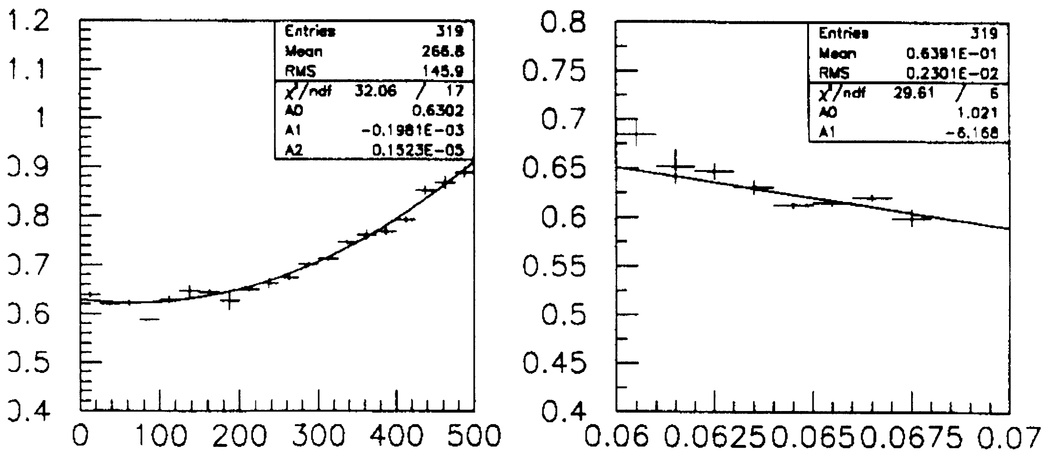

Figure 4: Dependence of the length (cm) of the luminous region on emittance wiggler current (left) and Q_s (right). Only fills with good logging information are included

6 Centre of mass energy spread.

The beam energy spread was affected by the use of emittance wigglers during physics in 1992 [4]. It can be measured using the length of the luminous region measured in the detectors, which gives the bunch length.

The average bunch length was found to be 1.0 cm, corresponding to a beam energy spread of 36.4 MeV. The dominant errors are the uncertainties in the actual value of the average synchrotron tune, Q_s, and the momentum compaction factor, α_c, used to relate the bunch length and energy spread. Assigning conservative 5% errors to both of these results in a beam energy spread estimate of 36 $\pm$ 2 MeV.

The spread in the centre-of-mass energy of the collisions has previously been estimated [1] as $\sqrt{2}\sigma_E$ plus a small correction for the presence of dispersion at the IP. The dispersion introduces correlations between position and energy, and thus between the energies of the two beams at each point in the luminous region. It can be shown, however, that these correlations have no net effect on the luminosity-weighted centre-of-mass energy spread.

The spread in the centre-of-mass energy is then estimated to be 51 ± 3 MeV, where the error is from the systematic uncertainty in the optical parameters.

7 Final results

The centre-of-mass energy at each interaction point, starting from the average energy worked out in formula 7 and taking into account the IP-dependent corrections (see table 2), is then

$$E_{CM}^{ALEPH} = (2E_{FD}^{fill} - 67 \pm 18) \quad \text{MeV}$$

$$E_{CM}^{DELPHI} = (2E_{FD}^{fill} - 67 \pm 18) \quad \text{MeV}$$

$$E_{CM}^{L3} = (2E_{FD}^{fill} - 47 \pm 18) \quad \text{MeV}$$

$$E_{CM}^{OPAL} = (2E_{FD}^{fill} - 47 \pm 18) \quad \text{MeV}$$

where the errors are totally correlated.

The error on this correction is dominated by the spread in the calibrations done with resonant depolarization, which is not-understood.

References

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[2] G. Quast: Note on RF effects added to the minutes of the 28th energy meeting 15-3-1993

[3] L. Arnaudon et al., *Effects of Tidal Forces on the Beam Energy in LEP*, Proc 1993 Particle Acc. Conference, Washington, May 1993.

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A flux loop and polarization results

This table summarizes all flux-loop measurements collected in 1992. The calibrations are corrected to the reference temperature, $T_{ref} = 22.25°C$.

date	time	T_{16} [°C]	diff [o/oo] at 45 GeV
05/05/92	11:07	21.50	-1.156
11/05/92	10:08	22.51	-1.102
21/05/92	10:37	20.51	-1.100
01/06/92	17:26	22.66	-1.015
04/06/92	10:43	20.41	-1.018
29/06/92	16:47	23.75	-0.948
27/07/92	14:24	24.02	-0.985
05/08/92	09:59	24.15	-1.008
28/08/92	11:41	22.66	-1.084
14/09/92	12:44	24.16	-1.108
23/09/92	22:29	20.40	-1.053
12/10/92	13:50	23.69	-1.021
15/10/92	19:41	20.66	-1.134
16/10/92	08:56	23.11	-1.082
04/11/92	07:34	23.88	-1.196
12/11/92	01:29	24.10	-1.192
23/11/92	13:22	23.55	-1.219

This table summarizes all polarization measurements collected in 1992. The calibrations are corrected to the reference temperature, the average temperature recorded during polarization runs, $T_{ref} = 23.8°C$.

date	time	week	T_{16} [°C]	$E_{pol} - E_{FD}$ [MeV]	$E_{pol} - E_{FD}$ T-corr. [MeV]
13.9.92	15:42	37	24.15	-37.4 ± 1.0	-34.1 ± 1.3
14.9.92	7:20	37	24.15	-34.8 ± 2.0	-31.5 ± 2.2
12.10.92	5:36	41	23.35	-33.0 ± 1.2	-37.2 ± 1.6
4.11.92	0:24	45	23.65	-34.4 ± 1.5	-35.8 ± 1.5
4.11.92	1:21	45	23.70	-32.3 ± 1.2	-33.2 ± 1.2
4.11.92	6:05	45	23.87	-32.7 ± 2.0	-32.0 ± 2.0
11.11.92	-	46	24.02	-41.3 ± 0.2	-39.2 ± 0.5
11.11.92	-	46	24.12	-40.9 ± 0.2	-37.9 ± 0.7
23.11.92	12:19	47	23.62	-49.0 ± 1.2	-50.7 ± 1.3
23.11.92	12:27	47	23.62	-49.4 ± 1.0	-51.1 ± 1.1