2021 AI4EIC-exp workshop [102], which bring together the communities directly using AI technologies and provide a venue for discussion and identifying the specific needs and priorities for EIC.

8.6 Lepton and Hadron Polarimetry

Rapid, precise beam polarization measurements will be crucial for meeting the goals of the EIC physics program as the uncertainty in the polarization propagates directly into the uncertainty for relevant observables (asymmetries, etc.). In addition, polarimetry will play an important role in facilitating the setup of the accelerator.

The basic requirements for beam polarimetry are:

- Non-destructive with minimal impact on the beam lifetime
- Systematic uncertainty on the order $\frac{dP}{P} = 1\%$ or better
- Capable of measuring the beam polarization for each bunch in the ring - in particular, the statistical uncertainty of the measurement for a given bunch should be comparable to the systematic uncertainty
- Rapid, quasi-online analysis in order to provide timely feedback for accelerator setup

8.6.1 Electron Polarimetry

The most commonly used technique for measuring electron beam polarization in rings and colliders is Compton polarimetry, in which the polarized electrons scatter from 100% circularly polarized laser photons. The asymmetry from this reaction is measured via the scattered electrons or high energy backscattered photons. A brief review and description of several previous Compton polarimeters can be found in [103]. A particular advantage of Compton polarimetry is that it sensitive to both longitudinal and transverse polarization.

The longitudinal analyzing power depends only on the backscattered photon energy and is given by,

$$A_{\text{long}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)}(1-\rho(1+a))\left[1-\frac{1}{(1-\rho(1-a))^2}\right], \tag{8.1}$$

where r_o is the classical electron radius, $a = (1+4\gamma E_{\text{laser}}/m_e)^{-1}$ (with the Lorentz factor $\gamma = E_e/m_e$), ρ is the backscattered photon energy divided by its kinematic maximum, E_γ/E_γ^{max}, and $d\sigma/d\rho$ is the unpolarized Compton cross section. In contrast, the transverse analyzing power depends both on the backscattered photon energy and the azimuthal angle (ϕ) of the photon (with respect to the transverse polarization direction);

$$A_{\text{tran}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)}\cos\phi\left[\rho(1-a)\frac{\sqrt{4a\rho(1-\rho)}}{(1-\rho(1-a))}\right]. \tag{8.2}$$

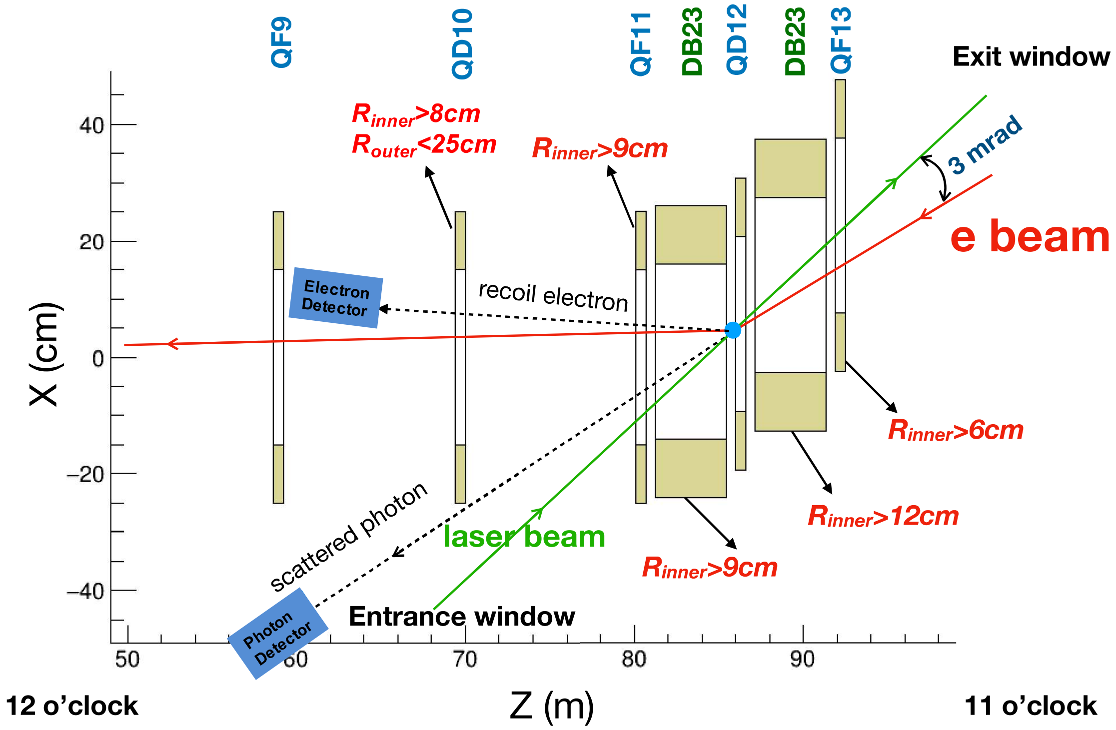

Figure 8.29: Layout of the Compton polarimeter at IP 12. In this figure the electron beam travels from right to left - the laser beam collides with the electrons just downstream of QD12. The dipole just downstream of the collision (DB12) steers the unscattered electrons allowing detection of the backscattered photons about 25 m downstream of the collision. DB12 also momentum-analyzes the scattered electrons, facilitating use of a position sensitive electron detector downstream of QD10. Also noted in the figure are constraints on required apertures of the magnets needed to allow transport of the laser beam, backscattered photons, and scattered electrons.

This azimuthal dependence of the asymmetry results in an "up-down" asymmetry (assuming vertically polarized electrons) and requires a detector with spatial sensitivity.

Plans for electron polarimetry at EIC include a Compton polarimeter at IP 12 or near IP 6. A Compton polarimeter could be easily accommodated at IP 12 (where the electron beam is primarily vertically polarized), however this location is far from IP 6 where the main physics detector will be located. Although the region near IP 6 is crowded, a Compton polarimeter can also be placed in this area with careful attention to integration of the polarimeter with the beamline elements. It is worth noting that a Compton polarimeter at IP 6, while closer to the main experiment, would measure a mix of longitudinal and transverse polarization (P_L=70% at 18 GeV and P_L=98% at 5 GeV), rather than the purely longitudinal polarization expected at the detector IP. A schematic of the placement of the Compton polarimeter at IP 12 is shown in Fig. 8.29 and at IP 6 in Fig. 8.30.

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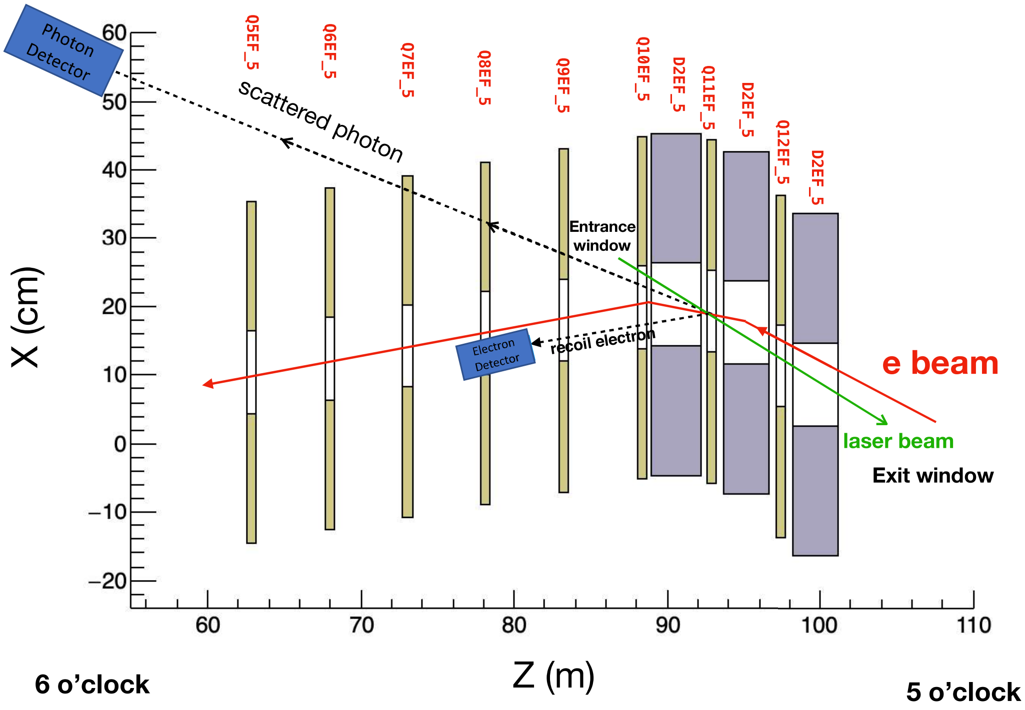

Figure 8.30: Layout of the Compton polarimeter at IP 6. The laser-electron collision point is at Q11EF. In contrast to the IP 12 layout, the backscattered photons will not clear the outer aperture of the downstream quadrupoles. However, an opening for the photons can be accommodated between the quadrupole coils and by creating a small hole in quadrupole steel where needed.

Nominal electron beam parameters at IP 12 are provided in Table 8.9. Beam properties are identical at the IP 6 Compton location, with the exception of the beam size, which is about 40% larger horizontally and about a factor of 2 smaller vertically. Of particular note is the relatively short bunch lifetime at 18 GeV. Since measurement of transversely polarized electron beams is generally more time consuming than for longitudinal polarization, we focus on measurements at IP 12 to set a conservative upper limit on the time required for polarization measurements. Table 8.10 shows the average transverse analyzing power, luminosity, and time required to make a 1% (statistics) measurement of the beam polarization for an individual bunch, assuming a single Compton-scattered event per crossing. The constraint of having a single event per crossing is related to the need to make a position sensitive measurement at the photon and electron detectors. Note that even with this constraint, the measurement times are relatively short and, in particular, shorter than the bunch lifetime in the ring.

Table 8.9: Beam parameters at IP12 for the EIC nominal electron beam energies.

Parameter	5 GeV	10 GeV	18 GeV
Bunch frequency [MHz]	99	99	24.75
Beam size (x) [µm]	390	470	434
Beam size (y) [µm]	390	250	332
Pulse width (RMS) [ps]	63.3	63.3	30
Intensity (avg.) [A]	2.5	2.5	0.227
Bunch lifetime [min]	>30	>30	6

Table 8.10: Transverse asymmetries, measurement times needed for a 1% statistical measurement for one bunch and needed luminosities for three different beam energies for a 532 nm laser.

E_{beam} [GeV]	σ_{unpol} [barn]	$\langle A_\gamma \rangle$	t_γ[s]	$\langle A_e \rangle$	t_e[s]	L[1/(barn·s)]
5	0.569	0.031	184	0.029	210	1.37E+05
10	0.503	0.051	68	0.050	72	1.55E+05
18	0.432	0.072	34	0.075	31	1.81E+05

Even for a single electron bunch (circulating through the ring at a frequency of ≈75 kHz), the luminosities provided in Table 8.10 can be readily achieved using a single-pass, pulsed laser. Since the electron beam frequency varies with energy, it would be useful to have a laser with variable pulse frequency. A laser system based on the gain-switched diode lasers used in the injector at TJNAF [104] would provide both the power and flexible pulse frequency desired. Such a system would make use of a gain-switched diode laser at 1064 nm, amplified to high average power (10-20 W) via a fiber amplifier, and then frequency doubled to 532 nm using a PPLN or LBO crystal. The repetition rate is set by the applied RF frequency to the gain-switched seed laser.

The detector requirements for the EIC Compton polarimeters are dictated by the requirement to measure the transverse and longitudinal polarization simultaneously. For longitudinal polarization, this means the detectors will require sensitivity to the backscattered photon and scattered electron energy. The photon detector can make use of a fast calorimeter, while the electron detector can take advantage of the dispersion introduced by the dipole after the collision point to infer the scattered electron energy from a detector with position sensitivity in the horizontal direction.

To measure transverse polarization, position sensitive detectors are required to measure the up-down asymmetry. This is particularly challenging given the very small backscattered photon cone at the highest EIC beam energy. At HERA, the vertical position of the backscattered photon was inferred via shower-sharing between the optically isolated segments of a calorimeter [105]. Calibration of the non-linear transformation between the true

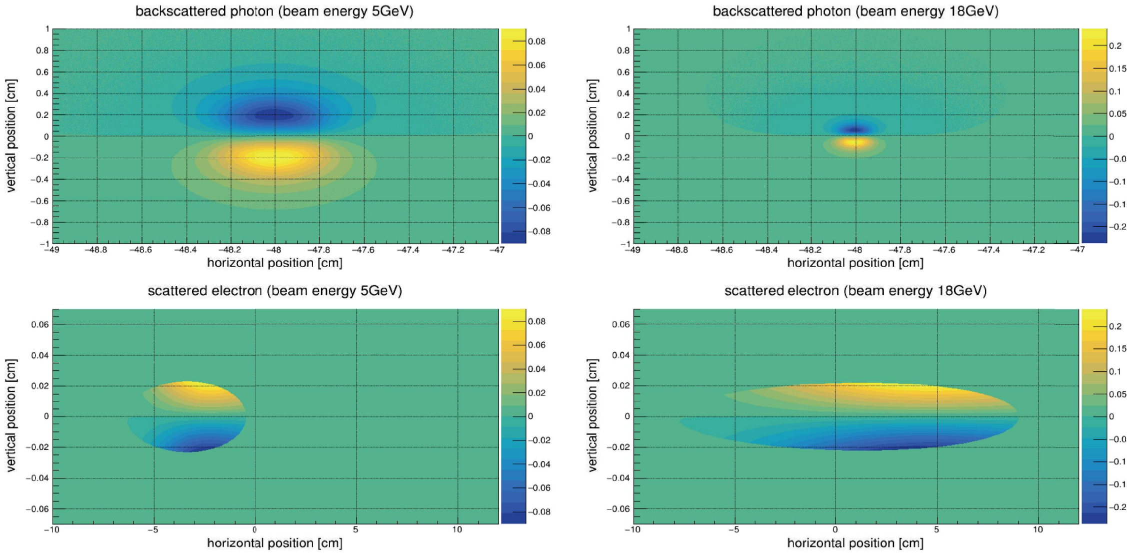

Figure 8.31: Compton (transverse) analyzing power at the nominal photon and electron detector positions for the IP 12 polarimeter.

vertical position and the energy-asymmetry in the calorimeter was a significant source of uncertainty. The detector for the EIC Compton will measure the vertical position directly via segmented strip detectors, avoiding the calibration issues faced at HERA.

The transverse Compton analyzing power vs. position at the detector for the IP 12 Compton for the backscattered photons and scattered electrons at 5 and 18 GeV is shown in Fig. 8.31. The backscattered photon cone will be largest at the lowest energy (5 GeV) - this will determine the required size of the detector. The distribution at 18 GeV, where the cone is the smallest, sets the requirements for the detector segmentation. Note that the scattered electrons are significantly more focused than the photons. Monte Carlo studies indicate that the transverse polarization can be reliably extracted at 18 GeV with a vertical detector segmentation of 100 µm for the photon detector and 25 µm for the electron detector. The detector size should be at least $16\times16\,\mathrm{mm}^2$ for the photons and 10 cm × 1 mm for the scattered electrons. The horizontal segmentation for the electron detector can be much more coarse due to the large horizontal dispersion introduced by the dipole. Note that for the IP 6 Compton, the same conclusions apply for the photon detector size and strip-detector segmentation assuming the detector is the same distance from the laser-electron interaction. Initial estimates for the IP 6 Compton electron detector suggest that the needed detector size will be similar to the IP 12 detector, about 8 cm × 1 mm, and the same general conclusions with respect to the relative vertical and horizontal strip detector pitch will apply.

Diamond strip detectors are a feasible solution for both the photon and electron detectors. Diamond detectors are extremely radiation hard and are fast enough to have response times sufficient to resolve the minimum bunch spacing (10 ns) at EIC. Tests of CVD diamond with specialized electronics have shown pulse widths on the order of 8 ns [106]. For the photon detector, about 1 radiation length of lead will be placed in front of the strip detectors to convert the backscattered photons. As an alternative to diamond detectors, HVMAPS detectors are also under consideration. The radiation hardness and time response of HVMAPS will need to be assessed to determine their suitability for this application.

As noted earlier, the photon detector will also require a calorimeter to be sensitive to longitudinal components of the electron polarization. Only modest energy resolution is needed; radiation hardness and time response are more important requirements for this detector - a tungsten powder/scintillating fiber calorimeter would meet these requirements.

Backgrounds are an important consideration for Compton polarimetry as well. The primary processes of interest are Bremsstrahlung and synchrotron radiation. Monte Carlo studies have shown that the contribution from Bremsstrahlung should be small for a beamline vacuum of 10^{-9} Torr. Synchrotron radiation, on the other hand, will be a significant concern. Careful design of the exit window for the backscattered photons will be required to mitigate backgrounds due to synchrotron. The electron detector is not in the direct synchrotron fan, but significant power can be deposited in the detector from one-bounce photons. This can be mitigated by incorporating tips or a special antechamber in the beampipe between the Compton IP and the detector [107]. The electron detector will also be subject to power deposited in the planned Roman Pot housing due to the beam Wakefield. Preliminary simulations indicate the Wakefield power should not be large enough to cause problems, but this will need to be considered in the detailed Roman Pot design.

In addition to measurements in the EIC electron ring, it is important to determine the electron beam polarization in or just after the Rapid Cycling Synchrotron (RCS) in order to facilitate machine setup and troubleshoot possible issues with the electron beam polarization. In the RCS, electron bunches of approximately 10 nC are accelerated from 400 MeV to the nominal beam energy (5, 10, or 18 GeV) in about 100 ms. These bunches are then injected into the EIC electron ring at 1 Hz. The short amount of time each bunch spends in the RCS, combined with the large changes in energy (and hence polarimeter analyzing power and/or acceptance) make non-invasive polarization measurements, in which the the RCS operates in a mode completely transparent to beam operations, essentially impossible. However, there are at least two options for making intermittent, invasive polarization measurements.

The first, and perhaps simplest from a polarimetry perspective, would be to operate the RCS in a so-called “flat-top” mode [108]. In this case, an electron bunch in the RCS is accelerated to its full or some intermediate energy, and then stored in the RCS at that energy while a polarization measurement is made. In this scenario, a Compton polarimeter similar to that described above could be installed in one of the straight sections of the RCS. The measurement times would be equivalent to those noted in Table 8.10 (since those are for a single stored bunch), i.e., on the order of a few minutes.

Another option would be to make polarization measurements in the transfer line from the RCS to the EIC electron ring. In this case, one could only make polarization measurements averaged over several bunches. In addition, the measurement would be much more time consuming due to the low average beam current ($\approx$ 10 nA) since the 10 nC bunches are extracted at 1 Hz.

The measurement time at 10 nA using a Compton polarimeter similar to the one planned for IP 12 would take on the order many days. The IP12 Compton limits the number of interactions to an average of one per crossing to count and resolve the position of the backscattered photons. A position sensitive detector that could be operated in integrating mode, would allow more rapid measurements. However, the required position resolution (25-100 µm) would be very challenging for a detector operating in integrating mode.

An alternative to Compton polarimetry would be the use of Møller polarimetry. Møller polarimeters can be used to measure both longitudinal and transverse polarization and can make measurements quickly at relatively low currents. The longitudinal and transverse Møller analyzing powers are given by,

$$A_{ZZ} = -\frac{\sin^2\theta^*(7+\cos^2\theta^*)}{(3+\cos^2\theta^*)^2}, \tag{8.3}$$

$$A_{XX} = -\frac{\sin^4\theta^*}{(3+\cos^2\theta^*)^2}, \tag{8.4}$$

where A_{ZZ} is the analyzing power for longitudinally polarized beam and target electrons, A_{XX} for horizontally polarized beam and target electrons, and θ^* is the center-of-mass scattering angle. Note that $A_{YY} = -A_{XX}$. The magnitude of the analyzing power is maximized in both cases at $\theta^* = 90$ degrees, where $|A_{ZZ}| = 7/9$ and $|A_{XX}| = 1/9$.

Extrapolating from typical measurement times from the Møller polarimeters at TJNAF (which provide a statistical precision of 1% for the longitudinal polarization in about 15 minutes for a 1 µA beam on a 4 µm iron target), we estimate that a 10% measurement could be made in about 1.5 hours in the RCS to EIC transfer line. This could perhaps be shorter depending the maximum foil thickness that could be used as the polarimeter target.

A key drawback of Møller polarimetry is that the solid foil targets are destructive to the beam, so cannot be carried out at the same time as normal beam operations. An additional complication is the requirement for a magneto-optical system to steer the Møller electrons to a detector system. In the experimental Hall A at Jefferson Lab, the Møller spectrometer employs several quadrupoles of modest length and aperture, combined with a dipole to deflect the Møller electrons into the detector system. The whole system occupies about 7 m of space along the beamline, but the space used by the quadrupoles can also be used for beam transport during normal operations (i.e., when Møller measurements are not underway).

The preferred choice for polarimetry at the RCS is a Compton polarimeter in the RCS ring, with measurements taking place during “flat-top” mode operation. However, if this “flat-top” mode is not practical, then a Møller polarimeter in the RCS transfer line could serve as a reasonable fallback, albeit with reduced precision and a larger impact on the beamline design.