Presentation 50

Optimisation of Transverse Polarisation

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50.1 Introduction

The energy calibration to very high accuracy which is requested by the physics community requires the beams to be polarised. The principle is to depolarise the beam with an RF transverse magnetic field. The beam responds to this field only if there is a particular relationship between the frequency of the excitation and the beam energy. In principle, the potential of the method is better than the stability of LEP. The prerequisite is of course to polarise the LEP beam at a sufficient level. Although this method of energy calibration is routinely used in small energy machine, it is a challenge for LEP.

The beams get spontaneously polarised along the direction of the guide field by rare events where the emission of a photon is accompanied by a spin flip. Any magnetic field which is not along the guide field produces depolarisation. The depolarising mechanisms are proportional to the square of the beam energy at least. The predictions of the polarisation level are difficult: this is why the possibility of polarising the LEP beams has been the object of much debate and calculations.

The positive result of last year's experiment gives confidence in the model which predicts high polarisation of the LEP beams once the depolarising resonances are carefully compensated.

50.2 Depolarisation sources

If all the magnetic elements are perfect and perfectly aligned, the beam motion is almost perfectly in the horizontal plane, in the absence of solenoids. Any vertical displacement of the beam will cause the spin to rotate away from the vertical when feeling the transverse field of the quadrupoles.

A vertical displacement of the beam may arise from:

- an imperfect vertical closed orbit,
- a vertical betatron oscillation arising from coupling,
- a vertical betatron oscillation due to the emission of Synchrotron Radiation (SR) photons at places where there is a spurious vertical dispersion,
- the synchrotron oscillation coupled to a spurious vertical dispersion,...

The primary source is the vertical closed orbit, and, for LEP, the skew fields arising from the Ni effect.

The following data illustrate the sensitivity of the spin: if the LEP orbit was perfect, in the absence of Ni, the polarisation would reach the maximum of 92.4 %. With a 1 mm r.m.s. vertical orbit deviation, the beam is almost totally depolarised. The polarisation level does not vary linearly with the orbit.

The asymptotic polarisation level is given by a closed formula (Derbenev-Kondratenko) which can be summarised as follows:

$$P \approx \frac{92.4\%}{1+\gamma^2|\vec{\Gamma'}|^2}$$

$\gamma\vec{\Gamma'}$ is called the spin-orbit coupling vector. $\vec{\Gamma'}$ depends on:

- the three emittances. The dependence on the longitudinal emittance is especially important for LEP.
- the linear optics and orbits,
- the non-linear optics,
- the spin kinematics.

$\vec{\Gamma'}$ exhibits a resonant behaviour whenever

$$\nu + k_x Q_x + k_y Q_y + k_s Q_s = k, \qquad k \in \mathcal{Z}$$

ν is the spin tune, or number of spin precessions per revolution. Unlike the betatron and synchrotron tunes Q_x, Q_y, Q_s, it is energy dependent and equal to 103.5 at the Z^0 energy. On or close to the resonances, the beam polarisation disappears.

Maximising the polarisation levels means:

- correcting the vertical orbit, dispersion and more generally optics as far as possible,
- searching an optimum position in the tune diagram,
- weakening or compensating the near-by spin resonances which are unavoidable.

For these three headings, we will analyse what is necessary to go beyond what has been already achieved.

50.3 Correction of the optics

50.3.1 The closed orbit

The best result achieved so far is an r.m.s. of the vertical orbit of 0.53 mm. Similar results were achieved in all machine experiments dedicated to polarisation. For the time being, the essential limitation seems to be the time required to correct the orbit. It should be pointed out that a large number of correctors were used.

50.3.2 Orbit measurement

In the absence of flexible software, the way to improve the accuracy of the measurement is to average several measurements. This also allows the averaging of a possible residual coherent oscillation. Unfortunately, ECA's are often missing due to time-outs. The averaged measurement misses all the ECA's which may have been missing for one measurement or the other. We need a special option by which all the ECA's which contain data are awaited.

In order to test the significance of the data, tools to check the overall reproducibility of the measurement would be helpful. Likewise, an operational tool to disconnect software-wise pickups would speed-up correction.

Of course any improvement in the accuracy of the measurement will speed-up correction and improve the final result. There is indeed evidence that 0.53 mm is not the ultimate that can be achieved now.

50.3.3 Rejection of the suspicious PU's

We now use a crude approach (distribution cut at n σ) which is obviously insufficient. A strategy to identify 'wrong' pickups, which will always be necessary, is not obvious. One should rather have several tools to test before a strategy emerges. Such tools could be: display of the normalised orbit versus phase, ability to fit a sine wave in a section, user-friendly analysis of the orbit and statistical tests of the presence of an orbit in the residuals.

50.3.4 Correction algorithms

The transfer of the correction algorithm MICADO on the DN10000 is a success and was very useful for polarisation runs.

We need more ...

- reconditioning of the MICADO response matrix, which becomes ill-conditioned if several successive PU's are missing, and which causes the development of bumps, especially in the low-β insertions,
- ability to select any iteration and not only the last one,
- modular filtering of the orbit,
- display of two orbits on top of each other,
- other correction techniques, possibly less sensitive to the noise. The harmonic correction could be an interesting candidate. The present technique is obviously very sensitive to the kind of 'noise' we have (it was possible to do systematically better with more time).

50.3.5 The vertical dispersion

The understanding and correction of the dispersion is critical for polarisation. An r.m.s. dispersion $D_y = 20$ cm destroys any polarisation. The closed orbit correction to 0.5 mm allowed a reduction of the dispersion to 13 cm. This seem to show that the source is distributed. The efficiency of the energy calibration experiments will depend on the progress on this front.

50.3.6 The stability and reproducibility of the optics

Refined corrections are really worthwhile if they can be maintained in a whole run and reproduced. This is especially important as the physicists would like ultimately an energy calibration per run. Data collection and analysis is required.

50.3.7 The Ni effect

The spurious skew gradient in the vacuum chamber reduces the maximum achievable polarisation level to some 50 %. This is by far sufficient for energy calibration. The demagnetisation will further improve the situation. Ultimately it will be necessary to compensate the spin resonances excited by the remaining parasitic fields.

50.3.8 The polarisation ramp

The ramp for physics is made in steps of 125 MeV. To optimise the polarisation level, steps of 10 MeV are required. While there is no problem in principle, the lack of flexibility of the ramping software made the implementation untractable. Work is needed.

50.4 Searching the best working point Integers

Systematic spin resonances arise when

$$\nu = Q_{x/y} + 8n, \qquad n \in \mathcal{Z}$$

They are driven by the harmonics of the vertical closed orbit close to $Q_{x/y}$.

There is a strong interest to be able to polarise the LEP beams at the most often used physics energy. The rise time of the polarisation is slow and experiments time consuming. Such a facility would save a lot of MD and speed up the development of polarisation. The most often used energy is of course the Z^0 energy which corresponds to a spin tune of $\nu = 103.5$. The following betatron tunes are thus forbidden:

$$Q = 104, 96, 88, 80, 72$$

$$Q = 103, 95, 87, 79, 71$$

Optics like the 71/77 or 71/76 do not allow polarisation at the Z^0 peak, 70/76 or even better 78/78 do.

50.5 Searching the best fractional part of the tunes

Unlike for the betatron motion, there is no driving force for the half-integer spin resonance $\nu = n + 0.5$. We are lucky that the Z^0 peak does correspond to such a condition : $\nu_{Z^0} \approx 103.5$.

To maximise the probability of polarisation, the other eigen-frequencies of the beam dynamics should be pushed away as far as possible from the half-integer towards the integers.

The best working point found so far is

$$Q_x = 71.12 \qquad Q_y = 77.20 \qquad Q_s = 0.085$$

The emittance ratio is minimised and the beam very stable.

50.5.1 Families of spin resonances

The spin resonances can be classified in families:

- $\nu = k$: integer resonances,
- $\nu = k \pm Q_s$: synchrotron resonances (very strong)
- $\nu = k \pm Q_{x/y}$: betatron resonances (e.g. excited by the Ni),
- $\nu = k \pm nQ_s$: higher-order satellites of the integers,
- $\nu = k \pm Q_{x/y} \pm Q_s$: higher-order satellites of the betatron resonances, ...

Analytical studies [Buon] have shown that the higher-order resonances are important for LEP, especially when the wigglers are used. Until now, we have no reliable means of computing their strengths for the actual LEP. Simulations [Koutchouk, Limberg] showed that the fine correction of the dispersion reduces their excitation to acceptable levels.

The driving terms of the first three families are related to some extent. In PETRA, the compensation of the integer resonances only was sufficient to weaken all the near-by resonances [Rossmanith, R. Schmidt]. It can be shown that the strength of the higher-order satellites are related to the strength of the mother resonance. Therefore the compensation of the well understood integer, synchrotron and betatron resonances has a high potential.

50.5.2 Harmonic spin matching

The principle is to modify the orbital dynamics to minimise the tilt of the polarisation axis or other quantities in the driving term of the spin resonances. For integer resonances, one should evaluate the static transverse magnetic fields felt by an observer precessing with the spin around LEP. Once known, additional compensating static fields (in the spin precession frame) may be added to compensate the imperfections and thus compensate one resonance. This method, called harmonic spin matching, was successfully used in PETRA.

In LEP, we retained the same principle, but modify it in such a way that the orbit is not disturbed all around the machine. We have procedures to compensate the resonances 103 to 107 based on patterns of closed orbit bumps (Figure 50.1). The selectivity is rather good as can be seen on Figure 50.2.

For the synchrotron spin resonances, we have procedures for the resonances 104 and $106 \pm Q_s$. The trick is to use patterns of vertical closed orbit bumps in the straight sections. In the absence of bending, all the small rotations suffered by the spin when traversing the bumps commute. There is no net effect. However, a wave of dispersion is excited by the bump and modifies the spin kinematics in the arcs. This is used to compensate the effect of the natural spurious dispersion.

We have not yet prepared procedures to compensate the betatron spin resonances which are weaker.

In all cases, the imperfections driving the spin resonances are so small that they are out of reach of any beam measuring device. The compensation of spin resonances must be done by trial and error, using the measured polarisation level. Given the rise time of the polarisation and the fact that each resonance has a sine and cosine term, it may be inferred that the compensation of resonances will be time consuming and that all efforts to correct imperfection at the source are worthwhile.

50.5.3 Minimisation of the rise-time

Asymmetric wigglers are being installed to reduce the polarisation time from 5 hours to 36 minutes. They will provide as well very strong additional damping which facilitates injection and accumulation. However, they increase the beam momentum spread and thus require a well controlled optics (dispersion, dynamic aperture,...). This is further required to avoid they depolarise the beams. Given their high potential, they will be commissioned very soon.

50.6 Conclusion

Obtaining high polarisation in LEP is very demanding. But the reward is at the level of the difficulty. A very accurate energy calibration will become possible, the way to longitudinal polarisation will be opened and the performance for every day operation will be improved. Indeed, the polarisation has nothing very specific; it simply pushes the requirement on LEP to high levels, not out of reach. It will act as an excellent detector of solutions like ' bandage on a wooden leg'.

In practice, the polarisation programme would profit from team work on closed orbit, dispersion, wigglers, new optics and machine reproducibility.

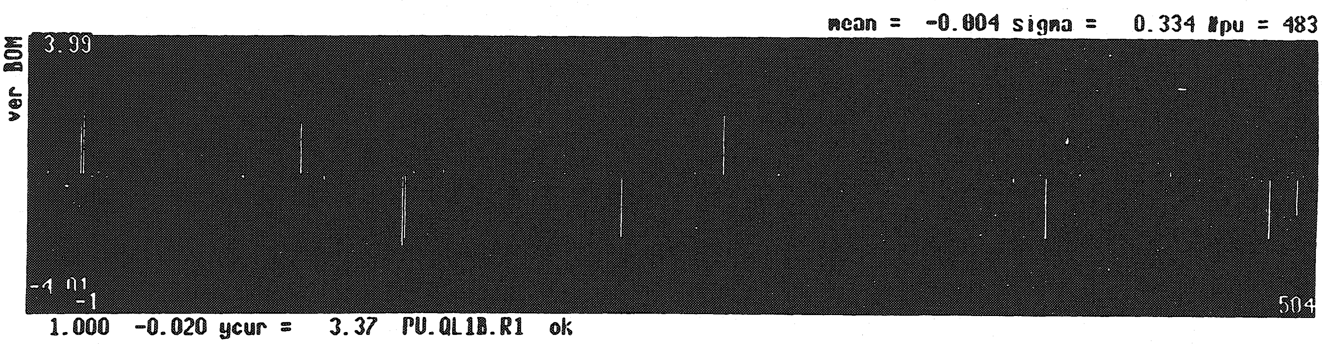

Figure 50.1: Compensating closed orbit bumps

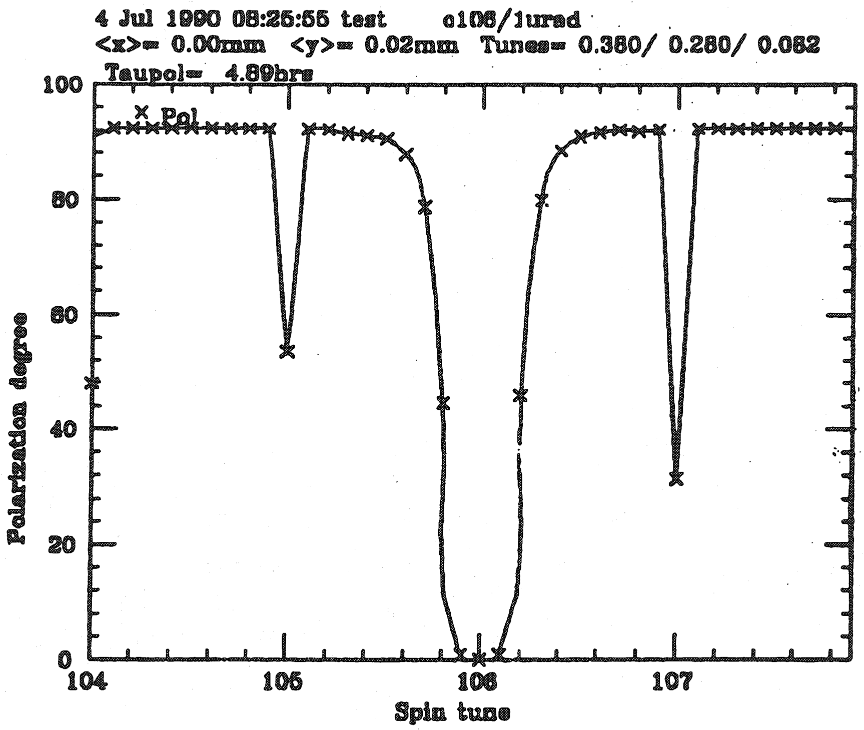

Figure 50.2: Degree of polarisation vs. spin tune