INTRODUCTION

Since the early days of the design study the possibility of obtaining polarized beams in LEP were discussed /1/ and more recently developed /2/, /3/. Although it seemed to be rather hopeless at the beginning, the general improvement in understanding the polarization effects in storage rings together with several new ideas tailored to the needs of LEP could enable to find a solution for obtaining both transversally and longitudinally polarized beams with alternating helicities without expensive modifications of the machine.

In this paper the necessary steps for obtaining transverse and longitudinal polarization are shortly summarized:

- measurement of polarization
- speeding-up the polarization by asymmetric dipole wigglers
- compensation scheme for transverse polarization for precise measurement of energies and masses
- longitudinal polarization and compensation of depolarizing effects

1. MEASUREMENT OF POLARIZATION

A detailed discussion of the LEP polarimeter can be found in /4/. Here only the essentials are presented. A circularly polarized laser beam is directed against the electron (or positron) beam. The laser peak power is several tens of megawatts, the pulse duration is in the order of 10 ns and the laser light is in the visible or near infrared region. The laser photons are backscattered by the particle beam and the vertical distribution of the backscattered photons is analyzed by a detector 300 m downstream of the laser-beam interaction region (fig.1). Asymmetries in the vertical distribution of the backscattered photons indicate that the beam is polarized. The high power of the laser enables a fast measurement of the polarization (within a few seconds) and its low duty cycle (~30 Hz repetition rate) considerably improves the signal to noise ratio.
II. ENHANCEMENT OF POLARIZATION RATE BY WIGGLERS

The build-up of the vertical polarization is caused by the emission of synchrotron radiation photons. At least for the first stage of LEP this effect is very weak and the build-up time of polarization very long (fig. 2). For speeding up the build-up so called asymmetric dipole wigglers were proposed /2/. These wigglers use the fact that the build-up time of polarization depends, for a given energy, on the third power of the bending radius. Short, but strong bending magnets can strongly influence the build-up of the polarization. Before and after the strong bending field a weak bending field of opposite direction makes the integral field strength and therefore the total beam deflection zero. Fig. 2 shows the influence of the asymmetric wigglers on the polarization rate.

This is a clear difference to all other machines and makes LEP unique from the polarization point of view: not the arcs polarize the beam but short bending magnets on defined positions.

With the above mentioned 'point-like' polarizers in form of antisymmetric wigglers the beam can be polarized, in principle, in any direction perpendicular to its momentum. The wiggler has to be rotated into the appropriate direction and clearly only two directions are of practical importance: the vertical and the horizontal.

This property will be developed in ch. V. to illustrate a possible method to obtain longitudinally polarized beams.

III. COMPENSATION SCHEME FOR TRANSVERSE POLARIZATION

It is well known from machines operating at lower energies that the vertical polarization direction is the most stable direction. Nevertheless, many depolarizing effects reduce the degree of polarization and several compensation schemes have to be applied. These schemes can be applied at LEP although the polarization is not only generated in the arc but outside by polarizers. For instance, the experimental solenoids (compensated against coupling by skew quadrupoles) will immediately depolarize the beam. To overcome these effects more or less complicated compensation schemes and changes in the optics would be necessary /5/.

A more fundamental problem is the depolarization in the arcs. These effects where studied in detail in PETRA /6/ and remedies against them were developed /7/ which can be applied directly in LEP.

The depolarization mechanism of the arc can be explained in a simple way: the spin precesses around the field axis. When the vertical closed orbit is distorted or the particles perform vertical betatron oscillations the spins precess in the bending magnets around the vertical direction and in the quadrupoles in between the bending magnets around the horizontal axis. Under certain conditions both
motions can be in resonance and the spin is bent from the vertical direction to the horizontal.

Each machine is misaligned up to a certain degree. The question is how strong can the closed orbit be distorted in order to still find polarization. Fig. 3 shows the degree of polarization vs. energy for an r.m.s. closed orbit deviation of 0.35 mm.

The orbit must be corrected better than 0.5 mm, otherwise there is no chance to find polarization. Once some polarization is measured it can be improved by the technique /7/ which consists of small modifications in the orbit and in the optics.

The principle of this scheme is shown in fig. 4. A computer calculates an orbit (or a small modification of the optics) where the spin motions both in the bending magnets and in the quadrupoles are in resonance. Such an orbit would be very dangerous for the polarization. This orbit is added to the existing orbit and the degree of polarization is observed. If the degree of polarization becomes worse the sign of the correction is reversed.

Summarizing: to obtain transverse polarization in LEP a compensation scheme must be installed and a carefully corrected closed orbit is required. The physics which can be done with transverse polarization is well established: the calibration of the beam energy and the precise determination of subnuclear masses in the LEP energy range. For this measurement to be done during the data taking the fields of all the experimental solenoids would have to be compensated locally against depolarizing effects.

IV. THE ABSOLUTE CALIBRATION OF THE BEAM ENERGY

Once the beams are polarized into the vertical direction they can be depolarized by a time dependent weak magnetic field. Revolution after revolution the spin is rotated a little more from the vertical into the horizontal until the beam is depolarized. The condition is that the direction of the depolarizing field follows the spin motion. The number of spin precession per particle revolution is \( a \gamma \), where \( a \) is the famous \((g-2)/2\) factor of the electron and \( \gamma \) is the Lorentz-factor. The condition for the depolarization is:

\[
(a \gamma - n) f_0 = f_d
\]  

where \( f_0 \) is the revolution frequency, \( f_d \) is the frequency of the weak time-dependent field and \( n \) is any integer.

The frequencies \( f_0 \) and \( f_d \) can be measured with high accuracy and \( n \) is derived from absolute field measurements of the machine dipoles.

Since \( a \) is one of the best known quantities in physics, \( \gamma \) can then be assessed with high accuracy. The electron mass is known with an uncertainty of \( 2.7 \times 10^{-6} /8/ \) and therefore the absolute energy of the
beam can be, in principle, determined by the same accuracy. In the experiments the obtained accuracy in measuring the J/ψ masses was only worse by a factor of 10 compared to the accuracy by which the electron mass is known. As an example, the result of an energy calibration at PETRA is shown in fig. 5.

In the following some effects which could influence the accuracy in LEP are shortly discussed.

-Kinematics. The beam energy varies along the LEP ring more than in previous machines. The above mentioned method measures the energy averaged over the circumference.

Assume that the two colliding particle bunches have Gaussian energy distribution but different central energies $E_a$ and $E_b$:

$$E_a \propto \exp\left[-\frac{(E-E_a)^2}{2\sigma_a^2}\right], \quad E_b \propto \exp\left[-\frac{(E-E_b)^2}{2\sigma_b^2}\right]$$

According to kinematical laws two particles with energies $E_1$ and $E_2$ can produce a particle with mass $M$ when the following condition is fulfilled (extremely relativistic case):

$$M^2 = 4E_1E_2$$

In most cases the following simplification holds:

$$E_a = E_0 - \Delta \quad \text{and} \quad E_b = E_0 + \Delta$$

$E_0$ is the average ring energy measured by the depolarizing method. $\Delta$ is the difference between $E_0$ and the actual energy which is a function of the azimuthal position in the ring.

For $\sigma=0$ Equ. (3) and (4) give

$$M^2 = 2E_0[1 - 0.5(\Delta/E_0)^2]$$

For a mass of 100 GeV, a $\sigma$ of 50 MeV and a given $\Delta$ the deviation of the measured $2E_0$ from the exact mass is given below:

<table>
<thead>
<tr>
<th>$\Delta$</th>
<th>$\Delta M / M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 MeV</td>
<td>5.10^{-7}</td>
</tr>
<tr>
<td>100 &quot;</td>
<td>2.10^{-6}</td>
</tr>
<tr>
<td>500 &quot;</td>
<td>5.10^{-5}</td>
</tr>
</tbody>
</table>

In the first stage of LEP an upper limit for $\Delta$ is 100 MeV and the error can therefore be neglected. Nevertheless, when the method is applied at higher energies this effect could be important.

-Energy fluctuations. It was first shown at PETRA /9/ that the
natural energy spread (in general in the order of $10^{-3}$ of the beam energy) is much higher than the width of the depolarizing resonance (several $10^{-8}$). This is due to the fact that the depolarizing field is weak and the depolarization occurs during many synchrotron oscillation wavelengths. Up to now a generally accepted quantitative theory describing the width of the resonance does not exist. So predictions for LEP on the width of the depolarizing resonance are more or less speculations and based on the observation gained at DORIS and PETRA /10/: the resonance width was nearly identical in both machines. When these observed scaling laws hold the width of the depolarizing resonance will be at LEP also in the order of $10^{-8}$.

-The stability of the power supplies. It is evident that unstable power supplies can influence the accuracy of the measurement. This effect will be hopefully not bigger than $10^{-5}$.

Summarizing: although there are still problems which are not completely understood nothing speaks at the moment against an accuracy of several $10^{-5}$ in the measurement of masses or even slightly better. Note that one problem is the long build-up time of polarization. Once the beam is depolarized one has to wait a long time before the experiment can be repeated. In order to overcome this problem one can think on reversing the polarization into the opposite direction instead of depolarizing the beam. This method has been experimented at Novosibirsk /11/. If this is also possible in LEP (the experimental results will show it) it can be very helpful.

V. LONGITUDINAL POLARIZATION AND CORRECTION SCHEMES

Although precise measurements of the masses of the $Z_0$ and of the top-mesons are of great importance, experimental physicists will be finally interested in longitudinally polarized beams /12/.

The conventional way is to polarize the beam into the vertical direction, to rotate the spin into the longitudinal direction in front of the experiment and back into the vertical direction after the experiment. Such a scheme was also proposed for LEP /13/. The application of such a system in LEP leads to severe and up to now unsolved problems, e.g. space availability, compensation of depolarizing effects etc.

An alternative scheme for obtaining longitudinal polarization is sketched in fig. 6.

Note that LEP has 8 straight sections, four of which will be equipped with detectors and RF-cavities. At the moment the non-experimental straight sections are more or less available for installing additional equipment.

In this scheme it is suggested to polarize the particles into the horizontal plane by an asymmetric dipole wiggler located in a non-
The method can be extended to provide, in all the four interaction OCR Output
depending on which bunch is polarized. The total helicity will have opposite sign
zero helicity is then to depolarize the electron or the positron bunch
in L.P. is zero (fig.7). One way to produce e* e' interactions with non
fields for electrons and positrons the total angular momentum at the
in the presented proposal the spin tune is identical for all particles;
advantage since the optics has to be modified according to the
-|t is cheaper than any system proposed before.
-Components are only installed at places where sufficient space is
-The optical problems, inherent to most of the conventional rotators,
do not exist. Conventional rotators with vertical bends conserve the
polarization only when the optics of the whole machine fulfills certain
conditions (so called spin matching conditions). This is an enormous
disadvantage since the optics has to be modified according to the
needs of polarization. In the proposed scheme this is no longer
necessary.
-One standard argument against polarization in accelerators like LEP
is that the beam energy spread is so large that always some particles
cross the depolarizing resonances. Due to this effect the beam becomes
depolarized.
In the presented proposal the spin tune is identical for all particles;
the energy spread has therefore no influence on the degree of
polarization.

VI. NON-ZERO HELICITY e+ e- INTERACTIONS

For all kind of rotators and systems described above using the same
fields for electrons and positrons the total angular momentum at the
L.P. is zero (fig.7). One way to produce e+ e- interactions with non-
zero helicity is then to depolarize the electron or the positron bunch
involved in the interaction. The total helicity will have opposite sign
depending on which bunch is polarized.
The method can be extended to provide, in all the four interaction
regions, collisions with helicity changing sign at each bunch X-ing. In this case operation with four bunches per beam is needed and two e* and two e- bunches must be depolarized.

The situation is illustrated in fig. 8 in which the two beams are assumed to have the following configuration:

\[ \begin{align*}
\rightarrow & \\
\rightarrow & \\
\leftarrow & \\
\leftarrow & \\
\end{align*} \]

\[ \begin{align*}
P_1 & \quad P_2 & \quad P_3 & \quad P_4 \\
E_1 & \quad E_2 & \quad E_3 & \quad E_4 \\
\text{(positrons)} & \\
\text{(electrons)} & \\
\end{align*} \] (6)

The bunch numerotation follows the injection order and the arrows indicate the longitudinally polarized bunches in each beam. The bunches involved and the total helicities at the four interaction points will be:

\[ \begin{align*}
\text{Diameter 2 - 6} & \\
\rightarrow & \\
\leftarrow & \\
\rightarrow & \\
\leftarrow & \\
\end{align*} \]

\[ \begin{align*}
P_1 & \quad E_2 & \quad P_2 & \quad E_3 & \quad P_3 & \quad E_4 & \quad P_4 & \quad E_1 \\
\end{align*} \] (7)

The result will not change if the role of the polarized/unpolarized bunches is different from (6) i.e. if the polarized bunches are P2 P4 and E2 E4.

VII. SUMMARY

Plans for transverse polarization in LEP are summarized. The layout of the laser polarimeter is introduced and schemes for compensation of depolarizing effects from the experimental solenoids are presented.

A possible scheme to obtain longitudinally polarized beams without important modifications to the machine layout is discussed together and a way to produce e+ e- interactions with non-zero helicity is suggested.

The ideas presented here have to be developed in the near future and a feasibility study has to be worked out.

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X. FIGURE CAPTIONS

Fig. 1 General layout of the LEP polarimeter in LSS1.
Fig. 2 Effect of asymmetric dipole wigglers on polarization rate.
Fig. 3 Degree of polarization vs. energy for an r.m.s. closed orbit
distortion of 0.35 mm.
Fig. 4 Block diagram for closed orbit correction scheme.
Fig. 5 Example of energy calibration at PETRA using the depolarizing
technique.
Fig. 6 Scheme for longitudinal polarization at LEP.
Fig. 7 Total angular momentum at each I.P. when all the bunches are
polarized.
Fig. 8 Non-zero helicity at the four I.P.'s when two out of four
bunches per beam are polarized.
Fig. 2

Fig. 3

\[ Q_x = 70.35 \]
\[ Q_y = 78.20 \]
\[ Q_z = 0.08 \]
\[ \langle Z \rangle = 0.35\,\text{mm} \]
Fig. 4

Fig. 5
polarizer

arc($\Delta \phi = 2n\pi + \pi/2$)

$\pi$ rotator

Fig. 6
Fig. 7

Fig. 8