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RECENT DEVELOPMENTS IN STORED POLARIZED ELECTRON POSITRON BEAMS*

R. Rossmanith
CEBAF
1200 Jefferson Av., Newport News, VA 23606, USA

Introduction

In nearly all electron or positron storage rings the beams are polarized vertically by the Sokolov-Ternov effect. The existence of polarized beams was established both in low energy rings such as ACO[1] (the first storage ring in which the Sokolov-Ternov polarization effect was measured), BESSY[2] or VEPP2[3] and in high energy rings such as TRISTAN[4], HERA[5] and LEP[6]. As a result beam polarization seems to be an inherent property of electron positron rings. It should be noted that this free polarization was never used for high energy experiments except in those instances in which exact energy calibration measurements were performed[7]. Proposals for using stored polarized beams for internal target experiments (for instance HERMES[8] and HELP[9]) are fairly new. Experiments with polarized longitudinal beams in LEP[10] are also still in the stage of planning.

The aim of this paper is to summarize the efforts of the last years in order to arrive at a better understanding of the spin dynamics in electron positron storage rings and to compare the experimental results with the theory. In the following polarimeters are not discussed. An excellent overview of modern polarimeters can be found for instance in[11]. The most advanced polarimeter, at the moment the LEP polarimeter, is described in more detail in[12].

Almost 6 years ago here in Trieste a paper was presented[13] which questioned the generally accepted assumption that a horizontal polarization component cannot survive in a storage ring. In the meantime, many (mostly unpublished) papers have dealt with this subject. The first one was a hand-written note by A. Chao[14] written 5 years ago during a visit at CERN followed by a note from C. Prescott[15].

Whether or not a horizontal component can survive for a sufficiently long period of time has practical consequences. Since most experiments require longitudinal polarization, the beam can be polarized by asymmetric wigglers[16] somewhere outside the experiment and the arc can be used as a spin rotator. Experiments with polarized beams would than become significantly easier and cheaper.

In the following the principal considerations on depolarizing effects are summarized.

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Afterwards the stability of a horizontal component is discussed and the conclusions are compared with measurements.

What are the Depolarizing Mechanisms in Storage Rings?

Spin motion and particle motion are related to each other. The spin is precessing around the direction of the field by an angle ϕ when the particle is deflected by an angle α by the same field. Both angles are directly related to each other:

$$\frac{(g-2)}{2}\gamma\alpha = a\gamma\alpha = \phi \tag{1}$$

γ is the Lorentz factor, $\frac{(g-2)}{2}=a$ is the anomalous magnetic moment. The spin is a unity vector moving on a sphere.

Equation (1) can be interpreted in the following way. Consider two particles with aligned spins and trace them through a storage ring: as long as their energy is the same and as long as they see the same fields (in other words experience the same α), the spins stay parallel for ever and the beam stays polarized. Particles see different fields when their trajectories are slightly different. In other words: depolarization is the consequence of the finite energy spread of the beam and the nonvanishing transverse beam dimensions.

In principle there are two different kinds of depolarizing resonances: integer resonances and resonances driven by betatron and synchrotron frequencies. Both resonances are based on a completely different mechanism.

A. Integer Resonances

In an electron storage ring the bending magnets polarize the beam vertically. Since the particle can be polarized at an arbitrary time in any bending magnet the direction of the net beam polarization has to be vertical in these magnets. Otherwise the net degree of polarization is reduced. How much it is reduced depends on the magnitude of the deviation. This statement is of course no longer true when the particles become polarized only in more or two (extra strong) magnets. This case will be discussed later.

In the general case where the bending magnets of the whole machine are used to polarize the beam the degree of polarization is calculated by the following method. Select a particle which moves strictly on the closed orbit. Find a spin direction along the closed orbit which repeats itself after one revolution. If the closed orbit is the ideal orbit going through the center of the quadrupoles, the closed solution is everywhere vertical. In general, there is only one closed spin solution called (for historical reasons) n-axis for the same reason that there is in general only one closed orbit.

As mentioned before, for a purely vertical n-axis the spins of the particles can be perfectly aligned. Assuming only vertical closed orbit distortions the spin direction is altered by kicks $\Delta z_i'$ in the quadrupoles. In the bending magnets in between the quadrupoles the spin is rotated by an angle α_i around the vertical axis. The vertical kicks in the quadrupoles change the direction of the n-axis:

$$|\delta n| = \frac{(1+\gamma \mathrm{a})}{2(1-\cos 2\pi\gamma \mathrm{a})}\left(\sum_{i=1}^{N}(sin(\mathrm{a}\gamma\alpha_i)\Delta z_i')^2 + \sum_{i=1}^{N}(\cos(\mathrm{a}\gamma\alpha_i)\Delta z_i')^2\right) \tag{2}$$

a formula which can be interpreted as a Fourier sum[17].

At the resonance $\cos(2\pi\gamma a)$ becomes 1 and the n axis is no longer defined. From a mathematical point of view the formalism fails and other techniques described later must be applied.

B. Betatron- and Synchrotron Resonances

In electron positron storage rings the particles perform damped synchrotron and betatron oscillations. Considering for a moment only damped betatron oscillations

$$\delta z(t) = \delta z_\beta(t)e^{-t/\tau_z} + \delta\epsilon cos(\psi_s(t))D_z(s)e^{-t/\tau_s} \tag{3}$$

δz_β is the betatron amplitude, $\delta\epsilon$ the relative change in energy, ψ_s is the synchrotron phase, D_z is the vertical dispersion and τ are the corresponding damping times. The variable s is the path length and is used for magnitudes varying along the circumference but are constant from revolution to revolution, t is used for magnitudes varying from revolution to revolution. The strength of these resonances can be expressed in the well-known way as a Fourier integral[17]:

$$b_z(s) = C(s)\frac{e^{2\pi i(\mathrm{a}\gamma \pm Q_z)}}{e^{-2\pi i(\mathrm{a}\gamma\pm Q_z)} - 1}\int_{s_0}^{s_0+L} e^{\pm i\psi_z}e^{i\phi}\sqrt{\beta_z}k(s)ds \tag{4}$$

where Q_z is the vertical Q-value, s_0 the point of emission, L the circumference of the ring, ψ_z the betatron phase, ϕ the spin phase, β_z the vertical beta function, k(s) the strength of the quadrupole gradient field and C(s) a parameter depending on the position of the photon emission.

The integral also can be developed into a Fourier sum. Equation (4) describes the fact that after the emission of a photon and many damping times the spin does not come back into its original position unless the integral is exactly zero. This effect is sometimes called spin diffusion.

C. Comparison of the two Depolarizing Effects

If we compare the description of the two resonances with the general description as presented at the beginning of this chapter, we must draw the conclusion only the betatron depolarization resonance is in agreement with this definition. In this definition it was stated that depolarization occurs when different fields act on the the particles. This is true for the betatron resonance but not necessarily true for the integer resonance. In order to explain this an example is given: the acceleration of a beam through an integer resonance.

When a beam is accelerated through an integer resonance, the following happens. Before the beam reaches the resonance the n-axis is vertical. In the proximity of the resonance the n-axis deviates from the vertical (described by equation 2), the polarization begins to rotate around the changing n-axis. After the resonance the n-axis is vertical again, the remaining polarization is described by the famous Froissart-Stora equation[18].

In principle the following can happen: the spins rotate around the n-axis but stay together. From a physics point of view the beam remains polarized although a polarimeter integrating over many revolutions would find out that the beam is unpolarized.

Summarizing these statements: in a storage ring these two resonances, $a\gamma = \pm n$ (integer resonance), and $a\gamma = n \pm Q_z$ are totally different. The betatron resonance is driven by quantum excitation and is (almost) unavoidable in a storage ring. The integer resonance leads in first order to a distortion of the direction of polarization and than, as a consequence, to a possible depolarization.

D. Machines with concentrated Sokolov-Ternov Polarizers

It was suggested for LEP that the beams are polarized by so-called asymmetric wigglers[16]. The asymmetric wigglers polarize the beams on a certain position of the circumference. The bending magnets of the rest of the machine are not or insignificantly contributing to the polarization. Since the n-axis in the machine is in general vertical, everything seems to be fine when the wigglers polarize the beam into the vertical direction.

Bearing the previous statement in mind that polarization outside the n-axis could (possibly) survive, the following experiment can be proposed[13]. The wigglers could be used to polarize the beam in the radial direction and the arc could be used to rotate the spin into the longitudinal direction. Experiments with longitudinal polarization could become very simple.

During the last years this opportunity was studied and the results compared with (the few) experimental facts. The theoretical investigations are mainly distributed as internal notes, so that they are not easily accessible [14 15 19]. Recently Koutchouk[20] has summarized the basic ideas in a CERN note.

In the following, the concept of the argumentation is briefly sketched. The beam is polarized somewhere in the straight section by an asymmetric wiggler. The wiggler polarizes the beam in the horizontal direction. The spin tune is an integer.

Without quantum excitation the particles would perform undamped synchrotron oscillations around the central energy:

$$\delta\gamma = \delta\gamma_o sin(\omega_s t + \phi) \tag{5}$$

ν_{spin} (the number of spin rotations for one revolution) varies according to equation (1): $\nu_{spin} = a(\gamma + \delta\gamma)$. The spin of a particle with $\gamma + \delta\gamma$ oscillates around the spin of a particle with γ. In such a system polarization does not reach the highest possible value but remains stable at that value. It is assumed that the beams are flat. In a real machine this undamped oscillation becomes damped:

$$\delta\gamma = \delta\gamma_0 sin(\omega_s t + \phi) e^{-\frac{t-t_0}{\tau}} \tag{6}$$

After an infinite time the spin of the off-energy particle deviates from the on-energy particle by the following amount:

$$\delta\phi_{spin} = \int_0^\infty a\delta\gamma dt \tag{6}$$

The depolarization effect is in nature similar to the depolarization effect caused by betatron oscillations.

Taking into account the number of emitted photons per second leads to the decay time of the polarization[20].

$$\tau_{spin} = \frac{2\pi^2 \tau_\epsilon^3 Q_s^4}{t_{rev}^2 \nu_{syn}^2 (\sigma_\epsilon / E)^2} \tag{7}$$

τ_ϵ is the energy damping time, Q_s the synchrotron tune, t_{rev} is the revolution time and ν_{syn} is the synchrotron frequency. For LEP the decay time of the polarization is circa 15 min. According to first calculations Prescott's[15] the horizontal decoherence time is 45 msec.

Experimental Verification

It is necessary to verify this result experimentally. Koutchouk[20] mentioned that two experimental facts support this result:

a) the relatively high RF field required for the complete depolarization of the LEP beam by an RF kicker;

b) The existence of a stable longitudinal polarization component in the TRISTAN storage ring.

A. The LEP measurements

In the following the LEP results are discussed in more detail. The experiment was as follows. The beam was allowed to get polarized in the vertical direction. In order to simulate an integer resonance an external RF field was applied. The naive picture is now the following. When the frequency of the RF field coincides with the spin motion the beam is rotated revolution by revolution a little bit further from the vertical direction into the horizontal. As a result a horizontal spin component was generated and the decay of this component was observed.

In LEP it was found experimentally that an RF-field of $\approx$ 5 Gauss.meter was required to depolarize the beam completely. The measured depolarization time was circa 10 sec. 24 kGauss.meter are required to rotate the spin by 90 degrees. Therefore the spin was rotated within 500 msec or 5.10^3 revolutions by 90 degrees. The 10 seconds correspond to 4 full rotations (360 degrees) of the spin before the beam is totally depolarized.

It is astonishing that the result seems to be in disagreement with both calculations: although it definitely prooves that the 45 msec theory is wrong, it does not agree with the 15 minutes theory.

B. RF-depolarization

The depolarization mechanism for LEP (spin tune of 100 and higher) is fairly complicated. In the following it is assumed that the original polarization is completely vertical. The spin is bent from the vertical by an RF-kicker and rotates in the storage ring around the vertical axis. The next passage through the RF-kicker either increases the deviation from the vertical axis or decreases it.

The spin motion can be calculated by matrix multiplication. For a perfectly flat beam the transfer matrix for one revolution is

$$\begin{pmatrix} s_x \\ s_y \\ s_z \end{pmatrix} = \mathrm{M_{ring}} \mathrm{M_{RF}} \begin{pmatrix} s_{x_0} \\ s_{y_0} \\ s_{z_0} \end{pmatrix} \tag{8}$$

where s are the spin directions and M are matrices describing the spin motion caused by the ring bending field and the kicker. $\mathrm{M_{ring}}$ is a matrix describing a rotation around the vertical axis, $\mathrm{M_{RF}}$ a matrix describing a rotation around the radial axis.

It should be noted that for a non-flat beam the ring matrix has to be broken up into matrices describing the rotation in one bending magnet followed by a matrix describing the vertical kick in the quadrupole by using the $\Delta z_i'$'s of equation (2). For the sake of simplicity only flat beams are considered in the following.

C. The influence of the energy spread on depolarization

The elements of the matrix in equation (8) are defined by equation (1). The spin rotations are $a\gamma$ times the bending angles. The bending angle for the whole ring is 2π.

Consider two particles: one with the central energy and one with an energy deviation of 10^{-3}. The spins of both particles are bent by the kicker from the vertical and they are oscillating in the ring around the vertical direction. Since their energy is different their spin motion is different.

With $a\gamma \approx 100$ the spin of a particle with no energy deviation differs after one revolution by 36 degrees from the spin of a particle with an energy deviation of 10^{-3}. Particles with energy deviations perform damped synchrotron oscillations around the central energy (equation 6).

With a synchrotron tune of 0.03 the synchrotron wavelength is circa 33 revolutions long. The spin deviation between the two particles accumulates over a quarter wavelength (33/4 revolutions) and becomes close to 180 degrees.

As a result, the spin of the on-energy particle is bent in a different way than the off-energy particle by the kicker. If the kicker increases the deviation from the vertical for the on-energy particle, it decreases it for the off-energy particle. The spins become incoherent as a result of this effect and the beam is depolarized.

D. Numerical Estimation of the Strength of this Depolarizing Effect

The exact calculation of spin behaviour has to take into account the 3-dimensional rotation on a sphere and is therefore very complicated due to the non-commutative motions on a sphere. It can only be simulated by tracking programs. In the following only a very simple estimation of the strength of the depolarization is presented.

The easiest way to calculate this effect is when the non-integer spin tune is 0.5. The spin of the on-energy particle arrives at the kicker at 0 degree during the first revolution, at 180 degree at the second revolution and again at 0 degree at the third revolution (see fig. 1 for angle definitions).

For the sake of simplicity, it is assumed that RF kicker affects the spins of the on-energy and the off-energy particle in the same way when their deviations are less than ± 90 degrees. They are kicked in the opposite direction when the the spin deviation is more than ± 90 degrees (see fig. 1 for angle definitions). As mentioned above the maximum deviation of the spins of the two particles are expected to be close to 180 degrees or twice the tolerated difference of 90 degrees. The amplitude of the 180 degree oscillation decays with τ_ϵ and is 90 degree at the time t_1:

$$e^{\frac{-t_1}{\tau_\epsilon}} = 0.5$$

or

$$t_1 = \tau_\epsilon ln(2)$$

In this simplified assumption, the spin of the off-energy particle is kicked by the RF-field during the first 0.7 damping times both towards and away from the vertical direction. As a result both spins are differently affected and the beam gets partly depolarized.

In order to ascertain how strong this effect really is, it has to be calculated how long the particle is outside the "magic" $\pm$ 90 degree boundary.

For an exponential function $x = Ae^{\frac{-t}{\tau}}$, x becomes 1 when t=t_1: $t_1 = \tau lnA$. 1 corresponds in the following to 90 degrees, 2 to 180 degrees etc. In order to find the average value in which the spin of the off-energy particle is outside the 90 degree boundary the time $t_1/2$ is taken as a representative value. Taking a 180 degree period of the synchrotron oscillation the average period in which the spin is outside the amplitude of 1 (90 degrees) is

$$< \Delta > = 2arcsin\left(\frac{1}{A}e^{\frac{lnA}{2}}\right)$$

For A=2 (180 degrees) $< \Delta >$ is 90 degrees.

As a result: the particle spin is kicked for the period of 0.7τ in both directions, towards the vertical and from the vertical. The spin is therefore during this period for this particle (in first order) not affected at all.

For LEP, τ_ϵ is 32 msec, $0.7\tau_\epsilon$ is therefore 22.4 msec. 500 milliseconds are required to rotate the spin by 90 degrees for the on-energy particle. The spin of the off-energy particle is rotated during this time only by (90-4.5) degrees.

E. Conclusion

The depolarization effect caused by the high spin tune and the energy spread in LEP is much stronger than the effect described in (7) ("horizontal decoherence") and is therefore dominating.

This effect may also explain why the high field of 5 Gauss.meter is needed to depolarize the beam. The depolarization is mainly caused by this effect and not by the "horizontal decoherence time". The strength of the RF has to be so big that the kicker has to rotate the spin significantly during several damping times of the energy oscillation.

Nevertheles, it is clear that the "horizontal decoherence time" is significantly longer than 45 msec.

Engineering Polarized Experiments in Storage Rings

Most of the proposed experiments require longitudinal polarization. In a low energy storage ring where the beams are polarized by all the bending magnets of the ring the spin has to be vertical in the magnets and is rotated in front of the experiment into the longitudinal direction by so-called spin rotators and afterwards back into the vertical direction[21].

When the "horizontal decoherence time" is really long for LEP and possibly also for HERA a different solution exists. The idea presented for the first time in [13] is sketched in fig. 2. In an appropriate corner of the ring an asymmetric wiggler is installed which is able to polarize the beam into the longitudinal direction. The whole arc is used as a spin rotator. The spin direction in the experiment is longitudinal.

This idea is working as long as $a\gamma$ is an integer.

The situation becomes more difficult when the experiment requires an $a\gamma$ which deviates from an integer (e.g. when an energy scan is required) or when the energy stability of the energy is not sufficiently high (energy drifts).

This problem can be solved in several ways: by a 180 degree spin rotator opposite to the wiggler[13] or by rotating the spin over a certain distance in the arcs into the vertical direction.

In order to maintain the polarization spin matching conditions have to be applied. One possibility is to use vertical beam bumps[22] for adjusting the spins of the particles. It was shown that a properly selected vertical beam bump can delay or advance the spins relative to $\delta\gamma$. This is especially easy in LEP since, as discussed before, $a\gamma$ is in the order of 100. Small vertical and horizontal deflections can produce significant spin deviations.

Summarizing: a high "horizontal decoherence time" would open many new possibilities in polarized beam physics. It is very important to measure more accuratly the decoherence time.

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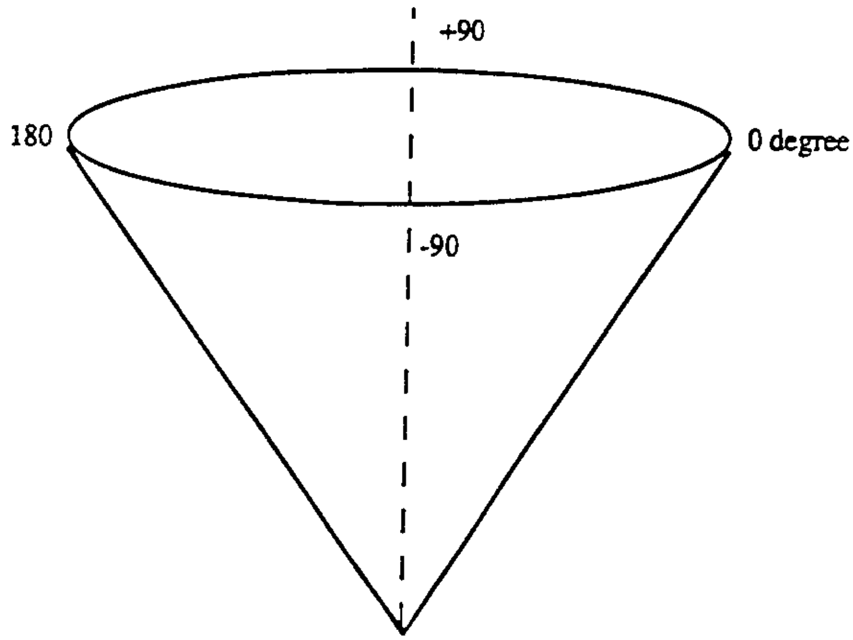

Fig. 1 Definitions of angles (see text)

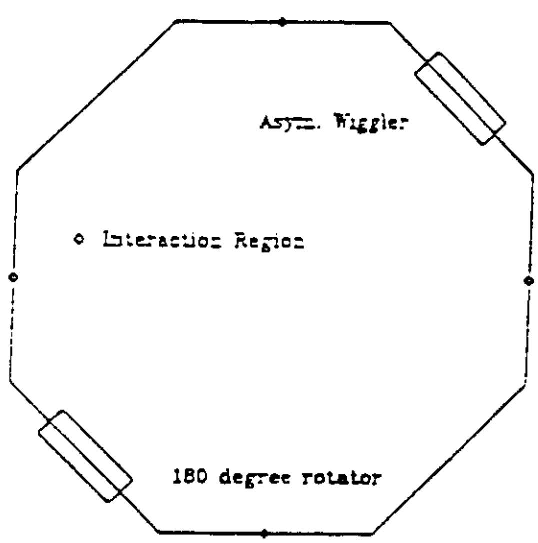

Fig. 2 Schematic diagram of LEP with a wiggler polarizing the beam in the radial direction and an 180 degree spin rotator