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Results for transverse beam polarization at LEP in 1993

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Run no.	Date
1557	25-May-1993
1568	27-May-1993
1578	1-June-1993
1579	1/2-June-1993
1589	3-June-1993
1616	14-June-1993
1617	14-June-1993
1636	20-June-1993
1637	21-June-1993
1734	4/5-August-1993
1772	29-August-1993
1849	11/12-October-1993

Keywords: POLARIZATION

Summary

The results of polarization measurements at LEP until October 1993 are presented. The depolarizing effects from the large experimental solenoids could be compensated such enabling polarization measurements and precise energy calibration at the end of physics coasts. Effects on polarization coming from the betatron tunes, squeeze, pretzel and wigglers have been studied. Polarization was measured as a function of spin tune (beam energy) and in particular two higher-order spin resonances were studied in detail. A fast, new procedure to estimate depolarizing effects directly from the measured closed orbit and to compensate them was established. High levels of polarization (30% up to 57%) could such be achieved in a reliable way and in a short time only limited by the build-up time of polarization. The principle of energy calibration by resonant depolarization and possible systematic errors in the spin tune measurements are discussed.

1 Introduction

Transverse beam polarization at LEP in 1992 was limited by depolarizing effects coming from machine imperfections to less than 10%. Whilst for the 1992 physics optics ($90^\circ/90^\circ$phase advance) no polarization at all was found, for a new $90^\circ/60^\circ$optics polarization levels of about 8% were unreliabely achieved. This was sufficient for energy calibration under optimised conditions. Energy calibration at the end of physics coasts, as needed for 1993, would not be possible.

A dedicated study [1] explained the lack of polarization for the $90^\circ/90^\circ$optics and showed that a vertical realignment of the LEP quadrupoles within a tolerance of .15 mm would increase the "typical" polarization from 10% to 30% ($90^\circ/60^\circ$optics). The actually measured polarization, however, can be much smaller than the "typical" 30% and depends on the details of the actual closed orbit.

So in spite of the tight realignment further studies on the optimisation of polarization were done. These studies showed that the "typical" polarization could be further improved and a high actual polarization could be achieved reliably when estimating the depolarizing effects in the imperfect machine directly from the measured vertical closed orbit [2]. This method would even benefit from improvements on the BOM system during the winter shutdown 92/93.

A procedure ("Deterministic Harmonic Spin Matching") was prepared for the vertical closed orbit and could already be tested in the first experiment this year, when only a disappointing 8% polarization was measured. By applying deterministic Harmonic Spin Matching of the vertical orbit the polarization was improved to better than 30%. With this level of polarization systematic studies on polarization and energy calibration became possible or much easier.

The main goal of the described experiments was mostly to prepare energy calibration by resonant depolarization at the end of physics coasts and/or to calibrate the beam energy. By leaving one of the eight bunches polarized several experiments could be performed by the side.

2 Parameters

For the analysis of the polarization data the following parameters have been used:

- **Polarization build-up time**: The polarization build-up time is determined by the configuration of the magnetic bending field for LEP. An exact integration of the bending field of LEP gives the precise polarization build-up time:

$$\tau_p = \frac{6.31 \text{ hours}}{(\nu/100)^5} = \begin{cases} 5.86 \text{ hours} & \text{with } \nu = 101.5, \\ 5.31 \text{ hours} & \text{with } \nu = 103.5, \\ 4.83 \text{ hours} & \text{with } \nu = 105.5. \end{cases} \tag{1}$$

  τ_p determines the polarization scale and therefore is a crucial parameter for polarization.

- **Tide coefficient**: As has been shown in 1992 the LEP beam energy is changed due to a variation of the LEP diameter with the earth tides [3]. The coefficient which connects the change in beam energy ΔE and the strength of tides α_{TIDE} (given by two programs) was measured to be:

$$\Delta E[\text{MeV}] = -5.3[\text{MeV}] \cdot \alpha_{\text{TIDE}} \tag{2}$$

- **Temperature coefficient**: The strength of the magnetic bending field and hence the beam energy varies with the temperature of the LEP bending magnets. It is assumed that the change of beam energy ΔE depends linearly on changes ΔT of the magnet temperature:

$$\Delta E[\text{MeV}] = 6[\text{MeV}/^\circ\text{C}] \cdot \Delta T[^\circ\text{C}] \tag{3}$$

3 Performance of the LEP polarimeter

The beam polarization in LEP is measured with a Compton polarimeter. The cross section for Compton scattering of photons on polarized electrons depends both on the polarization of the photons and on the polarization of the electrons. At LEP a selected electron bunch is illuminated with circular polarized light coming from a pulsed Yag-Nd laser (multi-photon measurement). Reverting regularly the helicity of the circular polarized light results in two different distributions of backscattered photons with a vertical center-of-gravity shift Δy which is proportional to the transverse beam polarization P:

$$\Delta y = \xi \cdot P \tag{4}$$

The polarization scale factor ξ is determined from measurements. The distributions of backscattered photons are measured seperately for both helicities with a 2 mm pitch silicon strip photon detector. The measured average distribution and the measured asymmetry for the two helicities are shown in fig. 1 for more than 50% transverse beam polarization. The center-of-gravity shift Δy is calculated by doing a cross correlation between the two measured distributions of backscattered photons.

The accuracy of the polarization measurement is determined by the number of backscattered photons (statistical error), the stability of the photon-electron interaction region with time and the quality of light polarization (systematic offset errors). In order to improve the accuracy of the LEP polarimeter and to facilitate its operation a new laser was installed for the 1993 run period. The repetition rate of laser shots was increased from 30 Hz to 100 Hz and the number of photons per shot from $2.45 \cdot 10^{17}$ to $3.26 \cdot 10^{17}$. From that an improvement in statistics by a factor 4.4 can be expected. A better laser focus in the interaction point would further increase the statistics and in total up to 10 times more backscattered photons than in 1992 were expected.

The goal to facilitate the operation of the polarimeter has been fully achieved and has lead to an important reduction in set-up time.

With the assumption of a stable photon-electron interaction region during a 1 minute measurement the errors in that time are of statistical nature and are determined by the number of backscattered photons. The distributions of statistical errors are compared for 1992 and 1993 in fig. ?? for two "good" experiments. The shown improvement in the statistical errors corresponds to about 5 times more backscattered photons. This high performance could not be obtained for all experiments and depends on the set-up of the polarimeter and the tuning of the overlap of the photon-electron interaction region. The average performance of the LEP polarimeter yielded an improvement in statistics by a factor 2.5 with an observed optimum performance yielding a factor 6.

The limited aperture of the LEP polarimeter leads in combination with changes in position and shape of the distributions of backscattered photons to systematic errors in the polarization measurement [4]. If the recoil photon beam is not very well centered with respect to the aperture the distributions of backscattered photons are asymmetrically attenuated while reversing the light helicity. This leads to a spurious center-of-gravity shift which does not correspond to beam polarization. It is shown in [4] that this systematic offset error is driven by the linear component in the circular polarized light from the laser.

To evaluate this systematic offset error quantitavely a typical experiment with a well measured exponential rise of the polarization is investigated. Only measurements with positions centered on the detector within 1.5 mm horizontally and 0.8 mm vertically are included into

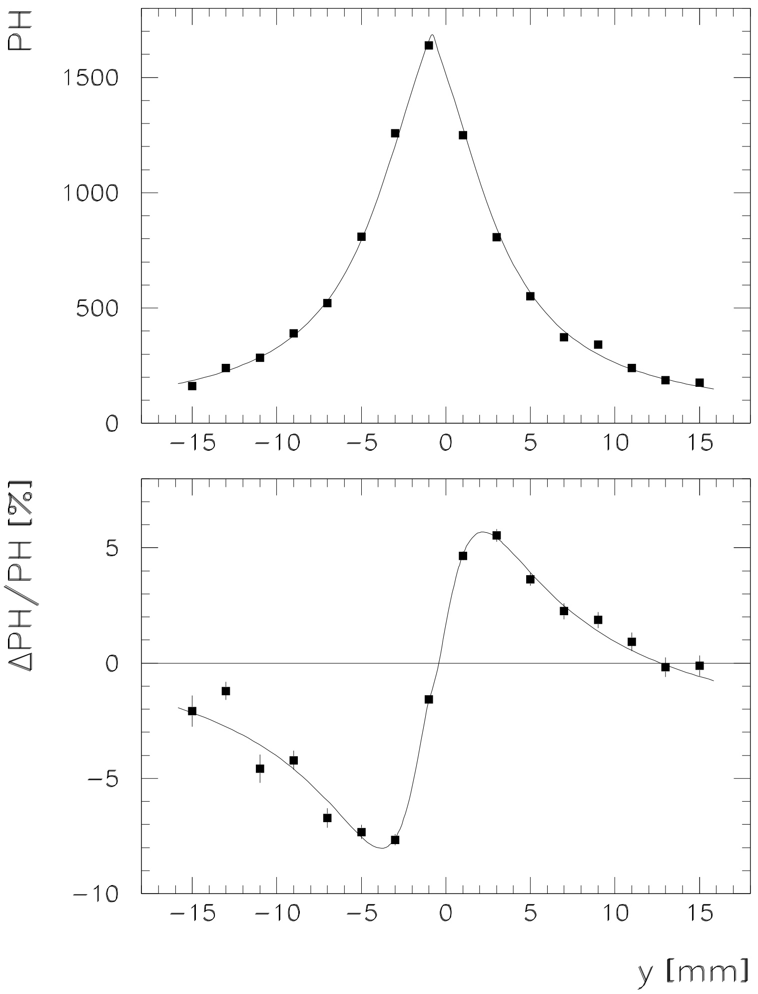


Figure 1: Top: Pulse height PH versus the vertical position y as measured in the 2 mm pitch silicon strip photon detector at LEP. The distributions of backscattered photons for the two helicities are averaged. Bottom: Asymmetry between the distributions of backscattered photons with positive and negative light helicities. The beam polarization is here about 50%.

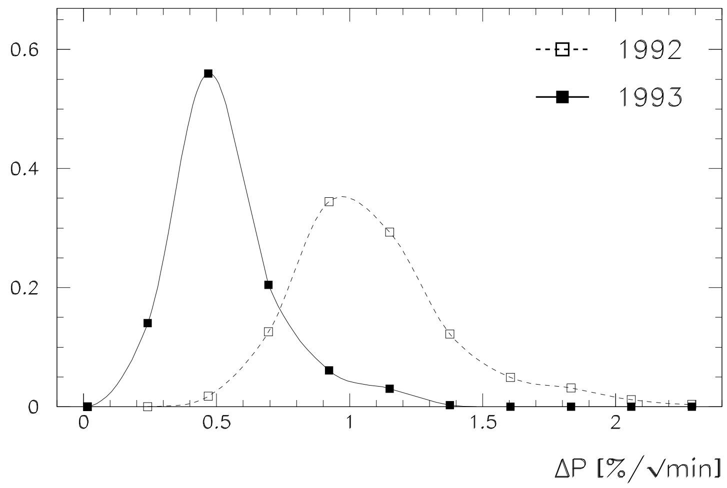


Figure 2: Distributions of statistical errors ΔP which have been achieved in 1 minute measurement with the LEP polarimeter in 1992 and 1993.

the analysis. The exponential rise is fitted and the RMS-deviation of the polarization from the expected value is defined as the total measurement error. The discrepancy between this total measurement error ΔP_{tot} and the average statistical error ΔP_{stat} gives the systematic error ΔP_{syst}. Including the error ΔP_{scale} from the determination of the polarization scale (see next chapter) the error on the polarization measurement is:

(5) $$\Delta P_{tot} = 0.8\% + \Delta P_{scale} \quad \text{(total error in 1 minute)}$$

(6) $$\Delta P_{stat} = 0.6\%/\sqrt{\min} \quad \text{(statistical error)}$$

(7) $$\Delta P_{syst} = 0.5\% \quad \text{(systematic offset error)}$$

(8) $$\Delta P_{scale} = 0.048 \cdot P \quad \text{(polarization scale error)}$$

The figure given for the systematic offset error must be interpreted in the following way: If the position of the recoil photon beam is kept within 1.5 mm horizontally and 0.8 mm vertically around the center of the detector an average systematic error of 0.5% is achieved. The actual systematic offset error, however, depends on the actual positions and eventually on the light polarization and increases very fast with a worsening positioning.

The data which will be presented in the following was often taken during ongoing energy calibration. With high polarization energy calibration by resonant depolarization is not disturbed by small systematic offset errors of a few percent. Therefore the tuning of the LEP polarimeter was not always kept optimal and larger systematic offset errors than possible occured. To exclude extreme effects measurements with positions more than 3.5 mm horizontally and 1.5 mm vertically away from the center of the detector were eliminated. Since these cuts are very wide essentially only a few measurements during the set-up of the LEP polarimeter are cut. The systematic offset error in the shown data is typically of the order of 1%. However, during the experiment when record polarization was achieved (see fig. 1) the strongly drifting orbit of the electrons caused much larger offset errors which went up to about 6/of the experiment. Later on with record polarization the systematic offset was measured to be 0.9% and was subtracted.

The accuracy of relative polarization measurements with the LEP polarimeter is dominated by systematic offset errors coming from the limited aperture and time dependent changes in the electron-photon interaction region. However, the error on the absolut degree of polarization is dominated by the error on the polarization scale if the polarization is higher than 30%.

Often only one or two monitor bunches were used to observe the rise of polarization. The other bunches were depolarized for energy calibration in the meantime. Polarization measurements for energy calibration on these bunches are generally left out for reasons of clarity. This explains the time intervals without any shown measurements in the plots.

4 Determination of polarization scale

A crucial issue for polarization measurements is the determination of the polarization scale. The beam polarization is measured as a vertical center-of-gravity shift between the distributions of backscattered photons with positive and negative helicity. The mean asymmetry in the distributions of backscattered photons when comparing positive and negative light helicities is shown in fig. 1 for more than 50% polarization. The measured vertical mean shift must be converted into beam polarization. Storage rings with radiative polarization like LEP can make use of a measurement of the effective build-up time of polarization. An exponential fit yields the effective build-up time τ_p^{eff} and the asymptotic mean shift Δy_∞. With the well known "natural" build-up time τ_p of LEP the asymptotic polarization P_∞ is given by:

$$P_\infty = \frac{\tau_p^{\text{eff}}}{\tau_p} \cdot 92.4\% \tag{9}$$

By comparison of P_∞ and Δy_∞ the polarization scale factor $\xi = \Delta y_\infty / P_\infty$ is defined. The most complete measurement of the build-up time is shown later in fig. 18. As the exact time of zero polarization and the asymptotic mean shift Δy_∞ was known the polarization scale can be determined accurately:

$$\xi = (4.36 \pm 0.21)\mu\text{m}/\% \tag{10}$$

This value of ξ is confirmed by several other exponential fits from 1993. Once, however, a ξ of 8.1 μm% was seen. This remains to be explained (wigglers on at low currents?).

5 Overview on experiments

The polarization results obtained from May to end of September 1993 are presented by topics and not chronologically. In tab. 1 a connection between the covered topics and the run numbers is established.

6 Spin matching of solenoids

An essential goal for 1993 has been the spin matching of the experimental solenoids in LEP as they destroy almost all polarization. Energy calibration at the end of physics coasts needs polarization with the experimental solenoids on. The spin compensation of the ALEPH solenoid was already demonstrated in 1992 [6].

The strong longitudinal field of a solenoid bends the polarization vector away from the optimum vertical axis. As the solenoid field is well known this effect can be calculated in theory and compensated by a configuration of π-bumps close to the solenoids [7]. In two fills all four experimental solenoids (ALEPH, DELPHI, OPAL, L3) could be spin matched by using the theoretically calculated orbit bumps (SOLSPIN). In fig. 3 the depolarizing effect of the ALEPH solenoid and the spin matching of ALEPH and DELPHI is shown.

OPAL and L3 have been compensated in a similar way. Some loss of polarization was observed after spin matching due to changes in the closed orbit. During all but the first two fills the four experimental solenoids were on and spin matched. Under this condition polarization up to 57% could be measured. The precision of the theoretical calculations is remarkable as the bumps had not been optimised empirically. However, to get even higher polarization the solenoid spin matching bumps would probably needed to be spin matched themselves as they produce a "depolarization strength" of $\tau_p/\tau_d \approx 0.3$. Compared to $\tau_p/\tau_d = 0.62$ which corresponds to the measured 57% of polarization it is not negligible.

It was noticed that the solenoid spin matching bumps produce significant betatron coupling. A double π-bump configuration was used to produce no vertical dispersion and to decrease the vertical amplitude of the bumps. The price to pay is a potentially larger coupling. Betatron coupling excites the Q_x spin resonances and therefore can become seriously limiting for polarization under special conditions (e.g. physics tunes, Pretzel).

Date	Run	β^* [cm]	ν	P_{meas} [%]	P_∞ [%]	P^{HSM}_{meas} [%]	P^{HSM}_∞ [%]	$\#PU_{miss}$	Experiments
May, 25	1557	21	105.476	8	8	29	35	10(13)	Solenoid spin matching: - ALEPH - DELPHI Harmonic Spin Matching. Damping wigglers.
May, 27	1568	21	$\approx$ 101.5	21-16	21-16	27	$>$ 40	7(14)	Solenoid spin matching: - OPAL - L3 Harmonic Spin Matching. Damping wigglers.
June, 1	1578	5	$\approx$ 103.5	4-12	4-12	-	-	-	Polarization in physics: - Physics tunes. - Two colliding beams. - Emittance wigglers.
June, 1/2	1579	21	101.485	-	-	9-27	9-61	23(46)	Physics/Polarization tunes.
June, 3	1589	21	101.480	15	15	40	56	22(28)	Energy calibration. Squeeze: beam lost.
June, 14	1616	var	101.455	-	-	30	$>$ 35	22(28)	Squeeze: β^* = 21 - 7 cm.
June, 14	1617	5	101.476	-	-	21	10-46	22(28)	Betatron tune scan.
June, 20	1636	21	101.465	-	-	39	46	24(30)	Systematic studies: - Polarimeter. - Energy calibration. - Harmonic Spin Matching.
June, 21	1637	5	101.483	-	-	29	>30	23(35)	Energy calibration. Pretzel: beam lost.
August, 4/5	1734	21	101.35-101.48	-	-	24	50	3(10)	Damping wiggler. Spin tune scan. Momentum compaction factor.
August, 29	1772	21	$\approx$ 101.5	-	-	57	57	4(14)	Energy calibration: - Dependence on temperature. Harmonic Spin Matching.
October, 11/12	1849	5	$\approx$ 101.475	-	-	30	30	5(12)	Energy calibration: - Pretzel ON. - Measurement of tides. - Width of depolarizer res.. Damping wigglers: - Reduction of τ_p.

Table 1: Overview on polarization experiments in 1993. If not explicitly mentioned pretzel was off and only the electron beam was filled. For each run the maximum polarization level with (P^{HSM}_{meas}) and without (P_{meas}) Harmonic Spin Matching and the estimated asymptotic values are given. The number of missing pickups for orbit measurement $\#PU_{miss}$ is given for the arc and overall. This number must be compared to a total number of 240 pickups in the arcs and 508 pickups overall. The fills with more than 20 missing pickups in the arcs suffered from a broken BOM-station with 16 pickups on it. Apart from the first two runs all solenoids have been on and were spin matched.

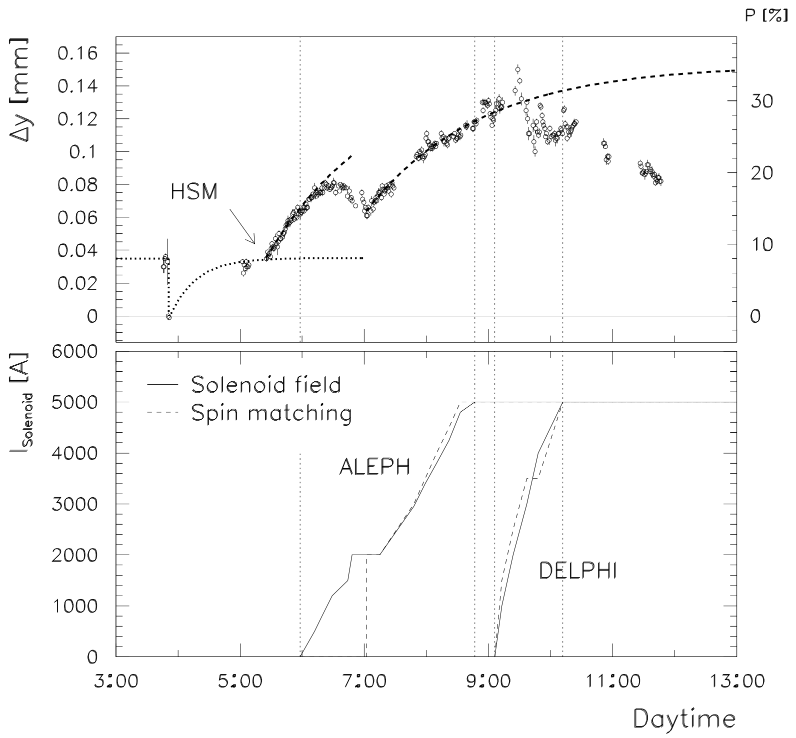


Figure 3: The first experiment in 1993 is shown. The polarization could be increased from 8% to above 30% by deterministic Harmonic Spin Matching of the vertical closed orbit. The depolarizing effect of the unmatched ALEPH solenoid and the spin matching of ALEPH and DELPHI is shown. After spin matching some loss in polarization can be observed. This is mainly due to changes of the closed orbit and betatron coupling.

7 Effect of squeezed optics on polarization

In a squeezed optics with small β^* vertical dispersion with a symmetry of four is potentially produced. This vertical dispersion would excite systematic Q_y spin resonances and would lead to depolarization.

During one fill the beam was squeezed from $\beta^* = 21$ cm down to $\beta^* = 7$ cm without any visible loss in polarization. On three occasions polarization experiments were performed with a β^* of 5 cm. Since polarization levels up to 30% with higher asymptotic values have been observed in this condition it is proved that the squeezed optics is no serious problem for getting high polarization.

8 Effect of damping wigglers on polarization

The natural time constant τ_p for the radiative build-up of transverse polarization at LEP to its maximum degree of 92.4% is between 5 and 6 hours when LEP is operated around the Z-resonance. τ_p is reduced to some effective build-up time τ_p^{eff} by the depolarization process, e.g. to about 30 minutes for 10% polarization. However, high polarization can only be observed after a time of the order of τ_p which is long for practical purposes.

Asymmetric wigglers can reduce τ_p substantially. The set of four damping wigglers in the dispersion suppressors would already reduce τ_p by a factor 2.9 when each wiggler is set to its maximum integrated field of 0.8 Tm. The damping wigglers are located in the dispersion suppressor. As their influence on the beam emittances is therefore small and as their behaviour is well understood they were used to study the effect of wigglers on the polarization level and on the polarization build-up time.

Wigglers do not only shorten the build-up time of polarization but at the same time decrease the natural polarization and more seriously increase the energy spread of the particle beam. Theoretical results on these three effects are shown in fig. 4 to fig. 6 in dependence of the integrated field per wiggler for a spin tune of 101.5. All four damping wigglers are at the same field.

In order to use higher-order theory for polarization the results from a relatively new code SODOM (higher-order) [9, 12] were carefully compared with results from SITF(linear) [11, ?]. The results on beam characteristics and linear polarization agreed perfectly. Both were cross-checked with analytical calculations on beam characteristics and good agreement was found. Therefore it is justified to use higher-order polarization calculations from SODOM with some confidence. The expected linear and higher-order polarization is shown in fig. 7 as a function of the integrated field per damping wiggler. In order to exclude possible effects from the beam emittances a perfect LEP model was only perturbed locally by Harmonic Spin Matching bumps. This way the spin resonances were excited while preserving a very small vertical emittance and a very small dispersion at the locations of the damping wigglers. The horizontal dispersion was smaller than 1 cm and the vertical dispersion smaller than 0.5 cm at the locations of the damping wigglers. The polarization of this LEP model is about 50% without damping wigglers. It was proved that essentially the same results are obtained when assuming a more realistic LEP model.

When the damping wigglers are ramped up the linear polarization in fig. 7 slightly decreases due to the decreasing natural polarization P_0 from fig. ??. However, the higher-order polarization is predicted to decrease much faster. As can be seen from fig. fig:dwig-dec this additional loss of polarization is strongly correlated to the increasing energy spread. These theoretical results indicate that the increasing energy spread restricts the use of wigglers for LEP to a small number of wigglers at low fields. This was already feared from analytical calculations in [13]. However, numerical higher-order calculations with SITROS for LEP predicted high polarization for even much stronger wigglers than the damping wigglers [14].

A first step in order to use wigglers at LEP was to measure experimentally their effect on the polarization. The effect of the damping wigglers on polarization was measured several times. A very clear example is shown in fig. 8. The polarization is shown for different settings of the damping wigglers. The spin tune during this experiment was very carefully kept between higher order spin resonances. It is clearly seen that polarization decreased substantially when the damping wigglers were ramped up.

The interpretation of the results is not straight forward since with most of the wiggler settings the equilibrium degree of polarization was not measured (there was not enough time to wait for it). The equilibrium polarization P_∞ can, however, be calculated from the measured *slope* P' of polarization at some time with initial polarization P_i. Without wigglers the depolarizaton strength τ_p/τ_d is given by

$$\frac{\tau_p}{\tau_d} = \frac{92.4\%}{P_i} - \frac{P'\tau_p}{P_i} - 1 \tag{11}$$

and the asymptotic polarization P_∞ is calculated as

$$P_\infty = \frac{92.4\%}{1+\frac{\tau_p}{\tau_d}} \quad . \tag{12}$$

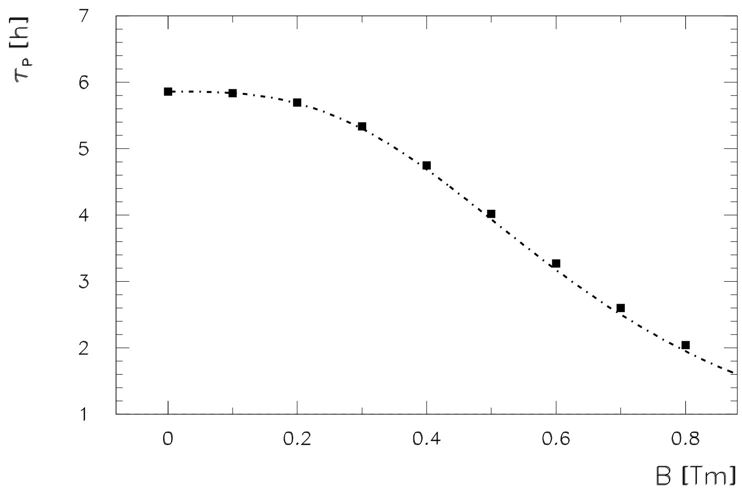


Figure 4: Natural polarization build-up time τ_p versus integrated field B per damping wiggler. All damping wigglers are at the same field and the spin tune is assumed to be at 101.5. The results from SITF and SODOM (points) are compared to an analytical calculation. From [8].

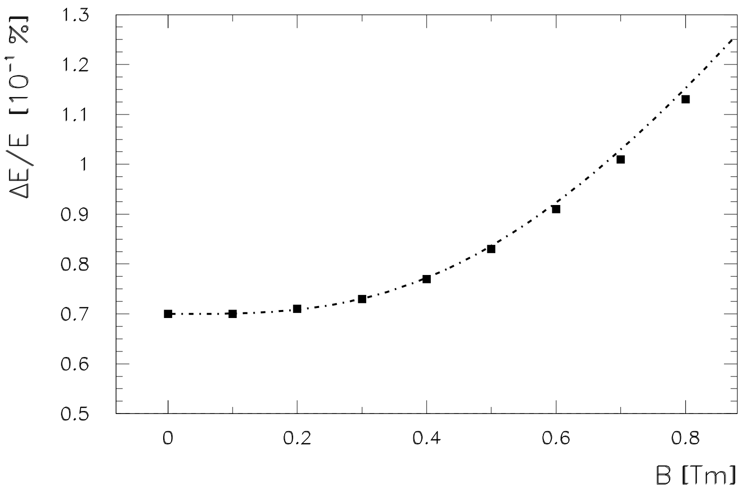


Figure 5: Energy spread ΔE versus integrated field B per damping wiggler. All damping wigglers are at the same field and the spin tune is assumed to be at 101.5. The results from SITF and SODOM (points) are compared to an analytical calculation. From [8].

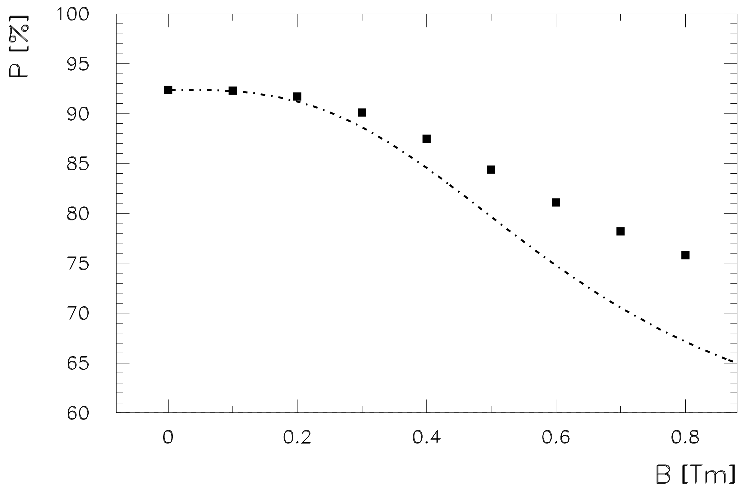


Figure 6: Natural polarization P_0 versus integrated field B per damping wiggler. All damping wigglers are at the same field and the spin tune is assumed to be at 101.5. The results from SITF and SODOM (points) are compared to an analytical calculation. From [8].

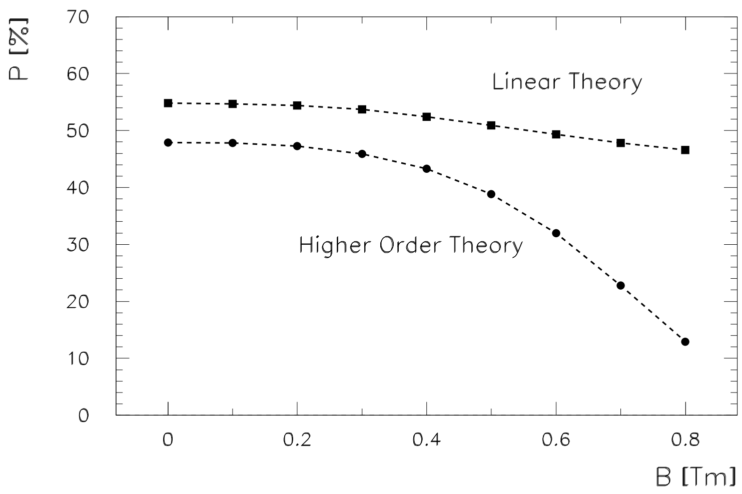


Figure 7: Polarization from linear and higher-order theory as a function of the integrated field per wiggler (SODOM). All damping wigglers are at the same field and the spin tune is assumed to be at 101.47. From [8].

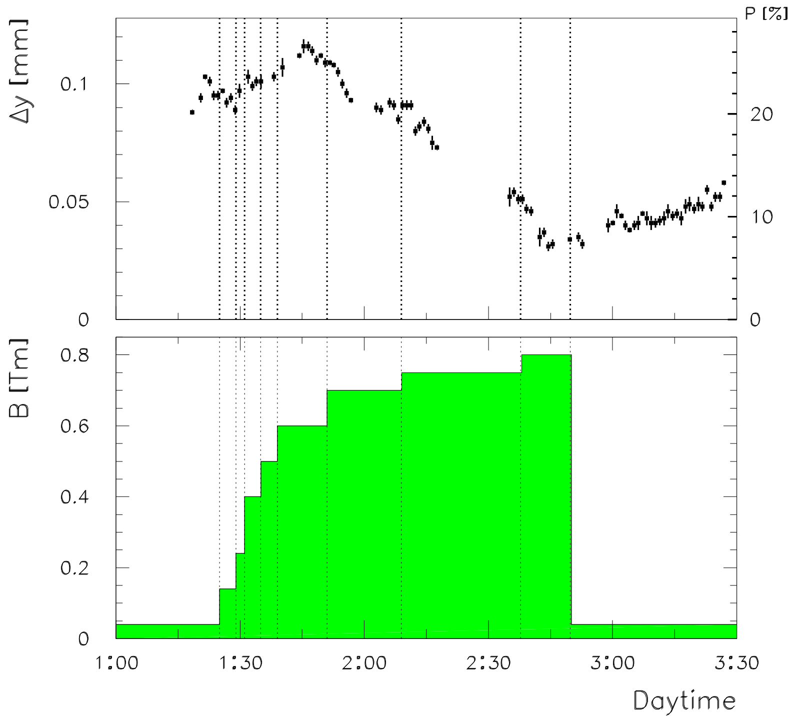


Figure 8: Polarization for different values of the B-field at the damping wigglers. The minimum field is 0.04 Tm.

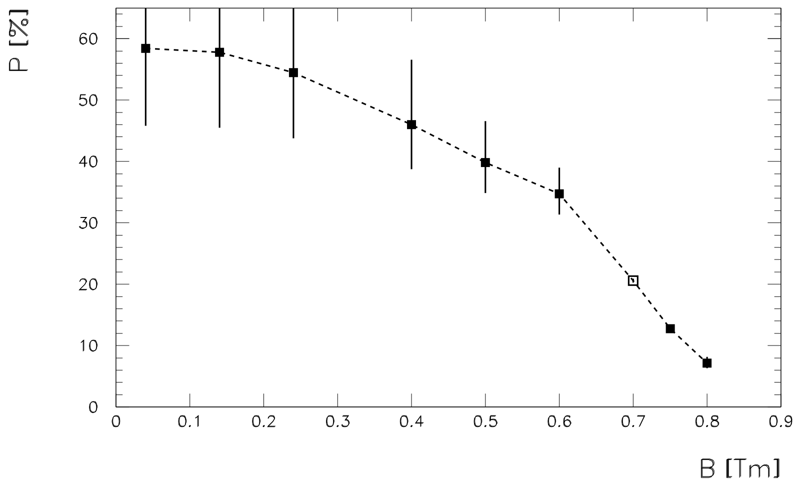


Figure 9: Equilibrium polarization P as a function of the magnetic field B at the damping wigglers. The point marked with the open square is measured, all others are calculated from the slope of polarization.

Taking into account the effects from wigglers the natural build-up time τ_p must be replaced by the its reduced value τ_p^W and the natural polarization $P_0 = 92.4\%$ must be replaced by its reduced value P_0^W.

Analysing the data with fitting the slope P' for each setting of the damping wigglers yields the dependence of the equilibrium polarization on the magnetic field in the damping wigglers. The result is shown in fig. 9. The equilibrium polarization is reduced to about 5% with the damping wigglers at full field. The experimental results confirm the numerical predictions from SODOM and the predictions from analytical theory.

Increased energy spread limits the use of wigglers at LEP e.g. to the set of damping wigglers at an integrated field of about 0.6 Tm each. The polarization build-up time τ_p can be approximately halfed.

This was tried experimentally. During an experiment to measure the beam energy variation with the earth tides the damping wigglers were set to 0.6 Tm each and the polarization build-up was measured three times (see fig. 10). An equilibrium polarization of 30% was achieved which is in good agreement with the theoretical prediction and previous measurements. A decrease in the natural polarization build-up time τ_p by a factor 1.8 was expected.

From a fit to the exponential build-up of polarization the asymptotic center-of-gravity shift Δy_∞ and the effective build-up time τ_p^{eff} is achieved. With the known natural build-up time τ_p and the natural maximum polarization P_0 (92.4% without wigglers) the polarization scale factor ξ is determined. ξ correlates the measured vertical center-of-gravity shift Δy to the beam polarization P and is determined mainly by the layout of the polarimeter. It does not depend on the field of the damping wigglers and its value is known (see determination of the polarization scale):

$$\xi^W = \xi = (4.36 \pm 0.21)/\% \tag{13}$$

Inserting the expression for ξ^W and resolving for the natural build-up time τ_p^W with the wigglers yields:

$$\tau_p^W = \frac{\tau_p^{\text{eff},W} \cdot P_0^W}{\Delta y_\infty^W} \cdot \xi \quad . \tag{14}$$

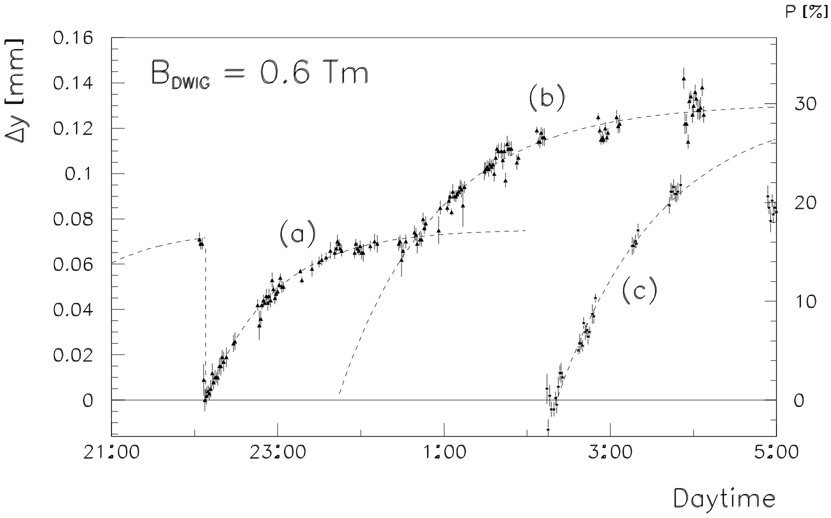


Figure 10: Three measured polarization build-up curves with the damping wigglers at 0.6 Tm each. Up to 30% polarization was achieved after a second step of deterministic Harmonic Spin Matching.

Case	τ_p^W [h]	τ_p/τ_p^W
(a)	3.82 ± 0.34	1.53 ± 0.14
(b)	3.23 ± 0.31	1.81 ± 0.17
(c)	3.35 ± 0.21	1.75 ± 0.11

Table 2: Reduced build-up time τ_p^W for the damping wigglers at 0.6 Tm each. The results are obtained from three different fits to the results shown in fig. ?? (case (a), (b) and (c)). The ratio τ_p/τ_p^W is also given and should be compared to the expected value of 1.8.

The natural maximum polarization P_0^W for the damping wigglers at 0.6 Tm is taken from theory and is 81.1%. Δy_∞^W and $\tau_p^{\mathrm{eff},W}$ result from the fits to the exponential rise of polarization. The results for τ_p^W from the fits in fig. 10 are given in table 2 where also the factor of reduction is given. An additional offset error on the center-of-gravity-shift of 5μm was assumed.

The results are compatible with the expected decrease of τ_p by a factor of 1.8. Especially the two fits with an asymptotic polarization of 30% (case (b) and (c)) agree very well the expectation. The first fit with a lower asymptotic polarization of 17% does not fit as well. The polarization rise is slower than expected from theory and the other two fits. One can argue that all results are in agreement within the errors and that they indicate a somewhat larger τ_p^W than expected from theory. A possible reason could be a slight miscalibration of the fields of the damping wigglers. Another explanation could be a non-linearity in the polarization scale for small center-of-gravity shifts. ξ would not be constant any more and would have a different value for case (a).

9 Effect of betatron tunes on polarization

Depolarizing spin resonances occur at spin tunes (equivalent to beam energy) which are determined by the betatron tunes Q_x and Q_y and the synchroton tune Q_s:

(15) $$\nu = a\gamma = n \pm k \cdot Q_x \pm l \cdot Q_y \pm m \cdot Q_s \qquad n, k, l, m \in N$$

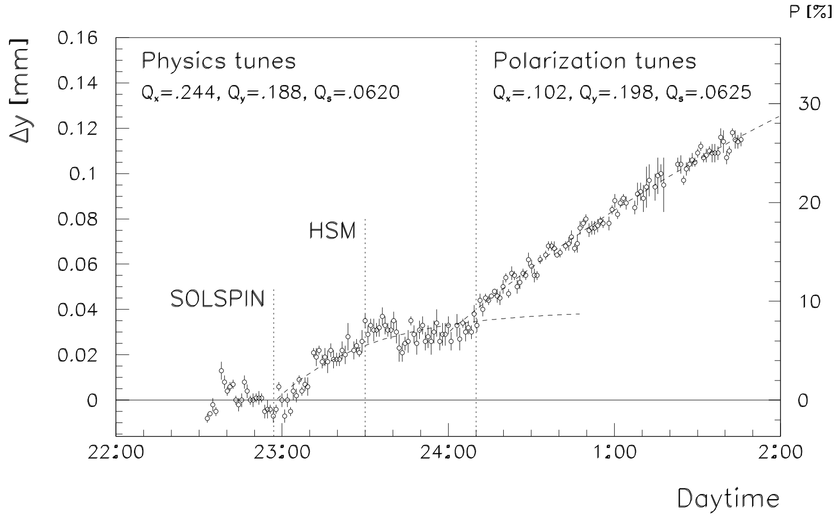


Figure 11: Polarization is shown for two different settings of tunes. With "physics tunes" polarization rose to about 9% after spin matching of the solenoids (SOLSPIN). Harmonic Spin Matching of the vertical closed orbit (HSM) could not improve polarization. After shifting the tunes to the polarization settings polarization rose to 30%.

Resonances with $k + l + m = 1$ are called linear spin resonances. The class of all other resonances is usually referred to as higher order spin resonances. The value of the synchroton tune Q_s is more or less determined by the available RF-voltage and the condition of maximum spacing between synchroton satellites of the integer spin resonances which are the strongest resonances for LEP. Q_s usually was set close to 0.0625.

The betatron tunes can be varied over a wide range. The tunes usually used for polarization experiments are $Q_x = 90.10$ and $Q_y = 76.20$. They are in the following referred to as the polarization tunes. In particular the horizontal tune differs very much from the tune used in physics coasts ($Q_x = 90.26$ typically). For operational energy calibration it is desirable to have polarization at physics tunes.

During two experiments it could be shown that at physics tunes, in particular with a high Q_x, large depolarization occurs. In fig. 11 LEP with "close" to physics tunes and polarization tunes is compared. Whilst only 9% polarization could be observed with physics tunes polarization improved to almost 30% with a much higher asymptotic value when shifting the tunes to the polarization settings. It is remarkable that the Harmonic Spin Matching of the vertical orbit did not improve the polarization with physics tunes. This indicates that the limiting depolarizing resonances are not excited by the harmonic content of the vertical closed orbit.

A more systematic study of the effect of betatron tunes on polarization is shown in fig. 12. With 20% of polarization (still rising) the tunes were changed to physics tunes and polarization decreased to 8-10%. Small changes in Q_x and Q_y could not reestablish high polarization. Then Q_x was changed with the goal to have optimum separation between synchroton satellites of the linear Q_x resonance. Polarization recovered up to 16% with a somewhat smaller asymptotic value of polarization than with polarization tunes (27% instead of 46%).

There are two possible conclusions from these results. Since Q_x is significantly higher for physics tunes, synchroton satellites of the linear Q_x spin resonances are of lower order close to the half integer and are therefore much stronger. They may cause strong depolarization. A possible other cause for the observed depolarization is the Q_x+Q_y higher order spin resonance which would be expected at a spin tune of ≈ 101.48 for the physics tunes. This is very close to the actual spin tune which was ≈ 101.465. The Q_x+Q_y spin resonance is excited by non-linear orbital motion.

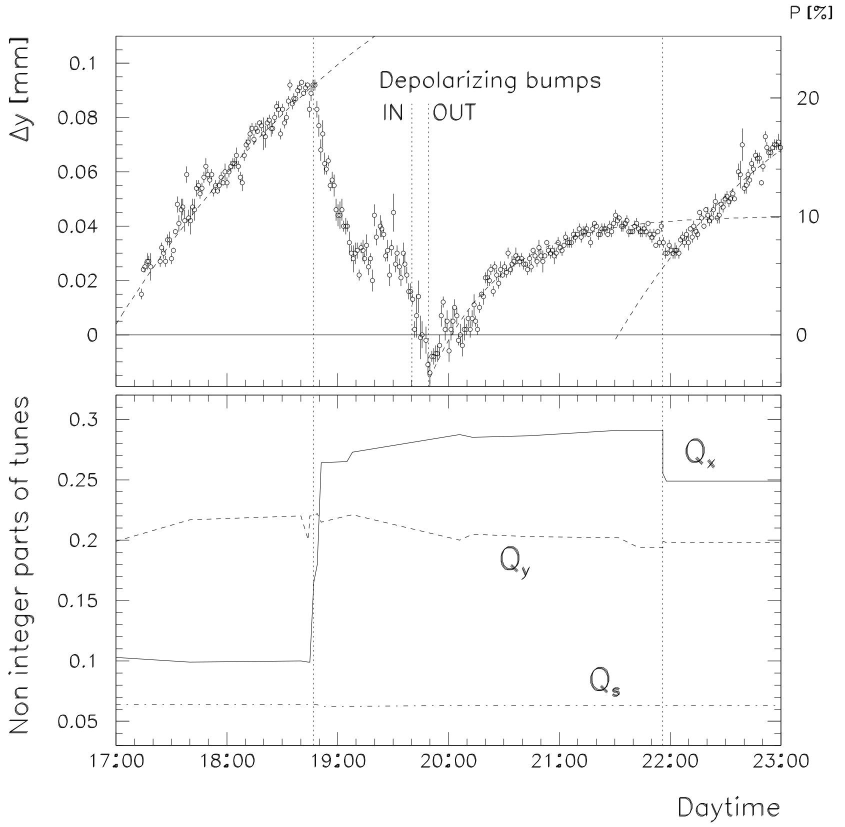


Figure 12: Polarization is shown for different tunes Q_x,Q_y and Q_s. In the beginning polarization above 20% was achieved with polarization tunes. After changing essentially Q_x close to its value in physics coasts polarization degraded to about 8%. The beam was depolarized and the build-up of polarization was measured. When changing Q_x in the end to some other calculated optimum point high polarization came back with a somewhat smaller asymptotic value.

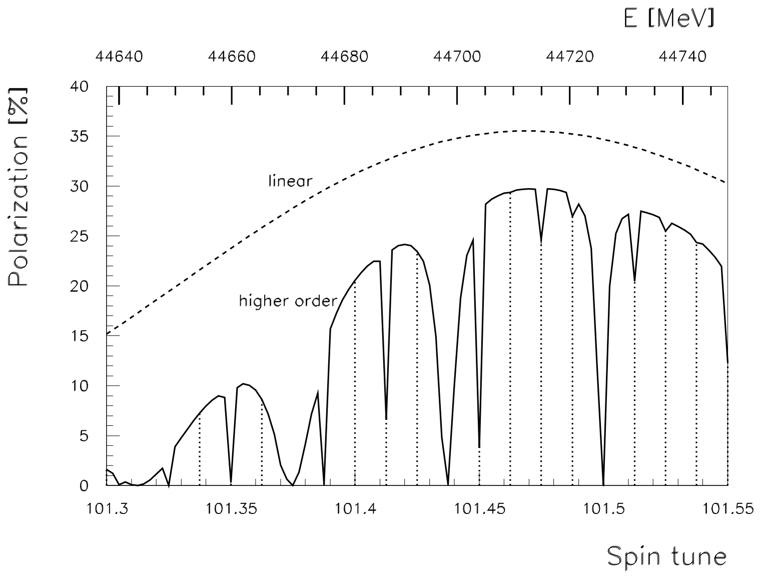


Figure 13: Theoretical calculation of polarization including higher order spin resonances for a realistic LEP with polarization tunes. All possible resonances are marked by dotted lines. The resonance conditions can be looked up in tab. 3. The calculation was done with the SODOM module inside MAD [9, 12]. From [8].

10 Measurement of higher order spin resonances

In eq. 15 the resonance condition for depolarization was given. The calculated pattern of resonances including higher order synchroton satellites is shown in fig. 13 for a realistic LEP model with about 30% polarization around the half integer and polarization tunes (Q_x=90.10, Q_y=76.20, Q_x=0.0625) [8]. All possible spin resonances are marked with dotted lines. The exact resonance conditions for the resonances can be looked up in tab. 3. From fig. 13 it is seen that the synchroton satellites of the integer resonances are strong and appear clearly visible at 101.3125, 101.375, 101.4375 and 101.5. They limit the asymptotic level of polarization. The other higher order spin resonances are weak and their width for the model used for these calculations is smaller than the binning. Due to the restricted knowledge of the "real" LEP their strengths cannot be predicted in detail.

In order to measure higher order spin resonances the spin tune (= beam energy) must be changed in a controlled way. This is done by changing the RF-frequency f_{RF}. The smallest possible change in f_{RF} is 2 Hz which is equivalent to a change of .00310 in spin tune or 1.37 MeV in beam energy (with the energy at peak-2 and a momentum compaction factor $\alpha_c = 1.86 \cdot 10^{-4}$). From fig. 13 it was decided that the sixth order synchroton satellite of 101 at 101.375 is sufficiently broad to be measured in detail with the available resolution in beam energy.

To get close to the selected synchroton satellite f_{RF} was changed in large steps. The spin tune was changed from 101.468 to 101.457, 101.417, 101.405, 101.393 and 101.357 and for each spin tune the energy was calibrated. As expected polarization degraded slowly when going down in energy but no unexpected higher order resonance with sharp depolarization showed up. By following this procedure a precise measurement of the momentum compaction factor α_c was also achieved.

The 101+6$\cdot Q_s$ resonance was measured with the minimum resolution in spin tune. The expected resonance centre was approached by jumping symmetrically from one side of the resonance to the other and measuring each point for at least 10 minutes. Such this measurement could be completed in a short time (2:20 hours) and in one go. That was important to avoid unwanted systematic changes in the spin tune. Here the only expected systematic change comes from the tidal effect but its behaviour is well known and can be taken into account. The fast measurement, however, has the disadvantage that not always the equilibrium degree of polarization could be measured. Therefore the same technique as described for the damping wigglers is used. The "depolarization strength" τ_p/τ_d and the equilibrium degree of polarization is estimated with the measured slope of polarization.

The resonance plot with the "depolarization strength" τ_p/τ_d versus spin tune is shown in fig. 14. Two resonances were measured. The smaller resonance has been detected only with the measured slope whilst the broad resonance was measured explicitly with very small equilibrium polarization values. The shapes of the resonances were fitted with the theoretically expected form:

$$\frac{\tau_p}{\tau_d} = \frac{\varepsilon}{(\nu - \nu_0)^2} + \left(\frac{\tau_p}{\tau_d}\right)_0 . \tag{16}$$

ε is the strength of the resonance, ν_0 the central spin tune of the resonance and $(\tau_p/\tau_d)_0$ is the depolarization from other resonances which is assumed to be constant over the considered range. The results from a combined fit are given in tab. 4.

The broad resonance can be easily identified as the 101+6$\cdot Q_s$ spin resonance. As can be looked up in tab. 3 there are essentially two possibilities for the narrow resonance. It can

Spin Tune	Resonance Condition	Spin Tune	Resonance Condition
101.3125	$101 + 5 \cdot Q_s$ $102 - 11 \cdot Q_s$	101.4375	$101 + 7 \cdot Q_s$ $102 - 9 \cdot Q_s$
101.3250	$101 + Q_y + 2 \cdot Q_s$ $102 + Q_y - 14 \cdot Q_s$ $102 - Q_x - Q_y - 6 \cdot Q_s$	101.4500	$101 + Q_y + 4 \cdot Q_s$ $102 + Q_y - 12 \cdot Q_s$ $102 - Q_x - Q_y - 4 \cdot Q_s$
101.3375	$101 - Q_x + 7 \cdot Q_s$ $101 + Q_x - Q_y + 7 \cdot Q_s$ $102 - Q_x - 9 \cdot Q_s$ $102 + Q_x - Q_y - 9 \cdot Q_s$	101.4625	$101 - Q_x + 9 \cdot Q_s$ $101 + Q_x - Q_y + 9 \cdot Q_s$ $102 - Q_x - 7 \cdot Q_s$ $102 + Q_x - Q_y - 7 \cdot Q_s$
101.3500	$101 + Q_x + 4 \cdot Q_s$ $101 - Q_x + Q_y + 4 \cdot Q_s$ $102 + Q_x - 12 \cdot Q_s$ $102 - Q_x + Q_y - 12 \cdot Q_s$	101.4750	$101 + Q_x + 6 \cdot Q_s$ $101 - Q_x + Q_y + 6 \cdot Q_s$ $102 + Q_x - 10 \cdot Q_s$ $102 - Q_x + Q_y - 10 \cdot Q_s$
101.3625	$101 - Q_y + 9 \cdot Q_s$ $102 - Q_y - 7 \cdot Q_s$ $101 + Q_x + Q_y + Q_s$	101.4875	$101 - Q_y + 11 \cdot Q_s$ $102 - Q_y - 5 \cdot Q_s$ $101 + Q_x + Q_y + 3 \cdot Q_s$
101.3750	$101 + 6 \cdot Q_s$ $102 - 10 \cdot Q_s$	101.5000	$101 + 8 \cdot Q_s$ $102 - 8 \cdot Q_s$
101.3875	$101 + Q_y + 3 \cdot Q_s$ $102 + Q_y - 13 \cdot Q_s$ $102 - Q_x - Q_y - 5 \cdot Q_s$	101.5125	$101 + Q_y + 5 \cdot Q_s$ $102 + Q_y - 11 \cdot Q_s$ $102 - Q_x - Q_y - 3 \cdot Q_s$
101.4000	$101 - Q_x + 8 \cdot Q_s$ $101 + Q_x - Q_y + 8 \cdot Q_s$ $102 - Q_x - 8 \cdot Q_s$ $102 + Q_x - Q_y - 8 \cdot Q_s$	101.5250	$101 - Q_x + 10 \cdot Q_s$ $101 + Q_x - Q_y + 10 \cdot Q_s$ $102 - Q_x - 6 \cdot Q_s$ $102 + Q_x - Q_y - 6 \cdot Q_s$
101.4125	$101 + Q_x + 5 \cdot Q_s$ $101 - Q_x + Q_y + 5 \cdot Q_s$ $102 + Q_x - 11 \cdot Q_s$ $102 - Q_x + Q_y - 11 \cdot Q_s$	101.5375	$101 + Q_x + 7 \cdot Q_s$ $101 - Q_x + Q_y + 7 \cdot Q_s$ $102 + Q_x - 9 \cdot Q_s$ $102 - Q_x + Q_y - 9 \cdot Q_s$
101.4250	$101 - Q_y + 10 \cdot Q_s$ $102 - Q_y - 6 \cdot Q_s$ $101 + Q_x + Q_y + 2 \cdot Q_s$	101.5500	$101 - Q_y + 12 \cdot Q_s$ $102 - Q_y - 4 \cdot Q_s$ $101 + Q_x + Q_y + 4 \cdot Q_s$

Table 3: Spin resonances from fig. 13 with polarization tunes (Q_x=90.10, Q_y=76.20, Q_x=0.0625) and for order 1 in Q_x and Q_y. The spin tunes between these resonances should be save for polarization. Higher order resonances in Q_x and Q_y would appear at the same locations as the given resonances. From [8].

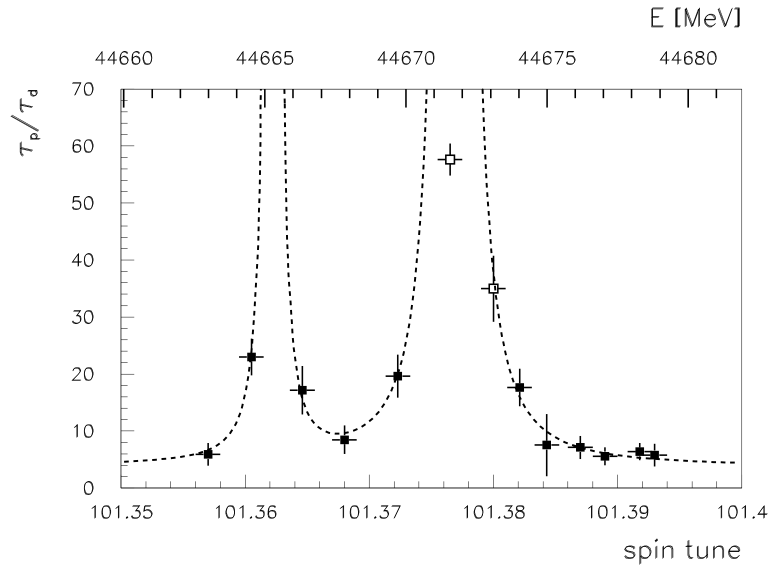


Figure 14: The measured depolarization τ_p/τ_d versus spin tune shows two higher order resonances. The expected theoretical resonant shape was fitted to the filled points. The open points have been excluded from the fit since systematic errors may become very large for high depolarization and low polarization (problem of small polarization offsets and inability to measure extremely large slopes).

$\varepsilon/10^{-4}$	ν_0	ν_{exp}	$\nu_0 - \nu_{\mathrm{exp}}$	$(\tau_p/\tau_d)_0$
3.35 ± 0.71	101.3771 ± 0.0005	101.3750 ± 0.0012	0.0021 ± 0.0013	3.77 ± 1.03
0.57 ± 0.15	101.3623 ± 0.0003	101.3625 ± 0.0014	0.0002 ± 0.0014	⋮

Table 4: Results of a combined fit to the higher order resonances of fig. 14. The fitted central spin tunes ν_0 are compared with the expected spin tunes ν_{exp} assuming that the observed resonances are the 101+6·Q_s and the 101+Q_x+Q_y+Q_s resonance. The accuracies in the tune measurements are assumed to be $\Delta Q_x = \Delta Q_y = .001$ and $\Delta Q_s = .0002$.

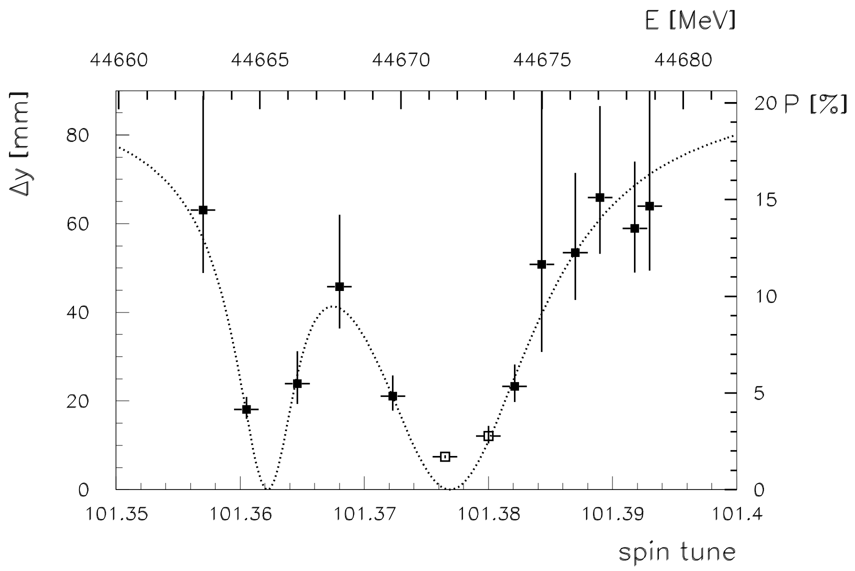


Figure 15: The two higher order spin resonances as seen in equilibrium polarization are shown. This figure is completely equivilant to fig. 14. The large errors for higher polarization result from the limited accuracy for the measured polarization slope and τ_p/τ_d.

be a first order synchroton satellite of the Q_x+Q_y spin resonance or a seventh or ninth order synchroton satellite of a linear Q_y spin resonance. There is a quite conclusive argument against the resonance being a synchroton satellite of a linear Q_y resonance. First it would be of very high order in Q_s which would imply that all Q_y resonances would be unexpectedly strong since they are driven with the RMS vertical dispersion. Then another much stronger synchroton satellite of a linear Q_y resonance with only third order in Q_s should certainly appear at a spin tune of 101.3875 where nothing can be seen in fig. 14. From that it can be concluded that the narrower spin resonance is of type $101+Q_x+Q_y+Q_s$. The two resonances as seen in equilibrium polarization are shown in fig. 15 which is completely equivalant to fig. 14.

In tab. 4 the fitted central spin tunes of the resonances are compared to the expected values as given by the tunes. The accuracy in the expected spin tunes is limited by the errors on the tune measurements. Within better than 1 MeV the resonances have been clearly found were expected from the measured spin tune and the measured machine tunes. The data is compatible with no offset between measured and real spin tune. This is an important result for energy calibration because no significant bias in the spin tune measurement by resonant depolarization was measured. Further more the results prove the important role of synchroton satellites of the integer resonances for polarization and confirm the predictions from theoretical calculations.

11 Harmonic Spin Matching

In a perfect machine almost all spins become aligned parallel to the B field axis and maximum polarization is obtained. In a real machine, however, the particles experience horizontal fields at the quadrupoles and their spins are bent away from the vertical axis. This can cause serious depolarization if the kicks on the spin add up. This is the case if the orbit distortions causing the kicks and the spins precessing around the vertical axis are in phase. The horizontal fields result in a distorted vertical orbit with the orbit distortions being proportional to the vertical kicks from the horizontal fields. The condition for depolarization can therefore be expressed in

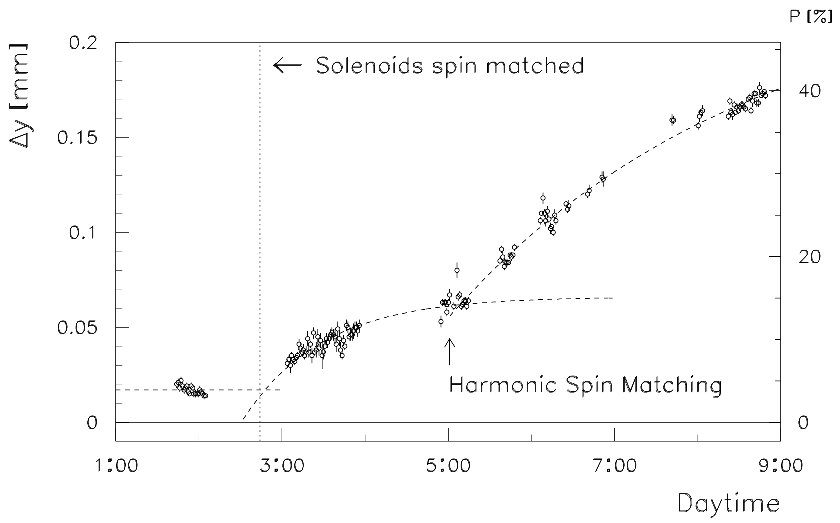


Figure 16: Polarization as a function of time showing the effect of spin matching of the four experimental solenoids and the effect of deterministic Harmonic Spin Matching of the vertical closed orbit for a spin tune of 101.5.

terms of the Fourier spectrum of the vertical closed orbit: Depolarization occurs if the Fourier spectrum of the vertical closed orbit in the frame with uniform spin precession shows strong harmonics close to the spin tune.

Assuming a spin tune ν of 101.5 (number of spin precessions per turn) the harmonics of the vertical closed orbit at 101 and 102 dominate depolarization. But improvement is possible since the vertical orbit harmonics can be compensated with vertical closed orbit bumps. They are in fact small spin rotators which rotate the spins back to the vertical axis. This procedure is well known, was studied for LEP in [14] and has been very successfully applied at PETRA [15] and HERA [16] where, however, the harmonics where found by trial and error. Doing it by trial and error Harmonic Spin Matching is a very lengthy procedure (several days at HERA) and would not be possible at LEP on a reasonable time scale.

Having this in mind the possibility of doing Harmonic Spin Matching for LEP in a deterministic way was studied [2]. The term deterministic in this context means that the relevant harmonics are extracted directly from the measured vertical closed orbit and are used to calculate the orbit bumps needed to increase polarization. The studies showed that at least polarization higher than 30% could be achieved by deterministic Harmonic Spin Matching and the improvements to the BOM system and the quadrupole alignment during the LEP winter shutdown 92/93. A software package was prepared for the LEP startup.

Already in the first polarization experiment deterministic HSM was tried successfully and polarization could be increased from 8% to more than 30%. Its clear effect on polarization has already been shown in fig. 3 for a spin tune of 105.5 with the harmonics 105 and 106 compensated. Another example is shown in fig. 16 for a spin tune of 101.5 and the harmonics 101 and 102 compensated.

On three occasions the improvement of polarization with deterministic HSM could be proven directly. After being sure about its beneficial effect on polarization it was used routinely for all polarization measurements. Fig. 17 shows all measured polarization degrees from the start of transverse polarization at LEP in 1990 up to now (excluding all energy calibration runs at end of physics coasts in 1993). A clear improvement of measured polarization by about a factor of three in 1993 compared to the previous years is seen. However, the potential is much higher. Once polarization was measured at an equilibrium degree of 57%. Most of the measured polarization degrees with HSM have not been the equilibrium values. At the time

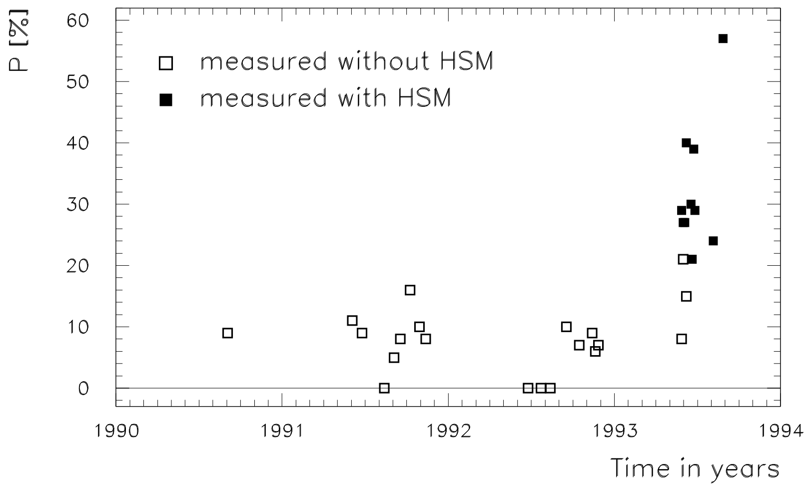


Figure 17: All measured maximum polarization degrees are shown from the beginning of transverse polarization at LEP in 1990 up to now. Polarization measurements from operational energy calibrations in 1993 are not included. Watch out: The measured polarization for 1993 with Harmonic Spin Matching (HSM) is often much lower than its estimated equilibrium value.

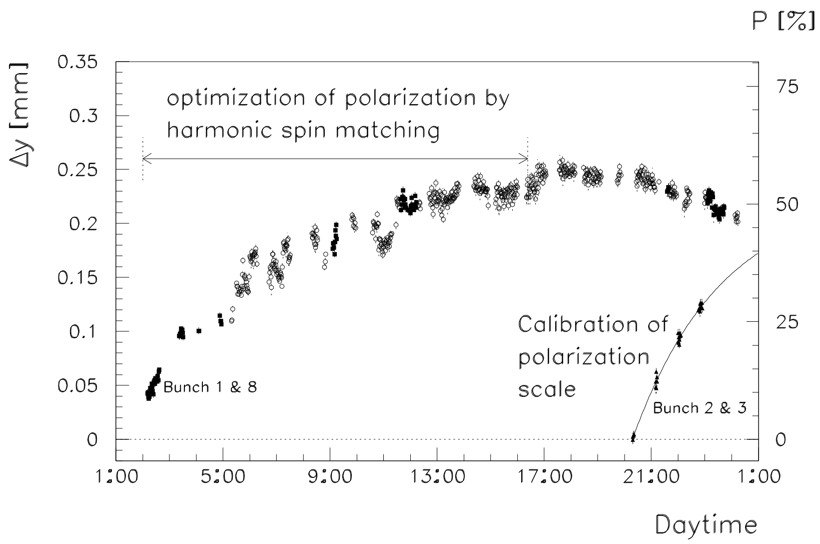


Figure 18: The temperature experiment with the polarization record of 57% is shown. Polarization was optimized by Harmonic Spin Matching. At the end of the experiment the polarization scale was calibrated.

when the maximum polarization was measured the polarization was still rising but could not be followed. The estimated asymptotic polarization values are much higher than the measured ones (three points would go to about 50% and higher) and can be looked up in tab. 1.

Record polarization up to now has been $(57 \pm 3)\%$ with a spin tune of 101.5. It has been achieved during an experiment dedicated to measure how the LEP beam energy depends on the temperature of the bending magnets. The polarization during that experiment is shown in fig. 18. Close to the end of the experiment the rise time of polarization build-up was measured. Since the time of zero polarization and the equilibrium degree of polarization are known a precise calibration of the polarization scale could be done with the assumption of an adiabatic loss of polarization towards the end of the experiment.

In the following Harmonic Spin Matching shall be illustrated in more detail for this case of record polarization. Fig. 19 shows the measured vertical closed orbit after final standard corrections. The integrated bending angle per cell is shown because it is the periodic variable for the Fourier analysis (selecting the frame where the spin precession is uniform). The Fourier spectrum obtained before and after sending the calculated orbit bumps for HSM is shown

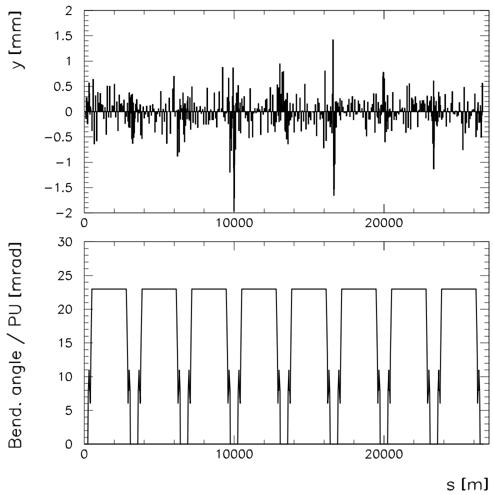


Figure 19: Top: Vertical closed orbit before HSM. Bottom: The bending angle per cell is the periodic variable of the Fourier analysis.

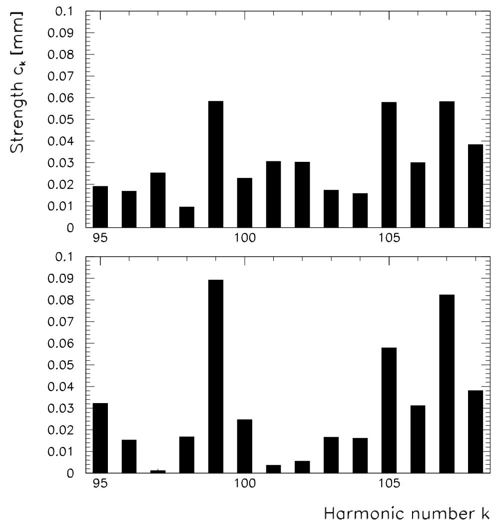


Figure 20: Fourier spectrum before (top) and after (bottom) HSM.

in fig. 20. The harmonics 101 and 102 before HSM can be used to predict polarization for perfect BOM and no quadrupole misalignment. Neglecting all other sources of depolarization (dispersion, coupling, misalignment, ...) polarization is predicted to be about 30% from fig. 21 by using higher order theory. Realistically some lower value (20% - 25%) must be expected.

After the HSM bumps have been applied the harmonics were almost cancelled completely in the Fourier spectrum as can be seen in fig. 20. The expected polarization for the idealised case was now higher than 85% and there was obviously no room for further deterministic improvement. At that point empirical improvements of HSM have been tried for the only time up to now. A single harmonic was changed and the change in polarization was observed. The history of changes to the four harmonics (Sine and Cosine) is shown in fig. 22. A further improvement of polarization could be achieved. Coming experiments will use an improved strategy and even higher polarization can be expected [17].

12 Polarization at the end of physics coasts

Regular and precise energy calibration at the end of physics coasts is needed in 1993 to improve the knowledge of the Z mass and the width of the Z resonance. During energy calibration runs polarization of about 10% was found at peak (103.5) and peak+2 (105.5) and polarization above 25% was found at peak-2 (101.5). The main difference to the MD-results is that Pretzel is always on during energy calibrations at the end of physics.

It was already mentioned that the solenoid spin matching bumps (SOLSPIN) produce coupling which potentially causes depolarization. This effect is worse for large horizontal orbit deviations as they are produced with Pretzel. Even worse at $106 = Q_x + 2{\cdot}8$ a subset of the spin resonances is systematically excited. This may be the reason for the reduced polarization at 105.5. 103.5 is close to $104 = Q_y + 7{\cdot}4$ where the Q_y and Q_s resonances are systematically excited, driven by the vertical dispersion. These kinds of systematic integer spin resonances

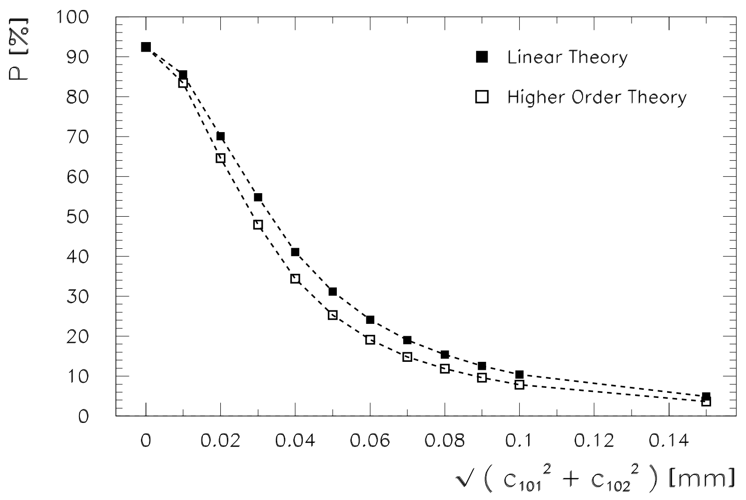


Figure 21: Polarization versus strength of the two neighbouring harmonics of the vertical closed orbit. It is assumed that the spin tune is close to the half integer 101.5. The dependence has been calculated with linear and higher order theory from SODOM. From [8].

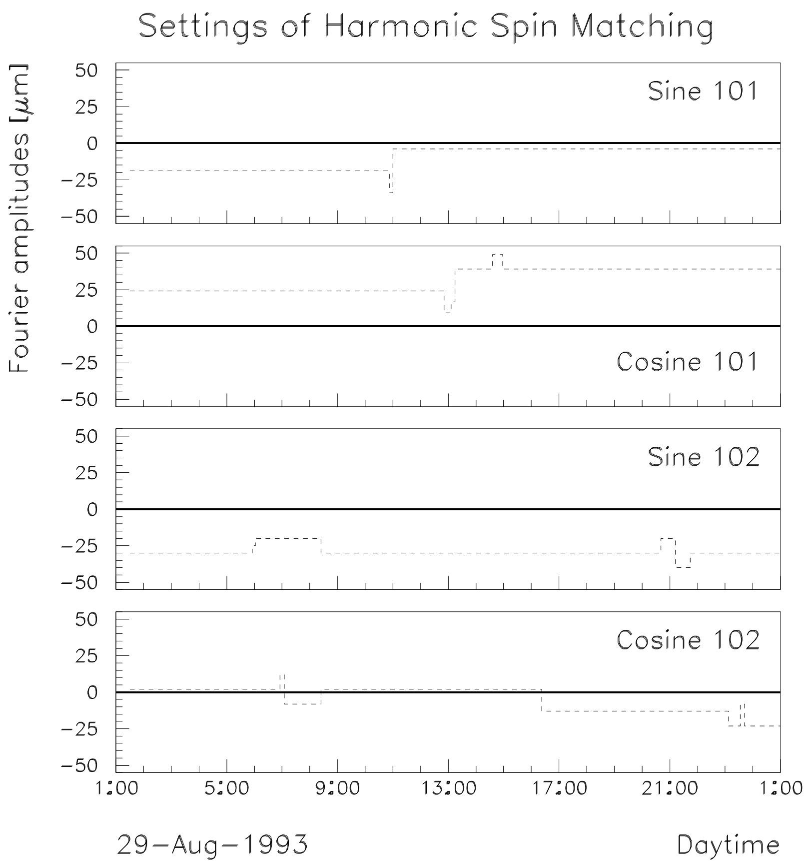


Figure 22: Strength of the compensated harmonics during the temperature experiment versus time. In the beginning the measured harmonics were compensated with deterministic Harmonic Spin Matching. Later on the harmonics were changed empirically to see changes in polarization and to optimise further.

are discussed more detailed in [18]. A spin tune 101.5 is safe and so it is expected that it yields the best polarization.

It is possible to reduce the depolarizing effects from the pretzel by a dedicated coupling compensation and a better closure of the SOLSPIN bumps.

13 Energy calibration

We will illustrate the principle of energy calibration with resonant depolarization and present results on systematic effects in spin tune measurements at LEP. The actual measurements and their connection to reference information is described elsewhere [19].

An important use of transverse beam polarization in 1993 is the precise calibration of the LEP beam energy. The number of spin precessions per turn, the spin tune ν, is proportional to E. If the spin tune is measured the beam energy is known.

13.1 Spin tune measurement

The spin tune can be measured very precisely by "kicking" the particle spins with an oscillating horizontal field. If the frequency of the perturbing field is in phase with the spin precession frequency the kicks add up, a very sharp depolarization occurs and the polarization can even become negative. Otherwise no polarization is lost. With the knowledge of the "kicking frequency" at which depolarization occurs the spin tune ν and the beam energy E follow straight away. It is very convenient for energy calibration that a single bunch can be depolarized selectively leaving the polarization of all other bunches unchanged.

At LEP the perturbing horizontal field is in practice not operated with a single fixed frequency. The frequency of the perturbing field is slowly varied in a given range. The width of range which is chosen determines the accuracy of the spin tune measurement. The used width in a standard energy calibration is .002 in spin tune or 0.9 MeV in beam energy. Fig. 23 shows an example of energy calibration. Three "scans" from .474 to .480 (= non-integer part of the spin tune) with the standard width in frequency range locate the non-integer part of the spin tune clearly between .476 and .478. The polarization was even flipped. Halfing the width of the scan a spin flip in polarization from 35% to -13% was found in .476 to .477. The negative polarization of that bunch was proved to be real by depolarizing it again. However, the spin tune could not precisely be located in .476 to .477 since depolarization also occurred in .477 to .478.

With the assumption of equal bunch energies this points at a limit in the accuracy of the spin tune measurement imposed by the width of the excited depolarizing resonance. For the example in fig. 23 the width of the resonance was seen during energy calibration on a level of .45 MeV.

13.2 Width of excited depolarizing spin resonance

When trying to calibrate the beam energy by resonant depolarization an artificial spin resonance at some known spin tune is excited. If the average spin tune of the particles is inside this resonance the beam is depolarized. Since the excited spin resonance has some width the reachable accuracy of spin tune measurement is limited.

The width of the excited depolarizing spin resonance was explicitly measured with a reduced bin width $\Delta\nu$ of .0005 in spin tune or .22 MeV in beam energy (1/4 times the usual). The stan-

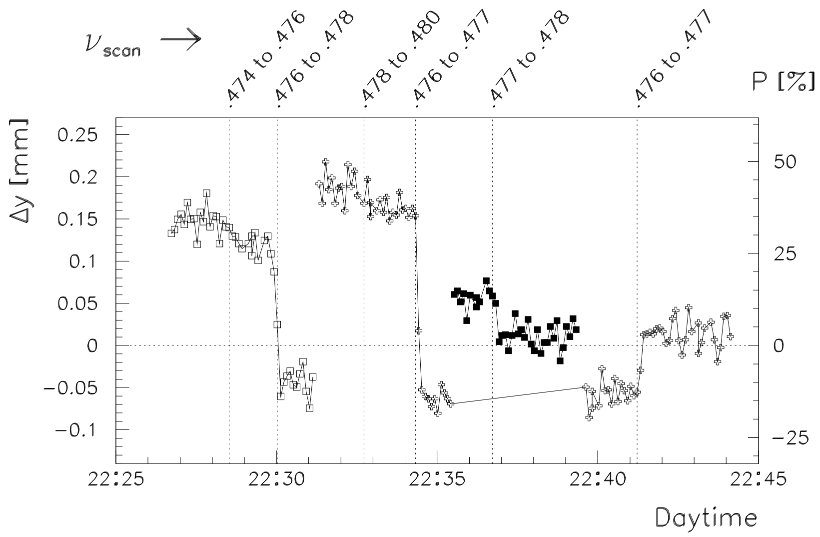
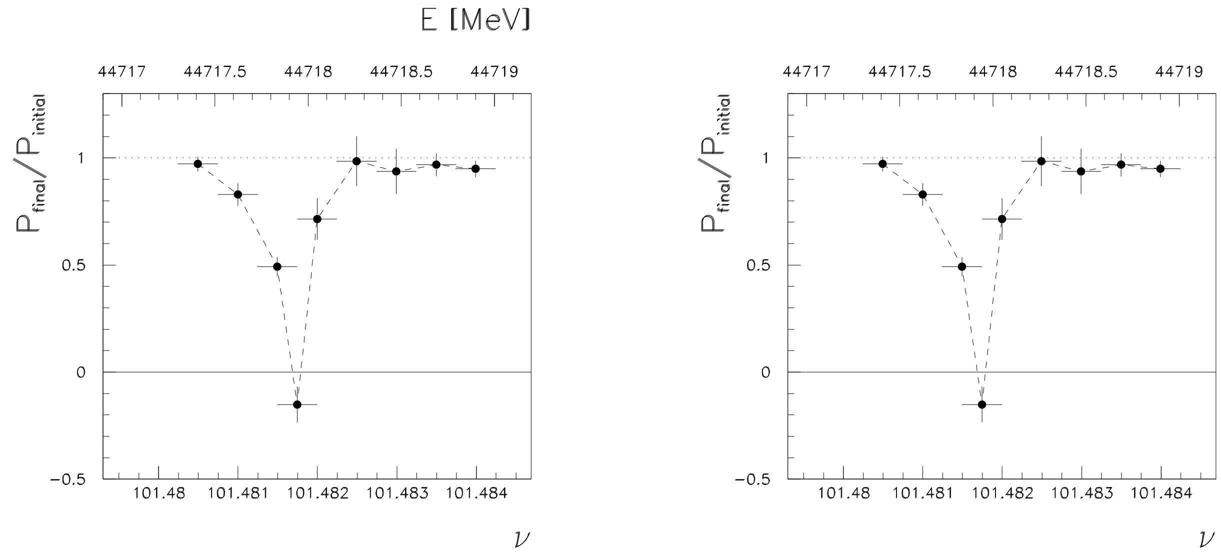


Figure 23: Example of energy calibration. Several bunches are used to measure the non-integer part of the spin tune. Spin flip to negative polarization was observed and checked by depolarization to zero.



(a) $\Delta\nu/\Delta t = 1.67 \cdot 10^{-4} s^{-1}$ (standard settings).

(b) $\Delta\nu/\Delta t = 4.17 \cdot 10^{-5} s^{-1}$.

Figure 24: Two measurements of the artificially excited spin resonance which is used for energy calibration are shown. Case (a) corresponds to a standard energy calibration. The slightly asymmetric resonance shape is due to tidal changes of the beam energy during the 12 minutes of measurement. In case (b) the slope of spin tune change with time is four times smaller and the resonance is excited much more. In this case different bunches were used to measure the resonance. They are marked by different symbols.

dard strength of the kicker ($0.2 \cdot 10^{-3}$ Tm) was used. The change in polarization $P_{final}/P_{initial}$ was then measured as a function of spin tune.

Two cases of slope of spin tune change with time $\Delta\nu/\Delta t$ were considered. The case (a) in fig. 24 was measured for the same parameters as used in a standard energy calibration. The FWHM of the resonance is 0.2 MEV. This width is sufficiently small for practical purposes of energy calibration where a precision of about 1 MeV is needed. At the same time the depolarization is strong enough to be observed easily.

Case (b) in fig. 24 was measured with a slope of spin tune change with time which was 4 times smaller than the standard value. That means that the kicking frequency is 4 times longer in phase with the precessing spin vectors than for the standard settings. As expected it was observed that the spin resonance in this case is excited much stronger. Its FWHM now is 0.8 MeV which is 4 times as much as with the standard settings. Slight differences of the beam energy for the different bunches might have caused the irregular shape of the bottom part of the resonance.

13.3 Mirror ambiguity, synchroton satellites and interference of resonances

To determine the energy two more measurements are required. Energy calibration with resonant depolarization cannot give any information whether the spin tune is above or below the half integer. A measured non-integer part of spin tune of .45 is compatible with a mirrored spin tune of .55 (1.00−.45). This so called "mirror ambiguity" must be solved by changing the beam energy with a RF-frequency change and by measuring the direction of change in measured spin tune.

Depolarization occurs also on a synchroton satellite of the spin tune. These satellites can be found at a distance Q_s in spin tune. The criterium which must be fulfilled for the main resonance is that it may not be shifted by changing the synchroton tune Q_s.

A complete example of energy calibration including all checks is shown in fig. 25. The measured spin tune at 5:35 h was taken as reference and the expected spin tune at other times was extrapolated including the effects from tides and magnet temperatures (solid line). The jumps in the spin tune ν have been caused by changes in the RF-frequency. The synchroton sideband at $-Q_s$ and the mirrored sideband from $+Q_s$ are also given. Additional steps for the sidebands indicate changes of Q_s. The measured spin tune follows nicely the expected curve. However, when the spin tune was closer to 101.5 only partial depolarization or no depolarization at all could be observed. Closer to the $8 \cdot Q_s$ sideband of the integer resonances 101 and 102 the spin motion is perturbed in such a way that artificial depolarization becomes harder and even impossible. This observation could be confirmed at another occasion.

Despite of this effect no shift in measured spin tune is observed. A significant bias of the spin tune measurements coming from an interference between the artificial depolarizer resonance and other strong spin resonances cannot be seen. It can be excluded when recalling the results for the higher-order spin resonances. It was shown that the $6 \cdot Q_s$ synchroton satellite was found within 1 MeV where expected from the measured spin tune. Further more the measured change of spin tune with the RF-frequency followed the expected linear behaviour with a momentum compaction factor α_c of $1.87 \cdot 10^{-}4$ which exactly matches the theoretical value for LEP when assuming realistic imperfections. Any significant interference with spin resonances would have disturbed this linear behaviour since the spin tune was changed from a very symmetrical pattern of spin resonances (half-integer) to a very asymmetric case.

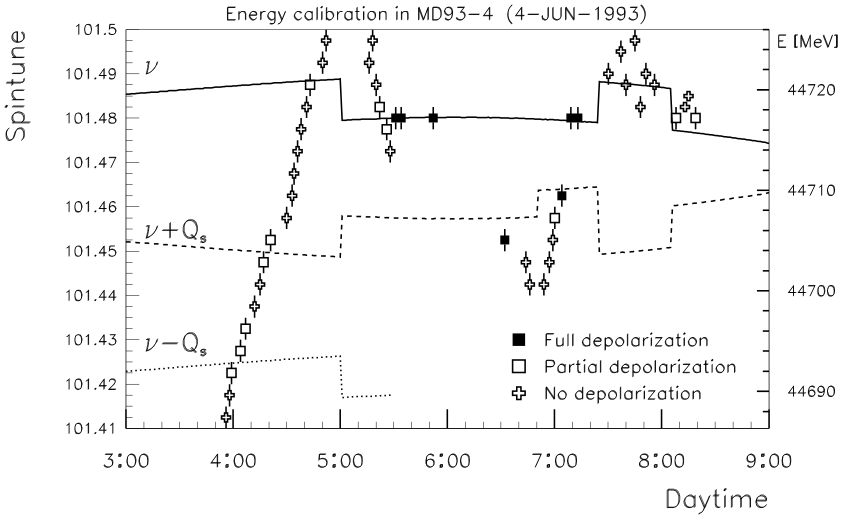


Figure 25: A complete example of energy calibration including checks for the mirror ambiguity and the synchroton satellites. The expected spin tune ν is extrapolated from the measurements at 5:35 h including tide and temperature effects.

13.4 Spin tune shifts due to imperfections

Usually it is assumed that the spin tune ν of the particles is a multiple of the beam energy E ($\nu = \mathrm{const}\cdot\mathrm{E}$). However, it has been shown that spin tune shifts can occur due to horizontal fields at the quadrupoles [20]. Those horizontal fields are caused by the vertical closed orbit and produce rotations that do not commute. With a large number of small rotations a spin tune shift ε can result with an expected RMS value of the order of 0.5 MeV. The exact spin tune shift depends on the vertical closed orbit and does not correspond to any change in the real beam energy E:

$$\nu = \mathrm{const}\cdot\mathrm{E} + \varepsilon(\text{vertical orbit}) \tag{17}$$

With the assumption of equal energies for the different bunches a spin tune shift after a change in the vertical closed orbit was seen during the energy calibration in fill 1811 . When the vertical orbit was corrected from a RMS-difference of 0.66 mm down to better than 0.29 mm a change in spin tune of .45 MeV to 1.35 MeV was measured. This effect has to be studied further.

14 Conclusions

- The performance of the polarimeter could be improved significantly resulting in a much shorter set-up time and better resolution than in 1992.
- The polarization scale could be determined with a relative accuracy of 4.8%.
- All four experimental solenoids could be successfully spin matched.
- No loss in polarization was observed with a squeezed optics.
- The effect of damping wigglers on polarization was studied in detail. With full power the damping wigglers destroy polarization. But it should be possible to gain a factor of 1.8 in the polarization build-up time with the damping wigglers at 0.6 Tm.

- The effect of the betatron tunes on polarization was studied. It is not possible to get high polarization with physics tunes. However, betatron tunes close to physics with polarization above 20% have been established.
- Two higher order spin resonances were measured. Within 1 MeV they have been found where expected from the measured beam energy and the measured tunes. That is compatible with no bias for energy calibration with resonant depolarization.
- The strength of the measured $101+6 \cdot Q_s$ resonance confirms qualitatively theoretical calculations and shows that radiative polarization at LEP is limited by the synchroton satellites of the integer spin resonances.
- The measured effect from the Q_x+Q_y resonance on polarization points at the importance of non-linear orbital motion for polarization at LEP.
- Due to tidal effects on the LEP beam energy a higher order spin resonance in Q_x was crossed with more than 50% polarization without any visible loss in polarization.
- The momentum compaction factor α_c was measured with very good accuracy to be $1.87 \cdot 10^{-4}$.
- A powerful procedure of deterministic Harmonic Spin Matching has been implemented and successfully used. A maximum measured polarization of 57% has been achieved and depolarization could be reduced by more than a factor of 10 when compared to 1992.
- The vertical dispersion did not limit polarization below 57%. Harmonic Spin Matching of the vertical dispersion is obviously not needed at LEP to obtain this level of polarization.
- Polarization at the end of physics coasts with Pretzel on and reduced time for machine set-up was successfully established for all three energies with LEP operation in 1993.
- Operational energy calibration was successfully commissioned.
- Several systematic errors on the spin tune measurements have been checked to be smaller than 1 MeV. In particular the width of the imposed depolarizing resonance was shown to be smaller than 1 MeV with standard settings for energy calibration.
- A possible small spin tune shift has been observed but must be studied further.

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