Polarized Protons in HERA – the Status

D.P. Barber[a], M. Vogt[a], G.H. Hoffstätter[b]

[a] *Deutsches Elektronen–Synchrotron, DESY,*
Notkestrasse 85, 22603 Hamburg, Germany

[b] *Institute of Applied Physics,*
Darmstadt University of Technology,
Darmstadt, Germany

Abstract

We describe the current status of the accelerator physics studies for obtaining spin polarized protons at high energy in HERA.

1 Introduction

This workshop and others have made it clear that the attainment of high proton spin polarization in HERA is a very worthwhile goal. Therefore, since and before the earlier workshops [1, 2] on polarized protons at HERA, extensive studies of proton spin dynamics at HERA energies have been in progress. In addition to people at DESY and the Darmstadt University of Technology, this work involves collaborators from the SPIN Collaboration, centered around the University of Michigan at Ann Arbor, from the Institute of Nuclear Research at Troitsk and from the Budker Institute of Nuclear Physics in Novosibirsk. The basic aspects of the project have already been described in considerable detail in the proceedings of the two previous meetings [1, 2]. Thus it seems inappropriate to reiterate too much of that material here. Instead, we will concentrate on developments that have taken place in the last year or so. Therefore this paper should be seen as an update on those reports and should be read in conjunction with them.

2 Some spin dynamics

Spin precession in electric and magnetic fields is described by the T–BMT equation [3, 4]:

$$\frac{d\vec{S}}{dl} = \vec{\Omega} \times \vec{S} \tag{1}$$

where $\vec{\Omega}$ depends on the electric and magnetic fields, the velocity and the energy. In magnetic fields equation (1) can be written as:

$$\frac{d\vec{S}}{dl} = \frac{e\vec{S}}{mc\gamma} \times ((1+a)\vec{B}_{\|} + (1+a\gamma)\vec{B}_{\perp}) \quad , \quad a = \left(\frac{g-2}{2}\right) \tag{2}$$

where $\vec{B}_{\|}$ and $\vec{B}_{\perp}$ are the magnetic fields parallel and perpendicular to the trajectory. The arc length is denoted by l and the other symbols have the usual meanings. The gyromagnetic anomaly, $\frac{g-2}{2}$, for protons is about 1.79. The T–BMT equation shows 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. Thus

$$\delta\theta_{spin} = a\gamma\delta\theta_{orbit} \tag{3}$$

in an obvious notation. So in one turn around the design orbit of a flat storage ring a non–vertical spin makes $a\gamma$ full precessions. We call this latter quantity the 'naive spin tune' and denote it by ν_0. It gives the natural spin precession frequency in the vertical dipole fields of the ring. At 820 GeV, ν_0 is about 1557. Therefore a 1 mrad orbit deflection will cause about 90 degrees of spin precession. Thus spin is extremely sensitive to perturbing fields and in particular to the radial fields in the quadrupoles.

As explained before [1, 2] to reach 820 GeV, the spins would, if no special measures were taken, have to pass though a very large number of spin orbit resonances characterized by the condition

$$\nu_{spin} = m + m_x \cdot Q_x + m_z \cdot Q_z + m_s \cdot Q_s \tag{4}$$

where the m's are integers and the Q's are respectively the horizontal, vertical and longitudinal tunes of the orbital oscillations. Here, ν_{spin} is the real (i.e. not naive) spin tune [2]. Many of these resonances can depolarize the beam and it is certain that no polarization would survive to high energy if no counter measures were taken. The sensitivity to resonances increases with energy and with the beam emittance.

Thus measures must be taken in DESY III, PETRA II, and HERA to prevent depolarization. The chief weapon for this is the 'Siberian Snake'[5, 6]. These are magnet systems designed to rotate spins by 180 degrees around an axis in the horizontal plane while introducing no nett orbit distortion outside the snake. With such devices it can be arranged that ν_{spin} is *independent* of the particle energy. Typically one would arrange to set $\nu_{spin} = 1/2$. Then at least the resonance conditions, $|m_x| + |m_z| + |m_s| = 1$ (first order intrinsic resonances) or $|m_x| + |m_z| + |m_s| = 0$ (imperfection resonances) are never satisfied and depolarization during acceleration can be strongly suppressed. The 180 degree rotation can be achieved using a strong solenoid or by special combinations of dipoles utilizing the fact that successive large rotations around the radial and vertical axes do not commute. If dipoles are used, one must ensure that the orbit distortion inside the snake is acceptable.

3 Overview

The acceleration chain for HERA consists of:
$SOURCE \rightarrow RFQ(750KeV) \rightarrow LINAC\ III(50MeV) \rightarrow DESY\ III(7.5GeV/c) \rightarrow PETRA\ II(39GeV/c) \rightarrow HERA(820GeV/c)$.
¿From the above comments about snakes and from [1, 2] it is clear that the attainment of polarized protons at high energy will entail considerable modification to some components of this chain. In summary the following modifications, marked by the underlining, will be needed:

- The source: high current, highly polarized source of H^- ions.
- Radio frequency quadrupole (RFQ) to 750 KeV: better optimization.
- DESY III: $50MeV \rightarrow 7.5GeV$: partial snake and pulsed quads or rf dipole.
- Transfer line DESY III to PETRA II: snakelike spin direction tuner.

- PETRA II: $7.5 GeV/c \rightarrow 39 GeV/c$: two Siberian Snakes.
- Transfer line PETRA II to HERA: snakelike spin direction tuner.
- HERA: $39 GeV/c \rightarrow 820 GeV/c$: Siberian Snakes and spin rotators.
- Polarimeters.

Furthermore, we divide the problem of obtaining high energy polarized protons at HERA into three broad aspects:

- The source and the acceleration up to the HERA proton ring injection energy of 39 GeV.
- Acceleration from 39 GeV up to above 820 GeV.
- Maintenance of useful polarization at 820 GeV for proton beam lifetimes of many hours.

We will now treat some of these steps one by one. For more details the reader is referred to the report prepared in conjunction with the SPIN@HERA collaboration [7]. Up to date detailed discussions of polarimetry issues can be found in the reports by E. Leader and P. Schüler in these Proceedings.

4 The source

In contrast to electrons which can become automatically spin polarized by the Sokolov–Ternov effect [8], there is currently no practical way to polarize protons *in situ*. Polarized protons must therefore be obtained from an appropriate source and accelerated with little loss of polarization. Furthermore, in our case the protons must also be initially disguised as H^- ions to allow multi–turn injection into DESY III. Physics with polarized beams is not interesting unless high luminosities can be obtained. Thus high source currents are needed. But in 1996 the maximum attainable continuous current of polarized H^- ions was about 1.5 mA [7], with about 80 percent polarization. In the meantime, great progress has been made by a group working at Triumf [9, 10] using an optically pumped polarized ion source (OPPIS) and it is now possible to obtain about 30 mA of unpolarized H^- ions in 100 microsecond pulses. The Triumf team is confident that with further investment of money and manpower they will be able to achieve a pulsed 80 percent polarized beam of about 20 mA with an emittance of 2π millimeter milliradians. Then with an accompanying improvement in the transmission efficiency of the radio frequency quadrupole the current stored in DESY III would match that obtained at present and 1997 luminosities could be achieved. Development of atomic beam sources is also taking place, namely at the the Institute of Nuclear Research at Troitsk [11].

5 DESY III and PETRA II

Since the maximum proton momentum of DESY III is only 7.5 GeV/c and since DESY III has eightfold symmetry there are very few, namely 1 strongish imperfection and 4 strongish intrinsic, resonances to cross. However, at such low momenta, the closed orbit distortion accompanying the use of dipole snakes is prohibitive. On the other hand it is not practical to obtain the 180 degree spin rotation using solenoids since the field integral would be very high. Therefore a full snake, which compensates both imperfection and intrinsic resonances, cannot be used and these

two types of resonances must be treated separately. The suppression of imperfection resonances is most conveniently achieved by using a so–called partial snake consisting of a ramped solenoid which rotates the spin by just a few degrees. This has little effect on the orbital motion but is equivalent to a large imperfection in the nominally vertical guide field of the ring and it causes total spin flip from 'up' to 'down' and *vice versa* during acceleration though imperfection resonances without decrease in the *value* of the polarization. The efficacy of partial snakes is now well established experimentally [12]. For DESY III a spin rotation of 9 degrees in the solenoid would probably suffice.

Polarization preservation on crossing intrinsic resonances is more difficult since the spin motion depends on the betatron amplitude of the particle. Two possibilities are foreseen. One could create jumps in the vertical betatron tune by pulsing special quadrupoles. In effect all the spins then pass through resonance so quickly that they have no chance to react to the perturbing fields. An alternative is to adiabatically excite a rf kicker magnet so as to create a coherent vertical oscillation of the beam. All particles then have large vertical betatron amplitudes and all spins will flip on passage through the resonance. The phase space distribution is then returned adiabatically to normal after the resonance is crossed. The efficacy of this method has just been demonstrated during tests at the Brookhaven AGS [13, 14] up to 22 GeV.

PETRA II must accelerate from 7.5 GeV/c up to 39 GeV/c and there are many resonances to cross. At the low energy end, snake design presents the same difficulties as at DESY III, namely, large orbit excursions. Probably only two snakes would be needed and these could be inserted into the North straight section and the South bypass respectively [7]. The current layout envisages combining normal dipoles with helical dipoles. The accompanying orbit distortion would be about 16 cm in a normal conducting snake. With a superconducting snake this distortion could be reduced to below 2.5 cm.

6 HERA

The HERA proton ring presents special difficulties. Not only must a few thousand resonances be crossed but the ring also contains interleaved vertical and horizontal bends on each side of the North, South and East straight sections. These interleaved bends cause massive distortion of the spin motion so that the periodic polarization direction on the design orbit would not be vertical in the arcs and the deviation from vertical would depend strongly on the energy. Thus the first step must be to neutralize these interleaved bends. As suggested by V. Anferov [7, 15] this could be achieved by inserting a snake with a radial precession axis at the mid point of each vertical bend section. We call these 'flattening snakes' since they effectively flatten the ring. They effectively convert each vertical bend section into a radial snake.

Of course, normal snakes are also needed and spin rotators too in order to obtain longitudinal polarization at the interaction points. These could be inserted in drift sections near the vertical bends. The snakes could consist of sets of conventional dipoles [7] or of helical dipoles as proposed for RHIC [16].

The number of snakes is restricted by the availability of space in the lattice and it is already clear that it would be difficult to accommodate more than four snakes without major modification to the arcs.

As explained earlier [1, 2], if the polarization survives to high energy it is still necessary that the equilibrium polarization direction ($\hat{n}$) at each point in phase space be as parallel as possible to the equilibrium direction on the closed orbit ($\hat{n}_0$) so that the polarization seen by the experiments is maximized. This requirement can be used to select snake schemes using a 'filtering algorithm'

[17] in which the best snake configurations are identified by searching through all possibilities which give a vertical $\hat{n}_0$ in the arcs, a real spin tune of one half and which minimize the spread of equilibrium polarization directions across the beam phase space. A snake configuration is characterized by the positions of the snakes and the orientation of the snake axes. The search procedure is based on a linearized approximation for the spin motion (the SLIM algorithm [18]) to save computer time. The results are then confirmed by calculating $\hat{n}$ across the phase space using the program SPRINT [19], which is based on 'stroboscopic averaging'.

Tracking simulations indicate that, at least for a perfectly aligned ring, the best 'four snake' configurations perform almost as well as some 'eight snake' configurations. Furthermore, for a perfectly aligned ring, and with a good four snake scheme, there should be little loss of polarization during acceleration to 820 GeV provided that most of the beam can be contained within horizontal and vertical emittances of 4 π millimeter milliradians ('1 sigma')[20]. Thus it is already clear that smaller beam emittances are needed and this implies that emittance blow–up in the preaccelerators must be prevented. It would therefore also be very useful to cool the beam before it enters HERA. Extending the LINAC III energy to 150 GeV and/or inserting a booster between LINAC III and DESY III would also help. Contrary to expectation, even in the presence of snakes, synchrotron motion can lead to loss of polarization during acceleration at the highest energies [20].

7 Further investigations

Now that snake schemes have been studied and an idea of the maximum allowable emittance has been acquired, the next step is to understand what improvements can be attained by careful choice of orbital tunes and optics, and then to address the following topics.

1. Understand the effects of misalignments. Find cures. (The most important additional limitation to the polarization is likely to be the spread in the $\hat{n}$-axes caused by misalignments.)
2. Determine the influence of the beam-beam effect.
3. Understand the influence of noise in power supplies.
4. Calculate with optical nonlinearities and coupling due to quadrupole errors.
5. Evaluate the effect of intra-beam scattering, if any.
6. Investigate the relevance and feasibility of spin matching [21] and in particular the 'strong spin matching' proposed by K. Steffen [22].

8 Summary

In the last two years we have made significant progress towards understanding the requirements for attaining proton polarization at high energy in HERA. Initial studies show that with four snakes, the centre of the beam out to one sigma suffers little depolarization during acceleration up to high energy. But so far the only way to avoid depolarization due to high orbit amplitudes is to reduce the emittance. Therefore we are continuing to study in detail the mechanisms of polarization loss.

Acknowledgements

We would like to thank V. Balandin and N. Golubeva for their contributions to this study. We also thank members of the SPIN collaboration and members of the HERA machine group.

References

[1] D. P. Barber. Possibilities for polarized protons at HERA. In *Prospects of spin physics at HERA*, DESY–Zeuthen, August 1995. DESY Report 95–200 (1995).

[2] D. P. Barber, K. Heinemann, G. H. Hoffstätter[b], and M. Vogt. Polarized protons in HERA. In *Future Physics at HERA*, Proceedings of the Workshop 1995/96. vol.2 (1996).

[3] L. Thomas. *Philosophical Magazine*, **3**, 1 (1927).

[4] V. Bargmann, L. Michel and V. L. Telegdi. *Physical Review Letters*, **2**, 435 (1959).

[5] Ya. S. Derbenev and A. Kondratenko. *Soviet Physics Doklady*, **20**, 562 (1976).

[6] Ya. S. Derbenev et al. *Particle Accelerators*, **8**, 115 (1978).

[7] SPIN Collaboration and the DESY Polarization Team. Acceleration of Polarized Protons to 820 GeV at HERA. University of Michigan Report UM–HE 96-20, November 1996.

[8] A. A. Sokolov and I. M. Ternov. *Soviet Physics Doklady*, **8**, N^{0}12 1203 (1964).

[9] A. N. Zelenski et al. *Proc. 6th Int. Conf. on Ion Sources (Whistler). Rev. Sci. Instrum.*, **67**, 1359 (1996).

[10] A.N.Zelenski et al. Invited talk at the *International Workshop on Polarized Targets and Polarized Beams*, Urbana, U.S.A., (1997).

[11] A. Belov et al. *Proc. 6th Int. Conf. on Ion Sources (Whistler). Rev. Sci. Instrum.*, **67**, 1293 (1996).

[12] H. Huang et al. Phys. Rev. Letts., **73**, 2982 (1994).

[13] M. Bai et al. Contribution to the 1997 Particle Accelerator Conference, May 1997, Vancouver, Canada.

[14] M. Syphers, private communication, November 1997.

[15] V. A. Anferov and R. A. Phelps. Nucl. Inst. Methods, **A 398**, 423 (1997).

[16] V. Ptitsin and Yu. M. Shatunov. Nucl. Inst. Methods, **A 398**, 126 (1997).

[17] G. H. Hoffstätter. Polarized protons in HERA. In *Proceedings of the DESY Accelerator Group Seminar,* St.Englmar, January 1996. DESY Report 96-05 (1996).

[18] A. W. Chao, Nucl. Inst. Methods, **180**, 29 (1981).

[19] K. Heinemann and G. H. Hoffstätter. Physical Review **E 54** N^{0}4, 4240 (1996).

[20] V. Balandin and N. Golubeva, private communication, September 1997.

[21] D. P. Barber et al. *Particle Accelerators*, **17**, 243 (1985).

[22] K. Steffen. *Particle Accelerators*, **24**, 45 (1988).