Feasibility Studies for an Experiment to Measure the Spin Dependent Nucleon Structure Functions at HERA

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1. Introduction

Early this year some of us have submitted to DESY two independent notes, PRC-88/1 and 88/2, in which we expressed our intent to measure the spin dependent structure functions of both proton and neutron using the longitudinally polarized electron beam of the HERA storage ring at beam energies between 30 and 35 GeV. For these measurement we proposed a new technique, this is to use internal polarized gas targets of hydrogen, deuterium and $^3$He developed by our groups. The target design is a thin-walled storage cell which is fed by a high intensity source of polarized atoms providing densities between $10^{14}$ atoms/cm$^2$ for $H$ and $D$ and easily more than $3 \times 10^{14}$ atoms/cm$^2$ for $^3$He. This novel technique is superior to conventional polarized target technology since it does not suffer the disadvantage that only a small fraction of the target nucleons is polarizable. The expected luminosity for a 60 mA circulating electron beam would be $3.5 - 10 \cdot 10^{31}$ cm$^{-2}$s$^{-1}$. This would allow to obtain high statistical precision for the polarized structure functions in relatively short runs of data taking in the order of 3 weeks per target.

Meanwhile the two groups have joined together with several other institutions in order to study in a first step in more detail the feasibility of the experiment and later on form a collaboration to submit a formal proposal.

An essential prerequisite for this experiment is a large longitudinal polarization of the beam which should be at least in the order of 50% and should also be well known with a relative accuracy of 3-5%. At present it is not yet possible to predict firmly the degree of polarization which can be achieved and the time scales involved to realize it. It is, however, evident that this problem is a challenge to DESY and will be treated with high priority as well theoretically as experimentally.

Also the use of an internal storage cell target would be an important technological progress. This is an additional motivation for us as it would open interesting new prospects for experiments with internal targets in storage rings.

In this document we present a preliminary layout of a possible detector which would be a rather conventional magnetic spectrometer with angular acceptance for the scattered electron between 40 and 200 mrad and would allow to cover a kinematic range in $Q^2$ between 1 and 20 GeV$^2$ and $x$ between 0.02 and 0.8. We discuss the expected accuracies for the measured asymmetries and some sources of possible background. The impact of the experiment on the machine has been discussed with several experts at DESY. The results of these discussions are summarized. Furthermore we give a description of the target and discuss related problems like a possible depolarization of the target by the
magnetic field of the beam and the proposed method for measurement of target polarization.

Finally we give a possible timeschedule for the experiment.
2. Motivation

A complete picture of fundamental hadronic interactions requires an understanding of the internal spin structure of the nucleon. The necessary information can be obtained from a measurement of the two spin dependent structure functions $g_1(x)$ and $g_2(x)$ of both proton and neutron via the spin asymmetries in deep inelastic scattering of longitudinally polarized leptons off polarized nucleons. $g_1(x)$ has a transparent interpretation in the context of the quark parton model, where it can be written in terms of quark densities $q_f(x)$ with helicities the same $(+)$ as or opposite $(-)$ to the helicity of the parent nucleon:

$$g_1(x) = \frac{1}{2} \sum_f e_f^2 \left( q_f^{(+)}(x) - q_f^{(-)}(x) \right)$$

where the sum runs over the quark flavours and $x$ is the usual Bjorken variable.

Until now few measurements of $g_1(x)$ have been performed for the proton only [2.1,2.2]. No data for the neutron exist.

Recently measurements of the spin asymmetry in polarized muon-proton deep inelastic scattering have been presented by the European Muon Collaboration at CERN [2.1]. The spin dependent structure function $g_1(x)$ has been derived from these measurements and $I_P^p$, its integral over $x$. The integral was found to be $I_P^p = 0.114 \pm 0.012 \pm 0.026$ for the EMC data alone and $0.116 \pm 0.009 \pm 0.019$ from a combined analysis [2.3] of the EMC data and the SLAC data. This result is in disagreement with the Ellis-Jaffe sum rule [2.4], which after QCD corrections predicted a value of $0.189 \pm 0.005$, by almost 3.5 standard deviations.

Assuming the validity of the fundamental Bjorken sum rule [2.5] the data imply that the neutron must have a much larger contribution to it than hitherto assumed, with $g_1^n(x)$ being largely negative over at least part of the $x$-range [2.6].

This result has also been argued to imply that the total spin carried by all the quarks and antiquarks in a polarized proton is consistent with zero and that the strange sea might have a large negative polarization [2.7-2.8], in contradiction to intuitive expectations.

Several attempts have been made to resolve this problem including claims of evidence against perturbative QCD [2.9].

It has been pointed out [2.10] that the final conclusion can depend very much on the assumed behaviour of both $g_1^p(x)$ and $F_2^p(x)$ as $x \rightarrow 0$. The argument that the behaviour of $F_2(x)$ at small $x$ may have a more singular behaviour than is given by the usual Regge analysis is however not generally accepted [2.11].
Other authors relate the discrepancy to a rapid \( Q^2 \) dependence of the integral either caused by large higher twist corrections \( [2.11] \) linked to the Drell-Hearn-Gerasimov sum rule \( [2.12] \) which gives a negative value of \( I_1^p \) at \( Q^2 = 0 \), or associated with the non-conservation of the \( U(1) \) axial current in QCD \( [2.13] \) as a consequence of the Adler-Bell-Jackiw anomaly \( [2.14] \). No significant \( Q^2 \) dependence is however visible in the \( Q^2 \) range of the existing data. It would be important to find out whether there is one at lower values of \( Q^2 \).

It has been suggested \( [2.15] \) that in a skyrmion model picture naturally the contributions of quarks to the spin of the proton disappear for all \( Q^2 \) and that this result is supported \( [2.8,2.16] \) by elastic antineutrino nucleon scattering data \( [2.17] \). In this picture the spin of the proton is not due to quark or gluon polarization but is orbital momentum which is carried dominantly by the quark constituents. Also other authors \( [2.18] \) suggest that orbital angular momentum contributions might be large.

It is also possible that the gluon carries a large fraction of the proton spin \( [2.19,2.20] \). It has been argued \( [2.21,2.22] \) that it is possible to have a consistent picture of the proton with a large component of the spin carried by valence quarks balanced by a sizeable gluon contribution arising from the axial anomaly.

The existing experimental information is however far from being accurate enough to decide which of the proposed solutions is the correct one. All conclusions depend on the magnitude of the integral \( I_1^n \) for the neutron which has been deduced from the proton data under the assumption that the Bjorken sum rule is strictly valid.

To clarify the situation it is necessary to remeasure in a clean way the spin dependent proton structure functions with much better statistical accuracy and smaller systematic errors than the previous experiments and to determine not only their integral but also their \( x \) dependence with high precision down to low values of \( x \). It is essential that also the polarized neutron structure functions will be measured with good accuracy. They can be obtained from measurements on both polarized deuterium and hydrogen and as an independent cross check from a polarized \( ^3He \) target.

In principle, the combination of \( g_1^p(x) \) and \( g_1^n(x) \) together contain all the information necessary to determine the internal spin structure of the nucleon. They will allow to separate the spin distributions of \( u \) and \( d \) quarks and of the (strange) sea and to determine the fraction of the nucleon spin carried by quarks which is, apart from a small correction, directly proportional to the integral over the polarized deuteron structure function. Furthermore they will provide a precise test of the fundamental Bjorken sum rule.
These measurements will therefore serve as a very tight constraint on existing models of the nucleon and also as an aid to developing improved models.

It has recently been pointed out [2.23] that for spin 1 targets there exists a new structure function $b_1(z)$ which is of leading twist in QCD. It means the extent to which a target nucleus deviates from a trivial bound state of protons and neutrons. For the deuteron, one expects $b_1 \approx 0$. $b_1(z)$ can be determined by measuring the deep inelastic cross section for scattering of unpolarized electrons on a target polarized along the beam. We could perform such a measurement on polarized deuterons in an early stage without requiring longitudinal polarization for the electron beam.


Fig. 3.1 shows the kinematical region which can be covered by the experiment for a beam energy of $E = 35$ GeV.

![Kinematic plane for an electron beam energy of 35 GeV](image)

Fig. 3.1: Kinematic plane for an electron beam energy of 35 GeV

We demand a minimal $Q^2$ of 1 GeV$^2$ to allow an interpretation of the data in terms of the quark parton model. An upper cut at $y = 0.85$ removes the region of large radiative corrections and high hadronic background, a lower cut at $y = 0.15$ suppresses events from elastic scattering and resonance production. With these cuts the accessible $x$ range extends from 0.02 to 0.8. It can be nearly completely covered by a spectrometer with an angular acceptance of $40 < \Theta < 200$ mrad, where $\Theta$ is the electron scattering angle.

To suppress low energy charged background, to discriminate electrons from positrons and to improve pion rejection a substantial magnetic field is required. Such a field must however be shielded from the electron and proton beam.

Fig. 3.2 shows the presently envisioned detector whose details are still being optimized by Monte Carlo studies.
Fig. 3.2: Schematic view of the proposed electron spectrometer.
The spectrometer is very similar to the one successfully used down to 20 mrad by the UA6 experiment at CERN [3.1]. Momentum analysis is accomplished by the use of a 1.5 Tm dipole magnet which is divided into two symmetrical parts by a horizontal iron plate. Both electron and proton beam, which are at the same height and horizontally separated by 88 cm, traverse this plate through a bore with very little rest field (in the case of UA6 this amounts to only 0.04 Tm compared to 2.3 Tm in the gap), which can be easily locally compensated (see section 6).

Due to this arrangement the spectrometer is divided into two identical halves and the detectors behind the magnet can be protected against background from the beampipes by a shielding of tungsten and/or lead of up to 20 cm thickness. Similarly the upstream region between minibeta quadrupole and target can be thoroughly shielded.

Charged particles will be tracked by sets of multiwire proportional chambers in front (8 planes, wire spacing 1 mm) and inside the magnet (9 planes, wire spacing 2 mm). Behind the magnet MWPC chambers (12 planes, 2 mm spacing) or mini drift chambers (3-5 mm driftdrills) will be used. In total this will amount to about 40000 readout channels.

We are investigating whether silicon strip detectors could be installed in the target region to improve the vertex resolution. The set-up could be similar to that for the leading proton spectrometer as being build for the ZEUS experiment [3.2]. Two sets of three microstrip $S\ell$ detectors (100 $\mu$m pitch) working at high time resolution would provide a precise constraint in the vertex fit for the scattered electron track.

The electron energy will be measured by a lead glass wall (cell size 7.5 · 7.5 · 36 cm) possibly including a preshower part of the same material, which provides good energy resolution (of order $5%/\sqrt{E}$), good pion discrimination (30-100), as well as coarse position measurement which will form part of the first level trigger in conjunction with a scintillator hodoscope. This will help to discriminate electrons from high energy photons.

Electrons from high energy photons via asymmetric pair production will be substracted using the measured positron yield (see 5).

Low energy particles will be suppressed by an energy threshold of the lead glass wall of 5 GeV.

The yield of background particles emitted from the target will be discussed in section 5. The ratio of pions to electrons above the threshold of 5 GeV is generally smaller than 100 (maximum found to be 250 for 5 GeV particles at intermediate angles of 7-8 degrees), is about 10 for 8-10 GeV and drops down to below 1 around 15-20 GeV.
The use of a Čerenkov counter for pion rejection has been examined. It seems unlikely that such a counter, 2 m long, would have a sufficient pion rejection between 10 and 20 GeV and at the same time a high electron efficiency.

To reject the pions we plan therefore to build a transition radiation detector (TRD). The rejection factor must be at least 100. A signal from the TRD must be delivered early enough to be included in the second level trigger.

The present scheme is derived from an existing TRD built at SACLAY for the D0 experiment at Fermilab [3.3]. The SACLAY detector with 3 units has a pion rejection factor of 50 for a 90% electron efficiency down to an energy of 5 GeV.

Each unit of this detector includes a radiator and a photon detector. The radiator is a polypropylene stack of 400 foils 18 microns thick, 150 microns gap. The radiator volume is filled with helium. The photon detector is a longitudinal drift chamber, filled with xenon, with a 16 mm drift zone. The time distribution of the signal, given by flash ADC's, shows a continuous background due to the charged particle and clusters due to the absorption of photons at different points of the drift zone.

The pion rejection is obtained by using algorithms on both the integrated signals and the existence of clusters in the time distribution.

As we don't have the severe spatial constraints of D0, we consider a TRD with 5 units and in total 2500 readout channels in the hope to get a rejection factor of 100 with algorithms based only on the integrated signals. This could be performed early enough for the the second level trigger. Programs exist at SACLAY to optimize the parameters of such a TRD for our experiment. Data will be available soon from a test run at CERN with the D0 TRD and will be used to predict the performances of different schemes. The technology developed at SACLAY would greatly help the construction of a new version for the HERA experiment.

With these devices the energy resolution of the spectrometer is between 1 and 2%, the angular resolution, including multiple scattering effects, is about 1 mrad. The resolution in $Q^2$ and $x$ is better then 5–6% over most of the kinematic plane, apart from the low $\nu$–low $\theta$ region, where the $x$ resolution is about 8%. This accuracy is better than actually needed, as we are measuring an asymmetry rather than an absolute cross section.

It is important to determine that the electron originated in the central 10 cm of the target gas (where the gas is fully polarized). We estimate the resolution in $z$ (the distance along the beam direction) as $\sigma_z < 1$ cm at $\theta = 40$ mrad, and less at larger scattering angles.

The detector shown in fig. 3.2 accepts particles with angles between 40 and
140 mrad vertically and 40 to 200 mrad horizontally. The acceptance is shown in fig. 3.3. The total length of the spectrometer is 6 m, the height 1.6 m and the width 2.7 m.

![Diagram showing angular acceptance of the electron spectrometer.](image)

Fig. 3.3: Angular acceptance of the electron spectrometer

We are considering to increase this length by up to 1.5 m to enlarge the total $\int B \, dl$, the lever arm for the MWPC behind the magnet and the space for the TRD.

[3.2] ZEUS Collaboration, Status Report 1987, PRC 87-02
4. Expected accuracies for the measurements of the spin dependent structure functions and the sum rules.

The statistical accuracy of such an experiment is mainly limited by the degree of beam and target polarization, $p^B$ and $p^T$, and $f$, the fraction of events originating from polarizable nucleons in the target, which is small for solid targets like ammonia or butanol but is unity in our case.

In Fig. 4.1 the result for $g_1(x)$ for the proton is shown which has been obtained by the muon experiment of the EMC [4.1] with a polarized $NH_3$ target ($f \approx 0.2, p^T \approx 0.8, p^B \approx 0.8$) in about 120 days of data taking.

![Graph of $g_1(x)$ vs. $x$ with data points for EMC and HERA (400h).]

Fig. 4.1: The proton spin structure function $g_1^p(x)$ as measured by EMC and the expected accuracy for this experiment which can be achieved in 400 hours of data taking.

With our proposed experiment ($L = 3.5 \cdot 10^{31} cm^{-2} s^{-1}, f = 1, p^T = 0.8, p^B = 0.5, Q^2 > 1 GeV^2, 0.15 < y < 0.85$) one could achieve this accuracy in about 10 hours (!!) of (100% efficient) beam time.
The projected data for 400 hrs of beam time are also shown in the figure. In addition to the statistical error an overall 7–10% systematic error has to be taken into account.

It is obvious that such a new experiment would allow a rather precise determination of the $x$ dependence of $g_1(x)$, which until now is only very badly determined at low $x$, and also of its integral $\int_0^1 g_1(x) \, dx$ with a statistical accuracy of about $5\%$. The result for $g_1(x)$ for the deuteron and its integral — which, apart from a small correction, determines the fraction of the nucleon spin carried by the quarks — will have a similar accuracy.

To determine the second polarized structure function $g_2(x)$ it is necessary to measure the cross section asymmetries for both longitudinal and transverse target polarization. These are related to the asymmetries $A_1$ and $A_2$ and to $g_1$ and $g_2$ by

$$A_{||} = D \cdot (A_1 + \eta \cdot A_2)$$

$$A_{\perp} = d \cdot (A_2 - \xi \cdot A_1)$$

$$g_1 = F_1 \cdot A_1$$

$$g_1 + g_2 = F_1 \cdot A_2 \cdot \frac{\sqrt{Q^2}}{2Mx},$$

where $d$, $D$, $\eta$ and $\xi$ are kinematical factors.

In the past $A_2$ has been neglected in the analysis and has been considered as part of the systematic error of $A_1$.

In our proposed experiment $A_2$ can be determined by a measurement of the transverse asymmetry $A_{\perp}$ in a separate run with a holding field perpendicular to the beam (vertical direction).

Table 4.1 shows for several $x$-bins the expected counting rates and the statistical errors $\delta A_1$ for the $Q^2$ averaged asymmetries $A_1(x)$ for proton, deuteron and neutron, which can be achieved with a longitudinally polarized hydrogen ($p^T = 0.8$), deuterium ($p^T = 0.6$) and $^3\text{He}$ ($p^T = 0.5$) target in 400 hours of beam time each and a luminosity of $3.5 \cdot 10^{31} \text{cm}^{-2}\text{s}^{-1}$ for $H, D$ and $10^{32} \text{cm}^{-2}\text{s}^{-1}$ for $^3\text{He}$. For these numbers $A_2$ has been neglected. Also given is the error for the quantity $A_{\perp} = A_2 - \xi \cdot A_1$, which can be obtained in a 400 hours run from a hydrogen target with transverse polarization.

The relatively large error bars for the neutron asymmetry $A_1$ are due to the subtraction of deuteron and proton data and the fact that $\sigma_p/\sigma_n$, which enters the weights of $\delta A_1^p$ and $\delta A_1^n$, and the dilution factor $f$ for $^3\text{He}$ increases continuously with $x$. However the accuracy in $A_1^p$ will be good enough to see whether it is largely negative at low $x$ and rises towards one for $x \to 1$ and to determine the magnitude and $x$ dependence of $g_1^n(x)$ over a wide range of $x$. 
Table 4.1: Statistical accuracies for $\delta A$.

400 hours measuring time for each target
$p^B = 0.5$
$p^T = 0.8$ Hydrogen 
$= 0.6$ Deuterium
$= 0.5$ $^3$Helium

\[ L = 3.5 \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1} (H, D) \]
\[ = 10. \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1} (^3 \text{He}) \]

<table>
<thead>
<tr>
<th>$x$-bin</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$H$</th>
<th>$D$</th>
<th>$^3$He</th>
<th>$H_\perp$</th>
<th>$\delta A^0_1$</th>
<th>$\delta A^d_1$</th>
<th>$\delta A^T_1$ (D-H)</th>
<th>$\delta A^T_1$ ($^3$He)</th>
<th>$\delta A^T_1$</th>
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<tbody>
<tr>
<td>0.02 - 0.03</td>
<td>1.2</td>
<td>0.090</td>
<td>0.171</td>
<td>0.745</td>
<td>0.018</td>
<td>0.009</td>
<td>0.008</td>
<td>0.019</td>
<td>0.015</td>
<td>0.019</td>
</tr>
<tr>
<td>0.03 - 0.04</td>
<td>1.4</td>
<td>0.112</td>
<td>0.211</td>
<td>0.924</td>
<td>0.023</td>
<td>0.009</td>
<td>0.009</td>
<td>0.020</td>
<td>0.016</td>
<td>0.019</td>
</tr>
<tr>
<td>0.04 - 0.06</td>
<td>1.8</td>
<td>0.191</td>
<td>0.359</td>
<td>1.570</td>
<td>0.039</td>
<td>0.009</td>
<td>0.007</td>
<td>0.018</td>
<td>0.014</td>
<td>0.017</td>
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<tr>
<td>0.06 - 0.10</td>
<td>2.4</td>
<td>0.296</td>
<td>0.549</td>
<td>2.414</td>
<td>0.060</td>
<td>0.008</td>
<td>0.008</td>
<td>0.019</td>
<td>0.015</td>
<td>0.018</td>
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<tr>
<td>0.10 - 0.15</td>
<td>3.0</td>
<td>0.275</td>
<td>0.499</td>
<td>2.210</td>
<td>0.055</td>
<td>0.011</td>
<td>0.011</td>
<td>0.028</td>
<td>0.021</td>
<td>0.026</td>
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<tr>
<td>0.15 - 0.20</td>
<td>3.5</td>
<td>0.197</td>
<td>0.350</td>
<td>1.563</td>
<td>0.039</td>
<td>0.016</td>
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<tr>
<td>0.20 - 0.30</td>
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<td>0.30 - 0.40</td>
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<td>0.134</td>
<td>0.620</td>
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<td>0.087</td>
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<td>0.005</td>
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<td>0.083</td>
<td>0.313</td>
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<td>9.8</td>
<td>0.004</td>
<td>0.005</td>
<td>0.026</td>
<td>0.001</td>
<td>0.141</td>
<td>0.161</td>
<td>0.707</td>
<td>0.588</td>
<td>0.370</td>
</tr>
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</table>

The errors for $A^d_1$ and $A^T_1$ obtained with $H$ and $D$ are shown in Figs. 4.2 and 4.3 together with curves which indicate the possible $x$ dependence of these quantities.

Fig 4.4 shows the resulting precision with which $g^1_1(x)$ can be measured in 20 days running time with the $^3$He target. In this figure the error bars include a pessimistic $\pm 15\%$ systematic error.

The systematic errors will mainly be determined by the accuracy of the measurement of beam and target polarization. Our aim is to reach 3-5% for $p^B$ and 2-3% for $p^T$. Together with other possible sources of systematic errors (uncertainties in $F_2$, $R = \sigma_L/\sigma_T$, radiative corrections etc) this would result in an overall systematic error on the integrals in the order of 7-10%.

Systematic uncertainties in the measured asymmetry due to radiative corrections can result both from uncertainties in the radiative corrections themselves, and from the unfolding procedure, which requires knowledge of the deep inelastic asymmetry. Accuracies in the radiative corrections on the order of 1% have recently been achieved in the deep inelastic electron scattering experiment E140 at SLAC. This precision resulted from improved knowledge of the cross sections over a wide range of kinematics due to new experiments, and to comparisons and cross-checks using several independent methods for calculating the corrections. Unfolding of the spin-dependent corrections involves an iterative procedure using an initial estimate of the kinematic dependence of the asymmetry. Both the SLAC-Yale and EMC experiments have shown that this iterative...
Fig. 4.2: Expected accuracy for the deuteron asymmetry $A_1^d(x)$ for 400 hours data taking

Fig. 4.3: Expected accuracy for the neutron asymmetry $A_1^n$ from hydrogen and deuterium
Fig. 4.4: Expected accuracy for the neutron spin structure function $g_1^n(x)$ from $^3$He
technique contributes little uncertainty.

To minimize the contribution to the total uncertainty from the radiative corrections, external corrections should be kept small and large contributions from elastic tails should be avoided. As the target is extremely thin, and there is no entrance window, the only significant contribution is from scattered electrons interacting with the storage cell and exit window. Using thin Be or Al walls will keep the external corrections to a small fraction of the internal, for most of the kinematic range of the experiment. Also the kinematic cuts ($y \leq .85$ and $Q^2 \geq 1$) keep the correction from elastic and quasielastic (for D and $^3$He targets) tails to less than 50%.

The corrections to the asymmetry are typically $\leq 5\%$ over a large segment of the kinematics but can be as large as 20 - 30\% at small $x$ ($x \leq .1$)[4.2]. The maximum uncertainty in the radiative corrections is thus of order 3 - 5\%.

5. High Energy Background Rates

The detector will be protected from most of the soft background caused by beam interactions with the vacuum chamber, Möller scattering from residual gas, backscattered synchrotron radiation and other sources by a hermetic shielding of the beampipes in the interaction region upstream the target and behind the magnet, thick shielding walls in front of the minibeta quadrupoles and a complete housing made of concrete and lead. In the following we concentrate therefore on sources of high energy background which could result in false triggers.

The estimates of direct charged particle production include deep inelastically scattered electrons, electrons from Möller scattering and charged hadron production. Charged hadrons constitute the main source of background in the section of the detector downstream of the magnet. Secondary sources of particle production including pair production, Compton scattering, etc. have been studied separately. The assumed luminosity was $10^{32}$ cm$^{-2}$ s$^{-1}$ corresponding to the worst case (from the point of view of rates) of a $^3$He target with a density of $2.7 \times 10^{14}$ atoms/cm$^2$ and a beam current of 60 mA.

The deep inelastic electron yields have been calculated assuming the scaling limit and using a standard form for the structure function $F_2$ [5.1]. The charged hadron rates were based on measurements from SLAC by Boyarski et al. [5.2] and reported in the SLAC Handbook [5.3]. These measurements utilized an 18 GeV incident beam and a 0.3 radiation length Be target and determined the inclusive yields of $\pi^\pm$, $\kappa^\pm$, $p$ and $\bar{p}$. Two corrections were made to these yields for the present case. First, the effects of the thick target photoproduction were 'removed' according to the prescription of Hyde-Wright, Bertozzi and Finn [5.4].

Second, an estimate was made of the dependence of the inclusive yields on incident energy. Wiser [5.5] measured inclusive photoproduction using a bremsstrahlung beam with endpoint energies ranging from 5 to 19 GeV. An extrapolation to 30 GeV was made with these data and the yields from Boyarski corrected accordingly. The correction factor was taken to be independent of production angle and varied from 2 at a hadron momentum of 4 GeV to 7 at a hadron momentum of 16 GeV.

The results of these calculations are shown in Figure 5.1. For a given bin in scattering (production) angle the rate per unit solid angle per unit particle momentum is shown. The most important conclusion of this study is that the total rates seen by the detector are relatively low and are easily handled using standard techniques. For example, the largest rate encountered is about 13 kHz/sr/(GeV/c) at a scattering angle of $2 - 3^\circ$. The total direct rate of charged
Fig. 5.1.: Cumulative charged particle rates for a luminosity of $10^{32}cm^{-2}s^{-1}(3He)$. a) $2^\circ < \theta < 3^\circ$, b) $7^\circ < \theta < 8^\circ$, c) $14^\circ < \theta < 15^\circ$
particles with energies larger than 5 GeV in the annulus corresponding to 2 - 3° and inside the spectrometer acceptance is about 120 Hz or about 1 every 100,000 bunches. For hydrogen, these numbers are about 8 times smaller.

Second, the ratio of pions to electrons is modest - a maximum of about 250 for the 7 - 8° bin at the lowest final energy we expect to make use of (corresponding to \( y = 0.85 \)). The maximum pion to electron ratio above 8 GeV is about 10. This can easily be handled using the TRD and electromagnetic shower counters and the global charged particle contamination in the data should be below 1 - 2%.

These results have been checked by generating deep inelastic events with the Lund Monte-Carlo program [5.6].

Electrons from Møller scattering constitute the highest background rate for the experiment. For an incident energy of 35 GeV, the cross section is essentially independent of angle between 2 and 15° (Figure 5.2) and gives a rate of about 15 MHz per steradian (about 1.5 per beam crossing per steradian) in the case of the \( ^3He \) target. In the case of the hydrogen target this number will be about 5.4 times smaller and the total rate in the acceptance of the spectrometer will only be in the order of 100 kHz for each of the spectrometer halves. The energy of the scattered electrons is low, however, varying from about 500 MeV at 2° to about 15 MeV at 15° (also shown in Figure 5.2). Therefore, whereas the detectors in front of and inside the magnet must operate in the presence of these electrons, the downstream detectors will not as the electrons will be deflected into the side of the magnet.

![Graph](image)

Fig. 5.2: Expected Møller rates for a luminosity of \( 10^{32} cm^{-2}s^{-1} (^3He) \)
The beam-restgas interactions and the secondary sources of particle production like pair production, Compton scattering, Bremsstrahlung etc. were calculated using the GEANT program [5.7] in combination with the Lund-Monte-Carlo program [5.6]. It turns out that the background of beam-restgas interactions can be suppressed by a shielding of the beam-pipe upstream the target. The rate is about 1% of the rate coming from the target for a vacuum of $3 \times 10^{-9}$ torr.

Sources for secondary interactions for particles generated in the target are the beam-pipe, the air, the silicon-strip detector, the target walls, the edges of the magnet and the foils and wires of the proportional chambers. In total, the scattered electron sees about 0.06 radation length on its way to the TRD. The resulting smearing of the electron track is about $0.1 \text{ mm}$ in the chambers in front of the magnet and about $1 \text{ mm}$ in the downstream chambers. About 1.5% of the high energy photons from the target convert into electrons with energies bigger than 5 GeV. This (low) rate can easily be corrected for by detecting the positrons from $\gamma$-conversion.

[5.3] SLAC Users Handbook, Section D.
[5.6] T. Sjöstrand et al., The Lund Monte Carlo Programs, CERN program library 1987
6. Impacts on the electron ring

The only suitable straight section for this experiment is the East Hall where the first set of spin rotators will be installed and tested.

The installation of additional spin rotators in the West Hall is not possible since this would require a substantial outwards displacement of the electron ring, in conflict with the proton ring and related installations.

In the standard configuration of the intersection region East electron and proton beam could only be separated vertically by about 1 cm. This is not sufficient for a safe installation of the target cell, if one requires that the proton beam passes the target region without being disturbed. Furthermore the amount of synchrotron radiation hitting the target cell and related equipment is untolerably high.

Therefore the installation of the experiment requires a modification of the straight section East in such a way that the proton ring stays essentially untouched while the electron ring is straightened out over $\pm 135$ m (or at least 90 m), by removing some dipoles (BI 01, BH 04), adding 3.1 mrad bending power at the position of BH 05 and realigning quadrupoles and RF components over that distance. The space for the detector could be enlarged by moving back the minibeta quadrupoles to $\pm 8$ m. In this configuration the electron ring and the proton ring are vertically at the same level and horizontally separated by 88 cm.

This arrangement has also important advantages for the optimization of spin dynamics (dispersion spin matching) and facilitates high longitudinal electron polarization.

There is no principal constraint against the realignment. Relatively little additional investment is required for this change in geometry. The modification entails however a considerable amount of work.

We propose that these modifications should be undertaken as soon as possible to allow an early installation and commissioning of the detector in its final position.

Compensation elements are required to compensate locally the longitudinal magnetic field of about 0.1-0.2 Tm, which is needed to avoid target depolarization (see 8), and the vertical residual field in the beam hole of the spectrometer magnet of about 0.04 Tm (see 3). For the measurement of the asymmetry $A_2(z)$ or the structure function $g_2(z$) the target has to be polarized in the vertical direction. In this case a vertical holding field is required instead of the longitudinal one. Its direction could however be opposite to the one in the magnet beam hole and partly compensated by it. The fields are small enough
to be easily compensated and to create no problem to the performance of the machine.

Further impacts of our experiment on the machine are a possible deterioration of the vacuum by the gas target and RF coupling between beam and target cell. Our calculations show (see 7.3 and 8.1) that these effects are negligible.

We want to stress that in this configuration our experiment could run simultaneously with H1 and ZEUS and would be completely compatible with these experiments.
7. Polarized Internal Gas Target

7.1 Basic principle

We propose as target a thin-walled storage cell [7.1] with tubes of suitable cross section for the circulating electrons, fed by a high-intensity source of polarized atoms (see fig. 7.1). The gas is confined by the cell to the region close to the beam axis, resulting in an increase of the areal target density by about two orders of magnitude compared to the density of the free atomic beam.

![Diagram of atomic beam interaction with storage cell]

Fig. 7.1: Principle of a storage cell target fed by an atomic beam

If an atomic beam of current \( i (\text{atoms/s}) \) is injected into a storage cell which is connected to the vacuum chamber by tubes of total gas conductance \( C_t \), then the volume density at equilibrium is given by:

\[
\rho = \frac{i}{C_t}
\]

and the areal density is \( n = \rho \cdot l \), where \( l \) is the length of the target. For a cylindrical volume of diameter \( d \) and length \( l \) the average number of wall collisions can be written as:

\[
\bar{N} = \frac{\pi}{4} \cdot \frac{d \bar{v} l}{C_t}
\]

with \( \bar{v} = \text{mean velocity of the diffusing atoms} \). The total gas conductance of the cell is given by the conductance of the entrance tube, which is determined by the atomic beam emittance, and the geometry of the beam tubes. Its value is approximately \( C_t \approx 10 \text{ l/s} \). With \( d = 3 \text{ cm} \) and \( \bar{v} = 3 \cdot 10^3 \text{ m/s} \) we obtain \( \bar{N}/l \approx 7 \cdot 10^3 / \text{m} \) e.g. 1400 wall collisions for a cell 20 cm long.
If in turn the length $l$ of the cell has been fixed e.g. by the maximum tolerable wall depolarization or by detector requirements, then the current $i$ required to achieve a certain target density $n(\text{atoms/cm}^2)$ is given by:

$$i = \frac{n \cdot C_t}{l}.$$  

A luminosity of $3.7 \cdot 10^{31}/\text{cm}^2\cdot\text{s}$ with a 60 mA beam corresponds to a target density of $10^{14}/\text{cm}^2$. For this density and $l = 10 \text{ cm}$ a current of $10^{17}\text{atoms/s}$ is required and with $l = 20\text{ cm}$ one needs $5 \cdot 10^{16}\text{atoms/s}$.

In the following we will discuss the parameters in more detail, which determine density and polarization of the target.

### 7.2 Atomic beam source (ABS) for the hydrogen and deuterium target

The source which will be employed to feed the target cell is based on the well-known principle of Stern-Gerlach separation of an atomic hydrogen or deuterium beam [7.2]. Sources of this kind have been developed for polarized proton and deuteron sources, where an as high as possible volume density at the ionizer has to be provided. A recent review of ABS was given in ref. 7.3. Currents of up to $3 \cdot 10^{16}\text{atoms/s}$ are reported for modern ABS, which employ cooled nozzles at the dissociator in order to reduce the velocity of the beam, thus increasing the density.

However, for a storage cell target the highest possible intensity into the acceptance tube is required, which leads to different design criteria of the ABS. A source of this kind for an internal target in an antiproton ring is being developed by the FILTEX collaboration [7.2]. Its design goal is $10^{17}\text{atoms/s}$ in a single substrate of hydrogen. With such a device the orientation of the target polarization can be reversed in ms by a high frequency transition, selecting another substrate.

Design studies have concentrated on two problems:

1. A dissociator and two-stage differential pumping systems based on turbo-molecular pumps for an $H_2$ throughput of up to 5 mbar l/s.
2. A system of sextupole magnets of novel design with pole tip field of about 1.5 T which are optimised using two different codes to simulate the transport of the atomic beam.

The FILTEX ABS is shown in fig. 7.2. The vacuum system consists of four chambers 1–4. Two valves at the entrance and exits of chamber 4 serve to protect the target chamber against vacuum failures from the source.
Fig. 7.2: The polarized atomic beam source

All the vacuum system and the dissociator has been constructed. It is now set up to perform test measurements on the formation of the atomic beam. With these results the magnet system will be constructed. The complete source is expected to be working in spring 1989.

This source is designed in a manner that it can be transported easily from one place to another. During the initial phase, the source may be applied both to the FILTEX and the HERA target. At a later time a similar source could be used which is now planned for construction at the University of Wisconsin.

7.3 Conceptual design of the HERA hydrogen and deuterium target

The storage cell will be located inside a vacuum chamber of conical shape with a thin walled large area Al exit window in the forward direction. Details of the geometry have not yet been finally fixed. Further optimisations to minimize RF losses due to changes in size and shape of the vacuum chamber will be done in the near future. Cryopumps upstream and downstream of the target cell with a total pumping speed of $10^4$ l/s and good hydrogen capacity should be used. With an input of $10^{-3}$ mbar·l/s H$_2$ equivalent by the polarized atomic
beam the pressure in the target chamber will be $10^{-7}$ mbar of H$_2$. This vacuum will be further reduced to the storage ring vacuum by differential pumping.

The cross section for the beam tubes of the cell will be chosen at least to 20n which means (see appendix A.1) ±6mm in the horizontal and ±2mm in the vertical direction.

The influence of the target gas on the emittance growth rate can be estimated as follows:

The whole electron ring at a pressure (N$_2$ equivalent) of $3 \cdot 10^{-9}$ mbar corresponds to $(p \cdot L)_{\text{Ring}} = 2 \cdot 10^{-5}$ mbar·m. The target including beam tubes and pressure bump amounts to a value of $(p \cdot L) = 8 \cdot 10^{-5}$ mbar·m of H$_1$. If we correct for the $Z^2$ and $\beta$ function dependence ($\beta_{\text{IP}}/\beta_{\text{Ring}} \leq 0.04$) of the growth rate, we obtain:

$$(p \cdot L)_{\text{Target}} \simeq 3 \cdot 10^{-8} \text{mbar} \cdot \text{m} \quad (\text{N}_2 \text{ equiv.})$$

This is about 0.2% of the contribution from the whole ring and therefore negligible. The beam lifetime due to bremsstrahlung caused by this target has been calculated to be 460 hours, which is much larger than the refilling time of about 5 hours.

The polarized atomic beam is injected from the ABS under an angle perpendicular to the electron beam axis. A sample atomic beam is extracted from the target cell for the measurement of the target polarization (see 9.1) in the vertical direction. In order to maintain the target polarization, a longitudinal guide field of about 0.3 T is required (see 8.2), which is produced by the coils shown in fig. 9.1. The entrance tube for the beam injected by the ABS and the exit tube for the diagnostic beam are located in a narrow gap between two coils. Another solenoid upstream the target is used to compensate for the longitudinal B-field.

One problem which needs more study is the distribution of synchrotron radiation near the target, which might disturb its operation. To this purpose detailed simulations have been started using preliminary lattice parameters for the straight section East [7.12] and a synchrotron radiation program [7.13]. Preliminary results give about 81 kW power radiated from the nearest dipole magnets 150 m away into a cone of 30 mrad aperture, which yields roughly a power density of 19 W/mm in a band with a hight of about ±2.5 mm at the target cell. For the power radiated from the quadrupole magnets we get approximately 500 W. The intensity is concentrated at the target in a size of ~ ±4 mm horizontally and ~ ±0.8 mm vertically. The mean intensity is about 40 W/mm$^2$ in this region and rises to about 400 W/mm$^2$ in the center. To this number, the dipol radiation of about 5 W/mm$^2$ has to be added. The
central part of the radiation will pass the beam tubes of the target cell without touching them. We intend to use collimators in order to reduce the radiation level to a value tolerable for the target cell.

Other components of the target will be position monitors and manipulators, used for the adjustment and, if required, for opening up the target during injection.

7.4 Conceptual design of the HERA polarized $^3$He target

A polarized $^3$He internal target provides a unique method of determining the deep inelastic neutron asymmetry. Faddeev calculations [7.4] show that to a 90% approximation the ground state of $^3$He is in a spatially symmetric state where the two protons couple to spin zero. Thus a polarized $^3$He target is a polarized neutron target to a good approximation. In our target design the $^3$He gas is polarized by optically pumping metastable atoms [7.5] (created by maintaining a weak discharge) in a pyrex cell at 1 Torr pressure. The ground state population of atoms also becomes polarized via metastability exchange collisions. Polarizations of at least 50% are easily achieved using present laser technology [7.6]. At Caltech polarization rates of $4 \cdot 10^{17}$ atoms/sec have been obtained [7.7]. One can expect that $10^{18}$/sec is quite feasible with increased laser power and/or pumping cell size. The gas is polarized in a glass pumping cell which is connected to a differentially pumped bottle target by a capillary tube. The polarized gas diffuses to the target cell which is located in the electron beam. With the above polarization rates, feed rates into the target cell of $10^{17}$/sec will not be a problem. This feed rate will result in a target density of $2.7 \cdot 10^{13}$/cm$^3$ or $2.7 \cdot 10^{14}$/cm$^2$ for a 10 cm long bottle. The luminosity will then be $10^{32}$/cm$^2$ sec with a 60 mA beam.

The beam lifetime due to bremsstrahlung caused by this target has been calculated to be 60 hours, which is much larger than the lifetime due to other losses.

7.5 Test of storage cells

A useful storage cell for the HERA experiment requires thin walls which permit at least several hundred wall collisions without significant depolarization. These walls have to be studied in a realistic environment, that is:

i) with an ionizing beam passing the target cell;

ii) in the presence of synchrotron radiation;

iii) in a strong guiding field.

Several tests of storage cells have been carried out so far, which are relevant to some of these problems, or are in progress.
The most detailed study is being performed by the Wisconsin group at Madison in connection with the FILTEX project [7.8]. An intense deuteron beam (40 keV, 1 mA) is sent through the cell in order to probe the electron polarization of the hydrogen gas in a weak guiding field. Due to the coupling of the proton and electron spin, also the nuclear polarization is tested in this experiment.

Measurements were performed with metal cells, coated with aluminium oxide, Teflon and Viton, in a temperature range from 100 to 300 $K$.

Cells with different geometry are used, which correspond to average numbers of wall collisions $\bar{N}$ of 25, 100 and 400. The results obtained with the fluorocarbon coatings indicate that for all these cases no significant wall depolarization takes place. Comparison with the free atomic beam suggested that the target polarization was above 80%.

Related studies of wall coatings which inhibit depolarization and recombination have also been performed at ANL in the environment of a spin-exchange cell [7.9] (low field, in the presence of alkali vapor). Polarization is routinely measured by optical detection of magnetic resonance transitions in less than a minute. The measurements indicate that the hydrogen relaxation probability per wall bounce is $\sim 1/300$ for a dri-film (hydrocarbon) surface. Earlier studies [7.10] indicate that significantly better results may be achievable.

It should be noted that due to the strong guiding field and decoupling of electron and proton spin the wall depolarization in the HERA target might be considerably reduced compared to the Wisconsin experiments, which are performed at low field.

An novel method to determine the electron polarization of hydrogen gas has been developed at Heidelberg [7.2]. Thermal hydrogen is excited by slow electrons to the $n = 3$ and higher levels and the circular polarization of the Balmer photons is measured. This 'Balmer polarimeter' detects the electron polarization of an atomic beam with good precision in a few minutes. It is now employed to study the depolarization of hydrogen gas diffusing out of a test storage cell. This technique will provide an efficient tool for surface studies. It might also be employed as part of the monitor for the target polarization (see 9.1).

$^3$He atoms have been routinely held in copper cells with relaxation times of greater than 10 minutes at Caltech. Since the storage time for an atom in the bottle target for HERA is only of order 10 msec, there should be essentially no wall depolarization at all.

In a joined effort between ANL and INP at Novosibirsk, the performance of a hydrogen-coated storage cell (470 bounce, 5.5 ms dwell time) in the VEPP-3
(2.0 GeV, 200 mA) electron ring is being studied using the existing deuterium
ABS [7.11]. After exposure to the operating environment of the VEPP-3 stor-
age ring for a period of 5 month, measurements of the asymmetry in $\bar{D}(e,e'p)$
scattering in July 88 indicated no statistically significant effects from wall de-
polarization.

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8. Influence of the HERA electron beam on the target

In order to ensure that the polarized gas stored in the target cell remains polarized to a high degree, several effects caused by the HERA electron beam (for the beam properties see appendix A.1) have to be investigated. They are summarized in Tab. 8.1.

Tab. 8.1: Influence of the HERA electron beam on the target.

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<td></td>
<td>material and coating</td>
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</tbody>
</table>

*) Rates given in Appendix A2

In the following the most important effects are discussed.

8.1 RF-heating by the bunched beam

When the bunched electron beam passes through a target cell with conducting walls, many resonant cavity modes in the frequency range of several $GHz$ are excited. Calculations using the programs URMEL and TBCI show [8.1] that in the case of a metal storage cell (e.g. Al) a total power of about 500 $W$ is dissipated in the walls. Therefore thick walls are required to carry off such an amount of heat, in contrast to the need for thin walls in order to minimize the straggling of scattered electrons. In addition the strong cavity modes might induce hyperfine transitions, thus depolarizing the target.

Therefore we propose to use insulating walls as thin as possible for the target cell in order to avoid RF heating. The final choice of the material depends on the radiation level, in particular synchrotron radiation. Materials like ceramics, Kapton or Al$_2$O$_3$ will be studied.

8.2 Depolarization by the bunch field

During the passage of an electron bunch very strong magnetic fields of up to $2-3 kG$ transverse to the beam direction are produced, which cause precession of
the magnetic moments and thus depolarization of the corresponding spins [8,2]. Therefore a strong guiding field $B_0$ has to be provided in order to decouple electron and nuclear spin and to reduce nuclear depolarization.

Quantum mechanical calculations have been performed by solving the time dependent Schrödinger equation. They are described in appendix A.3.

A detailed discussion (see appendix A.3) shows, that due to the fixed time intervals between bunches depolarizing resonances occur at certain $B_0$-values. The spacing of nuclear spin flip resonances at high $B_0$ is sufficiently large to avoid them. Calculations for hydrogen show that between these resonances, e.g. at 3.3 $KG$, the depolarization is very low ($< 1.2\%$) after 100 bunches of 1 $KG$ in amplitude with the atom seeing this field always in the same direction. For deuterium, where there are no such resonances above $B_0 = 890\ G$, the calculated depolarization at 3 $KG$ is even lower. It should be noted that electron spin flip resonances cannot be avoided because of their narrow spacing. They affect only slightly the nuclear polarization.

Monte Carlo type calculations are in preparation which take into account the fact that the atom sees a variation of the bunch field amplitude, as it diffuses slowly out of the cell. It is believed that the main features of the depolarizing process are already included in the calculations. In particular the nearly periodic nature of the perturbation and the correct order of magnitude of the bunch field are taken into account. Therefore no drastic changes of the present results are expected.

Depolarization of the deuteron by the bunch field has been experimentally observed at the VEPP-3 storage ring in Novosibirsk. It has shown to be the major depolarization mechanism in the storage cell depending very much on the magnitude of the guide field and the length of the bunch. Systematic studies of the depolarization at higher guide fields taking into account the constraints given by the calculations described in A.3 will be possible in the next phase of the ANL/INP collaboration, scheduled for December 1988.

The $^3$He atoms have no electronic spin, so are much less susceptible to depolarization from the magnetic field of the beam pulses. The $^3$He spin precesses $10^{-3}\ radians$ during a beam pulse if it is near the beam (within 0.1 mm or so). Only a fraction ($\sim 3 \cdot 10^{-4}$) of the atoms are close enough to the beam at any time. Thus the spins ‘random walk’ with step size $10^{-3}\ radians$ at about 0.3 msec per step, and so the mean rotation during the 10 msec residence time is about $6 \cdot 10^{-3}\ radians$ which is absolutely negligible.

The depolarization due to ionization is also very small. With the parameters quoted above, we expect a rate of ion production of $4 \cdot 10^{13}/sec$ which is much less than than the feed rate of $10^{17}/sec$. 

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9. Polarization measurements

9.1 Measurement of target polarization

The calculations on bunch-field depolarization show that for the stored hydrogen gas the two states 1 and 4 with nuclear magnetic quantum number \( m_I = 1/2 \) and electron magnetic quantum number \( m_J = \pm 1/2 \) dominate with nearly equal population \((N_1 \simeq N_4 \simeq 1/2)\). States 2 and 3 with \( m_I = -1/2 \) and \( m_J = \pm 1/2 \) are much less populated \((N_2 \simeq N_3 \ll 1/2)\). The proton polarization in the strong guiding field limit is given by:

\[
P_{prot} = N_1 + N_4 - (N_2 + N_3).
\]

For the experiment one has to determine this quantity averaged over the fiducial volume of the target. Because of the large number of wall collisions \((\sim 10^3)\) and passages of individual atoms through the beam cross section \((\sim 10)\) we are allowed to assume that the polarization is uniformly distributed over the storage cell. Therefore it seems appropriate to determine the proton polarization for a sample which is taken from the central part of the target. We plan to extract a sample atomic beam from the target cell through a thin tube of conductance \( C_s \) less than 10% of \( C_{tot} \). This beam is then analyzed by means of RF spectroscopy, as indicated in Fig. 9.1.

The high frequency transitions (HFT) follow the adiabatic passage method. They allow for a spin flip probability close to 100%, independent of velocity. The sextupole magnet selects the electron spin state \( m_J = 1/2 \) (state 1 and 2 for hydrogen). A quadrupole mass spectrometer (QMS) is used in conjunction with a chopper to detect the atoms transmitted by the sextupole magnet with low background. Under reasonable assumptions (distance nozzle-sextupole entrance 15 cm; sextupole magnet 20 cm long; \( B_0 = 1 \, T \); \( R_0 = 0.5 \, cm \); pumping speed at QMS \( 10^3 \, l/s \)) we estimate a \( H_1 \) partial pressure at the detector of \( 10^{-9} \, mbar \), a value well above the detection limit of \( 10^{-13} \, mbar \) or lower of modern partial pressure gauges. The background \( H_2 \) pressure is about \( 10^{-10} \, mbar \) and leads to an apparent \( H_1 \) contribution of \( 5 \cdot 10^{-12} \, mbar \). By chopping the sample atomic beam, this can be suppressed almost completely. Possible transitions to analyse the substate population are:

a) Multiple transitions between neighbouring states, induced in low field, both with static field increasing and decreasing along the atomic beam direction. In the hydrogen case these transitions probe the population difference 2-3 and 1-3, respectively.

b) The two level transition 2-4, which probes the difference in population between state 2 and 4.
Fig. 9.1: Proposed target polarimeter for the hydrogen and deuterium target

From the three measured ratios of $H_1$ partial pressure the proton polarization can be calculated. For deuterium the scheme is similar and involves up to four transitions instead of three.

Due to lock-in technique the pressure ratios can be measured with a precision better than 1%. For the absolute accuracy in the determination of the proton polarization we estimate a value of 2-3%, provided that the depolarization is less than 20%, a value which is larger than the one indicated by present results of storage cells (see 7.4) and calculations on bunch-field depolarization (see 8).

In the case of an $^3$He target one can indirectly monitor the target cell polarization by measuring the pumping cell polarization optically. Since the depolarization effects in the target cell are expected to be so small, these polarizations should be equal. The optical monitoring technique [9,1] relies on an atomic line emitted at 667 nm due to the presence of the discharge in the pumping cell. This line is circularly polarized to a degree proportional to the nuclear polarization (due to the hyperfine interaction). This polarization could be monitored continuously during the experiment.

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We are considering the possibility of trying to detect the 667 nm radiation from the target cell directly. Although there is no discharge present, the beam will be creating excited states. One could also imagine inducing excited states using RF techniques. If enough light can be detected, measuring the polarization of this light would directly yield the target cell polarization. In the case that the beam provides the excitation mechanism, the polarization of atoms actually in the beam are being measured, which would of course be ideal. The feasibility of this scheme will be investigated at Caltech. Reversal of polarization is simply accomplished by reversing the laser light polarization. Although this can occur very quickly, the atoms will take several seconds to reverse their polarization. If faster reversal is necessary, one could use NMR techniques to flip the spins in a fraction of a second.

9.2 Measurement of beam polarization

For the optimisation of the beam polarization it is important to have a fast polarimeter which allows to detect small changes in the polarization while tuning machine parameters.

For our experiment it is in addition essential to know the value of the longitudinal polarization to a precision of at least 3-5%.

To have such a Compton polarimeter ready in early 1990 it is necessary to start soon with the design and development of a polarimeter or possibly even two (one for transverse and one for longitudinal polarization) and to select and buy the high power laser and the optical components.

From previous discussions we understand that this is considered as a task to be taken over by DESY and that a group will be formed this autumn to work on this project.

We express however our willingness to contribute to this project, if necessary.

10. Time Schedule — Tests

Due to the challenging physics questions addressed by our proposed experiment we are interested to carry it out as soon as possible. It is our intention to be in a position to start the measurements of the polarized structure functions soon after DESY has achieved longitudinal polarization of the electron beam. It would, however, already be earlier possible to measure the novel structure function $b_1(x)$ with an unpolarized beam and a polarized deuterium target.

Since the proposed detector is conceptual not difficult and consists (apart from the target) of rather conventional components, a total construction time of two years should be sufficient.

If the experiment would be accepted by DESY around end of this year, the installation and checkout of the detector could start early 1991 and we could be ready for data taking mid-end 1991. This implies however that polarization studies will be performed with high priority and that the straight section East has been modified until that date.

To optimize the detector design it would be extremely helpful if we could study the environment of the interaction region while the electron beam is circulating. Prototype detectors could provide us with information on the soft background due to X-rays, Møller scattering from residual gas, beam interactions with the vacuum pipe and other sources and about the optimal shielding against this background.

Thus we request permission from DESY to perform such studies in a mode consistent with all other constraints on the machine when the HERA ring becomes operational.

The work at Novosibirsk by the Argonne group at the VEPP-3 storage ring will be vital to the final design of our storage cell target. There are however specific questions like interaction between beam and target cell and optimal size and position of collimators which can only be studied at HERA itself. It would be desirable to also be able to perform such studies.
Appendix

A.1 Parameters assumed for the HERA electron beam

<table>
<thead>
<tr>
<th>Beam parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circulating current</td>
<td>58 mA</td>
</tr>
<tr>
<td>Bunch length</td>
<td>1.0 cm</td>
</tr>
<tr>
<td>Bunch period</td>
<td>96.064 ns</td>
</tr>
<tr>
<td>Horiz. emittance</td>
<td>$4 \cdot 10^{-8}$ m</td>
</tr>
<tr>
<td>Vert. emittance</td>
<td>$2 \cdot 10^{-9}$ m</td>
</tr>
<tr>
<td>Horiz. betafunction at target</td>
<td>2 m</td>
</tr>
<tr>
<td>Vert. betafunction at target</td>
<td>0.7 m</td>
</tr>
<tr>
<td>Beam size $\sigma_x$ at target</td>
<td>0.28 mm</td>
</tr>
<tr>
<td>Beam size $\sigma_z$ at target</td>
<td>0.04 mm</td>
</tr>
<tr>
<td>Aperture required for beam ($&gt; 20\sigma$):</td>
<td></td>
</tr>
<tr>
<td>Horiz:</td>
<td>$\pm 0$ mm</td>
</tr>
<tr>
<td>Vert:</td>
<td>$\pm 2$ mm</td>
</tr>
</tbody>
</table>

Preliminary values for the modified straight section East; D. Barber, priv. comm.

A.2 Estimated rates for beam target interaction

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross section* $(\text{cm}^2)$</th>
<th>Rate $(\text{s}^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic excitation</td>
<td>$5 \cdot 10^{-10}$</td>
<td>$1.7 \cdot 10^{13}$</td>
</tr>
<tr>
<td>(mostly $n=2$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ionisation</td>
<td>$2 \cdot 10^{-10}$</td>
<td>$7 \cdot 10^{12}$</td>
</tr>
<tr>
<td>Sum of excitation and ionisation</td>
<td>$7 \cdot 10^{-10}$</td>
<td>$2.4 \cdot 10^{13}$</td>
</tr>
<tr>
<td>Photoionisation by synchrotron radiation:</td>
<td>$\sigma(10KeV)$ &lt; $10^{-28}$</td>
<td>$&lt; 10^5$</td>
</tr>
</tbody>
</table>

A.3 Depolarization in the hydrogen and deuterium targets by the bunched beam

The problem discussed here is the depolarization of hydrogen and deuterium atoms subject to magnetic field pulses generated by the electron bunches of HERA. The effect of the pulses is reduced if the target is placed in a static guiding field (coaxial with electron beam) of well-chosen field strength.

Calculations are done with a program solving the time-dependent Schroedinger equation in the full (4x4 or 6x6) spin space. The total Hamiltonian is the sum of the hyperfine Hamiltonian and the Zeeman Hamiltonian. The first one is constant and has the form $I \cdot S$ (for H or D in ground-state). The second term, given by $-B(t) \cdot M$, has a time-dependence coming from the magnetic field $B(t)$. $M$ is the magnetic moment of the H (D) atom. Given the spin matrices, the problem is then to solve a set of 4 (6) coupled differential equations. It is done numerically with a Runge-Kutta routine. The initial state is always defined with respect to the field at $t=0$. It means that the state vector coefficients refer to the eigenstates of the total Hamiltonian at $t=0$. In the present case, the starting field is the static guiding field. The program is organized in such a way that the magnetic field can be chosen completely free along $x, y$ and $z$. The program has been tested extensively, giving very good results in many cases where analytical solutions exist. A few examples are spin evolution in simple precession, spin rotation in slowly rotating fields, RF transitions with sinusoidal transverse fields and weak field Abragam Winter transitions.

In the following, the static field will be taken along the 'y' axis. The bunch field, along the 'z' axis, is assumed Gaussian with a width of 30 ps. The calculations on one bunch extend over an interval of 200 ps (100 ps before bunch maximum and 100 ps after). The interval between two successive bunches is taken as 100 ns. The expression 'bunch field' will refer to the field at the bunch maximum. The atoms are assumed at rest which imply that the field of successive bunches is always the same.

Effect of one bunch:

Table A.3a shows the final coefficients of H atoms after the passage of one bunch for a 0.3 T guiding field and different bunch field intensities. The coefficients are in fact the norm of complex coefficients. Atoms are initially in state 1.

From this table we see that the dominant transition is between states 1 and 4. This is the effect of the high guiding field that decouples the proton and electron spins. The relative strengths of the various transitions can be understood with the help of a few selection rules applying to the case considered here.
Table A.3a: Norm of the state vector coefficients after 1 bunch of various intensities. Atoms are initially in state 1.

| Bunch field | \(|1\rangle\) | \(|2\rangle\) | \(|3\rangle\) | \(|4\rangle\) |
|-------------|-------------|-------------|-------------|-------------|
| 100 G       | 0.99974     | 0.00276     | 0.00003     | 0.02268     |
| 500 G       | 0.90351     | 0.01373     | 0.00079     | 0.11287     |
| 1000 G      | 0.97487     | 0.02702     | 0.00313     | 0.22241     |
| 3000 G      | 0.82116     | 0.06765     | 0.02649     | 0.56610     |

First of all, for transitions induced by fields perpendicular to the quantization axis, the following rule always applies.

$$\Delta m_F = \pm 1.$$  

In a strong guiding field, the transition strength is related to the change in the nuclear magnetic quantum number. The results are summarized in table A.3b.

Table A.3b: Relevant transitions for hydrogen and deuterium.

<table>
<thead>
<tr>
<th>(\Delta m_F)</th>
<th>Transitions Hydrogen</th>
<th>Transitions Deuterium</th>
<th>Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1-4 2-3</td>
<td>1-6 2-5 3-4</td>
<td>Dominant</td>
</tr>
<tr>
<td>±1</td>
<td>1-2 3-4</td>
<td>1-2 2-3 4-5 5-6</td>
<td>Secondary</td>
</tr>
<tr>
<td>±2</td>
<td>-</td>
<td>3-6</td>
<td>Ternary</td>
</tr>
</tbody>
</table>

The dominant transitions (like the transition between states 1 and 4 in H seen in the above calculation) have opposite electron spins but identical nuclear spins (in the high field limit) so these transitions have almost no effect on the nuclear polarization.

Effect of many bunches

The important feature to consider in the calculation of many bunches is the relative phase of two successive bunches with respect to the natural oscillation of the complex coefficients of the various possible transitions. If two successive bunches are in phase for a given transition, their effect adds up and this transition is enhanced. Since the time between two electron bunches is a constant
fixed by the HERA machine, the relative phase can only be adjusted by varying the guiding field.

The resonance condition for a set of regularly spaced pulses can be expressed by

\[ \frac{\omega_{i\ell}}{\omega_b} = N, \]

where \( \omega_{i\ell} = (E_i - E_{f})/\hbar \) is the frequency for the considered transition and \( \omega_b \) is the repetition frequency of the electron bunches. \( N \) should be an integer to get a resonance (an anti-resonance is obtained if \( N \) is half-integer).

For the HERA target, the relevant transitions to consider are those involving nuclear spin-flip. Since \( \omega_{i\ell} \) depends on the guiding field, one gets for each transition a set of field values at which the resonance condition is fulfilled. These values are given in the table A.3c for the most important nuclear spin flip transitions.

Table A.3c: A few field values at which nuclear spin flip resonances occur. The field is given in gauss for the corresponding value of \( N \) in parentheses.

<table>
<thead>
<tr>
<th>Hydrogen</th>
<th>Deuterium</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>3-4</td>
</tr>
<tr>
<td>2218 (63)</td>
<td>2330 (70)</td>
</tr>
<tr>
<td>2542 (64)</td>
<td>2557 (78)</td>
</tr>
<tr>
<td>2972 (66)</td>
<td>2992 (77)</td>
</tr>
<tr>
<td>3572 (66)</td>
<td>3601 (76)</td>
</tr>
<tr>
<td>4468 (67)</td>
<td>4513 (75)</td>
</tr>
</tbody>
</table>

The effect of the resonance on the transition 1-2 in hydrogen is shown in the figure A.3a for a guiding field of 0.2972 T as function of the number of bunches. Because the transition 1-2 is weaker, it takes a larger number of bunches to perform the complete transition in comparison to the 1-4 transition shown before. Nevertheless, after some 60 bunches, the proton spin is almost completely reversed. The same picture also illustrates the results for a guiding field around 0.3250 T where the two proton spin flip resonances of hydrogen (transition 1-2 and 4-3) are well off-resonance. The resonant and nonresonant case for the 1-4 transition, which differ by 0.18 T, are shown in fig. A.3b and A.3c. We can see that the proportion of states 2 and 3, with reversed proton spin, remains always very low and that the nuclear polarization stays very close to 1. When the 1-4 transition is off-resonance (fig. A.3b), the nuclear
Fig. A.3: Evolution of the state vector coefficients and nuclear polarization (full curve) of hydrogen atoms initially in state 1. a) transition 1-2 (proton spin-flip) on-resonance; b) and c) transition 1-2 and 3-4 (proton spin-flip) off-resonance, b) 1-4 on-resonance, c) 1-4 off-resonance.
depolarization follows the variation on state 3 and the depolarization oscillates between 0 and 1%. When the transition 1-4 is on-resonance (fig. A.3c), the states 2 and 3 are less populated and the depolarization comes mainly from the fact that the state 4 is not pure. We can see that the polarization follows the population of this state. In this case, the depolarization varies between 0 and 1.2 %. In the HERA target cell, we cannot expect to achieve a field accuracy better than 0.1 T. Such an accuracy would be necessary to distinguish between on and off resonance for the 1-4 transition. As a result, the real case will be a mixing of these two. By averaging over the 2 cases and over time, we get an average depolarization of roughly 0.5%.

For deuterium, calculations have been performed for a guiding field around 0.3 T where the most important deuteron spin-flip transition (transition 1-2 and 5-6) are off-resonance. We have considered here also the two cases where the electron spin-flip is on and off resonance. Because the hyperfine splitting is smaller, the transitions to the states 2-3-4-5, with different nuclear spin projection, are reduced by roughly one order of magnitude. The depolarization should also be about 10 times smaller.