Some Design Considerations for the Hall C Compton Electron Detector

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Abstract

Some of the design parameters related to the Compton electron detector for the Hall C Compton polarimeter are discussed. This represents my current understanding of the detector requirements, and details work to be done in order to move towards a final design.

1 Motivation

The electron detector would have two main uses:

1. Energy calibration of the photon detector using the electron detector as a photon energy tagger.
2. "Independent" standalone determination of the beam polarization.

The detector would be positioned either just before or just after the fourth dipole in the magnetic chicane. The magnetic field of the third dipole of the chicane is then used to momentum analyze the scattered electrons. By the fourth dipole, the electrons are typically displaced by a few centimeters from the beam.

The electron detector must have certain design characteristics to achieve optimal performance:

- *granularity*: With the Compton edge maximally a few cm away from the primary beam, it is necessary to have granularity for good momentum resolution. However, the granularity (referred to hereafter as the "strip pitch") need not be less than about 100 μm, the typical size of the electron and laser beam spots at the Compton interaction point.
- *high rate capability*: Typical maximal rates are in the 50 kHz range. This is especially important at low (1 GeV) beam energies, where the Compton asymmetry decreases in magnitude. High rate capability is also important given that a pulsed laser will be used in Hall C. Depending on the laser pulse structure (which to our knowledge is not yet decided), this can result in high instantaneous rates in both the electron and photon detectors.

- *radiation hardness*: Given that the detector is located as close as possible to the primary electron beam, it is beneficial for it to be as impervious to radiation damage as possible. Additionally, a linear motion mechanism that removes the detector during beam tuning and coil pulsing is necessary. It is also desirable for the detector to have a positioning mechanism, over a range of order cm, so that variability in beam conditions and beam position can be accounted for.

Based on these considerations, Hall A has used a four-plane telescope of silicon detectors. Mainz has used a scintillating fiber detector.

For Hall C, we are pursuing silicon and diamond strip counters as possible technologies, based on the experience of Hall A.

2 Hall A Compton polarimeter

A schematic of the electron detector for the Hall A Compton polarimeter is shown in Fig. 1. The detector [1, 2] consists of four planes of silicon detectors, with an interplane separation of 1 cm. Each plane has 48 silicon microstrips, with a strip pitch of 650 μm. The planes are staggered to achieve a position resolution of 200 μm. The trigger for the detector generally requires that three of four planes fire. This requirement, with the staggering of plane to cover dead spaces between strips, is found to give a detection efficiency close to 100%.

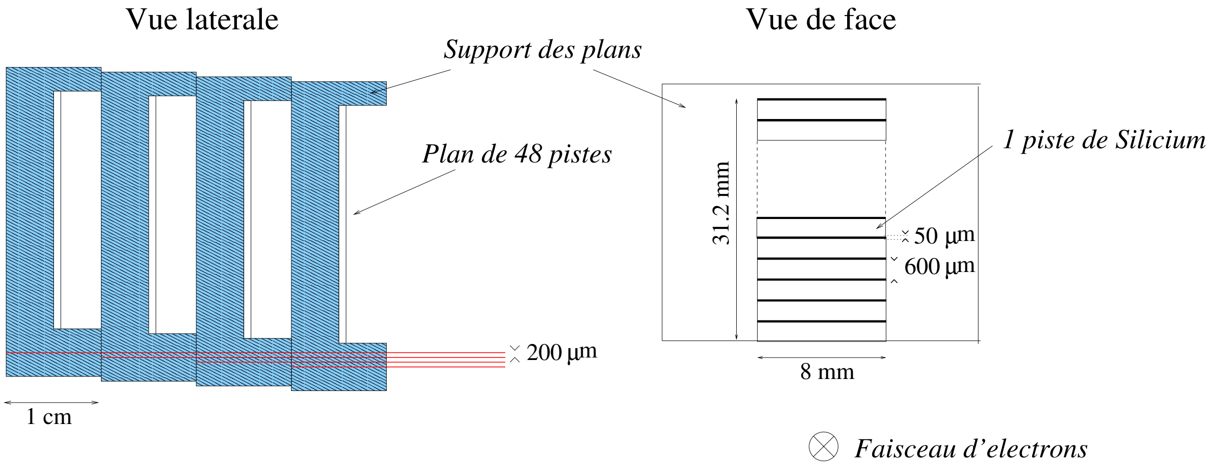

Figure 1: Hall A Compton polarimeter electron detector schematic [1]. Left: profile view. Right: beam view.

Table 1 summarizes the Hall A Compton parameters during a typical HAPPEx run (collected and derived from [3, 4, 5]). The chicane bend angle refers to the angle setting of each of the four dipoles in the chicane, which act to displace the Compton interaction point from the usual beam axis. The electron free drift distance refers to the distance past dipole 3 of the chicane, which magnifies the angular deflection of the Compton scattered electrons from the primary beam in the dispersive direction.

In the next three sections of the table, parameters related to three different classes of scattering are considered: scattering at the Compton edge, scattering at the zero crossing

Parameter	Symbol	Value
Beam energy	E	3.18 GeV
Laser wavelength	λ	1064 nm
Chicane bend angle	θ_{bend}	2.3°
Electron free drift distance	d_{drift}	4.11 m
Fractional photon energy at Compton edge	$\rho_{\max}$	$\equiv 1$
Photon energy at Compton edge	$k'_{\max}$	171 MeV
Electron displacement at Compton edge	$Y_{\max}$	12.3 mm
Maximum asymmetry (at Compton edge)	$A_{\max}$	0.055
Fractional photon energy at asymmetry zero	ρ_0	0.51
Photon energy at asymmetry zero	k'_0	88 MeV
Electron displacement at asymmetry zero	Y_0	6.3 mm
Asymmetry at asymmetry zero	A_0	$\equiv 0$
Fractional photon energy at electron detector edge	ρ_{gap}	0.41
Photon energy at electron detector edge	k'_{gap}	69 MeV
Distance from electron detector edge to beam	Y_{gap}	$\equiv$ 5 mm
Asymmetry at electron detector edge	A_{gap}	-0.0090
Electron detector position resolution	ΔY	0.2 mm
Fractional resolution at Compton edge	$\Delta Y/Y_{\max}$	1.6%
Systematic Uncertainty for electron detection mode	$\Delta P_e/P_e \approx 2\Delta Y/Y_{\max}$	3.2%

Table 1: Typical Hall A Compton Polarimeter Parameters

of the Compton asymmetry (generally at around half the Compton edge), and scattering where the electron just strikes the edge of the electron detector (here defined to be 5 mm from the primary, whereas this is more typically 4.5 mm in Hall A). For each of these cases, the following variables are reported:

- ρ, the photon energy relative to its maximum,
- k', the photon energy,
- Y, the electron displacement relative to the primary beam at the position of the electron detector,
- and A, the Compton asymmetry.

At the bottom of the table, information related to the position resolution of the electron detector is reported, and the effect of those parameters will now be discussed in detail.

2.1 Electron detector calibration of the photon calorimeter response function

The electron detector is dominantly used as a photon energy tagger to characterize the response function of the photon detector to the Compton-scattered photons. In order to achieve this, the fractional energy loss of electrons striking the electron detector must be calibrated (signified by their distance in the dispersive direction from the primary electron beam). The calibration is achieved by locating the strip position of the Compton edge. The relative photon energy width selected by any given strip is then the position resolution of the device divided by the distance from the primary beam. Because the device is calibrated using the Compton edge, the uncertainty in the position is equivalent to the resolution, and hence likewise for the uncertainty in the photon energy.

In the example of Table 1, this results in a photon energy resolution ranging from 1.6% at the Compton edge to 3.9% at the electron detector edge. This is considerably better than the resolution of the $PbWO_4$ photon calorimeter (typically 13% at 125 MeV incident photon energy [4]) which additionally suffers from a low-energy tail.

With this calibration performed, HAPPEx achieved a polarization systematic uncertainty from photon counting of order 2%.

2.2 Electron detector as a standalone polarimeter

Refs. [3, 4] state that the systematic uncertainty in the polarization determination from the electron detector alone P_e is dominated by the uncertainty in the vertical position of the scattered electrons. In particular, the fractional uncertainty in the polarization is related to the calibration uncertainty at the Compton edge:

$$\frac{\Delta P_e}{P_e} = 2 \times \frac{\Delta Y}{Y_{\text{max}}} \tag{1}$$

where the factor of 2 arises from the quadratic dependence of the Compton edge on the beam energy.

Taking the uncertainty ΔY to be 200 μm gives a fractional uncertainty of 3.2% in the example of Table 1.

3 Hall A Compton Upgrade

To provide improved accuracy at low beam-energies (850 MeV is required for the Pb parity experiment PREX), the following upgrades to the Hall A Compton polarimeter are being pursued:

- Frequency doubling resulting in a wavelength of 532 nm.
- Electron detector position resolution improvement to 150 μm using four planes with 300 μm strip pitch.
- Photon calorimeter material change for improved light yield resulting in as low as possible a threshold (materials such as BGO, LSO, or YAP). Integrating (HAPPEx-like) mode to reduce sensitivity to response function.

Additionally, it was identified that the ability to control the vertical position of the electron detector very precisely would be an important upgrade, might potentially impact the systematic uncertainties, and would certainly improve the ease of use at low beam energies, where minimal detector-beam gap is critical.

With these modifications, for an electron beam energy of 850 MeV, the resultant design parameters are shown in Table 2.

Parameter	Symbol	Value
Beam energy	E	0.850 GeV
Laser wavelength	λ	532 nm
Chicane bend angle	θ_{bend}	2.3°
Electron free drift distance	d_{drift}	4.11 m
Fractional photon energy at Compton edge	ρ_{max}	$\equiv 1$
Photon energy at Compton edge	k'_{max}	25 MeV
Electron displacement at Compton edge	Y_{max}	6.7 mm
Maximum asymmetry (at Compton edge)	A_{max}	0.030
Fractional photon energy at asymmetry zero	ρ_0	0.51
Photon energy at asymmetry zero	k'_0	13 MeV
Electron displacement at asymmetry zero	Y_0	3.4 mm
Asymmetry at asymmetry zero	A_0	$\equiv 0$
Fractional photon energy at electron detector edge	ρ_{gap}	0.44
Photon energy at electron detector edge	k'_{gap}	11 MeV
Distance from electron detector edge to beam	Y_{gap}	$\equiv 3$ mm
Asymmetry at electron detector edge	A_{gap}	-0.003
Electron detector position resolution	ΔY	0.15 mm
Fractional resolution at Compton edge	$\Delta Y/Y_{\text{max}}$	2.2%
Systematic Uncertainty for electron detection mode	$\Delta P_e/P_e \approx 2\Delta Y/Y_{\text{max}}$	4.4%

Table 2: Hall A Compton Polarimeter Upgraded for PREX

Clearly the ability to reduce the electron detector edge to beam distance to distances down to 3 mm would be crucial.

To achieve the 1-2% accuracy desired for PREX, the intention is to use the response function calibration method coupled with an integrating running mode, and new photon detector technology.

4 Hall C Conceptual Design

The Hall C Conceptual Design is presented in Ref. [6]. Table 3 reports the results of calculations using the parameters from Ref. [6], using the nominal Qweak beam energy of 1.165 GeV. The resultant systematic uncertainty for the polarization determined using electron detection mode is 1.3%. The improvement over the Hall A PREX case results primarily from the higher beam energy, coupled with the 3× larger bend angle.

We note that the detector array itself need span a distance of 24 mm $-$ 5 mm $=$ 19 mm. With a strip pitch of 300 μm, this would indicate 63 strips per plane.

Parameter	Symbol	Value
Beam energy	E	1.165 GeV
Laser wavelength	λ	514 nm
Chicane bend angle	θ_{bend}	10°
Electron free drift distance	d_{drift}	3.3 m
Fractional photon energy at Compton edge	$\rho_{\max}$	$\equiv 1$
Photon energy at Compton edge	$k'_{\max}$	48 MeV
Electron displacement at Compton edge	$Y_{\max}$	24 mm
Maximum asymmetry (at Compton edge)	$A_{\max}$	0.042
Fractional photon energy at asymmetry zero	ρ_0	0.51
Photon energy at asymmetry zero	k'_0	25 MeV
Electron displacement at asymmetry zero	Y_0	12 mm
Asymmetry at asymmetry zero	A_0	$\equiv 0$
Fractional photon energy at electron detector edge	ρ_{gap}	0.21
Photon energy at electron detector edge	k'_{gap}	10 MeV
Distance from electron detector edge to beam	Y_{gap}	$\equiv 5$ mm
Asymmetry at electron detector edge	A_{gap}	-0.008
Electron detector position resolution	ΔY	0.15 mm
Fractional resolution at Compton edge	$\Delta Y/Y_{\max}$	0.6%
Systematic uncertainty for electron detection mode	$\Delta P_e/P_e \approx 2\Delta Y/Y_{\max}$	1.3%

Table 3: Hall C Compton polarimeter conceptual design with Qweak beam energy.

However, deeming the resolution to be a more driving concern than minimal detector-beam gap, we relax the size of the detector to only reach the asymmetry zero at 12 mm, resulting similarly in a detector size of 12 mm. This reduces the number of strips to 40 per plane.

Note that further reduction in the detector strip pitch does *not* result in improved systematic uncertainty on electron polarization: the finite electron beam and laser spot sizes at some point begin to dominate. The typical sizes of these parameters are 100 μm, and it is therefore not profitable to consider strip pitches smaller than that.

We note that a larger bend angle, for example $\theta_{\text{bend}} = 20°$, would double all Y's quoted in Table 3, hence halving the resolution and uncertainties if the strip pitch were to remain the same. This would greatly relax the constraints on strip pitch. Additionally it could potentially drive the systematic uncertainty for an electron arm polarization measurement to the sub-percent level. We therefore strongly recommend that a larger bend angle be considered, particularly in the light of the decision to install the Compton polarimeter at the same time as the Qweak experiment itself.

Additionally, we present the ρ-dependence of the Compton cross-section and asymmetry for Qweak kinematics in Fig. 2.

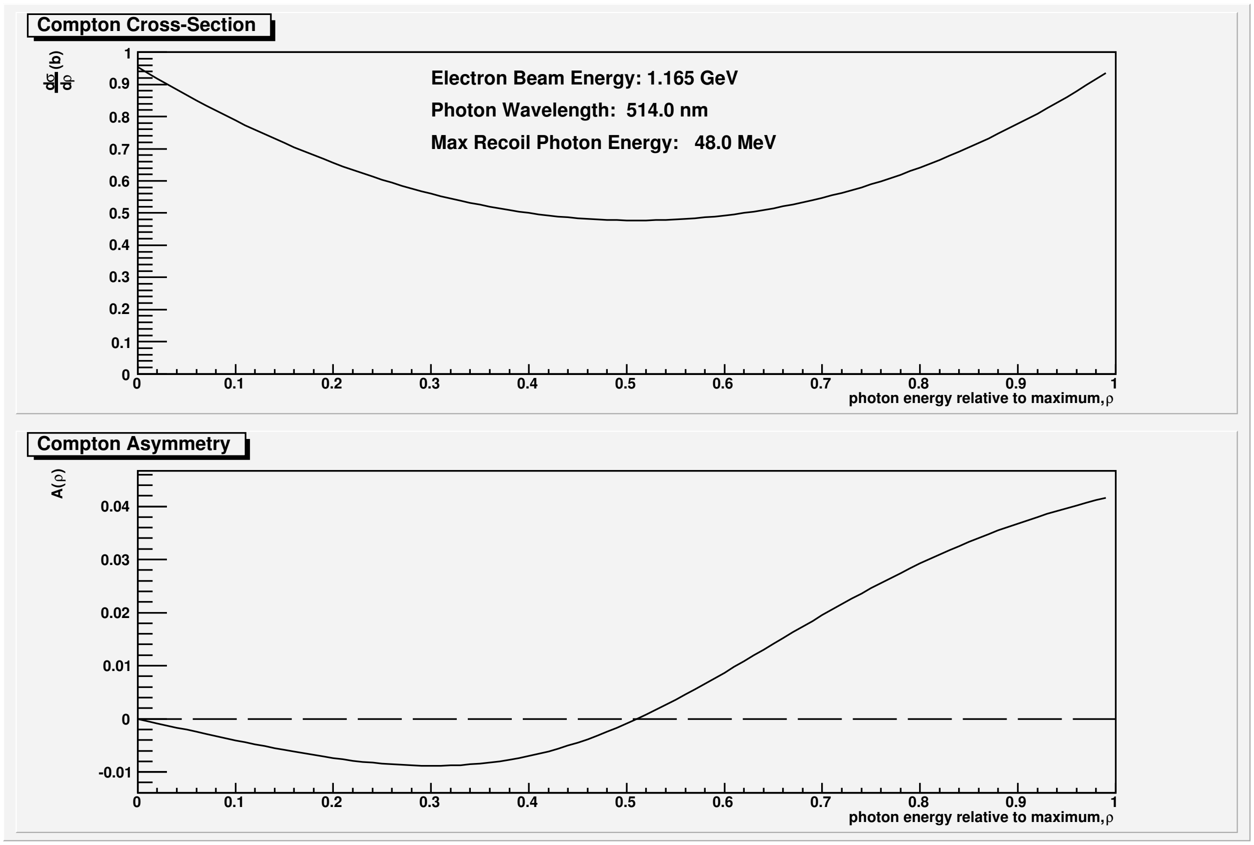

Figure 2: Cross section and asymmetry for Compton scattering at Qweak beam energy.

5 Remaining physics questions for the electron detector

Based on the considerations above, and still assuming a bend angle of $\theta_{\text{bend}} = 10^\circ$, we can begin to design an electron detector for the Hall C Compton polarimeter. However, the following design issues need yet be resolved:

- *backgrounds*: estimates of background rates based on first principles calculations and on scaling of Hall A's rates. Finalization of location of device relative to dipole 4 of the chicane. The trade-off there is level arm (free drift distance after dipole 3) vs. background (synchrotron radiation from dipole 3 itself, if located after dipole 4).
- *absolute signal rate*: estimates of luminosity, laser power, and laser pulse structure finalization.

We propose to at least partially address these remaining issues in Monte Carlo simulations in collaboration with University of Connecticut.

6 Roadmap to Cost Estimates

We conclude that four planes of silicon or diamond technology, given the excellent experience of Hall A, is likely the best option. The strip pitch of the detector should be maximally 300 μm and minimally 100 μm. The size of each plane in the dispersive direction should be not less than 12 mm.

While diamond detectors would be preferred due to their superior radiation hardness, to our knowledge no single vendor currently sells such detectors to the general public. Such detectors are generally only available through collaboration with research groups actively working on detector R&D. Large-area, ion-implanted silicon microstrip detectors, on the other hand, are more readily commercially available, in a variety of sizes and strip pitches. A decision should be made ASAP whether to pursue R&D on diamond, or commercially available silicon. We note however, that the general electronics requirements, presumed to be the driving cost, are independent of this decision.

A linear motion mechanism and control system should be budgeted for. Additionally high voltage (detector bias) and low voltage (preamplifier power) and slow controls should be accounted for.

There is possibly the need to thermally cool the detectors. This is particularly important if it is decided to locate the preamplifiers within the vacuum volume. We recommend budgeting for this option as well. Normally, an antifreeze chiller at zero Celsius is all that is required.

In terms of fast electronics, 32 channels of silicon electronics will be purchased in the near future at University of Winnipeg (purchase order signed by fall 2006). This includes preamplifiers, leading edge discriminators, and shaping amplifiers. Additionally, 32 channels of digitization readout will be purchased, encompassing peak sensing ADC's, TDC's, scalers, digital I/O, and a few channels of waveform digitization. These are general-purpose devices intended for use in the prototyping of silicon or diamond detectors.

For the final detectors, electronics will be the driving cost. Some information on the solution for Hall A is available from links found on their website [7]. Updated design, cost estimates, and quotes are required immediately. There is the possibility (through TRIUMF or elsewhere) to design custom electronics, if necessary. Such needs should be decided ASAP, at least at the level of a cost and manpower estimate.

References

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