High Energy Polarimetry of Positron Beams

D. Gaskell[1,a)]

[1]*Thomas Jefferson National Accelerator Facility, Newport News, VA, 23606, USA*

[a)]Corresponding author: gaskelld@jlab.org

Abstract. Møller and Compton polarimetry are the primary techniques used for high energy electron polarimetry at Jefferson Lab. In principle, both techniques can also be used for positron polarimetry. However, some modifications to the configuration and/or operating mode of the existing devices will likely be required for use with the types of positron beams currently under consideration at Jefferson Lab.

INTRODUCTION

Polarimetry of high energy electron beams (on the order of 1 GeV or larger) is typically accomplished using Møller and Compton polarimetry. Møller polarimetry makes use of the scattering of the polarized beam electrons from polarized target electrons, the latter usually found in a magnetized ferromagnetic foil. Compton polarimeters make use of collisions between the polarized electron beam and laser photons. The scattered electrons and backscattered photons from the Compton scattering process can both be used to make quasi-independent beam polarization measurements. Since both Møller and Compton scattering are QED processes, their analyzing powers are known to high precision and hence are ideal techniques for electron beam polarimetry.

Compton polarimetry was initially employed at high energy storage rings, but has lately been used at more modest energies and luminosities at fixed target accelerators like CEBAF at Jefferson Lab and MAMI at Mainz. The μA currents and sometimes low beam energies used at fixed target accelerators present certain challenges, but <1% precision measurements have been made at energies as low as ∼1 GeV.

Møller polarimetry is easier to employ at fixed-target machines due to the nearly energy-independent analyzing power and the ability to make statistically precise measurements in relatively short amounts of time. The need to use ferromagnetic foil targets leads to the measurements affecting the electron beam such that the polarization measurements become invasive.

Møller polarimeters are deployed in Halls A [1, 2], B [3], and C [4] at Jefferson Lab, while Compton polarimeters are only available in Halls A [5] and C [6]. In principle, Compton and Møller polarimetry can be employed for both electron and positron beam polarization measurements. The discussion here will focus on how the existing polarimeters at Jefferson Lab could be used to measure positron beam polarization. In the context of this discussion, we will assume positron beam currents of 100 nA and polarizations of 60%, with beam properties nearly identical to the existing Jefferson Lab electron beam.

COMPTON POLARIMETRY

The unpolarized cross section and longitudinal analyzing power for Compton scattering of a polarized electron beam colliding nearly head-on with a green laser are shown in Fig. 1. The cross section is nearly independent of beam energy, while the analyzing power changes dramatically between 1 GeV (≈4% at the Compton endpoint) and 11 GeV (≈30%). Note that the cross section and analyzing power are the same for positrons and electrons.

The Hall A and C Compton polarimeters at Jefferson Lab are very similar, and employ the following major components (see Fig. 2):

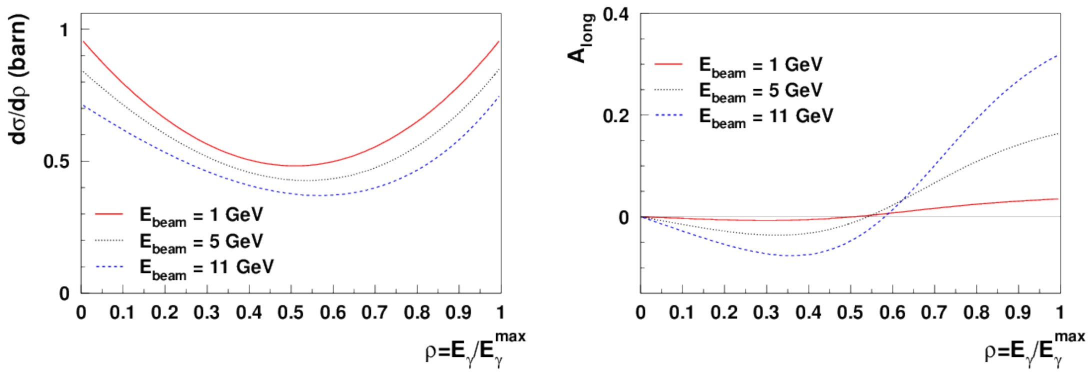

FIGURE 1. Unpolarized cross section (left) and longitudinal analyzing power (right) for GeV-scale electrons colliding with a green laser.

1. 4-dipole magnetic chicane, to first deflect the beam vertically to the laser interaction region and then restore the beam to its nominal trajectory.
2. Laser system consisting of a CW laser coupled to an external Fabry-Pérot cavity.
3. Photon detector downstream of the 3rd dipole (at laser-electron collision height).
4. Segmented strip detector for the scattered electrons, located just upstream of the fourth dipole.

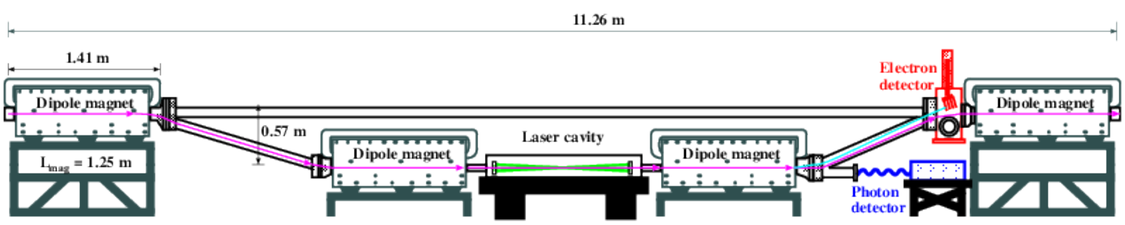

FIGURE 2. Layout of the Hall C Compton polarimeter (as used during the Q_{weak} experiment). The layout of the Hall A Compton polarimeter is similar, although differs in the overall chicane length and vertical beam deflection. Figure from Ref. [6], licensed under CC BY 3.0 [7].

Repurposing either the Hall A or Hall C Compton polarimeters for use with positron beams, to first order, requires no hardware changes; just a simple change of polarity of the dipole chicane. However, the relatively low positron beam currents projected to be feasible at Jefferson Lab will have a significant impact on the practicality of using the existing Compton polarimeters without modification.

The figure-of-merit for a Compton polarimeter can be defined in terms of the time required for a measurement of a given precision, $\Delta P/P$. In the case where the energy of the scattered electron/backscattered photon is determined event-by-event, the time needed is given by,

$$t^{-1} = \mathcal{L}\sigma\left(\frac{\Delta P}{P}\right)^2 P_e^2\langle A^2\rangle, \tag{1}$$

where σ is the Compton cross section, $\mathcal{L}$ is the luminosity of the beam-laser collision, and $\langle A^2\rangle$ is the mean value of the square of the Compton asymmetry. For Gaussian laser and electron beams colliding at a small angle, α_c, the luminosity is given by,

$$\mathcal{L} = \frac{(1+\cos\alpha_c)}{\sqrt{2\pi}}\frac{I_e}{e}\frac{P_L\lambda}{hc^2}\frac{1}{\sqrt{\sigma_e^2+\sigma_\gamma^2}}\frac{1}{\sin\alpha_c}, \tag{2}$$

where I_e is the electron beam current, P_L is the laser power, and σ_e and σ_γ are the electron and laser beam spot sizes. From Equations 1 and 2, it is clear the measurement time is driven by the size of longitudinal asymmetry, the electron beam current, laser power, and laser/electron beam sizes.

The figure-of-merit expression in Equation 1 is a little too simple in that it ignores laser-off periods for background measurements, detector inefficiencies etc. To make a more realistic estimate of expected measurement times using positron beams at Jefferson Lab, we scale using experience with the Hall C Compton polarimeter as used during the $Q_{\rm weak}$ experiment. In that case, the 1.16 GeV beam energy gave an endpoint analyzing power of about 4% and the high beam current (180 μA) resulted in a Compton event rate (in the electron detector) of about 150 kHz at a beam polarization of 89%. For an 11 GeV positron beam, the endpoint analyzing power is 32%, but the rate decreases to 185 Hz (100 nA beam current), and the beam polarization is expected to be no larger than 60%.

In the $Q_{\rm weak}$ case, a 0.47% measurement took about 1 hour. Using Equation 1 to scale to the 11 GeV positron conditions implies that a precision of about 2.5% could be achieved in a similar amount of time. Note that this is a bit optimistic since we are scaling using just the endpoint asymmetry - using the average value of A^2 results in a 3% precision in one hour. A measurement of 1% statistical precision would then take about 9 hours.

While 9 hours is possibly a reasonable amount of time, it does make it challenging to perform systematic studies and track rapid changes in polarization. It would be desirable to make 1% measurements in time scales on the order of one hour. The easiest way to accomplish this is likely an increase in laser power. The Fabry-Pérot cavities used in the JLab Hall A and Hall C Compton polarimeters store 1-5 kW of CW laser power. Higher powers have been achieved at JLab (10 kW), but they are hard to maintain routinely. The effective luminosity of the beam-laser interaction could be enhanced, however, by taking advantage of the electron beam pulse structure. An RF-pulsed laser coupled to a Fabry-Pérot cavity, operating at the same frequency as the electron beam with a comparable pulse width would significantly enhance the effective luminosity, although at the expense of technical complexity. Such laser systems have been accomplished using mode-locked laser systems, but do place some constraints on the Fabry-Pérot cavity geometry, and are not commonplace.

MØLLER POLARIMETRY

As with Compton polarimetry, Møller polarimetry can also be readily applied to both electron and positron beams. The polarized CM cross section ($d\sigma/d\Omega^*$) and longitudinal analyzing power ($A_{\|}$) for Møller scattering are given by,

$$\left(\frac{d\sigma}{d\Omega^*}\right)^{\text{Møller}} = \frac{\alpha^2}{\sqrt{2m_e(E_b+m_e)}}\frac{(3+\cos^2\theta^*)^2}{\sin^4\theta^*}[1+P_eP_tA_{\|}(\theta^*)], \quad (3)$$

$$A_{\|} = \frac{-(7+\cos^2\theta^*)\sin^2\theta^*}{(3+\cos^2\theta^*)^2}, \quad (4)$$

where α is the fine structure constant, E_b is the electron beam energy in the lab frame, and θ^* is the CM scattering angle. For Bhabha (positron-electron) scattering, the expression for the unpolarized cross section is a bit different, but the longitudinal analyzing power is the same [8],

$$\left(\frac{d\sigma}{d\Omega^*}\right)^{\text{Bhabha}} = \frac{\alpha^2}{4\sqrt{2m_e(E_b+m_e)}}\frac{(3+\cos^2\theta^*)^2}{(1-\cos\theta^*)^2}[1+P_eP_tA_{\|}(\theta^*)]. \quad (5)$$

The magnitude of the longitudinal analyzing power is a maximum value of 7/9 at θ^* =90 degrees and is independent of beam energy for GeV-scale beams. In practice, the analyzing power is diluted by the need to use ferromagnetic foils for the polarized electron target. The effective target polarization is on the order of 8%, so the maximum possible asymmetry is then ~6%.

Møller polarimeters have been built in various configurations and modes of operation. Detection of only the scattered electron results in sometimes non-trivial backgrounds due to Mott scattering. It is now more common to detect the scattered and recoiling electrons in coincidence, which eliminates virtually all physics backgrounds. Møller polarimeters also require magneto-optical systems to steer the electrons to a detector system. Various optical solutions are possible (dipole-only, quadrupole-only, quadrupole+dipole). At Jefferson Lab, experimental Halls B and C use a 2-quadrupole optical system, while Hall A uses multiple quadrupoles with a dipole. The layout of the Hall C system is shown in Fig. 3.

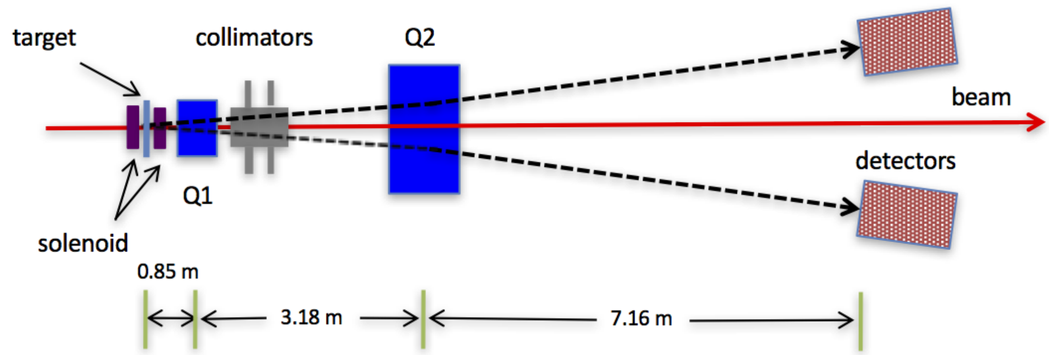

FIGURE 3. Layout of the Hall C Møller polarimeter. The first quadrupole horizontally focuses the scattered and recoil electrons, while the second quadrupole horizontally de-focuses and steers the electrons to the lead-glass detectors, which are separated from the nominal electron beam path by 49 cm. Figure from [9], licensed under CC BY 4.0 [10].

The use of quadrupoles in the Møller polarimeter optics presents a practical challenge for the use of the JLab polarimeters for positron measurements. The magneto-optical systems presume that both the scattered and recoiling particles have the same charge so that the steering effects/focusing from the quadrupoles will be the same. Clearly this is not the case for positron beams and the detection of the scattered positron and recoiling electron in coincidence is not possible with the existing optical configurations. However, there are two relatively simple options that would allow the use of the existing JLab Møller polarimeters with no or relatively modest modification.

Single arm Møller Polarimetry

A simple option for operation of the JLab Møller polarimeters for positron beams would be to operate them in single-arm mode, not requiring a coincidence between the scattered and recoiling particle. This has the advantage of requiring no changes to the magneto-optical systems. However, operation in this mode would result in larger backgrounds due to Mott scattering. Even more problematic is that the optical systems of the JLab polarimeters are not configured for easy fitting and subtraction of the Mott background.

Constraint of the Mott backgrounds in single-arm mode could be perhaps most simply accomplished using electron beam data at the relevant positron beam energy. In this case one could compare the asymmetries extracted in coincidence (background-free) mode to those extracted in single-arm mode. The inferred size of the Mott backgrounds could then be applied to measurements taken under similar conditions with positron beams.

It's worth noting that, even with the Mott backgrounds properly determined, the figure of merit for the measurement will decrease due to the smaller measured asymmetry.

Dipole-only optics

The JLab Møller polarimeters could be operated with positron beams in coincidence mode by replacing the quadrupole-based optical systems with a dipole-only system. In this case, the oppositely-charge particles travel through a vertical magnetic field and are both bent away from the beamline, into detectors. Figure 4 shows an example of this potential implementation in the Hall C system. In this case, the first quadrupole is not used, and the second quadrupole replaced by a large gap (~3.5 inch) dipole with integrated field on the order of 1 T-m. While the example shown here is for the Hall C system, it is likely possible with the Hall B system as well due to the similar layout. Application to the Hall A system would be more problematic since a dipole is already used there to bend both scattered and recoil electrons down, below the nominal beam path.

The drawback to this solution is the requirement for a new magnet. In addition, the system can not be easily swapped between electron and positron mode - some significant installation time is required for switching between the two modes.

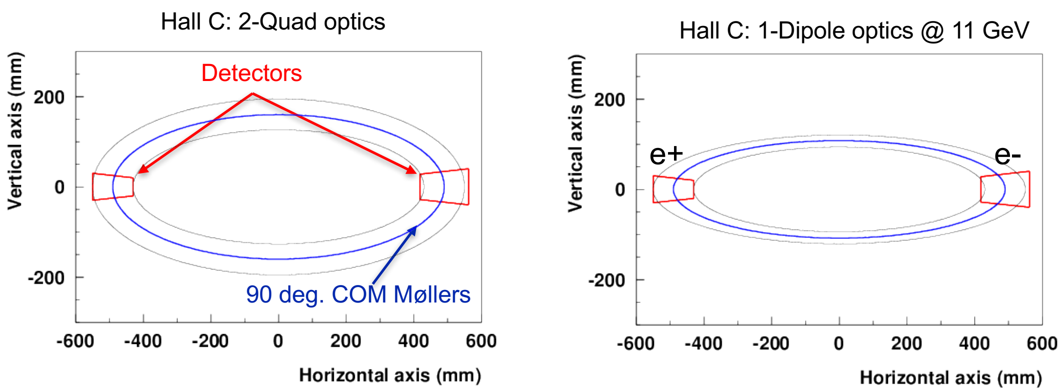

FIGURE 4. Envelope of Møller events at detector plane. Left: 2 quad optics for scattered/recoil electron pair. The quads focus the relevant Møller events to form an ellipse at the detector plane. The acceptance of the detectors is described by the red trapezoids. Right: Single dipole optics for positron/electron detection at 11 GeV. While the height of the ellipse has changed, the particles scattered at 90 degrees in the CM are still steered to the detectors.

SUMMARY

Positron polarimetry of GeV-scale beams can be readily accomplished using the standard techniques of Compton and Møller polarimetry. In particular, the polarimeters at JLab can potentially be used for these measurements, either with some modification or compromise in performance. The primary challenge for the JLab Compton polarimeters is the relatively low beam current (100 nA) projected to be feasible for polarized positron beams at JLab. This low current leads to rather lengthy measurement times. Measurement times could be reduced with improvements to the Compton polarimeter laser systems, although this would require some R&D and expense. The Møller polarimeters at JLab, on the other hand, use magneto-optical systems designed to detect two particles of the same charge in coincidence. Møller polarimetry with positron beams would ideally detect the scattered positron and recoil electron. The JLab Møller polarimeters could be operated in single-arm mode, resulting in non-trivial Mott backgrounds and potentially larger systematic uncertainties (although the Mott backgrounds could potentially be understood by comparing single-arm and coincidence measurements with electrons). Another option would be to replace the quadrupole-based polarimeter optics with a dipole-based system. This would enable the detection of the positrons and electrons in coincidence. Extra time would be needed, though, to switch between positron and electron operating mode.

ACKNOWLEDGMENTS

This work is supported by the United States Department of Energys Office of Science contract number DE-AC05-06OR23177 under which Jefferson Science Associates, LCC operates the Thomas Jefferson National Accelerator Facility.

REFERENCES

[1] A. V. Glamazdin *et al.*, Fizika **B8**, 91–95 (1999), arXiv:hep-ex/9912063 [hep-ex] .
[2] O. Glamazdin, Nuovo Cim. **C35**, 176–180 (2012).
[3] B. A. Mecking *et al.* (CLAS), Nucl. Instrum. Meth. **A503**, 513–553 (2003).
[4] M. Hauger *et al.*, Nucl. Instrum. Meth. **A462**, 382–392 (2001), arXiv:nucl-ex/9910013 [nucl-ex] .
[5] S. Escoffier *et al.*, Nucl. Instrum. Meth. **A551**, 563–574 (2005), arXiv:physics/0504195 [physics] .
[6] A. Narayan *et al.*, Phys. Rev. **X6**, p. 011013 (2016), arXiv:1509.06642 [nucl-ex] .
[7] Creative Commons Attribution 3.0 Unported, `https://creativecommons.org/licenses/by/3.0/`.
[8] G. Alexander and I. Cohen, Nucl. Instrum. Meth. **A486**, 552–567 (2002), arXiv:hep-ex/0006007 [hep-ex] .
[9] J. A. Magee *et al.*, Phys. Lett. **B766**, 339–344 (2017), arXiv:1610.06083 [physics.ins-det] .
[10] Creative Commons Attribution 4.0 International, `http://creativecommons.org/licenses/by/4.0/`.