The first electron beam polarization measurement with a diamond micro-strip detector

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A diamond multi-strip detector was used for the first time, to track Compton scattered electrons in a new electron beam polarimeter in the experimental Hall C at Jefferson Lab. We report the first high precision beam polarization measurement with electrons detected in diamond multi-strip detectors. The analysis technique leveraged the high resolution of the detectors and their proximity to the electron beam ($\gtrsim$ 0.5 cm). The polarization was measured with a statistical precision of $<$ 1%/hr, and a systematic uncertainty of 0.59%, for a 1.16 GeV electron beam with currents up to 180 μA. This constitutes the highest precision achieved for polarization measurement of few-GeV electron beams.

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INTRODUCTION

High precision nuclear physics experiments using polarized electron beams rely on accurate knowledge of beam polarization to achieve their ever improving precision. A parity violating electron scattering (PVES) experiment in the experimental Hall C at Jefferson Lab (JLab), known as the $Q_{\rm weak}$ experiment, is the most recent example [1, 2]. The goal of the $Q_{\rm weak}$ experiment is to measure the Standard Model parameter known as the weak mixing angle, at a low energy (relative to the Z^0 mass) with unprecedented precision. With a goal of $<$ 1% uncertainty, determination of electron beam polarization is one of the largest experimental uncertainties of the $Q_{\rm weak}$ experiment. The experiment utilized an existing Møller polarimeter [2, 3] and a new Compton polarimeter to monitor the electron beam polarization. The Compton polarimeter is the only polarimeter at JLab Hall C that can non-destructively monitor the beam polarization at the exact running conditions of the $Q_{\rm weak}$ experiment.

The use of Compton scattered electrons and/or back–scattered photons to measure the Compton asymmetry and thereby the electron beam polarization, is a well established polarimetry technique [4–9]. Most previous Compton polarimeters, other than the one used in the SLD experiment [6], relied primarily on detection of the scattered photons to measure the beam polarization. The SLD Compton polarimeter, which detected scattered electrons (and used detection of photons as a cross-check), was operated at a beam energy of 50 GeV and reported a precision of 0.5%. The relatively low energy of the electron beam at JLab leads to a smaller Compton analyzing power, and makes it significantly more challenging to achieve the same level of precision. Nonetheless, the Compton polarimeter in Hall A at Jefferson Lab has reported a relative precision of $\sim$ 1% by detecting the Compton scattered electrons at a beam energy of 3 GeV [10].

The JLab Hall C Compton polarimeter detects the scattered electrons in a set of tracking detectors. The low energy of the electron beam (1.16 GeV) and other operating parameters of the $Q_{\rm weak}$ experiment, presented the most challenging set of conditions to achieve the goal of $<$ 1% uncertainty in measurement of the beam polarization. For example, it constrains the tracking detector to be placed as close as 0.5 cm from the electron beam. Further, the polarimeter was operated at the highest beam current (180 μA) ever used by any experiment at JLab

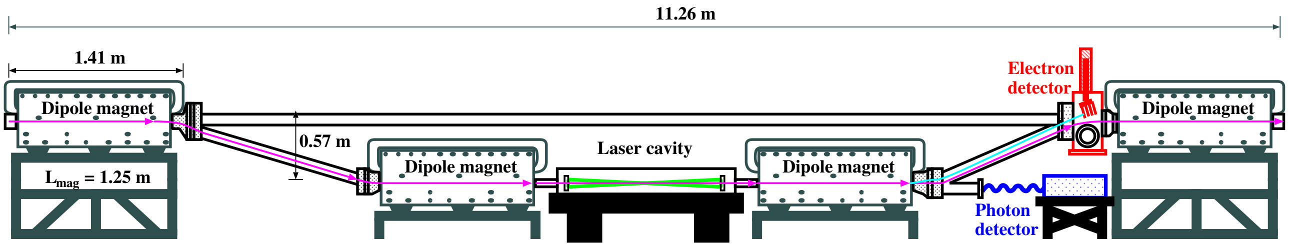

FIG. 1: Schematic of the JLab Hall C Compton polarimeter.

and ran for over 5000 hrs, thereby subjecting the electron detectors to a rather large cumulative radiation dose (> 10 MRad, just from electrons). In order to withstand the large radiation dose, a novel set of diamond micro-strip detectors were used to track the scattered electrons.

The use of *natural* diamond in the detection of charged particles and radiation has a long history, however, the use of synthetic diamond grown through a process known as "chemical vapor deposition" (CVD), is a relatively recent development. Detailed reviews of diamond as charged particle detectors can be found in [11–13]. Thin sheets of centimeter-sized diamond are grown using the CVD process and the plates of diamond are then turned into charged particle detectors by depositing suitable electrodes on them [14]. A minimum ionizing particle (MIP) passing through a thin layer of diamond leaves behind a trail of electron-hole pairs. In the presence of an external electric field the electrons and holes move away from one another, and this movement of the charges induces a signal in the external circuit attached to the electrodes. The signal per electron-hole pair is proportional to the mean separation of the electron and hole before they become trapped in the material.

Compared to the more commonly used silicon detector, the signal size in a diamond detector is significantly smaller, but the higher electron and hole mobility of diamond leads to a faster and shorter duration signal. However, the well-established radiation hardness of diamond [15, 16] is by far the most important consideration for the use of diamond detectors in nuclear and particle physics experiments. In this letter we report the first use of diamond micro-strip detectors as a tracking detector in a nuclear physics experiment and the first high precision measurement of electron beam polarization with this device.

THE HALL C COMPTON POLARIMETER

A schematic of the Compton polarimeter in Hall C at JLab is shown in Fig. 1, it consists of four identical dipole magnets forming a magnetic chicane that displaces a 1.16 GeV electron beam vertically downward by 57 cm. A high intensity ($\sim$ 1 - 2 kW) beam of $\sim$ 100% circularly polarized photons is provided by an external low-gain Fabry-Pérot laser cavity which consists of an 85 cm long optical cavity with a gain between 100 and 200, coupled to a green (532 nm), continuous wave, 10 W laser (Coherent VERDI). The laser light is focused at the interaction region ($\sigma_{\rm waist} \sim 180\ \mu$ m), and it is larger than the electron beam envelope ($\sigma_{\rm x/y} \sim 40\ \mu$ m when optimally tuned). The degree of circular polarization was determined by two methods; first by monitoring the polarization state of the transmitted laser light and using a transfer function to translate it to the Compton interaction point, and second a more precise method of measuring the leakage of the back-reflected power from the laser cavity.

The laser was operated in $\sim$ 90 second cycles, where it is active for $\sim$60 s (laser on period) and blocked off (laser off period) for the rest of the cycle. The laser off data was used to measure the background. The helicity of the laser beam was reversed very infrequently (6 times during the entire experiment).

The maximum scattered photon energy was approximately 46 MeV. A calorimeter consisting of a 2 $\times$ 2 matrix of 3 cm $\times$ 3 cm $PbWO_4$ scintillating crystals attached to a single photo-multiplier tube was used to measure the scattered photon energy. The signal from the photon detector was digitally integrated with no thresholds over a full helicity state ($\sim$ 1 ms) using a 200 MHz flash analog to digital converter.

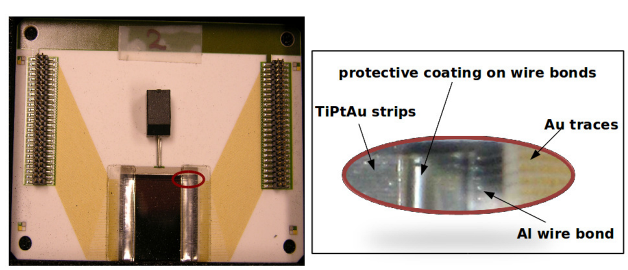

FIG. 2: A CVD diamond plate mounted on an alumina substrate which forms a single detector plane (left). The red oval indicates the area that has been shown in the enlarged view (right).

The Compton scattered electrons were momentum analyzed by the third dipole magnet of the chicane. The maximum separation between the primary electron beam and the Compton scattered electrons, just in front of the fourth dipole, was ~ 17 mm. The deflection of the scattered electron with respect to the primary electron beam, from the maximum down to distances as small as ~ 5 mm, was tracked by a set of four diamond micro-strip detectors. This range allowed the detection of a large fraction of the Compton electron spectrum, from beyond the kinematic maximum (strip 55 in Fig. 3) down past the zero-crossing point of the Compton asymmetry. The electron detectors are made from 21 mm$\times$21 mm$\times$0.5 mm plates of CVD diamond [17]. Each diamond plate has 96 horizontal metalized electrode strips with a pitch of 200 μm (180 μm of metal and 20 μm of gap) on one side (front) and a single metalized electrode covering the entire diamond surface on the opposite (back) side. Details about these detectors can be found in Ref. [2]. A single detector plane is shown in Fig 2.

Only 3 out of the 4 detector planes were operational during the experiment. A typical charge normalized Compton electron spectrum, as well as a charge normalized background spectrum, is shown in Fig 3. A statistical precision of $< 1\%$ per hour was routinely achieved with these detectors. By comparing the expected to the observed rates, the detector efficiency was estimated to be $\sim 70\%$. The large inefficiency is mostly due to the large separation between the detector and the readout electronics. Over the 2 year period of the Q_{weak} experiment, the detectors were exposed to a radiation dose of $\sim$ 10 MRad (without including the dose from Synchrotron radiation). No significant degradation of the signal size was observed during this period, demonstrating the radiation hardness of the diamond detectors.

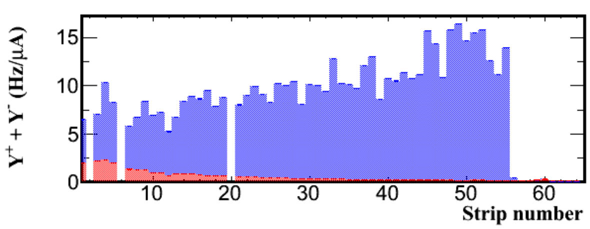

FIG. 3: A typical spectrum of normalized yield $(Y^+ + Y^-)$ from the detector strips for a single detector plane. The charge normalized background subtracted spectrum is shown in blue and the charge normalized background is shown in red.

DATA REDUCTION AND RESULTS

The electron beam helicity was reversed at a rate of 960 Hz in a pseudo-random sequence. In addition a half-wave plate in the polarized electron photo emission source [18] was inserted or removed about every 8 hours to reverse the beam helicity relative to the polarization of the source laser. The background yield measured during the laser-off period was subtracted from the laser-on yield for each electron helicity state, and a charge normalized Compton yield for each detector strip was obtained for the two electron helicities (as shown in Fig. 3). The measured asymmetry was built from these yields using,

$$A_{exp} = \frac{Y^+ - Y^-}{Y^+ + Y^-}, \quad (1)$$

where $Y^\pm = \frac{N^\pm_{on}}{Q^\pm_{on}} - \frac{N^\pm_{off}}{Q^\pm_{off}}$ is the charge normalized Compton yield for each detector strip, $N^\pm_{on/off}$ and $Q^\pm_{on/off}$ are the detector counts and the beam charge accumulated during the laser on/off period for the two electron helicity states ($\pm$), respectively. The Compton yields were averaged over two different time intervals, 1 million helicity cycles and 1 laser cycle. The asymmetry extracted from both time intervals was found to be consistent with each other. A typical asymmetry spectrum during the laser-on and -off period for one detector plane is shown in Fig. 4. The background asymmetry is consistent with zero within the statistical uncertainties, and given the large signal-to-background ratio (see Fig. 3) the dilution to the measured asymmetry due to the background is negligible.

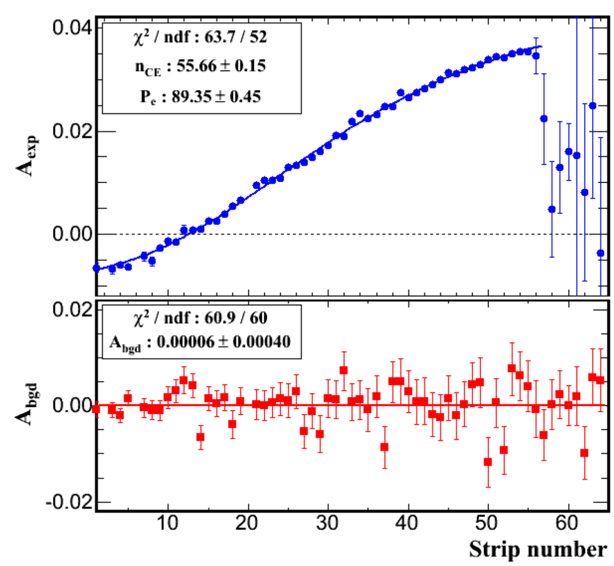

FIG. 4: The measured asymmetry as function of detector strip number for a single detector plane during the laser-on period (top) and the background asymmetry from the laser-off period (bottom). The dashed line in the top panel corresponds to $A_{exp} = 0$. The solid blue line (top) is a fit to Eq. 2 and the solid red line (bottom) is a fit to a constant value. Only statistical uncertainties are shown in this figure.

The electron beam polarization P_e was extracted by fitting the measured asymmetry to a calculated Compton asymmetry using;

$$A_{exp}(y_n) = P_e P_\gamma A_{th}(y_n), \quad (2)$$

where P_γ is the polarization of the photon beam, A_{th} is the calculated Compton asymmetry and y_n is the scattered electron displacement along the detector plane for the n-th strip. The Compton asymmetry, (A_{th}), is typically calculated as a function of the dimensionless quantity $\rho = E_\gamma / E_\gamma^{max}$, where E_γ and E_γ^{max} is the energy of the back-scattered photon and its maximum value, respectively. However, in order to directly compare with the measured asymmetry, ρ was mapped to the displacement of the scattered electron along the detector plane, (y_n). The scattered electron displacement y_n in mm is given by, $y_n = y_{max} - 0.2 * (n_{CE} - n)$, where y_{max} is the maximum displacement of the scattered electrons from the primary beam (the Compton Edge), the width of each strip is 0.2 mm, and n_{CE} is the strip number corresponding to the maximum displaced electrons. The maximum displacement, (y_{max}), was determined from the dimensions and the dispersion of the chicane magnets, and the exact location of the detectors with respect to the third dipole.

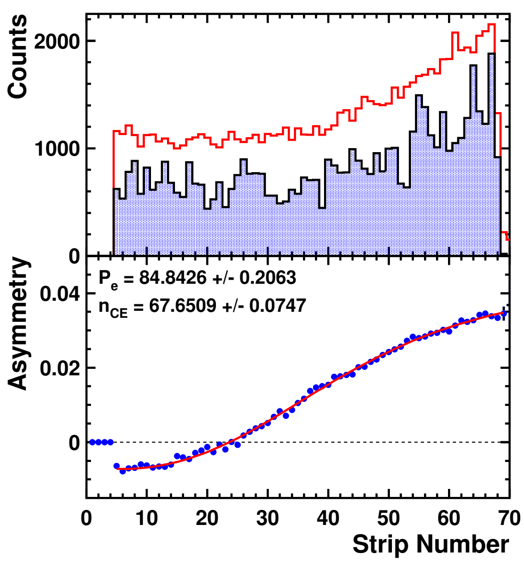

FIG. 5: (top) A typical Monte Carlo simulated Compton spectrum for a single detector plane, with (blue, shaded) and without (red) detector inefficiency. The counts have been scaled by a factor of 10^{-3}. (bottom) The Compton asymmetry extracted from the simulated spectrum including detector inefficiency (blue circles), and a two parameter fit to the calculated asymmetry (red line). The input asymmetry was 85%.

The measured asymmetry (A_{exp}) for each $\sim$ 1 hour long interval (run) was fit to Eq. 2 for each detector strip, with the beam polarization (P_e) and the non-integer strip number corresponding to the maximum displaced electrons (n_{CE}) as the two independent parameters of the fit. The number of degrees of freedom was typically between $50 - 60$, which was made possible by the high resolution of the detector, and the proximity of the detector to the primary electron beam. The detection of a large fraction of the Compton electron spectrum, spanning both sides of the zero crossing of the Compton asymmetry, significantly improving the robustness of the fit and the analysis technique. A typical fit is shown in Fig. 4. The χ^2 per degree-of-freedom of the fit ranges between $0.8 - 1.5$ for all production runs reported here.

A full Monte Carlo simulation of the Compton polarimeter was built using the Geant3 [19] detector simulation package. In addition to Compton scattering, the simulation included backgrounds from beam-gas interactions and beam halo interactions in the chicane elements. The simulation also incorporated the effects of detector inefficiency, track-finding trigger, and electronic noise. A typical simulated strip-hit spectrum (with and without detector inefficiency), and the asymmetry extracted from simulated spectra are shown in Fig. 5. The simulation was used to validate the analysis procedure and to study a variety of sources of systematic uncertainties. For each source, the relevant parameter was varied within the expected range of uncertainty, and the change in the extracted polarization was listed as its contribution to the systematic uncertainty. The list of contributions is shown in Table I.

The Monte Carlo simulation demonstrated that secondary particles knocked out by the Compton scattered electron passing through the first plane produced a 0.4% change in polarization in the subsequent planes. Such a plane-to-plane variation was indeed observed in the polarization extracted from the second and third planes. One can calculate a correction for the later planes but at the cost of a slightly higher systematic uncertainty and hence only the results from the first detector plane are quoted here.

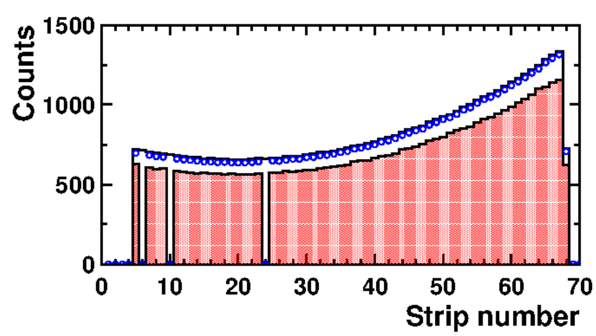

FIG. 6: A typical Modelsim simulated spectrum (without noise and detector inefficiency) of a single detector plane, for un-triggered (blue open circles) and triggered (red shaded) DAQ modes. The input spectrum is shown as the black histogram. The counts have been scaled by a factor of 10^{-3}.

There are several sources of inefficiencies associated with the data acquisition (DAQ) system, such as, the algorithm used to identify electron tracks and form the trigger, and the dead-time due to the hold off (busy) period in the DAQ. The entire DAQ chain was simulated on a platform called Modelsim [20]. While in Monte Carlo simulations, events are generated based on the probability distribution for the relevant physics process, in contrast Modelsim is a simulation technique based on time steps. It employs the same firmware, written in the hardware description language for very high speed integrated circuits (VHDL), that operated the field programmable gate array (FPGA) based logic modules [21] in the Compton DAQ. A front end module, called "test-bench", was used to control the DAQ firmware in the simulation.

The test bench includes signal generators that mimic the electron, the background and the noise signals, along with a detailed accounting of delays due to the signal pathways and the electronic chain external to the FPGA. Fig. 6 shows the output spectra from a Modelsim simulation, for the triggered and the un-triggered modes, along with the input spectrum. Noise and detector inefficiencies were not included in these simulations as they were shown to have minimal impact on the determination of the DAQ inefficiencies. The small difference between the input and the un-triggered counts is a result of the DAQ being disabled during helicity reversal. The difference between the triggered and the un-triggered counts is due to the DAQ inefficiency. The average DAQ inefficiency was found to be directly related to the aggregate detector rate.

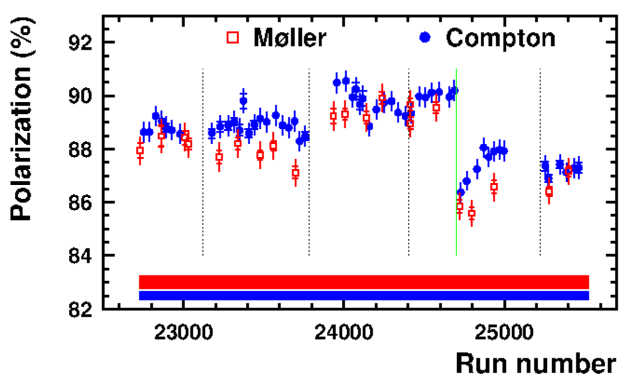

FIG. 7: The extracted beam polarization as a function of run-number averaged over 30 hour long periods, during the second run period of the Q_{weak} experiment (blue, circle). Also shown are the results from the intermittent measurements with the Møller polarimeter [2, 3] (red, open square). The inner error bars show the statistical uncertainty while the outer error bar is the quadrature sum of the statistical and point-to-point systematic uncertainties. The solid bands show the additional normalization/scale type systematic uncertainty. The dashed and solid (green) vertical lines indicate changes at the electron source.

The DAQ simulation was used to determine the correction to the detector yield for each 1 hr run, based on the aggregate detector rate during the run. The DAQ inefficiency correction resulted in $< 1\%$ change in the extracted polarization. The validity of the corrections and the systematic uncertainty due to the corrections (listed in Table I) was determined by comparing the polarization extracted from triggered vs un-triggered data over a wide range of beam currents (rates) and several different trigger conditions. Thus, the Modelsim simulation provided a robust method to determine the inefficiency of the DAQ.

TABLE I: Systematic Uncertainties

Source	Uncertainty	det.P/P%
Laser Polarization	0.18	0.18
Plane to Plane	secondaries	0.00
magnetic field	0.0011 T	0.13
beam energy	1 MeV	0.08
detector z position	1 mm	0.03
inter plane trigger	1-3 plane	0.19
trigger clustering	1-8 strips	0.01
detector tilt(w.r.t x)	1 degree	0.03
detector tilt(w.r.t y)	1 degree	0.02
detector tilt(w.r.t z)	1 degree	0.04
detector efficiency	0.0 - 1.0	0.1
detector noise	up to 20% of rate	0.1
fringe field	100%	0.05
radiative corrections	20%	0.05
DAQ inefficiency correction	40%	0.3
DAQ inefficiency pt.-to-pt.		0.3
Beam vert. pos. variation	0.5 mrad	0.2
helicity correl. beam pos.	5 nm	< 0.05
helicity correl. beam angle	3 nrad	< 0.05
spin precession in chicane	20 mrad	< 0.03
Total		0.59

The extensive simulation studies provided a comprehensive list of contributions to the systematic uncertainties, as tabulated in Table I, with a net systematic uncertainty of 0.59% for the Compton polarimeter. The extracted beam polarization for the entire second running period is shown in Fig. 7. The results from the Compton polarimeter were also compared to the intermittent measurements made with the Møller polarimeter [2, 3] and two polarimeters were found to be consistent with each other within the systematic uncertainties of the measurements.

CONCLUSIONS

We have measured the electron beam polarization of a 1.16 GeV beam using a set of diamond micro-strip detectors for the first time. The high resolution of the detectors and their proximity to the primary beam helped record a large fraction of the Compton electron spectrum, spanning both sides of the zero crossing of the Compton asymmetry for the first time. These detectors, coupled with a robust analysis technique and rigorous simulations of the polarimeter and the DAQ system, produced a very reliable, high precision measurement of the polarization in a very high radiation environment. They demonstrate that diamond micro-strip detectors are indeed a viable option as tracking detectors, and they are the appropriate choice for tracking detectors that are exposed to very high radiation dosage. We have also demonstrated that it is possible to achieve high precision with a Compton polarimeter operated at beam energies as low as ~ 1 GeV. This has very positive implications for the future PVES program at the upgraded JLab.

ACKNOWLEDGMENTS

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