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Polarisation measurements on $e^{\pm}$ beams ⋆

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Abstract

The current status of $e^{\pm}$-beam polarimetry at the HERA *ep* collider is reviewed, giving the performance achieved to date and the status of the various upgrade projects together with a summary of the expected performance. In addition, the polarimeter that has been proposed for the TESLA e^+e^- collider is described.

Key words: Polarisation, polarimetry, HERA, TESLA

1 Introduction

Precise measurements made using polarised lepton beams have been crucial in the development of the Standard Model (SM) [1,2] and in elucidating the structure of the nucleon [3–5]. Achievement of high $e^{\pm}$ beam polarisation and, equally important, precise beam polarimetry are also essential elements in the current physics program of the HERA ep collider [6,7] and will be of utmost importance for future e^+e^- linear colliders.

In the SM, the couplings of left- and right-handed particles to the W and Z bosons are different, while extensions of the SM involve particles with non-zero spin and with couplings that depend upon the particle helicity. Hence, the sensitivity and physics reach of an e^+e^- linear collider such as TESLA

⋆ Talk presented at the 8$^{\rm th}$ International Conference on Instrumentation for Colliding Beam Physics, Budker Institute for Nuclear Physics, Novosibirsk, Russia, 28$^{\rm th}$ February to 6$^{\rm th}$ March 2002 operating at centre-of-mass energies in the range 500-800 GeV will be greatly enhanced if the electron and positron beams are polarised [8].

The HERA accelerator and the three experiments HERMES, H1 and ZEUS which use its polarised $e^{\pm}$ beam have recently undergone major upgrades. This includes a five fold increase in luminosity and the installation of additional spin rotators to provide longitudinal beam polarisation at the collider experiments H1 and ZEUS. It will enable these two experiments to carry out electroweak precision tests by measuring the spin dependence for neutral and charged current processes [6]. The fixed target experiment HERMES, which had already employed spin rotators and longitudinal $e^{\pm}$ beam polarisation since 1995, will continue its physics program to unravel the spin composition of protons and neutrons with a variety of polarised and unpolarised gas targets [5,9]. The spin physics of the three experiments will also benefit greatly from recent and ongoing upgrades of the two Compton beam polarimeters, which will be described in this paper. Furthermore, with an eye on the next generation of instrumentation for colliding beam physics, we will describe a Compton beam polarimeter study for the TESLA linear collider.

2 Polarisation at HERA

2.1 *Polarising the $e^{\pm}$ beam at HERA*

An unpolarised electron or positron beam is injected into the HERA lepton ring and accelerated to 27.5 GeV. Transverse polarisation evolves naturally for a carefully optimised machine through the Sokolov-Ternov effect [10], $P(t) = P_{\infty}(1 - \exp(t/\tau))$. HERA has achieved asymptotic polarisation values $P_{\infty} \sim 55 - 60\%$ with associated rise times of $\tau \sim 25$ minutes. The relationship between asymptotic polarisation and rise-time can be used to calibrate the HERA polarimeters [14]. The transverse polarisation built up in the storage ring must, however, be transformed locally into longitudinal polarisation in order to obtain useful spin physics effects at the experiments. This is done with suitable 'spin rotators' placed immediately upstream and downstream of the interaction points [11] which cause the spin to precess relative to the momentum vector. Note that the magnitude of the beam polarisation vector is invariant around the ring. The $e^{\pm}$ beam polarisation in HERA is measured with two different Compton polarimeters (TPOL and LPOL) in opposite straight sections of the 6.3 km circumference of the storage ring. The transverse polarimeter (TPOL) measures the polarisation along the vertical guide field direction of the ring. This is the natural polarisation direction everywhere around the ring, except between the spin rotators. The longitudinal polarimeter (LPOL) is located between the spin rotators at the HERMES experiment. It measures the longitudinal polarisation component along the beam direction at that location.

2.2 The HERA transverse polarimeter

The transverse polarisation of an electron or positron beam may be measured by bringing it into collision with a beam of circularly polarised light and detecting the associated angular anisotropy of the back-scattered high-energy Compton photons [12,13]. The transverse polarimeter (TPOL) at HERA is based on this principle. The original configuration and performance of this instrument has been described in considerable detail [14]. The TPOL has since evolved further in many technical aspects and in particular in the precision of the polarisation measurement. The following paragraphs summarise the experimental set-up used prior to the HERA luminosity upgrade and outline the upgrade to the TPOL carried out during the long shutdown in 2000-01.

An Ar-ion laser is used to give a 10 W continuous-wave beam of green light with a linear polarisation in excess of 99% at a wavelength of 514.5 nm (2.41 eV). A shutter is used to interupt the laser beam for background measurements. A Pockels cell is used to convert to right-handed or left-handed circular polarisation with a modulation frequency of $\sim$ 90 Hz. The laser beam is transported in vacuum with a system of computer-controlled mirrors into the HERA tunnel, where it is focused to intercept the electron or positron beam with a small crossing angle of 3.1 mrad. The degree of polarisation of the laser beam is monitored after it has passed through the Compton interaction point (IP) by means of a rotating Glan-Thompson prism.

Backscattered Compton photons are detected some 60 m downstream from the Compton IP in a tungsten-scintillator sampling calorimeter (CAL) composed of 12 layers of 6.2 mm thick (1.6 X_0) tungsten plates interleaved with 2.6 mm thick scintillator plates. The top and bottom halves of each scintillator plate are optically isolated, essentially splitting the calorimeter vertically in two. The scintillator light is collected using four wavelength shifters, one on each of the four sides of the calorimeter. Photomultiplier tubes (PMs) are used to turn the light from the wave-length shifters into electrical signals which are subsequently digitised. The signals from the top and bottom halves of the CAL give E_u and E_d respectively, while the sum of the left and right PM signals yields an estimate of the total energy deposited in the CAL which is used for triggering. The up-down energy asymmetry, $\eta = (E_\mathrm{u} - E_\mathrm{d})/(E_\mathrm{u} + E_\mathrm{d})$, is evaluated event-by-event and the mean of the η distribution calculated for left- and right-circularly polarised laser light ($<\eta>_\mathrm{L}$ and $<\eta>_\mathrm{R}$ respectively). The $e^\pm$ polarisation, P, is then determined by evaluating $P = (<\eta>_\mathrm{L} - <\eta>_\mathrm{R})/\Pi$, where Π is the analysing power which is obtained either experimentally through rise-time calibrations (see Table 1) or from Monte Carlo simulations.

Table 1
TPOL Analysing Power from Rise-Time Calibrations

Machine Status	Rotators Off	Rotators On
Year	1994	1996/97
Analysing Power	0.0961	0.0961
$\Delta P/P$ Syst. Error	$\pm 3.4\%$	$\pm 1.8\%$

The next stages of the physics programmes of the ZEUS and H1 collaborations require a precision of $\Delta P/P \leq 1\%$ in the polarisation measurement. Furthermore, a differentiation between colliding and non-colliding bunches is necessary. To meet these requirements a completely new data acquisition system has been implemented which allows a bunch-by-bunch measurement of the polarisation [15]. The analog signals are preamplified behind the PMs and shaped at the end of the cables, before they are digitised. The ADCs are mounted on custom designed VME cards. They have a resolution of 12 bits and are running at 40 MHz (4 times the HERA clock frequency). The digitised information is stored in a pipeline on the board. The pipeline is 4x220 samples deep, thus allowing the storage of one full bunch train from HERA. The readout of the TPOL upgrade system is configured around a VME based PowerPC computer which is equipped with a MFCC (Multi-Function Computer Core) card developed by the CES company. The MFCC card communicates with the ADC card through a dedicated high speed Altera bus (48 bits, 20 MHz). It can be programmed to perform simple logical operations and control functions. The new DAQ system is operational and has been tested, but so far only under unpolarised HERA beam conditions.

In order to calibrate the position response function, $\eta(y)$, of the calorimeter in situ during data-taking, a silicon-microstrip detector system has been implemented. This system is composed of two 60×60 mm^2 microstrip planes placed in front of the CAL and behind a 1 X_0 thick lead pre-radiator. The strip pitch of the detector measuring the vertical coordinate is 80 μm. A detector with a strip pitch of 120 μm and for which every second strip is read out is used to measure the horizontal coordinate. A high flux of photons enters the TPOL detector. The energy deposited by these photons gives a dose of ~ 5 MRad per year over an area of only a few mm^2. In order to identify and correct for the effects of differential radiation damage in the silicon-microstrip detector, a scintillating fibre will be used. The fibre which is mounted on a precision stage behind the pre-radiator will be scanned periodically across the face of the silicon detector in vertical steps of 2.5 μm. The new TPOL detector components have been evaluated using test beams at DESY and at CERN. The system has been installed and commissioned with beam in the HERA tunnel.

Improvements in the analysis procedure are being developed which, combined with the performance of the upgraded detector, should yield a measurement of the polarisation with a precision $\Delta P/P$ of 1% or better.

2.3 The HERA longitudinal polarimeter

The Compton process is particularly well suited for the measurement of longitudinal beam polarisation at high beam energy where it exhibits large spin-dependent asymmetries in the energy specta. The LPOL polarimeter [16] employs a green (532 nm) frequency-doubled pulsed YAG laser which crosses the $e^{\pm}$ beam under 8.7 mrad about 50 m downstream from the HERMES detector. The laser has a pulse length of 3 ns and is operated at a pulse energy of 100 mJ and a pulse repetition rate of 100 Hz. The circular polarisation of the laser beam is controlled by a Pockels cell and is modulated on a pulse-by-pulse basis. The energy of the backscattered Compton photons is measured with a radiation hard $NaBi(WO_4)_2$ Cerenkov crystal calorimeter at a distance of 54 m from the Compton IP. Alternatively, a tungsten-scintillator sampling calorimeter may also be used. A single laser pulse generates many Compton photons and produces a large analog signal (multi-photon method). One can form a multi-photon asymmetry $A_m = (I_{1/2} - I_{3/2})/(I_{1/2} + I_{3/2})$ from the energy-weighted spectrum integrals for the two different helicity configurations from which the beam polarisation is then determined. The multi-photon method has the advantage of large signals and negligible background, but requires considerable diligence in quantifying non-linearities in the energy response which distorts the analysing power and which contributes the dominant systematic error (see Table 2). When the LPOL was brought into operation in 1996, it was discovered that the colliding (175) and non-colliding (15) $e^{\pm}$ bunches in HERA may polarise to very different levels. For the collider experiments it is therefore essential that the polarimeters can measure individual bunches.

Table 2
LPOL Systematic Uncertainties

	Analysing Power	Total Syst. Error
$\Delta P/P$	$\pm 1.2\%$	$\pm 1.6\%$

In order to overcome the drawbacks of the multi-photon method, an ambitious new laser system is being developed in Paris as an upgrade for the LPOL [17]. The aim is to install a high-gain Fabry-Perot laser cavity in the $e^{\pm}$ beam line which is coupled to a small infrared feed laser that is precisely tuned for resonance with the external cavity. It is then possible to achieve very high cw laser power of several kW in the cavity. The associated Compton event rate could be as high as 1 MHz or even higher, where 10% or more of the HERA bunch crossings would contribute. A prototype cavity has already been tested successfully for several months in Paris. It is anticipated to install such a powerful facility in the HERA tunnel at the end of this year. It should reduce the error in the polarisation measurement $\Delta P/P$ to 1% or better and furthermore speed up and improve the polarisation tune-up of HERA to reach the highest possible beam polarisation.

3 Polarisation at TESLA

Beam polarisation and its precise measurement will be extremely important at future e^+e^- linear colliders. A detailed Compton polarimeter study has been carried out for TESLA [8,18] from which we extract here only the essential conclusions. The much lower average beam current (45 μA) and bunch repetition rate (14100 Hz) of TESLA in comparison with HERA (30 mA, 10 MHz) appears to be a challenge, but can be compensated by employing a special laser that can operate at the peculiar pulse and bunch pattern of the accelerator and that delivers short pulses in the 10 ps and 10-100 μJ regime. Such a laser is not commercially available but has been developed at Max-Born-Institut for the TTF photoinjector gun at DESY, where it has been in operation for some time [19,20]. This multi-stage solid-state laser system employs Nd:YLF and operates at a fundamental wavelength of 1047 nm in the infrared, which is converted in two steps to 2nd and 4th harmonic, for a final wavelength of 262 nm in the UV. The laser has delivered up to 250 μJ (IR) and 50 μJ (UV) per bunch, with associated pulse widths σ_t of $\sim$ 10 ps. The mean IR power is $\leq$ 2W. A variant of this TTF laser system would also be well suited for the Compton polarimeter. The luminosity that can be achieved with such a laser is typically six orders of magnitude higher than with a continuous laser of similar average power and emittance. The table gives some of the kinematic parameters for a beam energy of E_0 = 250 GeV and a green laser with an energy $\omega_0 = 2.3$ eV. The spectra of the scattered photon and electron are continuous with a maximum photon energy ω_{max} and a corresponding minimum electron energy E_{min}.

Table 3
Kinematic parameters for TESLA-500

E_0 (GeV	λ (nm)	ω_0 (eV)	ω_{max} (GeV)	E_{min} (GeV)
250	532	2.33	225	25

It will be advantageous to choose a Compton IP location upstream of a bend in the beamline. The scattered electrons are then dispersed and can be momentum analysed and detected with a gas Cerenkov hodoscope (14 channels) behind the bending magnet. A suitable location in the TESLA beamline has been identified which fulfills all necessary and desirable requirements for a high-quality beam polarisation measurement. The polarimeter will operate in the multi-event regime with $\sim 10^3$ Compton events per bunch or $\sim 10^7$ events per second which will not be counted but recorded as integrated flux signals for every bunch. Statistical errors will be negligible. We expect an overall precision of $\Delta P/P \leq 0.5\%$ for the measurement of the beam polarization. The table gives typical polarimeter parameters for TESLA-500. The performance is similar for other energy regimes of TESLA.

Table 4
TESLA Compton Polarimeter Parameters at 250 GeV

	e^+/e^- *beam*	laser beam
energy	250 GeV	2.3 eV
charge or energy/bunch	$2 \cdot 10^{10}$	35 μJ
bunches/sec	14100	14100
bunch length σ_t	1.3 ps	10 ps
average current(power)	45 μA	0.5 W
$\sigma_x \cdot \sigma_y$ (μm)	$10 \cdot 1$	$50 \cdot 50$
beam crossing angle	10 mrad	
luminosity	$1.7 \cdot 10^{32} cm^{-2} s^{-1}$	
cross section	$0.136 \cdot 10^{-24} cm^2$	
detected events/sec	$1.0 \cdot 10^7$	
detected events/bunch	$0.7 \cdot 10^3$	
$\Delta P/P$ stat. error/sec	negligible	
$\Delta P/P$ syst. error	$\leq 0.5\%$	

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