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The first achievement of longitudinal spin polarization in a high energy electron storage ring

D.P. Barber[a], M. Böge[a], H.-D. Bremer[a], R. Brinkmann[a], W. Brückner[b], M. Düren[c], E. Gianfelice-Wendt[a], C. Großhauser[c], H. Kaiser[a], R. Klanner[a], M. Lomperski[a], G. Meyer[a], N. Meyners[a], Ph. Oelwein[b], G. Ripken[a], K. Rith[c], G. Schmidt[d], E. Steffens[b], W. Wander[c], W. Wümpelmann[a], K. Zapfe[a], F. Zetsche[d]

[a] *Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany*
[b] *Max Planck Institut für Kernphysik, Heidelberg, Germany*
[c] *University of Erlangen-Nürnberg, Germany*
[d] *University of Hamburg, Germany*

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Abstract

A pair of spin rotators has been installed in the electron ring of HERA. Longitudinal spin polarizations up to 65% have been reached reproducibly during dedicated measurement time. This is the first time that longitudinal spin polarization has been produced in a high energy electron storage ring.

1. Introduction

An integral part of the design of the HERA *ep* collider [1] has been the provision of longitudinal electron spin polarization at the interaction points (I.P.). This feature is to be used for physics measurements by the H1 and ZEUS experiments (e.g. precision electroweak tests) and by the HERMES collaboration for the measurement of the spin structure functions of the proton and neutron.

Stored electron beams can become vertically polarized through the emission of synchrotron radiation in the arcs (the Sokolov-Ternov effect [2]). Since the efficient generation and maintenance of this natural polarization requires that the polarization direction be vertical in the arcs, a pair of 90° spin rotators must be used to achieve longitudinal polarization at an I.P. in a straight section. The first rotates the spins into the beam direction and the second turns the spins back to the vertical direction before the beam enters the next arc. The rotators developed for use at HERA are the Mini-Rotators proposed by Buon and Steffen [3], consisting of interleaved horizontal and vertical bending magnets. The rotators are designed to operate in the range of electron beam energies from 27.5 to 35 GeV and the spin direction at an I.P. can be reversed by remote control of the vertical bending magnets.

In a real (i.e. not perfectly aligned) storage ring there are strong depolarizing effects which can limit the achievable polarization; for a survey of polarization phenomenology see [4]. These effects can be compensated with harmonic spin-orbit corrections [5,6]. The installation of spin rotators introduces additional, strong depolarization even in an

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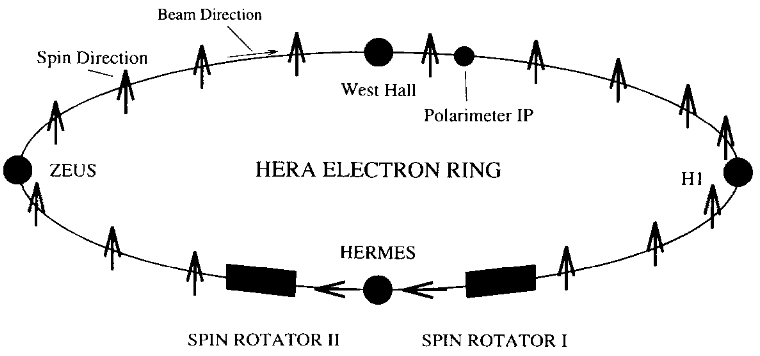

Fig. 1. A sketch of the HERA electron ring showing the positions of the spin rotators and the polarimeter I.P. The directions of the momentum and the spin polarization of the electron beam are indicated; the current orientation of the spin direction at the East I.P is parallel to the beam direction. The polarization is vertical at the position of the polarimeter I.P.

ideal storage ring. On the basis of analytical calculations and Monte Carlo tracking simulations, it has been shown [7] that these effects can in principle be strongly suppressed by a special modification to the optics known as spin matching. However, because the spin matching conditions are based on a linear approximation, the effects of higher order spin resonances, in particular the synchrotron sideband resonances associated with the energy spread of the electron beam, are not directly suppressed. In the absence of experimental data, and owing to the difficulty of both complete numerical tracking calculations and complete analytical calculations, there has been a large degree of uncertainty in the effectiveness of spin matching of high energy storage rings, and thus in the predictions for the achievable polarization at HERA with spin rotators.

The natural vertical polarization of the HERA electron beam was observed for the first time in 1991. The polarimeter and these first results are described in [8]. After optimization of the harmonic spin-orbit corrections and the electron beam parameters (e.g. energy and orbital tunes), vertical polarization levels of about 65% were achieved in 1992-93 during dedicated machine time; the results could be reproduced during regular luminosity operation of the HERA *ep* collider, i.e. with collisions of the electron and proton beams and excitation of the solenoids and compensators of the H1 and ZEUS detectors. A description of the harmonic spin-orbit correction scheme and the optimization procedure as well as the results of the 1992 measurements can be found in [6].

The first pair of rotators to be used in a high energy electron storage ring was installed in HERA during the 1993-94 shutdown; see Fig. 1. During this time the area around the East I.P. was rebuilt for the installation of the rotator-pair and in preparation for the installation of the HERMES detector. Measurements of the beam polarization are made using the polarimeter located in the West area, where the electron beam is vertically polarized. In this paper the Mini-Rotators and the method of spin matching which is used at HERA are described, followed by a report of the measurements of the HERA electron beam polarization performed during May 1-7, 1994. These measurements are the first experimental evidence of the effectiveness of spin matching for the suppression of spin diffusion in the presence of spin rotators.

2. Polarization with spin rotators

The difference in the rates for spin flip by the emission of synchrotron radiation for electrons with spins parallel or antiparallel to the magnetic guide field can lead to the build-up of the polarization of a stored electron beam. In an ideal storage ring (i.e. a ring with no magnet misalignments), which is also flat (i.e. contains no vertical bending magnets), the polarization is aligned antiparallel to the bending field and builds up in time according to

$$P(t) = P_{\rm ST}\left(1 - e^{-t/\tau_{\rm ST}}\right). \qquad (1)$$

The asymptotic Sokolov-Ternov polarization $P_{\rm ST}$ is 92.4%, and the corresponding time constant $\tau_{\rm ST}$ for HERA at 27.5 GeV is 37 minutes.

Spin precession in magnetic fields is described by the Thomas-BMT equation [9]. The spin precession angle $\Delta\phi_{\text{spin}}$, defined relative to the orbit, can be written

$$\Delta\phi_{\text{spin}} = a\gamma\Delta\phi_{\text{orbit}} \tag{2}$$

where a is the gyromagnetic anomaly $(g-2)/2$, γ is the Lorentz factor, and $\Delta\phi_{\text{orbit}}$ is the change in the orbital angle. In an ideal flat machine the number of spin precessions per turn, the spin tune ν, is equal to $a\gamma$. At a beam energy of 27.5 GeV, the spin tune is about 62.5.

In general the magnetic fields along the closed orbit of a storage ring are not everywhere vertical: vertical bending magnets are used in the Mini-Rotator and in a real storage ring there are misaligned quadrupoles and vertical correction magnets. The spin polarization of a stored electron beam builds up, in general, along the periodic solution $\hat{n}_0(s)$ to the Thomas-BMT equation along the closed orbit; s is the longitudinal coordinate around the ring. In the presence of horizontal and longitudinal fields on the closed orbit, the $\hat{n}_0$ axis is tilted from the vertical. The equilibrium direction of the spins is not antiparallel to the field at all positions along the closed orbit, so that P_{ST} is less than 92.4%. The Sokolov-Ternov polarization in HERA with one pair of rotators[1] is 89% and the corresponding build-up time τ_{ST} is 36 minutes. In a real storage ring, the $\hat{n}_0(s)$ axis is tilted from its design direction as a result of the horizontal fields on the closed orbit produced by misaligned quadrupole magnets and vertical correction coils. In HERA with transverse alignment tolerances of 0.3 mm, one expects an rms tilt of $\hat{n}_0$ of the order of 30 mrad after standard orbit corrections. This tilt has a negligible effect on the value of P_{ST}.

The emission of synchrotron radiation can, in addition to producing beam polarization, be the source of strong depolarizing effects. For example, the energy loss excites horizontal oscillations of the electrons about the closed orbit. The electrons experience varying vertical fields in quadrupoles which provide the horizontal focussing. Spins which are not vertical will precess in these fields around the vertical axis. Thus if the average spin direction, $\hat{n}_0$, is tilted from the vertical then this precession reduces the projection of the spins on the $\hat{n}_0$ axis. Due to the stochastic nature of the photon emission, this process represents a diffusion of the spins which can be thought of as competing against the Sokolov-Ternov effect. The polarization build-up in the presence of spin diffusion is also described by Eq. (1), and the asymptotic polarization, $P_{\max}$, and the corresponding build-up time, τ, in this case are determined by the equilibrium of the two processes. Spin diffusion can be much stronger than the Sokolov-Ternov effect, and the maximum polarization $P_{\max}$ is then much less than P_{ST}. The Monte Carlo program SITROS [11,12] can be used to calculate the equilibrium polarization for a realistic storage ring by determining the time constant of the diffusion process. Good agreement has been found between the results of simulations using this program and the maximum polarization in HERA without rotators [12].

Spin diffusion can be particularly strong in a ring containing spin rotators. One reason is that between the rotators, $\hat{n}_0$ can be considered to be maximally tilted and the spins precess in the vertical quadrupole fields around an axis perpendicular to the equilibrium direction, so that the diffusion caused by these fields is maximum. A second reason is that synchrotron radiation emitted in the rotators, where the vertical bends generate local vertical dispersion, excites vertical orbital oscillations. Spin diffusion can in principle be minimized by organizing the quadrupole strengths and hence the optic so that for a particle on an arbitrary betatron orbit the spin projection on the $\hat{n}_0$ axis remains unchanged after one orbit around the ring. Thus in an ideal machine, stochastically excited orbital oscillations do not cause precession of the spins away from $\hat{n}_0$ and thus, overall, there is no net spin diffusion. This procedure in the design of the optic is known as spin matching [3].

As mentioned above, the misalignments of quadrupole magnets cause the $\hat{n}_0$ axis to be tilted from the vertical in the arcs. At HERA with an rms tilt of $\hat{n}_0$ of 30 mrad in the arcs, spin diffusion can limit the maximum polarization $P_{\max}$ to less than 20%. Since the tilt is due to the misalignments of hundreds of magnets it is not well known, and thus the method of spin matching cannot be used to obtain an optic in which the depolarizing effects of the tilt are compensated. Instead, the rms tilt of $\hat{n}_0$ is reduced using the

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[1] An uncertainty in P_{ST} of the order of a few percent is introduced in a ring with rotators if the spin-orbit coupling term, $\gamma\partial n/\partial\gamma$, in the numerator of the Derbenev-Kondratenko formula [10] is neglected.

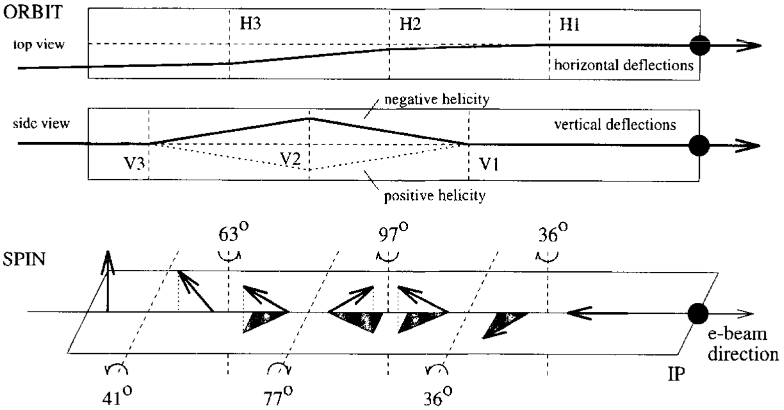

Fig. 2. A functional diagram of the Mini-Rotator, showing schematically the horizontal and vertical orbit deflections produced by the dipole magnets and the corresponding spin precession angles. The rotation angles of the $\hat{n}_0$ axis correspond to a beam energy of 27.52 GeV. The net horizontal bend of the rotator is equal to that of two arc dipoles. The amplitude of the closed bump produced by the vertical deflections $V3$, $V2$ and $V1$ is approximately 20 cm. The two vertical bumps in a rotator pair are anti-symmetric, and to change the helicity of the polarization at an I.P. the directions of the bumps must be reversed; the dotted line indicates the bump geometry for the opposite helicity.

method of harmonic spin-orbit corrections in a form generalized for use in rings with spin rotators [13]. This correction scheme was used at HERA in 1992-93 to achieve polarization levels of 65%. Owing to uncertainties in the knowledge of the positions of the beam position monitors at HERA, the correction amplitudes must be optimized empirically.

3. The mini-rotators

The "Mini-Rotator" design, developed by Buon and Steffen [3], is used at HERA. A single mini-rotator consists of three horizontal bends interleaved with three vertical bends; see Fig. 2. The orbit deflections produce, see Eq. (2), rotations of the spins about the vertical and horizontal (perpendicular to the beam direction) axes; the rotation angles for 27.5 GeV are also indicated in Fig. 2. Because $a\gamma$ is large, small and hence commuting orbit deflections can be used to generate large, non-commuting spin precessions. Thus it is possible using a sequence of dipole magnets to tilt the initially vertical spins into the horizontal plane while generating only a small overall change in the orbit direction. Because the relation, Eq. (2), involves the energy, the orbit deflections, and thus the geometry of the rotator, must be changed to maintain a 90° spin rotation if the beam energy is changed.

The magnet lattice in the region of the East I.P. is shown in Fig. 3; the lattice of the rotators to be installed in the North and South regions, where the proton and electron beams collide, is somewhat different. The rotator is only 56 m long, and thus the use of quadrupoles to provide focussing within the rotator can be avoided. The vertical bending magnets produce a closed bump with an amplitude of about 20 cm. The selection of the rotation angles around the vertical axis is constrained firstly by the fact that the two dipoles H2-a and H2-b are connected in series with the arc dipoles, and therefore produce a fixed orbit deflection, and secondly by the requirement that the sum of the horizontal orbit deflections from H1 and H3 together with that from H4 is equal to zero.

The vertical bumps of the two rotators in a pair are antisymmetric. To invert the spin direction at an I.P. the directions of the vertical bumps must be reversed. To facilitate this the magnets are mounted on remotely controlled jacks. The amplitude of the vertical bumps can be remotely adjusted to allow operation over the specified energy range, but the horizontal motion necessary for changes in the beam energy greater than ±100 MeV must be performed manually.

The spin matching procedure actually used for HERA is most easily understood by recalling that the solutions to the linearized equations of orbit motion can be written in terms of 6×6 transfer matrices [14]. The six coordinates describe the orbital motion of electrons in the horizontal, vertical and longitudinal

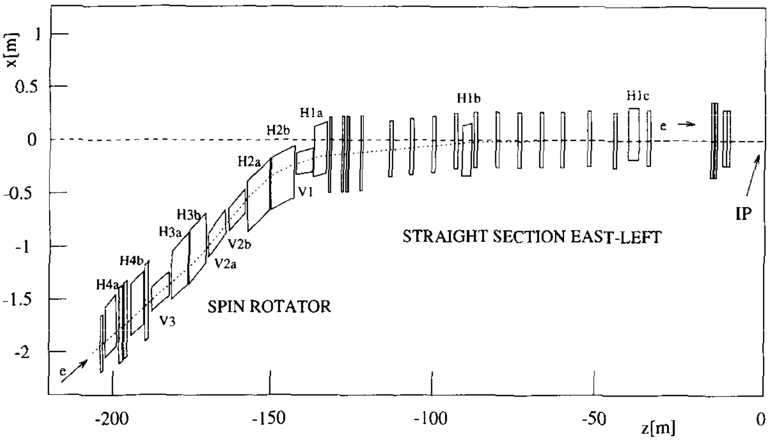

Fig. 3. The layout of one 90° Mini-Rotator as seen from above, showing the electron orbit and the magnet lattice in the straight section East-left. The dipole magnets (labeled, refer to Fig. 2) and the quadrupoles are shown. The proton beam is offset by 71 cm at the East I.P. and is not shown. The forseen layout of the rotators for the North and South areas, where the beams collide, is somewhat different. The horizontal deflection H1 is split, with H1-c chosen to be a relatively weak dipole, in order to reduce the synchrotron radiation background at the HERMES interaction region; the dipoles H1-b and H1-c provide a rotation of the spins of 11°. The magnets H4-a and H4-b are not utilized for the spin rotation but for the adjustment of the net horizontal orbit deflection in the rotator. As discussed in Section 3, the actual spin match for HERA with one pair of rotators is achieved by obtaining spin transparency across the I.P. between magnets V2-b on the left and V2-b on the right; and separately, around the remainder of the ring.

directions with respect to the closed orbit. In linear approximation the deviation of a spin away from $\hat{n}_0$ can be represented by two small angles. The solutions of the combined linearized equations of spin-orbit motion can then be represented by 8 × 8 matrices [15]. If the twelve matrix elements which represent the dependence of the spin motion on the six orbital particle coordinates are put to zero for a piece of the lattice, then in this linear approximation the spin diffusion due to orbital motion excited by photon emission elsewhere in the lattice will receive no contribution from the piece of lattice being considered. This piece of lattice is then described as "spin transparent". Note that in this picture spin transparency is a local property of the lattice and is independent of the entrance and exit Twiss parameters [3].

Since the Mini-Rotators are short they do not need to contain focussing elements (quadrupole magnets). Therefore the spin-orbit matrix elements for a rotator are already small. Then as described in [3], by considering the locations of the dipoles and the known (design) geometry of the $\hat{n}_0$ axis one can show that a one-turn spin match (i.e. spin transparency) is most conveniently obtained by imposing a spin match across the interaction region between the rotators and separately, for a ring with a single pair of rotators, around the remainder of the ring. The mirror symmetry of the ring about the line through the East and West I.P.'s simplifies the specification of the spin matching conditions. If the spin-orbit matrix elements for both sections are zero, then by matrix multiplication the spin match condition for the whole ring is satisfied. We refer to this method of spin matching sections of the ring separately as strong spin matching. This is in contrast to harmonic spin matching whereby selected harmonics in a Fourier analysis of the spin-orbit matrix elements for the whole ring are set to zero [3]. More information on the method of strong spin matching utilized at HERA can be found in [16,17].

The optical functions in the straight sections of a typical storage ring-collider are dictated by the matching of the design values at the interaction points with those in the arcs, and by the values needed in the accelerating cavities. Twelve independent quadrupole circuits in the straight sections provide sufficient flexibility to fulfill these needs. Additional flexibility is needed to obtain an optic which, in addition, is spin matched. In anticipation of this need, almost all mirror symmetric quadrupole pairs between the mid-points of the straight sections and the eighth FODO cell of the arcs were given independent power supplies. The spin match of the section between the rotators is obtained through the adjustment of the 17 quadrupole power supply circuits for this region; the spin match of the remainder of the ring is obtained using the 14 quadrupole circuits between the rotators and the eighth arc cells in the East area, and the corresponding circuits in the other six octants. With the large number of independent parameters it is possible to satisfy the strong spin matching conditions and at the same time create an optic for which the quadrupole strengths are within the allowed ranges and with the required Twiss parameters and phases at each point in the ring. A typical fit to the spin and optical match conditions in the arc involves varying 26 quadrupole strengths and fitting 26 constraints simultaneously.

The spin match is carried out with a modern version of the program SPINOR [18]. As indicated earlier, the spin matching is done in a linear approximation; higher order effects are not included. Simulations of the depolarizing effects of strongly spin matched realistic rings are made with the program SITROS. The results indicate that polarizations of 70% are possible with one pair of rotators on.

4. The polarization measurements

The measurements were performed during dedicated time, with the proton ring not operating and using the spin matched optic[2] prepared for collider operation in 1994. The solenoids and compensators of the H1 and ZEUS detectors were normally on. The first step of the measurements was to achieve a polarization of at least 50% with the rotators off, i.e. with the rotator magnets in the plane of the ring and with the vertical bending magnets turned off. After turning on the rotators, the beam parameters, including the energy and the amplitudes of the harmonic spin-orbit corrections, would once again be empirically optimized to achieve the maximum polarization.

The ring was set-up in the following way, on the basis of the experience from previous years:

- The beam energy was set to 27.535 GeV, compared to 26.67 GeV in 1992-93. This energy corresponds to the lowest practical operating energy of the ring with rotators, and to a half-integer spin tune for a flat ring. The energy scale is set by the current in the main dipoles, corrected by an offset of 35 MeV derived from measurements performed in 1993 using resonant spin depolarization [12,19].
- The RF frequency was increased from the nominal value by 350 Hz to account for the shortening of the length of the ring by 3 mm with the vertical bumps of the rotators off.
- The horizontal and vertical betatron tunes were $Q_x = 47.1$ and $Q_y = 47.2$, respectively. These tunes are somewhat smaller than the tunes used for luminosity operation, namely 47.2 and 47.3.
- The circumferential RF voltage was typically 125 MV, resulting in a synchrotron tune Q_s of 0.06.
- After standard orbit corrections, the rms distortion of the closed orbit was 1.1 mm vertically and 1.5 mm horizontally.

Typical beam currents were 10 mA in 168 bunches, with a beam lifetime of about 5 hours. The statistical error of the polarization measurement was about 1.5% per minute; the systematic error is about 10% of the polarization value. In the following only the statistical errors are given.

The polarization values which were initially observed were about 5-10%. About 1.5 days were taken for polarization optimization studies and a maximum of about 65% was reached.

The rotators were then turned on by moving the rotator magnets vertically and exciting the vertical orbit bumps. The energy was reduced to 27.521 GeV to keep the spin tune at a half integer.[3] In Fig. 4 are shown the measured (transverse) polarization during the last fill with the rotators off, and during the first fill with the rotators on. A fit of the expected exponential build-up curve to the data measured with the rotators on gives an asymptotic polarization of 56.6 ± 0.5%.

After reducing the beam energy to 27.492 GeV polarization alues of 65% were reached. During the following two days of machine studies, the high polarization values could be reproduced. These polarization values are in good agreement with the expectations from SITROS simulations [12,17].

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[2] I.e. an optic which becomes spin matched with the rotator pair on

[3] The complicated spin precession geometry of the rotators shifts the spin tune from the flat-machine value of $a\gamma$.

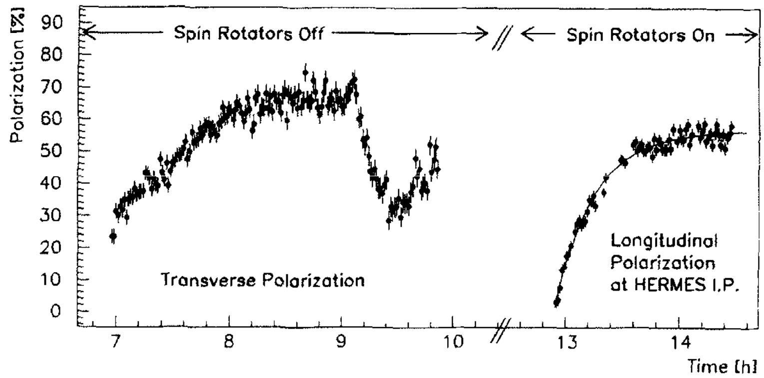

Fig. 4. The polarization plotted as a function of time, measured on May 4, 1994. Shown are the measurements during the last fill with the spin rotators off, and the first fill with them on. The beam currents were initially 3 and 9 mA, respectively. The maximum polarization during the run before the rotators were switched on was 66.5 ± 1.0%. Between 10:00 and 12:45 the beam was dumped, the rotators switched on, and a new electron fill was injected and accelerated to 27.521 GeV. The polarization measured during this first fill is shown and the result of a fit of the expected exponential build-up curve to the data is overlaid. The results are $P_{\max} = 56.6 \pm 0.5\%$ and $\tau = 20.8 \pm 0.7$ minutes. The H1 solenoid and compensator were off during these measurements.

The longitudinal polarization is not measured at the East I.P. The uncertainty in the angle of the polarization at the East I.P. with respect to the beam direction comes from two sources: tolerances on the alignment of the quadrupoles in the arcs, which result in a tilt of $\hat{n}_0$ from the vertical at the entrance of the rotator, and the tolerances on the fields of the rotator magnets. Preliminary studies indicate that random field errors in the rotator magnets within the rms tolerance of 0.05% cause a tilt at the I.P. of less than 10 mrad. Random alignment errors of the quadrupoles in the arcs within the tolerances cause an rms tilt in the arcs of about 30 mrad, which results in a error in the spin direction at the I.P. of as much as 40 mrad. The achievement of high polarization levels is, however, an indication that the rms tilt of the $\hat{n}_0$ axis in the arcs is less than 30 mrad. The error in the angle of the longitudinal polarization at the East I.P. is then expected to be less than 50 mrad.

5. Conclusions

A pair of spin rotators was installed in the electron ring of the HERA *ep* collider during the 1993-94 shutdown. A spin-matched optic was prepared which, on the basis of simulations, could be used to strongly suppress the strong depolarizing effects introduced by the rotators. Utilizing a transverse polarimeter located outside of the rotators, high beam polarizations of up to 65% were measured reproducibly during dedicated measurement time in May 1994. The direction of the spin polarization at the East I.P. is parallel to the beam direction within an expected uncertainty of less than 50 mrad. This is the first time that a longitudinally polarized electron beam has been produced in a high energy electron storage ring, and is the first experimental verification of the suppression of spin diffusion effects achievable using spin matching. The consistency of the measurements with results obtained from the SITROS program demonstrate the predictive power of this program for the calculation of spin diffusion in real storage rings.

During further machine studies we intend to optimize the beam parameters for polarization during collider operation of HERA. Simulations with SITROS indicate that significant improvements can be obtained by utilizing the technique of beam-based alignment [20]. Other techniques for spin matching, including harmonic spin matching, will also be tested. Longitudinal electron polarization will be used by the HERMES experiment in 1995 and later by the two collider experiments H1 and ZEUS.

Acknowledgements

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