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Electron polarimetry at EIC

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The Electron-Ion Collider will be the first collider to use both polarized electron beams and polarized protons and light ions . This will offer unique opportunities to study the structure of protons and nuclei and answer fundamental questions in QCD. The uncertainties on the polarization measurement translate directly into the uncertainties of final physics observables. Hence, a precise measurement of the hadron beam polarization and a good control of the uncertainties are critical for the success of the spin program at the EIC. The requirements for beam polarimetry are non-destructive with uncertainty less than 1%. At the Electron Storage Ring (ESR) and the Rapid Cycling Synchrotron (RCS), the electron beam polarization will be measured using well-established Compton polarimetry techniques. However, the EIC Compton polarimeter will face unique challenges, demanding further developments. A Mott polarimeter will also be employed at the source for initial polarization measurements. Both longitudinal and transverse polarization will be measured, with the capability to monitor polarization on a bunch-by-bunch basis. Achieving these precise measurements will be critical to controlling systematic uncertainties and ensuring the overall success of the EIC's physics objectives.

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1. Introduction

The Electron-Ion Collider (EIC) is a next-generation particle accelerator facility planned for construction at Brookhaven National Laboratory on Long Island, New York, under the leadership of the United States Department of Energy [1]. The EIC will enable the collision of high-energy polarized electron beams with polarized proton and light-ion beams, offering unprecedented capabilities to explore the fundamental structure of matter.The requirement for the polarization of the planned EIC is the capability to achieve high polarization ($\sim$ 70%) of both electron and proton beams. The precise measurements of the beam polarization would be critical to achieve the physics goal of the EIC. Accurate and precise measurements of beam polarization are essential to fulfilling the EIC's scientific objectives, as they are critical for interpreting experimental results and realizing the facility's physics goals. In the Electron Storage Ring (ESR) and the Rapid Cycling Synchrotron (RCS), electron beam polarization will be measured using well-established Compton polarimetry techniques. Furthermore, a Mott polarimeter [2] will be employed at the source to perform initial polarization measurements. This paper presents a comprehensive analysis of the design and implementation of the Compton polarimeters proposed for the ESR and RCS.

2. Compton polarimeter at Electron Storage Ring

The most commonly used technique for measuring electron beam polarization in rings and colliders is Compton polarimetry. In this method, polarized electrons scatter off 100% circularly polarized laser photons. The resulting asymmetry from the scattering process is measured through either the scattered electrons or the high-energy backscattered photons. A detailed review of previous Compton polarimeters can be found in [3–5].

A key advantage of Compton polarimetry is its sensitivity to both longitudinal and transverse polarization. The longitudinal analyzing power depends only on the energy of the backscattered photons and is expressed as:

$$A_{\text{long}} = \frac{2\pi r_0^2 a}{\left(\frac{d\sigma}{d\rho}\right)} (1 - \rho(1 + a)) \left[1 - \frac{1}{(1 - \rho(1 - a))^2}\right],$$

where r_0 is the classical electron radius, $a = (1 + 4\gamma E_{\text{laser}}/m_e)^{-1}$ (with the Lorentz factor $\gamma = E_e/m_e$), $\rho = E/E_{\max}$ is the backscattered photon energy normalized to its kinematic maximum, and $d\sigma/d\rho$ is the unpolarized Compton cross-section[6, 7].

In contrast, the transverse analyzing power depends on both the backscattered photon energy and the azimuthal angle (ϕ) of the photon relative to the transverse polarization direction. It is given by:

$$A_{\text{tran}} = \frac{2\pi r_0^2 a}{\left(\frac{d\sigma}{d\rho}\right)} \cos\phi \left[\rho(1 - a)\sqrt{\frac{4a\rho(1 - \rho)}{1 - \rho(1 - a)}}\right].$$

At the Electron Storage Ring, a Compton polarimeter is planned for installation at IR6. While a Compton polarimeter at IR6 is closer to the main experimental area, it would measure a mix of longitudinal and transverse polarization as opposed to the purely longitudinal polarization expected at the detector interaction point. The schematic layout of the Compton polarimeter placement at IR6 is shown in Figure 1.

2.1 Laser Interaction and Detector Layout

The laser interaction point (IP) is located upstream of magnet D4EF, approximately 72 meters from IP6. The photon detector is positioned ahead of the Crab Cavity, separated by 29 meters from the laser IP. To mitigate synchrotron radiation (SR) background at the photon detector, the beamline includes two weak dipoles positioned before and after the laser IP.

Electron detectors are placed 0.5 meters upstream of quadrupoles QD6 and QF5, respectively. To ensure photon transmission, QD6, QF5, and QD4 are designed with an open midplane. Magnet experts have confirmed the feasibility of creating sufficient clearance using a hole in the yoke.

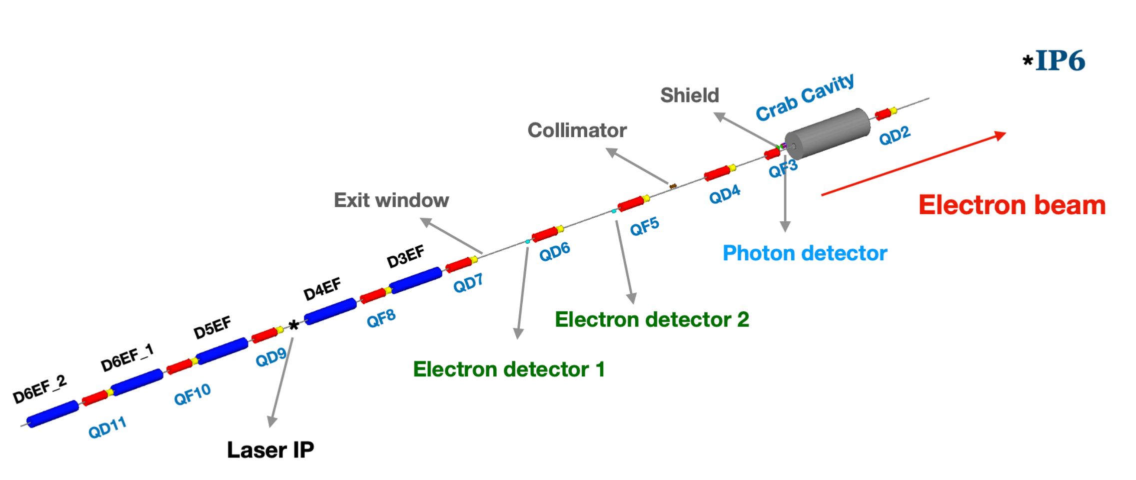


Figure 1: Layout of IR6

2.2 Photon Detector Design

The photon detector consists of two subsystems to measure both longitudinal and transverse polarization. The calorimeter measures photon energy asymmetry (P_L) for longitudinal polarization, while the position-sensitive detector measures left-right asymmetry (P_T) for transverse polarization.

For longitudinal polarization measurements, the photon detector must achieve good energy resolution, covering a range from approximately 0 to 7 GeV, along with a fast time response to handle 10 ns bunch spacing. The detector must also be radiation-hard, tolerating doses up to 80 Gy/h. A W/SciFi calorimeter with an integrated preshower detector is being considered to meet these requirements. The preshower consists of two lead planes followed by diamond strip detectors. The diamond strip detectors are expected to have segmentation between 100 and 400 μm.

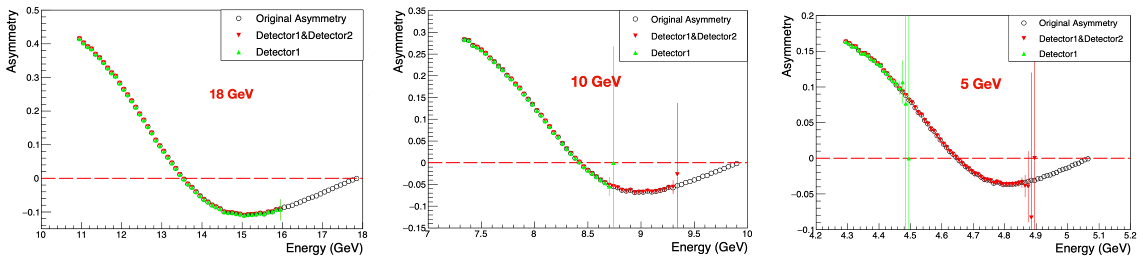
Operating in threshold-less integrating mode with effective background control will help mitigate the relatively lower energy resolution of the W/SciFi calorimeter. Simulations of detector response and background levels are ongoing to refine these design choices.

2.3 Electron Detector Design

The electron detector is optimized for longitudinal polarization measurements, as high dispersion introduced by the dipole magnet limits transverse measurements. The minimum detector width is set at 8.2 cm to capture the full electron spectrum, including the zero-crossing and endpoint, for an 18 GeV beam. To ensure sufficient resolution, segmentation with a strip pitch of approximately 550 μm is required, providing 30 bins at 5 GeV, where the spectrum is most compact.

To extend coverage and capture the zero-crossing, a second detector (Detector2) will be integrated. A diamond strip detector, similar to the JLab Hall C design [4], is being evaluated. It offers radiation hardness, fast time response, and compatibility with the required segmentation. Figure 2 illustrates the asymmetry of recoil electrons for 18 GeV, 10 GeV, and 5 GeV beams, comparing the original asymmetry, the asymmetry covered by Detector1, and the combined coverage of Detector1 and Detector2.

The FLAT-32 ASIC, currently under development for the MOLLER experiment at JLab, supports EIC timing requirements and may be employed for readout electronics.



(a) 18 GeV Asymmetry **(b)** 10 GeV Asymmetry **(c)** 5 GeV Asymmetry

Figure 2: Recoil Electron Energy Asymmetry

2.4 Laser System Requirements

Compton measurements, conducted on a timescale of approximately one minute, require an average of one backscattered photon per bunch crossing. This can be achieved using a pulsed laser system with around 5 W average power at 532 nm.

The proposed laser system includes a gain-switched diode seed laser operating at variable frequency with 10 ps pulses at 1064 nm. A fiber amplifier provides 10-20 W average power, and an optional frequency-doubling system, such as LBO or PPLN, can be included [9]. An insertable in-vacuum mirror will allow for laser polarization adjustments. The laser exit window is positioned near QD7, perpendicular to the scattered photon trajectory. The schematic layout of the proposed laser system is illustrated in Figure 3.

2.5 Background

Synrad+ was utilized to simulate synchrotron radiation (SR), record photon data, and integrate it into the Geant4-based electron polarimeter setup [8]. A tungsten shield, 2 cm in thickness, is required to block SR from strong dipoles (D6EF and D3EF). However, this shield degrades energy resolution and renders position measurements nearly impossible. To mitigate these issues, two weak

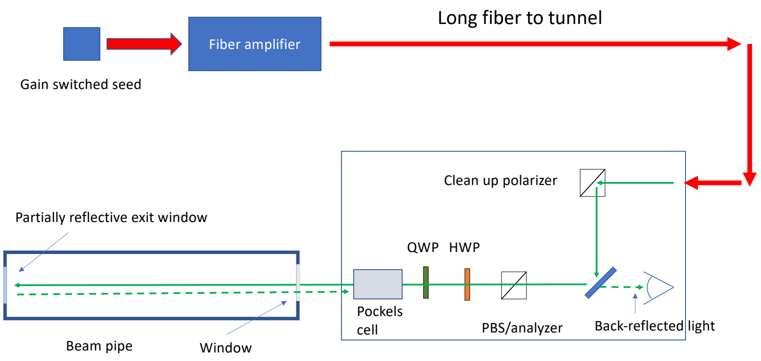


Figure 3: Schematic layout of the proposed laser system, showing the position of the gain-switched seed laser, fiber amplifier, and frequency-doubling components.

dipoles are introduced before and after the laser interaction point (IP) to prevent SR from the strong dipoles from reaching the photon detector. SR originating from the quadrupole QD9 reliably enters the photon detector's acceptance range.

In the current beamline configuration, a 2 mm beryllium exit window combined with a 0.5 mm tungsten shield effectively blocks SR. A 1.2 mm tungsten shield is required, assuming the beam tail comprises 5% of the core's integral. The transverse dimensions of the beam tail are approximately four times the horizontal root-mean-square (RMS) beam size ($4\sigma_x$) and ten times the vertical RMS beam size ($10\sigma_y$) relative to the core.

Collisions between electrons and residual hydrogen gas (H_2) in the beam pipe are considered, assuming a uniform gas pressure of 1.0×10^{-8} mbar, typical around IP6. This assumption will be updated if more precise data from the electron polarimeter region becomes available. Bremsstrahlung events along the 40-meter beamline, focused around the laser IP, were generated by integrating the double-differential cross section for Bremsstrahlung, accounting for beam dynamics. The total cross section for photons with $E_\gamma > 0.1$ GeV is 185.723 mb. Photon energies range from 0.1 GeV to the beam energy, with most photons emitted in the forward direction. Scattered electrons are deflected by the magnet, ensuring that only Bremsstrahlung photons reach the photon detector.

The photon detector registers approximately 1.76×10^5 GeV/s of energy from Bremsstrahlung. With 2.29×10^7 bunches per second, the energy deposited per bunch from Bremsstrahlung is approximately 0.0077 GeV. By comparison, Compton events deposit around 3.4 GeV per bunch, making the Bremsstrahlung contribution negligible.

3. Rapid Cycling Synchrotron and Polarimetry Challenges

Rapid Cycling Synchrotron (RCS) will accelerate, accumulate, and inject up to two 28 nC polarized electron bunches per second into the EIC electron storage ring (ESR). At peak current, the RCS receives two trains of four 7 nC bunches, totaling 8 bunches, injected from the LINAC at 400 MeV. The LINAC operates at 50-100 Hz, filling the RCS within 0.04-0.08 seconds by delivering two 7 nC bunches per cycle. These bunches occupy two trains of four adjacent 591 MHz buckets, requiring a 1.69 ns rise time for injection into neighboring buckets. A specialized RF-crab cavity kicker system provides the necessary kick profile. The bunch trains are then accelerated to 1 GeV, held for 0.15 seconds, and merged into two 28 nC bunches [1].

Polarimetry in the RCS presents several challenges. The analyzing power depends strongly on beam energy, and the low average current, combined with short bunch dwell times, complicates measurements. A Compton polarimeter can be employed to measure polarization in the RCS. Measurements can be averaged over multiple bunches, and tagging accelerating bunches allows extraction of information on bunches at fixed energy. Accurate measurements require operation in multiphoton mode, producing approximately 1000 backscattered photons per crossing. The RCS polarimeter is to be placed in the IR6 region; however, since PSTP2024, the RCS has been relocated, so the position of the Compton polarimeter will have to be determined. Ongoing studies aim to refine the design and ensure the polarimeter's integration aligns with operational requirements and system constraints.

4. Conclusions and Future Work

Precise electron polarimetry is essential for the EIC's success. A Compton polarimeter at IR6 in the Electron Storage Ring (ESR) will measure both longitudinal and transverse polarization, with a focus on minimizing synchrotron radiation background and achieving high-resolution measurements. Development of the Compton laser system and detector simulations is ongoing.

In the Rapid Cycling Synchrotron (RCS), polarimetry faces challenges like low beam currents and short bunch dwell times. Design efforts focus on using multiphoton mode measurements and optimizing detector placement.

Future work will refine detector designs, beamline configurations, and shielding to ensure accurate measurements. These efforts are crucial for achieving the EIC's polarization goals and advancing its scientific objectives.

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