EIC Electron Beam Polarimetry Workshop Summary

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Abstract. A summary of the Precision Electron Beam Polarimetry Workshop for a future Electron Ion Collider (EIC) is presented. The workshop was hosted by the University of Michigan Physics Department in Ann Arbor on August 23-24, 2007 with the goal to explore and study the electron beam polarimetry issues associated with the EIC to achieve sub-1% precision in polarization determination. Ideas are being presented that were exchanged among experts in electron polarimetry and source & accelerator design to examine existing and novel electron beam polarization measurement schemes.

INTRODUCTION

To answer some of the fundamental questions in QCD, e.g. how the gluons contribute to the spin structure of the nucleon, or how well the Bjorken Sum Rule holds, strong requirements are placed on precision polarimetry both for electrons and positrons and for hadrons. In a workshop held in Ann Arbor in August 2007, fifteen physicists and engineers working at four different laboratories (BNL, HERA, JLab, MIT-Bates) reviewed which physics processes might be most appropriate for electron (positron) polarimetry at the EIC, and which technical issues need to be addressed that influence the design of the collider and the interaction region.

Two possible realizations of the EIC project are currently considered (see Fig. 1): [eRHIC] the addition of a high energy polarized electron beam facility to the existing RHIC, and [ELIC] the addition of a high energy hadron/nuclear beam facility at Jefferson Lab (JLab). At the present time no preference is given to either option.

Thus, the current design of the EIC project foresees collisions of 3-20 GeV longitudinally polarized electrons on 30-250 GeV protons or 50-100 GeV/u heavy ions (such as gold) to provide center of mass energies of 20-100 GeV. Bunch separations of 3-35 ns are discussed to achieve machine luminosities in electron–proton collisions of about 10^{33}-10^{34} cm^{-2} s^{-1}. The luminosity goal for ten years of running is 50 fb^{-1}. There are requests to provide beams of polarized electrons (positrons), protons and light ion beams (e.g. ^{3}He). It is anticipated that the electron beam polarization is 70% or better and that it needs to be measured with high precision ($\lesssim$1% systematic uncertainty). Unfortunately, a polarized electron bunch has no macroscopic properties that could be useful for measuring its polarization [1]. It is argued that a polarized electron bunch represents a very weak magnetic dipole which has a strength that is roughly seven orders of magnitude less than a piece of magnetized iron of comparable size. Therefore, one is inevitably lead to consider microscopic processes, i.e. spin-dependent scattering processes. The simplest

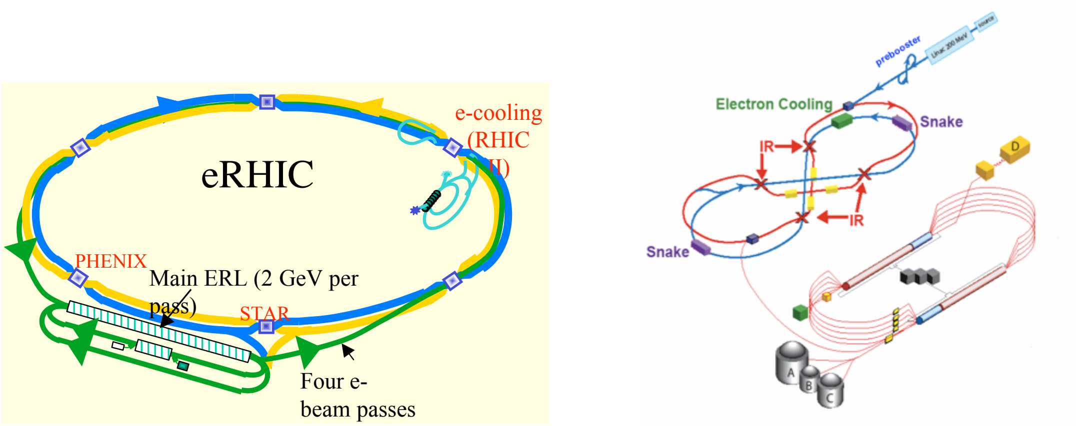

FIGURE 1. Two possible design layouts of the Electron Ion Collider project. Left panel: [eRHIC] the EIC version at RHIC is shown. Right panel: [ELIC] is the corresponding version at JLab .

such processes are the elastic processes which have three very useful properties: a) the cross sections for elastic scattering are usually large, b) elastic scattering processes have simple kinematical properties, and c) the physics of elastic electron (positron) scattering is quite well understood.

There are commonly three different targets used to measure the polarization of electron (positron) beams: nuclei, electrons, and photons. Mott scattering, or e^-– nucleus scattering, is mainly used at low energies (30 keV - 5 MeV) to measure the polarization of electrons from polarized sources. It is destructive to the beam. The Mott asymmetry results from the spin-orbit coupling of the incident polarized beam electrons with the potential of the target nucleus. Møller (Bhabha) scattering, or $e^-(e^+)$– electron scattering is widely used for polarized beams in the 100 MeV to many GeV energy range. The Møller asymmetry arises from the interaction of the incident polarized beam electrons with the atomic electrons in iron (or iron-alloys) which are polarized by external magnetic fields. Unfortunately, it is destructive to the beam and therefore not suitable for storage rings. In contrast, Compton scattering, or $e^\pm$– photon scattering, which is suitable for energies above 1 GeV, and ideal for energies above 10 GeV, is not destructive to beams in storage rings and is therefore the only choice to date for high energy storage rings, with the exception of a new idea discussed below.

There are many polarimeters that have been in use, are in use, or are planned at various laboratories. Rather than describing individual polarimeters in detail, a general comparison of Møller and Compton polarimetry is made, before an overview of existing polarimeters and their precision in electron polarimetry is given.

COMPTON VS MØLLER POLARIMETRY

In Compton scattering, laser photons are scattered off beam electrons. The backscattered Compton photons are detected at an angle of 0° with respect to the electron beam, while the Compton electrons are detected with some energy loss after being separated from

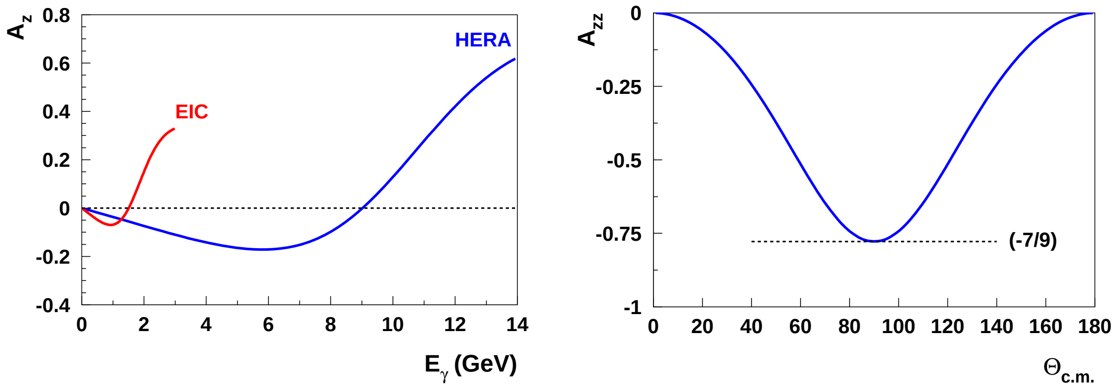

FIGURE 2. Left panel: The analyzing power A_z for a 532 nm laser photon scattering off a 10 GeV (EIC curve) or a 27.5 GeV (HERA curve) beam electron. Right panel: The analyzing power A_{zz} as a function of center-of-mass angle Θ_{cm}.

the electron beam by a dipole magnet. Due to the large variation in the analyzing power A_z versus scattered Compton photon energy, E_γ, as seen in Fig. 2 (left panel), good energy resolution is needed in the Compton photon detector. In addition, the asymmetry at the Compton edge increases linearly with beam energy (for $E_b \lesssim 20$ GeV). In Møller scattering, the electron is detected at a center-of-mass angle of 90°, where the analyzing power A_{zz} varies slowly, is independent of beam energy, and has a value of -7/9 (see Fig. 2 right panel). In Compton Scattering, the target (i.e. laser beam) is effectively 100% polarized while in Møller scattering the target (i.e. polarized electrons in iron foils) are only about 8% polarized. Furthermore, Compton scattering measurements are non-invasive, while Møller scattering measurements are destructive due the need of using iron or iron-alloys. Compton scattering is ideal for high beam currents, while Møller scattering measurements suffer from beam induced foil heating effects at beam currents above a few μA.

Table 1 shows an overview of existing polarimeters and their precision in electron polarimetry. The systematic uncertainties in beam polarization measurements for Compton polarimeters are reported to be in the 0.5-2% range, but they can get larger as measurements get pushed to lower beam energies ($E_b \lesssim 1.0$ GeV). For Møller scattering the systematic uncertainties are typically 2-3%, and may approach 1% or below at high magnetic fields.

The "Spin Dance" Experiment

In July 2000, a multi-hall cross-normalization of the relative analyzing power of the five JLab electron polarimeters, listed in Table 1, was performed [3]. The purpose of this high precision comparison between the Mott, Compton, and Møller polarimeters was to reveal possible differences between the polarimeters that are systematic in nature and that ultimately may help to realize 1% or better absolute electron polarimetry.

In order to deliver simultaneous beam at the same energy to each polarimeter, the accelerator was configured for five-pass recirculation and a final beam energy of 5.65 GeV. The strained GaAs photocathode delivered beam polarizations of 75% or higher to the

TABLE 1. Overview of existing polarimeters and their precision

Laboratory	Polarimeter	Relative precision	Dominant systematic uncertainty
JLab	5 MeV Mott	∼1%	Sherman function
	Hall A Møller	∼2-3%	target polarization
	Hall B Møller	1.6% (→ 2-3%)*	target polarization, Levchuk effect
	Hall C Møller	0.5% (→ 1.3%)†	target polarization, Levchuk effect, high current extrapolation
	Hall A Compton	1% (@ > 3 GeV)	detector acceptance + response
HERA	LPol Compton	1.6%	analyzing power
	TPol Compton	3.1%	focus correction + analyzing power
	Cavity LPol Compton	?	still unknown
MIT-Bates	Mott	∼3%	Sherman function + detector response
	Transmission	>4%	analyzing power
	Compton	4%	analyzing power
SLAC	Compton	0.5%	analyzing power

* 1.6% is quoted by Hall B. 2% or even larger might be more realistic.
† 1.3% is best quoted value in an experiment. 0.5%, as quoted by Hall C polarimeter group, seems possible.

three experimental halls. A Wien filter in the injector was varied from -110° to 110° to vary the degree of longitudinal polarization in each hall. A series of polarization measurements as a function of spin orientation of the electron beam were performed to determine the relative analyzing power between the five polarimeters. The results are displayed in Fig. 3 (left panel) with the open symbols. There is significant discrepancy between the polarimeters, even if the systematic uncertainties are included.

Since the Hall A and B Møller polarimeters may have systematic effects that depend on the transverse components of the electron beam polarization, which are large when the longitudinal components are small, the data shown in solid symbols have been

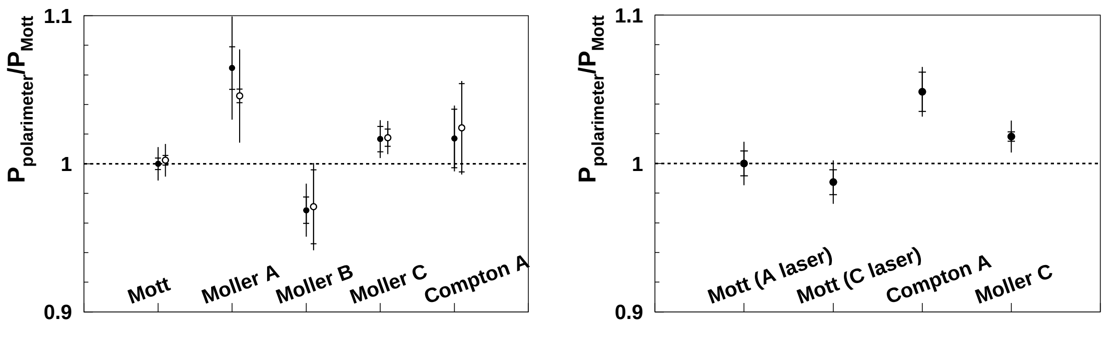

FIGURE 3. Left panel: Relative analyzing power for the five JLab electron beam polarimeters, normalized to the Mott polarimeter for comparison. The filled symbols are the results for the entire data set. The open symbols represent the results for the data set limited to be within 25% of the maximum measured polarization. They are slightly offset for better visibility. Right panel: The relative analyzing power for a subset of JLab electron beam polarimeters.

restricted to be within 25% of the maximum polarization value [3]. These results indicate that the horizontal component of polarization may be an important source of systematic effects for the Hall A Møller polarimeter. For the reduced data set, the discrepancy among the five polarimeters becomes less significant when the systematic uncertainties for each polarimeter are included.

In April 2006, a mini "Spin Dance" experiment was performed to ensure purely longitudinal polarization in Hall C Hall. Since the Hall A Compton polarimeter was online during that time, it was included in this experiment. The results, shown in Fig. 3 (right panel), indicate that there is relatively good agreement between the Hall C Møller and the Mott polarimeters, and between the Hall C Møller and the Hall A Compton polarimeters, but still a relatively large discrepancy between the Mott and the Hall A Compton.

As a result of the spin dance experiments, the Hall A Møller polarimeter will be implementing a Hall C style target to be able to isolate instrumental from target polarization effects.

POLARIMETRY AT THE EIC

Experience at the HERA storage ring, at JLab, and at the South Hall Ring at MIT-Bates has demonstrated that it is imperative to include polarization diagnostics and monitoring capabilities in the design of the electron beam lattice. The specifics depend on the design of the electron machine, but are crucial for a ring or a linac option. In either case, one has to ensure that the beam polarization can be measured continuously during physics runs to minimize systematic uncertainties associated with the beam polarization, such as drifts or luminosity related variations in polarization. The cross-comparison of the analyzing power of various polarimeters at JLab has shown that providing or even proving precision at the 1% level is very challenging. It further made clear that multiple devices and maybe even multiple techniques are absolutely crucial for testing the systematic uncertainties of each polarimeter. There has to be at least one polarimeter that can measure the absolute polarization of the beam, while others might do relative measurements. Although the absolute polarization measurement does not have to be very quick, the relative measurement has to be fast and precise.

The advantages of Compton scattering are that the laser polarization can be measured accurately, that Compton scattering is a pure QED process where no atomic or nuclear corrections have to be applied, and where radiative correction uncertainties are at the 0.1% level [4]. Compton scattering is non-invasive, thus allowing for continuous monitoring of the beam polarization. The backgrounds are relatively easy to measure and it is the ideal process for high energy, high beam current electron (positron) beams. Compton scattering has the disadvantage, though, that at low beam current, measurements are time consuming, and that at low beam energies, the analyzing power gets small. This has the effect that high precision systematic studies are difficult to accomplish, and that the systematic uncertainties get harder to control, respectively.

For Møller scattering, the advantages are that the measurements can be performed rapidly with high precision because the rates are high. The analyzing power is large (-7/9) at the center-of-mass angle $\theta_{cm} = 90^\circ$, but gets diluted by the need to use iron foils to create the polarized electrons. At high magnetic fields (3-4 T) the iron foils can be completely saturated such that total systematic uncertainties of 0.5-1% seem possible. The biggest disadvantage though is that the use of iron foils makes Møller scattering a destructive process, where only low currents ($I_b < 2$-$4\ \mu$A) are allowed to prevent heating of the foils and associated loss of magnetization. The target polarization for iron foils is low (8%), and the Levchuk effect [5, 6] contributes approximately 1% to the systematic error budget.

To achieve sub-1% precision in the electron beam polarization determination, all these considerations have to be taken into account, and if possible, new and innovative ideas have to be employed.

New ideas for the EIC

Most of the major disadvantages of Møller scattering might be overcome with a new idea that employs polarized atomic hydrogen in an ultra-cold magnetic trap [2]. It is argued that at 300 mK, the electrons of the hydrogen atoms are brute-force polarized to 100% within a factor of 10^{-3}, and a polarization measurement with a statistical uncertainty of 1% can be achieved in 10 min with a beam current of 100 μA and a target density of 3×10^{15} cm^{-3}. Employing an atomic hydrogen target has the advantage that it is non-invasive and can be used to continuously measure the beam polarization, and that it may provide a systematic uncertainty below 0.5%. It has the disadvantage, though, that the target is very complex, and that gas heating effects by radiation grow with the beam intensity squared. This might be a serious limitation for the high currents envisioned for the EIC. One solution around the gas heating effect might be to consider a hydrogen jet target instead. Further studies are underway to explore this interesting idea.

New developments in laser technology might give a big boost to Compton scattering based polarization measurements, where it has been necessary to build either delicate laser cavity lasers or use high power pulsed lasers to get Compton rates that allow polarization measurements within reasonable time scales. This technology is being borrowed from fiber based drive lasers at electron sources that provide very high power, and use gain switching, as compared to mode locking which is sensitive to phase lock problems. The advantages are that they can be gain locked to the actual beam of the accelerator (30 ps pulse at 499 MHz), therefore providing a nearly 100% duty cycle which translates in lower instantaneous rates for counting. In addition, fibre lasers can be easily accessed since they are external to the beam line vacuum system (unlike the cavity laser for the Hall A Compton polarimeter). They further provide excellent stability, low maintenance, and straightforward implementation. Efforts are underway to build a Compton polarimeter using the fibre lasers for a new Hall C Compton polarimeter.

There is some notion that detection of Compton electrons might be more critical for high precision polarimetry than detection of Compton photons. Since the analyzing power depends strongly on the momentum of the Compton electrons, Compton electrons are typically analyzed by fitting the asymmetry shape over parts or the entire available momentum range. Alternatively, the Compton edge (which corresponds to the minimum energy of the back-scattered Compton electrons), can be used to determine the electron beam polarization. These methods however depend strongly on the response function of the detector, which must be calibrated and monitored carefully. A new idea to do a zero-crossing Compton electron analysis has been presented. It relies on the well-defined energies of the zero crossing of the asymmetry (corresponding to 90° scattering in the electron rest frame) and of the Compton edge. This analysis is based on a linear fit of the zero crossing of the Compton asymmetry, and an integration of the asymmetry spectrum from that point to the Compton edge, instead of a fit to the spectrum shape between those points. It has the advantage that no absolute energy response calibration of the detector is necessary, and that the corrections due to finite detector position and energy resolutions are small ($\ll 1\%$).

A possible polarimeter for the EIC

Based on the experience gained at the HERA storage ring a rough idea for a polarimeter suitable to withstand the high luminosity at EIC was presented, as shown in Fig. 4. The main elements were to minimize background rates, to detect both the Compton electrons and photons, and to incorporate counting (single photon) and integrating (multi photon) modes for the Compton photon detection. Minimizing bremsstrahlung background requires to have a short section of beam line, like introducing a chicane with soft bends to also minimize synchrotron background. Added benefits from a chicane are the separation of the Compton photon cone from the electron beam allowing ample space for the Compton photon detector, and a convenient way to separate the Compton electrons from the beam electrons in one of the soft bending magnets of the chicane. The Compton photon detector must be operable in counting and integrating mode. While this has been incorporated into a single detector at HERA, these two functions could be established by two different detectors that are positioned along the backscattered Compton photons. A pair spectrometer consisting of a variable converter (to select the appropriate rate of e^+e^- pairs in counting mode), a dipole magnet (to separate the pair-produced electrons and positrons), and position sensitive detectors could be configured for photon counting. Downstream of the pair spectrometer a radiation hard and fast (< 35 ns) position sensitive sampling calorimeter could be used to operate in integrating mode. If appropriate photomultiplier tubes are used, the sampling calorimeter can be operated in counting and integrating mode. The advantages of such a design are that the polarimeter employs multiple detection schemes, and that it is essentially luminosity independent.

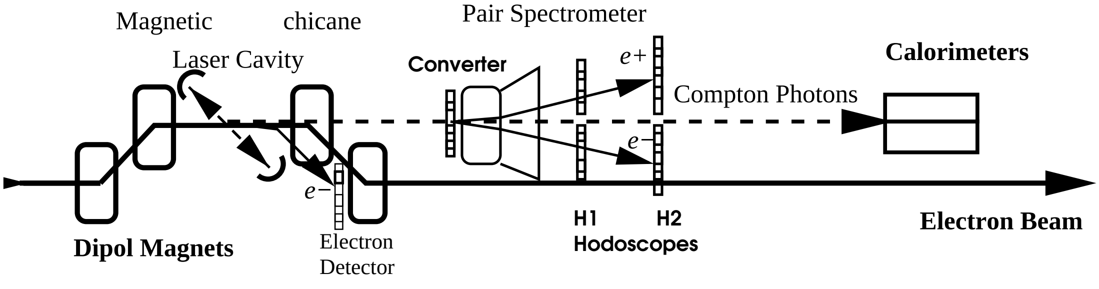

FIGURE 4. Schematic view of a possible Compton polarimeter for the EIC.

Summary

In summary, it appears that electron beam polarimetry between 3-20 GeV seems possible at the 1% level: there are no apparent show stoppers. Nevertheless, this is not easy to accomplish. It is imperative to include polarimetry in the beam lattice and the interaction region design. It is crucial to use multiple devices and even techniques to control the systematic uncertainties at the sub-1% level.

There are however several issues that require careful scrutiny. The beam crossing frequency is proposed to be somewhere between 3-35 ns. This is very different from the crossing frequencies at RHIC (106 ns) and HERA (96 ns). HERA has demonstrated that beam-beam induced depolarization becomes important at high luminosities. An entirely new concept is crab-crossing of bunches. What effect will it have on the beam polarization, and how can these effects be measured?

How important is it to measure longitudinal polarization only, or is transverse polarimetry needed as well? The longitudinal polarization is measured via rate or energy asymmetries, which are generally much easier to measure than spatial asymmetries as in the case of transverse polarization. Is polarimetry needed before, at, or after the interaction region, and how can it be incorporated with the spectrometer design? Should there be a dedicated interaction region, which is separated from the experiments?

Thus, many open questions remain to be solved before a viable option can be presented. In order to address these, and many other questions in a timely fashion, the workshop attendees have agreed to be part of an electron polarimetry task force which will be coordinated by Wolfgang Lorenzon, who will overlook the initial activities and directions.

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