# A Polarized HERA Collider

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A brief review is given of the status of nucleon spin structure functions as determined from polarized deep inelastic lepton-nucleon scattering, including current outstanding problems. The characteristics of a polarized HERA collider, some of the particle physics topics it could address, and the accelerator physics challenges it must meet are discussed.

## 1. INTRODUCTION

It is often said that physics studies involving spin can lead to surprising results. We list some outstanding examples below.

**Some Surprises With Spin**

1. Space quantization associated with quantized spin directions. Stern, Gerlach, 1921.
2. Atomic fine structure and electron spin magnetic moment. Goudsmit, Uhlenbeck, 1926.
3. Proton anomalous magnetic moment; $\mu_p = 2.79$ nm. Stern, 1933.
4. Electron spin anomalous magnetic moment. $\mu_e = \mu_0$ (1.00119); QED. Kusch, 1947.
5. Electroweak interference from $\vec{e}_1 d$ DIS parity nonconservation. Prescott & SLAC-Yale Collaboration, 1978.
6. Proton spin structure; puzzle or crisis. EMC, 1989.

Hence from an historical viewpoint the spin variable is a promising one for discovery.

The first experiment, beginning in the mid-1970's, on polarized lepton-proton deep inelastic scattering was a series of two measurements at SLAC by a SLAC-Yale group, using an atomic beam polarized electron source built at Yale and an electron beam energy of ~20 GeV. The virtual photon-proton asymmetry $A_1^{\rm p}$ was measured in the $x$ range from 0.1 to 0.7 and found to be large. The values were consistent with a plausible quark-parton model satisfying the Bjorken sum rule, and also satisfying the Ellis-Jaffe sum rule if Regge extrapolation of $g_1^{\rm p}(x)$ to $x = 0$ was employed [1].

The European Muon Collaboration (EMC) in the mid-1980's made a similar measurement of $A_1^{\rm p}$ using a polarized $\mu^+$ beam with energy up to 200 GeV. In addition to confirming the SLAC results for $x > 0.1$, their data extended down to $x = 0.01$. Unexpectedly, the $A_1^{\rm p}$ data at low $x$ fell well below the extrapolated SLAC data. The consequence was violation of the Ellis-Jaffe sum rule at the 3 standard deviation level, and the conclusions were that only the small fraction $\Delta = 0.12 \pm 0.17$ of the proton spin is due to quark spins and that strange quarks have a substantial negative polarization [2].

This discovery by EMC has led to major new experiments at CERN, SLAC and DESY which were reviewed by R. Windmolders in this workshop.

Some outstanding questions relevant to spin structure remain: 1) Behavior of $g_1^{\rm p}(x)$ at small $x$ and the value of the first moment $\Gamma_1^{\rm p}{=}\int_0^1 dx g_1^{\rm p}(x)$. 2) Contribution of gluons to proton spin and the polarized gluon distribution. 3) Contribution of the orbital angular momentum of quarks and gluons to proton spin. 4) Hadronic spin structure of the photon. 5) Chiral structure of any observed contact interaction or leptoquark beyond the standard model.

Experiments such as polarized lepton-nucleon scattering which require a polarized beam and a polarized target are sometimes spoken of as spin physics and are sometimes regarded as not of central interest. However, it is well known that the hadronic tensor $W^{\mu\nu}$, which describes the proton in DIS $ep$ or $\mu p$ scattering, involves four scalar functions: $F_1(x)$, $F_2(x)$, $g_1(x)$ and $g_2(x)$, which are required for a complete knowledge of $W^{\mu\nu}$. The functions $F_1$ and $F_2$ do not

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Table 1
A Polarized HERA Collider

| | Electron Beam | Proton Beam |
|---|---|---|
| Beam Energy | 26 – 30 GeV | 800 – 930 GeV |
| Polarization Status | Polarized Sokolov | Negligible polarization |
| | Ternov Effect (SKE) | due to SKE |
| | $P_e \sim 60\%$ in 1/2 hour | Need polarized source |
| Expected Polarization | 70% | 70% |
| Uncertainty $\delta P/P$ | $\leq 2\%$ | $\leq 3\%$ |
| Integrated Luminosity | $\sim 500$ pb$^{-1}$, 3 years running with 150–170 pb$^{-1}$/year | |

involve the spin variables, whereas $g_1$ and $g_2$ do. Perhaps the principal achievements of HERA to date are the measurement of $F_2(x)$ at small $x$ and also at high $Q^2$, the determination of the unpolarized gluon distribution in the proton, study of the hadronic constituents of the photon, and extension of the limits on a contact interaction or leptoquark search. A polarized HERA collider will address these same topics from a different viewpoint. Spin is a fascinating tool but it is not the goal of these experiments.

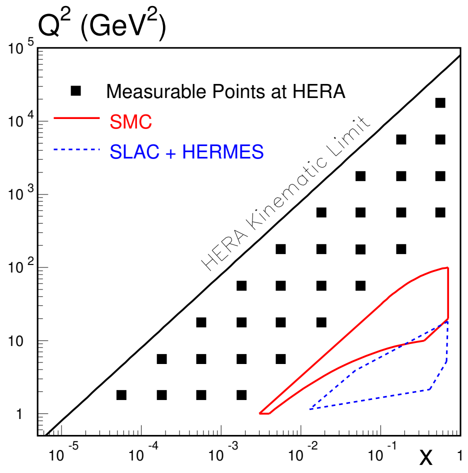


Figure 1. The $x - Q^2$ range of HERA compared to the fixed target experiments at CERN, SLAC and DESY.

## 2. CHARACTERISTICS OF A POLARIZED HERA COLLIDER

There has been considerable interest in a possible polarized HERA collider with the characteristics indicated in Tab. 1, in several workshops associated with HERA[3, 4]. At present of course there is a polarized electron beam in HERA which is used in the HERMES experiment. Development of a polarized proton beam is required. Then one or both of the existing collider detectors –ZEUS,H1– could be used for measurements of polarized $e^{\pm}p$ DIS.

The huge increase in the $x - Q^2$ range for measurements of spin variables possible with a polarized HERA collider is shown in Fig.1. Two orders of magnitude increase in both $x$ and $Q^2$ range is possible for exploring the spin structure of the proton. If a sufficiently intense source of $^3He^-$ can be developed, measurements of the spin structure of the neutron could be done[3].

## 3. PARTICLE & NUCLEAR PHYSICS WITH POLARIZED HERA

### 3.1. Measurement of $g_1^p$ at low $x$

The behavior of $g_1^p$ at low $x$ is of fundamental interest and the largest uncertainty on the first moment of $g_1^p$ now comes from the unmeasured low $x$ region, $x < 0.003$ [5]. The statistical uncertainties for a measurement of $g_1^p$ with a polarized HERA collider (Tab. 1), using the H1 or ZEUS detector, are shown in Fig. 2. Even though the predicted asymmetries are as small as $3 \times 10^{-4}$ at low $x$, false asymmetries associated with correlations of proton beam intensity

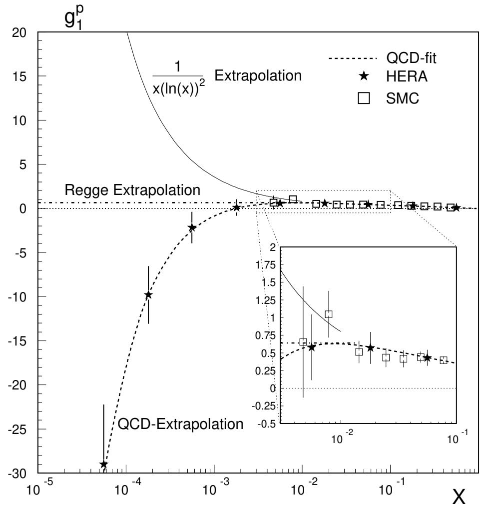


Figure 2. The statistical uncertainty on $g_1^p$ from possible measurements at HERA with 500 pb$^{-1}$ is shown along with different theoretical predictions for the low $x$ in the kinematic region $x < 0.003$.

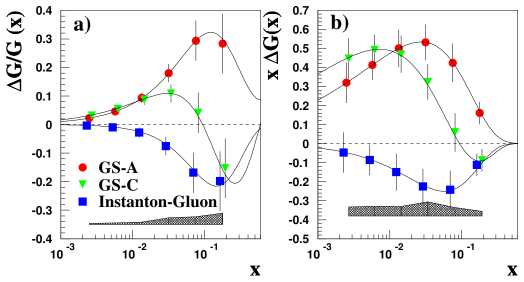


Figure 3. Statistical accuracy possible for the measurement of $\Delta G(x)$ using 2 jets from the PGF process shown with different predictions for $\Delta G(x, Q^2 = 20\ \text{GeV}^2)$.

or bunch crossing angle with proton polarization, or with time variation of detection efficiencies can be kept still smaller by modulation of the spin direction. From the polarized H$^-$ source any desired polarization can be provided for a proton bunch so that rapid modulation for successive interactions is achieved. Also in the HERA ring at high energy, all of the spin directions of the proton bunches can be flipped periodically by a microwave pulse. Recently [4] it has been checked using a fast detector simulation that the detector smearing and event migration does not hinder the measurement $g_1$. Also shown in Fig.2 are the various low $x$ predictions for the structure function arising from models and QCD fits consistent with the presently available data.

### 3.2. The Polarized Gluon Distribution

Determination of the polarized gluon distribution $\Delta G(x, Q^2)$ inside a nucleon and its first moment $\Delta G$ have become important goals of all experiments proposed and planned in the next decade. Polarized HERA can contribute significantly, through the various different and independent ways in which it can measure $\Delta G(x, Q^2)$.

Perturbative QCD analysis of $g_1^p$ allows a determination of $\Delta G(x, Q^2)$ through a next-to-leading order analysis[5]. The published value of $\Delta G = 1.0^{+1.2}_{-0.3}(\text{stat})^{+0.4}_{-0.2}(\text{syst})^{+1.4}_{-0.5}(\text{theo})$ [5] indicates that statistical and theoretical uncertainties dominate our lack of knowledge of $\Delta G(x, Q^2)$. A study [3] using simulated HERA data and the presently available fixed target data indicates that the statistical & theoretical uncertainties could be reduced by factors $\sim 2$ & $\sim 3$, respectively.

In the Photon Gluon Fusion (PGF) process the gluon is involved at leading order (LO). The measurement of such a process through detection of 2 high–$p_T$ jets and the scattered electron allows access to the polarized gluon distribution[3]. Figure 3 shows the statistical uncertainty achieved by polarized HERA collider (Tab. 1). Also shown are three widely different predictions for $\Delta G(x, Q^2)$ at LO, all consistent with the fixed target data, which HERA data can easily distinguish between. Expected uncertainty on $\Delta G/G$ after HERA measurements of 2-jets is $\pm 0.1$[3]. It has also been checked that the detector smearing and migration effects due to the measurement process do not affect the measurability of $\Delta G$. Recently, NLO corrections to this process were evaluated and found to be small.

Both H1 and ZEUS collaborations have published results on the parton distributions inside the unpolarized photon $q^\gamma$. With polarized

HERA one could investigate the structure of the polarized photon $\Delta q^{\gamma}$. A study[3], using single and 2 high-$p_T$ jets or hadron tracks from the PGF process in photoproduction, showed that a luminosity of 100 $pb^{-1}$ was sufficient to resolve the polarized photon and the gluon structure.

## 4. POLARIZED HERA: ACCELERATOR ASPECTS

Production of a high energy polarized proton beam in HERA requires first a polarized $H^-$ source and then acceleration to high energy through the DESY acceleration chain with retention of polarization (Fig. 4). The full initial study[6] of the requirements for a high energy polarized beam in HERA identified two crucial problems. One is the development of an adequate polarized $H^-$ source, and the second is the acceleration and retention of proton polarization in HERA.

### 4.1. Polarized Source for HERA

The design specifications for a polarized $H^-$ source for HERA are[6]: I=20 mA, in 100$\mu s$ pulses at 0.25 Hz with emittance $2\pi$ mm·mr, and $P_p = 0.8$. At present the most promising approach is the Optically Pumped Polarized Ion Source (OPPIS) development at TRIUMF by A. Zelenski *et al.* [7]. The overall source arrangement is shown in Fig. 5.

A polarized $H^-$ source is now being developed at TRIUMF for the Relativistic Heavy Ion Collider (RHIC) at BNL for their RHIC-Spin program. Development of an OPPIS source suitable for HERA is progressing with optimism.

### 4.2. Acceleration of Polarized Protons

The acceleration and then storage of polarized protons from the ion source to the high energy HERA ring is a major problem dominated principally by depolarizing resonances. Because of the large anomalous magnetic moment of the proton ($\mu_{\rm p} = 2.79$ nm), the relativistic equations of spin motion [8] show that at high energy the number of spin precessions per orbit –the spin tune– is large, indeed equal to $G\gamma$ which is $\sim$1530 at E=800 GeV. Hence the spin motion is very sensitive to the magnetic field, and in particular the many intrinsic and imperfection resonances can lead to depolarization. Avoidance of depolarization involves the use of the Siberian Snake principle[9]. Extensive simulation calculations by spin tracking codes have been done[8]. Figure 6 shows for two energies the equilibrium polarization distribution or the spin vector for the stored proton beam in HERA, using 8 snakes. Although such results are encouraging, much further intensive study of spin motion is required to assure adequate proton polarization at high energy. Electron cooling in the DESYIII ring is being considered to reduce the beam emittance and thus make it simpler to obtain high proton polarization.

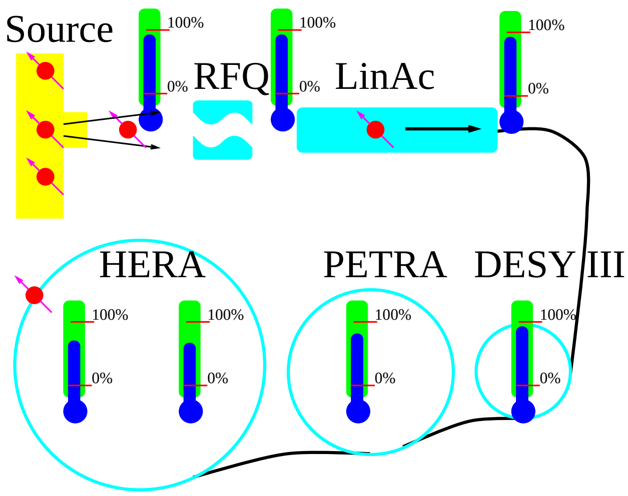


Figure 4. The various stages of the proton acceleration from the polarized source to the HERA ring.

### 4.3. Proton Beam Polarimetry

Measurement of proton beam polarization at high energy is under active development at BNL, mainly for the RHIC Spin program in which polarized proton beams up to 250 GeV will collide. Three types of polarimeter are presently consid-

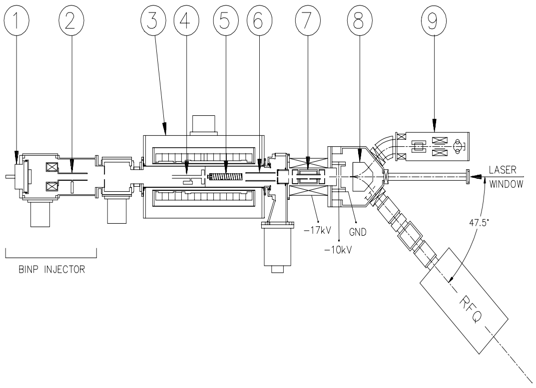


Figure 5. The TRIUMF Optically Pumped Polarized Ion Source: 1. plasmatron proton source, 2. hydrogen neutralizer, 3. superconducting solenoid, 4. helium ionizer, 5. optically pumped Rb vapor cell, 6. deflection plates, 7. Na vapor ionizer, 8. bending magnet, 9. Lyman-alpha polarimeter

ered[4]: 1) Inclusive pion production $\vec{p} + C \to \pi^+ + X$, 2) $\vec{p} + C$ elastic scattering in the Coulomb Nuclear Interference (CNI) region, capable of $\sim$ 8% absolute accuracy determined by the theoretical uncertainty of the hadronic spin flip amplitude, and 3) $\vec{p} + p$ elastic scattering involving a polarized jet target. This method equates the asymmetry $A$ in the elastic scattering $(p_{\rm b} + \vec{p}_{\rm jet})$, for which the polarization of the jet $P_{\rm jet}$ is known, to the beam polarization $P_{\rm b}$ for $(\vec{p}_{\rm b} + p_{\rm jet})$ scattering for the same scattering kinematics. It is capable of $\sim$ 3% absolute accuracy.

## 5. SUMMARY

Important physics results can be expected from $\vec{e} + \vec{p}$ collisions with the polarized HERA collider. However, increased effort is needed *now* to solve the challenging accelerator physics problems associated with achieving high energy polarized protons in the HERA ring.

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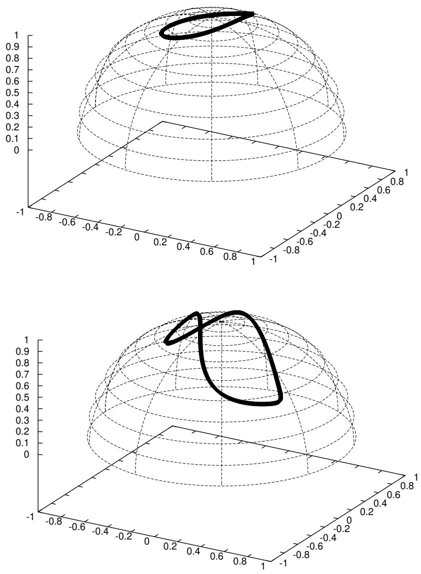

Figure 6. SPRINT simulation of the resultant spin vector at 800 (802) GeV proton beam above (below). Shown is the effect of $4\pi$ mm mr deviation from the nominal spin direction.

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