Letter of Intent for a pulsed laser system for Compton polarimetry at the future EIC facility

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1. Description of project

This letter focuses on the laser system needed in order to achieve the most stringent goals of the the EIC design. In summary we find that a mode-locked pulsed laser cavity would be needed in order to be able to meet all the requirements of the EIC polarimetry program. While simpler to implement, a CW cavity would incur a significant luminosity penalty due to the crossing angle between the laser and the electron beam.

The goals for this letter are to:

- establish a baseline for further calculations regarding the Compton laser system;
- prove the need for a high-finesse cavity in order to meet the requirements at the EIC;
- attract laser optics experts to build a robust laser system;
- spur further discussion with the EIC polarimetry WG regarding technology choices for the EIC polarimeters.

This document presents the polarimetry requirements at the EIC followed by a description of Compton scattering (the primary tool foreseen in both the BNL and JLab designs for polarimetry measurements). Further on, the currently available machine details are used to determine the feasibility of different measurement techniques that could be employed. Lastly, the preliminary conclusions are drawn and further work is mapped out until the next call for EIC R&D proposals.

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2. Polarimetry requirements at the EIC

The polarimetry requirements at the EIC have been detailed within the Polarimetry WG [1]. In this LOI we will focus only on electron polarimetry.

- high precision polarization measurement with small systematics ($\leq 1\%$)
- flexible spin orientation bunch to bunch
- ability to measure polarization bunch by bunch in a reasonable period of time
- ability to measure polarization for small bunch charge

3. Compton scattering basics

Compton polarimetry has a long history of use at both collider and fixed target facilities because it can provide a non-destructive measurement. It has also been the standard technique used in storage rings (such as HERA). Recently, high precision results have been obtained in Hall C at Jefferson Lab [2] with lower than 1% systematics.

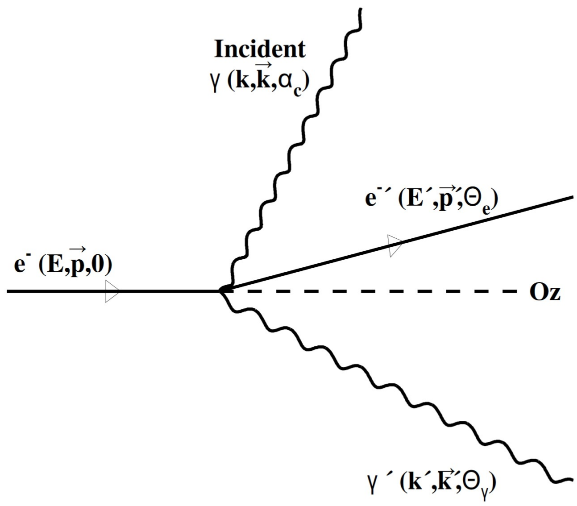

Figure 1: Compton scattering kinematics [3].

The kinematics for Compton scattering can be seen in figure 1. An important feature of the detailed derivation presented in [3] is the non-zero crossing angle (α_C) between the incoming photon and the electron direction. While it complicates the derivation, it is important because in practice we cannot have a laser system on the same axis as the electron beam.

The scattering process is described in detail in several papers (see [3] or references in [4]). This letter follows the formalism presented in [4]. The unpolarized cross section is given by equation 1 and can be see in figure 3 as a function of the fractional photon energy for three possible energies of the electron beam.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\rho} = 2\pi r_0^2 a \left[\frac{\rho^2(1-a)^2}{1-\rho(1-a)} + 1 + \left(\frac{1-\rho(1+a)}{1-\rho(1-a)} \right)^2 \right] \tag{1}$$

where

- r_0 is the classical electron radius 2.819 10^{-13} cm,
- $\rho = k'/k'_{max}$ is the scattered photon energy normalized to the maximum energy,
- and the kinematical factor $a = \left(1 + 4kE_{\mathrm{laser}}/m^2\right)^{-1}$.

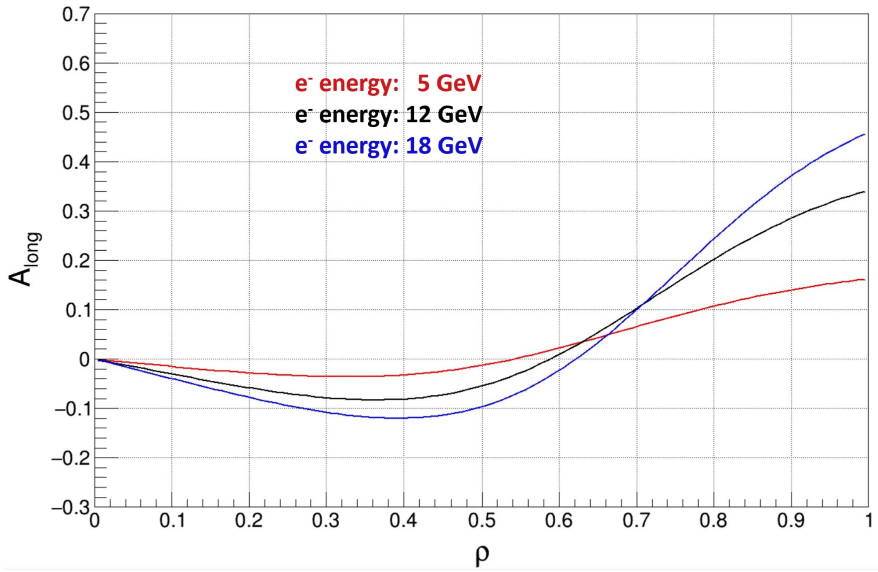

Figure 2: Compton longitudinal asymmetry as a function of backscattered photon energy, for electron energy 5, 12 and 18 GeV (red, black and blue respectively).

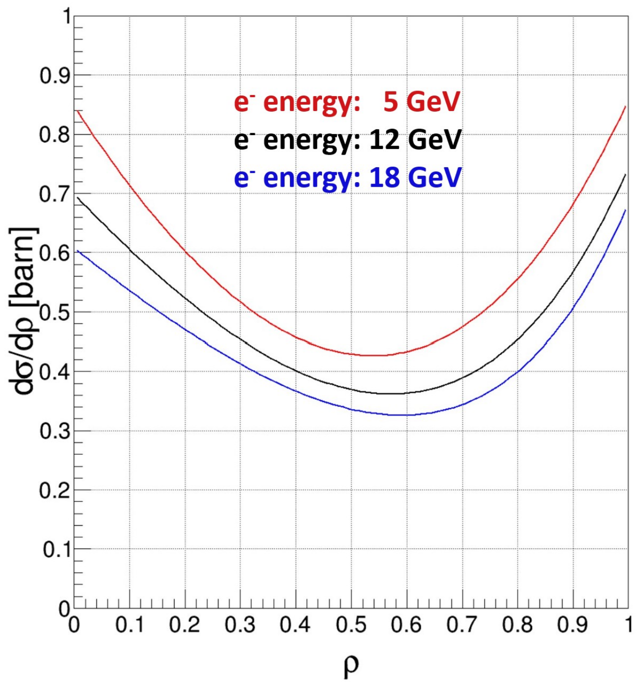

Figure 3: Compton unpolarized cross-section as a function of backscattered photon energy, for electron energy 5, 12 and 18 GeV (red, black and blue respectively).

The longitudinal and transverse asymmetries are given by equations 2 and 3 below:

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

$$A_{trans} = \frac{2\pi r_0^2 a}{\mathrm{d}\sigma/\mathrm{d}\rho}\cos(\phi)\left[\rho(1-a)\frac{\sqrt{4a\rho(1-\rho)}}{(1-\rho(1-a))}\right] \tag{3}$$

Figure 2 shows the longitudinal asymmetry as a function of the fractional photon energy. One important feature of the asymmetry is the change in sign that occurs between 0.5 and 0.65 of maximal photon energy. The analysis in this letter is done for a 532 nm laser wavelength. A smaller laser wavelength would increase the maximum analyzing power, however the most robust laser systems are Nd:YAG providing a 1064 nm laser which can be doubled to 532 nm with the use of PPLN crystal.

Figure 4 shows the transverse asymmetry (on the z-axis) as a function of the fractional photon energy and azimuthal scattering angle. Unlike the longitudinal asymmetry, this asymmetry has an important positional dependence (it is generally measured as an up-down asymmetry).

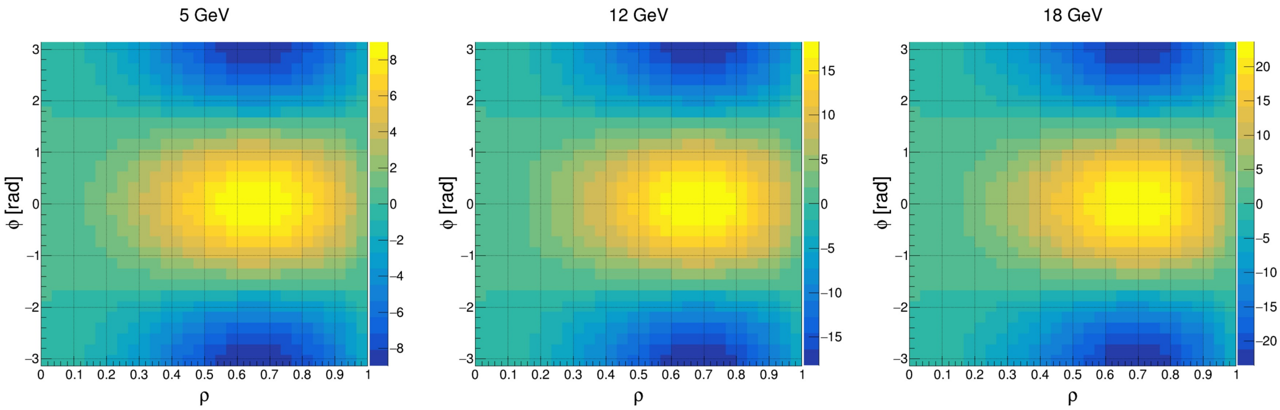

Figure 4: Compton transverse asymmetry (z-axis) as a function of back-scattered photon energy and azimuthal scattering angle.

4. Results for different measurement techniques

There are two types of laser systems that could be employed for Compton polarimetry: a continuous wave laser (CW) or a pulsed laser (timed synchronously with the electron bunch). For powers larger than a few tens of Watts a Fabry-Perot cavity needs to be employed.

Following the derivation in [3] and [5] one can determine the luminosity for a CW and pulsed laser system as a function of different crossing angle:

$$\mathcal{L}_{\rm CW} \approx \frac{1+\cos(\alpha_C)}{\sqrt{2\pi}\sin(\alpha_C)} \frac{I_e}{e} \frac{P_L \lambda}{hc^2} \frac{1}{\sqrt{\sigma_e^2+\sigma_\gamma^2}} \tag{4}$$

$$\mathcal{L}_{\rm pulsed} \approx \frac{1+\cos(\alpha_C)}{2\pi\sin(\alpha_C)} \frac{I_e}{e} \frac{c}{f_{beam}} \frac{P_L \lambda}{hc^2} \frac{1}{\sqrt{\sigma_e^2+\sigma_\gamma^2}} \left(\sigma_{e,z}^2+\sigma_{\gamma,z}^2+\frac{\sigma_e^2+\sigma_\gamma^2}{\sin^2(\alpha_c/2)}\right)^{-1/2} \tag{5}$$

For this derivation it was assumed that the transverse size in x and y is symmetric for both the laser and the electron beams (the equations can be easily generalized for different profiles).

In order to continue the calculation we use the following machine([6] based on the BNL EIC machine design) and laser parameters:

- Laser wavelength: 532 nm
- Laser power : 1 kW (requiring a cavity)
- Laser transverse size: 100 μm
- Laser longitudinal(z) size: 12 ps
- e^- bunch charge: 10 nC (this calculation is done for 1 bunch)
- e^- beam transverse size: 100 μm
- e^- beam longitudinal(z) size: 13 ps
- e^- bunch frequency: 78 kHz

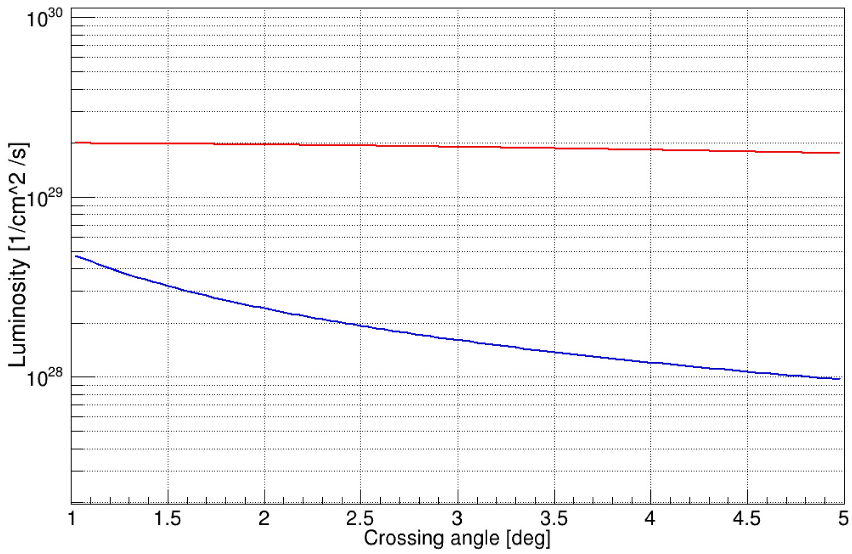

Figure 5: Luminosity for a pulsed laser system (in red) and continuous wave laser system (blue) as a function of crossing angle.

Figure 5 shows the luminosity for the two types of laser system with the parameters detailed above. One can see that while the CW system has a strong dependence on crossing angle the pulsed system sees only a small drop in luminosity all the way up to 5 degrees (the HERA polarimeter had a crossing angle of 3.3 degrees).

As in [3] let us consider three types of measurements that could determine the polarization of the electron bunch:

- Differential (single photon/electron) measurement: each scattered photon/electron can be individually measured. The asymmetry as a function of energy can be obtained and compared to the calculated analyzing power (as in figure 2);
- Integrated (multiple photon/electron) measurement: for each "interaction" of the electron beam with the laser we obtain multiple scattered particles. The asymmetry is averaged over the entire energy range;
- Energy weighted integrated measurement: in this case we either measure in a limited energy range $[E_-, E_+]$ or the scattered particles produce a signal proportional to the their energy. The measured asymmetry will be energy weighted.

The raw asymmetries measured in these three methods will be significantly different (the averaged asymmetry in the integrated method will be reduced because of the change of sign at low energies). Ultimately the quantity of interest is time needed to reach a certain level of precision. As detailed in [3] this time is inversely proportional to the square of the raw asymmetry in each method:

$$t_{meth} = \left(\mathcal{L}\ \sigma_{\mathrm{Compton}}\ \mathrm{P_e^2 P_\gamma^2} \left(\frac{\Delta \mathrm{P_e}}{\mathrm{P_e}} \right)^2\ \mathrm{A^2_{meth}} \right)^{-1} \tag{6}$$

The $\mathrm{A^2_{meth}}$ for the integrated, energy weighted integrated, and differential methods can be ordered as:

$$\langle \mathrm{A} \rangle^2 < \frac{\langle \mathrm{E} \cdot \mathrm{A} \rangle^2}{\langle \mathrm{E}^2 \rangle} < \langle \mathrm{A}^2 \rangle \tag{7}$$

For this letter we will focus on estimation of laser power needed for a longitudinal measurement, however a similar method would be appropriate to use for transverse measurements. The following will give estimates for times required to measure **a single electron bunch** polarization.

Differential measurement

For this method we should expect to have at most 1 photon/electron per crossing of the measured electron bunch to clearly associate the asymmetry with each event. Table 4 shows the time needed for a 1% electron beam polarization measurement with this method. We assume the same electron beam and laser parameters as detailed above. For this calculation we assumed a laser polarization of 100% and an electron beam polarization of 85%.

beam energy [GeV]	Unpol Xsec[barn]	$\langle A_{\text{long}} \rangle^2$	t[s]
5	0.569	0.0061	29
12	0.482	0.0244	7
18	0.432	0.0414	4

Table 1: Unpolarized cross sections, asymmetry, and time needed to obtain a 1% statistical measurement, for a single electron bunch, for three electron beam energies.

From the assumption of at most 1 photon per crossing we can estimate the luminosity needed for this measurement. Comparing this to the calculated luminosity for a 1 kW laser system (see figure 5) we can estimate the power needed to obtain this precision in the times listed.

beam energy [GeV]	Unpol Xsec[barn]	$\mathcal{L}$ [1/(barn^{2}s)]	Laser Power [kW]
5	0.569	137439	0.687
12	0.482	162139	0.811
18	0.432	180968	0.905

Table 2: Luminosity and laser power needed to achieve measurement times listed in table 4.

Integrated measurement

For the integrated measurements we use the luminosity at 3.3 degrees for the pulsed laser system from figure 5 and the appropriate raw asymmetry (and the same unpolarized cross sections as in table 4). Table 4 lists the times a 1 kW pulsed laser system would require to measure the longitudinal polarization of an electron beam for three different energies (we still assume 100% laser polarization and 85% electron beam polarization).

beam energy [GeV]	$\langle A_{\text{long}} \rangle^2$	time [s]	$\frac{\langle \mathrm{E} \cdot \mathrm{A} \rangle^2}{\langle \mathrm{E}^2 \rangle}$	time [s]
5	0.0012	104	0.0022	55
12	0.0033	43	0.0064	22
18	0.0041	39	0.0085	19

Table 3: Times needed to reach a 1% statistical precision for the integrated method (columns 2 and 3) and energy weighted integrated method (columns 4 and 5). These estimates are for a single electron bunch.

5. Conclusions and further work

Considering the luminosity difference between a CW and pulsed system the time needed for be able to make a measurement similar to those detailed above would be a factor of ≈12 larger. Furthermore, in order to be able to differentiate between different bunch crossings would require a very fast detector. While a CW cavity is more robust it would not be able to make measurements in a short enough period of time (considering that at the higher energies it is estimated that the electron bunches will be replaced every few minutes).

A pulsed laser system synchronized to the electron bunches and scanning the different bunches would allow for measurements of each individual bunch. The results in tables 4 and 4 are for only one bunch and do not take into account the time needed to measure the background (as a first estimate we can assume it would take at least the same amount of time). The results show that we can achieve all the requirements detailed in section 2 only if we employ a cavity with at least 600 Watts of power. While the differential measurement shows factor of 2 improvement over the energy weighted integrated method it can be significantly more sensitive to high backgrounds and would require different powers inside the cavity at different energies in order to achieve the desired 1 photon per crossing. On the other hand the integrated energy weighted method allows for decreased times by increasing the laser power. A very fast detector would be required even for a pulsed system if we intend to measure the polarization of all bunches at the same time. However, a setup where the laser scans through the different bunches sequentially is a reasonable fallback considering the relative short times needed for a 1% statistical precision.

Until the next EIC R&D call for proposals we plan to study the transverse asymmetry and obtain similar measurement times for the different measurement methods. Furthermore, we plan to develop a design for a state of the art laser system which would meet all requirements for the polarimeter together with a detailed budget.

References

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