The first attainment and the routine use of longitudinal spin polarization at a high energy electron storage ring

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Abstract

The HERA electron ring is the first and only high energy electron storage ring at which longitudinal spin polarization has been obtained. This paper describes the spin rotators, the optical set up, the first observation of longitudinal polarization and the plans for its routine exploitation.

I. INTRODUCTION

An integral part of the design of the HERA *ep* collider [1,2] has been the provision of longitudinally spin polarized electrons for the high energy physics experiments at the interaction points.

Stored electron beams can become vertically polarized due to the emission of spin flip synchrotron radiation– the Sokolov-Ternov (S-T) effect [3]. The maximum polarization achievable is 92.4% corresponding to a planar ring. To provide longitudinal polarization at an interaction point the naturally occuring vertical polarization in the arcs must be rotated into the longitudinal direction just before the interaction point (IP) and back to the vertical just after the IP using special magnet configurations called spin rotators.

Synchrotron radiation not only generates polarization but can also cause depolarization [4]. This is especially the case in the presence of spin rotators. Furthermore the ratio: (depolarization rate/polarization rate) increases strongly with energy. However, the depolarizing effects can in principle be minimized by special choice of the optic called 'spin matching'. Nevertheless, owing to the difficulty of obtaining reliable numerical predictions of the polarization in the presence of rotators throughout the preparatory stage of the project and because of the initially very pessimistic predictions, it was by no means clear that longitudinal polarization could be obtained even after spin matching.

II. THE SPIN ROTATORS.

Dipole spin rotators exploit the prediction of the Thomas-BMT equation [5] for spin precession that for motion transverse to the magnetic field, the spin precesses around the field at a rate which is $a\gamma$ faster than the rate of rotation of the orbit direction. Here, $a = (g-2)/2$ where g is the electron g factor. Thus

$$\delta\theta_{spin} = a\gamma\delta\theta_{orbit} \tag{1}$$

in an obvious notation. At HERA energies $a\gamma$ is between 60 and 80. So it can be arranged that small commuting deflections of the orbit can result in large noncommuting precessions of the polarization vector. For HERA, the Mini-Rotator design of Buon and Steffen [6] was adopted. In the Mini-Rotators the rotation is achieved by interleaving three horizontal bends with three vertical bends. See figure 1 which shows the ordering of the magnets and the spin precession angles for the chosen running energy of 27.52 GeV. The orbit bend angles are of the order of 10 mrads and the horizontal bends replace the bend angle of one arc cell. The whole rotator is inserted into the end of the arc with minimum disturbance to the rest of the machine. The total vertical bend of this rotator is zero and it is only 56 m long so that no quadrupoles need be included among the constituent dipoles. The vertical orbit excursion is about 20 cm. The required rotator dipole fields and hence the shape of the rotator depend on the energy chosen. By mounting the dipoles on coupled, remotely controlled mechanical jacks and by having flexible joints between sections of vacuum pipe, it is possible to tune the rotator to give the correct spin transformation over the range 27-35 GeV and to obtain both helicities. The vertical bumps in a pair of rotators are antisymmetric with respect to the IP. The first two rotators were installed on either end of the East straight section at the beginning of 1994 so as to provide longitudinal polarization for the HERMES experiment which uses a polarized internal gas target to study the deep inelastic spin structure of nucleons. Figure 2 is a sketch indicating the positioning of the rotators in the HERA ring and the azimuthal spin axis variation. At the chosen energy of 27.52 GeV, the S-T polarization level is reduced below 92.4% to about 89% with one pair of rotators by the presence of the vertical bend magnets. This

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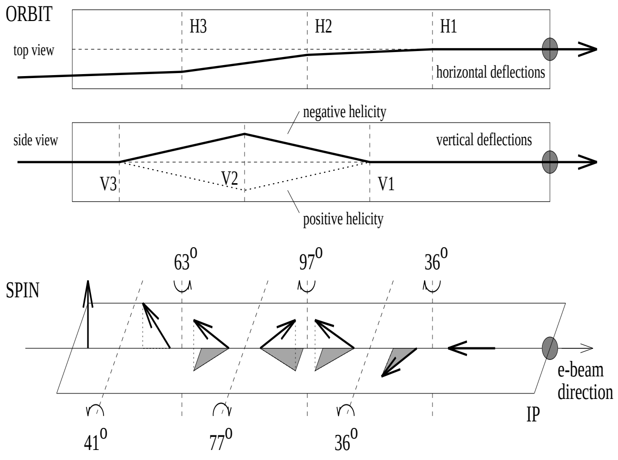

Figure 1: Layout of the Mini-Rotator bends and the consequent spin configuration at 27.52 GeV.

energy corresponds to a fractional spin tune of 0.5 and is thus maximally distanced from resonances. See equation 2.

III. The optics.

In addition to the S-T effect producing the polarization, there can be spin diffusion i.e. depolarization due to the stochastic excitation of the electron orbits by emission of synchrotron radiation photons. The depolarization is especially strong if the resonance condition

$$\nu = k + m_x Q_x + m_z Q_z + m_s Q_s \qquad (2)$$

is satisfied where k, m_x, m_z, m_s are integers, the $Q_{x,z,s}$ are orbital tunes (47.1,47.2 and 0.06 resp.) and ν, called the spin tune, is the number of spin precessions per turn on the closed orbit.

In perfectly aligned planar rings the equilibrium spin axis is vertical, the beam would have almost zero vertical emittance and the depolarization would actually almost vanish. But in real rings with their typical misalignments, the closed obit is distorted and the equilibrium spin axis defined along the closed orbit is tilted from the vertical and the spin diffusion can then take hold [1,4]. This depolarization has been successfully combatted by the application of harmonic spin-orbit corrections [1] using special families of closed bumps to return the equilibrium spin axis to the vertical.

However, the installation of spin rotators can result in additional strong depolarization even in an ideal ring. One reason is that between the rotators the spin axis is horizontal and can be considered to be maximally tilted. Another reason is that there is local vertical dispersion inside the rotators so that synchrotron radiation emission in the rotators excites vertical betatron motion. In principle these two consequences of the presence of rotators can, in HERA, be largely eliminated by a special choice of optics called ‘strong spin matching’. This consists of arranging the quadrupole settings so that the relevant parts of the 2 x 6 matrix describing the coupling of the spin to the orbit in linear approximation vanish in the section between the rotators straddling the interaction point and in the remainder of the ring [1]. Since the rotators contain no quadrupoles, spin matching inside the rotators is not needed. A spin matched section of ring is said to be ‘spin transparent’. As well as minimizing these matrices, the usual optical properties of the machine must be acceptable. At HERA, it has been possible to satisfy these requirements by giving every mirror symmetric pair of quadrupoles in the section between the rotators and in the first seven cells at the beginning of each arc its own power supply.

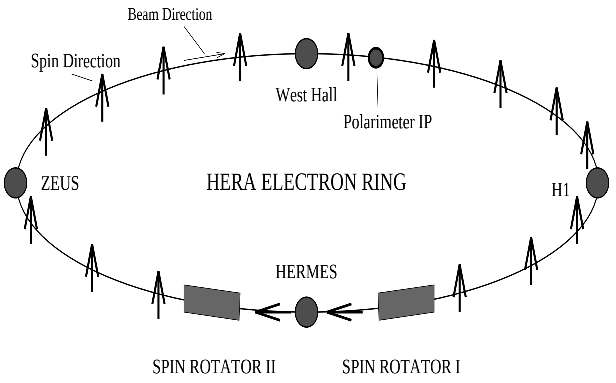

Figure 2: The locations of the rotators in the ring

IV. The first tests.

In the years up to 1994 it had become routine to have obtain over 60% vertical polarization (measured using a Compton polarimeter in the West area– see figure 2)[1]. The first test of the rotators took place in May 1994 with electrons. After achieving about 65% vertical polarization with the vertical bends off and the rotators ‘flat’, by the usual application of the harmonic spin-orbit bumps, the rotators were activated and a beam was stored without additional orbit adjustment. Then without further ado the polarization as measured at the West area polarimeter rose according to the expected exponential law [1]

$$P(t) = P_\infty \left(1 - e^{t/\tau_{pol}}\right) . \qquad (3)$$

to about 56%. See figure 3. Note that the *value* of the polarization is the same everywhere in the ring but the direction can be changed by rotators. Since a tilt of the polarization vector by more than a few tens of milliradians in the arcs would lead to very strong depolarization we conclude that we had achieved longitudinal polarization at the East IP.

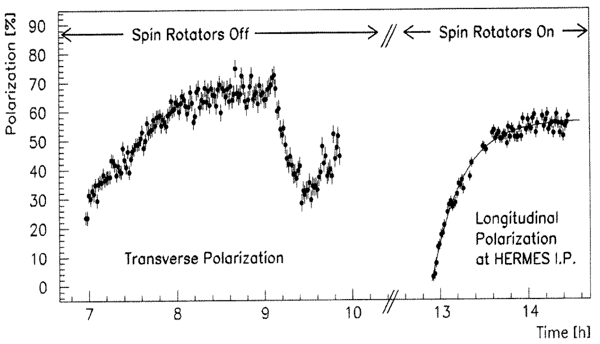

Figure 3: Longitudinal polarization vs. time (hours) with electrons in May 1994. The dip after 09.00 was due to further attempts at optimization.

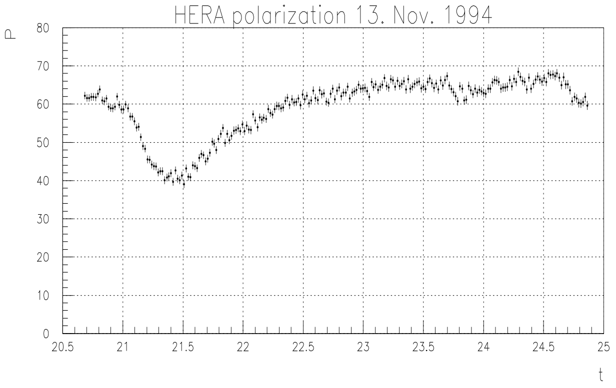

Figure 4: Longitudinal polarization vs. time (hours) with positrons in November 1994. The dip at 21.30 was due to further attempts at optimization.

This was the first time in the history of high energy storage ring physics that longitudinal spin polarization had been achieved and demonstrated that, with suitable spin matching, it is indeed possible to rotate spins at the machine circulation frequency of 47.35 kHz and in a strongly stochastic environment. In the following days, after further machine optimization, a longitudinal polarization of about 65% was reached consistent with simulations from the Monte-Carlo spin tracking program SITROS [7].

In November 1994 about 65% longitudinal polarization was obtained with positrons.

These measurements with the rotators turned on were made without *ep* beam-beam interaction at the North and South IP's occupied by the experiments H1 and ZEUS (See figure 2). Measurements made in 1994 with the rotators off showed that with up to 40% of design luminosity (beam-beam electron tune shifts of about 0.02) there was no clear degradation of the vertical polarization. This is also consistent with simulations by SITROS [8].

V. Plans for 1995.

HERA is now coming online for the 1995 luminosity run and HERMES also. This will be the first time that a physics experiment on a high energy electron storage ring is supplied with longitudinal polarization. SITROS simulations indicate that at full luminosity there could be beam-beam depolarization[8]. In that case extra spin matching will be needed and an algorithm has been prepared. It might also be necessary to increase the vertical emittance by introducing a vertical dispersion bump. The latter can also cause depolarization and the so called 'vertical harmonic dispersion matching' based on the generation of extra dispersion bumps [9] will be needed. Another major source of depolarization is of course the closed orbit distortion. A large reduction in the effect of the latter is expected with the implementation of the beam based calibration of the monitor positions [10]. SITROS simulations suggest that a longitudinal polarization of 80% could then be achieved in the absence of beam-beam effects.

VI. Conclusion and outlook.

At HERA a major milestone in the science of radiative spin polarization in storage rings has been achieved. In 1995 we will supplying longitudinal polarization to an experiment on a regular basis. Two more pairs of spin rotators are in manufacture and will be installed in the '96-'97 shutdown to provide longitudinal polarization for H1 and ZEUS.

VII. Acknowledgements

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VIII. References

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