Proton Polarization in HERA

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March 11, 2002

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1 Introduction and objective

Over the last few years, beginning in 1995, scientists at DESY have been studying the feasibility of obtaining high intensity polarized proton beams at very high energy in HERA [1, 2, 3, 4, 5, 6]. A polarized proton beam would be a useful complement to the existing polarized electron/positron beam. However, more study is needed.

The purpose of this letter is to reiterate the physics case for a high intensity, high energy polarized proton beam in HERA and to specify the resources needed for further studies. The aim of such studies would be the production of a report to the DESY management from the DESY community by the end of 2003.

A polarized deuteron or ^{3}He beam can also be considered. See the Appendix.

2 Particle physics justification

The physics case for studying polarized $e-p$ scattering at HERA has been studied rather extensively at a number of workshops, the last of which was at DESY in May 1999 [4]. The general physics interest for a polarized HERA is similar to that for HERA itself. For the proton there are two spin independent structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$ which are determined by electromagnetic unpolarized $e-p$ scattering. One of the principal interests and accomplishments of HERA research has been the accurate measurement of F_2 for very small x and high Q^2 and the observation of the rapid rise of F_2 at small x. This has provided a critical test of perturbative quantum chromodynamics (pQCD) in the region where the gluon density is high and it is of major theoretical interest. The spin dependent structure function $g_1(x,Q^2)$ provides information on the spin structure of the proton and is of comparable importance to F_2. It will be most valuable to extend greatly with HERA the kinematic range of information on g_1. With present fixed target data on $g_1(x,Q^2)$ the range is $0.003 < x < 0.7$ with $1 < Q^2 < 60$ GeV^2. A polarized HERA collider would extend the region to lower x by a factor of 100 and to higher Q^2 also by a factor of 100. (See figure 1).

pQCD predicts that $g_1(x,Q^2)$ will decrease dramatically at low x where the gluon density is high, in contrast to the observed rapid rise in F_2 at low x. Such behaviour would provide an important test of pQCD. In particular, g_1 is sensitive to large logarithms of $1/x$, having a $(\ln 1/x)^2$ dependence, and thus putative low–x effects are much more strongly enhanced than for non–polarized structure function measurements.

With HERA data on $g_1(x,Q^2)$ the polarized gluon distribution function $\Delta G(x,Q^2)$ and its first moment $\int_0^1 \Delta G(x,Q^2)dx$ could be determined through the equations for pQCD. The quantities $\Delta G(x,Q^2)$ and $\int_0^1 \Delta G(x,Q^2)dx$ which are of central importance for the proton spin structure, are largely unknown at present and are needed to solve the nucleon spin puzzle. This is the main focus of the COMPASS experiment at CERN and the experiments at RHIC which will collect polarized $p-p$ data. The big trump card of $e-p$ collisions at high energy at HERA is the additional sensitivity to the polarized gluon density via photon gluon fusion (PGF) processes through direct observation of, for example, dijets. Realistic studies of the data obtainable on $g_1(x,Q^2)$ and on ΔG from dijets, which include NLO treatment, detector characteristics and radiative corrections indicate that the data will be accurate and useful. Figures 2 and 3 indicate the quality of data that could be obtained in a 3 year run (500

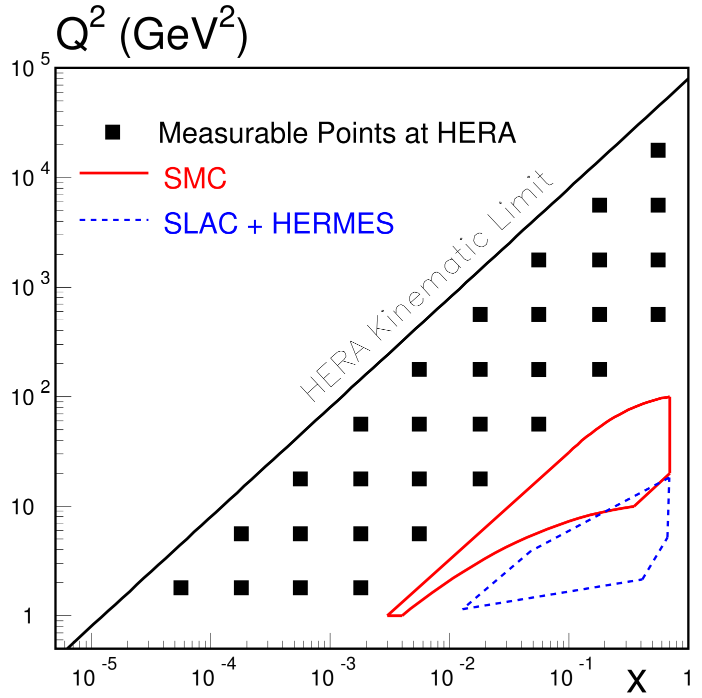

Figure 1: x–Q^2 region measurable with polarized HERA shown with the regions currently explored by fixed target experiments at CERN(SMC), SLAC, and DESY(HERMES), and the kinematic limits measurable at HERA.

pb^{-1}) assuming polarizations $P_p = P_e = 0.7$. Apart from using dijets, the polarized gluon distribution can be accessed by analyzing events with high p_T tracks, via forward–backward particle asymmetries, and in jet and particle production in photoproduction events. In all, HERA can access the polarized gluon distribution in a variety of different ways, allowing the gluon density to be pinned down.

Most of the topics studied now at HERA with unpolarized protons have their counterpart in polarized $e-p$ scattering. A few examples are the polarized structure function g_5, which allows to access the polarized parton distributions of different quark flavours separately; photoproduction which gives a unique opportunity to measure and study the polarized parton distribution in the photon, an entirely unexplored area as far as existing data is concerned; the disentangling of a chiral structure of any observed anomaly, and extending search limits for new phenomena at large Q^2; the study of polarization effects in diffraction in deep inelastic scattering which were found to be a potential referee on the perturbative or non–perturbative nature of this phenomenon; study of polarization effects in the proton target region to further understand target universality; measuring the transition from zero Q^2 to a few GeV^2 etc.

Also fixed target experiments could be done using the high energy polarized proton beam and an internal gas target (e.g. HERA–N). This would allow for measurements of the gluon density at high-x values, measurements of transversity and much more.

Each of these topics is discussed in the DESY Workshop Proceedings [4]. We believe that the physics case for having polarized high energy protons in HERA has been well developed

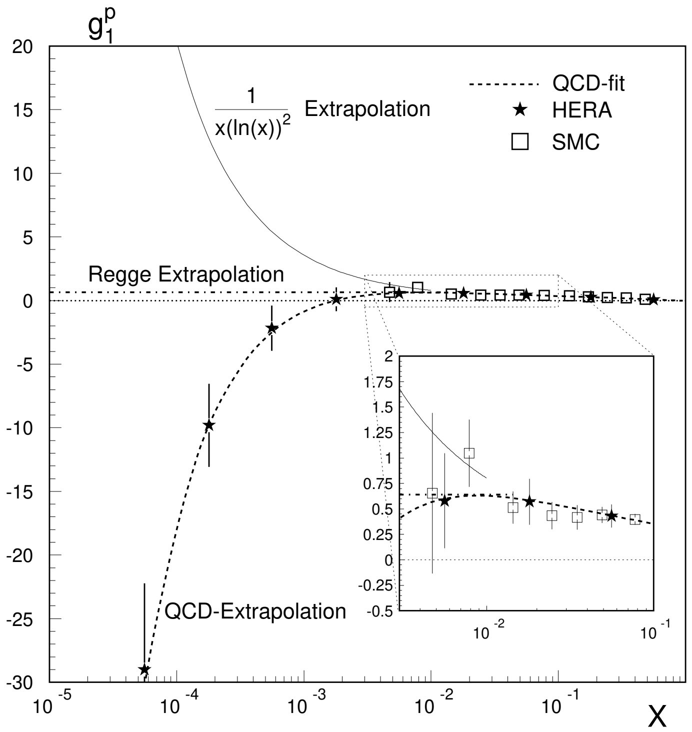

Figure 2: The statistical uncertainty on the structure function g_1^p measurable at HERA for $Q^2 = 10$ GeV^2 with an integrated luminosity $\mathcal{L} = 500$ pb^{-1} and a comparison of various low-x behaviours of g_1^p. The SMC measurements are also shown. Starting from the values of g_1^p measured by SMC, the possible values for g_1^p at low-x are shown for three scenarios: valence like Regge behaviour $g_1(x) \propto x^{-\alpha}$ with $\alpha = 0$, a strong powerlike positive rise $g_1(x) \propto 1/(x \cdot (lnx)^2)$, and the pQCD prediction based on the present best fit. A detailed comparison in the SMC low-x measured region is shown in the inset.

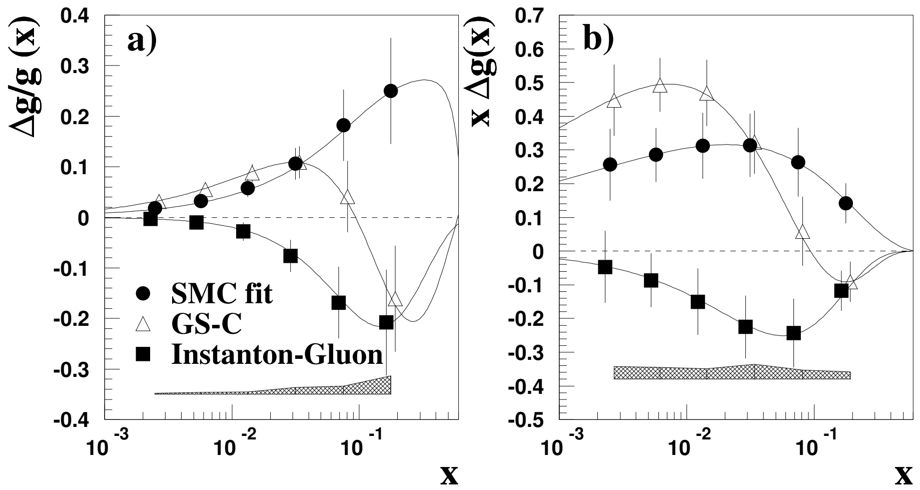

Figure 3: The precision (errors bars) that can be obtained for (a) $\Delta g(x)/g(x)$ and (b) $x\Delta g(x)$ from a measurement of di-jet events with a polarized HERA at $Q^2 = 20$ GeV^2 assuming an integrated luminosity of 500 pb^{-1}. The error bars show the expected statistical error. An estimate of systematic uncertainties is reflected in the shaded error band. As input for the parton distributions, three different parameters were used. (see [13]).

and documented.

3 Accelerator physics

3.1 Introduction

Early work on the accelerator aspects has been summarized in a major report entitled "Acceleration of Polarized Protons to 820 GeV in HERA" which was produced in 1996 jointly by the SPIN Collaboration and the DESY Polarization Team [1]. This report and an update [2] concluded that from the accelerator physics viewpoint, the goal seemed reasonable but identified two critical aspects, which require further research and development. One is the production of a highly polarized H^- beam with an intensity of 20 mA [7]. The second is the stability of proton spins in HERA. This requires a theoretical study of the proton spin motion in HERA and the arrival at a solution that ensures that proton polarization can be maintained during acceleration and storage in HERA with practical Siberian Snake magnet elements and also that longitudinal polarization can be provided at the ZEUS and H1 detectors with spin rotation magnets. Several subsequent reports [3, 4, 5, 6] and workshops have greatly extended the understanding of the accelerator aspects for a high energy polarized proton beam in the HERA ring. The recent achievement at BNL of a polarized proton beam in the RHIC storage ring is also most important. This achievement also included the successful measurement of the polarization of the high energy proton beam by elastic pC scattering through pC Coulomb Nuclear Interference (CNI).

3.2 RHIC SPIN

Within the past year and half major and dramatic advances have been made at BNL which are relevant to the attainment of high-energy polarized protons in HERA. In addition to successful commissioning of RHIC and initial data taking on relativistic heavy ion collisions, polarized protons from the AGS have been injected and stored in RHIC and accelerated to 100 GeV in both of the RHIC rings using pairs of Siberian Snakes consisting of a high field (4 Tesla) helical dipoles. The dependence of the polarization on the snake settings was as expected, demonstrating the efficacy of the helical snake concept [8]. Snakes of a similar design would probably be used at HERA. The proton polarization has been successfully measured by the pC CNI process at the AGS energy of 22 GeV and also at 100 GeV in RHIC. Yale physicists have been involved in these polarimetry measurements. It can be expected that pC CNI polarimetry will be useful for measuring polarization of protons up to 250 GeV and probably up to 800 GeV with a precision of about 10 percent. A polarized H jet target is being developed as an absolute polarimeter to measure proton polarization with a precision of about 5 percent. Indeed, extensive development of proton polarimetry will occur at BNL during the next few years, which should provide the basis for accurate measurement of proton polarization in HERA [8].

The early stages of proton acceleration at RHIC are similar to those at HERA, so that the storage of polarized protons in RHIC has provided great encouragement for the HERA project for all stages up to the HERA ring. RHIC can now store polarized protons at the highest energy ever achieved. The success at RHIC SPIN including the demonstration that the snake has the expected influence on the spin motion has enhanced confidence in the community and has been the important ingredient that we have been waiting for before submitting this report.

3.3 Polarized beam source

For RHIC SPIN a polarized H^- source with an intensity of 1 mA and a polarization P_p of 80 percent was operational in Fall 2000. It is based on the method of the optically pumped polarized ion source (OPPIS). A design goal for the polarized beam intensity in HERA is $2 \cdot 10^{13}$ stored protons in 180 bunches, or about 10^{11} polarized protons/bunch. The injection time from the LINAC to DESY III is only 33μsec and each LINAC current pulse is split into 11 bunches. Therefore, assuming 50 percent current losses from the source to the end of the LINAC and another 50 percent losses in the LINAC through the DESYIII–PETRA–HERA chain, the source current must be at least 20 mA. The present unpolarized H^- ion source current is 50-70 mA. The polarized source H^- should have a proton polarization of 70 to 80 percent. The feasibility of a 10 mA polarized H^- ion beam with 40 percent polarization has already been demonstrated [7]. The polarization is limited by the available superconducting solenoid and can be increased to 80 percent by the use of a high field (3 Tesla) solenoid which has a magnetic field homogeneous to 10^{-3} over 80 cm. Indeed, a current of unpolarized H^- greater than 30 mA was obtained at the test bench at TRIUMF and we expect that most of this current can be polarized to 80 percent by using a superconducting solenoid as indicated. The recent progress in atomic hydrogen beam technology, in lasers and in a sodium-jet ionizer provides all the tools for a 20 mA pulsed H^- source (OPPIS). A still higher beam intensity of 30-50 mA can be obtained by using the BINP (Novosibirsk) proposal for geometrical beam focusing at extraction [9] and a sodium-jet ionizer cell biased to -20 kVolt for polarized beam acceleration immediately after ionization to avoid the high-current beam losses in the low energy beam transport line. All of this development of a prototype polarized H^- source for DESY can be done parasitically with the present OPPIS source for RHIC SPIN. The request to DESY is to provide the superconducting solenoid mentioned above. BINP is a potential manufacturer of this solenoid. In addition some supplementary manpower (perhaps 1/2 time) is needed for work with A. Zelenski on this research and development.

3.4 Proton spin motion for a polarized HERA collider

The principal scientific problem in obtaining polarized protons at high energy involves the HERA ring itself, where the polarized protons must be accelerated to high energy and retain their polarization in the storage mode. Acceleration through a multitude of depolarizing resonances must be accomplished. A very strong depolarizing resonance at about 803 GeV appears to limit the upper energy for polarized protons in HERA to 800 GeV. Since 1995 extensive theoretical and numerical spin tracking studies have been carried out for HERA at DESY, based on a rigorous definition of the proton polarization vector at each point in phase space (figure 4) [1, 2, 3, 5, 6]. Simulations have shown that by a careful choice of orbital tunes and Siberian Snake layout, polarization can be preserved during acceleration up to 800 GeV out to about 2.0 sigma in horizontal, vertical and longitudinal phase space.

Tracking simulations for HERA thus far have been made with linearized orbital motion and linear magnetic fields. Beam–beam forces have been ignored. Moreover so far, only initial investigations have been made of the important effects of misalignments: the simulations refer to a perfectly aligned ring, but the very preliminary calculations have shown that with realistic closed orbit distortions special methods (item 1 below) will be required to prevent depolarization from limiting operation to about 300 GeV. The theoretical and numerical studies also show that it would be desirable to limit the transverse emittances of the proton beam by electron cooling. Thus there is a great need for further theoretical and numerical studies of proton spin motion in the HERA ring as indicated above. Additional manpower is urgently needed for the following topics:

1. Effect of closed orbit distortions to determine the tolerable limits on such distortions and to develop orbit correction schemes analogous to those used for electrons.

2. Further tracking simulations with "snake matched" schemes [5].

3. If the effect of closed orbit distortions can be neutralized, beam–beam forces, nonlinear effects and various sources of noise should be studied.

4. Studies of proton spin motion in DESY III and in PETRA, including a proposed electron cooler section [10], involving extensive spin–orbit tracking simulations. In HERA further cooling to maintain the very small vertical emittance during the ramp would probably not be needed.

5. Feasibility study for high field (6 Tesla to save space) snakes and rotators.

6. Design study for practical rotator layouts.

The critical and immediate need for the accelerator theory work is at least 2 young physicists to work at DESY with D. Barber and G. Hoffstätter. Barber's PhD student M. Vogt completed his work and has left DESY. There may be some physicists at BINP who would be interested in these problems. Every effort should be made to exploit modern Linux computers like the 300 parallel channel MAP machine in Liverpool. This currently allows 300 particles to be tracked in parallel and can be expanded to a few thousand channels.

4 Comparison with other projects

Most current experiments and proposed new projects have as their main aim the measurement of the polarized gluon distribution. HERMES produced a first measurement in 1999, in the region of high–x. The COMPASS experiment at CERN will use photoproduction events in polarized muon–proton scattering to measure ΔG around $x = 0.1$, from charm and high p_T particles. RHIC will measure both polarized quark and gluon distributions down to and below 10^{-2} but for the gluon one relies mainly on the prompt photon process, which so far has unfortunately encountered theoretical problems prohibiting the extraction of the gluon distribution even in the unpolarized case.

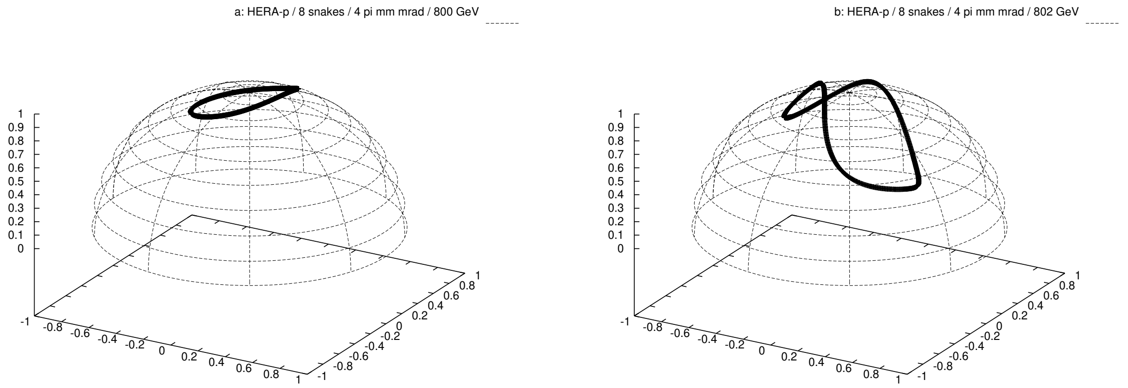

Figure 4: The invariant spin field $\hat{n}$ for vertical betatron motion in HERA–p calculated with `SPRINT` *on* the 4π mm mrad ellipse at 800 GeV and 802 GeV. A normalised emittance of 4π mm mrad $\equiv$ "$1-\sigma$".

HERA not only has the largest reach down in x, but deep inelastic scattering is certainly the reaction which is suited best to measuring hadron structure. We also note that HERA already has two excellent experiments, which were purpose–built for the study of the structure of the proton, and which over the years have mastered the control of systematics to reach impressive precision in the unpolarized measurements. Hence HERA is ideally suited for the polarized measurements.

A possible new competitor, labeled eRHIC, may emerge from the studies carried out at BNL, where it has been proposed that an electron machine be added to the RHIC ring in order to have $e-A$ and $e-p$ collisions (both polarized and unpolarized). The cms energy is expected to be about 100 GeV, leading to an order of magnitude less in reach for x and Q^2 compared to HERA. eRHIC is scheduled to have an order of magnitude larger luminosity than HERA. Currently, it is not expected that this (not yet approved) machine will be finished before the end of the decade. Moreover, a brand new detector for the (un)polarized $e-p$ measurements will be required.

A workshop has been organized for July 2001 in Trento (Italy), where the physics of these future projects will be compared.

5 Resources needed.

In order that a report can be prepared, the following resources would be needed:

1. OPPIS polarized H^- Source.
   - i) Highly homogeneous high field superconducting solenoid.
   - ii) One physicist, half time, to work at BNL on the source.
2. Theoretical and numerical work on proton spin motion.

i) At least two physicists to work with D. Barber, full time at DESY a) on, among several other things, methods to suppress the destructive effects of closed orbit distortions. b) spin dynamics in DESY III and in PETRA with cooling.

These matters are now very urgent if sufficient information on the feasibility of providing polarized protons in HERA is to be available in 2003 when a decision on such a project has to be taken.

The additional manpower required may be available from BINP or at Protvino but then some additional financial (or equivalent) support would be needed from elsewhere.

6 Organization of the Study for a Polarized HERA Collider

We suggest that the overall responsibility for the entire study leading up to a letter of intent should lie with a steering committee of interested people including the four organizers of the latest DESY Workshop entitled "Polarized Protons at High Energies - Accelerator Challenges and Physics Opportunities", held in May, 1999 [4]. They are D. Barber (DESY), A. De Roeck (CERN), V. Hughes (Yale) and F. Willeke (DESY).

Subsidiary responsibilities:

- OPPIS polarized source - A. Zelenski (BNL),
- theory of proton spin motion - D. Barber,
- liaison for RHIC SPIN and proton polarimetry - V. Hughes.

The success at RHIC adds to our conviction that we should proceed with these studies.

References

[1] "Acceleration of Polarized Protons to 820 GeV at HERA", SPIN Collaboration and the DESY Polarization Team. Univ. Michigan UM HE–96–20 (1996).

[2] Update report: "Acceleration of Polarized Protons to 920 GeV at HERA", SPIN Collaboration and the DESY Polarization Team, Univ. Michigan UM HE–99–05 (1999).

[3] D.P. Barber, G.H. Hoffstätter and M. Vogt, proc. 13th International Symposium on High Energy Spin Physics (SPIN98), Protvino, Russia, 1998, World Scientific (1999).

[4] "Polarized Protons at High Energies - Accelerator Challenges and Physics Opportunities" ed. A. DeRoeck, D. Barber and G. Rädel, DESY-PROC–1999–03 (1999).

[5] G.H. Hoffstätter, Habilitation Thesis, Technical University of Darmstadt (2000). Accepted for publication by Springer.

[6] M. Vogt, Ph.D. Thesis, University of Hamburg, DESY–THESIS–2000–054 (2000).

[7] A. N. Zelenski et al., DESY–PROC–1999–03 loc. cit., p. 177.

[8] T. Roser, talk at the 14th International Spin Physics Symposium, Osaka, Japan Oct. 2000.

[9] V. Davydenko, DESY–PROC–1999–03, loc. cit., 187.

[10] K. Balewski et al., Nucl.Instrum.Meth. **A441**, 274 (2000).

[11] A. Skrinsky, proc. of the workshop EPIC99, ed. L.C. Bland et al., Bloomington, USA, April 1999, World Scientific.

[12] Y. Derbenev, private communications, and
V. Anferov and Y. Derbenev, Phys. Rev. PRST-AB 12, 1345 (2000).

[13] A. De Roeck et al., Eur. Phys. J., **C6**, 121 (1999).

Appendix: Polarized deuterons at high energy

The interesting possibility that high energy polarized deuterons with longitudinal polarization might be obtained at HERA is not discussed in this document. This is a relatively new idea and, of course, has not yet been developed as fully as the case for high energy polarized protons. The study of producing a polarized D^- ion source at BNL is proceeding, and if Barber's theory group at HERA is strengthened, they may consider the case of high energy polarized deuterons.

Polarised deuterons have the advantage that they are less affected than protons by the depolarizing resonances due to their smaller gyromagnetic anomaly. Hence the storage and acceleration problems are expected to be less severe. On the other hand the small value of the gyromagnetic anomaly ensures that practical spin rotators cannot be built. Then other means, such as the recently suggested use of external radial frequency fields [11, 12], must be considered for arranging that the spins align longitudinally at the interaction points. The feasibilty of these ideas must be checked by long term spin–orbit tracking.

Another question is the availability of polarized deuteron sources with sufficiently high current.

If the deuteron spectator target could be tagged with sufficient efficiency, one could measure the neutron and proton spin properties simultaneously, making this an attractive option.