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Presented by D.P. Barber**

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Abstract

A report is presented on the status of attempts to obtain and measure spin polarization in electron-positron storage rings. Experimental results are presented and their relationship to predictions of calculations discussed. Examples of methods for decoupling orbital and spin motion and thus improving polarization are discussed.

Introduction

Since the realisation in the 1960s[1] that the emission of synchrotron radiation in electron positron storage rings can lead to a build up of spin polarization along the direction of the guide field, there have been many theoretical and experimental studies of the phenomenon. However, although polarization has been observed at several centres, it has remained something of a curiosity. It has indeed been used in investigations of quark angular distributions at SPEAR[2], and to obtain accurate calibration of beam energies. However it becomes most powerful at high energies, above a few tens of GeV, where longitudinal polarization provides a tool for investigation of the couplings in weak interactions[3] and where, unfortunately, the generation of polarization becomes more difficult.

In this article I report on the experimental study of the machine physics aspects of polarization at SLAC and Novosibirsk and on the status of the successful attempts to obtain polarization at the highest energies available, namely at PETRA.

I restrict discussion to vertical polarization which is the necessary precursor to longitudinal polarization.

Before proceeding, I remind the reader of some basic properties of the polarization mechanism in storage rings[4)].

a) Synchrotron photon emission can lead to a build up of vertical polarization due to the difference between the spin-up to spin-down transition rate and the spin-down to spin-up transition rate[1,4)]. The maximum achievable polarization due this mechanism is 92.38 %.

b) The polarization vector points along the so called $\hat{n}$ axis, a periodic unit vector for the spin direction which is dependent on the shape of periodic (closed) orbit of the beam and on the energy. An arbitrary spin vector precesses around $\hat{n}$ by $a\gamma$ times per revolution where γ is the Lorentz factor, $a = (g-2)/2$ where g is the electron g factor and $a\gamma$ is called the spin tune.

c) Synchrotron radiation both creates polarization and causes its destruction: sudden energy loss by photon emission causes a particle suddenly to follow a new orbit in the focussing system with the result that the correlation between orbital and spin motion is lost and depolarization can occur.

d) In travelling around the ring, particles experience horizontal and vertical betatron oscillations and longitudinal or energy oscillations known as synchrotron oscillations.

e) The depolarizing effects are strongest at the so called depolarizing resonances where:

$$a\gamma = k \qquad \text{(imperfection resonances)} \qquad (1a)$$

$$a\gamma = k \pm Q_I, \; I = x,y,s \qquad \text{(linear intrinsic resonances)} \qquad (1b)$$

$$a\gamma = k \pm n_x Q_x \pm n_y Q_y \pm n_s Q_s \qquad \text{(non-linear intrinsic resonances)} \qquad (1c)$$

where k and n_x, n_y, n_s are integers and Q_x, Q_y, Q_s are the orbital tunes.

In short, electron beam behaviour is dominated by focussing, damping and stochastic excitation effects and these have a profound effect on polarization.

Measurement of Polarization

In order to investigate the behaviour of polarization and to use it to specify the running conditions of the physics experiments we clearly need polarimeters which provide reliable and reproducible measurements which are independent of the High Energy Physics effort. The polarimeters should be fast so that feed back can be applied to the machine conditions and so that measurements can be statistically accurate. It should be possible to make measurements on single beams.

The best way to satisfy these requirements is to backscatter circularly polarized laser light off the electrons as shown in Fig. 1 which illustrates the layout of the PETRA polarimeter. Electrons entering a straight section from the left collide with photons of 2.42 eV from an argon ion laser. The photons are Compton scattered through 180° into a shower counter 50 meters down stream behind a vertically steerable slit. The scattering angle θ and the photon energy are correlated by kinematics and θ is of order $1/\gamma$. For example for 16 GeV electron energy, θ is typically 30 microrad and the scattered photon energy $\leq$ 5 GeV. If the electrons are vertically polarized, the angular distribution of scattered photons has the following form[5,6,7]:

$$\frac{d\sigma}{d\theta\ d\varphi} \propto [f(\theta) \pm P \cos\varphi\ g(\theta)] \qquad (2)$$

and where P is the electron polarization and thechoice of + or - sign depends on the laser photon helicity. Eq. 2 shows that there is an up/down asymmetry and an asymmetry under reversal of photon helicity. The asymmetries are proportional to the degree of vertical polarization of the beam which can then be measured by recording the rate in the shower counter for each photon helicity and as a function of the vertical position of the slit. In practice we can reduce systematic errors by combining these rates into on overall asymmetry:

$$\hat{A}(y) = \frac{1}{2}\,(A(+y)-A(-y))$$

where $$A(y) = (N_+(y)-N_-(y)) \,/\, (N_+(y)+N_-(y))$$

and where $N_{+/-}(y)$ is the photon rate for positive (negative) helicity at position y. The maximum of $\hat{A}(y)$, $\hat{A}_m$ occurs at $\theta \approx 1/\gamma$ i.e. at $|y| \approx 1.5$ mm at PETRA.

Since from Eq. 2, $\sigma_p/P \approx \sigma_A/A$ and since $\sigma_A \approx 1/\sqrt{N}$, the error on polarization is minimized if the rate is high and A is large. This implies use of high laser power and high electron-photon collision luminosity. The high rate also reduces contamination of the signal by backgrounds. At PETRA, where $\hat{A}_m$ is $\approx$ 10 % it is routinely possible to achieve $\sigma_p/P \approx 2$ % with count rates of order 20 kHz.

If we begin with an initially unpolarized beam, the asymmetry increases in time as:

$$\hat{A}_m(t) \propto P(t) = 0.92 \frac{\tau_e}{\tau_p} \left[1-\exp-t/\tau_e \right] \qquad (3)$$

where τ_p is the polarization build up time for a perfect machine, and is proportional to $(\text{Energy})^{-5}$, $\tau_e = \tau_p \tau_d/(\tau_p + \tau_d)$ and τ_d describes depolarising effects in a real machine. Fig. 2 shows a typical measurement of the rise of $\hat{A}_m$ at PETRA at 16.5 GeV. The smooth line is the fit to the exponential shape of Eq. 3 and corresponds to τ_e = 13.6 ± 0.8 min. τ_p = 17.9 min. and from Eq. 3 we deduce that the asymptotic polarization, P (∞) was 70 ± 4 % in agreement with the degree of polarization deduced from the asymptotic value of $\hat{A}_m$ and knowledge of the polarimeter acceptance.

We can see clearly from this example that use of laser polarimeters is a well established technique. Nevertheless improvements in count rate are welcome and a high power Nd-Yag laser is now being installed at PETRA.

Calculation of polarization

In addition to our being able to make measurements it is obviously essential that we are able to calculate and predict polarizations as an aid in optimising machine design. Unfortunately, since the mechanism of depolarization is so complex, it is extremely difficult to obtain complete meaningful analytic predictions. Until recently, the only practical method which incorporates all aspects of the lattice of a particular machine has been to use the program SLIM written by A. Chao[4,8]. This program is based on a linear perturbation theory which extends the 6x6 transport matrix formalism of conventional machine optics to a linear, coupled spin-orbit formalism using 8x8 matrices.

Thus the formalism only predicts linear intrinsic resonances but it does superimpose all resonance effects simultaneously. Lack of space prohibits further discussion but further information may be found in Ref. 9. SLIM is the program that everyone uses and I will comment on comparison of predictions with experimental results below.

A more complete description of depolarization including non-linear effects can be obtained by a tracking simulation in which a bunch of electrons is followed around the ring, emitting photons. This approach of course consumes large amounts of computer time but it has recently borne fruit[10] with the prediction of non-linear resonance effects in PETRA.

Control of depolarization effects

In a perfectly aligned (flat) storage ring particles travelling on the closed orbit feel vertical magnetic fields and the $\hat{n}$ axis is vertical. In reality, storage rings are never flat and the closed orbit is "wavy". Since electrons on the closed orbit now feel the radial fields of the quadrupoles, the $\hat{n}$ axis is no longer exactly vertical. Within the framework of the first order perturbation theory of SLIM it may then be shown that the spin vectors of individual particles which are executing horizontal betatron oscillations experience varying degrees of precession around the $\hat{n}$ axis depending on their amplitude and phase. The ensemble of spin vectors thus becomes smeared or depolarized. Also, since the beam now has vertical thickness, similar smearing results from precession of the (almost) vertical spins around the radial fields of the quadrupoles during vertical betatron motion. These effects are strongest near energies satisfying the resonance conditions of Eq. 1 and they increase with energy.

Clearly , the effect of horizontal motion can be suppressed if the $\hat{n}$ axis can be returned to vertical with the aid of correction coils which control the vertical closed orbit. This would then be an example of how to decouple spin and horizontal motion. It may be shown that the deviation of the $\hat{n}$ axis from vertical is proportional to[5]:

$$[\int B_r(s) \cos \varphi_s \, ds]^2 + [\int B_r(s) \sin \varphi_s \, ds]^2 \qquad (4)$$

where φ_s is the spin precession phase and $B_r(s)$ is the radial field on the closed orbit.

The chief contributions to these integals come from Fourier harmonics in the periodic $B_r(s)$ which are closest to the spin tune and which may comprise only a small part of B_r. If these harmonics can be empirically suppressed by selective excitation of vertical correction coils in a way that does not cause undue additional distortion of the orbit by excitation of other harmonics, then $\hat{n}$ may again be brought close to vertical.

This scheme, has been successfully applied at PETRA and experimental results are discussed below.

Experimental studies

a) Single beams at low energy

As mentioned above, depolarizing effects increase with energy and it is expected that it is easier to obtain polarization at low energies than at high energies. With this in mind, Fig. 3a shows an amalgamation of single beam measurements for SPEAR[11]) obtained over many different machine runs spanning 3.52–3.76 GeV. We see regions of high polarization partitioned by linear and non-linear resonances. The smooth curve is hand drawn to guide the eye. By selecting suitable energies in this range there seems to be no particular difficulty in obtaining good single beam polarizations. Fig. 3b shows the measured dependence of τ_e on energy at SPEAR away from resonances. The straight line is the absolute theoretical prediction and is in good agreement with the measurements. Our earlier comments on SLIM are illustrated in Fig. 3c[4]) which shows a comparison between measurement and SLIM prediction near 3.6 GeV. SLIM indeed predicts the linear resonances $a\gamma - Q_x = 3$ and $a\gamma - Q_y = 3$ but as expected fails to predict the non-linear resonance at $a\gamma - Q_x + Q_s = 3$.

b) Single beams at high energy

At the higher energies of PETRA,[6]) success was initially more elusive, with measured polarizations rarely above 30 % and not reproducible. However the situation improved radically with the introduction of the closed orbit correction scheme described above. The measurements were made near 16.52 GeV. ($a\gamma = 37.5$) so that the dominant closed orbit harmonics were the 37th and 38th.

Figs. 4a and 4b show the dependence of the asymmetry on the 38th sine and cosine harmonics and Fig. 4c shows the energy dependence of the asymmetry after optimisation of all four harmonics at 16.52 GeV. There is then a range of about 150 MeV where the asymmetry is high. This behaviour is reproducible and after calibration with a rise time measurement is seen to correspond to maximum polarizations above 70 %. This represents a major success in attempts to understand and control depolarization effects at high energy[6].

At these high energies, where the depolarizing effect of closed orbit distortions becomes strong, quantitative predictions of SLIM must be treated with some caution since the orbit distortions which would need to be fed into SLIM are difficult to measure with precision. However, SLIM still provides a very useful qualitative framework for simulating correction schemes and the gross features of depolarizing effects.

c) Beam-beam effects

The results presented above were all obtained with a single beam circulating. With both electron and positrons circulating, the particles are subject to strong nonlinear electromagnetic forces as the bunches pass through each other. There is a tendency for the beam diameters to increase and for the luminosity to suffer. The beam-beam force is also a source of depolarization.

The beam-beam effect has also been investigated at PETRA[6]. After optimising the closed orbit as described and establishing a single beam polarization of more than 70 %, measurements were made with a range of equal electron and positron currents. The ratio of single to double beam asymmetries is shown in Fig. 5 and it is seen that the polarization is unaffected until currents of $\approx$8 ma are reached. Then, not only the polarization but also the luminosity decreases and the vertical beam height increases. At PETRA the luminosity and polarization are thus limited at similar currents and if beam blow up can be avoided it looks as if polarization will probably also remain high.

Colliding beam polarization has also been observed and used[2,11] at SPEAR. Broadening of resonances by non-linear effects has been seen and high polarizations have been obtained at normal luminosity but in general they find that their results are somewhat unpredictable. Colliding beam polarization has also been observed at VEPP4 but not at full luminosity[12].

Depolarizers

Surprisingly, it is also very useful to be able to depolarize the beam in a controlled manner with the aid of a weak oscillating radial magnetic field[13]. Depolarization occurs if the resonance condition:

$$w_d = w_c\,(a\gamma - k) \quad \text{or} \quad w_c\,(k' - a\gamma) \qquad (5)$$

is satisfied where w_c is the circulation frequency, w_d is the depolarizer drive frequency and $a\gamma$ -k or k'-$a\gamma$ are the fractional parts of the spin tune. w_d can be measured precisely and since w_c is large, a small change in γ results in an easily measureable change in w_d. Measurement of w_d then allows precise calibration of the central energy of the beam. Fig. 6 shows the variation of polarimeter asymmetry as a function of depolarizer frequency near 16.5 GeV at PETRA[5].

From Eq. 5 the energy was found to be 16509 ± 0.13 MeV. The error corresponds to the 1/2 width of the depolarization curve. Thus a fractional energy error of $\approx 10^{-5}$ is achievable although the fractional energy spread of the beam is $\approx 10^{-3}$. This technique has been exploited at VEPP4[12,14] for example, to determine the mass of the γ to be 9459.7 ± 0.6 MeV and in earlier VEPP machines to determine the mass of the ρ, K^{+-0}, J/ψ, ψ' to one part in 10^4 or 10^5.[12,14] The depolarizer technique can also be extended to allow measurement of the momentum compaction factor and incoherent synchrotron frequency thus opening up the possibility of measuring machine dynamics parameters otherwise not so easily accessible. Depolarizers can also be used to ensure that the polarization is zero or for selectively depolarizing one beam during High Energy Physics experiments.

Solenoids

Finally, I report on some recent studies of the depolarizing effects of detector solenoids . With vertically polarized beams, uncompensated solenoids cause depolarization by tilting the $\hat{n}$ axis and because spin is disturbed by the betatron motion in the solenoid field. For example, Fig. 7 shows how the PETRA polarization falls as two uncompensated solenoids are run up. In the case of longitudinal polarization the $\hat{n}$ axis is unaffected but the betatron effect still remains.

The preferred remedy is to compensate each solenoid by adjacent opposite strength "antisolenoids" but normally there is no space owing to the proximity of the focussing quadrupoles. It has now been found that a solution to this second difficulty is to place the antisolenoids further out among the quadrupoles and to use an optics in which the particle direction at the solenoid is the same as that at the antisolenoid[15,16]. This is then a second example of how the machine conditions can be adjusted so as to decouple spin and orbital motion.

Summary

In summary it is clear that there is now no particular difficulty in obtaining good vertical polarization in single beams at low energies. The generation of polarization at high energies in the PETRA range is much more difficult but there has been a big increase in confidence and understanding following the success of the PETRA closed orbit correction scheme. However much more remains to be done, the region of high polarization at PETRA must be widened and polarization must be obtained at the new maximum PETRA energy of about 22 GeV and finally, realistic schemes for obtaining longitudinal polarization must be found.

Acknowledgements

We wish to thank Prof. G.-A. Voss for continued encouragement and support.

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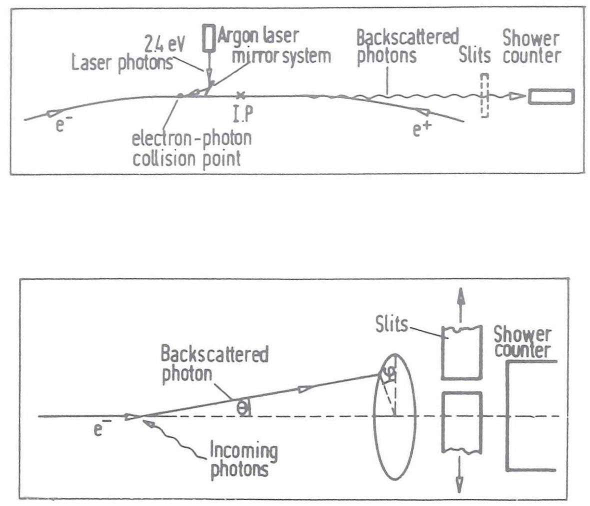

Fig. 1. Layout of PETRA polarimeter

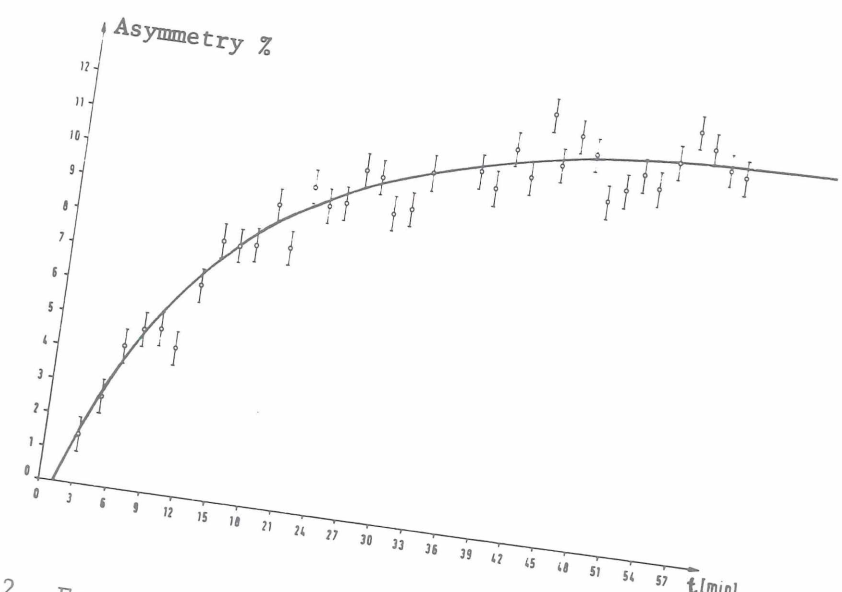

Fig. 2. Exponential build up in time of the polarimeter asymmetry at PETRA at 16.5 GeV

Fig. 3a. Polarization as a function of energy measured at SPEAR. (From Ref. 11)

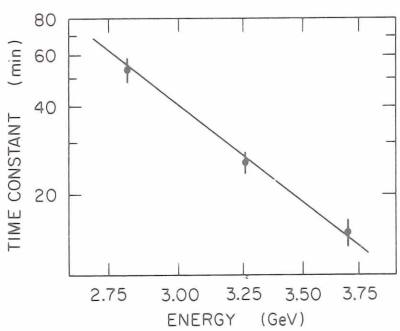

Fig. 3b. Polarization build up time as a function of energy measured at SPEAR. (From Ref. 11)

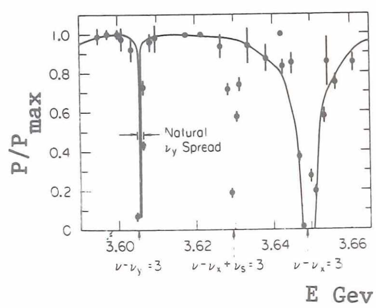

Fig.3c. Detail of SPEAR polarization curve showing non-linear resonance: $a\gamma - Q_x + Q_s = 3$

(From Ref. 11)

Fig. 4a. Polarimeter asymmetry at PETRA vs. the strength of the 38th cosine harmonic in the closed orbit (arbitrary units).

Fig. 4b. As in Fig.4a but for the 38th sine harmonic.

Fig. 4c. Polarimeter asymmetry at PETRA as a function of energy after closed orbit optimisation.

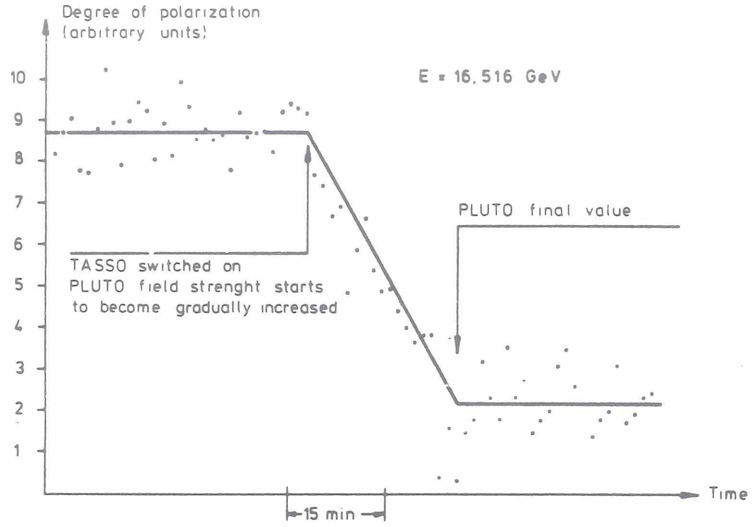

Fig. 7. Polarization vs. time as two experimental solenoids are run up at PETRA.