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PLANS FOR POLARIZED BEAMS IN LEP

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Abstract

Plans are presented for the implementation of polarized beams in LEP Phase 1 up to about 50 GeV. They include polarimeters, enhancement of polarization rate, error correction methods and spin rotators for longitudinal polarization.

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1. INTRODUCTION

The feasibility of obtaining polarized beams in the Large Electron Positron (LEP) storage ring /1/ has been under regular review since the early days of the design studies. Although the initial estimates of depolarizing effects were rather discouraging /2/, it later became evident that the model used for this calculation was unduly pessimistic. In recent years the greatly improved understanding of spin motion in storage rings has given us confidence that highly polarized e^+e^- beams can be obtained in LEP up to energies in the 50 GeV range and perhaps even higher.

The measures that have to be taken to achieve this are similar to those that have been successfully used in PETRA and in other storage rings. However, in this high-energy region the strengths of depolarizing resonances are particularly sensitive to machine imperfections, and the error correction procedures, whilst mainly conventional in principle, require further refinement in their practical application. An important requirement will be fast, high-resolution polarimeters, in order to minimize the time required for the correction process.

Although the size of LEP corresponds to a maximum energy of about 100 GeV, the earlier operation in Phase 1 is likely to be dominated by the physics around the Z^0 . Here, polarized beams could be valuable in testing for deviations from the standard model or the existence of right-handed neutral currents, as well as enhancing a number of other measurements /3/. Our plans have therefore concentrated on the energy range up to about 50 GeV. This brings the advantage that depolarizing effects should be somewhat easier to control than at higher energies but the disadvantage that the natural polarization rate from the Sokolov-Ternov effect is rather low. Means must therefore be provided to enhance this rate.

To exploit the full physics potential of polarized beams in e^+e^- collisions one requires longitudinal polarization at the interaction region. Although the spin rotators needed for this purpose will not be introduced until transversely-polarized beams have been demonstrated, a conceptual design is required at an early stage to ensure that sufficient space is available for their subsequent installation.

In this paper we outline the plans for implementation of polarized beams in LEP and the means foreseen to avoid depolarization. For a detailed discussion of these topics the reader is referred to the general review paper by one of the present authors /4/.

2. DEPOLARIZING RESONANCES

The natural polarization in an electron storage ring resulting from the Sokolov-Ternov effect is in competition with the depolarizing action of the spin resonances, which have the general form

$$\nu = \gamma a = k_0 + k_x Q_x + k_z Q_z + k_s Q_s .$$

Here $a = (g-2)/2$ is the anomalous part of the gyromagnetic ratio, Q_x, Q_z are the betatron-oscillation tunes, Q_s is the synchrotron-oscillation tune and γ the Lorentz energy factor. For $k_x = k_y = k_s = 0$ the integer k_0 is associated with spin perturbations from Fourier harmonics of closed-orbit deviations, which arise from errors in alignment and field of the magnetic elements. Integers k_x, k_z and k_s , as well as k_0 , are associated with the corresponding amplitudes of free particle oscillation around the closed orbit, and resonant driving terms can occur in combination with orbit-error harmonics.

In the energy range of LEP the strongly quantized nature of the synchrotron radiation enhances the depolarizing influence of the spin resonances and imposes tighter conditions on orbit correction than at lower energies. In order to reduce these effects it is obviously desirable to start with a carefully aligned machine and to choose operating conditions such that the spin motion is as insensitive as possible to the errors. This can be helped by an appropriate choice of energy, reduced excitation of the strong quadrupoles near the interaction region ("detuned low- β ") and a suitable value of Q_s . Such conditions favour the appearance of a measurable level of initial polarization and facilitate the correction procedures.

2.1 Correction of Closed-Orbit Errors

Deviations from the ideal closed orbit arise from misalignment of quadrupoles, tilts of bending magnets and other disturbances of the magnetic field. These field perturbations can be represented by the spectrum of their Fourier space harmonics which, for a machine with many elements, extends up to high harmonic numbers. The response of the orbit to these perturbations is greatest in the vicinity of the betatron tune Q , and the measurable orbit deviations are therefore mainly associated with harmonic numbers $k_0 \sim Q$. The normal orbit-correction procedures aim at minimizing the peak and r.m.s. orbit errors measured at a limited number of pick-up electrodes, by applying correcting dipole fields. The effect of this is to reduce those orbit harmonics near to Q but, unless extra conditions are imposed, higher harmonics may be enhanced in an

uncontrolled fashion. This is a distinct possibility in LEP with $Q_z = 78.2$ and $\nu \sim 114$ at 50 GeV, and it is therefore desirable to constrain the normal orbit-correction algorithm so as not to produce harmonics near the spin tune.

There remain the higher harmonics which were already there before correction. These are likely to be of rather small amplitude, and their compensation by a special algorithm should not give rise to appreciable changes in the orbit. By the same token however, the information necessary to correct these harmonics cannot be extracted from the pick-up signals, and an initially measurable degree of polarization is required in order to avoid time-consuming scans of parameters.

For a machine such as LEP, in which an appreciable fraction of the circumference is composed of long straight sections, there is a subtlety in the evaluation of harmonics which we have ignored in the above discussion. A natural reference frame to choose for describing the spin motion is the so-called orbit frame, which has one component $\hat{y}$ everywhere tangent to the ideal closed orbit with orthogonal components $\hat{x}$ and $\hat{z}$ in the radial and vertical directions respectively. In this frame the unperturbed spin is stationary in the straight sections, but in the bending arcs precesses at a higher rate than the average by a factor R/ρ , where R is the average radius and ρ the bending radius of the machine. This modulation gives rise to a spectrum of precession frequencies rather than a single line, and complicates the relation between perturbation harmonics and spin precession.

To avoid this we can evaluate the spin perturbations in the "constant-precession" frame, in which the spin phase advances at a constant rate such that the spin tune spectrum consists of a single line at ν . This reference frame rotates forwards with respect to the orbit in the bending magnets at a rate $\nu(R/\rho - 1)$, and backwards at a rate $-\nu$ in the straight sections. For given errors the perturbation harmonics are a function of energy in this frame.

2.2 Spin Matching

Another correction technique we plan to investigate for LEP is "spin matching", proposed by Chao and Yokoya /5/ and extended by Steffen /6/ and Yokoya /7/. This method requires the choice of betatron and dispersion parameters such as to make ten integrals vanish. If these conditions are applied at a particular point of the machine lattice with the integrals evaluated over one revolution, the orbit perturbation resulting from quantum emission at this point does not perturb the spin motion and the machine is said to be "spin transparent" at this

azimuth. One should note that the spin-matching conditions are energy dependent, since the integrals contain the unit vectors $\hat{x}$ and $\hat{z}$ of the spin reference frame.

Since quantum emission can occur anywhere around the machine it might seem necessary to satisfy the ten conditions at every element, which would impose a very large number of constraints. However the "harmonic spin matching" proposed by Steffen /6/ avoids this by applying similar conditions which suppress only the nearest spin resonances. This results in degeneracy of the matching integrals, which can then be satisfied at any point around the ring by relatively few constraints to make these resonances vanish.

LEP should have enough flexibility in the adjustment of its beam-optics parameters to enable spin matching to be applied over at least some energy ranges. This will be a useful measure for de-sensitizing the spin motion to errors in the initial polarization tests.

2.3 Spin Satellites from Synchrotron Oscillations

It is characteristic of high-energy electron storage rings that the energy spread in the beam tends to be rather large, because of the hard synchrotron-radiation quanta. This gives rise to a large spread in spin tune, which can occupy a substantial fraction of the available space between spin resonances. The situation is aggravated by the presence of synchrotron oscillations, which cause single spin resonances to split up into families of satellites, further reducing the space available to accommodate the spread in spin tune. This problem has been investigated by Biscari, Buon and Montague /8/, and the results expressed in a "depolarization enhancement factor" due to the presence of satellites. A further paper by Biscari /9/ indicates somewhat more favourable results from a higher-order calculation, but the effect remains quite important for LEP.

The basic cure for spin satellites is to reduce the strength of the parent resonance by the methods described above. However another possibility is to modify the form of the energy distribution and hence the distribution in spin tune so that the overlap integral with the spin satellites is reduced. This can be done by non-linear wigglers, which increase the radiation damping for particles with large oscillation amplitudes. Originally discussed in Ref. /8/ using dipole-octupole wigglers, it now appears that quadrupole-sextupole wigglers are more favourable /10/. Since these could also be useful against some beam instabilities it is planned to pursue this work further.

3. LASER POLARIMETER

The most practical means available for measuring the polarization state of e^+e^- beams in storage rings makes use of the spin dependence in Compton scattering of laser photons. A circularly-polarized laser beam incident on a vertically-polarized electron beam is back-scattered with an up/down asymmetry in the cross-section, which is greatest for photons scattered at around 90° in the electron rest frame, corresponding to an angle of about $1/\gamma$ to the electron beam in the laboratory. The method has been described in detail by Gustavson et al. /11/, together with its embodiment in SPEAR. It has also been used successfully in the PETRA and DORIS storage rings. In LEP the asymmetry is quite large, over 30%, corresponding to a back-scattered photon energy of around 25 GeV for 50 GeV electrons.

The design of a laser polarimeter for LEP is under way, the first step being to determine the overall layout in view of the civil engineering requirements. Experience has shown that the laser should be accessible during machine operation, because of the fine optical adjustments required, and it will therefore be located in an optical laboratory near the bottom of Pit 1, together with other equipment for monitoring of synchrotron radiation.

In order to minimize background due to beam-gas and beam-beam bremsstrahlung the interaction point between the laser and electron beams should be located upstream of a bending magnet, so that the back-scattered photons emerge from the machine in a short distance. Good resolution of the $1/\gamma$ ($\sim 10 \mu\text{rad}$) up/down separation requires that the scattering take place in a region where the electron beam has minimum divergence in the vertical plane, i.e. in a vertically-focusing quadrupole.

The schematic layout is shown in Fig. 1. The laser beam from the optical laboratory is directed towards a beam splitter located in the middle of the straight section, half the laser power being reflected in each direction. This enables a single laser to serve for both e^+ and e^- polarimeters. The large energy loss per turn in LEP results in the electrons and positrons following slightly different trajectories around the machine, and the depolarizing effects are therefore not necessarily identical for the two beams. Furthermore, the use of adiabatic spin reversal of one species will make separate e^+ and e^- polarimeters essential.

From the splitter, the laser beams are directed along the straight section for over 300 m and brought into collision with the electron (positron) beams inside the quadrupole QL14. The back-scattered 25 GeV photon beam leaves the machine at an angle of about 15 mrad to the straight section and reaches the detector, located at the wall of the tunnel, after a flight path L of about 130 m. This distance determines the exact position of the collision region inside QL14, since the betatron envelope parameters β , α here must satisfy $L = \beta/\alpha$ for maximum resolution.

In order to introduce the laser beam into the collision region and to provide a free path for the back-scattered photons, some modifications are required to the standard design of vacuum chamber in this region. In addition, the last B4 bending magnet must be installed with the yoke reversed. These details are currently being studied.

Two types of laser are under consideration, an argon-ion laser of around 100 W peak and a Nd-YAG laser of 80 MW peak. The argon laser is capable of operating at the high repetition rate of individual bunch passages, 40 kHz, permitting the detector to measure both position and energy of individual photons and make use of the correlation between these quantities to reduce background influence. The Nd-YAG laser can only be pulsed at a relatively slow rate and the detector must therefore rely on a calorimeter with only spatial resolution because of the high instantaneous photon rate. The choice between the two types of laser and the design of the corresponding detector will depend on the results of computer simulations which are planned for the near future.

4. ENHANCEMENT OF POLARIZATION RATE

The rate of radiative polarization from the Sokolov-Ternov effect is a very steep function of the energy, varying as γ^5 . Whilst in LEP at 100 GeV the polarization time-constant is only seven minutes, at 50 GeV it is about 3 1/2 hours. This time can be reduced by increasing the quantum excitation rate with the aid of high-field wigglers, i.e. dipole magnets of alternating polarity arranged such that the closed orbit outside the region is unchanged. Such wigglers will be required in LEP for reducing the damping time at injection energy, and also possibly for adjusting the beam dimensions in luminosity optimization. However, if in the wiggler magnets the alternating sections were of equal magnetic field strength, the asymptotic polarization level would be substantially reduced below the theoretical 92.4%. What is required is an "asymmetric wiggler", in which short strong magnets alternate with long weak

magnets, the strong magnets having the same polarity as the normal bending magnets of the machine. In this way the polarization is strongly enhanced in the right direction and only weakly diminished by the magnets of opposite sign.

As a first step in polarization enhancement the LEP damping wigglers have been designed to have a useful degree of asymmetry /12,13/. Each unit consists of a strong centre pole flanked by two end poles with 40% of the central field, these ends providing the return flux path for the centre. With this field ratio of 2.5 and the eight wiggler units foreseen, the polarization time at 50 GeV can be reduced from 210 minutes to 80 minutes or less, with an asymptotic polarization level still as high as 77%. The asymmetric design does not prejudice the primary functions of these wigglers but will enable the early polarization tests to be conducted more rapidly without the additional cost of manufacturing and installing dedicated polarization wigglers.

A full scale model of this wiggler, shown in Fig. 2, has now been constructed and successfully tested. Its magnetic characteristics are completely satisfactory and in agreement with the 3-dimensional field computations used for the design (private communication from T.M. Taylor).

5. LEP SPIN ROTATOR

In order to exploit fully the physics possibilities of polarized beams in LEP, longitudinal polarization at the interaction point is required. The spin rotators needed for this purpose are made up of an alternating sequence of horizontal and vertical bending magnets, and constitute not only an appreciable capital expenditure but also a major perturbation to the normal machine orbit. We therefore do not plan to install rotators until it has been demonstrated that transversely-polarized beams can be obtained reliably under normal operating conditions.

However, it is important to ensure that sufficient space is available in the LEP tunnel for the later installation of such facilities, in order to avoid additional civil engineering work during the operation phase. This requires a conceptual rotator design and a preliminary evaluation of its performance. Such a design has been presented by one of the present authors /14/ at this Conference. The orbit excursions in this rotator are such that it can be accommodated in the LEP tunnel with sufficient margin for later improvements in design details. Being anti-symmetric in both planes the system can be operated over a wide energy range without the need for special compensating magnets.

6. IMPLEMENTATION PROGRAMME IN LEP

In the early stages of running-in, polarized beams are likely to have low priority. Nevertheless, with the polarimeters working, some parasitic observations can be made without interfering with other activities. In particular, the machine will be operating initially in the detuned low- β mode, which will favour the appearance of some observable level of polarization.

Somewhat later we would expect to have some development time during which the machine parameters could be chosen specifically to favour polarization. This would permit the systematic correction of the appropriate orbit harmonics and the adjustment of various parameters to bring the polarization up to a useful level. At this point it would be useful to scan over a range of energies in order to verify theoretical predictions of the "sensitive" regions and to test the efficacy of correction procedures at these energies. If all goes well the adjustments can then be refined to maintain the polarization level under normal operational conditions, including the full excitation of the low- β quadrupoles.

At this stage the exploitation of polarized beams becomes feasible. An immediate application is the measurement of beam energy to high precision using a depolarizer, in the form of a time-dependent beam bump which generates an artificial spin resonance under controlled conditions. This device is also useful for asymmetry checks in the polarimeter and possible also in experimental detectors. In addition it opens up the possibility of adiabatic spin reversal of either e^+ or e^- /15/, in order to obtain helicity-two states at the interaction point after spin rotators are installed, as well as permitting selective depolarization of one beam.

Transversally-polarized beams could already be of value in some LEP experiments. However, the main interest is in having longitudinal polarization at one or more interaction regions. By the time it becomes necessary to make decisions on the installation of spin rotators there will be much more information available, both on the behaviour of the LEP machine and on the benefits of polarized beams for e^+e^- physics.

The plans outlined above, based on our present knowledge and expectations, will be kept under review in the coming years. Although polarized beams have the reputation of being "difficult", they offer advantages in the LEP energy range which warrant a serious effort. The history of particle accelerators has repeatedly shown that these machines can greatly exceed their initial expectations, especially when subjected to the challenge of an exacting programme of experimental physics. Polarized beams in LEP are a logical evolution of this development.

REFERENCES

1. LEP Design Report Vol. II, Rpt CERN-LEP/84-01 (1984).
2. D. Möhl and B.W. Montague, Nucl. Instr. and Methods, 137 (1976) 423.
3. C. Prescott, Europhysics Study Conference on Electroweak Effects at High Energies, Erice, Sicily, Feb. 1-10, 1983 (to be published by Plenum Publishing Corporation, New York).
4. B.W. Montague, Physics Rpts 113, (1984) 1 .
5. A.W. Chao and K. Yokoya, Rpt. KEK 81-7 (1981).
6. K. Steffen, Rpt. DESY HERA 82/02 (1982).
7. K. Yokoya, Rpt. KEK 81-19 (1981).
8. C. Biscari, J. Buon and B.W. Montague, Nuovo Cimento No 2, V. 81/B (1984) 128.
9. C. Biscari, Nuovo Cimento No 2, V. 81/B (1984) 143.
10. J.M. Jowett, Proc. 12th Int. Conf. on High Energy Accelerators, Fermilab 1983 (1983) 300.
11. D.B. Gustavson, J.J. Murray, T.J. Phillips, R.F. Schwitters, C.K. Sinclair, J.R. Johnson, R. Prepost and D.E. Wiser, Nucl. Instr. and Methods, 165 (1979) 177.
12. J.M. Jowett and T.M. Taylor, 1983 Particle Accelerator Conf. Santa Fè, IEEE Trans. on Nucl. Sci. NS-30, No 4 (1983) 2581.
13. T.M. Taylor and T. Tortschanoff, Proc. 8th Int. Conf. on Magnet Technology, Grenoble 1983; Journal de Physique, Colloque C1, supplément No 1, Tome 45 (1984) C1-313-316.
14. J. Buon (this Conference).
15. A.A. Polunin and Yu. M. Shatunov, Novosibirsk Preprint 82-016 (1982).

Fig. 1 Schematic layout of e-polarimeter showing the laser beam path and the gamma -detector inside the LEP tunnel.

Fig. 2 Photograph of the full scale prototype for one of eight "asymmetric wigglers units to be provided.