# Deterministic Harmonic Spin Matching in LEP

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*Abstract*

Spontaneous spin polarization is observed at LEP with the highest beam energy so far. As depolarizing effects become more severe with increasing energy special efforts must be taken to achieve a high polarization degree. In LEP it was improved during 1993 from below 20% to almost 60% with a well established method called "Harmonic Spin Matching". The implementation is improved at LEP by using orbit bumps instead of orbit oscillations and by doing a harmonic analysis of the measured closed orbit. Up to some accuracy the strengths of the depolarizing spin resonances can thus be calculated directly from the vertical orbit and Harmonic Spin Matching can be done routinely in a deterministic and fast way.

## 1 INTRODUCTION

With higher beam energies the unavoidable machine imperfections decrease the asymptotic polarization level below its maximum of 92.4%. In order to keep imperfections small, a vertical realignment of all quadrupoles in LEP was done during the winter shutdown 92/93. The remaining imperfections are compensated to some extent by the closed orbit correction. The expected polarization for LEP after the realignment is shown in fig. 1 for a well corrected closed orbit. Since the natural polarization degree is limited to about 25% a specific compensation of the spin resonances is required.

## 2 HARMONIC SPIN MATCHING

### 2.1 *Principle*

The well known technique of Harmonic Spin Matching [4, 5, 6] relies on the fact that the strengths of most depolarizing spin resonances are proportional to the strengths of the integer spin resonances (also called imperfection resonances). They are related to the dipole imperfections seen by the particles, which are reflected in the disturbed closed orbit. $y_i$ is the vertical displacement of the closed orbit in the quadrupole $i$. For $N$ quadrupoles the following Fourier spectrum is considered:

$$a_k = \frac{1}{\pi}\sum_{i=1}^{N} y_i \cos\left[k\alpha_i\right]\delta\alpha_i$$

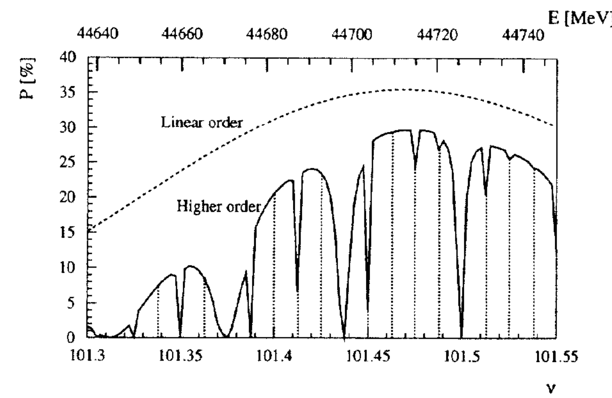


Figure 1: Calculated polarization degree $P$ as a function of the spin tune $\nu = a\gamma$. The calculations include higher order spin resonances and was done for a realistic LEP model with polarization tunes ($Q_x = 90.10, Q_y = 76.20, Q_s = 0.0625$). All possible resonances apart from those clearly showing up are marked by dotted lines. The calculation was done with the SODOM module inside MAD [1, 2].

$$b_k = \frac{1}{\pi}\sum_{i=1}^{N} y_i \sin\left[k\alpha_i\right]\delta\alpha_i$$

$$c_k = \sqrt{a_k^2 + b_k^2}$$

where $k$ is the harmonic number of the Fourier spectrum. The bending angle $\alpha$ is the periodic variable of the Fourier analysis. This corresponds to the frame with uniform spin precession. $\alpha_i$ is the integrated bending angle, whilst $\delta\alpha_i$ is its change at the quadrupole $i$. $\delta\alpha_i$ is defined as:

$$\delta\alpha_i = \frac{\alpha_{i+1} - \alpha_{i-1}}{2}.$$

such minimizing disturbing effects, caused by the irregular bending angle in the transition from the arcs into the straight sections of LEP. One can show that the depolarization $\tau_p/\tau_d$ in high energy synchrotrons is to a good approximation determined by the Fourier strengths $c_k$ [7, 3]:

$$\frac{\tau_p}{\tau_d} \propto \nu^2 \sum_k \frac{|c_k|^2}{(\nu - k)^4} \qquad (1)$$

The given formula is only valid in a linear approximation. It assumes that $Q_s$ is small and that the synchrotron oscillations of the particles dominate depolarization. If the

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| Source | 1992 | | 1993 | |
|---|---|---|---|---|
| | Size | $\sigma_k$ | Size | $\sigma_k$ |
| $\sigma(\Delta y^{\mathrm{PU}})$ | 0.30 mm | 24.3 | 0.15 mm | 12.2 |
| $\sigma(\Delta y^{\mathrm{QUAD}})$ | 0.45 mm | 28.4 | 0.15 mm | 9.5 |
| $N_{\mathrm{miss}}$ | 50 | 22.6 | 15 | 3.6 |
| $\sigma_y^{\mathrm{PU}}$ | 0.70 mm | | 0.35 mm | |
| $\sigma_k^{\mathrm{tot}}$ | 44 $\mu$m | | 16 $\mu$m | |
| $\sqrt{2\sigma_k + 2\sigma_{k+1}}$ | 88 $\mu$m | | 32 $\mu$m | |
| $P_{\mathrm{HSM}}$ | 13% | | 51% | |

Table 1: Expected resolution $\sigma_k$ in $\mu$m for each $a_k$ and $b_k$. The different sources of errors in LEP are compared for 1992 and 1993.

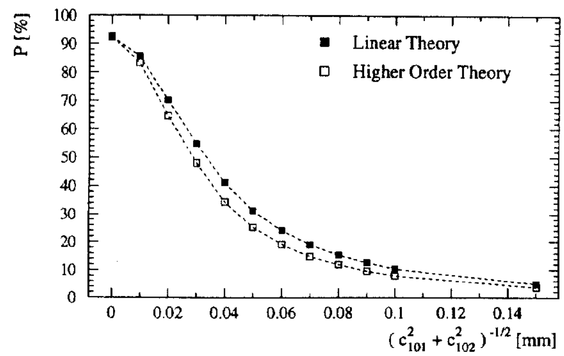


Figure 2: Polarization versus strength of the two neighbouring harmonics of the vertical closed orbit. It is assumed that the spin tune is close to the half integer 101.5. The dependence has been calculated with linear and higher order theory from SODOM. From [3].

spin tune $\nu$ is set close to the half-integer $k_0 + 0.5$ then only the two closest vertical orbit harmonics $c_{k_0}$ and $c_{k_0+1}$ contribute significantly to the depolarization. The equilibrium polarization $P$ is obtained from:

$$P = \frac{92.4\%}{1 + \tau_p/\tau_d}$$

In fig. 2 the polarization is shown as a function of the strengths of the two nearest resonances. If the depolarization strength is considered, the calculated polarization follows exactly the linear relation from eq. 1.

## 2.2 Measured Fourier spectrum

The $y_i$ are measured with the beam position monitors (pickups) at the vertically focusing quadrupoles. The calculated Fourier coefficients $a_k$ and $b_k$ have certain errors $\sigma_k$. Those errors depend on the pickup reading errors $\sigma(\Delta y^{\mathrm{PU}})$, the vertical quadrupole misalignment $\sigma(\Delta y^{\mathrm{QUAD}})$, the number $N_{\mathrm{miss}}$ of missing pickups and the measured vertical RMS orbit deviation $\sigma_y^{\mathrm{PU}}$. The errors were studied in detail in [3] and they are summarized in table 1 for 1992 and 1993 parameters. If the measured $a_k$ and $b_k$ are eliminated to the given accuracy a polarization degree of $P_{\mathrm{HSM}} = 51\%$ was expected for 1993. This must be compared to an expected polarization of 13% for 1992, thus clearly demonstrating the beneficial effect from the realignment of the quadrupoles and the improved accuracy and reliability of the pickups.

A measured Fourier spectrum is shown in fig. 3 at the top. Since the spin tune was at about 101.5 the strengths of the harmonics 101 and 102 can be used to predict the expected polarization from fig. 2. Before HSM, the polarization is expected to be about 30% in higher order theory.

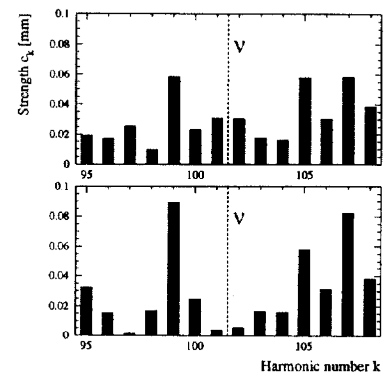


Figure 3: Measured Fourier spectrum before (top) and after (bottom) Harmonic Spin Matching.

## 2.3 Harmonic compensation

From the measured Fourier spectrum a pattern of 8 vertical closed orbit bumps is calculated to compensate exactly one of the harmonics. The symmetry of the pattern is chosen such as not to perturb the three near-by harmonics. The spectrum of the corrected orbit is shown in fig. 3 at the bottom after applying the calculated orbit bumps for the two closest harmonics. After application of the HSM bumps the harmonics were almost cancelled in the Fourier spectrum as can be seen in fig. 3. The expected polarization for the idealised case is now higher than 85% and there is no room for further deterministic improvement by this method.

Being implemented in the control room software the whole procedure of deterministic Harmonic Spin Matching takes less than 5 minutes. Its effect on polarization is shown in fig. 4. From fig. 5 it is seen that polarization could always be improved to more than 35% in 1993 with the average around 50%. The maximum measured polarization is shown in fig. 6. After further empirical improvements a polarization degree of 57% ± 3% was measured.

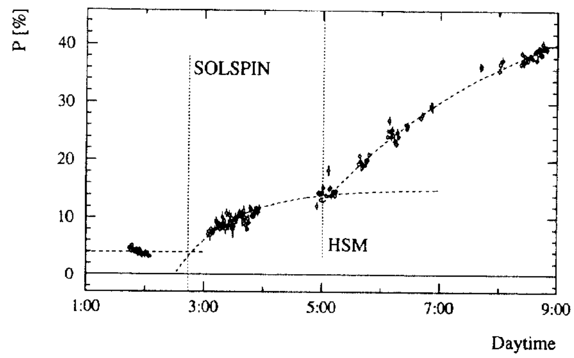


Figure 4: Measured polarization as a function of time showing the effect of spin matching of the four experimental solenoids (SOLSPIN) and the effect of deterministic Harmonic Spin Matching (HSM) of the vertical closed orbit for a spin tune of 101.5.

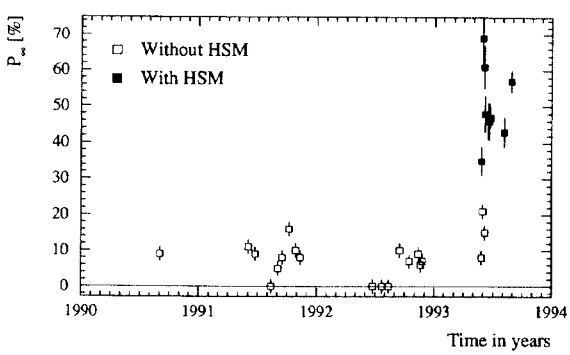


Figure 5: Achieved equilibrium polarization degrees $P_\infty$ are shown from the beginning of transverse polarization at LEP in 1990 up to now. Most polarization measurements from operational energy calibrations in 1993 are not included.

## 3 CONCLUSION

Transverse beam polarization was effectively optimized in LEP by a deterministic approach of Harmonic Spin Matching. The transverse polarization degree could routinely be optimized, yielding an average polarization of about 50% after deterministic Harmonic Spin Matching. Vertical dispersion is estimated to limit the obtainable polarization at about 70%.


## 4 ACKNOWLEDGEMENTS

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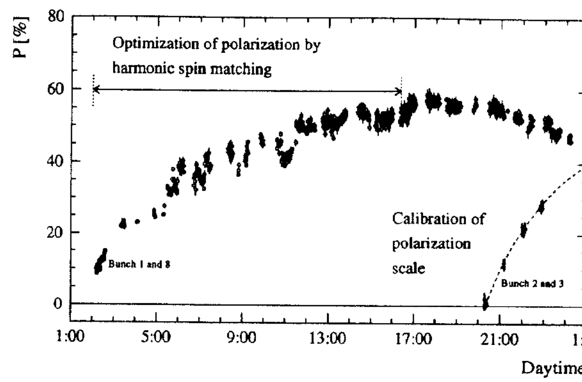


Figure 6: The experiment with the maximum measured polarization of 57% ± 3% is shown. Polarization was optimized with deterministic and empirical Harmonic Spin Matching. At the end of the experiment the polarization scale of the polarimeter was calibrated.

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