Polarized electron beams in storage rings *

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Abstract

This paper gives a brief review of the phenomenology of spin polarization in electron storage rings and then proceeds to emphasize some points of particular importance for the Beijing Tau–Charm Factory.

1 Introduction

The Beijing Tau–Charm Factory (BτCF) project presents a fascinating challenge from many points of view. Not only must the ring provide very high luminosity and large beam lifetimes but in addition high longitudinal spin polarization is required over a wide energy range!

Fortunately, the science and art of obtaining and maintaining high polarization in $e^{\pm}$ storage rings has been brought to a high level in the last decade with the $e^{\pm}$ ring at the HERA ep collider regularly delivering high longitudinal polarization and the LEP ring having achieved up to 57 percent vertical polarization at 46 GeV [1, 2].

However, the BτCF presents additional special challenges:

- Whereas the high energy beams can become polarized by the emission of synchrotron radiation (the Sokolov–Ternov effect) the natural build up time at the BτCF tends to be big in comparison with the beam lifetime so that probably prepolarized beams must be injected and stored.
- In a ring like the BτCF, where space is limited, it is not trivial to devise suitable spin rotators.

Since many underlying concepts are common both to high and to low energy I will begin this article with a brief review of polarization in general and then illustrate some key points by reference to longitudinal polarization at the HERA electron ring. I will then continue with remarks specific to the BτCF.

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2 Phenomenology and calculations

2.1 The Sokolov–Ternov effect

Stored electron beams can become spin polarized antiparallel to the guide field by the emission of spin flip synchrotron radiation — the Sokolov-Ternov (S–T) effect [3]. In a planar ring a maximum polarization, P_{ST}, of $\frac{8}{5\sqrt{3}} = 92.4\%$ can be reached. The Sokolov–Ternov polarizing process is slow on the time scale of other dynamical phenomena occurring in storage rings, and the inverse time constant for the exponential build up is [4, 5].

$$\tau_{ST}^{-1} = \frac{5\sqrt{3}\gamma^5\hbar e^2}{8\rho^3 m^2 c^2} \tag{1}$$

where γ is the Lorentz factor, ρ is the radius of curvature in the magnets and the other symbols have their usual meanings. For example at HERA the time constant is 40 minutes at 27 GeV and at LEP at 46 GeV the time constant is about 300 minutes.

Although the polarization mechanism is weak, polarization has been observed in most low energy electron storage rings. It has been detected at ACO and high levels have been seen in all Novosibirsk machines (VEPP2,VEPP3,VEPP4) and at CESR, SPEAR and DORIS [6].

2.2 Depolarization

The original S–T treatment dealt with uniform magnetic fields [3]. In real rings however, the fields experienced by the stored electrons are much more complicated. Thus a more complete treatment is needed and this begins with a study of spin precession in general fields.

The polarization vector, defined in the rest frame, of a relativistic electron in the magnetic fields in a storage ring precesses according to the Thomas–BMT equation [7, 8]:

$$\frac{d\vec{P}}{ds} = \frac{e\vec{P}}{mc\gamma} \times ((1+a)\vec{B}_{||} + (1+a\gamma)\vec{B}_{\perp}) \ , \quad a = \left(\frac{g-2}{2}\right) \tag{2}$$

where $\vec{B}_{||}$, $\vec{B}_{\perp}$ are the magnetic fields parallel and perpendicular to the trajectory, s is the distance along the ring and g is the electron g factor.

An essential consequence of equation 2 is that the number of spin rotations per turn around a perfectly flat ring is $a\gamma$ (denoted by ν_0). This is called the spin tune and represents the natural spin precession frequency of the system. For example at 27.54GeV ν_0 is about 62.5. Away from integer values of ν_0, a stable unique periodic solution of equation 2 on the periodic (closed) orbit exists and is denoted as $\hat{n}_0$. In a perfectly flat ring, $\hat{n}_0$ is vertical and so is the equilibrium polarization, $\vec{P}_{eq}$. In machines with vertical bends and/or where there are misalignments, there are horizontal fields on the closed orbit so that $\hat{n}_0$ is no longer everywhere vertical. But $\vec{P}_{eq}$ is still parallel to $\hat{n}_0$ [5]. Thus we know the direction of the polarization vector in the general case also.

So far I have ignored spin diffusion processes but electrons experience stochastic disturbances as they recoil during photon emission and in a simple classical picture where spins 'ride' on electrons one would expect the spins to undergo extra stochastic precessions according to equation 2 in the magnetic fields in the quadrupoles and that the spins would then diffuse or depolarize.

However in a flat perfectly aligned ring, i.e. when $\hat{n}_0$ is everywhere vertical and the beam is a flat ribbon, the stochastic motions do not lead to depolarization. But in real rings with misalignments the closed orbit is distorted and $\hat{n}_0$ becomes tilted. Then depolarization does occur and becomes larger as the misalignments increase and, in particular, as the tilt increases. Thus synchrotron radiation can create polarization but it can also lead to its destruction! The final equilibrium polarization depends on the relative magnitudes of the two effects. Furthermore, spin diffusion is strong and hence the polarization small when the frequencies of the orbital motion (which drives the spin diffusion) satisfy the following resonance condition:

$$\nu_0 = k + m_x Q_x + m_z Q_z + m_s Q_s \ , \tag{3}$$

where k, m_x, m_z, m_s are integers, and the $Q_{x,z,s}$ are orbital tunes of the horizontal, vertical and longitudinal motion respectively. Thus energy scans reveal energies where the polarization is zero over certain narrow energy ranges. These are the energies corresponding to depolarizing resonances. A good example of such a scan can be found in [9].

The order of a resonance is defined as $|m_x| + |m_z| + |m_s|$. The strongest resonances are usually the first order resonances (either $m_x = \pm 1$ or $m_z = \pm 1$ or $m_s = \pm 1$). The next most dangerous are the synchrotron side band resonances of parent first order resonances (either $m_x = \pm 1$ or $m_z = \pm 1$ while $m_s =$ a small integer) [10, 11]. These are associated with modulation of the spin tune due to the synchrotron (energy) oscillations.

2.3 Calculations and simulations

Naturally, one must be able to calculate the expected polarization using real lattice descriptions so that optimization schemes can be tested and some idea of the achievable polarization can be obtained. In the last seventeen years there have been several contributions in this field. Some will be described below. I begin with analytical methods.

The first program which could read an optic file describing a storage ring with its electric and magnetic fields and its misalignments and automatically calculate spin diffusion effects was the code SLIM by A. Chao [4]. In the SLIM formalism the orbital motion is linearized and described by 6 x 6 symplectic transfer matrices. Since the polarization is parallel to $\hat{n}_0$ it suffices (at low energy) to assume that the spins themselves are almost parallel to $\hat{n}_0$ and to describe their deviation from $\hat{n}_0$ by two small angles. The equations of motion for spin can then be linearized too and the combined spin–orbit motion can be described by 8 x 8 transfer matrices. These matrices contain a 2 x 6 submatrix describing how spin is coupled to and driven by the orbital motion. The picture is completed by adding stochastic and damping effects to the orbital motion [12, 13]. The formalism based on the 2 x 6 matrix is very transparent. For example one can see immediately why a tilted $\hat{n}_0$ can be dangerous and how big the terms are. Since the spin motion is linearized one only expects the SLIM formalism to be able to predict the existence and strength of the first order resonances. This is indeed the case and the strengths of each type of first order resonance can be traced directly back to terms in the 2 x 6 matrix. Thus we are in the position to carry out diagnostic investigations of the sources of depolarization [14]! Maximization of the polarization then boils down to adjusting the optic so as to to minimize the relevant elements of the 2 x 6 matrix. This procedure is called spin matching. We return to this topic in section 3.2. Spin matching can also be carried out in terms of the so called spin–orbit integrals [15, 16].

So far in this article I have been relying on a simple picture of quantum mechanical polarization build up competing with classical spin diffusion. But it is possible to describe the whole process in a unified manner using the semi–classical quantum mechanical treatments given by Derbenev and Kondratenko in 1973 and Mane in 1987 [17, 18]. The key task in this approach is to evaluate the vector field $\hat{n}$, which is the phase space dependent semi–classical spin quantization axis, and then to calculate its derivative $\gamma\ \partial\hat{n}/\partial\gamma$ [17, 18] at each point in phase space. On the closed orbit $\hat{n}$ reduces to $\hat{n}_0$. Other overviews of the theory can be found in [19, 20].

Two programs exploiting this formalism have been in common use, namely SMILE by S. Mane [18, 11] and SODOM by K.Yokoya [21]. The SMILE calculations are based on a perturbation expansion for $\hat{n}$ and automatically include interference between resonances. These perturbation expansions show explicitly how the spin diffusion varies with energy at each order. The expressions for the first order diffusion terms in SMILE are algebraically and numerically identical to those in SLIM. SODOM avoids explicit perturbation expansions by calculating $\gamma\ \partial\hat{n}/\partial\gamma$ after representing $\hat{n}$ as a Fourier series.

More recently, a new way to calculate $\hat{n}$ based on a method called 'stroboscopic averaging' has been developed and implemented in the computer code SPRINT [22]. Work is now in progress at DESY to extract $\gamma\ \partial\hat{n}/\partial\gamma$ from this algorithm.

The algorithms described so far are analytical. However, a Monte–Carlo model of naive classical spin diffusion can also be used, as for example, in the program SITROS originally written by J. Kewisch [23] and now in extensive use at DESY for predicting the polarization at HERA [24]. In SITROS an equilibrium ensemble of electrons is tracked with the inclusion of orbital damping and excitation effects and the depolarization time constant τ_{dep}, is estimated for spins originally aligned along $\hat{n}_0$. SITROS results agree qualitatively with measurements at HERA [24]. Beam–beam kicks can also be included.

So several options are now available for predicting the polarization in a ring but since they only include single particle effects, since the equilibrium polarization depends sensitively on the misalignments and on the details of the particle dynamics and since these can at best only be approximately modelled, the calculations can usually only yield approximate information about the attainable polarization. But this is still useful for the optimization and design of the machine.

2.4 Optimization I

A detailed inspection of the various perturbative formalisms for calculating spin diffusion reveals that the rate of depolarization is given by the polarization rate (equation 1) multiplied by a polynomial in powers of ν_0 and where each term contains resonance denominator factors corresponding to the depolarizing resonances. Thus as the energy increases spin diffusion effects begin to dominate and one can expect that it is more difficult to achieve high polarization at high energy. Conversely, at low energy, as at the BτCF only the first order resonances will be important. In the first order formalism the depolarization rate increases roughly with the seventh power of the energy. In cases where the depolarization rate is sensitive to the tilt of the $\hat{n}_0$ axis from the vertical, it could even depend on the ninth power of the energy.

In spite of the reservations about high energy, vertical polarization was observed at PETRA at 16.5 GeV where levels exceeding 70% were obtained in 1982 [25]. Vertical polarization has also been seen at TRISTAN [26]. Furthermore, 57% vertical polarization has been observed at LEP at 46 GeV [2] and in 1993 a vertical polarization of 60% and above was obtained at HERA at 26.7 GeV [27].

The first step to getting vertical polarization (i.e. controlling depolarization) in a simple ring is to choose an energy near to a half integer value of ν_0 i.e. a working point centered between the first order resonances. In this context it is also useful to choose small values for the fractional parts of Q_x and Q_z. Solenoid fields should be locally compensated or spin matched. The machine must be well aligned and, for example at HERA, the closed orbit must be corrected with correction coils so that the typical rms horizontal and vertical deviations from the design orbit are less than 1 mm. However the quadrupole fields on the closed orbit together with the required correction fields are still enough to ensure that $\hat{n}_0$ is tilted by tens of milliradians so that the polarization is small. So a method of reducing the tilt is needed. Fortunately, it can be shown that the tilt of the $\hat{n}_0$ axis is dominated by certain harmonics in a Fourier decomposition of a spin–orbit function appearing in the expression relating the tilt to the fields on the closed orbit [28, 27, 29, 30]. Thus one can control the tilt using special sets of vertical correction coils with excitation currents chosen so as to artificially excite each of the dangerous harmonics. Then the measured polarization is maximized by cancelling each of the dangerous harmonics empirically in turn. The approach used at HERA is based on the program FIDO [28, 29] and involves the use of eight short closed vertical bumps which allow the eight harmonics to be targeted individually [27] while disturbing only a small length of the orbit. Since this method is empirical and the polarization typically takes many minutes to react to changes, an optimization can take many hours.

An alternative and faster approach is to measure the orbit so well that the relevant harmonics can then be calculated and corrected deterministically [2]. At HERA a method called kick minimization derived from beam based calibration of the position monitors has been successful [31].

3 Longitudinal polarization

The high energy physicists at BτCF wish to have longitudinal electron (positron) polarization at the interaction point. This is also the case at HERA. Thus I will now use the latter to illustrate the main problems in obtaining longitudinal polarization.

Since the polarization vector must be vertical in the arcs in order to 'drive' the S–T polarization process, the polarization must be rotated into the longitudinal direction just before the interaction points and back to vertical afterwards. This can be achieved with special arrangements of magnets called spin rotators. At HERA we use rotators based on dipole magnets.

3.1 The HERA spin rotators

Dipole spin rotators exploit the prediction of equation 2 that for motion transverse to the magnetic field, the spin precesses around the field at a rate which is $a\gamma$ faster than the rate of rotation of the orbit direction. Thus

$$\delta\theta_{spin} = a\gamma\delta\theta_{orbit} \tag{4}$$

in an obvious notation. Note that in dipoles, the spin deflection is proportional to the energy. Thus dipole rotators are particularly suitable for high energy machines. On the contrary, from equation 2 it is clear that at very low energies, spin rotation is best achieved using longitudinal fields (solenoids) to rotate the spin around the longitudinal axis. At HERA energies, $a\gamma$ is between 60 and 80. So it can be arranged that small commuting deflections of the orbit can result in large non–commuting precessions of the polarization vector. This is the basis of the Mini–Rotator design of Buon and Steffen[15] adopted for HERA. In the Mini–Rotators the rotation is achieved by interleaving three horizontal bends with three vertical bends. The orbit bend angles are of the order of 10 mrads and the horizontal bends replace the bend angle of one arc cell. The whole rotator is inserted into the end of the arc with minimum disturbance to the rest of the machine. The total vertical bend of this rotator is zero and it is only 56 m long so that no quadrupoles need be included among the constituent dipoles. The vertical orbit excursion is only about 20 cm. The required rotator dipole fields and hence the shape of the rotator depend on the energy chosen. By mounting the dipoles on coupled, remotely controlled mechanical jacks and by having flexible joints between sections of vacuum pipe, it is possible to tune the rotator to give the correct spin transformation over the range 27–35 GeV and to obtain both helicities. The vertical bumps in a pair of rotators are antisymmetric with respect to the IP. The first two rotators were installed on either end of the East straight section at the beginning of 1994 so as to provide longitudinal polarization for the HERMES experiment which uses a polarized internal gas target to study the deep inelastic spin structure of nucleons. At the chosen energy of 27.52 GeV, the (purely) S–T polarization level is reduced below 92.4% to about 89% with one pair of rotators by the presence of the vertical bend magnets. With the rotators switched on this energy corresponds to the required fractional spin tune of 0.5.

Space was made in the lattice for rotators and studies of the feasibility of spin matching (see below) were made with this layout before the machine design was frozen. This foresight was pivotal to the success in obtaining longitudinal polarization.

3.2 Optimization II

Unfortunately the longitudinal polarization generated by rotators does not come free of charge. As we have already seen, machine distortions which lead to a tilt of the $\hat{n}_0$ axis can lead to depolarization. So it is not surprising that the installation of spin rotators can result in additional strong depolarization even in a perfectly aligned ring. One reason is that between the rotators the spin axis is horizontal and can be considered to be maximally tilted. In addition there is local vertical dispersion inside the rotators so that synchrotron radiation emission in the rotators excites vertical betatron motion. This can also depolarize. In principle these two consequences of the presence of rotators can, in HERA, be largely eliminated by spin matching. As announced in section 2.3 this consists of arranging the quadrupole settings so that the relevant parts of the 2 x 6 matrix describing the coupling of the spin to the orbit in linear approximation, vanish in the section between the rotators straddling the interaction point and in the remainder of the ring [14, 1]. Since the rotators contain no quadrupoles, spin matching inside the rotators is not needed. A spin matched section of ring is said to be 'spin transparent'. As well as minimizing these matrix elements, one must ensure that the usual optical properties of the machine are acceptable. At HERA, it has been possible to satisfy these requirements by giving every mirror symmetric pair of quadrupoles in the section between the rotators and in the first seven cells at the beginning of each arc its own power supply.

In 1994 longitudinal polarization was obtained at HERA at 27.52 GeV. HERA now regularly runs with almost 60% longitudinal polarization and sometimes achieves 70%. HERA is the first machine to deliver longitudinal polarization derived from the S–T effect.

The observation of high polarizations in the high energy machines HERA and LEP shows that in spite of the potential for strong depolarization, the art of obtaining radiative polarization has come of age. Indeed, the fact that we regularly attain 60% longitudinal polarization at HERA is evidence of the efficacy of combined spin matching and harmonic orbit correction.

4 Polarization at BτCF

After this overview I now come to the BτCF.

It would be unrealistic here to try to make hard and fast recommendations regarding the fine details of the machine layout needed for polarization since the optimization of the machine as a whole involves many competing aspects which are beyond my control. Furthermore many of the basic elements needed for getting polarization are well known to the designers already and it is clear that much thought has already gone into the design as one can see from [32, 33, 34]. Also the design is presumably still evolving. Instead, I will make a number of points which I believe to be important as a result of my experience with getting polarization at DORIS, PETRA and HERA.

In spite of the fact that the BτCF is a low energy machine (1.5–3.0 GeV per beam) so that one expects the depolarization to be weak, this machine presents its own special problems. The main problem is that the energy is so low for a machine of this average radius that the S–T time is typically several hours. See equation 1. At the same time it is planned to achieve very high luminosities and high currents. Thus the beam lifetime will be limited to the order of an hour and the polarization will have no time to grow to high levels.

So it is very likely that the beam will have to be injected already polarized. Polarized electrons could be obtained from a polarized source but there are no polarized sources for positrons. The alternative would be to have a very small radius polarizing ring in the injector chain to provide both polarized electrons and positrons. Or one could install strong asymmetric wigglers or superconducting dipoles in the arcs as a way of enhancing the S–T effect. But such measures would bring an increase in rf power consumption and in energy spread and are not very practical.

The second problem is that at these energies it is not straightforward to generate the spin rotation needed to obtain longitudinal polarization at the interaction point. If dipoles were to be used, the design orbit distortion would be very large and furthermore there is not too much space in the vertical plane between the electron and positron rings.

Thus one must then take seriously the possibility of using solenoids.

I will therefore base my comments on the favoured scenario presented in [32].

Although the S–T effect is weak at these energies, this machine still radiates significant amounts of synchrotron radiation and care must be taken that the lifetime of the polarization due to spin diffusion is longer than the beam lifetime. Thus, as I have pointed out above, it is normally very desirable to have $\hat{n}_0$ vertical in the arcs. The solenoid rotators would then work as follows. Coming from the arc, the solenoid would rotate a vertical spin into the radial direction. The radial spin would then be rotated into the longitudinal direction by a further dipole. Another dipole–solenoid pair on the far side of the interaction point would return the spin to the vertical and thereby ensure that the periodic solution $\hat{n}_0$ is vertical in the arcs and longitudinal at the interaction point. This is the scheme proposed in [32] for 2 GeV operation. Naturally the polarization is exactly longitudinal only at one energy. Each solenoid would need a field integral of about 10 Tesla metres to achieve a spin rotation of 90 degrees at 2 GeV.

As in the case of longitudinal polarization at HERA, the region between the rotators presents a potentially strong source of depolarization. But in contrast to the dipole rotators of the HERA type, strong solenoids are themselves a potential source of 'spin opacity' owing to betatron motion both in the radial end fields and in the longitudinal fields itself. Furthermore the spin precession in a longitudinal field depends on energy. For a review of the mechanisms and a detailed discussion of spin matching with solenoids see [35, 14]. Thus spin matching must involve adjusting the straight section optic in such a way that as many elements as possible of the 2 x 6 matrix of the whole stretch from the beginning of the first solenoid to the end of the last solenoid are as small as possible, not just for the quadrupole section between the solenoids. My experience with simulations shows that such a spin match is very necessary for delivering low depolarization over a large energy range. Even if the maintenance of an acceptable optic makes a perfect match impossible, a partial match would also be beneficial.

It can be argued that in a machine where a prepolarized beam is injected, one is not trying to find the optimum balance between the S–T effect and depolarization, and that one should only try to reduce depolarization to a level which ensures that the depolarization time is longer than the beam lifetime. On the contrary, I believe that it is good practice to do the best possible job on the optic from the beginning and not cut corners.

A dipole–solenoid rotator designed to deliver longitudinal polarization at 2.0 GeV will deliver the wrong spin orientation in the low energy range (1.5–1.8 GeV). It has therefore been suggested that the most economical way to obtain polarization for the low energies would be to move the solenoids to the long straight section diametrically opposite the interaction point and to run in a mode in which they cause a rotation of $\hat{n}_0$ of 180 degrees [32, 33]. This is the so called Siberian Snake configuration [36] and it causes $\hat{n}_0$ to lie in the horizontal plane in the arcs and be longitudinal (as desired) at the interaction point. With horizontal $\hat{n}_0$ in the arc dipoles the S–T polarization vanishes and injection of prepolarized beams is unavoidable. Since such a spin rotation is accompanied by a 90 degree rotation of the beam cross section, skew quadrupoles and quadrupoles must be added to the solenoid layout in such a way as to ensure that the snake as a whole has a decoupled optical transfer matrix. Although I pointed out above that one should strive to keep $\hat{n}_0$ vertical in the arcs, at very low energy the case involving a snake can be an exception to this rule. In fact, provided that the snake simply behaves as a device which only rotates spins around the longitudinal axis independently of the particle energy, the snake has the effect of suppressing much of the depolarization associated with having a horizontal $\hat{n}_0$ in the arcs. This is easily demonstrated by simulations with SLIM and an examination of the 2 x 6 matrix or by other spin diffusion calculations [37]. However, as in the case of the dipole–solenoid rotators mentioned above, snakes of this type tend already to be somewhat spin opaque simply because of the interaction of the synchrobetatron motion with the strong solenoid fields and the complicated in–built quadrupole and skew quadrupole fields. In fact, a very detailed study of the 2 x 6 matrix and the depolarization rate that I carried out for a similar scheme at the 900 MeV AmPS ring at NIKHEF in Amsterdam [38, 39], showed that neglect of the effects of betatron motion in the snake can lead to strongly over optimistic estimates for the polarization lifetime. Thankfully, however, it has shown [16] how to set up the overall optic of the ring so that non–zero 2 x 6 matrix elements in the snake associated with betatron motion can be balanced against those of the arc with the result that the overall 2 x 6 matrix can be made small. This short story does however, illustrate that a sound understanding of the first order spin diffusion is very useful for optimizing the ring.

Although, as I pointed out above, there are several programs available for calculating spin polarization effects, at these energies first order calculations should normally be sufficient. That means that one only needs SLIM or one of its clones. This also means that one has a simple diagnostic tool available. One can turn terms on and off in the 2 x 6 matrix and discover which parts of the ring are potentially depolarizing and which not. For spin matching at HERA we use a modern version of the program SPINOR [40]. K. Yokoya has developed a program, SOM, for combined calculation of polarization, spin matching and adjustment of the ring geometry [34].

So far I have not discussed the depolarizing effects of the beam–beam interaction. At LEP the beam–beam depolarization can be weak [2] and at HERA no clear beam–beam depolarization has been detected. But in the BτCF, the high currents will restrict the beam lifetime and it is likely that the polarization will suffer correspondingly. Since the beam–beam interaction is strongly nonlinear, programs like SLIM are of little help beyond the approximation of treating the beam–beam force as being generated by a linear lens. Probably the best way to study the beam–beam effect is to use a Monte–Carlo tracking program like SITROS. It is even probably sensible to carry out beam–beam studies very early on in case it turns out that the beam–beam effect represents a very fundamental limit to the achievable polarization.

The chief limitation to polarization at HERA and LEP is spin diffusion caused by machine distortion and a very large effort has been invested in orbit correction and machine alignment schemes. Thus with the benefit of this experience, every effort should be made to ensure that the BτCF is built in a way which allows it to be very well aligned and to stay aligned. Furthermore, the very best beam position monitors should be installed and in sufficient numbers. This might be very important for maintaining polarization at 1.76 GeV, a favourite energy among experimenters, but an energy which unfortunately would be very close to an integer resonance if solenoid rotators were to be used. If the orbit measurements are good enough deterministic harmonic orbit corrections can be made. With prepolarized beams, empirical orbit correction would be very difficult.

Once polarization has been achieved, one needs to be able to measure it. But modern experiments need to know the polarization with a precision at the one percent level and this is not trivial to achieve. At HERA and LEP enormous efforts have been invested in polarimetry. In both cases the polarization is obtained by measuring asymmetries in Compton back–scattering of laser photons off of the electron beam [41]. At LEP the polarimeter was added after the machine was built. At HERA however, we decided on the machine geometry at the position of the polarimeter before the machine was built. The decision was based, among other things, on the need to have low gas bremsstrahlung and synchrotron radiation backgrounds, a small beam spot on the photon detector, a large lever arm up to the detector and ease of bringing the photon beam into the beam pipe. This approach has led to enormous simplification in the day to day running of the polarimeter and in the reduction of systematic errors.

Thus our experience has shown that one should not try to add a polarimeter as an afterthought and that careful design work should be taking place now. The same is true of rotators.

5 Conclusion

It has been demonstrated that high longitudinal polarization can be obtained at high energy on the basis of the S–T effect. So there must be a good chance to maintain polarization in the BτCF. But provision for polarization must be made right at the start! It is normally very difficult to add rotators, polarimeters, position monitors and special magnet mounts at a later stage.

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