TECHNIQUES FOR LONGITUDINAL POLARISATION IN ELECTRON STORAGE RINGS*

J. Buon
Laboratoire de l'Accélérateur Linéaire
91405 Orsay Cedex (France)

Abstract

Polarised electron and positron beams in storage rings appear still practicable in the tens of GeV energy range. Recent results at PETRA show the possibility of reducing depolarising effects of ring imperfections and the possibility of polarised beams in collision at high energy. The main limitation comes from the large beam energy spread at very high energy. 90° spin rotators for longitudinal polarisation are in progress.

Introduction

The physics interest of electron and positron beams in storage rings increases very much with energy, due to the increasing role of electroweak interactions. Polarised electron and positron beams are foreseen in both ep and e^+e^- new facilities.

A natural polarisation build-up has been observed in storage rings at low energies. However it is expected that depolarisation effects become stronger and stronger as energy increases. This is due to the fact that spin rotates faster and faster than the particle velocity does.

The purpose of this report is to review the feasibility of polarised beams in electron storage rings at high eenrgy. It is restricted to the use of "conventional" devices, which appear the simplest ones at the moment. The only polarisation mechanism studied is the Sokolov-Ternov[1] effect. One does not consider "Siberian snakes", for reducing depolarisation effects, not easy to use, although they may become necessary at very high energies.

The Sokolov-Ternov polarisation mechanism is studied in section 1 from a practical point of view. Generalities on depolarisation effects are reviewed in section 2. The possibilities of reducing these depolarising effects are studied in section 3 as well as the increase of depolarisation due to large energy spread. In section 4 information on beam-beam depolarisation is reported. Two current examples of 90° spin rotators are discussed in section 5 for obtaining longitudinal polarisation. Finally in section 6 the experimental use of longitudinal polarisation is studied for ep or e^+e^- interactions.

1. Polarisation Mechanism

The Sokolov-Ternov[1] polarisation mechanism in electron storage rings has been widely observed and is still the only practicable one up to now. It is due to a small asymmetry of the synchrotron radiation : for an electron the radiation probability with spin-flip is slightly greater when the electron spin is parallel to the bending magnetic field. The population of the antiparallel spin state increases gradually with time and transerve polarisation reaches a 92.4 % maximum value in an homogeneous magnetic field. In the same way positrons are also transversally polarised parallel to the magnetic field.

The characteristic polarisation time τ_p is inversely proportional to the photon emission rate times the mean square relative photon energy ε/E

$$\tau_p^{-1} = \frac{9}{11} < \dot{N} \frac{\varepsilon^2}{E^2} >$$

and varies rapidly with electron energy E :

$$\tau_p(\text{sec}) = 98.66 \frac{\rho^3_{(m)}}{E^5_{(GeV)}} \times \frac{R}{\rho}$$

where ρ is the magnet bending radius and R the ring average radius.

Fig. 1 shows the polarisation time for high energy electron rings. Short times, less than one hour, are obtained in their upper energy range.

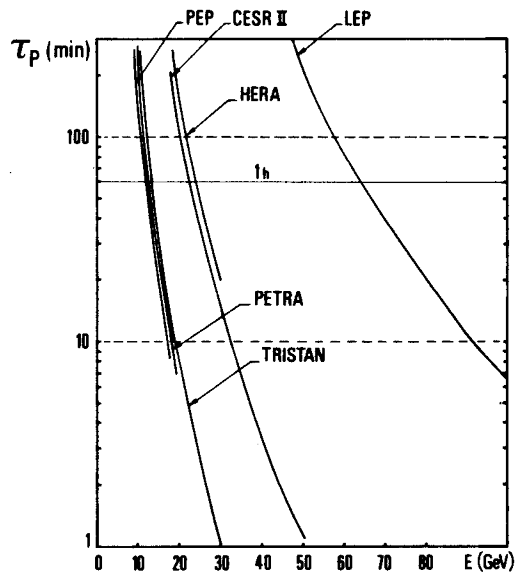

Fig. 1. Polarisation time τ_p versus beam energy E for several electron storage rings.

However for LEP phase I (50 GeV) the polarisation time (∿ 3 h) is too long, and needs to be reduced. This can be achieved using an asymmetric wiggler (fig. 2) with a high field (1.25 T) central part. A polarisation time less than one hour would be obtained at the price of a ten percent increase of synchrotron energy loss, mainly concentrated downstream the wiggler, and a large increase (× 1.8) of beam energy spread.

* Work supported by the "Institut National de Physique Nucléaire et de Physique des Particules"

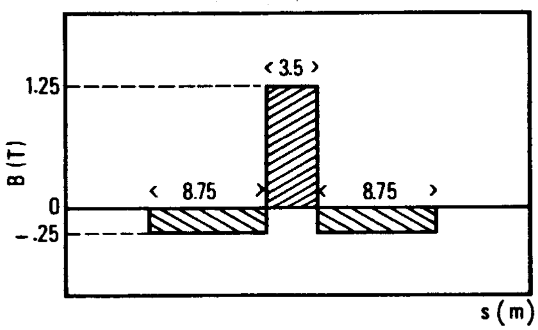

Fig. 2. The magnetic field versus the distance in an asymmetric wiggler proposed for LEP phase I.

The polarisation level will only be reduced by ten perçents due to the compensating low field of the wiggler in the example given here.

One conceivable alternative[2] to the Sokolov-Ternov polarisation mechanism is to collide the stored electron beam with a circularly polarised photon beam. The polarisation mechanism results from the spin dependence of Compton scattering and from a spin-orbit coupling of the stored electron. The photon beam must have a very long wavelength (> 100 μ) and high intensity. An adequate photon source, probably a free electron laser, may become available in future.

2. Depolarisation effects in general

Small field imperfections always reduce the effective polarisation level[3] below the 92.4 % maximum value. These imperfections lead to a vertically distorted orbit, and consequently to small spin tilts from the vertical direction. These tilts depend on the particle energy and the amplitude of its betatron oscillation. Hence depolarisation results from the finite distribution in energy and betatron amplitude among the particles. Moreover jumps in energy and amplitude are steadily generated by synchrotron photon emission, and produces a spin diffusion. At the end an equilibrium between the Sokolov-Ternov effect and the spin diffusion is reached with a polarisation level given by the ratio τ_p/τ_d of their respective characteristic times.

$$P = \frac{92.4\ \%}{1 + \tau_p/\tau_d}$$

A large depolarisation needs a constructive effect of successive small spin rotations. It occurs when the spin precession frequency coincides with some frequency of fields rotating the spin. The general resonant condition is given in terms of the spin tune* ν by :

$$\nu = k + k_x\nu_x + k_y\nu_y + k_s\nu_s$$

where ν_x, ν_y, ν_s are respectively radial, vertical and synchrotron tunes, and k, k_x, k_y, k_s are any integers.

The most important depolarisation resonances due to machine imperfections are :

i) integer resonances $\nu = k + k_s\nu_s$ including synchrotron satellites. ($k_s = \pm 1, \pm 2, ..$)

ii) betatron resonances $\nu = kS \pm \nu_{x,y}$ where S is the ring superperiodicity. They are driven by betatron oscillations around closed orbit.

At high energies, the most important imperfections are the radial field errors due to magnet tilts and vertical misalignments of quadrupoles.

3. Depolarisation resonances of a single beam

The integer resonances $\nu = k$ are dangerous as they are ordinarily strong and separated only by 440 MeV in energy. Their depolarisation effect scales roughly like the square of the particle energy. For example corresponding to a 25 % polarisation at 15 GeV, observed at PETRA, one can only expect about 5 % polarisation at 50 GeV, for CESR II and LEP, assuming similar orbit distortions.

These resonances cannot be sufficiently reduced even with a very careful alignment of the magnetic elements. However the harmonic components of the orbit distortion which drive these resonances can be canceled out. Such an harmonic correction procedure needs only a special programming of the correcting coils already used for reducing the average orbit distortion. A first recent attempt[4] of harmonic correction at PETRA has been successful. The polarisation has been increased from 20 % up to 80 % at 15 GeV. Quite similarly a complete concellation of some integer resonances has been recently achieved[5] in the proton synchrotron SATURNE. These resonances can be crossed during the acceleration cycle without any appreciable loss of polarisation.

Betatron resonances are also very dangerous. However in rings with superperiodicity S larger than one, the strongest betatron resonances can be made more spaced than the integer ones. The maximum separation between these betatron resonances is equal to the superperiodicity S in units of the spin tune. It is obtained by choosing the betatron tunes ν_x, ν_y with an integral part being a multiple of S/2. Therefore the depolarisation effect of betatron oscillations is strongly reduced at energies midway between two successive betatron resonances.

At low energies (< 25 GeV), considering again the integer resonances, their synchrotron satellites $\nu = k + k_s\nu_s$ are weak, except the first one ($k_s = \pm 1$), as the beam energy spread is small compared to the resonance spacing (440 MeV). The preceding conclusions on integer resonances are not affected, as ν_s is normally small (< .1).

*The spin tune is the spin precession number per turn :

$$\nu = \gamma\,\frac{g-2}{2} = \frac{E_{(GeV)}}{.44065}$$

However energy spread increases with energy (fig. 3). Consequently synchrotron satellites become stronger and stronger. Unavoidably spin tune is always in the vicinity of these satellites and the depolarisation due to closed orbit distortion increases.

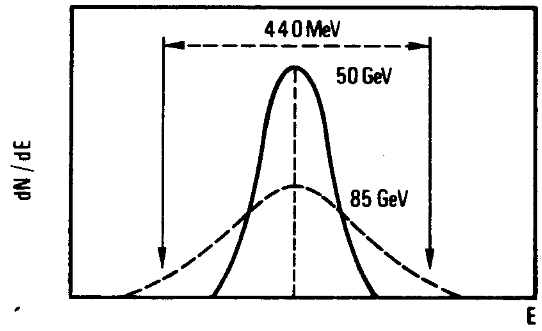

Fig. 3. Energy distribution of a stored beam in LEP at 50 GeV and at 85 GeV.

This phenomenon can be understood as follows. The synchrotron oscillation of energy leads to a frequency modulation of spin precession :

$$\nu = \nu_o + a \cos\nu_s\theta$$

where a is the modulation amplitude, proportional to the energy spread σ_E/E, and θ is the azimuth giving the particle location in time. The spin precession can be looked at as a gyroscope modulated in frequency. Its phase angle is given by :

$$\psi \simeq \int \nu d\theta = \nu_o\theta + \frac{a}{\nu_s} \sin\nu_s\theta$$

The frequency spectrum of such a gyroscope is a set of satellite lines :

$$\nu + k_s\nu_s$$

The amplitude of these lines is governed by the modulation index $I = a/\nu_s$, which is in average proportional to the energy spread :

$$I \simeq \frac{\sigma_E}{E} \cdot \frac{\nu}{\nu_s}$$

Above 30 GeV the modulation index becomes generally large ($\geqslant$ 1) and several satellites are strongly excited.

At the moment a preliminary study[6] indicates that appreciable polarisation could only be achieved up to about 50 GeV, depending of how much the strength of the integer resonances can be reduced by harmonic correction.

The only proposed alternative is to use double siberian snakes[7] which make the spin tune equal to 1/2, independently of energy variations. However they greatly complicate the ring design and could affect its performances.

4. Beam-beam depolarisation

The spin motion is perturbed by the space charge field of an opposite beam as well as the particle trajectory. Depolarisation resonances will be excited by this perturbation. A theorical approach is difficult due to the non-linearity of the space charge field.

Experimentally 70 % polarisation has been observed at SPEAR with e^+e^- colliding beams at 7.4 GeV centre of mass energy. This polarisation has been used in a well-known experiment[8], which has played an important role in the progress of understanding high energy interactions. However polarisation in colliding mode could not be observed again at a later stage of SPEAR operation.

Very recently at PETRA again[4] polarisation has been observed with two colliding beams. A polarisation level of 80 % for the electron beam has been measured at a luminosity of $2.7 \times 10^{30} cm^{-2}$ and at 16.5 GeV energy per beam.

Polarisation in collision mode has to be more investigated in order to find good operating conditions for experiments.

5. Longitudinal polarisation

Assuming that transversally polarised beams can be obtained in an electron ring, one has still to rotate the spin by 90° in order to obtain longitudinal polarisation at some interaction points.

Several types of 90° spin rotators have been proposed in the past. However they were never really optimized in what concerns beam optics and polarisation. Only recently, one has begun to study this optimisation in particular for the ep rings HERA and for the e^+e^- ring CESR II.

In the case of CESR II an "S-bend rotator" is studied[9]. It consists (fig.4) of vertical bends antisymmetric with respect to the interaction point. At this point the reference orbit is bent by an angle (14 mrad at 50 GeV) which corresponds to 90° rotation for the spin. At other energies it is necessary to maintain the same orbit geometry for beam optical properties and for synchrotron background. Therefore the fields in vertical bends are ramped in energy as the fields in the horizontal magnets. Consequently the spin rotation is not exactly 90°. However the longitudinal component is only reduced by less than 10 % in a large energy range : ± 30 %.

The antisymmetry of the S-bend rotator allows to restore the vertical spin direction in the rest of the ring. It avoids depolarisation that a tilted spin direction in the major part of the ring would produce, as discussed in section 2. This is true at any energy and allows the S-bend spin rotator to be operated in a large energy range,as desirable for e^+e^- physics.

In the case of HERA a pair of 90° spin rotators has been considered[10] for each interaction region. These two rotators are symmetrically located with respect to the interaction point, between the arcs and the RF sections, at more than 100 m from the interaction point.

Each rotator is a "mixed rotator" including vertical bends and an horizontal bend (fig. 5). At the designed energy each vertical bend rotates the spin by 45°. The horizontal bend, which is part of the normal radial bending in the ring, rotates the spin by 180°. At the end of each rotator the orbit is again in the plane of the ring.

The corresponding vertical bends in the two rotators of an interaction region are opposite. Therefore each pair of rotators is antisymmetric in the vertical plane with respect to the interaction point. However the corresponding horizontal bends are identical as they both participate to the normal radial bending. Each pair of rotators is symmetric in the horizontal plane.

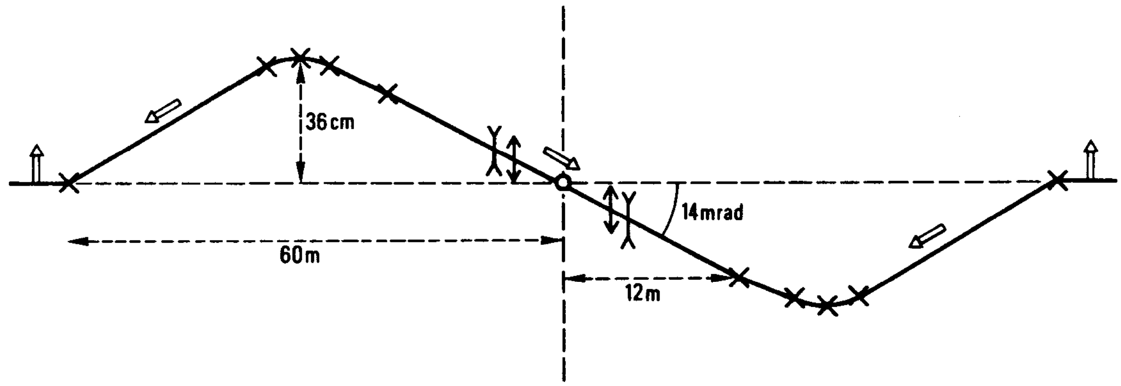

Fig. 4. Schematic side view of an "S-bend rotator" proposed for the CESR II e^+e^- ring.

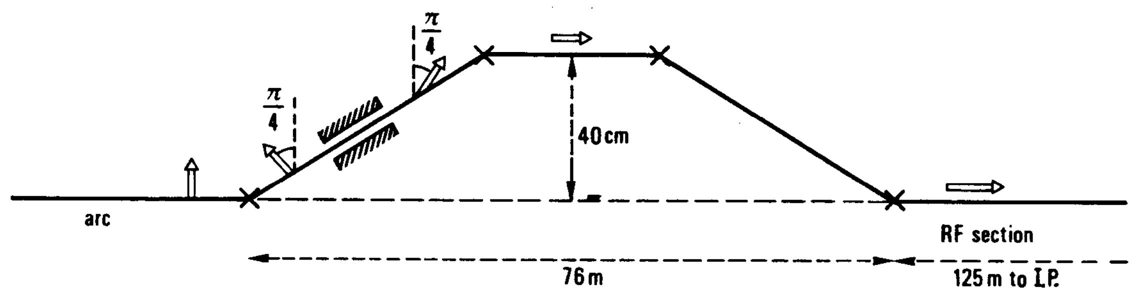

Fig. 5. Schematic side view of a "mixed rotator" proposed for the HERA electron ring.

The magnetic field in these horizontally bending magnets must be ramped in energy as normal magnets in the arcs.The 180° spin rotation is only obtained at the designed energy (27.5 GeV for HERA). What is more, the vertical spin direction in the arcs of the ring is only restored at this designed energy. This tilt of spin direction at off-energy set can be corrected[11], but only in a small energy range (± 3%).

This small energy range is the main difference of the "mixed rotator" with the "S-bend rotator". The mixed rotator can be sufficient for an ep facility as the electron ring energy, much smaller than the proton ring energy, does not need to be varied.

One must also mention that both types of rotators slightly increase the synchrotron energy loss and the vertical beam emittance, but only by a few percent.

Finally one must also minimize new depolarising effects introduced by the rotators.

Firstly the Sokolov-Ternov polarising effect is slightly reduced in the rotator bends as the spin direction is no more parallel to the magnetic field. Normally this reduction of the maximum degree of polarisation is small (a few percent) for not too strong magnetic fields.

Secondly, and what is more, the rotator vertical bends, acting as field errors do, excite depolarisation resonances, in particular the betatron ones. For example the radial betatron resonances are excited due to the longitudinal spin direction in the interaction region. A particle undergoing a radial betatron oscillation experiences a vertical field in the quadrupoles of the interaction region. This field will rotates the spin which is longitudinal by an angle depending on the betatron amplitude. Consequently radial betatron resonances are strongly enhanced.

However, contrary tho the usual field errors, the rotator vertical bends are "known errors", and can be corrected. For example one can manage that the spin rotations, due to radial oscillations in the interaction region, cancel out exactly. This can be obtained by a proper phase advance of these oscillations in the interaction region[12]. One can find similar conditions[13] for other depolarisation resonances excited by the rotator bends.

Any ring lattice, including spin rotators, must be designed in order to satisfy these conditions. This operation is called[14] "spin matching". One must realize that introducing rotators in a ring after completion will need a modification of the lattice in order to satisfy "spin matching". This modification may be difficult and expensive.

6.Experimental use of longitudinal polarisation

In an electron ring of an ep facility one would like to accelerate electrons and positrons. They can be obtained longitudinally polarised in the same way. One would like also to have both helicities for each of them. Both helicities can only be easily obtained by reversing the fields of the vertically bending magnets.

For an electron-positron ring the cross-section of e^+e^- annihilation is[15]

$$d\sigma = (1 - P^+_{\parallel} \cdot P^-_{\parallel}) d\sigma_{unpol} + (P^+_{\parallel} - P^-_{\parallel}) d\sigma_{\parallel}$$

according to the standard model of electroweak interactions. ($P^+_{\parallel}$, $P^-_{\parallel}$ are the longitudinal polarisation of positrons and electrons respectively).

Compared to the cross-section $d\sigma_{unpol}$ with unpolarised beams, a new information, contained in the cross-section $d\sigma_{\parallel}$, is obtained with polarised beams.

Even striking spin effects are excepted : the annihilation rate would vanish for 100 % polarised beams of same helicity. However this effect is reduced for partially polarised beams.

On the contrary the rate would be increased for opposite electron and positron helicities, but this cannot be easily achieved.

In fact it is much more important and more interesting to build a longitudinal polarisation asymmetry[16]. Assuming two bunches of electrons (and also of positrons), it can be easily obtained by depolarising selectively one of the two electron bunches (and also one of the two positron bunches). At every interaction point one will observe alternatively (fig. 6) collisions of polarised electrons with unpolarised positrons, and collisions of polarised positrons with unpolarised electrons.

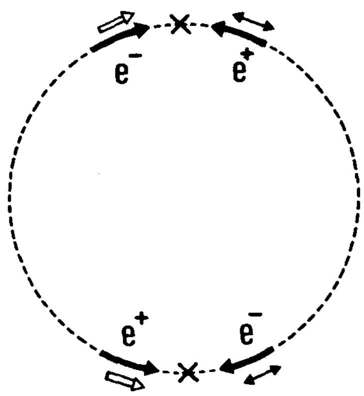

Fig. 6. Collisions of two electron bunches with two positron bunches. For each beam one bunch is longitudinally polarised, and the other bunch is unpolarised.

The obtained longitudinal polarisation asymmetry is linear in the beam polarisation $P_{\parallel}$:

$$A = \frac{N(e^- \Uparrow) - N(e^+ \Uparrow)}{N(e^- \Uparrow) + N(e^+ \Uparrow)} = P_{\parallel} \frac{d\sigma_{\parallel}}{d\sigma_{unpol}}$$

and picks-up the parity violating contributions to the cross-section. This asymmetry measurement has the great advantage to cancel out most of systematic errors.

Conclusion

The Sokolov-Ternov polarisation mechanism allows to obtain short polarisation times in upper energy range of electron rings. However an asymmetric wiggler is needed for LEP at 50 GeV.

Large transerve polarisation has been easily observed in low energy rings. However depolarising effects increase with the energy. At high energies it becomes necessary to choose carefully the energy and the betatron tunes for avoiding the main depolarisation resonances. It becomes also necessary to correct imperfections in a similar way to the usual orbit correction. A recent experiment on PETRA at 15 GeV shows that efficient correction procedures exist.

The possibility of transerve polarisation in presence of beam-beam interaction at high luminosity has been investigated at SPEAR (2 × 3.7 GeV) and now at PETRA (2 × 16.5 GeV). The results are encouraging.

However at very high energies polarisation is questionable due to the increase of energy spread which becomes comparable to the depolarisation resonance spacing. The limit in energy for polarisation is not yet known. It will depend on the efficiency of correction procedures.

The design of 90° spin rotators is presently studied for new electron rings. The conditions for efficient spin rotation have been found. They must be included in the lattice design.

The conventional ways to obtain polarised electron beams, studied here, are still practicable in the tens of GeV energy range. However one must be more and more clever as the energy increases.

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