Polarization above 60 GeV

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Abstract

Radiative polarization of the particle beams provides the most accurate tool to measure the beam energy in LEP. In order to determine the W mass with the required accuracy it is important to establish polarized beams for the highest possible energies. The LEP polarization measurements up to 60.6 GeV are discussed and compared with theoretical expectations.

In order to establish polarization at even higher energies one can either try to extend the LEP1 regime of polarization or to enter into a new and unknown regime. Both possibilities are discussed with special emphasis on the required values of beam parameters. It will be shown that an extension of polarization to about 70 GeV can be hoped for from theory.

The regime at 100 GeV promises little polarization from the theoretical point of view. However, the relevant theory does not fully apply for LEP and was never tested in experiment. The need for experimental tests is discussed.

1 INTRODUCTION

Polarized beams have been used since 1991 for the precise calibration of the absolute beam energy in LEP. The average beam energy $E = \gamma / (mc^2)$ and the spin precession frequency ν are uniquely related in a storage ring:

$$\nu = a\gamma = \frac{E}{440.6486\,\mathrm{MeV}} \tag{1}$$

Note that ν is the spin precession frequency in units of the LEP revolution frequency (it is also called the spin tune). The polarization vector of the beam can be resonantly rotated if a horizontal magnetic perturbation is brought into resonance with the spin precession. In resonance, the frequency of the perturbing field is an accurate measure of the spin precession frequency and the average beam energy. The absolute LEP beam energy is determined with an accuracy of better than 1 MeV [1].

The method of "resonant depolarization" has been used extensively for the precision measurement of the Z-mass [2]. In fact it is the by far most accurate method to determine the beam energy in storage rings. In order to calibrate the energy scale of the W it is crucial to determine the absolute LEP beam energy via resonant depolarization at the highest possible LEP energy. Using other methods it is then extrapolated to the W range [3]. The extrapolation error depends on the energy range that must be extrapolated. The goal is to keep the systematic error on the W-mass from the knowledge of the beam energy below the error from the available W statistics.

In view of the energy calibration requirements it is important to establish polarized beams at the highest possible LEP energies. As depolarizing effects become very strong with increasing beam energies it is a difficult task to extend polarization towards the range of the W mass.

In this paper the successful measurements of polarization are reviewed. Polarization was established for the first time at 60.6 GeV in 1998. The chances to extend polarization towards even higher beam energies are discussed.

2 THEORY OF POLARIZATION AT ULTRA-HIGH ENERGIES

The particle beams in LEP spontaneously polarize due to the Sokolov-Ternov effect [4]. As the electrons and positrons are bent into their circular orbit, they emit synchrotron photons. With respect to the vertical bending field we can consider the spin state of a single particle. Initially there is equal probability to find the spins parallel or anti-parallel to the direction of the magnetic field; the beam is unpolarized. As a particle emits a synchrotron photon its state of spin can remain unchanged or it can be flipped. It turns out that there is a much greater probability for spin flips from the parallel to the anti-parallel spin state than for the opposite direction. As a results LEP electrons will slowly build up a polarization vector anti-parallel to the bending field. This process is characterized by a polarization build-up time τ_p and leads to an asymptotic polarization degree of 92.4%. For LEP it is:

$$\lambda = \frac{1}{\tau_p} = 3.9 \times 10^{-19} \cdot \nu^5 \tag{2}$$

Note that the polarization rate λ is the inverse of the build-up time τ_p and is here given in units of the LEP revolution frequency. It is a steep function of the spin tune ν (equivalent to beam energy, see Eq. 1). For higher beam energies the polarization rate becomes very large, the polarizing time very short.

The numerical evaluation of τ_p for LEP is shown in Figure 1. The polarizing time τ_p for an asymptotic polarization degree of 92.4 % is several hours for Z-energies and drops to several minutes at W-energies. The short build-up times at high energy are advantageous because less time is required to observe changes in polarization degree. Polarization is more responsive to manipulations and the empirical optimization of the polarization degree becomes much easier. However, if the build-up time is too short, it becomes difficult to reliably observe resonant depolarization for the purpose of energy calibration.

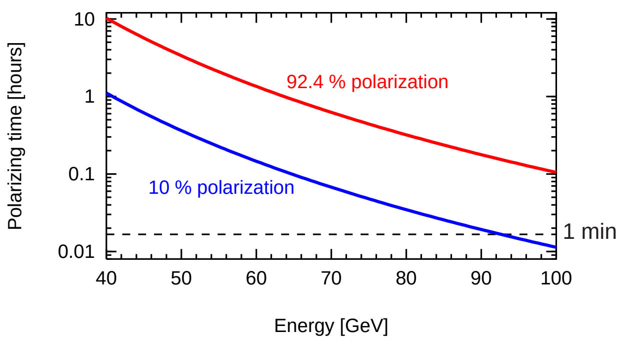

Figure 1: Polarizing time in LEP as a function of beam energy for asymptotic polarization levels of 92.4% and 10%. Note that the vertical scale is logarithmic. The polarizing time is reduced from ~ hours at LEP1 to ~ minutes for LEP2.

Unavoidable imperfections in the vertical orbit cause horizontal magnetic fields that perturb the spin motion. As a result the asymptotic polarization degree is reduced. It turns out that synchrotron radiation drives both polarizing and depolarizing processes. The depolarization is characterized by a depolarization time τ_d.

The asymptotic degree of polarization in the presence of polarizing and depolarizing processes can be written as:

$$P = \frac{92.4\%}{1 + \tau_p / \tau_d} \qquad (3)$$

Polarization theories aim at estimating the depolarization term τ_d for a storage ring. Here, we follow the basic theory by Derbenev, Kondratenko and Skrinsky from their summary paper in 1979 [5].

2.1. Basic Quantities

A few basic beam and machine parameters determine the behavior of polarization:

- The spin tune ν describes the energy dependence of polarization.
- The polarizing rate λ determines the speed of polarization buildup (see Eq. 2).
- The synchrotron tune Q_s gives the distance between synchrotron sidebands of spin resonances.
- The spin tune spread σ_ν causes a smearing out of spin precession frequencies so that they eventually overlap Q_s sideband resonances. It Is related to the relative beam energy spread σ_E/E:

$$\sigma_\nu = \nu \cdot \frac{\sigma_E}{E} \qquad (4)$$

The particles in LEP traverse the ring about 11000 times per second. Let's assume the average spin tune ν_0 is not on any resonance. However, particles perform synchrotron oscillations around the average spin tune: $\nu = \nu_0 + \delta\nu$. Depending on the spin tune spread some particles might be on a spin resonance, for example $\nu = n \cdot Q_s$. During a large number of subsequent turns the particles will periodically cross the spin resonance. In order to evaluate the depolarizing effect on the ensemble polarization, it must be evaluated whether subsequent passings of a spin resonance are correlated or not. As shown by Derbenev, Kondratenko and Skrinsky, the criterion for correlated passings is:

$$\alpha = \frac{\nu^2 \lambda}{Q_s^3} << 1 \qquad (5)$$

If subsequent passings are correlated then spin rotations can average out to some extent and their effect is less severe. The next section will discuss depolarization in the case, that subsequent passings of spin resonances are indeed correlated.

2.2. Correlated Spin Resonance Passings

The following theory applies if the correlation criterion in Equation 5 is true. This regime of depolarization is well-known and thoroughly tested with simulations and measurements at LEP1. Polarization can be described by:

$$\frac{\tau_p}{\tau_d} = \frac{11}{18} \nu^2 \sum_{k,m} \frac{|w_k|^2 \langle T_m^2 (\Delta / Q_s) \rangle}{\left[(k - \nu - mQ_s)^2 - Q_s^2 \right]^2} \qquad (6)$$

Here, w_k is the complex strength of the spin resonance at integer k, ν is the spin tune averaged over the ensemble and m an integer giving the order of the synchrotron sideband resonance. The equation contains a Bessel function term T_m. Assuming a Gaussian distribution over squared amplitudes Δ from synchrotron oscillations one obtains:

$$\langle T_m^2 \rangle = I_m \left(\frac{\sigma_\nu^2}{2 Q_s^2} \right) \cdot \exp\left(- \frac{\sigma_\nu^2}{2 Q_s^2} \right) \qquad (7)$$

The I_m are the modified Bessel functions. The spin tune spread is of central importance for the strength of the T_m term. The above equations are valid in the approximation of high energy. Note that betatron spin resonances with the transverse tunes Q_x and Q_y do not appear. For high energy lepton storage rings they are much weaker than synchrotron resonances and are therefore neglected here.

Two regimes are distinguished in the regime of correlated spin resonance passings. If the spin tune spread is much smaller than the synchrotron tune then higher order synchrotron sidebands are not important and only the linear spin resonances (k + Q_s) affect the achievable polarization degree. In the following this is called the "linear" theory. If the spin tune spread becomes larger than the synchrotron tune then the higher order synchrotron sidebands limit the achievable polarization degree. This is referred to as "higher-order theory".

2.2. Uncorrelated Spin Resonance Passings

A different situation is encountered if subsequent passings of spin resonances are uncorrelated. They are uncorrelated if the criterion from Equation 5 is not true and in addition:

$$\sigma_\nu >> \nu_\gamma \tag{8}$$

In this case passings of synchrotron resonances are completely uncorrelated. With $\sigma_\nu << 1$ the polarization can be calculated from:

$$\frac{\tau_p}{\tau_d} = \frac{11\pi^4}{54} \cdot \nu^2 \cdot \left|w_{[\nu]}\right|^2 \cdot \left[1 + \frac{108\exp(-2\sigma_\nu)^{-2}}{11\pi^3\sqrt{\pi}\,\nu^2\,\lambda}\right] \tag{9}$$

In the case of $\sigma_\nu >> 1$ Derbenev, Kondratenko and Skrinsky have obtained a very simple result for the expected depolarization:

$$\frac{\tau_p}{\tau_d} = \frac{\pi\left|w_k\right|^2}{\lambda} \tag{10}$$

Polarization does not show any resonant dependence on beam energy in this regime, but exhibits an increase with energy, as the polarizing rate λ becomes very short for highest energies. This is a notable result, as polarization is usually expected to decrease with energy. In this regime the spin tune spread σ_ν is very large and particles constantly sweep over spin resonances. As the polarization rate increases, depolarization does not increase as rapidly any more.

Note a limitation in the theory of radiative polarization by Derbenev, Kondratenko and Skrinsky: the energy sawtooth that develops for LEP at high energies is not included. The energy of a single particle can be written as:

$$E(\text{particle}) = E + \Delta E(\text{synchr}) + \Delta E(\text{sawtooth}) \tag{11}$$

E is the energy averaged over all particles and the whole ring, as used in the above formalism. The average energy and synchrotron oscillations are included in the described theory. The energy sawtooth is not. It is produced by the fact that energy is lost all around the ring but put back only in 4 short regions in the LEP storage ring.

The resulting energy variation for LEP is shown in Figure 2 for a beam energy of 97 GeV. Note that energy variations of up to about ± 500 MeV are present at this energy. In other words, the single particles will constantly cross the integer and linear spin resonances. The effect on spin motion is unclear. The crossings are very fast, about 40 times faster than the synchrotron oscillation. Therefore the associated crossings of spin resonances might be fully correlated and cause little harm. However, the consequences of the sawtooth on the spin motion in LEP are not clear and require further study.

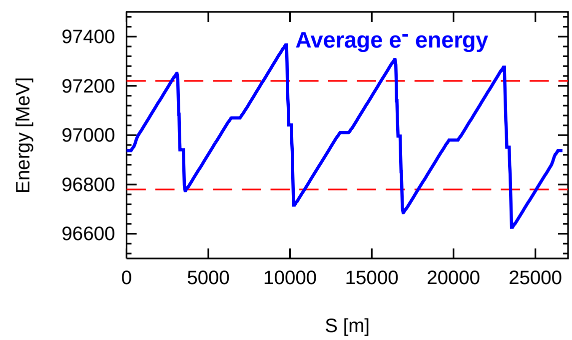

Figure 2: Average beam energy around the LEP ring at 97 GeV. The particles constantly loose energy in the arcs. The short acceleration sections sharply increase the beam energy in four locations. The dashed lines indicate the 440 MeV separation between integer spin resonances.

3 LEP MEASUREMENTS

Transverse spin polarization has been observed in LEP since 1990. Initial polarization measurements were performed at around 45.6 GeV and initially showed a polarization degree of about 5-10%. Polarization was optimized by a number of measures and finally a maximum beam polarization of 57% was observed at 44.7 GeV [6]. Since 1995 polarized beams are studied at higher beam energies always trying to establish at least 5% transverse polarization, as required for energy calibration.

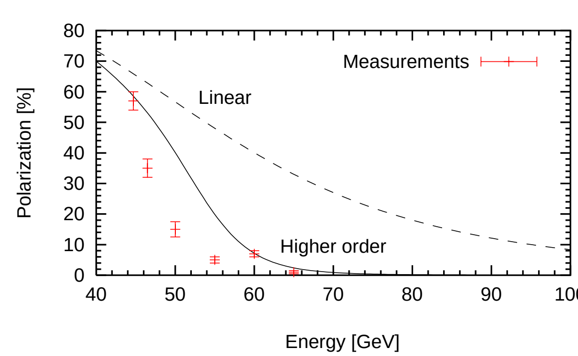

Figure 3: Measured maximum polarization degrees in LEP for different beam energies. The solid line extrapolates the measurement at 44.7 GeV towards higher energies using the higher-order correlated polarization theory.

The dashed line indicates the corresponding linear polarization.

The maximum polarization values measured in LEP for different beam energies are summarized in Fig. 3. The measurements were performed with a 90°/60° optics before and a 60°/60° optics after 1997. In 1998 transverse beam polarization of 7% was established at 60.6 GeV. Generally it is observed that polarization drops sharply with beam energy. The observed decrease from 44.7 GeV to 60.6 GeV is in good agreement with the expectation using the higher-order theory in the correlated regime. The measurements at 44.7 GeV and 60.6 GeV were optimized for maximum polarization level and can therefore be compared. The measurements in between those two energies were not fully optimized for maximum polarization degree. As soon as the 5% polarization level as required for energy calibration was achieved polarization was not further optimized.

The successful extension of beam polarization from 55 GeV in 1997 to 60.6 GeV in 1998 was made possible by a number of optimizations. It is beyond the scope of this paper to explain the details of this optimization, a short list should be sufficient:

- Use of new 1998 K-modulation data for BPM offsets.
- Careful correction of vertical orbit with elimination of bad BPM's and π-bumps.
- Verification that initial spin harmonics of the vertical orbit are small.
- Careful adjustment of beam energy to avoid spin resonances.
- Deterministic Harmonic Spin Matching.
- Use of new dispersion-optimized spin bumps in the arcs.
- Semi-empirical Harmonic Spin Matching.

The optimization of polarization is a time consuming procedure though it profits from the short polarizing times at high energies.

4 NUMERICAL PREDICTIONS

In order to discuss the possibility of polarization above 60.6 GeV the theory by Derbenev, Kondratenko and Skrinsky must be evaluated numerically for the different beam and machine parameters. The following numerical LEP dependencies are used:

- The polarizing rate λ (in units of the revolution frequency) is determined by a numerical factor describing the configuration of the LEP bending and the beam energy E:

$$\lambda = \frac{1}{\tau_p} = 3.9 \times 10^{-19} \cdot \left(\frac{E}{0.44065\ \mathrm{GeV}} \right)^5 \qquad (12)$$

- The resonance strength w_k is calculated from the 57% measurement at 44.7 GeV and then scaled with the beam energy E:

$$|w_k|^2 = 1.94 \times 10^{-10} \cdot \left(\frac{E}{0.44065\ \mathrm{GeV}} \right)^2 \qquad (13)$$

- The spin tune spread σ_ν is proportional to the square of the beam energy E:

$$\sigma_\nu = 6.76 \times 10^{-6} \cdot \left(\frac{E}{0.44065\ \mathrm{GeV}} \right)^2 \qquad (14)$$

Those relationships are good approximations for the basic parameters of LEP polarization and their energy dependence.

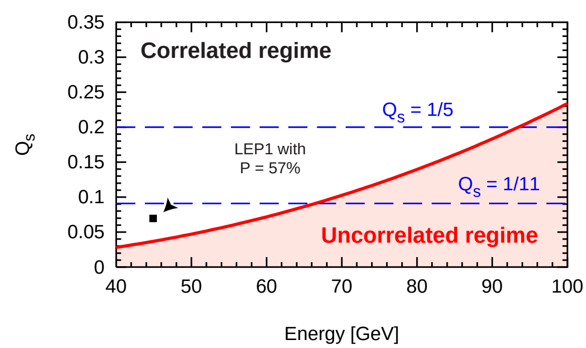

Figure 4: Evaluation of the correlation criterion from Equation 5 as a function of beam energy and Q_s. LEP can stay in the correlated regime by increasing the value of the synchrotron tune Q_s.

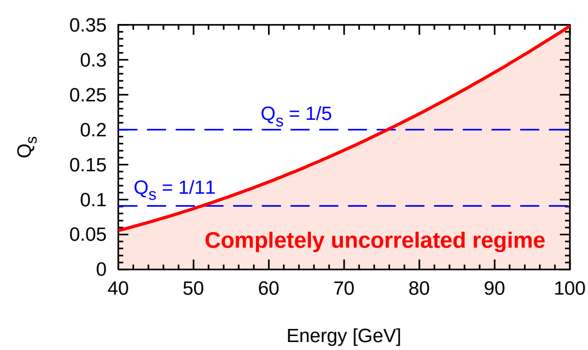

Figure 5: Evaluation of the criterion for subsequent spin resonance passings being completely uncorrelated.

4.1. Correlation Criteria

As a first step the criteria for correlation of subsequent spin resonance passings are evaluated. Figure 4 shows the numerical evaluation of the correlation criterion from Equation 5 as a function of beam energy and Q_s. It is seen that the LEP1 working point was clearly in the correlated regime. With a Q_s of 1/11 the working point at 60.6 GeV was also in the correlated regime. For higher beam energies the Q_s must be raised, for LEP to stay in the correlated regime. With high energy and small Q_s LEP moves into the uncorrelated regime of spin polarization. Figure 5 shows that spin resonance passings for LEP are always completely uncorrelated (Equation 8) if the correlation criterion is violated.

The LEP working point can remain in the well-known and favorable regime of LEP1 polarization. In this regime subsequent passings of spin resonances are correlated. The required condition is that the synchrotron tune Q_s is being raised for higher energies.

Plenty of RF voltage is required for the highest LEP energies around 100 GeV. In 1999 a total RF voltage of about 3 GV will be available. At low energies additional RF voltage can be used to increase the Q_s. The required voltage for a given Q_s is a steep function of the momentum compaction and hence of the beam optics.

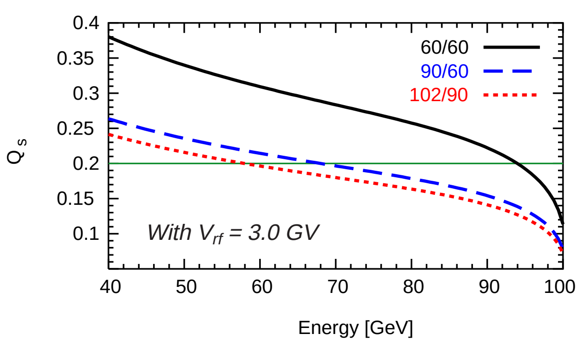

Figure 6: Maximum achievable Q_s as a function of energy and for three different optics. It is assumed that a total RF voltage of 3.0 GV is available.

The maximum achievable Q_s in LEP is shown in Figure 6 as a function of energy and for three different beam optics. For the polarization optics (60°/60°) a high Q_s of above 0.2 can be maintained up to 90 GeV. Up to about 64 GeV a synchrotron tune as large as 0.3 can be obtained. The other optics require significantly smaller Q_s values.

It can be concluded that the polarization optics can be used for high Q_s studies of polarization up to its aperture limitation at around 75 GeV. Polarization is expected to stay in the correlated regime. Beyond the limit of the polarization optics LEP-polarization can be studied in the uncorrelated regime using the physics 102°/90° optics.

4.2. *Correlated Regime*

The polarization optics allows a high Q_s of above 0.25 until its aperture limit at around 75 GeV. LEP remains in the correlated regime of spin resonance passings with that Q_s and the higher-order polarization theory can be used to predict the achievable polarization degree (Equations 6 and 7). Note that this theory correctly predicts the decrease of polarization with energy that is observed in LEP (see Figure 3). It has been cross-checked theoretically with detailed simulations [7] and experimentally using the LEP damping wigglers [6].

The predicted polarization degree has been evaluated as a function of beam energy and for different values of the synchrotron tune Q_s. In order to achieve the maximum distance to all spin resonances, Q_s is chosen to be equal to one over an odd integer. For illustration we consider Q_s values of 1/13 (LEP1 value), 1/5 and 1/3. The predicted dependence of polarization on energy is shown in Figure 7.

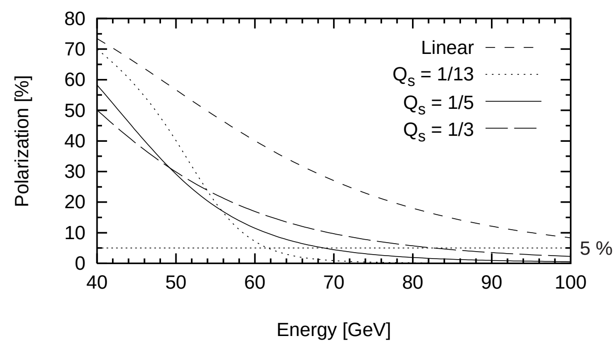

Figure 7: Predicted values of transverse spin polarization in LEP as a function of beam energy for different values of Q_s. The linear prediction is also plotted. The required polarization degree of 5% for energy calibration is indicated.

High Q_s values significantly improve the chances of spin polarization for higher beam energies. This is explained by the fact that for a high Q_s the synchrotron satellites overlap each other and their effect is reduced. For example a Q_s of 1/3 will mean that Q_s sidebands only appear at k, k+0.33 and k+0.66 in spin tune. If the beam is put to a spin tune of k+0.5 then it will be much less affected by synchrotron sidebands than with smaller Q_s.

For low energies high Q_s values decrease the expected level of polarization. For those energies higher order spin resonances are not important. The depolarization is stronger because the linear synchrotron sidebands at k+Q_s are moved closer to the beam spin tune around k+0.5.

From Figure 7 it can be concluded that it should be possible to establish polarization of at least 5% up to about 70 GeV using a high Q_s working point. This extension of LEP polarization with high Q_s should be tried in 1999.

4.3. *Uncorrelated Regime*

For the highest LEP beam energies around 90-100 GeV the beam polarization is in the completely uncorrelated regime of spin resonance passings. This is a theoretically unfavorable regime of spin polarization, depolarization is expected to become very strong. However, the uncorrelated regime has not yet been assessed experimentally. In addition the theory does not include the effect of an energy sawtooth as it appears in LEP.

We evaluate this regime under the assumption of a large spin tune spread ($\sigma_\nu >> 1$). Including the energy sawtooth LEP will just enter into this regime at the highest beam energies. This regime of spin polarization has the favorable property that the polarization is expected to increase with beam energy.

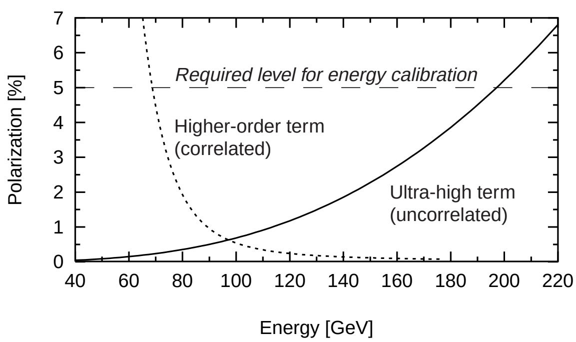

Figure 8: Expected polarization in LEP for ultra-high energies. The higher-order theory in the correlated regime (Q_s = 1/5) and the "ultra-high term" (Equation 10) in the uncorrelated regime are shown. LEP is expected to enter the uncorrelated regime at around 80 GeV.

The expected polarization is shown in Figure 8 for both the correlated and uncorrelated regime. For the highest LEP energies at 90-100 GeV the uncorrelated regime must be considered. It is seen that the polarization prediction in this regime increases with the beam energy, contrary to the experience in the correlated regime. At about 100 GeV a polarization degree of roughly 1% is expected. This is not sufficient for energy calibration. However, in view of the uncertainties in this energy regime (as discussed before), an experimental test is clearly warranted.

At the end of the 1998 run it was tried to measure polarization at 90 GeV. This attempt was unsuccessful due to problems in the detector shielding at high energies.

4.4. Further Improvements

Improvements in the polarization setup of the LEP storage ring are foreseen. A method of "dispersion-free steering" applies simultaneous minimization of the LEP orbit, the dispersion and the required corrector kicks. The method allows a fast and deterministic orbit optimization with automatic disabling of bad beam position monitors (BPM's) and automatic removal of π-bumps. This method has been tested during a polarization MD in 1998, providing record small vertical dispersion and beam size [8]. We expect that the setup time for polarization can be reduced by about 1-2 hours.

5 ENERGY CALIBRATION AT ULTRA-HIGH ENERGIES

For energy calibrations at energies up to 80 GeV no problems are expected. At the highest LEP energies the situation will become more complicated. We consider several possible problems:

1. The LEP polarimeter puts a laser beam and the particle beam in collision. The back-scattered photons are measured in a detector, providing the polarization signal. Synchrotron photons from the particle beam produce a noise signal that must be efficiently shielded without eliminating the signal from the backscattered. Additional shielding will be implemented in 1999. The shielding relies on the fact that there are five orders of magnitude in energy between back-scattered photons and synchrotron photons.
2. The fast kicker used for resonant spin vector rotation applies a horizontal field to the beam. The spin rotation from a given horizontal magnetic field is constant with the beam energy (for LEP parameters). Therefore the efficiency of spin vector rotation with the LEP kicker remains unchanged. No problem is expected.
3. The rise time of polarization is about 1 minute and is very short. After the beam has been depolarized it will polarize in a very short time making it hard to reliably observe depolarization. The LEP strategy for energy calibration must be changed. For example the kicker frequency can constantly be swept back and forth in a selected interval.
4. If spin decoherence becomes so strong that any horizontal spin component vanishes after a single turn then polarization can be slowly destroyed by an external perturbation at any frequency. Energy calibration by resonant depolarization will become impossible.

Though there are a few possible problems we expect that polarization can be used for energy calibration if a sufficient level can be established.

6 CONCLUSIONS

Transverse beam polarization and accurate energy calibration has been extended to 60.6 GeV in 1998. The additional range in energy calibration helps to reduce the extrapolation error for physics energies and the W mass.

The application of the polarization theory to LEP parameters shows that a 5% polarization degree can be expected up to about 70 GeV with the polarization optics and a high Q_s. This extension of polarization range will be studied at the end of regular energy calibrations in 1999. If polarization is found at up to 70 GeV it can be used for energy calibration.

The prospects for polarization in LEP at around 100 GeV are very uncertain. However, it cannot be excluded that polarization of a few percent is possible in the so-called uncorrelated regime. A dedicated experiment in 1999 will try a to explore this regime of beam polarization.

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