Polarized Beams and Polarimeters at Lepton Accelerators *

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Abstract

The parallel sessions with the above title are summarized.

INTRODUCTION

This article summarizes the twenty-two talks given in four parallel sessions under the above title at this symposium. The topics covered included polarimetry, polarized high-energy electron beams, polarized muon beams, spin flipping and mathematical techniques.

POLARIMETRY

When polarized electron or muon beams are used for testing the Standard Model or investigating the spin structure of nucleons, it is essential that the beam polarizations be known at the 1% level (1,2). The usual way to measure the polarization of an electron beam is to have it collide with a circularly polarized visible laser beam and measure the distribution of the (Compton) backscattered high-energy photons. This is one of several methods proposed by Baier and Khoze (3). If the electron beam is vertically polarized the polarization is proportional to the shift in the vertical plane of the centroid of the scattered photon distribution when the helicity of the laser beam is reversed.

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If the beam is longitudinally polarized, one measures the asymmetry in the backscattering rate instead, while tagging the scattered electron energies. The two methods are susceptible to very different systematic errors. For example vertical polarization involves measuring centroid positions to a few microns and longitudinal polarization requires that the electron-photon luminosity is independent of the laser beam helicity. The required specifications are difficult to achieve but the techniques are now sufficiently mature that variations on the theme are being tried out or proposed, mostly with the aim of improving the statistical precision achievable in a given time interval.

C. Cavata (4) explained how at CEBAF, the longitudinal polarization of the 4 GeV electrons will be measured by Compton scattering them from a Nd-Yag photon field trapped in an optical cavity formed from two mirrors. This is necessary since the analysing power is small at 4 GeV and the electron currents are only about 100 microamps. The cavity amplifies the scattering rate by a factor of ten thousand.

In his plenary talk M. Placidi (5) recalled that at LEP the polarization of both the electrons and the positrons is measured by using one laser and a mirror to reflect the "once used" laser light back though the positron beam.

At Novosibirsk G. Kezerashvili (4) and the ROKK-1M collaboration working on the VEPP-4M electron-positron ring uses three high power pulsed Nd-Yag lasers to produce frequency doubled, tripled and quadrupled beams. These are used for polarization measurements and the well collimated, intense backscattered photon beams, with energies up to 1.5 GeV can also be used for photonuclear physics experiments and for investigating nonlinear QED.

As reported by F. Zetsche (4), at HERA the backscattered photon rate is about 1.5 kHz per milliamp. The tungsten-scintillator sandwich detector can record single photons. So with electron beam currents of tens of milliamps, the readout electronics must be able to process photons at up to 100 kHz. The photon energies are recorded using 1 MHz 12 bit ADCs and a microprocessor accumulates a set of diagnostic and data histograms online so that they are immediately available for display. The control software now enables the polarimeter to run unattended. The statistical error is one to two percent per minute depending on the electron current.

At the SLC (2) the longitudinal electron polarization is measured behind the interaction point using a Compton polarimeter but also using Möller polarimeters at the beginning of the arc. With the strained GaAs source over 80% electron polarization is regularly delivered to the electron–positron collision point. However, initially the Möller measurements were about 15% below the Compton measurements. In Möller polarimetry one measures asymmetries when polarized electrons are scattered in magnetized foils. As explained by H. Band (SLAC)(4) and A. Afanasev (CEBAF) (4) this discrepancy is now understood and is due to the neglect of the atomic binding energies although these are only in the tens of KeV range. Once an appropriate correction is made the Compton and Möller results are compatible. The correction is always positive and depends on the design of the polarimeter.

A completely different technique, to be applied to stored beams was suggested by Ya. Derbenev (4,6). A polarized particle bunch has a magnetic moment and this can be used to set up an electromagnetic field in a suitably tuned superconducting rf cavity. This is reminiscent of a speculation put forward in 1983 (7) that it might be possible to measure the magnetic flux from the magnetic moment of bunches using superconducting loops.

POLARIZED STORED ELECTRON BEAMS

It is well known that electrons in storage rings can become spin polarized as the result of the emission of spin flip synchrotron radiation (8,9). This, the Sokolov-Ternov effect, results in a maximum of 92.4% polarization in uniform fields. Electron polarization is obtained regularly in low-energy rings. But depolarizing effects associated with orbit excitation resulting from the stochastic nature of photon emission, increase strongly with the beam energy and the degree of misalignment of the ring. The asymptotic polarization essentially results from a balance between the Sokolov-Ternov effect and the depolarization.

Nevertheless as the result of careful adjustments of the orbit and other parameters, over 65% vertical polarization has been obtained at HERA (27 GeV) and 57% at LEP (46 GeV) which is the highest energy electron ring ever built.

For LEP, R. Assmann (4) reported on deterministic closed orbit corrections and B. Dehning (4) on beam energy calibrations. The depolarization due to closed orbit distortion appears mainly via the resulting tilt from the vertical of the equilibrium spin axis. If this is more than about 20 mrad, spin diffusion due to horizontal orbit motion becomes serious. The orbit can be corrected (flattened) with correction coils but this does not automatically mean that the spin tilt is corrected. However, the tilt is dominated by harmonics close to the spin tune in a Fourier analysis of the orbit distortion (10). So the best way to correct the tilt is to use the correction coils to generate "anti-harmonics". This can be done empirically by maximizing the measured polarization but at LEP the characteristic reaction time of the polarization to changes in the conditions is measured in hours. Luckily, at LEP the beam position monitor system is so precise that the Fourier harmonics in the orbit can actually be measured. This allows the orbit to be corrected deterministically with a corresponding large saving of time. Another source of spin axis tilt is the fields of the solenoids in the detectors. At LEP there are no local compensating solenoids but instead the tilts are compensated by generating “anti-tilts” in orbit bumps placed on either side of each solenoid. It is the systematic application of these measures that has led to the 57% polarization even at this highest of energies. At LEP the quadrupoles are correctly positioned at the 0.1 mm level and the monitor positions are known to comparable precision. The ring has a circumference of 27 km. So we are witnessing a major achievement in accelerator construction.

The vertical polarization at LEP provides a route to the very precise beam energy calibrations needed for a full evaluation of the data at the Z. If a small radial rf field running in resonance with the natural spin precession frequency is applied to a vertically polarized beam, the beam is quickly depolarized and a measurement of the required rf frequency enables the beam energy to be estimated with great precision. Thus the width and mass of the Z are now known to 3.2 MeV/c^2 and 2.5 MeV/c^2 respectively. These depolarization methods also allow the change in ring length due to tidal forces to be measured.

It is also noteworthy that these resonant depolarization runs sometimes lead to spin flip. There *is* a decrease in the absolute size of the polarization but the fact that some polarization remains is surprising given that a recent calculation by D. P. Barber et al.(4) suggests that the projections of the spin vectors on the horizontal plane should effectively become decoherent within several damping times. This is clearly a topic which would benefit from further analytical and Monte-Carlo investigation as spin flipping with an rf field would provide an attractive way to reverse the spin direction (11) when spin rotators provide longitudinal polarization at the interaction points.

As pointed out by Yu. Shatunov (4), the calculation and realisation of spin flip is particulary tricky at half integer spin tune, where the assumption of adiabaticity breaks down. In this case it is necessary to arrange that the spins effectively see a circularly polarized rf field and he made suggestions as to how this could be achieved.

On the related topic of spin flip during polarized proton acceleration through intrinsic (i.e. spin-synchrobetatron) resonances, Ya. Derbenev (4) suggested how to use an rf field to prevent loss of polarization by forcing complete spin flip.

The year 1994 brought a major advance in the manipulation of polarization in storage rings: as reported by M. Düren (4,11), spin rotators were installed in the HERA electron ring and for the first time in the history of electron storage rings it was demonstrated that stable longitudinal polarization could be provided at an interaction point. Furthermore, the longitudinal polarization was achieved on the first occasion that the rotators were activated and reached about 55% compared to about 65% immediately before the turn on. The HERA rotator design adopted at HERA is the “MiniRotator” scheme of the late Klaus Steffen of DESY and of Jean Buon of Saclay (12). These rotators are installed at the ends of the arcs on either side of the East straight section and each rotator consists of strings of interleaved horizontal and vertical bending magnets which in horizontal bending angle replace two arc dipoles. The vertical bends form a closed bump with a total vertical excursion of only twenty centimetres. Thus the distortion of the standard machine geometry is minimal. That this is possible is due to the fact that the spin precession rate in a transverse field at the chosen energy of 27.52GeV is about sixty-three times larger than the orbit deflection. Thus small commuting orbit deflections can be used to generate large noncommuting spin precessions which turn the equilibrium polarization vector from vertical in the arcs to longitudinal at the interaction point and back again on entering the arc. All rotator magnets are mounted on remotely controlled jacks so that the spin helicity at the interaction point can be reversed by reversing the fields and geometry of the vertical bends.

The achievement of longitudinal polarization can be better appreciated when it is recalled that it had not been self evident that the polarization could be maintained in the presence of rotators (8). It was pointed out above that tilts of the spin axis from the vertical of just a few tens of milliradians can strongly reduce the polarization. Thus a "designed in" tilt of ninety degrees could be fatal. However, a detailed look at the linear theory of the relation of spin diffusion to synchrobetatron shows that the depolarization taking place in the region between the rotators can in principle be strongly suppressed by a suitable design of the optics. This technique is called strong spin matching (11) and such a spin matched optic was used for the rotator tests. However, strong spin matching does not take direct account of higher order effects such as the so called synchrotron sideband resonances. But the successful generation of longitudinal polarization at HERA shows that strong spin matching is sufficient and opens up a new vista for high-energy electron spin physics.

The potential for further improvement of the polarization at HERA was discussed by M. Böge (4). So far at HERA, the standard way to correct the tilt of the spin axis is to use empirical harmonic closed orbit correction. At HERA it is difficult to apply deterministic harmonic closed orbit correction since the positions of the beam position monitors with respect to the quadrupoles are not well enough known. However, by systematically perturbing the quadrupole strengths around the ring and thereby shifting the closed orbit by small amounts it is possible to measure the relevant monitor positions. Simulations for HERA with the SITROS program (13) show that once these are known, a conventional closed orbit correction already brings a large improvement in the polarization and that when harmonic orbit correction is applied in addition, polarizations of well over 80% should be possible. SITROS simulations with HERA orbits optimized so far by the existing methods now show (13) good qualitative agreement with the measurements of both vertical and longitudinal polarization at HERA.

As explained by H. Grote (4), there is also a spin matched design for rotators at LEP and a proposal has been submitted for a test installation. These rotators are of the vertical S-bend Richter-Schwitters type. In contrast to the MiniRotators, they contain quadrupoles but the spin matching can still be achieved and high polarizations as predicted by the SODOM program (14) are even expected in the presence of the synchrotron sideband resonances and distortions.

The existence of depolarization was first predicted by Baier and Orlov in 1966 (15) in a picture based on spin diffusion caused by orbit oscillations. At high energy these effects can be very strong and those of us who have been involved know how important it is to have reliable methods of calculating the depolarization that can be expected in a storage ring with a particular set of distortions, with and without rotators. One way to proceed is to model the spin diffusion process using the numerical Monte-Carlo tracking program SITROS . First order resonance effects can be calculated analytically by the SLIM program and its derivatives (16). However, it is also very desirable to have methods available which calculate the polarization analytically to high enough order that all the strong depolarizing resonances can be included. All of the existing analytical methods are based on a formalism introduced by Derbenev and Kondratenko in 1972 (17) and reinterpreted by Mane in 1987 (18). In this approach the consideration of high order depolarizing effects is greately simplified by the recognition that at equilibrium the direction of the polarization vector depends on the position in phase space and azimuth. The *value* of the polarization is independent of these. Once the polarization axis is known as a function of phase space position and azimuth, the equilibrium polarization can be calculated with a simple formula which implicitly contains the Sokolov-Ternov effect in the limit of zero depolarization. However, with conceptual simplification comes numerical and analytical complication: this position dependent polarization axis is difficult to calculate and faster and more reliable algorithms are in demand. The SODOM algorithm has already been mentioned. This can calculate the polarization in the limit of linear orbit motion up to arbitrary resonance order given a powerful enough computer. But it would be useful to have an analytical estimate of the effect of nonlinear orbit motion and the first analytic algorithm capable of doing that, the SPINLIE algorithm of Eidelman and Yakimenko, was presented by Yu. Eidelman (4). SPINLIE uses Lie algebraic methods to construct one turn spin-orbit maps and can calculate up to second order in spin and orbit motion. Calculations for HERA are in progress.

One turn maps can also be generated in Taylor series form by the method called Differential Algebra pioneered by M. Berz and his group. As explained by Berz (4), they have now generalized their COSY INFINITY program, which was originally designed for orbital motion, to handle spin motion too. The new version of COSY can calculate the position dependent polarization axis up to high order in both spin and orbit and this extention promises to have a wide field of application both in polarized electron and in proton studies.

The simple picture of polarization build-up balancing depolarization can sometimes be too naive. This becomes clear on inclusion of all the terms in the Derbenev-Kondratenko formula (19,20) and serves both as a warning against oversimplifying the picture and as an encouragement to use rigorous methods. For example, in his talk on spin manipulation at the MIT-Bates ring Yu. Shatunov (4) pointed out that in the presence of snakes the equilibrium polarization generated by synchrotron radiation would, if it were to be used, be a strong function of energy, even changing sign!

It has long been common practice and useful for rough calculations, to view synchrotron radiation as an inverse Compton scattering process: in the electron rest frame the static magnetic field is equivalent to a gas of virtual photons which scatter off the electron and appear as synchrotron radiation in the laboratory. In his talk, R. Lieu (4) explained how he and W.I. Axford have been able to reproduce the usual expressions for the synchrotron radiation spectrum including quantum corrections by a careful coherent addition of the scattered photon field. So the connection between synchrotron radiation and inverse Compton scattering is now formally established. But that is not all: Lieu has recently also shown that the standard spin flip rates of the Sokolov-Ternov effect can be obtained by further careful use of the Klein-Nishina formula. So the value of 92.4% for the maximum value of the polarization can be understood directly from Compton scattering theory in the electron rest frame without having to appeal, for example, to the use of a mixed rest frame and laboratory frame description (21). It is to be hoped that this will provide further insights into the spin flip of accelerated electrons.

In the very strong fields of the kind found in crystals, the forces acting on the spins are no longer simply of the Stern-Gerlach kind and as explained by Y. Bashmakov (4) they can be used to spacially separate electrons in different spin states.

MUON POLARIZATION

If electrons were to have no gyromagnetic anomaly, $(g-2)/2$, then according to the BMT equation (22) spin depolarization (see above) would be much weaker and dipole spin rotators would not work. As explained by G. Bunce (4) the $(g-2)/2$ for muons has a much subtler significance: it holds many clues to the electroweak contribution to the effective muon structure. Currently the difference between the measured and calculated value is $(4 \pm 9)10^{-9}$. When the new muon storage ring is running at Brookhaven the error on the measurement will be improved by a factor of twenty.

F. Feinstein (4) described muon polarimetry at the SMC beam at CERN based on measuring the decay positron spectrum and $\mu - e$ scattering.

CONCLUSION

When we look back to the dreams and plans of the early 1980's for spin polarization in high energy colliders we realise that the persistent efforts of the intervening years have paid off handsomely. These parallel sessions have demonstrated that the technology of spin polarization in lepton colliders is now almost a standard part of the accelerator engineer's toolkit. It is now up to the experimenters and theorists to exploit the new possibilities to the full.

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