SLAC-PUB-2600
September 1980
(A)

PROBLEMS IN OBTAINING POLARIZED e^+ AND e^- BEAMS AND PERSPECTIVES FOR PEP*

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BSTRACT

A matrix formalism for polarization calculation, as well as its omparison with other methods, is briefly discussed. The prediction for PEAR is compared with experimental measurements. An estimate is offered or the transverse polarization for PEP. Various schemes for obtaining he longitudinal polarization in PEP are studied.

NTRODUCTION

As we know, PEP has now been officially dedicated to do high energy hysics experiments. Beam polarization, among other things, will soon be easured. It is perhaps useful to summarize what we expect theoretically or the polarization before we make the measurements.

I will first describe a matrix method that is used in our polarizaion calculation. This method is applied to give estimates of the polariation expected for SPEAR and PEP. The SPEAR results are compared with he existing experimental data. Conditions for obtaining a significant ransverse polarization in PEP are discussed. Also included is a study f a few longitudinal polarization schemes as they are applied to PEP.

OLARIZATION AND DEPOLARIZATION

The spin polarization of a stored beam can potentially reach a level f 92%. The mechanism[1] for this is that, during the process of synchroron radiation in a magnetic field, the spin transition rate from the up tate to the down state is not equal to the transition rate from the down tate to the up state. The beam accumulates a net polarization as a esult.

It turns out that the very mechanism that gives rise to polarization, amely the synchrotron radiation, is also the main cause for depolarizaion.[2,3,4] As an electron emits a synchrotron photon, it receives a ecoil perturbation which excites its subsequent oscillatory orbital moions. The electron then sees a perturbing electromagnetic field, which s modulated by these orbital oscillation frequencies, causing its spin o precess. Summing over the uncorrelated photon emission events results n a diffusion of spin direction and hence a depolarization of the elecron. This depolarization is especially strong when the spin motion is oupled to the oscillatory orbital motions under resonant conditions.

The achieved level of polarization is determined by an equilibrium etween the polarizing and the depolarizing effects of the synchrotron adiation. The strength of the polarizing effect is already well-known.[1] he depolarization strength, on the other hand, depends on details of the torage ring operation. In order to calculate the depolarization strength ne needs to know how the spin and orbital degrees of freedom of an

Work supported by the Department of Energy, contract DE-AC03-76SF00515.
Invited talk presented at the 1980 International Symposium on High-Energy Physics with Polarized Beams and Polarized Targets, Lausanne, Switzerland, September 25 - October 1, 1980.)

electron couple among themselves. This is conveniently achieved by the matrix method [5] described below.

MATRIX METHOD

It is well-known [6] that in order to fully describe the orbital motion of an electron, one needs six canonical coordinates $(x, x', y, y', z, \delta)$, where x, y and z are the horizontal, vertical and longitudinal displacements of a particle relative to the trajectory of the beam center; $\delta=\Delta E/E_0$ is the relative energy error. In the linear approximation, the transformations of the six-dimensional vector as the electron travels through electromagnetic devices of the ring are described by 6×6 transport matrices.

In the matrix formalism, spin motion is included by adding two more spin coordinates (α,β) to the six-dimensional vector:

$$X = \begin{bmatrix} x \\ x' \\ y \\ y' \\ z \\ \delta \\ \alpha \\ \beta \end{bmatrix} \tag{1}$$

The quantities α and β are the Cartesian components of the deviation of the unit spin vector from its nominal direction $\hat{n}$; i.e., the spin direction is $\hat{n}+\alpha\hat{m}+\beta\hat{\ell}$, where $(\hat{n},\hat{m},\hat{\ell})$ form an orthonormal set of unit vectors. We assume $|\alpha|,|\beta| \ll 1$. The degree of depolarization of this electron is $(\alpha^2+\beta^2)/2$. The beam polarization, averaged over an ensemble of electrons, is along $\hat{n}$. The 8×8 transformation for X through a given electromagnetic device looks like

$$\left[\begin{array}{c|cc} \text{TRANSPORT} & \multicolumn{2}{c}{0} \\ \hline D & \begin{matrix} 1 & 0 \\ 0 & 1 \end{matrix} \end{array}\right] . \tag{2}$$

where TRANSPORT is the usual 6×6 transport matrix describing the transformation among the orbital coordinates; the upper right corner is a 6×2 matrix filled by 0's since the influence of spin on the orbital motion is negligible; the 2×6 matrix D is obtained from the spin precession equation of motion [7] in the electromagnetic field (linearized with respect to the orbital coordinates) of the device under consideration. The twelve elements of D are the spin-orbit coupling terms that are responsible for the spin diffusion.

Knowing the lattice of a given storage ring, we multiply the transformation matrices of all the EM devices successively around the ring, starting with position s, to obtain a total transformation matrix for one revolution. It will be designated by T(s). T(s) has four eigenstates: three orbital states and one spin state; each eigenstate being defined by a complex conjugate pair of eigenvectors of T(s). Any perturbation to the vector X at position s, such as the recoil perturbation resulted from emitting a synchrotron photon, can be projected onto the four eigenstates. The projections onto the orbital states give the contribution of this perturbation of the x,y,z-emittances, while the projection onto the spin state gives the contribution to spin diffusion.

More specifically, let the eigenvectors of T(s) be $E_k(s)$, $k = \pm I, \pm II, \pm III, \pm IV$. Let the fourth pair $E_{\pm IV}$ belong to the spin eigenstate and the other three pairs belong to the orbital states. The perturbation of emitting a photon whose energy deviates from the mean value by δE is given by

$$\delta X = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -\delta E/E_0 \\ 0 \\ 0 \end{bmatrix} \qquad (3)$$

Decomposing into eigencomponents, one has

$$\delta X = \sum_k A_k E_k(s) \qquad (4)$$

The projection coefficients $A_{\pm I,\pm II,\pm III}$ give the contributions of synchrotron radiation to the x,y,z-emittances. The coefficients $A_{\pm IV}$ give the contribution to spin diffusion.

In a storage ring, the diffusion in the x,y,z-emittances are counteracted by the usual radiation damping. [8] The balance between these two effects determines the equilibrium emittances of the beam. Similarly the diffusion in spin is balanced by the radiative polarization effect and the balance between them determines the equilibrium level of beam polarization, P_0. Table 1 summarizes the analogy. Since the beam emittances are routinely calculated by using matrix techniques, one expects to be able to calculate P_0 with similar accuracy by using the matrix method.

Table 1. Analogy Between the Physics of Beam Emittances and Beam Polarization.

	Diffusion ⟷	Damping	Equilibrium
orbital motion	quantum excitation $A_{\pm I,\pm II,\pm III}$	radiation damping	x,y,z-emittances
spin motion	spin diffusion $A_{\pm IV}$	radiative polarization	beam polarization

COMPARISON WITH ANOTHER METHOD

Another existing method [3,4] that calculates the polarization utilizes a Fourier harmonic analysis of the electromagnetic field configuration of the storage ring. It has been discussed in a previous talk by Professor Buon. [9] The key quantity in this language is a vector designated as $\gamma\partial\hat{n}/\partial\gamma$, which is a function of position s. The eigenvectors of the matrix method and the $\gamma\partial\hat{n}/\partial\gamma$ in the harmonic method are actually connected:

harmonic method matrix method

$$\gamma\partial\hat{n}/\partial\gamma = -2 \sum_{k=I,II,III} \mathrm{Im}\left[E^*_{5k}E_{7k}\hat{m} + E^*_{5k}E_{8k}\hat{\ell}\right] \quad (5)$$

where $(\hat{n},\hat{m},\hat{\ell})$ is the orthonormal set of unit vectors mentioned before with $\hat{n}$ the direction for the net beam polarization and E_{ik} the i-th component of E_k. With the above connection, the two methods are in principle equivalent. However, due to their different ways of analysis, they do have different regions of applicability and Eq. (5) holds only in the mutually applicable regions. It might be helpful to spend a few minutes on the comparison between these two methods. The comparison is summarized in Table 2.

Table 2. Comparison of Two Ways of Polarization Analysis

Method	Key Quantity	Nonlinear Resonances	Dominant Resonances for PEP	Application to LEP
matrix	E_k $k=\pm I,\ldots,\pm IV$	no	$\nu\pm\nu_{x,y,s}=n$	straightforward
harmonic	$\gamma\frac{\partial\hat{n}}{\partial\gamma}$	yes	$\nu=n$	multiple resonance crossing

A. In general, depolarization effect is enhanced near a resonance condition $\nu+n_x\nu_x+n_y\nu_y+n_s\nu_s=n$, where ν is the spin precession tune,† $\nu_{x,y,s}$ are the horizontal-betatron, vertical-betatron and synchrotron tunes, respectively; $n_{x,y,s}$ and n are integers (positive, negative or 0). The matrix method takes into account the integer resonances $\nu=n$ and, for each integer resonance, the six associated sideband resonances $\nu\pm\nu_{x,y,s}=n$. All higher order resonances are excluded from the matrix method, which is necessarily linear in nature. The harmonic method, on the other hand, takes into account the nonlinear resonances $\nu+n_x\nu_x+n_y\nu_y=n$. (Resonances involving synchrotron motion are usually ignored.)

B. In general, the integer resonances are negligibly weak in the matrix language, but since ν_s is generally much smaller than unity, the two synchrotron sidebands $\nu\pm\nu_s=n$ and the $\nu=n$ resonance overlap to form a single depolarization dip near the $\nu=n$ region. The harmonic method, on the other hand, ignores the synchrotron oscillation so that the integer resonances play the most important role. Furthermore, it is found in the analysis using the harmonic method that the betatron sidebands $\nu\pm\nu_{x,y}=n$

† In most practical cases, ν is very close to the value $(g-2)\gamma/2=E_0/440$ MeV with g the gyromagnetic ratio of the electron and γ the Lorentz factor. Note that ν is proportional to the particle energy.

are, in many practical cases, negligible;[3,4,10] while the matrix analysis seems to say that the betatron sidebands are important.

C. The harmonic method treats each resonance individually. The matrix method treats all linear resonances simultaneously and is sometimes useful when there is no single resonance playing the dominant role. For example, when the beam energy spread is of the order of or larger than the spacing of resonances (440 MeV) as is the case of LEP, the energy (and hence the spin tune) of a typical electron oscillates sinusoidally across two or more resonances during synchrotron oscillation.[11] The analysis that assumes separated single resonances must be modified. To do a calculation for LEP, the harmonic method establishes a concept of resonance crossing and includes a subtle analysis of the interference between resonances[4,11,23] during the synchrotron oscillation of an electron. Such modifications are not needed if one uses the matrix approach.

SPEAR

A computer code has been prepared for the polarization calcuation. It essentially multiplies a large number (~400 for SPEAR and 1500 for PEP) of 8×8 matrices and calculates the eigenvectors of the resultant matrix. The polarization is obtained from the eigenvectors according to the matrix method.

Without field imperfections, the ideal storage ring produces an equilibrium polarization[1] of 92%. To simulate field imperfections for SPEAR we introduce a random distribution of vertical orbit kickers. The produced vertical orbit distortion introduces more field imperfections in the sextupole and the quadrupole magnets. The rms orbit distortion after orbit correction is $\Delta y_{rms} = 1.2$ mm, which is typical for SPEAR operation. The resulting polarization P_0 is plotted in Fig. 1 as a function of the beam energy E_0 for a typical SPEAR configuration. Locations of the integer and the sideband resonances are indicated by arrows at the top of Fig. 1.

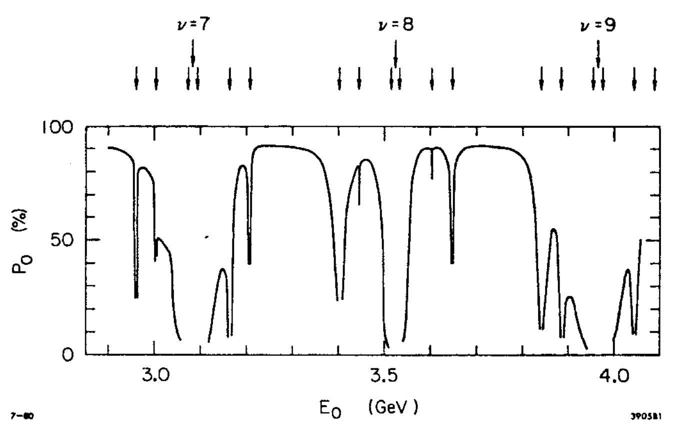

Fig. 1. Expected polarization P_0 versus beam energy E_0 for a typical SPEAR configuration.

Part of Fig. 1 is replotted in Fig. 2 with expanded horizontal scale. Superimposed are some data points taken by the SPEAR laser polarimeter team.[12] The data show three resonances in the energy range of Fig. 2. One first notices that the nonlinear resonance $\nu - \nu_x + \nu_s = 3$ is completely missed by the matrix method. This is expected as explained before. However, as long as the nonlinear resonances do not occupy a very wide range in energy, they can be regarded as fine corrections and ignored in our first effort of estimating the beam polarization.

(This should not be too disturbing since we are used to ignoring the nonlinear betatron resonances when calculating the beam x,y,z-emittances.)

One then notices that the resonance $\nu - \nu_y = 3$ predicted by the matrix method is too narrow compared with the experimental data. This discrepancy is attributed to the fact that the vertical betatron tune ν_y has a finite spread. Indeed the spread in ν_y indicated in Fig. 2) is comparible to the measured resonance width. Here again, we are not really concerned about those narrow resonances whose widths are dominated by the tune spreads; they can be easily avoided by a slight change in beam energy or a shift in the betatron tune.

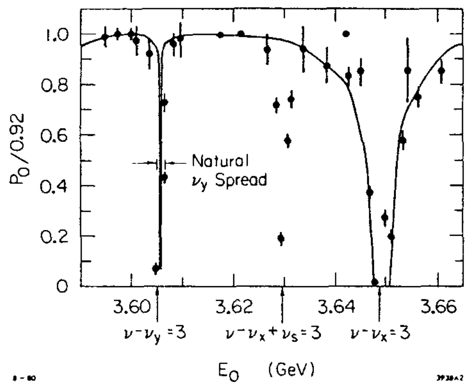

Fig. 2. Part of Fig. 1 with expanded horizontal scale; some data points are superimposed.

The third resonance $\nu - \nu_x = 3$, in Fig. 2 has a width wider than the tune spread and the prediction by the matrix method agrees with the experimental data. It is about those wide resonances that we are most concerned in terms of the achievable level of beam polarization. As we will see later, most of the linear sideband resonances for PEP are much wider than the tune spreads. The matrix method, therefore should be adequate for PEP.

I mentioned that the nonlinear resonances can be ignored. This is in fact an oversimplification. One example in which nonlinear depolarization resonances play an important role is the effect of the beam-beam collisions. When two beams collide in a storage ring, the spin of a particle experiences the highly nonlinear electromagnetic field produced by the charges of the on-coming beam. The problem is not that the beam-beam perturbation is so extremely strong, but that it is potentially capable of exciting a large number of depolarizing resonances. The locations of resonances in this case are $\nu + n_x\nu_x + n_y\nu_y = n$ with n_x = even and n_y = odd, plus their synchrotron sidebands. Given the beam energy and hence ν, there is almost always a depolarizing resonance nearby with some n_x and n_y.

The beam-beam depolarization has been studied theoretically using the harmonic method.[13] It was concluded that as long as the beam intensity is such that the orbital motions of a particle is stable against the beam-beam perturbation, as it must always be the case, then in between the infinitely dense population of depolarizing resonances, there exist regions of good beam polarization. The analysis is a very difficult one. This is not surprising since the problem of exactly how the beam-beam perturbation affects the orbital motions of a particle is already extremely difficult and its effect on the spin motion can only be more so.

The SPEAR polarimeter group has looked at the beam-beam depolarization experimentally.[12] They found that in regions of good single-beam polarization, the polarization is maintained in some energy regions while destroyed in some other regions with colliding beams. So far we do not yet have a good explanation for these results, but the main point here is that in a significant part of the energy range the polarization is not destroyed by the beam-beam collisions.

PEP

Calculations have also been done for PEP. The field imperfections are again assumed to come from a distribution of random vertical orbit kickers, but since the orbit correction scheme is more sophisticated in PEP than in SPEAR, we assume that the rms orbit distortion after orbit correction is $\Delta y_{rms} = 0.6$ mm, which is half of what we assumed for SPEAR. The polarization P_0 is plotted vs beam energy E_0 in Fig. 3. The configuration used has $\nu_x = 21.15$, $\nu_y = 18.75$ and $\nu_s = 0.05$.

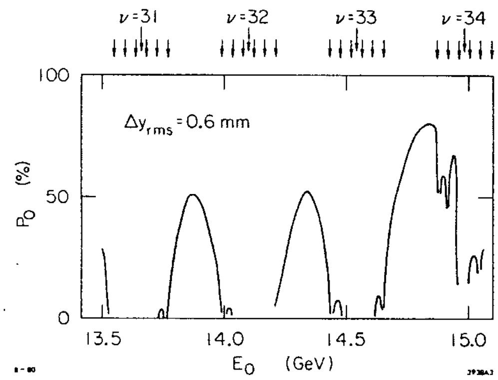

Fig. 3. Expected polarization P_0 versus beam energy E_0 for a PEP configuration.

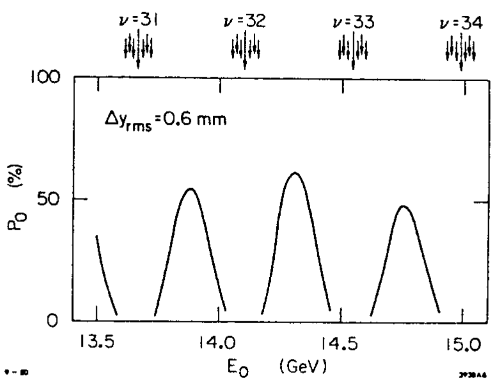

Fig. 4. Same as Fig. 3, but for a different PEP configuration.

The polarization is significant when the spin tune is far away from the sideband resonances. For the configuration studied, this occurs when ν is close to half-integral values. In particular, we find $P_0 \sim 50\%$ around 18.8 GeV ($\nu \sim 31.5$), 50% around 14.3 GeV($\nu \sim 32.5$) and 80% around 14.8 GeV ($\nu \sim 33.5$). Note that if the orbit distortion after applying the same maximum number of correctors is corrected to 1.2 mm rather than 0.6 mm, P_0 will decrease; for example, 50% becomes 20% and 80% becomes 60%. Control of the vertical orbit is crucial in order to obtain a respectable polarization.

Fig. 4 shows the result of a similar calculation for a different PEP configuration with $\nu_x = 21.88$, $\nu_y = 18.92$ and $\nu_s = 0.05$. The orbit distortion is again assumed to be $\Delta y_{rms} = 0.6$ mm after correction. The qualitative behavior of P_0 vs E_0 is essentially the same as that shown in Fig. 3.

It is necessary that the polarization at a given beam energy be maximized by shifting ν_x, ν_y around so that the spin tune is as far away from resonances as possible. The search for a possible optimum set of betatron tunes, however, is expected to require tedious efforts because the choice of tunes is not arbitrary due to, among other things, the beam-beam stability and luminosity optimization requirments.

It is also possible that one can change the strengths on a few orbit correctors to maximize P_0 empirically. We do not expect instant dramatic improvements by this method when the storage ring is operated away from depolarization resonances. Tedious efforts are again required.

LONGITUDINAL POLARIZATION

So far we have been talking about a vertical polarization in the direction $\hat{y}$ of the guiding magnetic field of the storage ring. Vertical polarization is a nice feature to have but a more useful polarization would be longitudinal, i.e., along the direction of motion of the beam. Several schemes have been invented to produce a longitudinal polarization at the collision point of the two beams in a storage ring. We have not studied all these possibilities. Those we have studied are

(a) Schwitters-Richter scheme,[14]
(b) Buon scheme,[15]
(c) Siberian snake, solenoid version,[16]
(d) Siberian snake, Montague version,[17]
(e) Double snake,[16]
(f) Collider schemes.[18,19]

In the Schwitters-Richter scheme, a series of four vertical bending magnets are inserted in the free space around the collision point as shown in Fig. 5. The polarization is bent successively by $\pi/2$, $-\pi$, π, $-\pi/2$ as the beam passes the bending magnets of this device. At the collision point the polarization is longitudinal. Outside this device, the polarization direction is restored to the vertical direction just like a conventional machine.

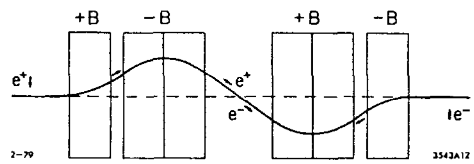

Fig. 5. Schwitters-Richter scheme for longitudinal polarization.

If we insert an S-R scheme in one of the interaction regions of PEP, the expected polarization P_0 behaves like that shown in Fig. 6. Most of the depolarization damage in Fig. 6 is caused by the $\nu-\nu_y=12$ resonance (PEP has a superperiod of six); the other possible depolarization resonances are very narrow and are not shown. The polarization level is only marginally acceptable, especially since on this figure one must superimpose the results shown in Fig. 3 or Fig. 4.

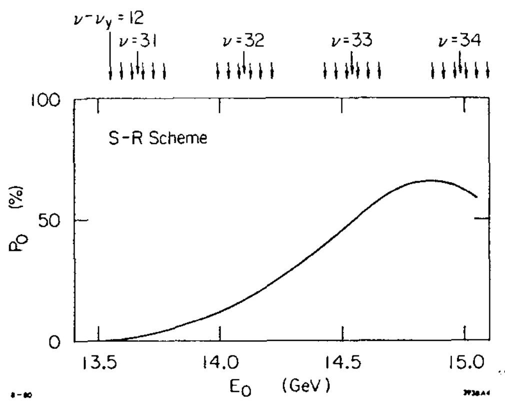

Fig. 6. Polarization for PEP with an S-R scheme inserted in one of the interaction regions.

In an S-R scheme, the vertical bending magnets must be capable of rotating the spin by large angles (π, $\pi/2$, etc.). Assuming a limited free space available, the magnetic field must be rather strong, which means synchrotron photons are heavily emitted in the S-R region. Furthermore, the vertical bending introduces vertical energy dispersion in the region. The noise caused by synchrotron radiation on particle energy can couple directly into the vertical orbital motion which in turn couples strongly to the spin motion. The main limitation of the S-R scheme is therfore due to the vertical dispersion and the strong synchrotron radiation in the S-R magnets.

The Buon scheme[15] can be regarded as a variation of the S-R scheme. An effort is made so that the amount of vertical bending is minimized by introducing a few additional horizontal bendings in the scheme. As compared with the S-R scheme, the vertical dispersion is reduced while the synchrotron radiation is enhanced. The hope of the Buon scheme is that the gain from the reduction in vertical dispersion more than offsets the loss in having a stronger synchrotron radiation. Unfortunately, this trade-off does not seem to help the polarization. When a Buon scheme is inserted in one of the PEP interaction regions, the polarization is found to be small.

A Siberian snake is a device that rotates the polarization around the direction of motion $\hat{z}$ of the beam by an angle of π. The beam polarization at the point in the storage ring exactly opposite to the Siberian snake will be longitudinal.[16] The simplest Siberian snake design is to use a solenoid. The beam polarization simply rotates around the magnetic field direction ($\hat{z}$ direction) in the solenoid. Another design that uses bending magnets, given by Montague,[17] contains three bending magnets (plus three more to restore the beam trajectory): one vertical bend of 27.4 KG-m, followed by a horizontal bend of twice the strength, and another vertical bend with -27.4 KG-m. The beam polarization rotates around the radial direction $\hat{x}$ or the vertical direction $\hat{y}$ in each of the magnets, but the net effect is a rotation around $\hat{z}$ by an angle of π. The expected polarization for both the solenoid and the Montague snake schemes is found to be small. Siberian snake schemes have, in addition to having the problem of radiation at positions where spin motion is sensitive to noise in particle energy, the problem that the equilibrium polarization direction $\hat{n}$ is perpendicular to the equilibrium polarization direction in the storage ring. As a consequence, the polarization along $\hat{y}$ built up from synchrotron radiation does not accumulate.[20] The use of Siberian snakes for proton synchrotrons, as was suggested originally, is an ingenious idea but extrapolation to electron storage rings still needs to be perfected.

Another variation of a Siberian snake scheme[16] is to insert a second snake in the region opposite to the first snake. The second snake rotates the spin around the radial direction $\hat{x}$ by an angle π. This double snake scheme solves the problem of having $\hat{n}$ perpendicular to $\hat{y}$ of the single snake schemes, but unfortunately the synchrotron radiation problem still remains. One design of double snake has been tested numerically on PEP; the polarization turns out to be small.

One very interesting possibility of longitudinal polarization is that of the collider. For example, one could collide the SLAC linac beam with the stored PEP beam.[18] The linac beam can be easily polarized longitudinally by controlling the polarization at injection. In the PEP lattice, we insert a set of by-pass magnets to displace the PEP beam vertically to meet the linac beam. The arrangement of the by-pass is identical to that of the S-R scheme. The only difference is that the by-pass is powered only when the linac particle bunch arrives at the collision point. Consequently, the stored beam is by-passed once every 757 revolutions and the depolarization strength is reduced by a factor of 757 as compared with the S-R scheme. One engineering problem is that these by-pass magnets must be very stable since jittering in their strengths is a source for spin diffusion.[21] Another more basic problem is that, although promising from the point of view of longitudinal polarization, the achievable luminosity of this SLAC/PEP collider scheme still needs to be studied more closely.[18]

Another collider scheme that looks promising in terms of longitudinal polarization and luminosity is the recently proposed SLAC linear collider.[19] Polarized e^+ and e^- beams are accelerated by the SLAC linac. At the end of acceleration they are spearated and each beam is made to follow a half-circular transport line so that the two beams collide head-on at the end of the two half-circles. The beam polarization at the collision point is controlled by the polarization at injection. Depolarization effects that are serious for a stored beam in a storage ring are not important for the transported beam in the linear collider.

It must be clearly said that, aside from the collider schemes, our studies assume that the longitudinal polarizer is inserted in the 21 meter free-space that is available in the PEP interaction region. It is possible to lengthen the space of a longitudinal polarizer so that depolarization effects caused by synchrotron radiation in the magnets of these schemes are reduced to an acceptable level. Furthermore, the conclusion that many of the schemes listed above do not provide good longitudinal polarization is valid only for PEP without a major overhaul of the storage ring lattice. With considerable efforts, it is possible that a very special lattice that does provide a good longitudinal polarization can be designed. This is especially the case thanks to the polarization term discovered by Derbenev and Kondratenko[22] for a storage ring with an inhomogeneous magnetic field configuration. Use of wiggler or laser to increase polarization are further possibilities.[9] At SLAC, the linear collider seems to be another interesting alternative at the present time.

SUMMARY

We have made an estimate of the expected transverse polarization for PEP with a single beam. It should be significant ($\gtrsim 50\%$) when the spin tune is kept away from resonances and the vertical orbit distortion is controlled to a level $\lesssim 0.6$ mm after applying the maximum number of correctors. Further improvements require careful and tedious efforts.

With colliding beams, the achievable transverse polarization is somewhat uncertain. But both existing theory and experimental data from SPEAR indicate that the transverse polarization will remain in at least part of the beam energy range of interest.

Attention must be given to a practical scheme for longitudinal polarization. There exist several schemes that work in principle. In practice, they must be made very long in order to minimize the depolarization effects of the synchrotron radiation. A practical scheme for PEP must be designed together with the storage ring lattice; details of a satisfactory solution have not yet been worked out. Our attention is also given to the possibility of longitudinal polarization in the SLAC linear collider.

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