# A REVIEW OF POLARIZED ELECTRON AND POSITRON BEAMS

D.P.Barber
Deutsches Elektronen Synchrotron, (DESY), Notkestrasse 85,
2000 Hamburg 52, Federal Republic of Germany.

## Abstract

A brief review of the status of the machine physics of polarized electron and positron beams is presented.

## Introduction

There are two ways of obtaining high energy polarized electron beams: Either electrons are created ready polarized at a source and then accelerated (Case A) or, the polarization is produced naturally owing to the emission of synchrotron radiation while the electrons circulate in a storage ring (Case B). The physics of Case A is well understood and the technique is almost standard. Case B is substantially understood at the theoretical level but the practice has a long way to go before naturally polarized beams can be considered to be an everyday affair in modern very high energy storage rings.

An article of this length cannot do justice to the whole field. Hence after a brief review of type A facilities I will concentrate on the problems of type B facilities.

## Generalities

Centre of mass spin motion in electric and magnetic fields is governed by the Thomas-BMT precession equation:

$$\frac{d\vec{s}}{d\theta} = \vec{\Omega} \times \vec{s} \tag{1}$$

where $\vec{\Omega}(\vec{B}, \vec{E})$ is a function of the fields and $\theta$ is the azimuthal coordinate[1].

An essential consequence of the structure of $\vec{\Omega}$ is that for motion transverse to the magnetic field, the spin precesses at a rate which is $a\gamma$ faster than the rate of rotation of the orbit direction. Here, $a = (g-2)/2$ where $g$ is the electron $g$ factor. Thus

$$\delta\theta_{spin} = a\gamma\delta\theta_{orbit} \tag{2}$$

in an obvious notation.

In a flat ring on the closed orbit, the spin precesses $\nu = a\gamma$ times per turn and is called the spin tune[2]. Away from integer values of $\nu$ a stable unique periodic solution of Eq. (1) on the closed orbit exists and is denoted as $\hat{n}_0$. In a flat ring $\hat{n}_0$ is vertical. For particles on quasi-harmonic betatron trajectories, we can construct analogously quasi-periodic solutions denoted as $\hat{n}$. Under Fourier analysis these solutions contain only betatron harmonics and harmonics reflecting the ring layout[3]. These solutions, which we give unit modulus, are needed in the theory of electron self polarization (see below). They become undefined if the resonance condition

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

(where $k, m_x, m_z, m_s$ are integers, and the $Q_{x,z,s}$ are orbital tunes) is satisfied. If a bunch of electrons with vertical spins is injected with finite oscillation amplitude into a closed imperfect but otherwise flat ring, the vertical spins see not only the vertical guide field but also error fields and quadrupole fields. Hence the spins precess away from the vertical. This precession is particularly strong if the spin and orbit frequencies are so matched that the resonance condition of Eq. (3) is satisfied. Strong depolarization or spin flip can then occur[4].

These comments are sufficient for a basic understanding of the behaviour of Case A systems.

## Acceleration of polarized electrons

In the last decade the acceleration of polarized protons, deuterons and electrons has become almost routine and several existing accelerator facilities for medium and high energy physics can provide polarized particles[5].

High current beams of polarized electrons are usually produced by shining circularly polarized light onto a gallium arsenide cathode. No such simple polarized positron sources exist. The maximum polarization attainable by this method is 50% but in practice it is typically 40%. Work is underway to achieve more[6]. The electrons can be then linearly accelerated and according to the Thomas-BMT equation there is no loss of polarization in the electric accelerating field.

If the beam is then injected into a ring for further acceleration or for phase space damping the spins, if not already vertical, must be turned into the vertical direction: Horizontal spins in vertical dipole fields and in the presence of energy spread, quickly fan out and the polarization is lost. Even then there is another hurdle to be overcome, namely that depolarization can also occur as the energy is increased and the electrons cross through spin resonances Eq. (3) [4].

A non-exhaustive list of examples of such systems includes the stretchers at NIKEF-K (0.9 GeV), MIT-Bates (1 GeV), and ELSA in Bonn (3.5 GeV), the recirculators at Mainz (0.84 GeV) and CEBAF (4 GeV) and the damping ring in the SLC (1.21 GeV)[7,8].

In most of these cases the peak energy is so low that few or no resonances need to be crossed. This is not the case at the accelerator-stretcher ELSA, where the peak energy is 3.5 GeV[9]. Depolarization can be controlled at ELSA by careful alignment of the closed orbit, by "resonance jumping", and by careful tuning of the vertical optics so that the coupling of the spin to the vertical betatron motion is minimised. The latter is called spin matching (see below). With such methods, over 90% of the initial polarization can be preserved[9].

Such polarization preserving techniques will probably not be needed at CEBAF since there, the beam will make at most four turns.

At the SLC the polarized electrons suffer some initial linear acceleration and then have their spins rotated into the vertical direction before entering the damping ring[10]. The spin rotation is achieved using superconducting solenoids. After damping, the spins are rotated by two more solenoids which allow arbitrary spin orientation in the linac. This in turn allows longitudinal polarization to be obtained at the IP at all final energies after the spins have precessed in the electron arc. Commissioning is now beginning.

The roots of the SLC concept can be found in VLEPP, the original and long standing 2 x 500 GeV linear collider project with polarized beams from Novosibirsk[11]. This machine will now be installed next to UNK at Protvino[12].

Although polarized positrons cannot be produced by illuminating a cathode with circularly polarized light, they can be produced by $e^+$–$e^-$ pair production when high energy circularly polarized photons hit a target. This will be the means for producing the polarized positrons and electrons in VLEPP. They will then be cooled in damping rings using the same kind of spin manipulations as in the SLC. The photons (of typically 20 MeV) are produced when re-used very high energy electrons (>100 GeV) traverse a short wavelength helical undulator.

So much for systems where the polarization is produced in a source and electrons spend only a limited time in the device; these techniques appear to have matured.

## Self polarization in high energy storage rings

It is a much more difficult undertaking to exploit and control natural polarization at high energy.

That electrons in storage rings could become self polarized was first noted by Loskutov, Korovina, Sokolov and Ternov who pointed out that the emission of synchrotron radiation in a simple storage ring can cause electron spins to flip from up to down and vice versa and that there is a difference in the rates[13]. Only a very small fraction of the synchrotron radiation power causes spin flip but nevertheless this asymmetry in the rates should lead to a build up of polarization along the vertical guide field. The equilibrium polarization should be $P_{eq} = \frac{8}{5\sqrt{3}} = 92.4\%$ and the time constant for the exponential build up should be

$$\tau_p{}^{-1} = \frac{5\sqrt{3}}{8}\frac{\gamma^5 \hbar e^2}{\rho^3 m^2 c^2} \tag{4}$$

where $\rho$ is the orbit radius and the other symbols have their usual meanings[2].

Typically, $\tau_p$ is in the range of minutes to hours: The polarization process is very weak!

Natural polarization was first detected at ACO and Novosibirsk[14]. It has also been seen at CESR, DORIS, PETRA, SPEAR, VEPP2M, VEPP4[14,15,16]. Three large high energy projects involving electron storage are under development namely, HERA, LEP and TRISTAN and it is planned to have polarization at VEPP4M[16,17,18,19]. As we shall see, it becomes more difficult to achieve polarization as the energy is increased.

The users of all four machines wish to have longitudinal electron polarization at the interaction points. Since (see below) the polarization vector must be vertical in the arcs in order to "drive" the polarization process, it is then necessary to rotate the polarization from vertical to longitudinal just before the interaction points and back to vertical afterwards. The Thomas-BMT equation tells us how to do this: For HERA, LEP and TRISTAN, $a\gamma$ is $O(10^2)$ and by Eq. (2), a small change in the orbit direction can cause a large tilt of the spin.

At HERA, the "Mini-Rotator" design of Buon and Steffen has been adopted[20]. This consists of a string of interleaved vertical and horizontal bending magnets for which the non-commutation of large rotations about mutually orthogonal axes is used to tilt the spin into the horizontal plane in as short a distance as practical with as small a vertical excursion as possible. The horizontal bends replace the bend angle of one arc cell and 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 so that the straight section is in the horizontal plane and it is only 60 m long so that no quadrupoles need be included among the constituent dipoles. By mounting the dipoles on coupled 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 27-36 GeV and to obtain both helicities. One pair of these rotators has been ordered and one complete rotator is undergoing mechanical tests at DESY prior to insertion in the tunnel.

At LEP a Richter-Schwitters scheme has been provisionally adopted[21]. This consists of an S-bend in the vertical plane and contains no horizontal bends. The centre part of the straight section is tilted and the geometry is fixed. Since the total length is about 200m, it must include quadrupoles and these must be included in the spin match (see below). A vertical S-bend scheme would also be used at TRISTAN. It is planned to use a solenoid-dipole combination at VEPP4M[16].

So far, we have been tacitly assuming that, with reliance on the natural polarization process, we are home and dry.

However, there is much more to the story: Electron orbits experience stochastic disturbance due to photon emission and there are damping processes. The balance of the two effects produces a stable phase space distribution. In a naive classical picture where spins ride on electrons one would expect the spins to "see" stochastic magnetic fields in the quadrupoles and that the spins would then diffuse or depolarize[2,22].

This can indeed happen: Synchrotron radiation can create polarization but it can also lead to its destruction! In Case A, the acceleration time is short and away from resonances, spin orbit coupling cannot cause much depolarization. Here, however, the storage time is comparable to the diffusion time scale. So, it is essential to understand how to compute these effects.

The first computer program which could digest a standard optic file and then analytically compute depolarization effects in the above simple picture was SLIM by Chao[2]. The final equilibrium polarization in SLIM depends on the relative strengths of the polarization and depolarization processes. One is not surprised to discover that the spin diffusion effects are strongest and hence the polarization small when the resonance condition of Eq. (3) is satisfied. However, the SLIM formalism linearises the 3-dimensional spin motion and as a direct result only the lowest order resonances with $m_x, m_z, m_s = \pm 1$ are predicted[23].

Alternatively, the program SITROS can be used to track classical spins numerically with built in radiation effects[24].

But, it is not necessary to appeal to naive pictures of classical spins riding on electrons and then somehow mix this in with a quantum mechanical picture of spin flip: A complete semi-classical quantum mechanical treatment which takes account of the various effects in a unified way has been given by Derbenev and Kondratenko as long ago as 1973 and Mane in 1987[25,26]. They give the following expression for the equilibrium polarization

$$P_{eq} = \frac{8}{5\sqrt{3}} \frac{\langle \frac{1}{|\rho|^3} \hat{b} \cdot \left[ \hat{n} - \gamma \frac{\partial \hat{n}}{\partial \gamma} \right] \rangle}{\langle \frac{1}{|\rho|^3} \{ 1 - \frac{2}{9} (\hat{n} \cdot \hat{v})^2 + \frac{11}{18} \left| \gamma \frac{\partial \hat{n}}{\partial \gamma} \right|^2 \} \rangle} \tag{5}$$

where $\hat{n}$ has been defined above and $\hat{b} = \bar{v} \times \dot{\bar{v}} / \mid \bar{v} \times \dot{\bar{v}} \mid$ where $\bar{v}$ is the particle velocity. The angle brackets denote a ring and ensemble average and $\gamma\ \partial \hat{n} / \partial \gamma$ is a partial derivative with respect to energy encapsulating the quantum mechanics of the effect of the orbit motion on the spin. Thus in this formalism, it is this quantity which describes the depolarization effects. In a perfectly aligned flat machine, $\hat{n}$ is vertical and parallel to the guide field and $\gamma\ \partial \hat{n} / \partial \gamma$ is zero leaving just the natural polarization component which gives 92.4% as before. In real machines $\gamma\ \partial \hat{n} / \partial \gamma$ can be large. It is particularly large when (again) the resonance condition of Eq. (3) for the spin tune $\nu$ is satisfied but in contrast to the SLIM picture, this now comes about because $\hat{n}$ is not well defined at resonances[3]. Furthermore, in principle, resonances can appear for all integers $m_k$ in Eq. (3). $P_{eq}$ is then small.

Mane has written the first program, SMILE, for calculating $\hat{n}$, $\gamma\ \partial \hat{n} / \partial \gamma$ and hence the polarization, which operates on standard optic files. The calculations are *analytical* and are based on a perturbation expansion for $\hat{n}$. It can be set to calculate the polarization to arbitrarily high order in the resonance structure and by definition automatically includes all resonance interference effects. It also becomes immediately clear in the formalism that although based on a different picture, SLIM calculations correspond algebraically *exactly* to the lowest order version of the general SMILE theory.

Thus SMILE represents a major advance and since its algorithm is analytical it enables analysis of various effects to be made. With this program agreement with measurements made at SPEAR can be obtained[26]. Previously,to study higher order effects, Eq. (5) could only be used to make general qualitative statements about restricted catagories of effects[14,27]. A further quantum mechanical treatment has been given by Hand and Skuja[28].

Away from resonances, $\hat{n}$ is closely parallel to $\hat{n}_0$. Inspection of the numerator in Eq.(5) shows that to obtain high polarization, $\hat{n}_0$ must be fairly parallel to the guide field in most of the ring i.e. the Sokolov-Ternov "driving" effect must be maximised. $\hat{n}_0$ also defines the direction of the ensemble polarization vector. We can now see that in machines with dipole rotators, the maximum achievable polarization will be below 92.4%. For example, at HERA, with two rotator pairs in the ring, the maximum polarization would be about 87%.

These theoretical maxima can only be achieved if $\gamma\ \partial\hat{n}/\partial\gamma$ is small at those places in the ring where $1/\rho^3$ is large. Futhermore, $\gamma\ \partial\hat{n}/\partial\gamma$ increases with energy!

Inspection of the perturbation theory for $\hat{n}$ shows that $\gamma\ \partial\hat{n}/\partial\gamma$ depends on multiple integrals which describe how the spin motion is coupled to and driven by the orbital motion. Each integral increases with energy and is to be multiplied by a factor which resonates at the resonance energies of Eq. (3). At lowest order (SLIM order) one has single one-turn integrals over products of orbital and spin functions. In machines with a longitudinal or horizontal component of polarization in the straight sections on either side of the IP and/or with vertical dispersion i.e. in any machine with dipole spin rotators, some of these one-turn integrals can be large and as a result, even at SLIM level there is no hope of obtaining significant polarization without taking special measures. These consist of carefully choosing the geometry and the designing of sufficient flexibility into the optics and the power supply layout so that the optics can be adjusted to bring the relevant integrals to zero. Naturally, the resulting optic must be acceptable on all other grounds such as aperture requirements, tunes etc etc. Thus, even at the lowest order in the theory, the minimizing of depolarizing effects has a major influence on the design of the machine and severely constrains the optics. In the current jargon, these manipulations are called "first order spin matching"[29].

At HERA and LEP good, but not perfect, first order spin match solutions can be found for the rotator systems proposed and as expected, for a $perfectly$ aligned machine, SLIM (i.e. SMILE set to do a lowest order calculation) predicts high polarization (e.g.87% at HERA) with some weak resonances. Of course, no machine is perfectly aligned: The closed orbit is always distorted by a couple of millimetres and quadrupoles are always slightly twisted. The distorted closed orbit causes $\hat{n}_0$ to be tilted from the vertical in the arcs and results in spurious vertical dispersion and these immediately cause some "dormant" spin-orbit integrals to be non-zero so that large additional terms appear in $\gamma\ \partial\hat{n}/\partial\gamma$. Thus our previous spin match is partly destroyed and since machine distortions are, by their very nature, irregular and difficult to control, we are, even at lowest order, always confronted with an almost uncontrollable source of depolarization.

Luckily, there are algorithms for adjusting the closed orbit so as to minimise the tilt of $\hat{n}_0$ and the spurious dispersion and these offer a way to regain some control. Such methods were successfully used at PETRA at 16.5 GeV to obtain over 70% polarization[29,30].

What do analytic calculations beyond SLIM predict? Calculations with SMILE show that high order $Q_s$ resonances can be very dangerous and a careful analysis of the SMILE algorithm or a calculation by Buon which extends the original spin diffusion picture of SLIM to higher order in the classical spin motion, makes the reason clear: The majority of the dangerous $Q_s$ resonances are synchrotron sidebands of parent resonances resulting from the fact that there is an energy spread and that the spin tune is frequency modulated at the synchrotron tune as a result of synchrotron motion in the beam[31,32].

It is important to note here that although the Buon and SMILE calculations are based on very different philosophies, these analyses of the two calculations show that the relevant terms agree when applied to similar assumptions about the machine conditions: Any other theory including depolarizing effects *must* agree with these two[31,32].

The strength of the sidebands can be quantified. The relevant parameter is the modulation index:

$$\alpha = \left(\frac{a\gamma\frac{\sigma_E}{E}}{Q_s}\right)^2 \tag{6}$$

The sideband strengths depend on powers of $\alpha$. $\alpha$ is clearly a strongly energy dependent quantity and, in order to control the synchrotron sidebands it must be made as small as possible. At HERA, at 29GeV and with a $Q_s$ of 0.06, $\alpha$ is 1.4 and calculations with SMILE show little residual polarization – the sidebands are very strong. Similar indications are given by SITROS. However, if $Q_s$ is increased to 0.1 so that $\alpha$ is reduced, SMILE shows the expected dramatic improvement. Thus we will make every effort to run HERA at high $Q_s$. Figure 1 shows a polarization curve for a *perfectly* aligned HERA with two rotator pairs after spin matching and with $Q_s = 0.1$.

The potential for spin tune modulation to cause trouble has been known for many years. But the predictions were always qualitative. Now, with SMILE, analytical calculations on real optic files are available, leaving little room for doubt.

At HERA, in the absence of depolarizing effects the polarization time constant at 35 GeV (say) is 11 minutes. If depolarizing effects are present, the time constants are smaller. At LEP at 46 GeV per beam where $Z_0$ physics is studied, the time constant is 90 minutes. This is uncomfortably long. Thus at LEP it is planned to install dedicated asymmetric wigglers to enhance the polarization rate[33]. In the LEP scheme, the time constant can be reduced to 36 mins at 46 GeV. There is however a drawback, namely, that these devices increase the energy spread by a factor of three[33]. TRISTAN also has a relatively large energy spread[19].

A further source of depolarization is the beam-beam force which not only deflects particles but also tilts spins[34]. This could be an additional source of depolarization. Unfortunately it cannot be treated adequately in an article of this length.

Likewise, it will not be possible to discuss the beautiful experiments that are being carried out at Novosibirsk. There, clever spin gymnastics have been used to compare the $g$ factors of electrons and positrons[35]. Scattering of longitudinally polarized electrons on nucleon targets is also underway[36]. The interested reader is strongly encouraged to consult the references[35,36].

## Conclusion

In conclusion then, whereas the acceleration of polarized electrons over short periods of time appears to present no major problem, at least for the energies foreseen, the achievement of self polarization at high energy presents a challenge which will require unaccustomed machine tuning and the accumulation of experience.

It would be a great help if a new process could be found to amplify the natural polarization process——without increasing the depolarization.

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## Figures

**Fig.1 Polarization vs. energy for HERA, calculated with SMILE.**

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