POLARIZATION AS A TOOL AT HERA*

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The HERA ring has been upgraded to fivefold its luminosity and will provide longitudinal lepton beam polarization to the HERA experiments. The accurate polarization measurement and high luminosity opens a completely new field for HERA physics.

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1. Introduction

The HERA ring has been upgraded, during the 2000–2001 shutdown, to increase its luminosity by a factor of five (1fb^{-1} by end of 2006) and to provide longitudinal lepton beam polarization to the HERA experiments; the HERA II phase has begun. For this purpose major changes have been made to the HERA ring near the H1 and ZEUS interaction points. Superconducting magnets have been installed inside the H1 and ZEUS detectors to achieve strong focusing, and spin rotators have been installed near H1/ZEUS to flip the natural transverse polarization of the lepton beam in the HERA ring to longitudinal polarization. The maximum degree of lepton polarization is foreseen to be between 50% and 60%. Two polarimeters, the TPOL which measures the transverse polarization, and the LPOL which measures the longitudinal polarization, have been upgraded to improve their polarization measurement accuracy from about 4% to better than 1% (the LPOL upgrade is nearing completion). The accurate polarization measurement and high luminosity opens a new field for HERA physics at high Q^2.

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2. Polarization at HERA

At HERA leptons become naturally transversely polarized through the emission of synchrotron radiation (lepton spin flips), the so called Sokolov–Ternov effect. The lepton beam transverse polarization is converted into longitudinal polarization near the interaction points by spin rotators (at HERA I only for HERMES, at HERA II also for H1 and ZEUS). The HERA ring polarization is measured by two polarimeters independently: TPOL which measures transverse polarization, located in the HERA-West area nearby HERA-B; and the LPOL which measures longitudinal polarization, located in the HERA-East area nearby HERMES. Both polarimeters have been operating since several years.

Polarization should be known at the same level of precision as total luminosity because it enters linearly in the cross section of many processes *e.g.*: $\sigma^{\pm}_{\rm NC} = \sigma^{\pm}_{\rm NC,unpol} + P\sigma^{\pm}_{\rm NC,pol}$ and $\sigma^{\pm}_{\rm CC} = (1 \pm P)\sigma^{\pm}_{\rm NC,unpol}$ for neutral and charged current processes, with the sign indicating the lepton charge. For this purpose a polarimetry upgrade project has been setup in 1999 called POL2000 to improve the polarization measurement precision from about 4% to better then 1%, and so upgrade the HERA I polarimetry for the HERA II phase. The absolute value of the degree of lepton polarization is the same along the whole ring, so that the actual location of the polarization measurement does not need to be confined to the experiment interaction points. Precise measurement from the TPOL/LPOL polarimeters together with HERA machine lattice simulations, will provide confidence of having an accurate polarization measurement at the interaction points. Polarization builds up and settles asymptotically to an equilibrium value, see Fig. 1 (upper figure). The theoretical maximum achievable polarization is $\sim 92\%$, but this is reduced by counteracting depolarizing effects, which depend on the HERA ring characteristics and lattice structure (*e.g.* each set of spin rotators reduces the polarization by $\sim 3\%$). For the HERA I phase the degree of lepton beam polarization was typically between 55%–60%; while for HERA II it is expected to have as a startup value between 40%–50%. The aim is to increase the degree of polarization as much as technically possible, to a value probably between 50%–60%.

The polarimeters make use of the spin-dependent cross section for Compton scattering of polarized photons on polarized leptons ($e^{\pm}$). The degree of polarization is measured by scattering alternatively right and left circularly polarized laser light off the polarized lepton beam, producing back-scattered Compton photons, which are then detected in a calorimeter. The polarization is determined by measuring asymmetries. The two polarimeters operate differently. Transverse polarization is determined by measuring the spatial vertical up-down asymmetry of the back-scattered photons on the TPOL calorimeter face, while longitudinal polarization is determined by measuring the energy asymmetry in the LPOL calorimeter of the back-scattered photons. The polarization of lepton colliding and non-colliding bunches differs. This depends on the machine polarization tuning and varies over time (beam–beam effects). For HERA II operation an accurate per bunch per minute polarization measurement is therefore needed, which implies that the polarimeters have to be upgraded. The LPOL will be upgraded most probably during the next shutdown (probably in January 2003), with the installation of a Fabry–Perot cavity in the lepton ring to greatly amplify (by a factor 10k) the laser intensity; making it equivalent to a 10kW laser, and so operate in the "few photon mode", which allows direct calibration with the Compton edge. The TPOL upgrade is now completed. The TPOL upgrade consists of a fast DAQ to provide a precise per bunch per minute polarization measurement, and a radiation hard position sensitive silicon detector for in-situ $\eta - y$ (see below) calibration which is related to the vertical up-down asymmetry of the backscattered Compton photons. The TPOL calorimeter measures the total energy of the Compton photon and $\eta = E_{\rm up} - E_{\rm down}/E_{\rm up} + E_{\rm down}$ which is directly related to the vertical coordinate y of the photon impact point on the calorimeter face (measured by the silicon detector), see Fig. 1 (lower figure); the TPOL calorimeter consists of two separate half modules, an up and a down module that measure separately the deposited energy $E_{\rm up}$ and $E_{\rm down}$.

3. Physics with polarized lepton beams at HERA

The study of polarized lepton–proton deep inelastic scattering at high Q^2, which has never been carried out before, is now possible at HERA II: electroweak interactions, structure functions (G_2), and physics beyond the SM. **Electroweak interactions** [1] can be probed by using the four possible lepton charge/polarization combinations: $e^+, e^-, P > 0,\ P < 0$. The cross section measurement of charged current (CC) and neutral current (NC) deep inelastic scattering at high Q^2 using polarized lepton beams is one of the primary physics objectives of the HERA II collider experiments. The chiral structure of the Standard Model can be tested through a variety of measurements.

Measurement of the neutral current light quark (u,d) couplings: The polarization effect is large on the Neutral Current cross sections for $Q^2 \sim 10^4$ GeV^2; this different behavior is due to the Z^0 exchange, which gives a split, up to factor 2. The light quark(u,d) couplings to the Z^0 boson can be extracted by exploiting this difference, and by measurement and comparison of neutral current and charged current cross sections with all four charge/polarization combinations. With a total integrated luminosity of about $\sim 1000\,{\rm pb}^{-1}$ di-

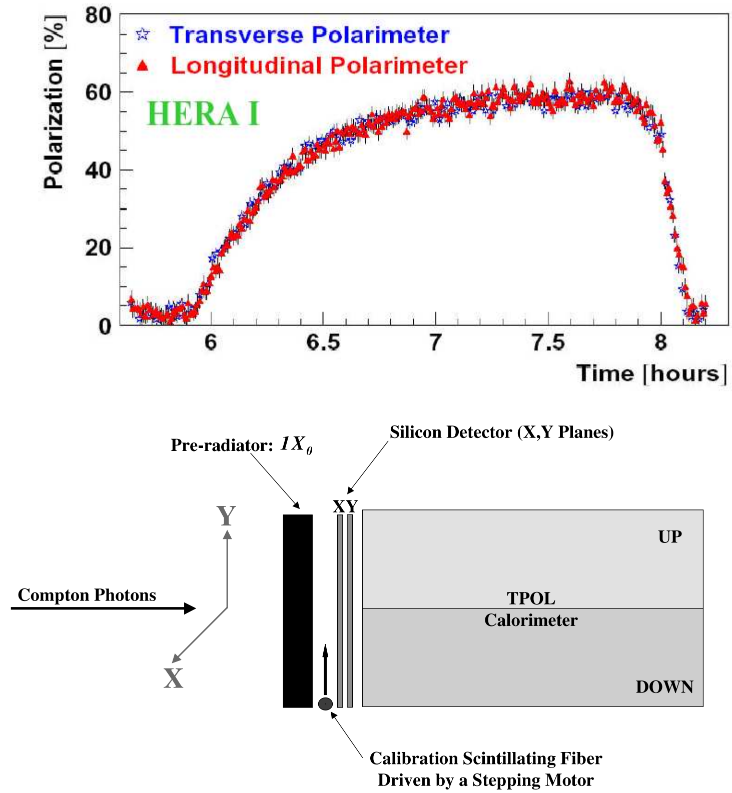

Fig. 1. Upper: schematic for the TPOL setup in the HERA tunnel. The TPOL consists of three sub-detectors: calorimeter, silicon and fiber detectors. The pre-radiator is needed to convert the Compton photons. The calorimeter is divided into two independent halves. There are two silicon planes to measure the X, Y position of the Compton photons. The scintillating fiber detector is used for calibration and monitoring the silicon detector planes; the fiber is moved vertically by a stepping motor. Lower: polarization buildup versus time measured by the LPOL and TPOL polarimeters at HERA I.

vided between the four charge/polarization combinations $e^+, e^-, P \sim \pm 70\%$, all four u and d type vector and axial-vector couplings can be measured with fractional errors on a_u, v_u, a_d, v_d of 6%, 13%, 17% and 17%, respectively, which is comparable to the accuracy obtained at LEP for the heavy quark (b, c) couplings.

Measurement of EW parameters (M_W): This measurement is a test of EW universality. In the SM there are 5 free parameters (α, M_Z, M_W, M_H, M_t). The values for α and M_Z can be fixed by taking the precise measurements from other experiments; the M_H mass can be fixed at 100 GeV (log dependence on M_H) and then study separately the effect of its variation. Therefore, by measuring the polarized neutral and charged current cross sections one can constrain the M_W and M_t masses on the (M_W, M_t) plane. The SM is consistent if the values obtained for M_W, M_t are in agreement with other experiments. With 1fb^{-1} of data from NC/CC cross sections with electron beam polarization $P = -70\%$ and constraining the M_t to ± 5 GeV (from TEVATRON), the M_W mass can be measured to a precision of $\sim \pm$ 55GeV. For this test left handed electrons give the highest precision because the cross section is largest.

***G_2* structure function** [2]: The G_2 structure function, arising from the γZ interference term, is defined as $G_2 = F_2^{\gamma Z} = 2x \sum e_q \nu_q (q + \bar{q})$; where x is Bjorken x, e_q is the quark electric charge, ν_q is the vector quark coupling, and q, $\bar{q}$ the quark/antiquark densities. G_2 can be measured from the neutral current parity violating asymmetry $A^\pm$

$$A^\pm = \frac{\sigma^\pm_{\rm NC}(P) - \sigma^\pm_{\rm NC}(-P)}{\sigma^\pm_{\rm NC}(P) + \sigma^\pm_{\rm NC}(-P)} \simeq \mp P K_Z a_e \frac{G_2}{F_2} \underset{\text{for } x \to 1}{\sim} \pm P K_Z \left(\frac{1 + d_v/u_v}{4 + d_v/u_v} \right) ,$$

where $\sigma^\pm_{\rm NC}(P)$ is the NC cross section for a given degree of polarization P and lepton charge, a_e is the electron axial charge, $K_Z \sim 10^{-4}/Q^2[\text{GeV}^2]$. Precise data for the valance quark density ratio d_v/u_v can thus be obtained by measuring $A^\pm$. Simulations show that G_2 can be well measured at high Bjorken x, *i.e.* for same lepton charge but opposite polarizations with $P = \pm 50\%$ and $200\,\text{pb}^{-1}$ for each polarization setting (see Fig. 2).

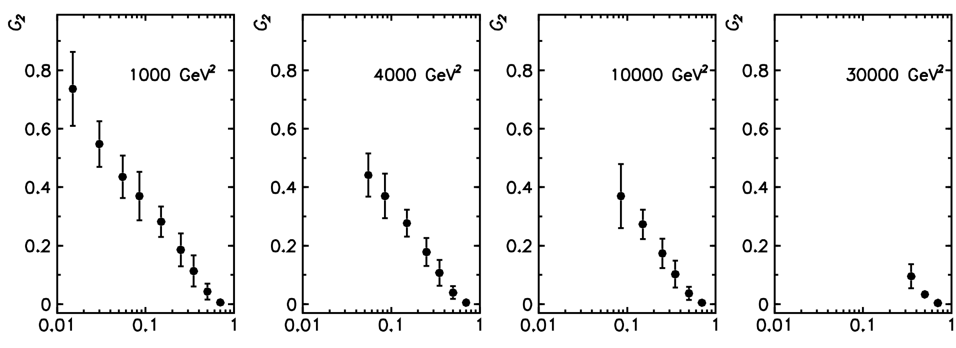

Fig. 2. Simulated statistical precision for the G_2 structure function: for same lepton charge but with both sets of opposite polarization settings, $P = \pm 50\%$ and $200\,\text{pb}^{-1}$ for each polarization setting.

Physics beyond the SM: Lepton polarization is a useful tool for searching new physics signals or for studying the chirality of new particles. SM backgrounds can be reduced by changing the degree of polarization. If new physics have different couplings, the signal/background ratio will increase. For example the chiral structure of newly discovered leptoquarks at HERA could be determined [3] with polarization.

Limits for right-handed charged currents [4]: can be obtained by measuring the polarization dependence of the cross section for the Charged Current (CC) process $\sigma^{\rm CC}(e^- p \rightarrow \nu X)$. The charged current process $\sigma^{\rm CC}(e^- p \rightarrow \nu X)$ occurs through the exchange of W bosons. According to the Standard Model only pure left-handed charged currents exist, *i.e.* the cross section vanishes for purely right-handed electrons. The total electron charged current cross section $\sigma^{\rm CC}(e^- p \rightarrow \nu X)$ is: $\sigma^{\rm CC}(e^- p \rightarrow \nu X) = (1-P)\sigma_{\rm L}^{\rm CC} + (1+P)\sigma_{\rm R}^{\rm CC}$ where P is the degree electron longitudinal polarization, with $P = -1$ corresponding to negative helicity *i.e.* a fully left-handed electron beam, and $\sigma_{\rm L}^{\rm CC}, \sigma_{\rm R}^{\rm CC}$, are the left and right handed electron charged current cross sections. With about one year of polarized data a lower limit on the mass of the hypothetical boson $M_{W^{\rm R}}$ can be set at the level of $W^{\rm R} > 400\,{\rm GeV}$. This is a direct search and is comparable to existing TEVATRON results.

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