ACCELERATION AND STORAGE OF POLARIZED ELECTRON BEAMS [a]

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I review recent developments in spin dynamics in electron storage rings and accelerators.

1 Introduction

This article provides an update on my review at SPIN96 [1] on activities surrounding spin polarization in electron storage rings and accelerators. In the written versions of previous talks at the Spin Symposia I have opened with a review of the basic theory of radiative spin polarization, spin precession and resonance phenomena. That background material is readily available in the proceedings of earlier Symposia and elsewhere [1, 2, 3, 4]. So to avoid repetition I will, on this occasion, launch straight into the main themes. Historical overviews of radiative polarization can be found in [1, 5].

2 High energy storage rings: HERA and LEP

HERA is the $e^{\pm}-p$ collider at DESY in Hamburg. The e^+ or e^- beams run at about 27.5 GeV. Up to the end of 1997 the proton ring ran at 820 GeV. In 1998 it has been running at 920 GeV. $e^{\pm}$ beams in storage rings can become vertically polarized by the Sokolov–Ternov effect (ST) [6, 3] and a key aspect of HERA is that since 1994 longitudinal spin polarization has been supplied to the HERMES experiment [7] with the help of a pair of spin rotators [8].

The *value* of the polarization in an $e^{\pm}$ storage ring is the same everywhere around the ring even with rotators running. However, at high energy, as at HERA, the polarization is very sensitive to the size and form of closed orbit distortions. With very careful adjustment of the vertical closed orbit distortion using *harmonic closed orbit spin matching* [4], up to about 70 % polarization has been seen at HERA with the HERMES rotators running. This is to be compared with the theoretical maximum for that configuration of 89.06 % .

The polarization at HERA can also be affected by the beam–beam (b–b) forces due to collisions with the proton beam at the H1 and ZEUS experiments where, incidently, the polarization is vertical. Since the b–b forces are very nonlinear it is very difficult to make analytical calculations of their effects on $e^{\pm}$ beams. And of course, it is even more difficult to make analytical estimates of the effects on the polarization. However, the naive expectation is that the b–b forces reduce the polarization and

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some spin–orbit tracking calculations support that view [9]. Normally is it assumed that it is a good idea to reduce the b-b tune shift (explained below) but as usual, there is no substitute for measurement and in 1996 even during collisions with 50 mA of protons, positron polarizations of about 70 % were observed with the rotators running. One such run lasted ten hours. So, at least in *those* optics, b–b forces had little influence.

Since a few proton bunches, which would normally be in collision with electrons (positrons), are by intent missing, not all electron (positron) bunches come to collision with protons. Towards the end of 1996 a second polarimeter, built by HERMES, came into operation [10]. In contrast to the original polarimeter which measures the level of vertical polarization in the West area by Compton scattering using the so called single photon technique [11], the new polarimeter, which employs Compton scattering to measure longitudinal polarization directly close to HERMES and which uses the multi–photon technique, can collect data more quickly. It then became possible to study the positron polarization with sufficient precision on a bunch–to–bunch basis. Figure 1 summarizes a typical measurement for collisions of positrons with about 60 mA of protons and in this example, contrary to intuition, the colliding bunches

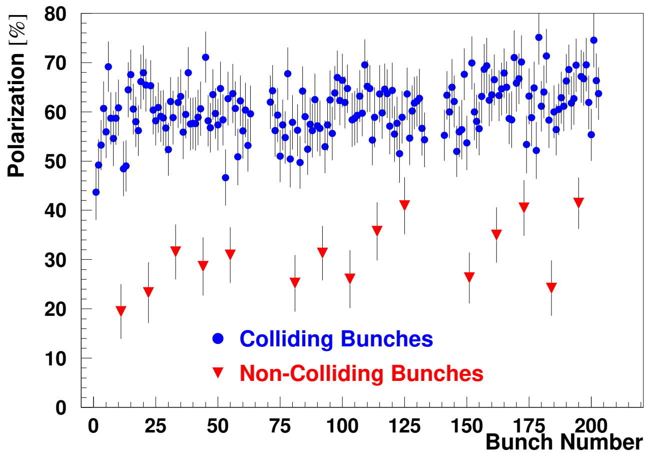

Figure 1: An example of a measurement with the longitudinal polarimeter of HERMES of the polarization of positrons colliding/not colliding with protons at HERA.

have *more* polarization than the non-colliding bunches. At present we interpret this unexpected result as being due to the b–b tune shift: an oncoming proton bunch appears to the positrons as a nonlinear lens and to a first approximation the colliding positron bunches have betatron tunes which differ from those of the non–colliding bunches. So, by the routine adjustment of some quadrupole strengths to get overall betatron tunes which lead to optically stable running conditions for the colliding bunches and to high polarization (averaged over the bunches), it is possible that the non–colliding bunches are close to a depolarizing spin–orbit resonance (probably a synchrotron sideband resonance of a parent resonance [4]) and likely that the colliding bunches are not on such a resonance. This interpretation is supported by the fact that on other occasions with slightly different machine tunes, there is either little difference between the colliding and non–colliding polarizations or the colliding bunches indeed have less polarization than the non–colliding bunches. For the measurement of figure 1 the vertical b–b tune shift was about 0.034 for each interaction point.

Apart from the sensitivity to orbital tunes one observes that in the presence of b–b effect the rise time for the polarization after injection is sometimes larger than that expected from standard radiative polarization theory and that the polarization level is sometimes relatively insensitive to the settings of the closed orbit harmonics of the harmonic closed orbit correction scheme [12]. Naturally, since the b–b effect can affect the rise time it makes little sense to calibrate a polarimeter by measuring the rise time after resonant depolarization [11] while the beam is in collision with protons.

The electron (positron) bunches in HERA come in three groups of about sixty bunches with gaps between the groups. This causes dynamic beam loading of the rf cavity system needed to replace the energy lost by radiation. That in turn can cause the synchrotron tune to vary along a group with the result that electrons (positrons) at the beginning of a group can be closer to a depolarizing resonance than those at the end (or vice versa). Thus we sometimes see a variation of the polarization of the colliding bunches across a group.

In 1997 under normal running conditions with typically 80 mA of protons we had about 50 % polarization, averaged over the bunches. Even towards the end of the year when we ran with over 100 mA of protons (vertical b–b tune shift $\approx$ 0.035) a polarization level of 50 % could still be reached. It might have been possible to attain more with careful adjustment of the closed orbit but we must normally make a compromise between tuning the orbit and providing stable running conditions for the high energy physics experiments.

Electrons and positrons can also become polarized in LEP, the $e^{\pm}$ collider at CERN in Geneva. The effect of b–b forces on polarization has also been studied there and it has been found that the polarization is very sensitive to optical parameters [13], just as at HERA.

So far, we cannot claim that we understand in detail all the effects of b–b forces on the polarization and it has not yet been conclusively demonstrated that it is impossible to get high polarizations in the presence of a b–b effect which is large but not large enough to disrupt the beam itself. More investigations under controlled and reproducible conditions are needed.

In the winter shutdown 1999/2000 we plan to change the geometry of the North and South interaction regions of HERA in order to increase the luminosity supplied to the H1 and ZEUS experiments by a factor of about 4.7 beyond the design value of $1.5{\cdot}10^{31}$ cm^{-2}sec^{-1} [14]. This will be achieved by reducing the beam cross–sections at the interaction points (IP's) and by reaching the design currents. The smaller beam sizes will be achieved by having smaller β functions at the IP's and by changing the optics in the arcs in order to decrease the horizontal emittance. These changes have profound consequences for $e^{\pm}$ polarization: smaller β functions imply that the focussing magnets must be moved closer to the IP's and this in turn means that the "antisolenoids" which currently compensate the H1 and ZEUS experimental solenoids will be removed. In fact new stronger combined quadrupole and dipole magnets will be installed on each side of the H1 and ZEUS IP's and their fields will overlap with the solenoid fields. At the same time additional spin rotators will be installed to enable H1 and ZEUS to run with longitudinal polarization. We plan to run these rotators in a slightly mistuned state designed so that they effectively compensate for the effect on the equilibrium spin axis of the overlap of solenoid and dipole fields and ensure that the spin axis is still vertical in the arcs — an essential requirement for high polarization [4]. The absence of the antisolenoids means that the resultant orbital coupling must be corrected away with skew quadrupoles and that the computer programs involved in the *strong spin matching* [4] and calculation of polarization must be upgraded to handle the new and complicated magnetic field configurations near the IP's. Accounts of the full implications for the maintenance of radiative polarization can be found in [14, 15].

Since the ratio: (depolarization rate/polarization rate) [4] rises strongly with energy, it was much more difficult to attain high polarization in LEP at the old running energy of about 46 GeV per beam (near the Z^0) than at HERA with 27.5 GeV. Moreover the vertical polarization of LEP (there are no spin rotators) is of little use for high energy physics and in any case the rise time for the polarization is a few hours compared with the twenty minutes of HERA. In spite of these difficulties the LEP team recorded a polarization of about 57 % in 1993 [13, 16] — a major achievement. Under routine running conditions at about 46 GeV, LEP ran with 5 – 10 % polarization. But this was sufficient for the exploitation of polarization to measure the beam energies, and hence the Z^0 mass, by means of resonant depolarization, leading to a precision of about 1.5 MeV [17, 16].

But now LEP runs at above 80 GeV per beam and the polarization is effectively zero; 5 % polarization was recorded at 55.3 GeV but this was down to 2 % at 60.6 GeV. However, vertical polarization can still be used for energy calibration — but indirectly by calibrating a flux loop and sixteen NMR probes in dipoles at about 41, 45, 50 and 55 GeV [18] and then using the calibrated flux loop and NMR probes at above 80 GeV. The estimated systematic error for this method is about 25 MeV per beam but the long term aim is for a precision of about 15 MeV per beam.

3 Accelerators

Because the rise time for ST polarization is typically in the range of minutes to many hours, extracted polarized e^- beams can only be obtained from accelerators by injecting a pre-polarized beam from a source. Modern gallium–arsenide sources [19] deliver up to about 80 % electron polarization. But that must then be preserved during acceleration. There are at present no suitable polarized positron sources and therefore no extracted polarized positron beams.

When dealing with polarized beams we can distinguish two basic types of accelerators, namely linear accelerators where, by design, the particle velocity and the accelerating electric field are essentially parallel, and ring accelerators where, in addition, the beam must make many thousands or even millions of turns in the magnetic guide field on the way to full energy. If the particle velocity and the electric field are almost parallel, then according to the T–BMT precession equation [4, 3] there is very little spin precession and hence little opportunity for depolarization. The (lack of) spin precession in the two mile long accelerating section of the SLC at SLAC in California is the prime example of this. The SLC has regularly delivered an electron beam of about 46 GeV with over 70 % polarization [19].

A good example of the other type is ELSA [20], the 3.5 GeV ring at Bonn, Germany which accelerates vertically polarized electrons. According to the T–BMT equation, in vertical magnetic fields, spins precess $a\gamma$ times per turn where $a = (g-2)/2$ is the gyromagnetic anomaly and γ is the Lorentz factor. If the spin precession is in resonance with the orbital motion: $a\gamma = m_0 + m_x\,Q_x + m_z\,Q_z + m_s\,Q_s$ where the m's are integers and the Q's are orbital tunes, the spins can be strongly disturbed and the polarization can be lost. Since the precession rate $a\gamma$ is proportional to the energy, and increases by unity for every 440 MeV increase in energy, several such resonances must be crossed on the way to 3.5 GeV. A typical example is at 1.32 GeV in ELSA. This corresponds to $m_0 = 3$ but $m_x = m_z = m_s = 0$. Spin perturbations in this case result from the radial fields "seen" by the spins in the quadrupoles when there is vertical closed orbit distortion. A first approximation for the polarization surviving the crossing of a resonance is given by the Froissart–Stora (FS) formula [21, 22]:

$$\frac{P_{\rm final}}{P_{\rm initial}} = 2\ e^{-\frac{\pi|\epsilon|^2}{2\alpha}} - 1 \tag{1}$$

where ϵ is the "resonance strength", a measure of the dominant spin perturbation at resonance, and α expresses the rate of resonance crossing. Thus if the resonance is crossed sufficiently quickly ($|\epsilon|^2/\alpha$ is small) the polarization is hardly affected but if it is crossed sufficiently slowly ($|\epsilon|^2/\alpha$ is large) a complete reversal of the vertical polarization can occur without much change in the magnitude. Measurements of the surviving polarization for a range of $|\epsilon|^2/\alpha$ values are now available from ELSA [20] both for 1.32 GeV and for 1.76 GeV ($m_0 = 4$). The measurements for $m_0 = 3$ show good agreement with the prediction of the FS formula. In particular, by running at $|\epsilon|^2/\alpha \geq 4.0$ one can preserve the value of the polarization by means of complete spin flip. However, for $m_0 = 4$ only partial spin flip with a $|P_{\rm final}/P_{\rm initial}| \approx 0.8$ is seen even out to $|\epsilon|^2/\alpha \approx 12.0$. This is probably due to the encroachment of stochastic spin decoherence owing to synchrotron radiation emission at the higher energy. If this is indeed the case, these measurements provide a window on what can be expected from attempts to flip $e^{\pm}$ spins in HERA [23, 24].

A good compromise between the space occupied by the SLC and the spin perturbation problems of ELSA, is provided by the ring at the Jefferson Laboratory in Virginia, U.S.A. This was designed to provide longitudinally polarized electrons at 4 GeV. However, it is already providing up to 77 % polarization at 5 GeV [25]. This ring combines the best of both worlds; it consists essentially of two parallel superconducting linear accelerators connected at their ends by semicircular arcs of bending magnets. The beam is accelerated to full energy in just five turns. In the arcs the energy is constant so that there is no resonance crossing and in the accelerating sections, just as in the SLC, spin perturbations are negligible. In any case, with so few turns and with such a large acceleration rate (large α) no depolarization is expected. This machine is already a wonderful tool for research with spin and in the long term with steady improvements it might even be possible to reach 12 GeV [25].

4 Kinetic polarization

At SPIN96 [1] I reported on progress towards obtaining longitudinal electron polarization in the AmPs ring in Amsterdam [26]. This ring runs at up to 900 MeV. The electron beam is injected pre–polarized and a Siberian Snake, based on a superconducting solenoid, is employed to stabilize the polarization and to ensure that the polarization is longitudinal at the internal target. A fascinating and educational aspect of this machine is that, because the normal radiative polarization process is eliminated owing to the fact that the equilibrium polarization lies in the horizontal plane, a weaker polarization mechanism, "kinetic polarization", might become observable [27]. As reported at this Symposium by Yu. Shatunov, measurements at AmPs have now provided preliminary experimental evidence for this effect [28]. Confirmation of these observations will vindicate efforts [3, 29, 30] to put the theory of the combined radiative polarization and radiative depolarization processes on a firm semiclassical basis. Moreover, kinetic polarization is expected to contribute $+/-$ a few percent to the $e^{\pm}$ polarization at HERA when the spin rotators are running. But since its magnitude depends sensitively on the details of the closed orbit distortion and since that cannot be measured with sufficient accuracy, kinetic polarization sets a limit to the precision with which the polarimeters can be calibrated by measuring the polarization rise time [11, 8] with the rotators in use.

Perhaps the work at AmPs can be extended at the BτCF ring being planned in Beijing [31] and at the MIT–Bates ring [32].

5 "Spinlight"

In high energy storage rings, $e^{\pm}$ polarization is normally measured using Compton scattering. In linear accelerators Moeller [33] scattering, which is destructive, can be used too. However, there is another possibility, namely to measure the tiny, O($\hbar$), component of synchrotron radiation ("spin light") which depends on the orientation of the spins [34]. This causes a small difference between the spectra of very high energy photons radiated from vertically polarized and unpolarized bunches. The difference, which has already been detected at low energy [35], is proportional to the polarization and therefore supplies a way of measuring the latter. Indeed, a feasibility study for a "spin light polarimeter" at HERA is now being undertaken by physicists from the Yerevan Physics Institute in Armenia and from DESY [36]. Furthermore, the correlation between the radiation spectra and the spin orientation lies at the heart of the kinetic polarization effect [27] so that even apart from the question of polarimetry, it would be of interest to make more detailed measurements and at high energy.

6 Fokker–Planck theory for spin diffusion

Now, to conclude, I would like to mention that a way has recently been found, using classical concepts, to write a diffusion equation describing stochastic spin dynamics in storage rings. The key is to work with the density in phase space of the spin angular momentum as a parallel to the use of particle density for orbital diffusion. If the Fokker–Planck equation for the orbital motion is known, the corresponding equation for spin can be written immediately. More details can be found in another article in these proceedings [37].

Conclusion

$e^{\pm}$ polarization in storage rings and accelerators is an active, developing and exciting field. Much is now routine but there are still many aspects to investigate and challenges to meet.

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