New methods for precision Møller polarimetry

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Abstract. Precision electron beam polarimetry is becoming increasingly important as parity violation experiments attempt to probe the frontiers of the standard model. In the few GeV regime, Møller polarimetry is well suited to high-precision measurements, however is generally limited to use at relatively low beam currents ($< 10 \mu\text{A}$). We present a novel technique that will enable precision Møller polarimetry at very large currents, up to $100 \mu\text{A}$.

1 Introduction

Until recently, electron beam polarimetry with 2-3% precision has been considered adequate for most electron scattering experiments. However, the next generation of parity violation experiments require ever increasing precision for electron beam polarization measurements. The approved Q_{Weak} [1] and lead-parity [2] experiments at Jefferson Lab require $dP/P \approx 1\%$. Møller scattering and parity-violating deep-inelastic scattering (DIS-parity) standard model tests envisioned for a 12GeV Jefferson Lab require polarimetry at the 1.0% and 0.5% level of precision, respectively.

The Basel Møller polarimeter in Hall C [3] marked a significant improvement in Møller polarimetry techniques by reducing the dominant systematic uncertainty, for a given target polarization. The Hall-C Møller is in principle able to make polarization measurements with systematic uncertainties on the order of 0.5%. However, this precision is confined to rather low beam currents (a few μA) due to target heating and subsequent depolarization at higher beam currents. We describe here a novel beam-kicker-based system that will mitigate these effects and allow beam polarization measurements that will achieve systematic uncertainties on the order of 1% at very high beam currents ($\approx 100 \mu\text{A}$).

2 The Basel Møller polarimeter in Hall C

Møller polarimeters can be used to extract an electron beam polarization via polarized electron-electron scattering. The electron beam polarization is extracted via,

$$A_{\text{meas}} = P_{\text{beam}} P_{\text{target}} A_{\text{th}}$$

where A_{meas} is the experimental asymmetry, P_{beam} and P_{target} are the beam and target electron polarizations, and A_{th} is the acceptance averaged theoretical Møller scattering asymmetry. This last quantity is known from QED and for longitudinally polarized electrons (beam and target) the asymmetry is $-7/9$ at 90 degrees in the center of mass. In the end, the dominant systematic uncertainty for most Møller polarimeters is influenced by the target electron polarization (2–3%).

2.1 Polarimeter overview

The Basel Møller polarimeter improves on earlier polarimeters by dramatically increasing the precision with which one knows the target polarization. In the past, polarized target electrons have been created using iron-alloy foils in a relatively small magnetic field (of

the order 100 gauss) aligned along the plane of the foil. The degree of target polarization then had to be carefully determined by measuring the magnetic flux with and without the foil present. In the end, systematic errors smaller than 2–3% on the target polarization are difficult to achieve.

The Basel Møller polarimeter instead uses a pure iron foil magnetized to saturation by a 3–4 tesla superconducting solenoid [4]. In this case, the solenoid field is aligned along the beam direction and the foil is magnetized out of plane. Since the saturation magnetization of pure iron is extremely well known, the net electron polarization can be known to better than 0.3%.

The Basel polarimeter also improves on earlier Møller polarimeters via the use of coincidence electron detection to suppress background from Mott scattering and the use of large-acceptance detectors, which reduces sensitivity to the orbital motion of electrons bound in the iron atom (the Levchuk effect [5]). The polarimeter layout is shown in fig. 1 with the dominant systematic uncertainties associated with the system given in table 1.

Fig. 1. Layout of the Basel Møller polarimeter in Hall C. A superconducting solenoid magnetizes a pure iron foil out of plane. Møller-scattered electrons are transported using a 2-quadrupole spectrometer to total absorption lead-glass detectors 11m from the target.

Table 1. Dominant contributions to the systematic uncertainty associated with the Basel Møller polarimeter.

Source	Systematic uncertainty
Levchuk effect	0.30%
Spin polarization in Fe	0.25%
Beam position	0.16%
Multiple scattering	0.12%
Quadrupole settings	0.12%
Total	0.47%

2.2 High-current operation

The systematic uncertainties listed in table 1 assume minimal depolarization of the iron target due to beam heating effects. The effect of foil heating on the iron magnetization is shown in fig. 2. A temperature increase of 60–70 °C results in a $\approx 1\%$ reduction in foil magnetization. In order to keep heating effects small enough to have negligible impact

on the total systematic error of the measurement, most polarimeter data are taken at rather low beam currents, 1–2 μA . Higher currents can be achieved by rastering the beam over a larger area of the iron foil, but for reasonable raster sizes, the maximum beam current is still on the order of 10 μA .

While delivering low current for operation of the Hall-C Møller polarimeter is straightforward, one must make the assumption that the beam polarization is the same at low currents (1–2 μA) as it is at high currents ($\geq 100 \mu\text{A}$). It has been suggested that the polarization of the electron beam may change at higher currents due to effects at the polarized source or due to changes in accelerator loading properties. It is desirable, therefore, to measure the beam polarization at currents comparable to the running conditions of the main experiment. As an example, the recent polarimetry uncertainty for the forward-angle portion of the G0 experiment was $dP/P = 1.2\%$ [6], and this was dominated by the (conservative) 1% uncertainty assigned due to the fact that the experiment ran at 40 μA while most polarization measurements were made at 2 μA . Higher-current tests were performed but only extended to a maximum current of 10 μA . In the next section, we describe a novel approach for mitigating these target heating issues.

Fig. 2. Relative magnetization vs. temperature for a pure iron foil driven to magnetic saturation (from [4]). The iron foil used in the Basel Møller polarimeter is normally at room temperature with no active cooling.

3 Kicker magnet for high-current Møller polarimetry

Target foil heating effects can be overcome by quickly scanning the electron beam over a wire or strip target. By minimizing the time on the target, the energy deposited in the foil is kept small and by allowing sufficient time between scans, the foil has a chance to cool before the next scan. A series of “kicker” magnets have been designed and built for this application. In general, these magnets share the following properties: 1) a fast kick that results in a total time on the polarimeter foil on the order of microseconds and, 2) a relatively small duty cycle to allow the target the opportunity to cool. The magnet itself is a very low inductance, air core magnet installed in the Hall-C beamline several meters upstream of the Møller polarimeter.

Fig. 3. Graphical representation of the original kicker magnet operating parameters. The kicker magnet kicks the beam 1–2mm (at the Möller target position) at a frequency between 100Hz to 10 kHz. During the “off” period, the beam proceeds unimpeded along the normal beam path to the Hall-C dump. During the 20 μ s kick period, the beam is deflected across either an iron wire or thin-foil strip target.

3.1 Kicker prototype tests

A first generation kicker was installed in 2003 and tested during the forward-angle phase of the G0 experiment. In that case, the kick duration was 20 μ s with an operating frequency between 100Hz and 10 kHz (see fig. 3). This first-generation kicker was used in conjunction a 20 μ m diameter iron wire target. While polarization measurements were made with this device up to 20 μ A, the uncertainties at the largest currents were quite large. At high currents, it was necessary to reduce the kick duty factor substantially to keep heating effects small. This led to quite small average luminosities, which required extremely long measurement times. In addition, since the beam size was comparable to the iron wire diameter, the instantaneous luminosity was quite large when the beam was scanning the target, leading to large random coincidence rates in the polarimeter.

To overcome the two problems encountered above, the target design was reconsidered and a 1 micron thick, strip target was installed. This target had the advantage that during the beam “kick”, the entire beam was incident on the target for most of the kick duration (in contrast to the wire target in which one could conceivably be measuring the polarization of the “beam tails” as the beam scans the wire). In addition, the thin foil greatly reduces the instantaneous rates and keeps the random coincidences at a manageable level.

This new target design was tested in December 2004 with very promising results. In this case we were able to make measurements of the beam polarization up to beam currents of 40 μ A with no noticeable effects from beam heating (see fig. 4). A slightly improved kicker was also used for this test, the waveform very similar to that shown in fig. 3 but with kick duration a factor of two smaller (10 μ s).

Fig. 4. Results of polarization measurements taken in December 2004 using the second-generation kicker magnet impinging on a 1 μm thick iron foil strip target. Measurements were made at beam currents up to 40 μA . Higher currents were not accessible due to beam losses from the deflected electron beam. Control measurements at 2 μA suggest instability at the polarized source, so these measurements cannot be used to prove 1% precision at high currents. However, the relative consistency of the results suggest the method should be feasible.

During early stages of the 2004 test, it was extremely difficult to transport the electron beam without tripping machine protection systems. Naively, since the kicker was tens of meters upstream of the Møller target, and the kick amplitude was quite small (on the order of 1mm), the beam should have easily propagated to the beam dump in Hall C. However, the focusing elements downstream of the Møller actually conspired to amplify the kick and resulted in the electron beam scraping various apertures in the downstream beamline. With support from the accelerator division scientists, we were able to set up the beam-line optics appropriately to suppress the kick amplitude downstream of the Møller target. Even with this configuration however, we were unable to successfully transport the beam at currents higher than 40 μA . Undoubtedly, the improved beam optics still resulted in the electron beam coming quite close to some aperture in the beamline.

Additionally, we should note that while very promising, the tests performed in 2004 cannot be used to verify the Hall-C Møller operation at 40 μA with 1% precision. Unfortunately, our control measurements with the polarimeter in its nominal configuration were not stable. Measurements made at 2 μA using our standard 4 μm foil yielded results that fluctuated between $\approx 78\%$ and $\approx 81\%$. This fluctuation can likely be attributed to non-optimal polarized source conditions.

3.2 Future plans

The eventual goal of this project is to make high-precision measurements using the Basel Møller polarimeter at currents on the order of 100 μA . To achieve this, the duration of the electron beam kick must be shortened to 2 μs . A magnet capable of this

rapid beam deflection has already been developed. In addition, this new kicker magnet has the capability to allow the beam to “dwell” on the target at a fixed position for a certain amount of time (see fig. 5). This modified kick cycle will allow us to form a gate such that data is only acquired when the beam is fully “on target” and is not transitioning over a foil edge which may have irregularities and non-optimal magnetization.

Fig. 5. Schematic of the operating mode of the new kicker magnet waveform. The beam is kicked 1–2mm in about 1 μ s and remains stationary on the Møller target for 1 to several μ s.

In addition we plan to improve the target design. The target used in the December 2004 tests suffered from wrinkles in the foil that had the potential to negatively impact the uniformity of the target magnetization. We are designing a new mounting mechanism to avoid these problems. We are also looking at alternate designs to improve the cooling and heat transport in the foil.

Initially, there were plans to conduct further tests of the kicker system during the backward-angle phase of the G0 experiment. However, the beam energies used were quite low (687MeV and 362MeV). Below 1GeV, the polarimeter becomes extremely sensitive to beam position and trajectory at the target (small position and angle offsets induce larger changes in acceptance and effective analyzing power than at higher energies) so that the measured polarization with and without the kicker magnet would undoubtedly be different. In addition, steering effects from the fixed field 3 tesla solenoid are significant at these low energies and difficult to overcome. Our next opportunity to perform further tests will likely be in the spring and fall of 2007, when higher-energy polarized beams will be available in Hall C.

References

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