Determination of electron beam polarization using electron detector in Compton
polarimeter with less than 1% statistical and systematic uncertainty

By

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The Q-weak experiment aims to measure the weak charge of proton with a precision of 4.2%. The proposed precision on weak charge required a 2.5% measurement of the parity violating asymmetry in elastic electron - proton scattering. Polarimetry was the largest experimental contribution to this uncertainty and a new Compton polarimeter was installed in Hall C at Jefferson Lab to make the goal achievable.

In this polarimeter the electron beam collides with green laser light in a low gain Fabry-Perot Cavity; the scattered electrons are detected in 4 planes of a novel diamond micro strip detector while the back scattered photons are detected in lead tungstate crystals. This diamond micro-strip detector is the first such device to be used as a tracking detector in a nuclear and particle physics experiment. The diamond detectors are read out using custom built electronic modules that include a preamplifier, a pulse shaping amplifier and a discriminator for each detector micro-strip. We use field programmable gate array based gen-

eral purpose logic modules for event selection and histogramming. Extensive Monte Carlo simulations and data acquisition simulations were performed to estimate the systematic uncertainties. Additionally, the Moller and Compton polarimeters were cross calibrated at low electron beam currents using a series of interleaved measurements. In this dissertation, we describe all the subsystems of the Compton polarimeter with emphasis on the electron detector. We focus on the FPGA based data acquisition system built by the author and the data analysis methods implemented by the author. The simulations of the data acquisition and the polarimeter that helped rigorously establish the systematic uncertainties of the polarimeter are also elaborated, resulting in the first sub 1% measurement of low energy (~ 1 GeV) electron beam polarization with a Compton electron detector. We have demonstrated that diamond based micro-strip detectors can be used for tracking in a high radiation environment and it has enabled us to achieve the desired precision in the measurement of the electron beam polarization which in turn has allowed the most precise determination of the weak charge of the proton.

Key words: parity violation, Compton, data acquisition, diamond micro-strip electron detector

DEDICATION

To Guruji.

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I can get the moral authority to present this document to the research community only if I thank some people for what has helped shape this document to this current state. This acknowledgement is not to scale because anything scaled to the bounty by Dr. Dipankar Dutta, my advisor, would appear small. To me he is a good definition of infinity; "bigger than anything that you pick". So having dedicated this dissertation to him, I move on to other contributors.

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and complete documents that I read on Compton polarimeter before I started writing my own dissertation. His name remains imprinted in courtesy on several of my macros, that could not be written without his help at that time.

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TABLE OF CONTENTS

DEDICATION	ii
ACKNOWLEDGEMENTS	iii
LIST OF TABLES	xii
LIST OF FIGURES	xiii
GLOSSARY OF ACRONYMS	xx
CHAPTER	
1. INTRODUCTION	1
1.1 Electron beam polarimeters	2
1.1.1 Mott polarimeter	3
1.1.2 Møller polarimeter	4
1.1.3 Compton polarimeter	6
1.2 The Compton process in QED	6
1.3 Principle of Compton polarimetry	14
1.4 History of Compton polarimetry	15
1.5 Relevance to Qweak	17
2. EXPERIMENTAL SETUP	19
2.1 Jefferson Lab	19
2.2 The Electron Beam	19
2.2.1 Generation	20
2.2.2 Steering Constraints	22
2.2.3 Beam related backgrounds	22
2.2.4 Helicity	23
2.3 Beamline Components	24
2.3.1 Half Wave Plate	24
2.3.2 Wien Flipper	25
2.3.3 Beam Position Monitor	26

2.3.4	Beam Current Monitor	27
2.4	Compton Polarimeter	27
2.4.1	Magnetic chicane	28
2.4.2	Laser	31
2.4.2.1	Laser polarization	33
2.4.2.2	Laser Lock	34
2.4.3	Photon detector	35
2.4.4	Electron detector	36
2.5	Other Polarimeters	38
2.5.1	Mott polarimeter	38
2.5.2	Møller polarimeter	39
2.6	Other Q-weak Apparatus	41
3.	THE ELECTRON DETECTOR	43
3.1	Introduction	43
3.2	The Diamond Detector	43
3.3	Detector Material and Properties	46
3.3.1	Charge Ionization Process	47
3.3.2	Number of Electron-Hole Pairs	48
3.3.3	Bremsstrahlung Effect	49
3.3.4	Creation of Secondary Electrons	49
3.3.5	Photon Excitations	50
3.3.6	Electrical Properties	50
3.3.7	Radiation Hardness	52
3.4	Charge Collection and Detection	54
3.5	Characterization	55
3.6	Installation and Arrangement	59
3.7	Flex Cable	61
3.8	QWeak Amplifier Discriminator Board	65
3.9	Data Acquisition	72
3.9.1	Conceptual Design	72
3.9.2	Input reconditioning	75
3.9.3	Triggering logic	80
3.9.4	Pipeline delay	84
3.9.5	Pattern buffer	86
3.9.6	Modeling and Simulation	88
3.9.7	Possible Improvements	90
3.9.7.1	Signal width	90
3.9.7.2	Trigger	91
3.9.7.3	Scaler readout	92
4.	ELECTRON DETECTOR AND DAQ SIMULATIONS	93

4.1	Overview	93
4.2	Monte Carlo simulation of the Compton polarimeter	93
4.2.1	Electron and Laser Beam	94
4.2.2	Beam Laser Interaction	96
4.2.3	Detector Response	98
4.2.4	Simulation Output	99
4.2.4.1	Luminosity weighted method	99
4.2.4.2	True Statistics method	103
4.3	Modelsim simulation of the Compton DAQ	104
4.3.1	The signal input	106
4.3.2	Estimating trigger inefficiency	113
5.	DATA ANALYSIS	122
5.1	Corrections to yield	124
5.1.1	Noise correction	125
5.1.2	Trigger related inefficiency	128
5.1.3	Background subtraction	135
5.2	Determining experimental asymmetry	135
5.2.1	Data cuts	136
5.2.1.1	Beam modulation cut	136
5.2.1.2	Laser power	136
5.2.1.3	Beam current	137
5.2.1.4	Laser cycle	137
5.2.2	Runlet average asymmetry extraction	137
5.2.3	Laser cycle average asymmetry extraction	139
5.2.4	Comparing the two averaging methods	141
5.2.5	Determining the theoretical asymmetry	142
5.2.6	Radiative correction	144
5.2.7	Magnetic analysis of scattered electrons	145
5.2.8	Polarization extraction via fixed Compton edge fit	151
5.2.9	Floating Compton edge	153
5.2.10	Comparison of data reduction methods	155
5.3	Detector efficiency, background and noise studies	158
5.3.1	Detector efficiency	158
5.3.2	Background	160
5.3.3	Electronic noise	163
5.4	Evaluation of Systematic Uncertainties	169
5.4.1	Determination of Compton edge	171
5.4.1.1	Fixed Compton edge analysis	171
5.4.1.2	Floating Compton edge analysis	172
5.4.2	Secondary electrons	172

5.4.2.1	Fixed Compton edge analysis	172
5.4.2.2	Floating Compton edge analysis	175
5.4.3	Detector tilt	176
5.4.3.1	Fixed Compton edge analysis	176
5.4.3.2	Floating Compton edge analysis	176
5.4.4	Dipole field strength	179
5.4.4.1	Fixed Compton edge analysis	179
5.4.4.2	Floating Compton edge analysis	180
5.4.5	Electron beam energy	182
5.4.5.1	Fixed Compton edge analysis	182
5.4.5.2	Floating Compton edge analysis	182
5.4.6	Detector longitudinal position	187
5.4.6.1	Fixed Compton edge analysis	187
5.4.7	Summary of Comparison	187
5.5	Additional systematic studies	189
5.5.1	Inter-plane trigger	189
5.5.2	Effect of noise and background	190
5.5.3	Detector orientation	196
5.5.4	Detector efficiency	202
5.5.5	Beam position at interaction point	202
5.5.6	Spin precession through chicane	204
5.5.7	DAQ related systematic uncertainties	205
5.5.7.1	Ratio of accumulator to scaler mode data	206
5.5.7.2	Uncertainty in DAQ inefficiency correction	208
5.5.8	Uncertainty in laser polarization	209
5.6	Summary	211
6.	RESULTS AND CONCLUSION	214
6.1	Dectector yield and rates	214
6.1.1	Charge normalized yield	214
6.1.1.1	DAQ change	215
6.1.1.2	Operating condition	217
6.1.2	Time normalized yield	219
6.1.3	Ratio of triggered yield to scalars	221
6.2	Asymmetry	222
6.2.1	Background asymmetry	224
6.2.2	Fitting the asymmetry	229
6.3	Polarization	232
6.4	Cross calibration between Møller and Compton Polarimeters	240
6.5	Results for Qweak	242
6.6	Conclusion and Future Possibility	245

REFERENCES	248
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LIST OF TABLES

1.1	Error budget of Q-weak experiment	17
1.2	Defining parameters for the Q-weak experiment at JLab	18
2.1	Typical Parameters for Hall C Compton polarimeter	38
3.1	Comparison of diamond and silicon properties at room temperature	51
5.1	Initial parameters	170
5.2	Effect of secondary electrons	175
5.3	Effect of secondaries	176
5.4	Comparing systematic contributions	189
5.5	Laser polarization systematic uncertainty	211
5.6	Preliminary Systematic Uncertainties	213
6.1	Mean polarization measurements during cross calibration	245

LIST OF FIGURES

1.1	Compton scattering schematic in the laboratory frame	8
1.2	Energy of Compton edge photons with changing beam energy	10
1.3	Theoretical asymmetry with respect to ρ in QED	12
1.4	Theoretical cross-section with respect to ρ in QED	13
1.5	Maximum Compton asymmetry with varying beam energy.	16
2.1	Jefferson Lab Schematic overview	20
2.2	JLab electron beam, bunched at 499 MHz	21
2.3	Scintillator rate for run2 averaged in clusters of 30 runs	23
2.4	Jefferson Lab Hall C Compton Polarimeter Layout	28
2.5	Technical Drawing of the Magnetic chicane	29
2.6	Magnetic field map in longitudinal direction	30
2.7	Magnetic field map in transverse direction along the pole	30
2.8	Schematic showing various components of the laser table	32
2.9	Photon detector yield for laser on (green) and laser off (blue) during data taking	36
2.10	Photon detector integrated pulse spectrum	37
2.11	Schematic view of Møller set up in Hall C	41
3.1	Diamond micro-strip detector	44

3.2	Charge normalized yield in a single plane of the electron detector	45
3.3	Cross sectional view of polycrystalline diamond film	47
3.4	Effect of radiation on CVD diamond	53
3.5	Schematic mechanism of detector operation	56
3.6	Schematic for characterization of detector prototype	57
3.7	Response of prototype diamond detector	58
3.8	Response of silicon detector from Sr-90	59
3.9	Response of diamond detector from Sr-90	60
3.10	Detector during alignment	62
3.11	Accessories used to hold the detector	62
3.12	Beam view of the installed detector	63
3.13	Vacuum can and motion mechanism	63
3.14	Detector, Flex, QWAD connection	64
3.15	QWAD-v2 output (10 μs time scale)	67
3.16	QWAD-v3 output (200 μs time scale)	68
3.17	Scope shot of calibration input	69
3.18	Discriminated output with 450 ns	70
3.19	Discriminated output with 600 ns	71
3.20	Electronic circuit of a single QWAD channel	71
3.21	Data acquisition conceptual Overview	74
3.22	Data Acquisition Schematics	75
3.23	Schematic diagram of reconditioning stage	76

3.24	Timing diagram of reconditioning	79
3.25	Trigger formation schematic using OR gates	82
3.26	Manipulation of strip information to form the Trigger decision	85
3.27	Pipeline Delay operation on every strip	86
3.28	v1495 Overall timing diagram	89
4.1	Schematic view of beam envelope in x-z (or y-z) plane	95
4.2	Interaction of laser and electron beam in y-z plane. $\theta = 23.53$ radian	97
4.3	Hits spectrum for detector strips without applying weights	100
4.4	Hits weighted by cross-section and luminosity	101
4.5	Hits spectrum with all 3 weights	101
4.6	Ideal hits distribution with corresponding difference and sum	105
4.7	Scatter plot from experiment	108
4.8	Scatter plot from simulation	109
4.9	Detector yield in simulation and experiment	111
4.10	Difference of rate detected in DAQ simulation compared to that observed .	112
4.11	Polarization from Modelsim data	114
4.12	Polarization extracted from GEANT3 and Modelsim simulations	115
4.13	Loss in triggered data	116
4.14	Relative loss in triggered data	117
4.15	Percentage Loss in triggered data w.r.t aggregate rate	118
4.16	Differential loss between H^+ and H^- rates	119
4.17	Extracted polarization after correcting for trigger inefficiency	120

5.1	Laser power histogram for a run	123
5.2	Laser turned off periodically (cavity unlocked	123
5.3	The aggregate rate for the entire run-2 period	126
5.4	Background yield at high current $\sim 180 \mu A$	127
5.5	Background yield at low current $\sim 4 \mu A$	127
5.6	Relative loss for typical signal rate	129
5.7	Relative loss for 2x signal rate	130
5.8	Intercept of the correction factor	132
5.9	Slope of the correction factor	133
5.10	The charge normalized aggregate accumulator yields	134
5.11	Asymmetry extracted in an hour long data set	139
5.12	Comparison of asymmetry extracted by laser cycle and runlet based average	141
5.13	Comparison of polarization between the two averaging methods	143
5.14	Statistical uncertainty from the two methods	144
5.15	Effect of radiative correction on Compton theoretical asymmetry	146
5.16	Schematic spatial distribution of Compton scattered electrons	148
5.17	The case of detector angle being different from θ_{bend}	148
5.18	Typical Compton yield measured in a run	152
5.19	Effective Strip Width parameter from fixed Compton edge (CE)	154
5.20	The Compton edge as determined in the floating CE method for all runs . .	155
5.21	Histogram of error on CE determination for all data sets in run2	156
5.22	Extracted polarization using fixed Compton Edge	157

5.23	Extracted polarization using fixed effective strip width	157
5.24	Ideal polarization with true statistics method	159
5.25	Distribution due to random strip efficiency for both helicity states	161
5.26	Extracted polarization with randomly varying strip efficiency	162
5.27	Hit-spectra with detector efficiency and background	164
5.28	Extracted polarization with background subtraction	165
5.29	Hit-spectra due to added noise	167
5.30	Polarization with detector efficiency, background subtraction and noise . .	168
5.31	Variation in polarization, chi-sq of fit and the effective strip width parameter	173
5.32	Correlation between the fit error for polarization and Compton edge parameters	174
5.33	Effect of detector tilt on polarization	177
5.34	Effect of detector tilt on polarization	178
5.35	Effect of Dipole field on polarization	181
5.36	Effect of fluctuation of Magnetic field	183
5.37	Histogram of beam energy throughout the period of run2	184
5.38	Effect of beam energy on polarization	185
5.39	Effect of beam energy fluctuation on polarization	186
5.40	Effect of detector position on polarization	188
5.41	Effect of inter plane Trigger on polarization	191
5.42	Effect of trigger cluster size on polarization	192
5.43	Effect of trigger condition on secondary electron acceptance	193
5.44	Hits distribution for Compton, background and noise events	194

5.45	Hits distribution for 2/3 plane trigger	195
5.46	Extracted polarization with trigger 1/3 plane	197
5.47	Extracted polarization with trigger 2/3 plane	198
5.48	Variation of polarization with detector tilt	199
5.49	Effect of detector rotation w.r.t y-axis	200
5.50	Effect of detector rotation w.r.t z-axis	201
5.51	Effect of individual detector strip efficiency	203
5.52	Ratio of polarization from accumulator mode data to scaler mode data . . .	206
5.53	Polarization before (solid) and after (open) the DAQ inefficiency correction	207
5.54	Difference in polarization due to the inefficiency correction for all runs . .	208
6.1	Accumulation mode yield averaged over 15 runs	215
6.2	Scaler mode yield of runs with 15 run average	216
6.3	Beam current through Run-2	217
6.4	Dipole current in Chicane through Run-2	218
6.5	Detector position measured with respect to an arbitrary reference	219
6.6	Compton edge variation through Run-2 averaged over each slug	220
6.7	Trigger inefficiency correction factors, averaged over 15 runs	221
6.8	Ratio of yield from triggered data to scalers	222
6.9	Typical asymmetry measurement using accumulation data	223
6.10	Typical asymmetry measurement using scaler data	223
6.11	Relative difference in asymmetry of accumulation and scaler data	224
6.12	A representative background asymmetry	225

6.13	Background asymmetry for Run-2	226
6.14	Histogram of A_{bgd}	227
6.15	Histogram of χ^2 in A_{bgd} determination	228
6.16	Difference in yield between runs with laser light physically blocked	229
6.17	Typical polarization extraction using two parameter fit with HWP in	230
6.18	Typical polarization extraction using two parameter fit with HWP out	230
6.19	Histogram of χ^2 per degree of freedom	231
6.20	Residual of Compton asymmetry fit to data	232
6.21	Histogram of fit residue for runs	233
6.22	Histogram of χ^2 in residue determination	234
6.23	Plot of extracted polarization throughout Run-2	235
6.24	Histogram of statistical uncertainty for the extracted polarization	236
6.25	Plot showing no correlation between polarization and the uncertainty	237
6.26	Plot showing correlation between statistical uncertainty on polarization . . .	239
6.27	Major event markers during Run 2	239
6.28	Polarization measured at $4.5\mu A$	243
6.29	Background asymmetry for the Compton measurements	244
6.30	Fit residue of Asymmetry fit used to extract the polarization	244
6.31	Polarization averaged over each slug	246

GLOSSARY OF ACRONYMS

Following are the technical abbreviations used in this dissertation while describing physics processes.

MPS Macro Pulse Signal

helicity The projection of a particle spin in the direction of its momentum. It can be +1 or -1

run One hour long data set

PWTL Pulse Width of Trigger Logic

FSD Fast shut down

Following generic abbreviations have been used in this dissertation.

JLab: Thomas Jefferson National Accelerator Facility
CEBAF: Continuous Electron Beam Acceleration Facility
TRIUMF: TRI University Meson Facility
QED: Quantum Electro Dynamics

CHAPTER 1

INTRODUCTION

Electron spin polarization, in general, refers to the property of an ensemble of electrons resulting from a preferred orientation of the electron spin, and in particular, is a measure of the degree of alignment of the electron spin with respect to a chosen direction, for example, its momentum direction. The concept of electron spin was first introduced by Uhlenbeck and Goudsmit [21] in 1926 as an intrinsic property in addition to the mass and charge. It was initially interpreted as the quantum number appearing as a result of the rotation of the electron about its axis as is reflected from the title of their paper "Spinning electrons and the structure of spectra". This gave the name 'spin' to the intrinsic angular momentum of the electron, although we cannot define a mechanical axis for an elementary particle. Observations of the Stern-Gerlach experiment [19] and anomalous magnetic moment [28] increased the interest in the study of the spin of free electrons as well as physics processes which are directly affected by the electron spin. The first definitive prediction of an observable effect due to the spin of free electrons was given by Mott [42, 43] in 1929, based on a theoretical investigation into the spin dependence of the elastic scattering of low energy (50-500 keV) electrons from heavy nuclei. This study by Mott formed the basis of the first polarimetry¹ technique.

¹polarimetry refers to the measurement of the degree of spin polarization

In 1956, the first review on electron polarization was published by Tolhoek [53]. The theoretical basis for the physics of the spin polarized electrons was reasonably mature by then, but most of the initial experimental advances in this field had to wait until the discovery that the parity violation in weak interactions could be studied using polarized electron beams [14, 15].

The intrinsic angular momentum of an electron can only be $\hbar/2$ and its projection along a reference direction can only take either $+\hbar/2$ or $-\hbar/2$. These two possible orientations are referred to as parallel and anti-parallel respectively, to the reference direction. It is impossible to measure the orientation of the spin of an individual electron. However, we can do a statistical measurement of the probability of an electron being in one of the two spin orientations. In any given ensemble of electrons, if N^+ and N^- are the number of electrons with their spin aligned parallel and anti-parallel to the reference direction, the degree of polarization is given by the fractional difference of populations of the two spin states,

$$P = \frac{N^+ - N^-}{N^+ + N^-}. \quad (1.1)$$

If the reference direction is parallel to the momentum of the electron beam, Equation (1.1) gives the longitudinal polarization of the beam, while if it is perpendicular to the beam momentum, the equation defines the transverse polarization.

1.1 Electron beam polarimeters

The spin dependent asymmetry in a differential scattering cross section is defined as $\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$, where $\sigma_{\pm}$ is the differential scattering cross section for electrons with spin oriented

parallel or anti-parallel to a chosen direction. All methods of measuring electron beam polarization are some variation of a scattering experiment, measuring the spin dependent asymmetry resulting from the two orthogonal spin orientations.

The theoretical asymmetry is called the physics analyzing power of the process and typically polarimeters are designed to operate close to this value, which is also the maximum attainable asymmetry. The effective analyzing power of a particular set up, drives the choice of operating parameters and also determines the energy range over which each technique is feasible. The spin dependent cross section gives a measurable asymmetry in the scattered flux, which is equal to the product of the beam polarization and the effective analyzing power.

Based on the target used for the spin dependent scattering, the three most popular polarimetry techniques are Mott, Møller and Compton. These are named after the scientists who discovered them or were the first to calculate their cross section. In the following sections, we will introduce the basic idea and limitations of each of these commonly used polarimeters.

1.1.1 Mott polarimeter

This polarimetry technique was the earliest to be used for measuring electron beam polarization. The method exploits the spin-dependence of the cross section for elastic scattering of electron from nuclei, where the asymmetry comes from the spin being parallel or anti-parallel to the electron's orbital angular momentum about the scattering nucleus. As an electron enters the Coulomb field of a nucleus, it experiences a magnetic field in its rest

frame, the strength of this magnetic field is proportional to the orbital angular momentum of the nucleus in the electron rest frame [42]. The orientation of the spin of electron causes a difference in the force exerted by the magnetic field hence creating an asymmetry in the probability for the electron to scatter. The Mott polarimeter measures this counting rate asymmetry in the elastic Mott scattering process ($\vec{e} + Z \rightarrow e + Z$). Since the orbital angular momentum is always perpendicular to the plane of scattering, the Mott scattering asymmetry is non-zero only for spin states that are perpendicular to the scattering plane, hence this polarimeter can measure transverse polarization.

Since the Coulomb field will be higher for a high atomic number element, gold, silver or copper are the typical choice of target material for Mott polarimeters. Even though the analyzing power of the Mott scattering increases with energy, the rapid drop in cross section with energy makes it increasingly difficult to use this technique for measurements at high energy. Also, the maxima of the analyzing power shifts to angles very close to 180° further making the measurement difficult. Due to these reasons, above 10 MeV, measurement of polarization using Mott polarimeter becomes impractical; hence most accelerators use this polarimeter near the electron beam source before the beam has undergone significant acceleration.

1.1.2 Møller polarimeter

This type of polarimeter has been used for measuring electron beam polarization, through the energy range of 100 MeV to few 10's of GeV [50]. The Møller electron scattering ($\vec{e} + \vec{e} \rightarrow e + e$) cross section differs when the beam and target electron spins are

aligned parallel or anti-parallel to one-another. This spin dependence of the cross section in the Møller process provides a measure of the beam polarization [34].

At high beam energies, the analyzing power in the center of mass reference frame becomes independent of energy. The maximum analyzing power for scattering longitudinally polarized beam electrons from longitudinally polarized target electrons is $-7/9$ for scattering at 90° in the center of mass reference frame. Similarly, Møller scattering of transversely polarized electrons is used to measure the transverse polarization of the beam, though with a maximum analyzing power of $1/9$. The measurement of transverse polarization is diluted by the fraction of target electrons that are polarized. The measurement of longitudinal polarization on the other hand, is helped by the comparatively large longitudinal asymmetry in the Møller process resulting in higher difference of rates between the two spin states. The longitudinal asymmetry is also independent of energy which simplifies the understanding of the polarimeter response, hence making it the common choice for measuring beam polarization at medium to high beam energies where an invasive measurement of the beam polarization is possible.

Møller polarimeters often use a thin ferromagnetic foil in a magnetic field as the polarized electron target. The beam and target electrons, scattered at 90° in the center of mass frame, when seen in the laboratory frame are two streams of electrons moving forward, moving at equal and opposite small angles to the incident beam direction in the scattering plane. A magnet is used to momentum analyze these scattered electrons. Some form of collimation is used to limit the vertical and azimuthal acceptances of the detectors measuring these rates.

Møller polarimeters suffer from the limitation of being an invasive measurement due to a solid target being used and that the beam current at which the measurement is done is limited a few μA to avoid depolarization effects due to target heating.

Attempts are being made to evolve a novel Møller polarimeter based on atomic hydrogen instead of an iron foil [7]. The idea is to replace iron foil, that makes the measurement invasive with atomic hydrogen stored in a ultra cold magnetic trap as the target for Møller scattering. This will enable Møller polarimeter to be non-invasive, provide continuous measurement at the beam current of the physics experiment. The atomic hydrogen target would also free the measurement from the Levchuk and the target heating effects which significantly adds to the systematic uncertainty. Development work is underway for this polarimeter at Mainz.

1.1.3 Compton polarimeter

The Compton polarimeter uses the spin dependence of the cross section for electron photon scattering to measure the beam polarization. This thesis will describe all aspects of Compton polarimetry starting with a discussion of the Compton scattering process.

1.2 The Compton process in QED

In the classic paper by Aurthur Holly Compton, describing the Compton effect [8] (published in 1923), a photon scatters elastically from an electron at rest. The scattered photon loses energy as it backscatters resulting in a change of wavelength (Equation (1.2)). Here k_0 and k are the incident and scattered photon momenta respectively, and θ_0 is the angle of scattering between the incident and scattered photon. In the center of mass frame,

which is same as the electron rest frame here. The equation holds true even if the electron is at relativistic speed in the lab frame.

$$\frac{m}{k} - \frac{m}{k_0} = 1 - \cos \theta_0. \quad (1.2)$$

The process as used today in medium and high energy physics accelerators, has a high energy electron scatter off a photon imparting some of its energy to the back scattered photon. We will use the laboratory frame of reference to describe the Compton kinematics as is relevant to our experiment in further detail here. Figure 1.1 depicts the scattering with the associated angles and conventions used in this dissertation. The direction of momenta of the scattered electron and photon can be used to define a scattering plane where the process can be seen as a 2 dimensional problem. We will use the X-Z plane for this 2 dimensional problem where we choose the z axis as the momentum direction of the incident electrons with energy E .

An electron with initial momentum $\vec{p}$ is scattered by an angle θ_e w.r.t the positive z axis and the scattered momentum and energy are p' and E' respectively. The four momenta of the initial and final states of the electron are given by,

$$p = (E, 0, 0, p) \quad (1.3)$$

$$p' = (E', p' \sin \theta_e, 0, p' \cos \theta_e). \quad (1.4)$$

The incident and scattered photons have energies k_i and k_f respectively with the scattering angle being θ_γ . In kinematics where the incident photon makes a small angle with respect to the +Z direction (known as the crossing angle), the angle can be ignored for the discussion below. For example if the angle is ~ 20 mrad (as was the case for the Hall-C Compton

polarimeter), ignoring the crossing angle costs a maximum error of $\sim 0.01\%$ [11] in polarization estimation. Ignoring the crossing angle, the four momenta of the initial and final states of the photon as given by,

$$k_i = (k_i, 0, 0, -k_i) \quad (1.5)$$

$$k_f = (k_f, k_f \sin \theta, 0, k_f \cos \theta). \quad (1.6)$$

Figure 1.1

Compton scattering schematic in the laboratory frame

We can write the energy of the scattered electron using conservation of energy. Similarly, we can write two equations for the momentum of the scattered electrons, one each for the X and Z axis using conservation of momentum. Using the above three equations, p' , E' and θ_e can be eliminated to obtain the relationship for scattered photon energy in terms of the incident electron and photon energy as

$$k' = k \frac{E + p}{E + k + (k - p) \cos \theta_\gamma} \quad (1.7)$$

It is useful to define a kinematic parameter a as the ratio of the minimum energy of the scattered electron to the energy of the incident electron (E) as given by Equation (1.8) using which Equation (1.7) can be further simplified to Equation (1.9) [3].

$$a = \left(1 + \frac{4kE}{m^2}\right)^{-1} \quad (1.8)$$

$$\frac{k'}{k} = \frac{4a\gamma^2}{1 + a\theta_\gamma^2\gamma^2} \quad (1.9)$$

where we have used the ultra relativistic approximation: $p \simeq E \left(1 - \frac{1}{2\gamma^2}\right)$.

It is customary to define another kinematic parameter ρ as the ratio of the energy of the scattered photon to that of its maximum value as

$$\rho = \frac{k'}{k'_{max}}. \quad (1.10)$$

As shown in Equation (1.9), the momentum of the scattered photon is directly related to the scattering angle and the maximum momentum transfer between electron and photon will happen for a completely backscattered photon ($\theta_\gamma = 0$). This kinematic limit is called the Compton edge and corresponds to $\rho = 1$. At the Compton edge, the scattered photon will have maximum energy ($k' = k'_{max}$) and can be extracted via Equation (1.9),

$$k'_{max} = 4ak \frac{E^2}{m^2}. \quad (1.11)$$

For a given initial photon energy, k'_{max} increases steadily with increasing electron beam energy as shown in Figure 1.2. For Hall C Compton kinematics, it was 45.9 MeV. The maximum scattered photon energy k'_{max} corresponds to the minimum scattered electron energy and is given by:

$$E_{min} \simeq E - 4ak \frac{E^2}{m^2} \quad (1.12)$$

Figure 1.2

Energy of Compton edge photons with changing beam energy

In the scattering process, let ψ be the angle made by the spin of the electron w.r.t the +Z-direction in the X-Z plane, let P_e be the electron polarization and P_γ be the circular polarization of the incident photon. The sign of P_e is implicitly carried in the definition of angle ψ which makes it positive for electron spin along the incident momentum direction. The scattered photon has a polar angle of θ_γ in the X-Z plane and an azimuthal angle of ϕ out of plane.

In this coordinate system, the total differential cross section of the Compton scattering of circularly polarized photons from polarized electrons is given by Equation (1.13) [48].

$$\frac{d^2\sigma}{d\rho d\phi} = \frac{d^2\sigma_0}{d\rho d\phi} \mp P_e P_\gamma \left(\cos \psi \frac{d^2\sigma_1}{d\rho d\phi} + \sin \psi \cdot \cos \phi \frac{d^2\sigma_2}{d\rho d\phi} \right) \quad (1.13)$$

where

$$\begin{aligned}\frac{d^2\sigma_0}{d\rho d\phi} &= r_0^2 \cdot a \left[\frac{(\rho(1-a))^2}{1-\rho(1-a)} + 1 + \left(\frac{1-\rho(1+a)}{1-\rho(1-a)} \right)^2 \right] \\ \frac{d^2\sigma_1}{d\rho d\phi} &= r_0^2 \cdot a \left[(1-\rho(1+a)) \left(1 - \frac{1}{1-\rho(1-a)} \right)^2 \right] \\ \frac{d^2\sigma_2}{d\rho d\phi} &= r_0^2 \cdot a \left[\rho(1-a) \frac{\sqrt{4a\rho(1-\rho)}}{1-\rho(1-a)} \right]\end{aligned}$$

a and ρ are as defined in Equation (1.10) and Equation (1.8) respectively while r_0 is the classical radius of the electron.

For a given photon energy, since the energy of the scattered photon is directly related to its polar angle θ_γ and hence each measured polar angle would correspond to a unique value of ρ (Equation (1.10)), hence, the angular dependence of the cross section is contained in ρ in the cross section (Equation (1.13)).

The sign of P_γ is taken here as positive and we choose the $-$ sign in Equation (1.13) for the case of the incident circularly polarized photons with spin projections along the direction of motion [28]. The first term in Equation (1.13) represents the total unpolarized cross section. The second term represents the term due to longitudinal polarization while the third term comes from the azimuthal dependence of the cross section. The third term arises because the transverse component of the electron spin breaks the azimuthal symmetry in the scattering process. When the electron is longitudinally polarized (as in the case of the Hall-C Compton), the cross section is averaged over all ϕ angles (0 to 2π) and this term goes to zero, as also $\sin \psi \approx 0$. If the incident photon has linear polarization components mixed with the circular polarization, the azimuthal dependence will occur in the cross section [48].

The total Compton scattering cross section per unit energy for the scattered photon integrated over the entire range of azimuthal angle ϕ in terms of ρ can be written as Equation (1.15).

$$\frac{d\sigma}{d\rho} = \frac{d\sigma_0}{d\rho} \mp P_e P_\gamma \cos \psi \frac{d\sigma_1}{d\rho} \quad (1.15)$$

An asymmetry in the cross section is introduced by the second term in Equation (1.15) which changes sign for different electron and photon polarizations. Figure 1.4 and Figure 1.3 show the total Compton scattering cross section and asymmetry respectively for 1.159 GeV electrons scattering from 532 nm photons.

Figure 1.3

Theoretical asymmetry with respect to ρ in QED

Figure 1.4

Theoretical cross-section with respect to ρ in QED

For a given ρ which can also be seen as a given energy bin of the scattered electrons (or photons), if we measure the asymmetry in the counting rate for that energy bin, while changing the helicity of either the electron or photon (only one of the two), we get:

$$A_{exp} = \frac{N^+(\rho) - N^-(\rho)}{N^+(\rho) + N^-(\rho)} = -P_e P_\gamma \cos \psi \frac{d\sigma_1/d\rho}{d\sigma_0/d\rho} \quad (1.16)$$

Since we are interested in longitudinal polarization, setting $\psi = 0$, we get Equation (1.17).

$$A_{exp} = P_e P_\gamma A_{QED} \quad (1.17)$$

where A_{QED} is the theoretical asymmetry which can be precisely calculated in the QED formulation. The experimental asymmetry (A_{exp}) is therefore equal to the calculated asymmetry (A_{QED}) scaled by the polarizations of the electron (P_e) and the photon (P_γ) beams (Equation (1.17)).

1.3 Principle of Compton polarimetry

The Compton polarimeter is based on the elastic scattering of longitudinally polarized electrons on circularly polarized (laser) photons. A system of reflecting mirrors is used to transport the laser conserving the circular polarization to the Compton interaction point where the electrons interact with the circularly polarized photon target. The electrons are further momentum-analyzed in a deflecting dipole magnet and detected in a position sensitive detector.

The total cross section for scattering between incident electrons with spins parallel to the spins of incident photons is larger than that of the corresponding antiparallel configuration.

Since the relativistic Compton scattering process of $\vec{e} - \vec{\gamma}$ is very well understood; this asymmetry in the Compton process is exploited to measure the beam polarization in a Compton polarimeter. It provides an absolute, local, online and non-destructive measurement of the beam polarization [44].

1.4 History of Compton polarimetry

Improvement in our understanding of the quantum mechanical process known as the Compton effect, along with several technological developments, has enabled the use of Compton scattered electrons and/or the back-scattered photons to measure the Compton asymmetry and thereby the polarization of the participating electron beam. The working of this polarimetry technique [35, 2] where the longitudinal polarization is extracted from the measurement of the counting rate asymmetry for parallel and antiparallel orientation of electron and photon helicity has been demonstrated at storage rings (NIKHEF [47], HERA [2]) and at high-energy colliders (SLAC [59], LEP [25]).

The Compton cross section asymmetry decreases almost linearly with the decreasing product of photon and electron energy. It reduces to a few percent at low beam energies, making the measurement particularly challenging at the JLab energies. Figure 1.5 shows the asymmetry as a function of electron beam energy for green laser.

Hall A, one of the experimental halls at JLab successfully installed a Compton polarimeter [4, 17] and have achieved a precision of $< 1\%$ using a photon calorimeter. The Hall A measurement was made possible by the use of a Fabry-Perot cavity fed by an infrared laser (later upgraded to green) to enhance the photon luminosity facilitating high

Figure 1.5

Maximum Compton asymmetry with varying beam energy.

statistical accuracy in an hour of data. Further the crossing angle between electron and photon beams was minimized to increase luminosity. The group has reported improved reduction of systematic uncertainties by using the energy weighted sum of the photon spectrum instead of using the counting mode data acquisition for each energy channel.

1.5 Relevance to Q_{weak}

A very large fraction of the high-energy and nuclear physics experiments at the intensity frontier require a polarized electron beam. In general, the uncertainty in the knowledge of the electron beam polarization is a significant contribution to the total uncertainty in the physics measurement.

The recently concluded Q_{weak} experiment [36] aimed to measure the weak charge of proton with a precision of 4.2% by measuring the parity violating asymmetry in polarized electron - proton elastic scattering with a precision of 2.5%.

Table 1.1

Error budget of Q-weak experiment

Source of error	$\delta A/A$	$\delta Q/Q$
Counting statistics	2.1	3.2
Hadronic structure	-	1.5
Polarimetry	1.0	1.5
Absolute Q^2 determination	0.5	1.0
Backgrounds	0.5	0.7
Helicity correlated beam properties	0.5	0.7
Total	2.5	4.1

Table 1.1 lists the major contributions to the final uncertainty in the measurement of the weak charge of the proton (Q_W^P). The second column shows the contributions to the parity violating physics asymmetry while the third column shows the eventual contribution to the Q_W^P measurement made by the experiment. Beam polarimetry makes the highest contribution to the experimental uncertainty in this precision measurement. As with Q_{weak} , in most experiments pertaining to parity violation, the uncertainty in polarimetry factors in directly in the uncertainty of the final physics measurement. Table 1.2 lists the defining parameters of the Q-weak experiment [45].

Table 1.2

Defining parameters for the Q-weak experiment at JLab

Parameter	Central Value
Beam energy	1.159 GeV
Beam polarization	85 %
Beam current	180 μA
Data taking time	2200 hours
Average Q^2	0.026 (GeV/c) ²
Average analyzing power	-0.28 ppm
Average experimental asymmetry	-0.24 ppm
Integrated cross section	3.9 μb

CHAPTER 2

EXPERIMENTAL SETUP

2.1 Jefferson Lab

Thomas Jefferson National Accelerator Facility commonly, known as Jefferson Lab (JLab) with its first experiment in 1995, to focus on medium energy physics. Until May 2012, JLab operated in the energy range of $\sim 0.6 - 6.0$ GeV. Initially known as the Continuous Electron Beam Accelerator Facility (CEBAF), it is a five-pass recirculating superconducting linear accelerator capable of simultaneous delivery to three experimental halls (Figure 2.1¹) with continuous wave electron beams. The beam generated in the injector is accelerated as it passes through linear accelerating regions (LINACs) that increase the beam energy to 1.159 GeV per pass in the Q-weak configuration. It delivers up to $200 \mu A$ electron beam current, nominally achieving $> 85\%$ polarization, geometric emittance less than $10^{-9} m Rad$, and relative momentum spread of a few 10^{-5} [37].

2.2 The Electron Beam

The Q-weak experiment used a one-pass beam from the accelerator with an energy of 1.159 ± 0.001 GeV for most part of the experiment. We routinely achieved a polarization of $\sim 89\%$ and used up to a maximum current of $185 \mu A$. JLab provides a very stable

¹Figure courtesy : M. Stewart

Figure 2.1

Jefferson Lab Schematic overview

beam with the total number of beam trips typically limited to 3-5 per hour. The beam also maintained a beam position stability of $\sim 100\mu m$ on the physics target.

2.2.1 Generation

At JLab, the electron beam is produced by shining a high intensity circularly polarized laser on a super-lattice of strained Gallium-Arsenide (**GaAs**), photo-cathode which then emits electrons due to the photoelectric effect. The beam current is proportional to the intensity of the laser light that is incident on the photo-cathode. These polarized electrons are produced by 3 lasers each at 499 MHz forming a continuous series of electron bunches, combined into one beam at a characteristic radio-frequency of the accelerator (1497 MHz). These bunches are accelerated further in an electrostatic field through vari-

ous stages using superconducting cavities. Each experimental hall receives these bunches at a rate of 499 MHz. JLab delivers what is effectively a continuous wave (CW) electron beam (Figure 2.2).

Figure 2.2

JLab electron beam, bunched at 499 MHz

The photo-cathode delivered up to 50 C of charge per laser spot during first phase of data taking and was upgraded to deliver up to 200 C during second phase. After using a particular spot on the photo-cathode for the beam generation, when the quantum efficiency drops significantly, the region on which the laser is focused is changed to another spot. This fall in the photocathode's quantum efficiency during electron emission is predominantly caused by ion back-bombardment and we could achieve a higher charge lifetime by increasing the laser spot size thus distributing the ion damage over a bigger region [22].

2.2.2 Steering Constraints

The beam size in the Compton interaction region had to approximately match that of the laser size with a target of $\sim 100 \mu m$ in the interaction region. Simultaneous focusing in the Compton interaction region and at the physics target was made possible by an array of quadrupole magnets before and after the Compton chicane. Four standard beamline quadrupole magnets placed before the Compton chicane together acted as the principle knobs for adjusting the beam in the Compton interaction region. There were another two beamline-style quadrupole magnets following the chicane and two larger quadrupoles (part of the Møller system) that allowed preparing the beam for the physics target.

2.2.3 Beam related backgrounds

The beam related backgrounds are largely referred as beam halo. It is a radial charge distribution in the annular region of the central charge bunch. It often has a characteristic Gaussian tail around the beam. It can be caused by parametric resonances or non-linear forces due to space charge, as well as field emission, light scattered on photo-cathodes, or by numerous other phenomena [20].

We monitored the beam halo in the Compton region along with the halo near the physics target. The halo rates as recorded in halo monitors were directly correlated with the width of asymmetry measured by luminosity monitors upstream of the physics target. We placed a scintillation detector in the Compton interaction region upstream of the Compton interaction point to monitor the halo as would be relevant to the Compton polarimeter. Figure 2.3 shows the beam halo in the Compton interaction region for the whole of run2. The x-axis of

the plot represents time in terms of run number, while the y-axis is the charge normalized rate [Hz/ μ A] measured in the scintillator.

Figure 2.3

Scintillator rate for run2 averaged in clusters of 30 runs

To put these rates in perspective one could note that past experiments have deemed acceptable, a background due to halo at 10^{-11} of the beam current [5]. In general our understanding of beam halo is very empirical.

2.2.4 Helicity

In order to suppress systematic effects due to slow gain drifts, target density fluctuations and beam drifts on the extraction of parity violating asymmetry, we reversed the helicity at a frequency of 960.015 Hz. A reversal pattern of (+ - - +) or (- + + -) was used for consecutive helicity quartets in a pseudorandom order. Each helicity interval is

split into $971.65 \mu s$ of stable helicity and a $70 \mu s$ of helicity transition period, the latter is commonly referred to as the MPS (Macro Pulse Signal). During the transition period, the triggered data collection is gated off. This introduces an effective deadtime of 6.8 %.

For achieving the helicity reversal, a linearly polarized laser beam (used to generate the electron beam) is passed through a piezoelectric crystal with birefringence dependent on applied voltage (commonly known as Pockels cell). The emerging laser beam is circularly polarized. Reversing the Pockels cell voltage reverses the birefringence of this optical element, hence reversing the laser beam helicity. As a result of reversing the photon helicity, during beam generation, the helicity of the photons is transferred to the electrons, resulting in the helicity reversal of the electron beam.

2.3 Beamline Components

This section describes all major beamline components at the CEBAF injector and upstream of Compton polarimeter that in some way can affect the beam or its properties in the polarimeter.

2.3.1 Half Wave Plate

An insertable half wave plate (IHP) is the first slow polarization flipping tool that was used to flip the linear polarization of the laser by 180° ; thus, taking what would have been an eventual left-handed state and producing a right-handed state and vice-a-versa. The IHP flips the polarization of a photon that results in the eventual flipping of the state of the emitted electron.

In the Q-weak convention, with the IHWP out, the positive helicity (h+) refers to the electron polarization pointing downstream in the beam direction, while negative helicity (h-) implies electron polarization pointing upstream.

We also used a rotatable half wave plate (RHWP) before the laser beam entered the Pockels cell to eliminate any residual linear polarization in the laser beam. Similar to the IHWP, a RHWP can also be used to reverse the e-beam polarization by flipping the laser polarization. But unlike the IHWP, it is always in beam, and is used to rotate the linear polarization of the laser by a small amount in order to take care of a possible systematic effect of change in beam path due to insertion of the IHWP. In effect, the RHWP leaves the path of laser beam through the Pockels cell unaffected and was the last optical element before the laser beam entered the Pockels cell. The insertion/removal of the IHWP took only few minutes and was changed approximately every 8 hours of data collection. During the whole experiment, $\sim 50\%$ of the data collected had the IHWP placed in the path of linearly polarized laser beam before it reaches the Pockels cell.

2.3.2 Wien Flipper

The Wien flipper [23] is also a slow polarization flipping tool at the CEBAF injector. Unlike the IHWP which reverses the electron beam polarization by inverting the laser polarization from left circularly polarized to right circularly polarized and vice versa, the Wien flipper directly reverses the polarization of the electron beam. The Wien flipper consists of two Wien filters separated by two solenoids placed between them. A Wien filter consists of crossed electric and magnetic fields that can be used to rotate the spin

of the electron without impacting its trajectory [52]. The first filter rotates the spin of a longitudinally polarized electron by 90° making the beam transversely polarized in the vertical direction. The solenoids then rotate the transverse polarization from vertical to horizontal. The second Wien filter rotates the electron's spin back to longitudinal, but rotated 180° with respect to the initial spin direction. The Wien flipper takes several hours to reverse and is hence used about every few weeks of data collection.

Apart from the IHWP and the Wien flipper discussed above, there were several other techniques used to reduce the helicity correlated changes in the beam properties. These include charge feedback and Pockels cell alignment. In the charge feedback mechanism, software continuously monitored the total charge in each helicity state and in the case of an asymmetry, makes minor adjustments to the settings to null the charge asymmetry. These methods ensure that the number of electrons produced in the $h+$ state are as close as possible to the number of electrons produced in the corresponding $h-$ state, so as to not create a false asymmetry. One can find more details on these in Ref. [36].

2.3.3 Beam Position Monitor

As the name suggests, a beam position monitor (BPM) monitors the beam's position. We have several BPMs installed throughout the beamline from the injector to the experimental hall. A typical BPM consists of a set of 4 RF antennas that are parallel to the beam-line and are evenly spaced azimuthally around the beam-line. It works on the principle of induction with the signal in each antenna being proportional to the beam current

and the distance between the beam and antenna. A comparison of the signals from the 4 antennas gives the position of the electron beam.

The BPMs are read out along with the physics data and are monitored to ensure beam position stability.

2.3.4 Beam Current Monitor

A beam current monitor (BCM) is used to measure the average current in the beam-line. A chain of well calibrated, gain matched BCMs, along the beam path can also be used to alert us to beam loss along the beam path. A standard BCM consists of a pair of temperature-controlled RF cavities with a probe inside built to be coupled to a resonant mode of the cavity. As the beam passes through the cavity a transverse electromagnetic mode is excited that is then sensed by the field probe. The size of the excitation is proportional to beam current. The monitors are calibrated based on an absolute calibration of $40 \text{ mV}/\mu\text{A}$ in a given operational range. These calibrations works best for current greater than $25\mu\text{A}$.

2.4 Compton Polarimeter

The Compton polarimeter was installed to measure the luminosity weighted average polarization in Hall C over a period of ~ 1 hour with both the statistical and systematic uncertainty within 1%. The polarimeter, was designed with the ability to operate at Q-weak running conditions ($E=1.159 \text{ GeV}$) and had to coexist with Møller polarimeter, but was kept configurable for running at higher energies up to 12 GeV after JLab upgrade.

Essential components used in our Compton polarimeter were a magnetic chicane (Sec - 2.4.1), laser (Sec - 2.4.2), photon-detector (Section 2.4.3) and electron-detector (Section 2.4.4). These are described in the following sections.

Figure 2.4

Jefferson Lab Hall C Compton Polarimeter Layout

2.4.1 Magnetic chicane

We use a magnetic chicane to deflect the Compton scattered electrons without disrupting the unscattered electrons in the beam line. It consists of a series of four dipole magnets each with an effective length of 1.25 *m* long and 0.33 *m* high as shown in Figure 2.4². The direction of the magnetic field of consecutive dipoles are reversed such that the electrons' motion through the chicane is completely orthogonal. In other words, the $\int \vec{B} \cdot d\vec{l} = 0$ for the chicane and the random changes in angles and energy of the beam from the resulting synchrotron radiation emitted is much smaller than the natural beam emittance and energy

²Figure courtesy: Donald Jones

uncertainty respectively. The chicane affects the spin precession by a small amount and is described in Section 5.5.6.

Figure 2.5

Technical Drawing of the Magnetic chicane

The dipoles used during the Q-weak experiment had a maximum design current of 250 A though they were operated at 104.5 A giving a field of 0.545 T. The field was uniform across the poles up to 10^{-4} T as shown in Figure 2.6 and Figure 2.7. Here z-direction is the direction of electron momentum while x-direction is the vertical direction perpendicular to the electron momentum. The dipole field strength determines the exact position of the Compton scattered electron on the detector, hence an accurate knowledge of the field is necessary for precision polarimetry. We also used a few turns of the dipole coils as what we call 'trim coil' of the dipole. This is used to make the field effectively linear during the passage of the beam electrons through the dipole.

Figure 2.6

Magnetic field map in longitudinal direction

Figure 2.7

Magnetic field map in transverse direction along the pole

2.4.2 Laser

We use a 10 W Coherent VERDI [26] green ($\lambda = 532 \text{ nm}$) laser locked to an external Fabry-Perot optical cavity, resulting in more than 1500 W of light incident on the polarized electron beam. A statistical precision of $< 1 \%$ was achieved because the luminosity of the $\vec{e} - \vec{\gamma}$ interaction could be multiplied manyfold due to Fabry-Perot cavity [29]. It comprises two identical high reflectivity, low loss, mirrors which amplify the photon density at the Compton Interaction Point (CIP) with a nominal gain of ~ 200 . The cavity is fed by a continuous wave laser and has a feedback on the wavelength.

The laser polarization was periodically monitored at the exit line during data taking. The exit line measurement can be used to evaluate the laser polarization inside the cavity using a polarization transfer function which is modeled using absolute polarization measurements inside the cavity and the exit line during intermittent maintenance periods. However, a new technique based on minimizing the amount of laser light reflected backwards through an optical isolation system was used for measurements presented here. The theoretical basis and details of the laser parameters in use are further elaborated in Section 4.2.1.

During the experiment, the circular polarization of laser in the cavity was maintained by finding the optimal setting between the Half wave plate and the Quarter Wave plate (marked 6 & 7 in Figure 2.8).

The optimal setting minimizes the amount of light transmitted back to the residual reflection photo-diode (RRPD, marked 15 in Figure 2.8) from the cavity.

Figure 2.8

Schematic showing various components of the laser table

2.4.2.1 Laser polarization

If we write the electric field vector of an electromagnetic wave traveling in Z-direction with the speed of light, we have

$$\vec{E}(t, z) = \vec{E}(0, 0) \cos(\omega t - kz - \phi), \quad (2.1)$$

where using common convention, t and z are the time and position of the wave vector being described; while ω and k ($=\omega/c$) denote the value of the angular frequency and wave vector of the wave; ϕ denotes an arbitrary phase. The corresponding magnetic field vector ($\vec{B}$) runs perpendicular to $\vec{E}$ with a magnitude of E/c . Both $\vec{E}$ and $\vec{B}$ are perpendicular to the direction of propagation ($\vec{z}$). The x and y components of the $\vec{E}$ can then be written as

$$E_x(z, t) = E_x(z, 0) \cos(\omega t - \phi_1) \quad (2.2)$$

$$E_y(z, t) = E_y(z, 0) \cos(\omega t - \phi_2) \quad (2.3)$$

In Equation (2.2), $\phi_{1,2}$ denote the two arbitrary phases of the x and y component respectively. Further, if we denote the angle between $\vec{E}(z, t)$ and positive X-direction as the polarization angle ψ . Then the polarization of the wave is given by the relative values of $E_x(z)$, $E_y(z)$, ϕ_1 and ϕ_2 [28]. Linear polarization results for the special case when $\phi_1 = \phi_2$, in which case the orientation of $\vec{E}$ depends only on the magnitude of $E_x(z)$ and $E_y(z)$ and is independent of time as the angle ψ remains constant.

If the two phases have a relative shift such that $\phi_1 = \phi_2 \pm \pi/2$, the tip of the electric field vector rotates in the x - y plane with angular frequency ω and the radiation is called circularly polarized. The sign of $E_y(z, t)$ which comes from the relative phase determines

the sense of the motion of $\vec{E}$. A positive sign of $E_y(z, t)$ corresponding to counter clockwise direction is commonly referred to as right handed circular polarization and a negative sign signifies left handed circular polarization.

Circularly polarized light reflected from the first cavity mirror is blocked by the linear polarizer (marked 5 in Figure 2.8) and dumped into a high power beam dump (marked 13). Residual linearly polarized light leaks through the linear polarizer and is measured by the photodiode (marked 12). This leaked light is used to attenuate polarization, monitored by RRPD.

The principle of optical reversibility [56] allows us to measure the polarization of the reflected laser beam to find the polarization of the light in the cavity. The degree to which the light is not perfectly circularly polarized determines the amount of reflected laser light. The reflected power is fit to a model to predict the degree of circular polarization in the cavity. Using this, we were able to get $\sim 100\%$ circularly polarized light in both left and right - handed states.

2.4.2.2 Laser Lock

To achieve a stable light output, the laser frequency is locked to one of the resonant frequencies of the cavity using the Pound, Drever and Hall feedback technique. Using this technique, the original input power of 230 mW infra red laser is enhanced to a maximum power of 1800 W with a coupling to the fundamental mode of 92%.

Naively one would think of achieving stable frequency lock by feeding back on the reflected or transmitted light from the cavity. Since the intensity of the reflected beam is

symmetric about the resonance peak, if the laser frequency drifts out of resonance with the cavity, it is not certain from the intensity of the reflected light if the frequency needs to be increased or decreased to bring it back into resonance. The Pound - Drever - Hall is a simple yet elegant technique where we use the fact that the derivative of the intensity about the resonance is anti-symmetric. Hence, the frequency is varied by a small fraction to see the response of the reflected laser beam. This measurement of the derivative of the reflected intensity with respect to the laser frequency is fed back into the laser to dynamically maintain a stable frequency lock.

2.4.3 Photon detector

We use a matrix of four crystals of Lead Tungstate ($PbWO_4$) scintillating crystals with dimensions of $3 \times 3 \times 20$ cm to detect the backscattered photons. The matrix of crystals is attached to a single 3' Hamamatsu H6526 photomultiplier tube.

We analyze the photon detector data by doing an energy weighted integration of the whole Compton spectrum with no threshold over a full helicity state. This makes us free from the need to do an absolute calibration. But this method also makes it very sensitive to pedestal subtraction. The integration is accomplished using a 200 MHz sampling flash analog to digital converter (FADC).

The FADC also has the capability of storing 'snapshot' of individual light pulses that hit the detector. These pulse snapshots allow the construction of a pulse spectra. The

Figure 2.9

Photon detector yield for laser on (green) and laser off (blue) during data taking

spectrum shown in Figure 2.10³ is the convolution of the Compton spectrum with detector response in the arbitrary units of energy bins of the FADC.

2.4.4 Electron detector

The Compton electron detector is used to give a standalone determination of the beam polarization. It can also be used for energy calibration of the photon detector (Section 2.4.3). The position at which an electron is detected directly relates to its momentum. Hence, the precise knowledge of the detector's position and inter-plane detector alignment was very important.

The aligned detector stack is installed to the bottom of a motion mechanism which is capable of reproducibly moving the detector-assembly by over 10 cm with a precision of

³The green, blue and black curves shows the laser on counts, laser off counts and the background subtracted counts for the Compton spectrum measured by the detector

Figure 2.10

Photon detector integrated pulse spectrum

0.01 mm. The arrangement also allows us to tilt the detector stack at an intended angle. We tilted the whole detector stack at $\sim 10^\circ$ to the vertical, so that the Compton scattered beam electrons hit the detector almost perpendicularly. The detector stack and motion mechanism are held in a vacuum can (Figure 3.13) which sits in the immediate vicinity and upstream of the 4th dipole in the magnetic chicane (Figure 2.5⁴). The motion mechanism is remotely controlled by an IDC one-axis microstepping smartdrive [27]. While in operation, the detector stack is nominally kept at a position such that the bottom of the detector (close to strip-1) is ~ 5 mm from the unscattered beam. While not taking data, the detector is retracted to a position out of the line-of-sight of the beam to avoid accidental scraping. This position is referred to as the 'garage position' and had a FSD connected to it for safety. The detector and its properties are further elaborated in chapter - 3.

⁴showing the 4 dipoles, the electron detector vacuum-can (Figure courtesy: E. Ihloff and C. Vidal, MIT-Bates)

Table 2.1 summarizes the nominal parameters relevant to the Compton polarimeter which are described in this chapter. Here, Compton edge is referred as 'CE'.

Table 2.1

Typical Parameters for Hall C Compton polarimeter

Parameter	Referred as	Nominal value
Beam energy	E	1.159 (GeV)
Beam current	I	180 μA
Laser power	P_γ	$\approx 1700 W$
Laser wavelength	λ	532 nm
Photon-energy at CE	γ_{CE}	46 MeV
Dipole field	B_{dipole}	0.54 T
Chicane bend angle	θ_{bend}	10.3°
Vertical beam deflection		57 cm
Diamond detector pitch		200 μm
Electron free drift	z_{drift}	~ 3 m
Electron displacement at CE	y_{CE}	17.29 mm
Maximum Compton asymmetry	A_{asym}^{CE}	4.04 %

2.5 Other Polarimeters

2.5.1 Mott polarimeter

We use a Mott polarimeter (introduced in Section 1.1) in the electron injector region to measure the beam polarization in the exit line at 5 MeV. It can measure both transverse components (horizontal and vertical of the beam polarization).

The beam electrons hit the gold target at an angle of $< 2 \text{ mrad}$. The polarimeter has two horizontal and two vertical electron detector arms, each placed diametrically opposite

with azimuthal symmetry. An internal collimator limits the detector acceptance to only Mott scattered electrons and ensures that it sees only the central part of the target foil.

The analyzing power of the target is determined by measuring the scattering asymmetry for a number of gold foils with varying thickness to facilitate extrapolation to zero foil thickness. This is then considered to be same as the analyzing power calculated for a single atom. The maximum analyzing power occurs at an electron scattering angle $\sim 172^\circ$ for 5 MeV beam energy and atomic number ($A = 197$) of the target nuclei. We use a 1 μm thin unpolarized gold foil as target. Though this yields a quick measurement, this has the dual limitation of measuring polarization at very low current as well as low beam energy. The effective analyzing power of our Mott polarimeter is ~ -0.40 [24]. The details of the setup are further elaborated by a report by M. Steigerwald [51].

The Mott polarimeter was not used to provide absolute polarization measurements during Q-weak experiment. However, it was periodically used to make sure that the vertical component of the polarization was small. (We checked the corresponding horizontal component with spin dance in Moller polarimeter)

2.5.2 Møller polarimeter

Before the Q-weak experiment, the Møller polarimeter was the only measure of polarization of the electron beam arriving in Hall-C. The polarimeter is designed to provide an absolute polarization measurement with accuracy better than 0.5% in a few minutes. Figure 2.11 depicts a schematic layout of the polarimeter, which is placed downstream of Compton polarimeter in the beam alcove but upstream of the target. A superconducting

solenoid magnet polarizes a pure iron foil out-of-plane by applying a field of 3.5 T (pure iron saturates at 2.2 T). The maximum of the analyzing power for Møller scattering occurs for 90° angle between beam and scattered electrons in the center of mass reference frame. Applying a Lorentz transformation to the laboratory system, we get two stream of electrons with equal energies (each having $\approx$ half of the incident beam energy), moving at equal and opposite small angles to the incident beam direction in the scattering plane. A pair of quadrupole magnets (Q1 and Q2) act as an optical lens to deflect these electrons, on to the detector array. A set of movable collimators placed between Q1 and Q2 are employed to further reduce the background without affecting the detector acceptance. The two detectors detect both scattered and recoil electrons in coincidence to eliminate Mott events. The effective analyzing power for our Møller polarimeter is ~ -0.06 [24] and it allows operation at any beam energy between $\sim 0.9 - 6$ GeV.

Though it yields a precise measurement very quickly due to high rates, the use of Fe foils as the target makes it an invasive method. The first order calculation of analyzing power assumes the atomic electrons of the Fe foil to be at rest. While electrons in the outer most orbit may have energy ~ 5 keV, those closer to the nuclei can have momenta up to 100 keV. Even though this energy is small compared to the 1.157 GeV beam energy used during the Q-weak experiment, those momenta are significant w.r.t the electron rest mass and can alter the center of mass energy by as much as 20% [1]. This effect known as the Levchuk effect [39], Thus the Møller measurements were made at beam currents much lower than that used in the Q-weak experiment. This was typically ~ 1.5 μA . Since the

Figure 2.11

Schematic view of Møller set up in Hall C

measurements were made at smaller beam currents, we have also included an uncertainty $\sim 0.5\%$ to the measurement due to extrapolation to high beam currents.

2.6 Other Q-weak Apparatus

Apart from the Compton polarimeter, the Q-weak experiment set several other physics and technical milestones. The experiment was made possible by innovations from over 80 collaborations from 14 institutions who made it possible to achieve the challenge of measuring the Q-weak asymmetry of the order of 300 ppb. Among other things, for this experiment, JLab delivered for the first time, a beam current as high as $180 \mu A$. We had the world's highest power hydrogen target capable of taking $\sim 2 kWatt$ of beam power.

The Q-weak apparatus and operation is described in detail in other dissertation work in references [36, 57].

CHAPTER 3

THE ELECTRON DETECTOR

3.1 Introduction

The passage of minimum ionizing particles (electrons, in this case) creates a charge pulse in the diamond micro-strip detector kept in a vacuum-can in the beamline. The charge pulse, is carried from the detector electrodes to a custom made electronic circuit board (called QWAD board) placed outside the vacuum by a specially designed flexible circuit board (called Flex cable). The QWAD board amplifies the charge pulse and converts into a digital signal and sends out the digital signals to Field Programmable Gate Array (FPGA) based data acquisition boards using 200 meters of shielded twisted pair cable. This chapter of the dissertation will elaborate on the working and response of the different segments of the signal chain mentioned above.

3.2 The Diamond Detector

The detectors are made from $21\text{ mm} \times 21\text{ mm} \times 0.5\text{ mm}$ plates of Chemical Vapor Deposition (CVD) diamond [40]. Each diamond plate has 96 horizontal metallized electrode strips with a pitch of $200\text{ }\mu\text{m}$ ($180\text{ }\mu\text{m}$ of metal and $20\text{ }\mu\text{m}$ of gap) on one side (front) and a single metallized electrode covering the entire diamond surface on the opposite (back) side. The electrodes consist of successive depositions of Ti, Pt and Au, using a photo-

lithography technique. The detectors were manufactured by Diamond Detectors Ltd [40]. Each diamond plate was mounted on a 60 mm $\times$ 80 mm Alumina substrate. Each strip on the diamond detector is wire bonded, with a pair of Al wires, to gold traces on the Alumina substrate, that terminate on a pair of 50 pin high density connectors. The diamond plate was glued to the Alumina substrate using a conductive silver epoxy that connected the electrode on the back side of the diamond to a miniature high voltage connector [54]. A single detector plane is shown in Figure 3.1.

Figure 3.1

Diamond micro-strip detector

The individual detector strip size of 180 μm enabled a corresponding position resolution of 180 μm in electron detection using a single detector plane. Using multiple planes of same strip size, in principle, we can get a better resolution.

During run-1 of the experiment, the first detector plane was non-operational due to physical damage during installation. During run-2, though we replaced the first detec-

tor plane, the fourth detector plane was not operational due to problems originating from associated connections and electronics. Hence, unless otherwise mentioned, we refer to 3 detector planes throughout the whole document. For the nominal beam energy, dipole field and geometry, the maximum scattered electron was $\sim 17.3 \text{ mm}$ from the unscattered beam. We operated the detector at a distance of $\geq 6 \text{ mm}$ from unscattered electron beam, hence the Compton edge was well within the first 64 strips. The subsequent discussion and the plots show the spectrum only up to the first 64 strips. A typical strip hit spectrum is shown in Figure 3.2. The desired statistical precision of $< 1\%$ per hour was achieved at the full beam current of $180 \mu\text{A}$.

Figure 3.2

Charge normalized yield in a single plane of the electron detector

By comparing the expected rate to the measured, we estimate an effective detector efficiency of $\sim 70\%$. The large inefficiency is attributed to the separation between the

detector and the readout electronics and the trigger inefficiency in DAQ. The following sections give a detailed description of the diamond micro-strip detector which was used as a tracking device in a physics experiment for the first time.

3.3 Detector Material and Properties

A semiconductor detector is the typical choice for tracking detector. Silicon has traditionally been used for high energy electron detection. Due to the relatively low beam energy and the dipole used in the experiment, the electron detector in this polarimeter had to be placed within a cm of the electron beam resulting in a rather large cumulative radiation dose. We chose diamond for our tracking detector, due to its known radiation hardness [10] which is further discussed in Section 3.3.7.

We used diamond films deposited by chemical vapor deposition (CVD) technology by E6 corporation [40] as our diamond micro-strip detector. In the CVD process [18], a hydrocarbon gas, such as methane is mixed with a large concentration of molecular hydrogen gas. The gas mixture is excited by a power source to create a carbon plasma on top of a substrate so that the atomic state carbon atoms link together on the substrate forming σ -type (strongest possible Carbon-Carbon bond) bonds which lead to a diamond lattice and eventually a polycrystalline film [60]. Figure 3.3 illustrates a typical cross-sectional view of a diamond film grown by CVD. The diamond films that we used were 500 μm thick owing to the limitation set by the charge collection distance (Section 3.4).

Diamond grown through CVD has several attractive properties [40] such as high band gap, high dielectric constant, high electrical carrier mobility, chemical inertness along with

Figure 3.3

Cross sectional view of polycrystalline diamond film

excellent electrical insulation properties which make it a suitable detector material in high radiation environment.

3.3.1 Charge Ionization Process

The rate at which energy is lost in a medium (per unit path length) decreases rapidly with increasing particle speed until it reaches roughly 95% of the speed of light. Such a particle is known as a minimum ionizing particle (MIP), and it has a relativistic energy about 3.2 times its mass. Further increases of velocity produce a slow (logarithmic) increase in energy loss as described by the Bethe-Bloch equation [38]. The electrons of interest in the diamond micro-strip detector are all MIP. When a MIP passes through a semiconductor material it leaves behind a trail of $e^- - h^+$ pairs. In the presence of an external electric field, these $e^- - h^+$ pairs move away from one another. This movement of the charges induces a signal in the external circuit attached to the electrodes. If charges e^+ and e^- move towards

the respective electrodes a distance x in a uniform electric field $\vec{E}$ the work done by the power source maintaining the field is exE . If the width of the detector across which $\vec{E}$ is maintained is l units and the applied potential difference is V the electric field is $E = V/l$ and the work done is exV/l . This work done creates a transient current that passes around the circuit and the integrated charge on the electrodes is given by the time integral of this current,

$$Q = \frac{ex}{l} \quad (3.1)$$

Thus, the signal per $e^- - h^+$ pair is proportional to the mean separation of the electron and hole before they become trapped in the material.

3.3.2 Number of Electron-Hole Pairs

The deposited energy directly translates into the number of $e^- - h^+$ pairs produced for a given semiconductor. As a reasonable estimate, the formation of each $e^- - h^+$ pair from the passage of a MIP, in all semiconductors, requires about three times the bandgap energy [32]. The number of pairs created, can be estimated from the total amount of energy deposited ($d\xi/dx$) compared to the energy needed to generate one $e^- - h^+$ (E_{pair}) pair as shown in Equation (3.2).

$$n = \frac{\frac{d\xi}{dx}}{E_{pair}} \quad (3.2)$$

For the case of diamond, which has an ionization energy of 78 eV, the energy deposited per unit length for every MIP is $1.84 \text{ MeV cm}^2 \text{ g}^{-1}$. Due to the high bandgap of diamond, we get an average of 36 $e^- - h^+$ pairs per MIP. To put it in perspective, this can be compared

to $108 e^- - h^+$ pairs produced per MIP in the case of silicon. Hence the signal formed by diamond is smaller than silicon.

3.3.3 Bremsstrahlung Effect

As the high energy electrons pass through the diamond film, they scatter and lose energy by collisions and undergo deceleration resulting in Bremsstrahlung radiation. The ratio of energy loss due to radiation to that due to Coulomb process can be approximated as [6]

$$\frac{\left(\frac{dE}{dx}\right)_{Brems}}{\left(\frac{dE}{dx}\right)_{Coulomb}} \approx \frac{ZE_i}{1600m_e c^2} \quad (3.3)$$

where Z is the atomic number of the matter, E_i is the incident electron energy and m_e is the rest mass of an electron.

From Equation (3.3), one can infer that for diamond ($Z=6$), the energy loss in the detector material due to bremsstrahlung exceeds that due to coulomb process (Section 3.3.1) for $E_i \geq 137 \text{ MeV}$. The QWeak beam energy was $\sim 1.16 \text{ GeV}$, hence the charged electrons will also lose their energy in the detector through bremsstrahlung, but our measurement method is only sensitive to the coulomb process.

3.3.4 Creation of Secondary Electrons

The Bethe-Bloch equation only estimates the mean energy loss as a particle travels through a medium. Some of the energy lost by the fast charged particles appear as secondary electrons and high energy photons. The energy loss process is statistical and has a Landau distribution. The high-energy tail of this distribution, due to close collisions with atomic electrons can sometimes acquire enough energy to travel through the detector. In

the case of diamond, if the deposited energy is $\geq 7.5 \text{ keV}$, these secondary particles escape the detector [13]. These are known as delta electrons and result in extra hits in subsequent detector planes. The secondary electrons can be ignored while looking at the first detector plane.

3.3.5 Photon Excitations

The detector is also subject to high energy photons (due to the bending of the fast moving electrons in the magnetic chicane). The absorption of electromagnetic waves is characterized by its absorption length which is defined as the distance in which the intensity drops to $1/e$ of the incident wave. As we know, diamond is transparent for visible light, i.e has an infinite absorption length; while it quickly changes with frequency to be $\approx 0.2 \mu\text{m}$ for x-rays [33]. Hence the $500 \mu\text{m}$ of the detector would completely absorb any x-ray produced in a synchrotron radiation. The energy deposited by this process is insufficient to cause a visible effect on the measured signal.

3.3.6 Electrical Properties

The electrical properties are determined largely by the band-gap of 5.45 eV, which is much larger than typical thermal energies at room temperature resulting in low thermal noise and high resistivity. The large band-gap also results in a larger creation energy for electron-hole pairs compared to Si. A larger $e^- - h^+$ pair creation energy results in a smaller signal for a given minimum ionizing particle.

The diamond signal being ~ 3.5 times smaller compared to silicon, is by far the only significant hurdle in terms of material properties. The cost involved in realizing the full

potential of diamond as a detector material has also inhibited the growth of this field. The two properties that come to rescue the smaller signal are high resistivity and high dielectric constant. The significantly higher resistivity of diamond results in a leakage current less than 1 nA/cm^2 at an electric field of $1 \text{ V}/\mu\text{m}$ [16], while the dielectric constant of diamond being double of silicon results in the load capacitance being reduced by half.

The response of diamond to ionizing beam is fairly well understood [16] and its electrical properties have been studied in depth [46]. Table 3.1 summarizes the comparison of silicon with diamond as a detector material.

Table 3.1
Comparison of diamond and silicon properties at room temperature

Property	Silicon	Diamond
Atomic number	14	6
Number of atoms (10^{22} cm^{-3})	4.96	17.7
Mass density (g/cm)	2.33	3.51
Radiation length (cm)	9.4	12.0
Intrinsic carrier density (cm^{-3})	1.45×10^{10}	$< 10^3$
Resistivity ($\Omega \text{ cm}$)	2.3×10^5	$> 10^{12}$
Band Gap (eV)	1.12	5.45
Electron mobility ($\text{cm}^2/\text{V/s}$)	1350	1800
Hole mobility ($\text{cm}^2/\text{V/s}$)	480	1200
Saturation velocity (cm/s)	0.8×10^7	2×10^7
Breakdown field (V/m)	3×10^5	2.2×10^7
Dielectric constant	11.9	5.7
Displacement energy (eV)	13-20	43
e-h creation energy (eV)	3.6	13
Mean MIP ionization ($e/\mu\text{m}$)	108	36
Charge collection distance (μm)	full	~ 250

In an electron detector, if two events are detected within the time span of charge integration (resulting in a single acquisition), they would result in a larger charge pulse, this is called pile-up. The charge collection time for diamond detectors is of the order of 1 *ns*. Due to the fast response time of diamond, pile up is not a problem for the electron detector in the Compton polarimeter, unlike the γ -detector. (The electronic board that was used to process the signal had a slow response time, so this became irrelevant in our case)

3.3.7 Radiation Hardness

Every material, whether natural or artificially grown has defects in its composition. These defects introduce energy levels inside the known band gap for the material. The charge carriers' transition between valence and conduction bands becomes more probable with the introduction of intermediate levels, the intrinsic carrier density increases, resulting in a higher leakage current. This intrinsic defect density is known to increase with exposure to radiation. Depending on the type and energy of impinging radiation, various defects may occur by atomic displacement or formation of smaller nuclear fragments. These defects could be vacancies, where a lattice position is unoccupied or interstitials, where an atom is posed in between the lattice. All these defects affect the detection efficiency by the creation of trapping and recombination centres, which decrease the carrier lifetime (τ_e) and thus the charge collection distance (d_c).

With a large band gap, and detector impurities below the ppm range, the leakage current in diamond remains negligible. Also, due to the highly packed lattice of diamond, it is less susceptible to the creation of lattice defects.

Figure 3.4

Effect of radiation on CVD diamond

Figure 3.4 shows that, as a result of exposing CVD diamond by $1.1 \times 10^{15} \text{ pions/cm}^2$, the mean charge per MIP reduced by $\sim 29\%$ from 4800 electrons to 3410 electrons [16].

A rough estimation suggests that diamond detectors are technically feasible as tracking detectors up to a hadronic fluence of at least $10^{15} \text{ particles/cm}^2$, which is ten times more than present silicon detectors allow [16].

Over the 2 year period of the QWeak experiment (Nov 2010 - May 2014), our diamond micro-strip detectors were exposed to a radiation dose of $\sim 10 \text{ MRad}$ (without including the dose from synchrotron radiation). No significant degradation of the signal size was observed during this period, demonstrating the radiation hardness of the diamond detectors.

3.4 Charge Collection and Detection

The charge induced on the electrodes depends on the average distance that electrons and holes drift apart in the electric field. This average distance is known as the charge collection distance (d_c). The charge collection distance can be estimated by the product of the carrier velocities (v_e and v_h) and lifetime (τ_e and τ_h), summed for both carriers. This can be expressed as;

$$d_c = d_{c,e} + d_{c,h} = v_e \tau_e + v_h \tau_h = (\mu_e \tau_e + \mu_h \tau_h) E \quad (3.4)$$

where μ_e and μ_h are the electron and hole mobility respectively in diamond and E is the bias field applied across the detector. Charge carrier mobility is an intrinsic property of the material and is comparatively high in diamond (Table 3.1).

Equation (3.4) which suggests a linear relationship between charge collection distance with the applied field, is true only in the linear region and tends to saturate as we increase

the field. The usual field strength for CVD diamond operation has become $1 \text{ V}/m$ after which the drift velocities saturate [16].

For good detection efficiency, the charge collection distance needs to be as high as achievable. A higher charge collection distance would result in a larger signal for each MIP. Due to the polycrystalline nature of CVD diamond, the grain boundaries are suspected to provide charge trapping and recombination centres. Improved growth techniques have enabled the fabrication of CVD diamond with fewer defect centres resulting in higher carrier lifetimes ($\tau_{e,h}$) and charge collection distance up to $250 \mu m$.

An alloy of titanium, platinum and gold is used as electrodes forming ohmic contact on the CVD diamond to apply voltage bias, and to extract the signal. This alloy is used due to its good adhesion properties to CVD diamond. The charge pulse created by the MIP is integrated by a charge-sensitive amplifier. A schematic of the detection of a minimum ionizing particle in a diamond detector is shown in the Figure 3.5.

We used a bias voltage of $\sim 400 \text{ V}$ across the detector. The detector signal (typically $\sim 9000 e^-$) is carried outside the vacuum can via a set of 55 cm long, 5-layer, flexible printed circuit boards made out of Kapton [31] called the Flex cable (Section 3.7). The signal was digitized and read out using QWADs (Section 3.8).

3.5 Characterization

A prototype diamond detector was studied using radioactive sources at the Medium Energy Physics laboratory at Mississippi State University. The primary focus of this study was to ensure that we would be able to measure the signal from the detector over the

Figure 3.5

Schematic mechanism of detector operation

background and get estimates of number of electrons collected per MIP. The prototype detector had fewer strips with larger pitch than that used in the final design, but the factors directly affecting the amount of charge collected were kept the same. These include the detector thickness ($500\text{ }\mu\text{m}$), the electrodes used for charge collection and the applied bias voltage. Similar to the mechanism of charge transfer eventually used, the detector strips were wire-bonded using double Aluminum wires to Gold traces which carries the charge pulse to the subsequent electronics. Figure 3.6 shows a schematic of the setup used. We used a $10\text{ }\mu\text{Ci}$ Cs-137 radioactive source as the source of minimum ionizing electrons.

Figure 3.6

Schematic for characterization of detector prototype

A scintillator attached to a PMT was placed behind the diamond detector. A collimator was placed before the scintillator to reject the electrons which have not passed through the

diamond detector. The data acquisition was triggered on the coincidence of a signal in the diamond detector as well as the PMT in a $1 \mu s$ time window. We used a multi-channel analyzer (MCA) to study the final signal. Over ~ 100 hours of source and background data were collected to get a statistically significant detector response distinguishable from background (Figure 3.7¹).

Figure 3.7

Response of prototype diamond detector

The MCA was calibrated using Cs-137 which has two internal conversion electron peaks at 624 keV and 655 keV which were detected in a $300 \mu m$ thick Silicon detector, thus

¹with threshold voltage of 50 mV and amplifier gain of 20

assigning an energy value to each channel number of the MCA. Thereafter, the position of the Sr-90 peak in the diamond detector was identified to correspond to 8858 electrons per MIP (Figure 3.9). Based on our study, we could also estimate the charge collection distance of $188\ \mu m$ for the prototype detector.

Figure 3.8

Response of silicon detector from Sr-90

3.6 Installation and Arrangement

We used four planes of the diamond detector (Figure 3.1) to detect the Compton scattered electrons. The four detector planes were stacked in a holder capable of lateral posi-

Figure 3.9

Response of diamond detector from Sr-90

tion adjustment to individual detector planes. A traveling microscope was used to ensure strip level alignment. The inter-plane distance in the detector stack was $\sim 1\text{ cm}$ as fixed by the dimensions of the detector holder. The whole detector stack was mounted inside a vacuum can and held at an angle of $\sim 11.3^\circ$ with respect to the vertical such that the Compton scattered electrons are approximately normal to the detector face. The detector stack was attached to a linear feed-through driven by a stepper motor that lowered and retracted the detector stack to and from its operating position. We used a carefully designed holder to align the different detector planes at the level of strip-to-strip matching. The detector is placed on the detector holder which in turn is placed on a traveling microscope (Figure 3.10). Each detector plane is individually screwed to the holder with a bolt that allows a shift of upto a millimeter. The detector is clamped with position holders that have sleeves (Figure 3.11) to manually push the detector in or out. These black screws allowed $\sim 0.5\text{ mm}$ motion per turn. While installation using a traveling microscope, the strip-1 of each plane was aligned to the preceding plane. Once this alignment is complete for the stack of all 4 detector planes, four separate screws are put on the corners of the holder to hold the alignment tightly.

3.7 Flex Cable

Under ideal circumstances, the charge pre-amplifier should be as close as possible to the detector strips. However, the vacuum separation and occasional detector movement made it necessary to have a cable between the detector output and QWAD boards. The length of these cables was limited to the minimum needed for the detector motion between

Figure 3.10

Detector during alignment

Figure 3.11

Accessories used to hold the detector

Figure 3.12

Beam view of the installed detector

Figure 3.13

Vacuum can and motion mechanism

operational position ($\sim 6 \text{ mm}$ from beam) and the garage position (Section 2.4.4) of the detector when not in use.

Figure 3.14

Detector, Flex, QWAD connection

A cable made out of a flexible circuit board, custom built for our use by KADFLX Inc. [31], transferred the charge pulse created by the detector strips for subsequent charge integration. The detector signal at this stage is most susceptible to noise pick up which dictates stringent constraints on the cable. The flex cable is $\sim 57 \text{ cm}$ long, has a minimal capacitance of 80 pF [30] and carries the charge pulse from 48 strips in 4 different layers, each carrying 12 strips and insulated from one another with a ground plane. The flex cable is connected to the detector using a high density connector on the alumina board of the detector plane and it connects to the QWAD via a vacuum feed-through on the vacuum-

can. The internal connections of the flex cable were made such that they exactly map the respective strip numbers and ground on the detector planes to the appropriate channels on the QWAD respectively.

3.8 QWeak Amplifier Discriminator Board

For signal digitization, we used a set of custom pre-amplifier and discriminator modules built by the TRI-University Meson Facility (TRIUMF). Each of these modules, known as QWeak Amplifier Discriminator (QWAD) boards, has 48 identical channels. Each channel independently receives via the Flex cable, the charge collected from an individual detector strip and outputs a digital signal. The signal in each channel goes through a low-noise pre-amplifier, a shaping amplifier and a discriminator. The gain on each pre-amplifier channel is typically between $100 - 130 \text{ mV}$ per 9000 electrons. Each channel has a tunable threshold applied to the analog signal before discrimination. The threshold could be varied between $\pm 60 \text{ mV}$. This was in addition to a global threshold that could be set for each QWAD board. Based on a study of the ambient noise in the beamline, we chose to use a threshold of $\sim 37 \text{ mV}$ on each channel, which corresponds to ~ 1200 electrons. The width of the discriminated signal was set by the time over threshold of the analog signal. Due to modulation added by electronic noise, the signal width was found to be typically between $400 - 600 \text{ ns}$.

Each QWAD board also carried a calibration signal which was a single input line carried to all 48 channels and was used to mimic a real detector signal for bench tests. The calibration circuit injected a charge of $\sim 10,000 \text{ electrons/mV}$ using a 1.6 pF capacitor

as shown in Figure 3.20. These QWAD boards were powered by a +6.0 V (1.58 A) and -6.0 V (0.36 A) linear DC power source and were housed in a VME-6U (Euro card) cage.

Each board constitutes a total of 8 internal layers. The top most of these layers carry the components and traces for analog signals for all the odd numbered channels. This plane is kept at the ground potential. The second layer carries the signal traces to distribute the calibration signal and the differential output from each odd numbered channels. This layer is maintained at a constant potential of +6 V. The fourth layer carries the input traces of all 48 channels. The input traces which feed the analog circuit of each channel is most susceptible to noise pick up and is hence sandwiched between a ground layer on either side, hence the third and fifth layers are pure ground planes. The sixth layer carries the differential output from each even numbered channel, this layer is kept at a constant potential of -6V. The seventh layer contains the calibration signal and differential output from each of the even numbered channel. In addition, this layer also contains the threshold traces. This layer is otherwise kept at the ground potential. The eighth layer, carries the components and traces for the even numbered channels. This bottom most layer is also kept at ground potential.

The QWAD boards had to undergo three revisions as the first two versions were found to have very high noise-pickup and channel to channel correlation. The third version of the electronic board which is described here was finally used. The major improvements between the second and third revisions of the electronic board came from a redesign of the circuit traces and components placing extra ground layers isolating the amplifiers' input from analog to analog and digital to analog crosstalk. We also placed individual RF shields

in each analog part of the circuit in the new version to suppress noise pick-up. Figure 3.15 and Figure 3.16 respectively shows the response of an earlier noisy version of the electronic board (QWAD's version-2) and a latter version-3 which was actually used. A 1 kHz calibration input was fed in to the electronic board for the displayed output. Here, the oscilloscope view was triggered on the output. Since the calibration input was of 1 kHz , one expects an output every $200\text{ }\mu\text{s}$. The Figure 3.15 clearly has several more digital pulses in a short time scale of $10\text{ }\mu\text{s}$ while the Figure 3.16 shows only the input signal along with its reflection (due to incorrect termination while measurement).

Figure 3.15

QWAD-v2 output ($10\text{ }\mu\text{s}$ time scale)

Separating different signal components with pure ground planes reduces capacitive coupling of these signals with those on subsequent layers. Deliberately large capacitors

Figure 3.16

QWAD-v3 output ($200\ \mu s$ time scale)

($10\ \mu F$) were added to the DC voltage line for each channel to suppress the transients crossing the board.

The QWAD boards were studied by giving a calibration input of $1\ mV$, based on our characterization studies that showed a diamond strip outputs 9,000 electrons for every MIP (Section 3.5). To get a higher signal to noise ratio in the generated calibration signal, the actual calibration signal was $10\ mV$ and was attenuated by a factor of 10 on the QWAD board itself. To mimic the detector's signal, the calibration input was a negative signal with $-10\ mV$ amplitude, a rise time of $10\ ns$ and exponentially decayed over a $10\ \mu s$ period (as seen for channel-1 of Figure 3.17 in blue color). The input frequency was chosen based on the intended study. Figure 3.17² shows a typical un-discriminated output (green) of

²and the corresponding analog and digital outputs

$\sim 126 \text{ mV}$ as well as the calibration input(blue). The brown histogram on the y-axis shows the pulse height spectrum of the signal in the un-discriminated output.

Figure 3.17

Scope shot of calibration input

The beam line had a fast raster running at $\sim 20 \text{ kHz}$ in the downstream neighbourhood of the Compton enclosure which was a constant source of high frequency noise. Individual RF shields and a threshold of 37 mV was used to reduce the effect of the ambient noise. The QWAD boards were also shielded with aluminium cover plates in the VME cage.

Post fabrication, different channels in the same QWAD board were found to have significant variations in gain due to different trace length and due to variation in impedance within their tolerance. This was partly compensated by individual tuning of thresholds. Further, the difference in gains resulted in different width of the discriminated output for

the same input signal. Figure 3.19 and Figure 3.19 shows two extreme cases of the same calibration input generating an output of 450 ns and 600 ns respectively in two different channels.

Figure 3.18

Discriminated output with 450 ns

As seen in Figure 3.20³, the QWAD is capable of accepting both positive going analog signals as well as negative going analog signals. The appropriate polarity can be selected by a jumper.

The digital output produced by QWAD was a LVDS (Low Voltage Discriminated Signal) level. This level scheme consumes lesser power compared to other differential voltage standards (eg. ECL) in its generation and being a differential signal is more robust against

³corresponding to each detector strip

Figure 3.19

Discriminated output with 600 ns

Figure 3.20

Electronic circuit of a single QWAD channel

noise pick up. This was necessary for us since the discriminated output at QWAD had to travel through $\sim 60\text{ m}$ of cable to reach our electronics enclosure away from the experimental hall. Channel-2 of the scope screenshot shown in Figure 3.19 (shown in blue) displays the LVDS output of the board.

3.9 Data Acquisition

The digitized signals from QWAD fed the input channels of the logic boards [55] for signal processing, trigger formation and storage on disk. We used Field Programmable Gate Array (FPGA) based general purpose v1495 CAEN boards (logic boards) to implement the readout logic. VHIC (Very High Integration Circuit) Hardware Description Language (VHDL) was used to program the logic boards and Altera's Quartus II 9.0 software was used to implement this readout logic. The following sections further describe the details and development of the firmware for the implementation of the Readout Logic.

3.9.1 Conceptual Design

For optimal use of ports available as input and output on the logic board, we chose to process the 96 strips of each diamond detector in groups of 32. One logic board (referred to as slave-1) processes the signals from the 32 adjoining strips of all 4 detector planes. Similarly, the other two logic boards (referred as slave-2 and slave-3) were used to perform reconditioning and track-finding for the strips 33 - 64 and strips 65 - 96 respectively for all planes. Signals from the three logic boards were then combined in a fourth logic module (referred to as the master board) to generate the final trigger signal. For each good trigger, internal registers in the logic boards were used to histogram the accepted tracks during each

beam helicity state of ~ 1 ms. The distribution of signals in different modules is further elaborated in Figure 3.21 and Figure 3.22.

Figure 3.21 shows a conceptual overview of the DAQ partitioned into detector, QWAD, the operations in the FPGA board and the readout CPU. The signal is processed in the same sequence from left to right from generation in detector to storage on CPU.

Figure 3.22 shows a schematic of the overall DAQ wherein it is shown that the 96 strips of the detector are treated in groups of 32 strips identified as separate strip clusters. We process each of these 32 strips from the four detector planes using an individual logic board. The signals in each logic board follow an algorithm to identify if it corresponds to a valid hit which is used to set a trigger signal. The trigger information from this set of 32 strips is sent to the master board which also receives the corresponding trigger information from other strip-clusters (Section 3.9.3). The final trigger is sent back from master board to the slave boards to carry out the readout via the VME backplane. Digital signals from next two groups of 32 strips of the 96 strip detector are similarly sent to two more logic boards.

We have implemented three readout modes, the single-event mode, accumulation mode and scaler mode (untriggered). The single event mode records a hit-map of all 96 strips for each valid trigger on the detector. The accumulation mode increments the strip-hit counter (for all strips) when a valid trigger is formed. These counters are read out during helicity reversal. The scaler mode records untriggered data which comprises everything that is distinguishable as two separate signals in the DAQ without ascertaining the validity of the event. The event and accumulation mode data collection was for asymmetry evaluation

Figure 3.21

Data acquisition conceptual Overview

Figure 3.22

Data Acquisition Schematics

and were hence gated during the helicity reversal period for which the helicity of the beam was in an uncertain state due to transition. The gating was achieved by blocking the trigger for the period when the helicity reversal signal (referred as MPS) was active. Though the scaler mode data was also read out on every helicity reversal, it is not gated and hence could not be used in the asymmetry analysis.

The logic boards process the signals through the logically independent stages elaborated below, namely: input reconditioning, trigger logic, pipeline delay, pattern buffer and readout.

3.9.2 Input reconditioning

The primary functions performed by the reconditioning stage were:

1. produce an output pulse when there was a leading edge on the input

-
- ```

graph LR
 Input[Input from Detector] --> RED[Rising Edge Detection]
 RED --> SM[strip Mapping]
 SM --> SMask[strip Masking]
 MaskingPattern[Masking pattern] --> SMask
 TriggerWidth[Trigger width] --> PWA_T[Pulse Width Adjustment of Trigger output]
 TriggerWidth --> PWA_P[Pulse Width Adjustment of Pipeline Delay]
 SMask --> PWA_T
 SMask --> PWA_P
 SMask --> HoldOff[Hold-off decision]
 HoldOffTime[Hold Off time] --> HoldOff
 HoldOff --> PWA_T
 HoldOff --> PWA_P
 PWA_T --> InputToTrigger((Input to Trigger Logic Circuit))
 PWA_P --> InputToPipeline((Input to Pipeline Delay Circuit))

```

### Schematic diagram of reconditioning stage

76



was determined by inspecting the QWAD's digital output with the detector turned off, thus identifying the average pulse-width of noise signals.

After accepting a signal as a possible electron induced signal in the previous step, we reject all other signals for a certain time for which we do not expect another signal based on our understanding of detector response. The time for which trailing signals were nominally held off after accepting one signal during the experiment was 500 ns. If two events on a single strip are closer than this time, the first event is accepted for processing and the second rejected. If the hold-off time is set to a value lesser than the pulse-width of the reconditioned signal, the hold-off time would be ignored. This feature implicitly introduces a deadtime in each strip determined by the signal rate in a given strip times the hold-off time (500 ns). The typical strip rate was  $\sim 2000\text{ Hz}$ , thus the deadtime introduced by the hold-off is  $\sim 2\text{ Hz}$ , hence negligible. The value of hold-off is globally set (i.e. same for all detector strips) but it is implemented on a strip by strip basis; i.e. a valid signal in one strip causes a hold-off only in that strip.

The detector strips were mapped to appropriate channels on the logic board so that the firmware implementation in the logic board was independent of how the detector was wired to the QWAD board. We found the noise level in certain detector strips to be significantly higher than the average noise level in the detector. The digital signal corresponding to these strips were not read into the logic board by masking the noisy strips.

The digital signal corresponding to a hit in the detector may vary in width depending on several factors like the energy deposited on the strip, the gain of the electronic channel processing that strip in QWAD, the threshold set for the individual QWAD channel etc.

Hence, we implemented an edge detection followed by fixed width assignment scheme, to ensure that all detector signals are treated the same by the logic board. The need for an enforced common width becomes obvious by studying the outputs shown in Figure 3.18 and Figure 3.19. The reconditioning stage is sensitive to only rising edges, with the width of the discriminated output having no effect on the reconditioned output as long as the width is larger than the minimum acceptable width.

The nominal pulse width of the reconditioned output referred to as PWTL (Pulse Width of Trigger Logic) was set to  $300\text{ ns}$  and was chosen by studying the maximum time separation in the response time of different QWAD boards (from successive detector planes). The DAQ trigger is decided by the overlap of detector output from all planes, hence the pulse width of output also sets the coincidence time window for the signals to form the trigger.

The minimum width rejection as well as pulse width modulation is done by keeping a count of the number of clock cycles after detecting the rising edge of each input pulse.

The rejection of signals below a minimum width, will result in lowering the effective dead-time of the DAQ due to noise pulses. For instance, consider the case for which the minimum rejection width is set at  $100\text{ ns}$ . When a signal shorter than  $100\text{ ns}$  is being checked for its width, the other signals at this channel gets rejected due to the active hold-off, but at the end of  $125\text{ ns}$ , the short  $< 100\text{ ns}$  pulse gets rejected and the channel becomes available for any new pulse. Hence, in this case, the Hold-off period is reduced from  $500\text{ ns}$  to  $125\text{ ns}$  increasing the live time by  $375\text{ ns}$ .

Using a logic probe (called a signal tap analyzer) to view the state of the signals inside the logic board (Signal tap Logic analyzer), it was determined that the firmware takes  $175\text{ ns}$  to generate the reconditioned pulse output with the minimum width rejection set at  $50\text{ ns}$ . This processing time would scale linearly with the set minimum width. The following diagram gives a quick view of the input and output signals of the reconditioning block showing the time consumption of this block.

Figure 3.24

Timing diagram of reconditioning

All those signals that are not generated in sync with the inbuilt clock of the logic board (referred to as asynchronous signals) are registered at-least twice as a part of the best practice to overcome any metastability issues in the signal.

The pulse width for the trigger stage, pipeline-delay stage, hold off time, the minimum width of signals to be accepted and the strips to be masked are parameters to be set by the user.

### 3.9.3 Triggering logic

The triggering logic consists of an algorithm used to decide whether or not a given signal corresponds to a valid event. There can be various possible approaches to this decision. Assuming detector planes to be perfectly perpendicular to each other and based on other details of the Compton setup, we see that the maximum deflection in an electron traversing from plane-1 to plane-3 is given by,

$$\Delta y = 2 \text{ cm} \cdot \tan(11.3^\circ - 10.55^\circ) = 262 \mu\text{m} \quad (3.5)$$

We implemented a cluster finding technique that looks for a hit within a set of 4 contiguous strips in some subset of the four planes to identify a valid event. Hence the maximum migration of an electron by up to a strip between the planes should not cause the event to be lost.

We form two different kinds of triggers namely the 'event' and 'accumulation' trigger. An event mode trigger initiates a readout of the hit-map of all the strips on the detector. On the other hand, in accumulation mode, there is a counter corresponding to each strip and every accumulation trigger increments the counter corresponding to the strip which created the trigger. The values in these counters are then read out on every helicity reversal. The way the above two triggers are used is different but the method of formation of the above two triggers are essentially the same. Though this logic block gets input pulses of a fixed width, the trigger output from this logic block has a variable width determined by the actual overlap time between signals from different detector planes.

The trigger logic processes reconditioned signals from the top, middle or bottom group of 32 strips of all 4 planes of the detector. These signals have a fixed width ( $=PWTL$ ) as set by the reconditioning stage. The trigger logic stage also sets the condition of forming a valid accumulation and event trigger respectively. For instance if the Trigger condition for event-trigger is set to 3, and that for accumulation-trigger is set to 2, then an event trigger is generated only when all 3 of the 3 planes report a signal in the same cluster; whereas an accumulation trigger is generated only when at least 2 out of the 3 planes report a signal in the same cluster of 4 strips during the trigger-coincidence time. The time window in which these trigger signals should overlap is decided by the width of the trigger signal itself. In the strictest case when we require a 4 plane trigger, if the width of trigger pulse is (say) 125 ns, then the trigger output of all four planes should arrive within 125 ns of the fastest arrived trigger pulse in order to successfully cause a 4-plane trigger.

This logic stage outputs the event and accumulation triggers along with the raw signals in the top and bottom two strips of each 32 strip group (top, middle and bottom), to the master board. The top and bottom two strips of each 32 strip group is used to identify any electron track which was formed in the overlap region of the top and middle or in the overlap region of the middle and bottom group of 32 strips respectively.

We implemented a very simple approach to forming the trigger. We 'OR' a group of 2 consecutive strips on the detector into a sub-cluster. Thus we get a total of 48 sub-clusters formed in the 96 strip detector. Two consecutive sub-clusters are then OR-ed again to form a cluster of 4 consecutive strips. Notice that each of two successive clusters have a 2 strip overlap. The motivation of allowing 4 strips in a trigger cluster was to allow for the

possibility of misalignment between detector planes. Since each strip is 0.2 mm wide, even a 1 mm misalignment would lead to an offset of 5 strips, hence despite careful installation, the trigger cluster size was 4 strips. The electrons that undergo maximum scattering also cross the detectors at a wider angle and can span upto 2 strips between the first and fourth detector planes for our geometry. The overlap of 2 strips between two contiguous clusters ensures that a wide angle electron spanning 2 strips also forms a trigger. Figure 3.25 depicts the above description. The rhombus in this diagram is used for conditional decision based on the trigger condition applied to the cluster signals from all planes.

Figure 3.25

### Trigger formation schematic using OR gates

The above formed clusters were then treated as individual signals and checked if they form a valid electron track between successive planes. This is done by checking for the status of the same signal-cluster in other corresponding planes within the time window

set for coincidence. This check can be as strict as 4-plane coincidence and as loose as a 1-plane coincidence based on the 'Trig Choice' parameter. The firmware allows us to set different trigger condition for the event and accumulation triggers.

The master board receives the trigger signal from each group of 32 strips and identifies any further possibility of overlap in the region between the 32 strips processed by each logic board. The master board issues a final trigger signal which is fanned out to all the slave boards. The returned final trigger in the slave boards is logically ANDed with the pipeline delayed signal of each strip. The strips that actually contributed to the trigger formation will result in a output from the logical AND, while the other strips will show no activity. The logical AND of the final trigger signal with each individual pipeline delayed signal makes the width of the two signals relevant. The width of the pipeline delayed signal ( $=PWTL$ ) is allowed to set the coincidence time between the final trigger and the strip-signal. The final trigger returned by master board retains only the information of the rising edge of the inter-plane signal overlap. If the signals between different planes are widely separated, the above mechanism of logical AND between strip-signal and the final trigger may result in losing the signal of that plane which was trailing in the trigger overlap signal. This led to complications in the analysis and made it necessary to check the effect of this loss through DAQ simulations.

Figure 3.26 shows the trigger processing for a simulated event when the trigger condition is set to 2 out of 3 (i.e any two of the three participating planes have a valid signal). In this dissertation, the '2 out of 3' trigger condition will be referred to as 2/3 plane trigger condition. The signal on the top is the clock signal with every action happening on

the rising edge of the clock. The successive pulses depict a typical case of the signals in various strips. Signals named 'p1\_st1' refers to the output of plane-1 and strip-1 of the detector. The diagram shows only the formation of plane-1's cluster-1 (comprising the first four strips) signal formed by individual strips. The diagram further shows how the trigger formed by strips in cluster-1 ORed with triggers formed from other clusters to form the final trigger sent out to the master board named Evt\_OUT. The accumulation trigger out is processed in exactly same way.

### **3.9.4 Pipeline delay**

The reconditioned input pulse propagates through a delay line to allow time for the Triggering Logic circuit to come out with a decision of whether this event corresponds to a good event or not. Hence adding a fixed time delay to the input pulse. The added delay was chosen based on the time taken for the formation of trigger.

The reconditioning block (Section - 3.9.2) makes two copies of its output and delivers a copy to each Trigger-Logic (Section - 3.9.3) and Pipeline Delay block. In this block, the incoming signal is delayed by a fixed amount in order to allow sufficient time for the trigger decision. The delay can be set to a desired value from an external set of parameters.

The timing diagram shown in Figure 3.27 shows the operation carried out by this logic block. The depicted case has a pipeline delay of 9 clock cycles, which is equivalent to 225 ns.

The optimum value for this parameter was chosen based on simulations followed by a scan of several delays, centered around the number suggested by simulation. This scan was

Figure 3.26

Manipulation of strip information to form the Trigger decision

Figure 3.27

### Pipeline Delay operation on every strip

done by making both the trigger and delay signal, 1 clock-pulse wide, and varying the value of pipeline delay around the number arrived from simulations as shown in Figure 3.27.

### 3.9.5 Pattern buffer

In order to continue processing the next event, while still recording the data on disc via VME (Virtual Machine Environment) backplane readout, we need to buffer the events that were identified by the trigger as a valid event. The buffer allows both read and write operations simultaneously from the VME backplane and the pipeline delay respectively in a first-in first-out basis.

To record the event mode data we used a pattern buffer which works as a FIFO (First In First Out). The trigger decision acted as a gate and the corresponding output of the pipeline delay was written into the buffer based on whether or not the trigger was fulfilled. Note that, on every instance of the trigger assertion, the corresponding data stream in the pipeline delay is recorded into the buffer, hence it is necessary that the data stream which caused the trigger formation should reach in coincidence with the trigger.

The buffer decouples the process of the data stream being written into the buffer and the data stream being read out of the buffer for writing to the disk. The operation of writing

into the buffer happens on the global clock sent out by the master board, while the readout operation happens on the local clock of the respective slave boards.

Since the write operation in the three slave boards is executed on the same global clock, the 32 bits of data from the three sections of each detector (having 96 strips) are written into the buffer synchronously. We are using a buffer which is 256 words deep. The event data has five 32-bit words in every slave board. The first, second, third and fourth data words are the strip-hit information of plane-1, plane-2, plane-3 and plane-4 respectively; while the fifth word is a collection of some redundant information like the buffer-busy, helicity information, the number of trigger counts received during the previous helicity reversal (MPS) signal etc.

As can be noticed, a parallel readout is made possible by giving the same trigger signal to all slave boards, hence ensuring that (say) the first word in the buffer of each slave corresponds to the same trigger and hence the same point in time. But the readout to disk from different boards can happen at different rates for a multitude of reasons. In order to ensure that the three slaves do not fall out of sync in writing the three parts of the data-stream which correspond to the top (slave-1), middle (slave-2) and bottom (slave-3) part of the detector, the readout is coordinated through a Trigger Supervisor.

The Trigger Supervisor ensures that the next trigger signal is delivered only when exactly one data word has been read from each slave board. We are operating the trigger supervisor in buffered mode hence six consecutive triggers can be saved while waiting for the previous readout to complete.

### 3.9.6 Modeling and Simulation

The time synchronization of the DAQ outputs was studied at various stages through simulation and test bench. Figure 3.28 shows a detailed timing diagram summarizing the same. The diagram is vertically divided into 5 sections. The first section addresses the timing of the QWAD board. The analog pulse monitored at different channels of the QWAD varied up to  $\sim 100$  ns for the same calibration input. After a processing time of  $\sim 100$  ns, the QWAD produces a digital (LVDS) signal, which is  $\sim 500$  ns. This signal travels 200 ft of twisted pair ribbon cable to reach the electronics enclosure referred to as the Counting House. This travel takes about 350 ns. In the second section, the slave board uses 175 ns of time to perform the functions mentioned in Section - 3.9.2. The minimum width of signals that are required to be rejected directly adds to this time. During this measurement, the test bench had 50 ns set for the minimum width parameter. The same copy of the output of the reconditioning stage is sent to the pipeline delay (Section - 3.9.4) and the trigger logic (Section - 3.9.3). The trigger logic stage takes 50 ns to form the trigger based on the signals of this slave FPGA board. The pipeline delay stage takes a total of 225 ns (50 ns + delay). The master board uses another 97 ns to output the final trigger after accepting the trigger signal from each of the respective slave boards. For event mode readout, the trigger is carried through the trigger supervisor which needs 68 ns to output signal to initiate the data readout based on the trigger.

After the completion of the experiment, several, more elaborate simulations were carried out using the a complete model of the DAQ with two slave boards and a master board,

Figure 3.28

v1495 Overall timing diagram

to mimic the experimental DAQ as closely as possible using Modelsim. These simulations and their results will be discussed further in Chapter 4.

### **3.9.7 Possible Improvements**

After analysis of the recorded data and detailed simulations conducted to understand some data patterns, we found some improvements that are possible in the DAQ design without compromising the performance or current features of the detector. The following is a list of the major improvements that could be made in a next version of the DAQ firmware design.

#### **3.9.7.1 Signal width**

The logic used for minimum width rejection could be implemented on a strip-by-strip basis hence giving a mechanism to change the effective threshold of different QWAD channels on the fly. This was found relevant due to some channels becoming noisy with time. The same feature can also be used to compensate for difference in gain of different channels. Comparing the output of all QWAD channels to a calibration input can be used to normalize the varying gains across QWAD channels. This can be achieved by setting a different value for the minimum width of different channels.

We could record and histogram the signal width spectrum of all the accepted signals before forcing them to become equal to PWTL. This information could be used to study the detector response and the energy deposited by the MIP.

### 3.9.7.2 Trigger

Since the successive detector planes were aligned using a traveling microscope ensuring inter-plane strip-to-strip alignment, we could have reduced the trigger cluster size to 2 strips, instead of the currently used 4 strips. A bigger cluster size allows the formation of more false triggers. A cluster size of at least 2 strips is necessary to accommodate the wide angle electrons. Its worth noting that a cluster size of 2, along with a one-strip overlap would have made 95 trigger clusters (compared to the current 47 clusters) from 96 strips and would have required more logic cells on the FPGA board.

The mechanism used for final trigger formation was a carry over of the event mode trigger, where each trigger signal was supposed to cause a hit-map of the entire detector on the trigger. We eventually could not collect event mode data because the trigger supervisor can handle only one signal resulting in readout. Since in accumulation mode, the data readout can be carried out at the end of the  $\sim 1$  ms helicity period, which was also needed for the photon detector. We chose to collect Compton data in the accumulation mode during the experiment. The accumulation mode trigger is planned separately with the intention of making it deadtime less. This was possible if each successful trigger formed by the conditional-check of the inter-plane strip cluster directly resulted in an increment of the corresponding strip's counter, but due to multiple strips being processed together the accumulation mode did not remain deadtime less.

Since all the trigger signals were eventually carried in the same line coming out of the master board, the aggregate trigger rate resulted in a trigger inefficiency for the DAQ. We can estimate it by noting that for 2-plane trigger accumulation mode data, the typical rate

per strip was  $\sim 3$  kHz. For a gross estimate, the total trigger rate due to 50 strips counting at 3 kHz would result in 150 kHz. Since each of these signals are 300 ns wide. The total coincidence probability is  $(150 \text{ kHz}) \cdot (150 \text{ kHz}) \cdot (300 \text{ ns})$  resulting in a loss of 6.75 kHz loss. This is equivalent to 4.5% of the signals being lost. This above inefficiency could be reduced to one-third if the individual slaves process their trigger separately. This would require a change in the way the firmware is programmed to receive and process signals.

### **3.9.7.3 Scaler readout**

We could have included the MPS gating in the scaler readout. We likely could have used the scaler readout. This would have reduced the uncertainty due to the deadtime to  $\sim 0.2 \%$ .



## CHAPTER 4

### ELECTRON DETECTOR AND DAQ SIMULATIONS

#### 4.1 Overview

Analysis of the asymmetry from the electron detector data involves the following broad steps - i) calculating background subtracted yields for each helicity state, ii) forming an asymmetry using the corrected yields, iii) fitting the measured asymmetry to the theoretical asymmetry in order to extract the beam polarization. A Monte Carlo simulation of the Compton polarimeter was used to validate the analysis procedures and to determine systematic uncertainties. A separate simulation of the DAQ was used to determine the trigger related inefficiencies and the yields were corrected for these inefficiencies. First we will discuss the simulation tools and their results, followed by a description of the data reduction procedures.

#### 4.2 Monte Carlo simulation of the Compton polarimeter

We have simulated the Compton polarimeter using the CERNLIB package GEANT3 [9]. The simulation includes the Compton scattering process along with other physical processes such as background due to the electron beam halo, Bremsstrahlung created by the electron beam hitting the gas molecules in the non-ideal vacuum, and the synchrotron radiation created while the electrons bend in the dipole magnets. These processes are imple-

mented as independent simulation modes which can be individually turned on/off. In order to make the Bremsstrahlung simulation less time consuming, the beam pipes are filled with hydrogen at Standard Temperature and Pressure(STP) instead of the usual vacuum and then rescaled appropriately.

#### 4.2.1 Electron and Laser Beam

For the laser and electron beams, the simulation uses a beam density profile given by the product of the two normalized Gaussian distributions in the two directions transverse to the propagation direction given by Equation (4.1). The propagation direction is taken to be along the z-direction and  $N_o$  is the normalization factor.

$$\begin{aligned} \rho(x, y, z) &= N_o \left( \frac{1}{\sqrt{2\pi}\sigma_x(z)} \exp\left(-\frac{x^2}{2\sigma_x^2(z)}\right) \right) \\ &\times \left( \frac{1}{\sqrt{2\pi}\sigma_y(z)} \exp\left(-\frac{y^2}{2\sigma_y^2(z)}\right) \right) \end{aligned} \quad (4.1)$$

$$\begin{aligned} \sigma_x(z) &= \sigma_y(z) \\ &= \sigma(0) \sqrt{1 + \frac{z^2}{Z^2}} \end{aligned} \quad (4.2)$$

Here  $x$ ,  $y$  and  $z$  are the space coordinates,  $\sigma_x(z)$  and  $\sigma_y(z)$  are the beam size at a longitudinal position  $z$ ,  $N_0$  is the normalization constant while  $Z$  is the Rayleigh range (Figure 4.1).

As suggested by Equation (4.2), the beam profile is symmetric about the transverse directions. The core of the beam profile is a Gaussian distribution described by the beam emittance at the entrance to the chicane as given by Equation (4.3). The emittance is a measure of the average spread of beam coordinates in position and momentum phase

Figure 4.1

Schematic view of beam envelope in x-z (or y-z) plane

space (independently in the transverse and longitudinal direction) of the beam electrons and is parametrized by the Rayleigh range  $Z$  as shown in Figure 4.1.

$$\epsilon = \tan^{-1} \left( \frac{\sigma(0)}{Z} \right) \quad (4.3)$$

The normalization factor  $N_o$  is deduced from the condition that the time rate of the density (Equation (4.1)) integrated over all space is equal to  $P_L/h\nu$  for the laser beam and  $I_e/ec$  for the electron beam where  $P_L$  and  $I_e$  are the total laser power and the beam current respectively.

The nominal values for the electron beam as used in the simulation are:

- energy  $E_e = 1.159 \text{ GeV}$
- energy spread  $\Delta E_e = 3 \text{ MeV}$
- intensity  $I_e = 180 \mu\text{A}$
- emittance  $\epsilon = 4.4 \times 10^{-10} \text{ m-radian}$

- $\sigma_{x,y}(0) = 60 \mu m$
- Raleigh range  $Z = 8 m$
- polarization  $P_e = 85.0\%$

The electron beam halo is simulated as a diffuse distribution with a flat radial dependence but power-law angular dependence. The halo is distributed uniformly in an annulus of inner radius 0.3 cm and outer radius 1.2 cm around the main beam and the ratio of particle density in beam halo to main beam is fixed at  $10^{-9}$ . The energy of electrons in the beam halo is the same as the energy of the electron beam.

The nominal values for the laser beam in the simulation are:

- wavelength  $\lambda = 532 nm$
- energy spread  $\Delta E_\gamma = 0.001 \%$
- power  $P_\lambda = 1000 W$
- emittance  $\epsilon = 3.0 \times 10^{-9} m\text{-radian}$
- $\sigma(0) = 148 \mu m$
- polarization  $P_\gamma = 100.0\%$

#### 4.2.2 Beam Laser Interaction

We assume that the electron and laser beams are symmetric in the transverse direction with their focal point as the origin of the laboratory coordinate system. The Compton scattered electrons and the back scattered photons are generated at the interaction point located in between the second and third dipole magnets. While, the Bremsstrahlung and synchrotron photons are generated and tracked from the beginning of the chicane. The Compton scattering vertex is randomly generated within a longitudinal distance, nominally

10 cm. The transverse size of the backscatter source is set by the beam radius at the interaction point. The Compton events are generated uniformly within the longitudinal direction which also determines the beam-laser interaction length. The nominal crossing angle for laser and electron beam ( $\theta$ ) was 23.53 milli-radian. After generating the event vertex, it is rotated into the frame of the laser using a  $3 \times 3$  rotation matrix and the laser is sampled using the density profile given by Equation (4.2).

The laser is shown in X-Z plane (Figure 4.2). A  $3 \times 3$  rotation matrix gives a rotation of ' $-\theta$ ' to the electron's coordinates.

Figure 4.2

Interaction of laser and electron beam in y-z plane.  $\theta = 23.53$  radian

To generate the scattering event, the incident angles are calculated from directions sampled from the laser and electron beam distributions. These scattering angles are generated uniformly in the center of mass frame for which the electron and photon flux is calculated in the directions of laser ( $\hat{l}$ ) and electron ( $\hat{e}$ ) beams respectively. The event is then transformed back to the lab frame, to calculate the luminosity integrated over the interaction length.

$$\gamma_{\text{flux}} = \rho_{\gamma}(x, y, z) \frac{P_{\gamma}}{h\nu} \quad (4.4)$$

$$e_{\text{flux}} = \rho_e(x, y, z) \frac{I}{e} dz \quad (4.5)$$

$$\text{Luminosity} = \gamma_{\text{flux}} e_{\text{flux}} \frac{(1-\hat{l} \cdot \hat{e})}{c} \quad (4.6)$$

where the  $\rho_e$  and  $\rho_{\gamma}$  are given by Equation (4.1). The Compton electrons are then bent by the third dipole in the chicane and may hit the electron detector.

### 4.2.3 Detector Response

In the experiment the detector response for each strip was recorded as a hit or a no-hit while the energy deposited in each strip was not recorded. However, in the simulation the energy deposited from each hit is recorded and used to simulate the discriminator threshold applied in the readout electronics. The energy deposited is also used to help identify secondary (delta electrons) and to study their effect on the asymmetry and the extracted beam polarization.

#### **4.2.4 Simulation Output**

We have used two different simulation methods. The first used weight factors for the cross-section and asymmetry and achieves high precision results very quickly. The second actually generates the true number of events recorded during an hour long data collection run. We used both these simulation methods for different systematic studies. In both the outputs, we generate and record all of the following:

1. vertex position
2. energy and momentum of the photon and electron for each event
3. the energy that was deposited in each detector strip.
4. total number of electrons that were hit in the detector including secondaries

##### **4.2.4.1 Luminosity weighted method**

The simulation produces one Compton photon per event thus creating the same number of back-scattered photons irrespective of the laser and beam intensity or the quality of the alignment. The numbers are then turned into actual rates by using 3 weights.

1. cross-section weight
2. luminosity weight
3. polarization asymmetry

The power of this technique is in the fact that the simulation is more time efficient and can be used to extract diverse information from a single simulated data set by using different combinations of weights, such as the contribution to the systematic uncertainties due to strip inefficiencies, energy cuts and trigger condition.

The generator produces Compton scattering events with a uniform angular distribution in the center of mass frame. They are then transformed into the lab frame (Figure 4.3) where each event is weighted by a differential cross-section and luminosity (Figure 4.4). To finally obtain the difference between the rates with opposite beam helicity (Figure 4.5), an asymmetry weight is assigned to each event, given by the product of the electron beam polarization, laser beam polarization and the asymmetry as a function of the scattered electron energy.

Figure 4.3

Hits spectrum for detector strips without applying weights

The theoretical asymmetry of the Compton scattering is calculated as a function of the energy of the Compton scattered electron, which also dictates the detector strip that the

Figure 4.4

Hits weighted by cross-section and luminosity

Figure 4.5

Hits spectrum with all 3 weights

electron hits. To obtain the simulated asymmetry, the energy cut and trigger condition is applied to the generated events along with the above three weight factors while filling histograms from the generated data.

$$A_{sim} = \frac{(N^{h^+} - N^{h^-})}{(N^{h^+} + N^{h^-})} \quad (4.7)$$

The hits for each strip is weighted by the asymmetry, cross-section and luminosity weights to get the numerator of the asymmetry (Equation (4.7)). To get the denominator of the asymmetry only the cross-section and luminosity weights are applied. These are used to form the asymmetry for each strip. A 2-parameter fit is then performed between the simulated asymmetry and the theoretical asymmetry for each detector strip. The beam polarization is extracted as one of the two fit-parameters. The two parameter fitting method used to extract the polarization has been discussed in section 5.4.1.1 and 5.4.1.2. Unlike the case of simple counting statistics, the uncertainty in the case of using weights is non trivial. In order to understand the uncertainty assigned to the asymmetry in the luminosity weighted method of simulation, let us consider the following generic case of a weighted sum in Poisson statistics.

We know for Poisson statistics that every measurement is independent and the fluctuation or uncertainty in any of the individual measurements are not correlated. If  $n_\alpha$  and  $n_\beta$  are the counts in two event sets governed by Poisson statistics and  $\delta n_\alpha$  and  $\delta n_\beta$  are the fluctuations in the measured counts, we can write:

$$\langle \delta n_\alpha \delta n_\beta \rangle = \delta_{\alpha\beta} n_\alpha \quad (4.8)$$

where  $\delta_{\alpha\beta}$  is the Kronecker delta symbol. If we form a weighted average,  $\bar{X}$ , from the Poisson statistics where each measurement has the weight,  $W$ , then:

$$\bar{X} = \frac{\sum W X}{\sum W} = \frac{\sum_{\alpha} \sum_i n_{\alpha,i} W_{\alpha} X_i}{\sum_{\alpha} \sum_i n_{\alpha,i} W_{\alpha}} = \frac{A}{B} \quad (4.9)$$

Here  $A$  and  $B$  are used to represent the numerator and denominator of the above equality.

In order to determine the uncertainty on this weighted average, we do a Taylor expansion of the fluctuations in  $\bar{X}$ ,

$$\begin{aligned} \delta \bar{X} &= \left( \frac{1}{B} \frac{\delta A}{\delta n_{\alpha,i}} - \frac{A}{B^2} \frac{\delta B}{\delta n_{\alpha,i}} \right) \delta n_{\alpha,i} \\ &= \left( \frac{W_{\alpha} X_i}{B} - \frac{A W_{\alpha}}{B^2} \right) \delta n_{\alpha,i}. \end{aligned} \quad (4.10)$$

We therefore can determine the uncertainty of  $\bar{X}$  by noting that:

$$\langle \delta \bar{X} \delta \bar{X} \rangle = \sum_{\alpha,\beta,i,j} \left( \frac{W_{\alpha} X_i}{B} - \frac{A W_{\alpha}}{B^2} \right) \langle \delta n_{\alpha,i} \delta n_{\beta,j} \rangle \left( \frac{W_{\beta} X_j}{B} - \frac{A W_{\beta}}{B^2} \right) \quad (4.11)$$

and that Poisson fluctuations are independent as in  $\langle \delta n_{\alpha,i} \delta n_{\beta,j} \rangle = n_{\alpha,i} \delta_{\alpha\beta} \delta_{ij}$ .

Using Equation (4.11) and replacing the variables  $A$  and  $B$  we can write,  $\sigma_{\bar{X}}$  the uncertainty of  $\bar{X}$  as:

$$\sigma_{\bar{X}} = \sqrt{\frac{\sum W^2 X^2}{(\sum W)^2} + \frac{(\sum W X)^2 \sum W^2}{(\sum W)^4} - 2 \frac{(\sum W X) \sum W^2 X}{(\sum W)^3}} \quad (4.12)$$

Using the asymmetry, cross-section and luminosity as respective weights in Equation (4.12), we determine the uncertainty on the asymmetry in the luminosity weighted method. This method is described in reference [58].

#### 4.2.4.2 True Statistics method

In this method in order to mimic the experimental statistics, we simulated a certain number of events such that even after applying the various cuts and efficiency losses, the

successful events equaled the number of events recorded in a typical hour long data set. As part of the cuts and loses, each of the generated electrons is checked to see if it would participate in the trigger formation or not, based on a randomly generated efficiency for each strip. These strip efficiencies were allowed to vary within a range of 0.1-1.0. Hence, unlike the luminosity weighted method, the effect of trigger and detector efficiency is incorporated as part of the event generation process. This allowed us to use the same set of generated events for several different conditions of trigger and energy cuts, hence significantly saving time. Half of these participating electrons are then assigned a weight factor given by the product of cross-section and  $(1 + A(E))$  where  $A(E)$  is the asymmetry as a function of the scattered electron energy, while the other half is assigned the weight given by the product of cross-section and  $(1 - A(E))$ . Figure 4.6 <sup>1</sup> shows the hit spectrum as obtained with ideal parameters in true statistics method for 2/3 trigger. The hits spectra are shown for the two different helicity states along with the difference and the sum of the two helicity state which are used to form the asymmetry. Here the uncertainty for the asymmetry is formed in the same way as data by taking the actual counts for each helicity.

### 4.3 Modelsim simulation of the Compton DAQ

There are several sources of possible inefficiencies associated with the DAQ. These include dead-time due to the hold off period in the DAQ that was introduced to match the shaping time of the readout electronics, the pseudo tracking algorithm used to identify electron tracks through the set of four detector planes and the trigger formation. Attempts were made to directly measure the inefficiency using the traditional method of varying

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<sup>1</sup>for opposite helicities

Figure 4.6

Ideal hits distribution with corresponding difference and sum

gate widths, but with limited success partly because we did not anticipate it to be the main source of inefficiency. A more robust method for determining the inefficiency is to perform a full simulation of the DAQ using realistic Compton, background and noise signals. The entire DAQ chain was simulated using the platform named Modelsim [41]

Unlike Monte Carlo simulations which generate events based on the respective probability distribution as described for the relevant physics process, Modelsim is a simulation technique based on time steps as needed by the processes described. This simulation keeps hopping to the next nearest time step at which the next execution is required by the compiled code.

The simulation uses the same VHDL source code that was used to program the FPGA boards in the Compton DAQ. A front-end wrapper code (called a test-bench in Modelsim) was used to control the DAQ firmware similar to the run-control program used by the CEBAF Online Data Acquisition (CODA) at Jefferson Lab. The test bench includes signal generators that mimic the electron signal and noise from the QWADs. It also implemented a detailed accounting of delay due to the signal pathway and electronic chain external to the FPGA.

#### **4.3.1 The signal input**

The signal generators used the rates as measured by the scalar mode in a typical run as inputs. It has two components, the electron induced signals (constituting the Compton scattered electrons and the beam background) and the electronic noise. The noise rates were taken from beam off period during the experiment while the rates for electron induced

signals were obtained from laser and beam on periods after noise subtraction from detector plane-1. The final signal that went into the firmware was a simple addition of the noise and electron-like signals. Note that even though, the actual event rate on different planes would slightly differ, due to secondaries, missed electron tracks and varying strip efficiencies, this remains unaccounted in the DAQ simulation.

A random number generator is used to initialize a signal in a given time step for each strip. The time step is determined by the inverse of the event rate in that strip. Assuming that an electron event goes through the same strip of all planes<sup>2</sup>, the electron induced signal for a given strip in all the planes was generated using the same seed. The signal is then fanned out to the firmware associated with each plane.

The inter-plane time variation in the electron induced signals, caused by the variations in gain and noise rate in their respective readout electronic chain, is simulated by adding a random time variation uniformly spread between 0-150 ns to the signal fanned out to each individual plane. The signals from different planes are processed by a different QWAD, hence to cover the possibility of having a fixed shift in the signals of one plane w.r.t another plane, a fixed time delay can be added to the signals of a particular plane. This shift can be varied between 0-100 ns.

The signals representing electronic noise were simulated using a different random seed to initialize the random number generator for each strip and each plane. To mimic the distribution of widths in the noise signal, we distributed the input noise rate into three different widths. 60% of the noise rate was generated with a width of 50-75 ns, 30% with

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<sup>2</sup>This is not entirely true for true electron events. Given the geometry, an electron track can be spread over two detector strips from plane - to - plane

a width of 75-100 ns and 10% with a width of 100-125 ns. This width distribution in noise signals was guided by observation during preparatory tests before the experiment, but were fixed by determining the noise widths that best reproduced both the measured accumulator mode rates and scaler mode rates. The other simulation parameters such as the signal widths, the maximum of the random inter-plane time variation, the constant time difference between planes and the signal delay all were optimized to best reproduce the measured rates in the experiment.

Figure 4.7

Scatter plot from experiment

In Figure 4.7 the accumulator rates for 1/3 plane trigger and the scaler rates from an actual Compton data set are plotted for all 64 strips of detector plane-1. The points in the

Figure 4.8

Scatter plot from simulation

lower left corner of the plot have a slope of  $\sim 0.8$  and originate from the strips beyond the Compton edge (CE) while the strips having signals from Compton scattering events show up with a larger variation. These scattered points have an overall smaller slope of  $\sim 0.6$  reflecting a higher loss of data in accumulation mode. These points also have a scatter, which is caused by a differential loss in each strip which is dictated by the data rate in each strip. Note that the rate in each of these strips is also impacted by their efficiency and cross talk etc. Using the optimized simulation parameters, and the scaler rates from an actual Compton data set as input, the DAQ was simulated for 200 ms for the 1/3 plane trigger condition. The simulation output is shown in Figure 4.8, where the accumulator rates are plotted against the scaler rates for the first 64 strips of the detector. Figure 4.7-Figure 4.8

show that the measured and simulated rates have a similar behavior for both the strips up to the Compton edge as well as the post Compton edge strips.

After the simulated data is processed by the firmware it is transferred to registers and written to file during the  $70\ \mu s$  long helicity reversal period<sup>3</sup>, replicating the process used in the Compton DAQ. In order to validate the simulation, we plotted the simulated detector yield for every strip for a given input signal rate. The blue stars in Figure 4.9 shows the input rate as obtained from the scaler counts in an experimental run, the red circles show the simulated scaler counts, while the black triangles show the typical simulated yield in the accumulation mode (with trigger = 2/3 plane). The agreement between the blue and red markers demonstrate that the simulation accurately reproduces the input scaler rates and that there is no significant deadtime associated with scaler data collection. The black markers representing the simulated accumulation mode rates show a lower rate (as expected) and also agrees well with the scaler rates,

Using the set of optimized parameters, we ran the simulation for the trigger condition of 2 out of 3 and compared it with an experimental run with the same trigger condition and found good agreement as shown in Figure 4.10. Here we plot the percentage difference of the accumulation mode rate obtained in the experiment for plane-1 to that in simulation. The agreement is good for most of the strips up to the Compton edge (55 for this run). The strips that are more than one standard deviation away from zero were identified as those masked off in the other planes. The strips masked in detector planes downstream of plane-1 also affect the data collection in plane-1 via the trigger condition. Noticing this

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<sup>3</sup>This was  $110\ \mu s$  for the experimental DAQ

Figure 4.9

Detector yield in simulation and experiment

Figure 4.10

Difference of rate detected in DAQ simulation compared to that observed

effect in simulation, we discard all those strips from the analysis of plane-1 data which are masked in any of the planes participating in the trigger (although the impact on the extracted polarization would not be large).

### 4.3.2 Estimating trigger inefficiency

In an initial test of the Modelsim simulation, the rates for each strip extracted from a GEANT3 simulation (see Section 4.2.4), were used as the input rate for the Modelsim simulation. The polarization extracted by analyzing the GEANT3 output was  $P_e = 84.70 \pm 0.29$  (Figure 4.11, note that this value differs from the input polarization of 85% because of a slight geometry mismatch between the simulation and analysis script, which does not affect the conclusions of the test described here). However, the polarization extracted from the output of the DAQ simulations was  $P_e = 84.23 \pm 0.23$  (Figure 4.12) which was significantly different from the polarization extracted from the GEANT3 simulation. This highlighted a non-ideal behavior of the DAQ. In order to identify the origin of the non-ideal behavior of the DAQ, a suite of DAQ simulations were carried out using just Compton signals (i.e. an ideal simulation without noise or jitter), these simulations and their results are described below.

The measured ungated scaler rates for Compton events (i.e. raw rates corrected for background and noise) were used as the input for the DAQ simulation. Figure 4.13 and Figure 4.14 shows the result of this simulation, plotting the difference between ungated (from scaler) and triggered counts (from accumulator). Each data point in these plots represent the counts in a given strip. The simulated counts are plotted against the ungated

Figure 4.11

Polarization from Modelsim data

Figure 4.12

Polarization extracted from GEANT3 and Modelsim simulations

scaler counts in the left panel and against the corresponding strip number in the right panel. Figure 4.13 demonstrates that the signal loss is proportional to the scaler rates. The triggered signals are gated off during helicity change (unlike the scaler data), hence a 6.8% difference is expected just from the gating with the MPS signal, but Figure 4.13 shows a loss of over  $\sim 13\%$ . Further Figure 4.14 suggests that even though the signal loss per strip linearly depends on the individual strip rate, the relative loss is constant over all strips within the limited statistical precision of this simulation. We define the relative loss as the ratio of difference between ungated (scaler) and triggered (accumulator) rates, to the ungated rate.

Figure 4.13

Loss in triggered data

Figure 4.14

Relative loss in triggered data

Figure 4.15

Percentage Loss in triggered data w.r.t aggregate rate

Figure 4.15 demonstrates that the relative signal loss is directly proportional to the aggregate input rate (summed over all strips).

Figure 4.16

Differential loss between  $H^+$  and  $H^-$  rates

This loss results from the loss of corresponding trigger signal in the DAQ trigger channel where the trigger information of all planes and strip clusters merge. This trigger channel has to handle a signal rate which is empirically related to the scaler rate aggregated over all strips of the concerned plane. We use the ideal DAQ with only Compton events with no signal jitter or noise to determine an appropriate correction factor for the measured yield to account for this signal loss (described further in Section 5.1.2). Since the signal to noise

Figure 4.17

Extracted polarization after correcting for trigger inefficiency

in the electron detector was  $> 20$ , this correction is a reasonable estimation of the total trigger related inefficiency in the DAQ.

The DAQ was then simulated separately for rates from both helicity types and we found that the relative loss of signals between scaler and accumulation data modes was different between the two helicities as shown in Figure 4.16. We expect a loss of 6.72% between scaler and accumulation (accum) mode data due to the helicity gate. Here the rate corresponding to  $h^+$  loses an additional 5.58% beyond the above fraction expected due to gating, while that loss for  $h^-$  is only 5.42%. The yield was correspondingly corrected by respective factors. The purpose of this correction is to undo the effect of differential loss in the two helicities which reflects in the corresponding asymmetry. After correcting the simulated yield for the two helicities for their respective loss, the new extracted polarization (Figure 4.17,  $P_e = 84.68 \pm 0.23$ ) is consistent with the input polarization. This method is used to estimate correction factors in the yield caused due to trigger inefficiencies in the data and is described in Section 5.1.2.

## CHAPTER 5

### DATA ANALYSIS

During each hour long run, the number of hits registered in each detector strip, the accumulated charge and the laser power transmitted out of the cavity are recorded independently for each helicity state ( $\sim 1$  ms long). The accumulated yield ( $Y^\pm$ ) of the scattered electrons for the positive and negative helicity states, as a function of the detector strip that was hit, is used to form an asymmetry defined by Equation (5.1)

$$A_{exp} = \frac{Y^+ - Y^-}{Y^+ + Y^-} \quad (5.1)$$

A typical measurement cycle for the  $\vec{e} - \vec{\gamma}$  interaction consists of a period of  $\sim 60$  Sec with the laser turned on<sup>1</sup> (cavity locked) and  $\sim 30$  Sec with the laser turned off<sup>2</sup> (cavity unlocked). The electron yield measured when the laser interacts with the electron beam includes contributions from several background processes. The contributions from these background processes are determined by measuring the yield when the laser is turned off.

In the analysis, the laser-off period was defined as those when the laser power was less than 2000 units (Figure 5.1) which is in the arbitrary unit of the scalar counts recorded in the DAQ<sup>3</sup>. The laser-on period was defined with laser power greater than 90% of the max-

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<sup>1</sup>laser power  $> 10^5$  in Figure 5.1

<sup>2</sup>laser power  $< 1800$  in Figure 5.2

<sup>3</sup>The transmitted laser power was monitored by a fast photodiode which provided a DC voltage proportional to power. This voltage was fed through a voltage - to - frequency converter and read out in the DAQ

Figure 5.1

Laser power histogram for a run

Figure 5.2

Laser turned off periodically (cavity unlocked)

imum laser power for that run. Note that the beam and laser being on does not necessarily imply we have collisions. To ensure proper collisions we periodically scanned the beam vertical position using the Compton dipole chicane current to identify the maximum overlap of electron and laser beams. During regular data collection, the beam position stays locked to the coordinates that yielded maximum background corrected yield in the photon detector.

From each hour long data-set the total number of hits in a strip for the laser-on periods with positive beam helicity ( $N_{on}^{h^+}$ ), negative helicity ( $N_{on}^{h^-}$ ), and the laser-off periods with positive ( $N_{off}^{h^+}$ ) and negative helicity ( $N_{off}^{h^-}$ ) are extracted.

## 5.1 Corrections to yield

The measured yield for a given detector strip have background contributions from non-Compton events which are measured in order to appropriately subtract from the respective yields for laser-on/off for both helicity states before forming the asymmetry. Contributions to the measured counts ( $N_{on}^\pm$ ) include electrons from Compton scattering as well as from other processes like Bremsstrahlung, halo and electronic noise. Equation (5.2) shows these contributions explicitly without the super-script representing helicity.

$$N_{on} = q_{on}n_{on} + q_{on}n_{off} + t_{on}r_{on}^I \quad (5.2)$$

$$N_{off} = q_{off}n_{off} + t_{off}r_{off}^I \quad (5.3)$$

Here  $q_{on}$  and  $q_{off}$  are the charge during laser on and off respectively,  $n_{on}$  and  $n_{off}$  are the charge normalized counts during laser on and off respectively,  $t_{on}$  and  $t_{off}$  are the time for



which laser was on and off respectively during a given laser cycle while  $r_{on}^I$  and  $r_{off}^I$  are the noise rates during laser on and off.

The correction was applied in the order in which they are described below as noise correction, trigger related inefficiency and beam related background.

### 5.1.1 Noise correction

The rate measured by the DAQ for each detector strip has some electronic noise contribution from the corresponding electronic channel used for the strip. The electronic noise had its origin in RF noise being picked up and amplified by the QWAD board, cross-talk between adjacent strips, and noise in the power supply of the QWAD board. The amplifier circuit in the QWAD board implemented a threshold in order to reject most of the noise signals. In the accumulation mode, the noise was further rejected by the multi-plane trigger. As expected, the 3/3 plane trigger provided the maximum noise rejection. Figure 5.3 <sup>4</sup> shows the rate summed over all strips for the entire run-2 period. The blue, red and black points show the Compton rates, background rates and noise rates respectively. The substantially low noise rate around the runs 23500 - 24000 is due to the use of a 3/3 plane trigger for that period. The noise rate in the accumulation mode was always less than  $\sim 1\%$  of the Compton rates and typically about  $\sim 0.2\%$  of the Compton rates.

At low beam currents the noise rates contributed a significant fraction of the yield, and even though there is no asymmetry in the electronic noise, it became a major dilution factor in the asymmetry measurement and had to be accounted for. We took samples of electronic noise opportunistically during beam off periods. For this analysis, we used the

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<sup>4</sup>for Compton events, background events and electronic noise events

Figure 5.3

The aggregate rate for the entire run-2 period

Figure 5.4

Background yield at high current  $\sim 180 \mu A$

Figure 5.5

Background yield at low current  $\sim 4 \mu A$

beam off periods from within the run (if statistically significant data were available) to determine the noise correction for that data set. In cases, where a sufficiently long beam-off was not available in the same run, a previous nearby run was used. We see in Figure 5.4 and Figure 5.5 that the laser-off rate on the detector shows the expected beam profile of a Gaussian tail. It demonstrates that the noise subtraction becomes more important for lower current data because of its larger relative contribution to the yield. The dark blue shade shows the noise corrected yield, while the light blue shade represents the raw yield without noise correction for the same run. Unlike other sources of background, the noise contribution is only dependent on time, and does not carry an asymmetry, hence a single rate is used to correct the laser-on yields and the laser-off yields for both helicities. The noise sampled during beam off periods is not a true representation of the noise during beam on periods, since the Compton and background rates suppress some fraction of the noise. This effect is important only for low current runs. The effective noise correction in the two averaging methods (runlet based and laser cycle based) is compared in Section 5.2.4.

### **5.1.2 Trigger related inefficiency**

There was a trigger related inefficiency which is effectively a deadtime in the yield measurement. We apply a correction to the measured yield based on the relative loss estimated by the DAQ simulation. The relative signal loss as defined in Section 4.3.2 was simulated for a broad range of input rates. For each of these rates, the relative loss was fitted to a straight line. Figure 5.6 shows a two parameter fit of the same data shown in

Figure 4.16 which represents the typical signal rate for Compton events only. Figure 5.7 shows the relative loss when we gave an input equivalent to 2x of the typical event rate.

Figure 5.6

Relative loss for typical signal rate

Each of these two parameters in the fits of the type shown in Figure 5.7 is then plotted against the aggregate rate in that simulation. The slope parameter vs rate is fit with a straight line which is forced to go through 0 at 0 rate as shown in Figure 5.8 and similarly the intercept parameter vs rate is fit to a straight line that is forced to go through 0 at 0 rate as shown in Figure 5.9.

Figure 5.7

Relative loss for 2x signal rate

The fit parameters from the two fits shown in Figure 5.8 and Figure 5.9 are used to extract the correction factor for any signal rate.

To get the correction factor for a run, we calculate the aggregate rate by summing over the rate in each strip. Using this aggregate rate, we find the appropriate intercept and slope parameters ( $c_0$  and  $c_1$  respectively) and use them to calculate the corrections for each strip. Since these corrections are rate dependent, they are calculated separately for the laser on and off states for each of the two helicity states. As described in Section 4.3.2, the effect of MPS is already subtracted from these correction factors. The new  $n'$  obtained for each of  $N_{on}^+$ ,  $N_{off}^+$ ,  $N_{on}^-$  and  $N_{off}^-$  gives the new charge normalized counts corrected for trigger inefficiency which is used for the asymmetry calculation.

$$N' = (1 + c_0 + c_1 \cdot \text{strip})N \quad (5.4)$$

$$N' = c_2 N \quad (5.5)$$

$$n' = \frac{c_2}{Q} N \quad (5.6)$$

The charge normalized yields summed over all strips are shown in Figure 5.10 <sup>5</sup>. The blue (red) points show the yields before (after) the trigger inefficiency correction. This plot shows the average size of the correction that is applied (typically between 3 - 6%). The effects of these corrections on the polarization are discussed in Section 5.5.7.2. The reduced yield between 23200-2400 is due to the 3/3 plane trigger condition during that period.

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<sup>5</sup>before (blue) and after (red) trigger inefficiency corrections

Figure 5.8

Intercept of the correction factor

Figure 5.9

Slope of the correction factor

Figure 5.10

The charge normalized aggregate accumulator yields

### 5.1.3 Background subtraction

The background due to non-Compton processes scales with the charge, therefore the laser-off counts are normalized by the ratio of the charge accumulated during a laser-on cycle to the charge accumulated during a laser-off cycle (Equation (5.9)). After subtracting off the normalized laser-off counts from their laser-on counterparts for each helicity, we form the yield and asymmetry as given in Equation (5.7) for each strip.

$$n_{off}^{h^\pm} = \frac{N_{off}^{h^\pm}}{q_{off}} \quad (5.7)$$

$$n_{on}^{h^\pm} = \frac{N_{on}^{h^\pm}}{q_{on}} \quad (5.8)$$

$$Y^{strip} = (n_{on}^{h^+} - n_{off}^{h^+}) + (n_{on}^{h^-} - n_{off}^{h^-}) \quad (5.9)$$

## 5.2 Determining experimental asymmetry

The charge normalized yields (Equation (5.9)) and the asymmetry (Equation (5.10)) were extracted over two different time scales. In one case we summed the events over about 15 minutes corresponding to a runlet. In the second case, the events were summed over a more natural scale of a laser cycle (about 1.5 minute). The comparison of results extracted using these two time-scales allowed us to check the sensitivity of the data to beam and laser fluctuations. For the analysis, the beam was considered 'on' if the beam current was higher than 80 % of its maximum value during that run while it was considered off if the beam was less than 20  $\mu\text{A}$ , during regular beam operations.

$$A_{exp}^{strip} = \frac{(n_{on}^{h^+} - n_{off}^{h^+}) - (n_{on}^{h^-} - n_{off}^{h^-})}{(n_{on}^{h^+} - n_{off}^{h^+}) + (n_{on}^{h^-} - n_{off}^{h^-})} \quad (5.10)$$

### **5.2.1 Data cuts**

We applied some cuts on the raw data before extracting the asymmetry. This was to ensure that periods where any component required in the Compton setup was not working were excluded and that no bias is introduced in the data. These cuts included but were not limited to helicity correlated changes in experimental condition.

#### **5.2.1.1 Beam modulation cut**

The position and angle of the beam was slightly varied periodically to estimate the sensitivity of the parity violating asymmetry measurement to changes in energy, position and angle of the beam. This is referred to as beam modulation. A gate corresponding to the period of the beam modulation was included in the data stream (or DAQ). This beam modulation gate was used to throw out the quartets during which the beam modulation is active.

#### **5.2.1.2 Laser power**

There were fluctuations in the power stored in the Fabry-Perot cavity and we put a strict cut on the laser power. Those events when the laser power was less than  $\sim 80\%$  of the recorded maximum power during the run were not included in laser-on events and those events when the laser power was greater than  $\sim 1200$  were not included in the laser-off events.

### **5.2.1.3 Beam current**

The electron beam sometimes tripped off. Recovery from trip was associated with beam position instability and corresponding inability to ensure best beam-laser overlap. In order to avoid contamination from these fluctuations, we discard about 200 ms of data before and after a beam trip as part of the beam trip. When the beam falls to 50% of its maximum (for a given run) or below  $2\mu A$ , we consider it the beginning of a beam trip. Similarly when the beam reaches above 50% of its maximum while recovering, we consider it to have recovered the beam trip.

### **5.2.1.4 Laser cycle**

During regular high current data collection, we were not limited by statistics. We have hence chosen to discard any laser cycle which had a beam trip. This avoids the possible bias from beam position instability while the beam is ramping to its nominal value

## **5.2.2 Runlet average asymmetry extraction**

In this method, all hits and charge for the relevant laser on and laser-off periods are summed over a 15 minute segment of a run (called a runlet) and were used to extract the charge normalized yield and to form the asymmetry for each strip.

Both the accumulated hits in laser-on and laser-off periods are explicitly corrected for electronic noise determined using the beam-off period of a given run. The electronic noise (beam-off rate) scales with time hence the charge normalized background subtraction using the laser-off yields cannot correct for the time dependent background. This becomes a

consideration because the measured rates between laser on and off can change due to beam fluctuations within a run.

The yield, asymmetry and its statistical uncertainty for individual runlets are evaluated as elaborated in Equation (5.11) and Equation (5.14) respectively.

$$Y^{\pm} = \frac{N_{on}^{\pm} - t_{on}^{\pm} n_0}{q_{on}^{\pm}} - \frac{N_{off}^{\pm} - t_{off}^{\pm} n_0}{q_{off}^{\pm}} \quad (5.11)$$

$$Y = Y^{+} + Y^{-} \quad (5.12)$$

$$A = \frac{Y^{+} - Y^{-}}{Y^{+} + Y^{-}} \quad (5.13)$$

$$\begin{aligned} \delta A^2 = & \left( \frac{1-A}{Y} \right)^2 [N_{on}^{+} + (t_{on}^{+} - r^{+} t_{off}^{+})^2 n_0 + r^{+2} N_{off}^{+}] \\ & + R^2 \left( \frac{1+A}{Y} \right)^2 [N_{on}^{-} + (t_{on}^{-} - r^{-} t_{off}^{-})^2 n_0 + r^{-2} N_{off}^{-}] \\ & - 2R \left( \frac{1-A^2}{Y^2} \right) (t_{on}^{+} - r^{+} t_{off}^{+})(t_{on}^{-} - r^{-} t_{off}^{-}) n_0 \end{aligned} \quad (5.14)$$

where

- $N_{on}^{\pm}$  and  $N_{off}^{\pm}$  are the total counts collected in different helicity states for laser-on and laser-off periods of a runlet respectively
- $t_{on}^{\pm}$  and  $t_{off}^{\pm}$  are the time for which the laser was respectively on and off for different helicity states in the runlet
- $n_0$  is the time rate of beam-off counts in a pedestal run
- $r^{\pm} = \frac{q_{on}^{\pm}}{q_{off}^{\pm}}$
- $R = \frac{q_{on}^{+}}{q_{on}^{-}}$

Finally an error weighted average over all runlets (Equation (5.15)) is used to obtain  $A_{exp}^{strip}$ . A detailed derivation of the error calculation is posted in the 'DAQ & Analysis' section of polarimetry ELOG # 310.

$$A_{run} = \frac{\sum (A_{runlet} / \delta A_i^2)}{\sum (1 / \delta A_i^2)} \quad (5.15)$$

Following this method, the experimental asymmetry for each strip was evaluated as shown in Figure 5.11.

Figure 5.11

Asymmetry extracted in an hour long data set

### 5.2.3 Laser cycle average asymmetry extraction

In this method, all hits and charge were accumulated over one laser cycle (consisting of  $\sim 60$  s laser-on, followed by  $\sim 30$  s laser-off) to extract the charge normalized yield and an asymmetry for each strip in that laser cycle.

Rearranging the terms in Equation (5.12) from the runlet averaging method, we obtain Equation (5.16). Here the 'N' and 'q' represent the counts and charge accumulated over a laser-cycle ( $\sim 1.5$  min) instead of a runlet ( $\sim 15$  min). In this case, due to a smaller averaging time, the current during laser on/off period remains reasonably constant. Also, in this equation it is more clearly visible that the amount of electronic noise that contributes to the yield in this analysis is suppressed by the beam current. One would also intuitively expect noise to be suppressed for higher beam current.

Once the charge normalized yield ( $Y$ ) and the corresponding experimental asymmetry ( $A$ ) were extracted for each laser cycle, the statistical uncertainty of the asymmetry was calculated using Equation (5.20). Finally, an error weighted average over all laser cycles (Equation (5.21)) in a run was used to extract  $A_{exp}^{strip}$ .

The laser-cycles containing either beam or laser fluctuations beyond the limits defined for them to be considered 'on' were entirely discarded. Thus the laser cycle analysis ends up discarding more events than the runlet analysis because it uses only whole laser-cycle periods with stable beam intensity and laser power but this method is more sensitive to background fluctuations due to possible slow drift in beam or laser stability.

$$Y^{\pm} = \left( \frac{N_{on}^{\pm}}{q_{on}^{\pm}} - \frac{N_{off}^{\pm}}{q_{off}^{\pm}} \right) + \left( \frac{n_0}{I_{off}^{\pm}} - \frac{n_0}{I_{on}^{\pm}} \right) \quad (5.16)$$

$$Y^{\pm} = \left( \frac{N_{on}^{\pm} - t_{on}^{\pm} n_0}{q_{on}^{\pm}} - \frac{N_{off}^{\pm} - t_{on}^{\pm} n_0}{q_{off}^{\pm}} \right) \quad (5.17)$$

$$Y = Y^{+} + Y^{-} \quad (5.18)$$

$$A = \frac{Y^{+} - Y^{-}}{Y^{+} + Y^{-}} = A_{laserCycle} \quad (5.19)$$

$$\begin{aligned} \delta A^2 = & \left[ \frac{1}{Q_{on}^{+}} \left( \frac{1-A}{Y} \right) \right]^2 N_{on}^{+} + \left[ \frac{1}{Q_{on}^{-}} \left( \frac{1+A}{Y} \right) \right]^2 N_{on}^{-} \\ & + \left[ \frac{1}{Q_{off}^{+}} \left( \frac{1-A}{Y} \right) \right]^2 N_{off}^{+} + \left[ \frac{1}{Q_{off}^{-}} \left( \frac{1+A}{Y} \right) \right]^2 N_{off}^{-} \end{aligned} \quad (5.20)$$

$$A_{exp}^{strip} = \frac{\sum (A_{laserCycle} / \delta A_i^2)}{\sum (1 / \delta A_i^2)} \quad (5.21)$$

Here Equation (5.17) shows the noise subtraction as implemented in the analysis performed at the scale of laser cycles; we have used the same notation as in Equation (5.12) describing runlet based analysis. The Equation (5.14) and Equation (5.20) are equivalent when explicit noise subtraction is not implemented.



### 5.2.4 Comparing the two averaging methods

Figure 5.12 shows the difference between the asymmetry calculated by averaging over a laser cycle and averaging over a runlet. Since the same events are analyzed in the two methods, and we notice in general the laser cycle method gives larger uncertainties due to lower statistics, we have used the uncertainty of the laser cycle method as the uncertainty on the difference of the asymmetries. The red line is a linear fit of the mean difference and is consistent with zero. Note that the range of the y-scale in Figure 5.12 is a factor of 10 smaller than the maximum theoretical asymmetry.

Figure 5.12

Comparison of asymmetry extracted by laser cycle and runlet based average

To further check if there was a difference in the extracted polarization over a period of several runs, Figure 5.13 <sup>6</sup> shows the polarization as extracted in the two averaging methods. The bottom panel of the plot shows us that the extracted polarization is in agreement to within 0.07% with each other. Here the error bars were calculated like these events were independent measurements.

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<sup>6</sup>over 24 hours of data

In the laser cycle method, we end up throwing away more quartets because of rejecting the whole of laser cycle with a beam trip. This results in a slightly higher statistical uncertainty in the laser cycle method as seen in Figure 5.14.

Since we are not limited by statistics, using the laser cycle averaging method gives an easy way to use a clean data set, where we throw out any laser cycle with a beam trip, getting rid of the effects related to beam position fluctuations associated with beam trip. Unless otherwise stated, the rest of the document uses the results from the laser cycle averaging method. Further, the averaging over a laser cycle is more effective in accounting for slow monotonic drifts in operating conditions, such as beam background, laser-electron beam overlap and laser power.

### 5.2.5 Determining the theoretical asymmetry

The Compton scattering cross section and asymmetry as a function of the momentum of the scattered electron can be calculated exactly in Quantum Electro-dynamics (QED). In order to determine the Compton asymmetry of electrons detected by a particular strip ( $A_{QED}^{strip}$ ), the momenta of the scattered electrons hitting a given strip on the detector needs to be known. Using precise knowledge of the dipole field ( $\sim 0.554$  T), the electron beam energy ( $\sim 1.159$  GeV) and the maximum energy of Compton interactions ( $\sim 46$  MeV), the spatial distribution of Compton scattered electrons on the detector can be precisely determined. Further, precise knowledge of the detector location and geometry gives us the precise position coordinates of each strip w.r.t the unscattered beam.

Figure 5.13

Comparison of polarization between the two averaging methods

Figure 5.14

Statistical uncertainty from the two methods

### 5.2.6 Radiative correction

The incident and scattered electrons undergo radiative processes which include emission of real photons, virtual photon emission and re-absorption, and other higher order processes. These processes affect the incident and final energy of the electron and hence the detector yields. Radiative corrections refer to the corrections applied to the data so that we may extract the Born-level asymmetry.

In the low energy limit, QED corrections to the Compton scattering cross section vanish to all orders of perturbation theory because the relative corrections are suppressed by a factor of the electron velocity  $\beta (= \frac{E_e}{m_e})$ . However, the radiative correction to asymmetries are not suppressed with  $\beta$  since the asymmetry itself vanishes for  $\beta \rightarrow 0$ .

For the low energy approximation as applicable in the case of JLab beam energy, theoretical studies [11] have estimated the correction to be  $\sim 0.3\%$  and can be calculated by Equation (5.22).

$$A_{rad} = A_{born}(1 + \delta) \quad (5.22)$$

$$\delta = \frac{\alpha}{\pi} \frac{3\cos(\theta_{CM}) - 1}{4(\beta_{CM} + \cos(\theta_{CM}))} \quad (5.23)$$

where  $\theta_{CM}$  and  $\beta_{CM}$  are defined in the center of mass frame as the scattering angle and the ratio of photon and electron energy respectively. The energy of the electron ( $E_e$ ) and photon ( $E_\gamma$ ) is already known in the lab frame. The corresponding center of mass equations are given in Equation (5.24)

$$\beta_{CM} = \frac{\beta E_e - E_\gamma}{E_e + E_\gamma} \quad (5.24)$$

$$\cos(\theta_{CM}) = \frac{E'_e - \gamma E_e}{E_\gamma \gamma \beta_{CM}} \quad (5.25)$$

We apply the correction to the theoretical asymmetry ( $A_{born}$ ) and compare the measured asymmetry to  $A_{rad}$  in order to extract the beam polarization. Figure 5.15 shows the theoretical asymmetry with and without radiative correction in the top panel of the plot. The bottom panel explicitly shows the difference in the asymmetry due to the correction as a function of scattered electron energy.

### 5.2.7 Magnetic analysis of scattered electrons

The magnetic force ( $\vec{F}_{mag} = e(\vec{v} \times \vec{B})$ ) exerted by the dipoles in the Compton chicane adds a curvature to the electrons' path with radius depending on their linear velocities as

$$R = \frac{1}{\sqrt{1 - \beta^2}} \frac{m_e v}{eB} = \frac{p}{eB} \quad (5.26)$$

Figure 5.15

Effect of radiative correction on Compton theoretical asymmetry

where  $\beta$  is  $\frac{v}{c}$ ,  $B$  is the magnetic field in the dipole while  $m_e$ ,  $v$ ,  $e$  and  $p$  are the mass, velocity, charge and relativistic momentum of the electron.

For the unscattered beam, the Compton chicane is perfectly symmetric, i.e, both the transverse and longitudinal properties of the electron beam remains unchanged before and after the chicane. Since the Compton scattering process takes place between dipole-2 and dipole-3, Equation(5.26) shows that the electrons that lose more energy in the  $\vec{e} - \vec{\gamma}$  Compton interaction are bent more by the magnetic field of dipole-3 compared to the un-scattered electrons.

Figure 5.16 diagrammatically elaborates the mapping between electron momentum and position on the detector. This schematic, shows the path of electrons through dipole-3. The blue line through the dipole shows the unscattered electron beam while the red line depicts the electrons that lose the maximum energy in the scattering process and correspond to the Compton edge. All of the Compton scattered electrons are distributed between these lines and the electron detector, placed upstream of dipole-4, intersects the electrons as shown in Figure 5.16. The relation between the momentum of the scattered electron and the angle of deflection for the electron incident on the  $i^{th}$  strip is given as

$$\frac{\sin(\theta_i)}{\sin(\theta_{bend})} = \frac{p_{bend}}{p_i} \quad (5.27)$$

Depending on the amount of energy lost during the interaction, the Compton scattered electrons are deflected by varying angles between  $\theta_{bend}$  and  $\theta_{max}$  where  $\theta_{bend}$  is the deflection of the unscattered electrons, while  $\theta_{max}$  is the deflection of the electrons losing the maximum energy (corresponding to the the kinematic maximum of Compton Scattering)

Figure 5.16

Schematic spatial distribution of Compton scattered electrons

Figure 5.17

The case of detector angle being different from  $\theta_{bend}$



in dipole-3. Upon exiting the dipole-3, the electrons follow a straight path. In the Compton setup at Hall-C, JLab,  $\theta_{bend} \sim 10.13^\circ$  and  $\theta_{max} \sim 10.55$ . The detectors were inclined such that the electrons deflected by 10.08 degree are incident exactly normal to the detector plane.

The vertical separation ( $h$ ) between Compton scattered electrons and the unscattered beam at the exit face of dipole-3 is,

$$h = R_{max}[1 - \cos(\theta_{max})] - R_{bend}[1 - \cos(\theta_{bend})] \quad (5.28)$$

where  $R_{max}$  and  $R_{bend}$  are the radius of curvatures of the electrons that lose the maximum energy in the Compton scattering and the unscattered electrons respectively.

As seen in Figure 5.16, this separation increases with increasing drift distance ( $z_{drift}$ ) from the 3rd dipole and is different for electrons incident on different detector strips. For the  $i^{th}$  strip it is given by,

$$\Delta x_i = [R_i (1 - \cos(\theta_i)) + z_{drift}^i \tan(\theta_i)] - [R_{bend}(1 - \cos(\theta_{bend})) + z_{drift}^i \tan(\theta_{bend})] \quad (5.29)$$

where  $R_i = L_{mag} / \sin \theta_i$  and  $\theta_i$  can be obtained for each Compton scattered electron using Equation (5.27).  $L_{mag}$  (=1.246 m) is the length of the dipole magnet and  $z_{drift}^i$  is the horizontal distance between the exit face of dipole-3 and the  $i^{th}$  detector strip on which the electron is detected. The  $z_{drift}^i$  for strips of plane-1 is

$$z_{drift}^i = Z_{drift}^1 - x_i \sin(\theta_{det}) \quad (5.30)$$

where  $Z_{drift}^1$  represents the horizontal distance between the exit face of the dipole and the middle of detector plane-1 (1.689 m) and  $x_i$  is the vertical distance between the bottom

of the detector and the  $i^{th}$  strip (the strip that is hit), as shown in Figure 5.16. Here  $\theta_{det}$  is the angle of inclination of the detector. Since the detector is not oriented vertically, Equation (5.29) is further corrected to incorporate the bend angle of the beam and detector as

$$X_i^{det} = \frac{\Delta x_i \cos(\theta_{bend})}{\cos(\theta_{det} - \theta_{bend})} \quad (5.31)$$

Since the theoretical asymmetry is calculated in terms of  $\rho$  (scattered photon energy normalized to maximum scattering photon energy), instead of the scattered electron energy, we need to map each value of rho to the corresponding position on the detector. Inverting Equation (5.29) to obtain a value of  $\rho$  is impractical. Therefore, a look-up table is created by dividing the ratio  $\rho$ , which lies between 0 and 1, into 1000 bins ( $\rho_j$ ). For each  $\rho_j$ , the momentum of the scattered electron  $p_j$  is calculated via conservation of momentum as;

$$p_j = p_{beam} + k_0 - \rho_j * k'_{max} \quad (5.32)$$

where  $p_{beam}$  and  $k_0$  are the momentum of the incident electron and photon respectively. Here  $k'_{max}$  is the maximum scattered photon momentum. For each  $p_j$  the corresponding bend radius  $R_j$ , the bend angle  $\theta_j$  and the vertical deflection  $\Delta x_j$  is calculated using Equation (5.27) - Equation (5.29). This provides a table of  $\rho$  vs  $x$ .

The  $\rho - x$  table is then fit to a 4th order polynomial which provides an analytical expression for the relation between the ratio  $\rho$  and the distance along the detector plane, of each detector strip, relative to the unscattered electron beam ( $X_i^{det}$ ). The distance corresponding to  $\rho = 1$  is the maximum allowed deflection of the scattered electrons ( $X_{max}$ ). If

the maximum scattered electrons are incident on strip number  $n_{CE}$  (i.e. the Compton edge strip), the distance of deflection for the  $i^{th}$  strip number  $n_i$  is given by Equation (5.33)

$$X_i^{det} = X_{max} - [0.2 * (n_{CE} - n_i)] \quad (5.33)$$

Using the deflection distance of Equation (5.33) and the analytical relation obtained from the polynomial fit of the  $\rho - x$  table, the strip number on which a scattered electron is incident can be converted into the corresponding  $\rho$  and obtain the corresponding asymmetry of that strip. Clearly the generated  $\rho - x$  table is dependent on the strip number on which the Compton edge is located, and hence the table has to be re-created whenever the location of the Compton edge changes.

$$A_{exp}^{strip} = P_e P_\gamma A_{QED}^{strip} \quad (5.34)$$

where  $A_{QED}^{strip}$  calculated using the  $\rho$  obtained for each strip as described above,  $P_\gamma$  is very precisely measured periodically and  $A_{exp}^{strip}$  for each strip is extracted using Equation (5.10).

We fit the Equation (5.34) from each strip up to the Compton edge with  $P_e$  as a fit parameter over the entire range to obtain our beam polarization.

### 5.2.8 Polarization extraction via fixed Compton edge fit

One of the employed analysis method fixes the position of Compton edge (CE) to an integer strip. The Compton edge is the kinematic maximum of the Compton scattering cross-section (Equation (5.36)). The Compton edge is identified by using the characteristic sudden fall off in the detector yield between adjacent strips. It was identified with the integer strip number where the signal to background ratio recorded for two adjacent strips differ by a factor of five compared to the signal to background recorded in strips to the right

of the Compton edge as shown in Figure 5.18 where the blue and red bars represent the background subtracted yield (Equation (5.37)) and background counts ( $N'_{off}{}^{h\pm}$ ) respectively. As seen in Figure 5.18 the Compton edge can be easily identified and Equation (5.33) becomes,

$$X_i^{det} = X_{max} - [\langle \text{stripWidth} \rangle \times 0.2 \times (n_{CE} - n_i)] \quad (5.35)$$

$$Y = Y^+ + Y^- \quad (5.36)$$

$$Y^\pm = (N_{on}^{h\pm} - N'_{off}{}^{h\pm}) \quad (5.37)$$

Figure 5.18

Typical Compton yield measured in a run

The asymmetry  $A_{exp}^{strip}$  is extracted for each strip up to the Compton edge strip (typically strip number 55 or higher). The measured asymmetry is then fitted to the calculated

asymmetry for each strip, up to the strip identified as the Compton edge. Each strip is thus an independent instance of Equation (5.34). A two parameter fit is used with the beam polarization and an "effective strip width" as the two parameters. The effective strip width parameter is a multiplicative factor to the strip width of  $200 \mu\text{m}$  in order to account for any deviations from nominal that would impact the electron deflection (strength of magnetic field, detector tilt, etc).

In order to verify the hypothesis that the second parameter in section 5.2.8 represented the "effective" strip width as seen by the incident electrons, it was histogrammed over a large set of runs. Since this is a geometrical factor, it is expected to stay constant as long as the detector and beam position are fixed. Figure 5.19 (Figure courtesy: Vladas Tvaskis) shows the mean value of this parameter for all the planes to be close to 1.0. This is expected for the factor of effective strip width parameter if the extracted effective strip width parameter and the assumed geometry is correct.

### 5.2.9 Floating Compton edge

A second fitting method was also used where the two fit parameters were the polarization and the strip location of the Compton edge. In this method the Compton edge returned by the fit can have non-integer values. The fitting routine is provided with an initial value for the Compton edge that is determined as described in Section 5.2.8 and Equation (5.33) changes into:

$$X_i^{det} = X_{max} - [0.2 * (\langle \text{Compton edge} \rangle - n_i)] \quad (5.38)$$

Figure 5.19

Effective Strip Width parameter from fixed Compton edge (CE)

Note that in this case, no "effective strip width" is used. Here we assume that all quantities that impact the differential electron position are known.

It was found that the overall systematic uncertainty is smaller when the two-parameter fit uses the beam polarization and the floating Compton edge, hence this method was chosen for the final analysis. The Compton edge as determined from the fit for all of run-2 is shown in Figure 6.6.

Figure 5.21 further shows that the uncertainty on Compton edge was constrained in the fit to well within a strip, in contrast to the fixed Compton edge analysis which has an implicit uncertainty of  $\pm 0.5$  strips.

Figure 5.20

The Compton edge as determined in the floating CE method for all runs

#### 5.2.10 Comparison of data reduction methods

We compare the two analysis methods for a representative hour long data set in Figure 5.22 and Figure 5.23. The fit in Figure 5.22 uses the effective strip width as the second fit parameter (the CE was fixed to an integer strip number determined from the detector yield spectra as described in Section- 5.2.8 above). Figure 5.22 shows the fit using the Compton edge as a fit parameter with the effective strip width parameter fixed to 1.0. The two fitting methods applied to the same data set can yield polarization values that can differ by over 1%. This difference can be explained when we study the systematic change in the extracted polarization when varying the Compton edge by 1 strip (Section- 5.4.1). When using the effective strip width as the second fit parameter the CE is fixed to an integer value and can be incorrect by up to 1 strip. Hence, using the Compton edge as the second fit parameter leads to a smaller overall uncertainty.

Figure 5.21

Histogram of error on CE determination for all data sets in run2

Figure 5.22

Extracted polarization using fixed Compton Edge

Figure 5.23

Extracted polarization using fixed effective strip width

We have chosen to use floating Compton edge as the second fit parameter for the rest of the analysis unless otherwise specified.

### **5.3 Detector efficiency, background and noise studies**

The GEANT3 simulation was used to study the robustness of the data reduction methods with respect to detector efficiency, random electronic noise, trigger condition and backgrounds. In this case we used the "true statistics" simulation as described in Section 4.2.4.2. Detector efficiency and noise can vary randomly from strip to strip, they can potentially change the shape of the asymmetry spectrum and hence change the extracted polarization. The luminosity weighted method (section 4.2.4.1) where the statistical uncertainty of the simulated asymmetry of each strip is negligible cannot be used to study the influence of detector efficiency and noise. The effect of these two factors must be verified with the statistical significance of the actual data. (These studies are used to validate the analysis method, and do not provide estimates of systematic uncertainties.) The results shown below, were simulated for a 2/3 plane trigger condition.

In Section 4.2.4.2 the hit spectra from the true statistics method were shown in Figure 4.6. The asymmetry from these hits spectra is shown in Figure 5.24. It yields a polarization of  $84.72 \pm 0.15$  which is used as the reference for identifying any systematic deviation while we vary the parameters discussed in this section.

#### **5.3.1 Detector efficiency**

The number of counts recorded on a detector strip is reduced by its efficiency. (The studies which will be described in Sections 5.4.1.2 to 5.5 assumed 100% detector effi-

Figure 5.24

Ideal polarization with true statistics method

ciency). We studied the effect on the extracted polarization randomly allotting an efficiency between 0.2-0.8 to all participating strips. Based on the assigned efficiency of a given strip, a certain fraction of the events were not recorded on that strip. Figure 5.25 shows the simulated hits spectra in plane-1 with the allotted inefficiencies for the corresponding detector strips. This yielded a polarization of  $84.84 \pm 0.21$ , as shown in Figure 5.26, which agrees with the polarization extracted with 100% efficient strips within 0.1% of the absolute polarization as shown in Figure 5.24.

### 5.3.2 Background

For the preceding studies, we generated only Compton events and extracted the polarization for a variation in corresponding parameters, but the experimental data set undergoes background subtraction before it is used to extract polarization. To identify a possible effect of background subtraction and to quantify any bias due to the method employed, we generated background data independently, using different random seeds to mimic the background subtraction.

The total number of background events were normalized to be equal to the number of laser-off events collected during a typical hour long run. This is equivalent to the charge normalized background subtraction used for experimental data since the periods for laser on and off were not the same. One set of simulated background events was added to the simulated Compton events (Equation (5.39)) where  $N_{on}^{h\pm}$  represents the number of laser-on events in a particular strip for either helicity states,  $N_{Comp}^{h\pm}$  represents the number of true Compton events for either helicity states and  $N_{BG1}^{h\pm}$  represents the number of background-

Figure 5.25

Distribution due to random strip efficiency for both helicity states

Figure 5.26

Extracted polarization with randomly varying strip efficiency

only events for either helicity states. Similarly the laser-off events are represented by  $N_{off}^{h\pm}$  and  $N_{BG2}^{h\pm}$ . The simulated asymmetry,  $A_{sim}$  was formed using Equation (5.41).

The background generated from one of the above two sets was added to the Compton events while that from the second set was used for explicit background subtraction.

Figure 5.27 shows the hit-spectra of the Compton events with normalized background.

$$N_{on}^{h\pm} = N_{Comp}^{h\pm} + N_{BG1}^{h\pm} \quad (5.39)$$

$$N_{off}^{h\pm} = N_{BG2}^{h\pm} \quad (5.40)$$

$$A_{sim} = \frac{(N_{on}^{h+} - N_{off}^{h+}) - (N_{on}^{h-} - N_{off}^{h-})}{(N_{on}^{h+} - N_{off}^{h+}) + (N_{on}^{h-} - N_{off}^{h-})} \quad (5.41)$$

The asymmetry( $A_{sim}$  thus obtained for every strip was fitted to extract polarization (Figure 5.28) and was found to yield the same polarization within statistical uncertainty as was extracted from the Compton only events (Figure 5.24).

### 5.3.3 Electronic noise

We call the beam on, laser-off events as 'background' while 'noise' is used to refer to events which do not correspond to an electron hitting the detector but instead are caused by electronic noise. Unlike signal background, noise events are independent of the beam current.

The ratio of event rate without beam to the event rate with beam for each strip was used to determine the relative strength of noise in each strip ( $r_{noise}$ ). In the simulation, for each Compton event a random number was generated between [0,1], and if the random number was less than  $r_{noise}$  it was designated as noise and added to the Compton event.

Figure 5.27

Hit-spectra with detector efficiency and background

Figure 5.28

Extracted polarization with background subtraction

Each event tagged as noise was assigned the corresponding event's Compton asymmetry when simulating a trigger condition of 2/3 plane or 3/3 plane while it was not assigned any asymmetry weight for trigger condition of 1/3 plane. This was done to account for the fact that a trigger condition dependent on any other plane would pick noise signals as often as the signals in other planes appear which in turn is dependent on the asymmetry.

The total event set for noise study was created by adding the simulated Compton, background and noise events as shown in Equation (5.42) where  $N_{on}^{h\pm}$  is the total number of hits registered on a given strip for both helicities respectively. The constituents are  $N_{Comp}^{h\pm}$  as the pure Compton events,  $N'_{BG1}^{h\pm}$  as the pure background events normalized to have the same signal-to-background ratio as is found in experiment and  $N'_{Comp.noise1}^{h\pm}$  as the pure noise events normalized to have the same proportion as is present in an hour long run.

Unlike the noise for Compton events, noise for background events (Equation (5.45)), was generated from the beam halo generator where no asymmetry was assigned to the noise events. In Equation (5.45),  $N_{off}^{h\pm}$  represents the total number of hits on a strip for laser-off for both helicities,  $N'_{BG2}^{h\pm}$  represents the total number of background events from a different seed than 'BG1' after due normalization and  $N'_{BG1.noise1}^{h\pm}$  represents the normalized noise events created from the background simulation.

$$N_{on}^{h\pm} = N_{Comp}^{h\pm} + N'_{BG1}^{h\pm} + N'_{Comp.noise1}^{h\pm} \quad (5.42)$$

$$N_{off}^{h\pm} = N'_{BG2}^{h\pm} + N'_{BG1.noise1}^{h\pm} \quad (5.43)$$

The noise generated from the second set of seeds was used to subtract noise from the total Compton and background events (Equations (5.44)) before evaluation of asymmetry.

Figure 5.29

Hit-spectra due to added noise

Figure 5.30

Polarization with detector efficiency, background subtraction and noise

In Equation (5.45)  $N'_{Comp.noise2}{}^{h\pm}$  represents the normalized noise events created using the Compton event generation for 2/3 plane trigger with a seed different for that used for 'noise1' while  $N'_{BG.noise2}{}^{h\pm}$  represents the duly normalized noise events created using the background event generation.

$$N'_{on}{}^{h\pm} = N_{Comp}{}^{h\pm} + N'_{BG1}{}^{h\pm} + N'_{Comp.noise1}{}^{h\pm} - N'_{Comp.noise2}{}^{h\pm} \quad (5.44)$$

$$N'_{off}{}^{h\pm} = N'_{BG2}{}^{h\pm} + N'_{BG.noise1}{}^{h\pm} - N'_{BG.noise2}{}^{h\pm} \quad (5.45)$$

$$A_{sim} = \frac{(N'_{on}{}^{h+} - N'_{off}{}^{h+}) - (N'_{on}{}^{h-} - N'_{off}{}^{h-})}{(N'_{on}{}^{h+} - N'_{off}{}^{h+}) + (N'_{on}{}^{h-} - N'_{off}{}^{h-})} \quad (5.46)$$

Figure 5.29 <sup>7</sup> shows the hit-spectra with noise added to the Compton and background spectra after due normalization. As seen in this hit-spectra, the noise level of up to 0.2% (as also seen in experimental data) is significantly suppressed by the electron induced signals. The polarization extraction as shown in Figure 5.30 yields a value of  $84.87 \pm 0.48 \%$  which agrees with the ideal polarization in Figure 5.24 within statistical uncertainty.

## 5.4 Evaluation of Systematic Uncertainties

While extracting the polarization from the simulated data, a set of relevant physical parameters of the Compton polarimeter was varied up to a few times of their experimental uncertainty. The variation in polarization resulting from the variation of a parameter by 1 standard deviation was assigned as the systematic uncertainty associated with that parameter. The polarization can be extracted from the data using two fitting methods, the fixed Compton edge method (described in Section 5.2.8) and the floating Compton edge method (described in Sec. 5.2.9). In Section 5.4.1 - Section 5.4.5 the systematic uncer-

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<sup>7</sup>Red and blue histograms show the case for positive and negative helicity respectively

tainty for several key parameters is extracted using both the fitting methods and compared against each other. Based on the comparison between the two methods it was established that the floating Compton edge method results in a relatively smaller overall systematic uncertainty and hence the floating Compton edge method was chosen for the analysis of the experimental data. The contribution to the systematic uncertainty due to several additional parameters are described in section 5.5, these were evaluated using only the floating Compton edge method after establishing that this was the superior method. The nominal parameters used in the simulation are listed in Table 5.1.

Table 5.1

Initial parameters

| Parameter             | Nominal      | Variation |
|-----------------------|--------------|-----------|
| mag. field            | 0.55264 T    | 0.2%      |
| detector tilt         | 10.3 degree  | 1 degree  |
| detector z position   | 24.5 cm      | 1 cm      |
| beam energy           | 1.159 GeV    | 1 MeV     |
| effective strip width | 1.0059       | 0.0       |
| trigger condition     | 2 (out of 3) | 1-3       |
| trigger cluster       | 4 strip      | 2-6       |

The electron beam polarization is extracted from the simulated data using the same analysis steps that are used for the experimental data. For both the simulated and experimental data the asymmetry for each detector strip is fit to the calculated Compton asymmetry. We derive polarization of the electron beam by performing this fit up to the strip where the Compton Edge is located. We used the two different fit methods that were employed

in the analysis of the experimental data. In the first method, the Compton edge was identified by an integer strip number based on an algorithm where the signal to noise ratio for the strips recording Compton events differ by 5 times the standard deviation of the signal to noise distribution from the strips beyond the Compton edge that recorded background events. Subsequently, the asymmetry in the strips were fitted up to this Compton edge with 'polarization' and 'effective strip-width' as the 2 fit parameters. The effective strip-width parameter absorbs our ignorance of partial detector misalignment, lesser precise knowledge of magnetic field in the dipoles and other geometric factors. In the second method the location of the Compton edge was used as a fit parameter instead of the effective strip width.

#### **5.4.1 Determination of Compton edge**

##### **5.4.1.1 Fixed Compton edge analysis**

In the fixed Compton edge fit, the Compton edge is determined by identifying the integer detector strip where the signal over background for two consecutive strips differ by a factor of 5. In the simulation, the Compton edge is an input parameter. Given that the strip pitch is  $200\text{ }\mu\text{m}$ , an integer assignment of Compton edge strip will have a minimum uncertainty of  $100\text{ }\mu\text{m}$ . This uncertainty in the location of the Compton edge results in the largest contribution to the systematic uncertainty in extracting the polarization using the fixed Compton edge fit and was determined to be 0.65%. It was determined by evaluating the variation in the extracted beam polarization with the Compton edge fixed at the position of the left and right edge of Compton edge strip. This variation is shown in Fig-

ure 5.31<sup>8</sup> [49]. Note that when the Compton edge is fixed to an integer value the effective strip parameter is used as a free parameter.

#### **5.4.1.2 Floating Compton edge analysis**

In the floating Compton edge analysis, the two fit parameters are polarization and the location of Compton edge. The fit also returns an uncertainty for the location of the Compton edge. In this method the Compton edge is no longer restricted to integer values and thus uncertainty in the polarization due to shift in the Compton edge is not required. Moreover, the uncertainty of the polarization obtained in the fit includes the effect of the uncertainty in the Compton edge as well as the effect of the detector resolution. This is demonstrated by the correlation between the fit error in the polarization parameter and the fit error in the Compton edge parameter, shown in Figure 5.32

### **5.4.2 Secondary electrons**

#### **5.4.2.1 Fixed Compton edge analysis**

Our analysis extracts a polarization value from the participating strips of each detector plane. This extraction is done independently for each plane. We find a systematic decrease in the polarization for detector planes as we move further downstream relative to the plane facing the Compton scattered electron. This systematic decrease in polarization was attributed to the electrons knocked out by the Compton scattered electrons when interacting with the detector material (secondary electrons). The affect of secondary electrons is particularly difficult to determine in the fixed Compton edge fit, since the Compton edge

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<sup>8</sup>as function of shift in the Compton edge

Figure 5.31

Variation in polarization, chi-sq of fit and the effective strip width parameter

Figure 5.32

Correlation between the fit error for polarization and Compton edge parameters

naturally shifts by up to  $\sim 20\mu\text{m}$  between adjacent detector planes due to a horizontal separation of 1 cm between two consecutive planes. To disentangle the affect of shift in the Compton edge due to inter-plane separation from the affect of the secondary electrons, the inter-plane shift in Compton edge was taken into account while performing the fixed Compton edge fit.

Table 5.2 shows the systematic variation due to secondary electrons to the polarization evaluated from individual planes. To exclude secondary electrons only events with one hit per plane were used in the analysis. This same condition was relaxed for obtaining the affect of secondaries on polarization.

The polarization measurement from plane-1 after allowing secondary electrons is consistent with the expectation that it should not depend on the secondaries being rejected.

Table 5.2

Effect of secondary electrons

| Plane | Polarization(%)<br>secondaries excluded | Polarization(%)<br>secondaries allowed |
|-------|-----------------------------------------|----------------------------------------|
| 1     | 85.15                                   | 85.15                                  |
| 2     | 85.15                                   | 84.92                                  |
| 3     | 85.11                                   | 84.67                                  |

This study finds that secondary electrons causes an average decrease in polarization by 0.24% plane. The polarization obtained from plane 1 is unaffected by secondary electrons.

#### 5.4.2.2 Floating Compton edge analysis

In this analysis, the fit naturally takes into account the inter-plane shift in the exact position of Compton edge for different planes. Also, the affect of secondary electrons is absorbed by both the fit parameters, hence the maximum variation in polarization from plane 1 to plane 3 is only 0.25 as compared to 0.48 in the fixed Compton edge analysis. Table 5.3 shows the variation of polarization for different planes in this method. The average change of polarization per plane is 0.2%. Notice that the trigger condition of 2/3 plane also suppresses some effect of secondary electrons in the recorded data. But since most of the data was recorded at 2/3 plane, we are estimating the uncertainty contribution at the same trigger value.

Table 5.3

Effect of secondaries

| Plane | Polarization (%) | Compton edge |
|-------|------------------|--------------|
| 1     | 84.71            | 53.07        |
| 2     | 84.46            | 53.37        |
| 3     | 84.59            | 53.79        |

### 5.4.3 Detector tilt

#### 5.4.3.1 Fixed Compton edge analysis

A data set was simulated at the nominal angle of 10.3 degree but was analyzed assuming ignorance of the true detector orientation and varying the tilt angle between 0 and 14 degrees as shown in Figure 5.33. As shown in this figure, the polarization changes  $\sim 0.28\%/10^\circ$ .

Hence for the estimated error in detector tilt of 1 degree, the corresponding systematic contribution is 0.03%.

#### 5.4.3.2 Floating Compton edge analysis

The current in the dipoles of the magnetic chicane dictates the angle at which the detector will be normal to the unscattered Compton beam in the chicane. Keeping the dipole current fixed such that the nominal detector tilt is 10.27 degree, several data-sets were simulated while varying the detector tilt angle. Each simulated data set was analyzed using the same detector tilt at which it was created to find the sensitivity of our analysis on the detector tilt.

Figure 5.33

Effect of detector tilt on polarization

Figure 5.34

Effect of detector tilt on polarization

The study also showed that the number of electrons hitting a detector strip is affected by the trigger cluster size. When the detector assembly is not normal to the incident electrons, the exact strip that was hit can change as the electron traverses between planes 1 and 4. Therefore a more restrictive trigger cluster size will reject such events. Hence the recorded hits on the detector are more sensitive to detector tilt in the case of cluster-size of 2 (corresponding to red data points on Figure 5.34) as the detector is tilted away from the ideal 10.27 degree.

Figure 5.34 contrasts the effect of detector tilt variation on polarization at two different trigger clusters. The effect of trigger cluster is also separately discussed in section 5.5.1.

The experiment recorded data at a trigger cluster of 4 (corresponding to blue points). Hence from the variation of blue data-points in Figure 5.34 we see that the polarization varies by up to 0.1% while the detector tilt changes by 1 degree on either side of the nominal tilt.

#### **5.4.4 Dipole field strength**

##### **5.4.4.1 Fixed Compton edge analysis**

The Compton dipole steers the trajectory of the Compton electrons affecting its position on the electron detector. All the analysis methods discussed here assumes that the Compton edge remains fixed during a given run. Fortunately, the largest error in the knowledge of the dipole field is expected from its positioning. The effective length was derived from a measurement of half of the magnet length. This could result in a positional error of

up to 2 mm which translates to an error in the field map in  $\vec{B} \cdot d\vec{l}$  along the beam path of 0.16%.

Being conservative we studied the effect of dipole field variation by up to 1% relative to the operational value of 0.5526 T and found that the polarization measured by each plane remains unchanged within statistical uncertainty (0.01%) of the extracted polarization. The second panel of Figure 5.35 shows that as the field is varied, the effective strip width parameter absorbs the effect of the magnetic field variation leaving the polarization measurement unchanged for each of the detector planes.

The dipole used additional trim coils for setting a uniform field along its length. The maximum variation in the field integral due to the trim coils during run2 was within 2500 Gauss-cm. This is compared to the typical field integral from the main dipole of  $\sim 690750 \text{ Gauss} - \text{cm}$ . This can effect the field to a maximum of 0.04% hence will not add to the total systematic contribution.

#### 5.4.4.2 Floating Compton edge analysis

A variation in dipole field strength will affect the path of electron beam in the chicane hence affecting the Compton edge location. Hence one would expect the floating Compton edge analysis to be most sensitive to variations in the dipole field. To study this effect, data were simulated at the nominal dipole field, but was analyzed at magnetic field varying by up to 0.2%, to estimate the sensitivity of evaluated polarization to a possible error in the knowledge of dipole field strength. Figure 5.36 plots the variation in polarization against

Figure 5.35

Effect of Dipole field on polarization

varying dipole magnetic field. For an estimated fluctuation in the magnetic field of 0.2% of the nominal 0.55264 T, the polarization variation is 0.13%.

#### **5.4.5 Electron beam energy**

The beam energy was very stable throughout the running period. Figure 5.37 shows a histogram of the energy measurement during the runs for which polarization is reported in this dissertation. The energy used for each run was based on the measurement made during that run itself.

##### **5.4.5.1 Fixed Compton edge analysis**

A shift in the energy of electron beam would shift the energy of the Compton electrons hence changing the extracted polarization in a way that cannot be accounted for by the effective strip width parameter. We studied the contribution due to a 0.1% error in our knowledge of beam energy and found that the polarization can change by up to 0.14%. For this study, the data was simulated at the nominal beam energy while the analysis was done at a beam energy which was wrong by up to 0.1% ( $\sim 1\text{MeV}$ ) as shown in Figure 5.38. We see that the extracted polarization reduces as we progressively increase the beam energy used in the analysis. As one would expect, the 2nd fit parameter shown in the 2nd panel of the Figure 5.38 is unaffected by the change in beam energy.

##### **5.4.5.2 Floating Compton edge analysis**

The Tiefenback energy provides the nominal value of the beam energy every few seconds. The several measurements during a data-run are histogrammed to find the mean

Figure 5.36

Effect of fluctuation of Magnetic field

Figure 5.37

Histogram of beam energy throughout the period of run2

value to be used for the run. The measurement has a precision of  $\sim 10^{-3}$  GeV and should be made when the beam is stable. The measurements made during the run when a beam trip happened are discarded while histogramming the measurements. This is identified by putting a current limit of  $90 \mu A$  at the time of the energy measurement. The nominal value was measured to be around 1.157 GeV for the overall beam. This was found to have a negative offset of  $\sim 0.8$  GeV from the beam energy measurement in the arc based on simultaneous measurements at both locations. The final energy value used in the analysis was obtained by adding the fixed offset to the mean of the Tiefenback energy. This directly affects the determination of position of the Compton scattered electron on the detector as also the theoretical asymmetry (Section 5.2.5) and the radiative correction (Section 5.2.6).

Figure 5.38

Effect of beam energy on polarization

Figure 5.39

Effect of beam energy fluctuation on polarization

The energy of the incident electron beam was varied by 1 MeV from its nominal value of 1.159 GeV to see the corresponding shift in the evaluated polarization. Figure 5.39 shows that a variation in beam energy by up to 1 MeV results in a polarization change of up to 0.07%.

## 5.4.6 Detector longitudinal position

### 5.4.6.1 Fixed Compton edge analysis

In the simulation the detector's longitudinal position w.r.t to the beam is identified by its distance upstream of the 4th dipole. In order to identify the sensitivity of the extracted polarization to a longitudinal shift in the detector location in the beam direction the detector location in the analysis was offset by  $\pm 5$  cm in steps of 2.5 cm relative to the nominal location of the detector used for the simulation.

As shown in Figure 5.40 the polarization remained unchanged within statistical uncertainty while the detector was changed by  $\pm 5$  cm relative to the nominal distance of 24.5 cm from the 4th dipole. The 2nd panel of this figure shows that the affect of the translation was absorbed by the effective strip width parameter.

## 5.4.7 Summary of Comparison

This section summarizes the systematic study undertaken using the luminosity weighted method. Here we intend to look at the systematic uncertainties in the two analysis methods of fixed Compton edge and floating Compton edge. Table 5.4 lists the results for the two fitting methods which clearly shows that the floating Compton edge analysis gives an overall smaller uncertainty.

Figure 5.40

Effect of detector position on polarization



Table 5.4

Comparing systematic contributions

| Parameter           | Uncertainty      | floating CE (P/P%) | fixed CE (P/P%) |
|---------------------|------------------|--------------------|-----------------|
| CE determination    | 90 $\mu\text{m}$ | 0.0                | 0.65            |
| Plane to Plane      | secondaries      | 0.19               | 0.24            |
| Detector tilt       | 1 degree         | 0.10               | 0.03            |
| Detector z position | 1 cm             | 0.22               | 0.01            |
| Beam energy         | 1 MeV            | 0.07               | 0.07            |
| Magnetic field      | 0.0011 T         | 0.13               | 0.01            |
| Total               |                  | 0.34               | 0.70            |

Guided by the conclusion that the floating Compton edge analysis is superior, the subsequent uncertainty study were performed using only the floating Compton edge analysis.

## 5.5 Additional systematic studies

### 5.5.1 Inter-plane trigger

The trigger condition in data acquisition selectively records a certain fraction of the detector signals hence affecting the evaluated polarization. The trigger has a cluster finding algorithm to keep track of the detector strip fired by an electron in a given plane. Since we have 3 active detector planes, the signal detected in subsequent planes could be used to identify the validity of the signal in the upstream plane. There are two factors that affect this, the number of strips defining a cluster and the inter-plane trigger condition elaborated below. In order to account for possible misalignment between different detector planes, an OR of the signals from 4 adjacent strips was defined as a single cluster. The trigger was generated based on whether the same clusters were found in subsequent planes. Therefore, the fewer the number of adjacent strips that are used to define a cluster the stricter the

trigger condition. Figure 5.41 shows the variation in the extracted polarization with trigger condition for fixed cluster size, while Figure 5.42 shows the variation in polarization with cluster size for fixed trigger condition.

Trying to understand the sudden and significant difference in polarization for 2 strip cluster and 3/3 plane trigger condition compared to clusters of larger number of strips, it was found that the 2 strip cluster, rejects most of the secondary electrons and almost exactly reproduces the input polarization in the simulation. This is shown in Figure 5.43. Here the red curve shows the number of events accepted in a 4-strip cluster with 2/3 plane trigger condition. The green curve shows the same for a 2-strip cluster.

The cluster size was set to 4 strips throughout the experiment while the trigger condition was at 2/3 plane for most of the running period. Figure 5.41 shows effect of trigger cluster variation to be 0.2% on absolute polarization if the trigger was varied from 1/3 plane to 3/3 plane.

### 5.5.2 Effect of noise and background

Random electronic noise and the physics background effects the inter-plane trigger. In order to study their effect, simulations using the true statistics method was used. The noise and efficiency were together varied for both the 1/3 plane and 2/3 plane trigger conditions. For this study a random fraction of events between 0.02 – 0.04 % of the Compton events were added in the simulation with strips having random allotted efficiency between 0.0-1.0. Figure 5.44 <sup>9 10</sup> shows the resulting hits distribution for a trigger condition of 1/3

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<sup>9</sup>for 1/3 plane trigger

<sup>10</sup>Red and blue histograms in top two panels show the counts for positive and negative helicity

Figure 5.41

Effect of inter plane Trigger on polarization

Figure 5.42

Effect of trigger cluster size on polarization

Figure 5.43

Effect of trigger condition on secondary electron acceptance

Figure 5.44

Hits distribution for Compton, background and noise events

Figure 5.45

Hits distribution for 2/3 plane trigger

plane while Figure 5.45<sup>11 12</sup> shows the hits distribution for a trigger condition of 2/3 plane. Both the extracted polarization of  $84.83 \pm 0.35 \%$  (Figure 5.46) and  $84.89 \pm 0.35 \%$  (Figure 5.47) respectively for 1/3 plane and 2/3 plane trigger conditions are within statistical uncertainty of the ideal. This asserts that for the statistical precision normally achieved at full current from an hour worth of data the effect of noise, if any is within the statistical fluctuation.

### 5.5.3 Detector orientation

As the detector is tilted towards or away from the nominal beam in the chicane, the effective width of the detector strip visible to the beam reduces. To study the possible variation in polarization due to detector orientation we changed the orientation of the detector along the three possible axes to see the corresponding effect on the evaluated beam polarization. For this, different data sets were simulated by varying the detector angles with respect to different axes and was analyzed with the corresponding ideal angle at which it was generated to find the sensitivity of beam polarization to detector orientation. In the frame of the experimental hall, the forward direction of beam was taken as positive z-axis, the beam left direction was x-axis and the vertically upward direction was the y-axis.

A rotation of detector w.r.t x-axis will cause the detector to tilt towards or away from beam while still facing the beam. Separate data sets were simulated for detector angles  $\pm 5^\circ$  around the nominal detector angle of  $10.2785^\circ$  degree. Figure 5.48 shows the variation of extracted polarization with change in detector tilt.

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<sup>11</sup>for Compton, background and noise events

<sup>12</sup>Red and blue histograms in top two panels show the counts for positive and negative helicity

Figure 5.46

Extracted polarization with trigger 1/3 plane

Figure 5.47

Extracted polarization with trigger 2/3 plane

Figure 5.48

Variation of polarization with detector tilt

Figure 5.49

Effect of detector rotation w.r.t y-axis

Figure 5.50

Effect of detector rotation w.r.t z-axis

The maximum error in the knowledge of the detector tilt is estimated at  $1^\circ$  to the nominal orientation which yields a systematic relative polarization uncertainty of 0.3% in the fixed Compton edge analysis method.

The rotation of detector w.r.t y-axis was studied with the estimated maximum error to be up to  $\pm 0.5$  degree relative to the nominal of 0.0 degree. Figure 5.49 shows that it results in a systematic variation of up to 0.15% in the extracted polarization.

The estimated maximum error in z-axis rotation is  $\pm 0.5$  degree relative to the nominal of 0.0 degree. It is found that the systematic contribution in extracted polarization from the z-axis rotation of the detector is shown to be up to 0.22% in Figure 5.50.

#### **5.5.4 Detector efficiency**

The systematic contribution of detector strip efficiency was studied by randomly assigning an efficiency in all detector strips within an efficiency-range. The number of hits registered on any given strip was scaled down based on the assigned efficiency of that strip before forming its asymmetry. This analysis was repeated for different efficiency-ranges from 0.1-1.0. We found that the maximum variation in polarization happens up to 0.2% for the full range of efficiency-variation (Figure 5.51).

#### **5.5.5 Beam position at interaction point**

The Compton luminosity is determined by the overlap of the electron and laser beams. If one assumes a Gaussian intensity profile for these two beams, the luminosity is also a Gaussian function of the distance between the two beam centroids [12]. Since the optical axis of the cavity gets mechanically fixed by the mirror holder, the position variation of

Figure 5.51

Effect of individual detector strip efficiency

the electron beam directly affects the Compton luminosity with a sensitivity equal to the derivative of this Gaussian function. In order to minimize this effect, we use a feedback mechanism to lock the mean position of the beam trajectory at the point corresponding to the maximum of the Gaussian overlap curve, where the sensitivity to beam position goes to zero. Despite this, a small fluctuation possible.

We assume that the four beam parameters, the x-position, y-position,  $\theta_x$  and  $\theta_y$  are uncorrelated.

### 5.5.6 Spin precession through chicane

The magnetic moment of an electron of spin  $\vec{s}$  precesses in a static magnetic field  $\vec{B}$  perpendicular to the particular momentum by an angle  $\theta_P$  around  $\vec{B}$  given by Eqn. 5.47 [3],

$$\theta_P = \theta_m \gamma \frac{g - 2}{2} \quad (5.47)$$

where  $\theta_m$  is the electron trajectory rotation and  $g$  is the gyro-magnetic ratio for the electron.

In an ideal situation, a beam with pointlike width follows its reference orbit, central to magnets and acceleration fields with ideal symmetry interacting only with the transverse magnetic fields of the dipole magnets. In this case, the electron spin direction would have remained constant towards the longitudinal acceleration field with the magnetic fields precessing the electron spin relative to the momentum of the beam. But as expected, a finite beam-size and non-ideal particle motion causes the precession of the spin to be different than nominally expected. This effect is expected to be small.



### 5.5.7 DAQ related systematic uncertainties

The Modelsim package was used to simulate the DAQ and the results of these simulations described below were used to estimate the DAQ related systematic uncertainties. As described earlier in the scaler mode the data were collected untriggered gated by the MPS pulse. This led to a  $\sim 6.8\%$  dead time based on the MPS gate width. In the accumulator mode the trigger related inefficiencies lead to additional loss in the data. This loss varied based on the trigger type (1/3, 2/3 or 3/3 plane trigger). In addition, the scaler mode data carried a significantly larger contribution from electronic noise compared to the accumulator mode. The noise contribution was the least for the 3/3 plane trigger. All of these factors contributed to the difference in the yield between the scaler and accumulator modes.

Apart from the yields the asymmetry is also different between the scaler and accumulator modes. The helicity state is in transition over the period of the MPS pulse, hence, the asymmetry of the scaler mode data are diluted by the data collected during the MPS period. On the other hand, the trigger inefficiency is rate dependent and directly impacts the asymmetry in the accumulator mode as demonstrated in Section 4.3.2. Thus one expects the polarization extracted from the scaler mode asymmetry to be different from those extracted from the accumulator mode data. However, the ratio of the polarization extracted from the scaler mode to those extracted from the accumulator mode, is expected to be independent of all changes in the experimental conditions.

Figure 5.52

Ratio of polarization from accumulator mode data to scaler mode data

#### 5.5.7.1 Ratio of accumulator to scaler mode data

The ratio of polarization from the accumulator mode data to those from the scaler mode data are shown in Figure 5.52<sup>13</sup>. The polarizations have been averaged over clusters of 30 runs. They are indeed constant within statistical uncertainties, over the entire run-2 period. The few outliers are being investigated and typically indicate a few bad runs within the cluster of 30 runs. The ratio did show some variation before the trigger inefficiency corrections were applied. The polarization ratio being constant validates the inefficiency corrections as well as the overall analysis.

<sup>13</sup>The different colors indicate the different trigger types. The 2/3 plane trigger is shown in blue, 3/4 in green and 2/4 in magenta

Figure 5.53

Polarization before (solid) and after (open) the DAQ inefficiency correction

Figure 5.54

Difference in polarization due to the inefficiency correction for all runs

### 5.5.7.2 Uncertainty in DAQ inefficiency correction

The trigger/DAQ inefficiency correction were calculated based on the measured scaler rates, thus their effect on the polarization was studied over a period of runs where the scaler rates were relatively stable. Figure 5.53<sup>14</sup> shows the polarization extracted during this period before and after the corrections were applied. This period also recorded the highest rates for all of run-2, thus they show the largest effect on the polarization.

Most of the difference in the polarization after the DAQ inefficiency correction is a result of the difference in the correction between the two helicity states. This was verified by examining at the effect on the polarization when an identical correction was applied to both helicity states, which was found to be negligible ( $-0.06\% \pm 0.04\%$ ). We also examined the difference in the polarization when the strip-to-strip variation in the inefficiency correction

<sup>14</sup>during a period of relatively constant scaler rates

is ignored. A small  $0.14\% \pm 0.04\%$  difference was found with its sign consistent with the strip-to-strip variation. The inefficiency correction is determined from a simulation of an ideal DAQ which do not include the effect of electronic noise or the strip-to-strip and plane-to-plane jitter in the input signals. Thus is it difficult to estimate the systematic uncertainty of the inefficiency correction. In Figure 5.54 <sup>15</sup>, the difference in the polarization for all of run-2 is shown for clusters of 30 runs. The average difference in about 0.7%. We have used this number as the preliminary uncertainty due to the DAQ inefficiency correction. A 0.35% variation in the size of the correction about the average value is also observed, we use the 0.35% variation as an additional point-to-point uncertainty. The high current runs adjacent to the low current Møller-Compton-Møller runs are being investigated to obtain a better estimate of this uncertainty.

### 5.5.8 Uncertainty in laser polarization

As shown in Equation (5.34), the ratio of the measured Compton asymmetry is related to the product of the laser and electron beam polarization. The laser polarization must be factored out when extracting the electron polarization, hence any uncertainty in the laser polarization directly contributes to the systematic uncertainty of the electron beam polarization. This is one of the largest instrumental contributions to the systematic uncertainty of the Compton polarimeter. The polarization extracted by electron and photon detectors can be considered as two independent measurements of the polarization, except that they share the uncertainty in the laser polarization.

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<sup>15</sup>clustered in groups of 30

Typically, the degree of circular polarization of the laser is measured before the light is inserted into the cavity and a transfer function translates the measured polarization to the polarization inside the cavity. The transfer function itself is measured with the cavity open to air, unlike actual operating conditions when the cavity is under vacuum. This introduces large uncertainties in the transfer function due to, stress and alignment variations in the optical components under vacuum and heating during operation.

The QWeak experiment employed an alternative method, based on the principle of optical reversibility [56], which states that, if linearly polarized light is incident on an optical system that converts linearly polarized light into circularly polarized light, then any light that is reflected back to the input must be linearly polarized orthogonal to the incident light. In the Compton setup the laser beam is linearly polarized with a polarizing beam splitting cube and converted to circularly polarized light with a quarter wave plate. Together these two elements form an optical isolator as per the optical reversibility principle. The circularly polarized light was inserted into the Compton laser cavity and any reflected light from the cavity was measured behind the polarizing beam splitting cube. Therefore, the degree to which any returning reflected light is detected past the input linear polarizer is directly related to the degree to which the output light is not perfectly circularly polarized. By minimizing the residual reflected light from the Compton laser cavity, in-situ, the degree of circular polarization in the cavity is maximized. However, a relationship between the directly measured degree of circular polarization and the residual reflected light could be established only when the cavity was not locked at the resonance frequency. Using this measured relationship during the actual operation, when the cavity is locked,

introduces some uncertainties. The other sources of uncertainty include calibration of the photo-diode used to measure the residual light, the presence of unpolarized light in the cavity and the uncertainty due the validity of the method.

Table 5.5 summarizes the various sources with their corresponding uncertainty in the determination of laser polarization. The final quoted uncertainty for laser polarization is a quadrature sum of the various listed contributions.

Table 5.5

Laser polarization systematic uncertainty

| Source            | Uncertainty (%) |
|-------------------|-----------------|
| Method/Model      | 0.02            |
| Unpolarized light | 0.04            |
| Calibration       | 0.08            |
| Locked/unlocked   | 0.15            |
| <b>Total</b>      | <b>0.18</b>     |

The circular polarization of the laser was changed between left circularly polarized and right circularly polarized several times during the experiment and preliminary, we do not see any systematic effect on the extracted electron beam polarization.

## 5.6 Summary

The Compton data analysis procedure was validated using Monte Carlo and DAQ simulations as well as systematic checks of data collected simultaneously using different DAQ modes. The systematic uncertainties were studied and estimated rigorously using the

simulations as well various systematic test carried out during run-2. A preliminary list of systematic uncertainties is presented in Table 5.6



Table 5.6

## Preliminary Systematic Uncertainties

| Parameter                      | Uncertainty        | det.P/P% |
|--------------------------------|--------------------|----------|
| Laser Polarization             | 0.18               | 0.18     |
| Plane to Plane                 | secondaries        | 0.00     |
| Dipole field                   | 0.0011 T           | 0.13     |
| Beam energy                    | 1 MeV              | 0.08     |
| Detector z position            | 1 mm               | 0.03     |
| Inter plane trigger            | 1-3 plane          | 0.19     |
| Trigger clustering             | 1-8 strips         | 0.01     |
| Detector tilt(w.r.t x)         | 1 degree           | 0.03     |
| Detector tilt(w.r.t y)         | 1 degree           | 0.02     |
| Detector tilt(w.r.t z)         | 1 degree           | 0.04     |
| Detector efficiency            | 0.0 - 1.0          | 0.1      |
| Detector noise                 | up to 20% of rate  | 0.1      |
| Fringe field                   | 100%               | 0.05     |
| Radiative corrections          | 20%                | 0.05     |
| DAQ inefficiency correction    | 100% (preliminary) | 0.7      |
| DAQ inefficiency pt.-to-pt.    |                    | 0.3      |
| Beam vert. position variation  | 0.5 mrad           | 0.2      |
| Helicity correl. beam position | 5 nm               | < 0.05   |
| Helicity correl. beam angle    | 3 nrad             | < 0.05   |
| Spin precision through chicane | 20 mrad            | < 0.03   |
| Total                          |                    | 0.59     |

## CHAPTER 6

### RESULTS AND CONCLUSION

#### 6.1 Dectector yield and rates

The Compton yield as well as the beam background scales with charge. Hence a charge normalized subtraction of the laser off yield from the laser on yield, for each detector strip, provides the Compton yield. This is true irrespective of the actual period of the laser on and off states. The charge normalized detector yield as well as the detector rate is discussed in this section.

##### 6.1.1 Charge normalized yield

Figure 6.1 shows the plot of charge normalized yield (as defined in Equation (5.18)) from accumulation mode data for run-2 averaged over 15 runs to show the general trend. Here the X axis uses run number as the time scale where each run number typically represents about an hour worth of data. The green, magenta and blue data points represent the trigger condition of 2/4, 3/4 and 2/3 planes respectively. As expected the accumulation mode yield with 3/4 plane trigger is the smallest because the yield is effected by the product of the inefficiencies of 3 detector planes. The yield was obtained after subtraction of electronic noise and beam background. The yield corresponding to each run was obtained by taking an error weighted mean of the charge normalized yield from each strip. On simi-

lar lines, the yield in Figure 6.2 was obtained from charge normalized scaler mode data. As expected, the scaler yield is higher than its accumulation counterpart, and does not show the variation in yield due to changes in trigger condition as seen in the accumulation data. The run-to-run variations in the accumulation mode yield are due to changes that fall under two broad categories:

- DAQ change
- Operating condition

Figure 6.1

Accumulation mode yield averaged over 15 runs

#### 6.1.1.1 DAQ change

Changes in the trigger condition are the most significant cause of variation in the accumulator mode yield. We ran for various trigger conditions of 2/4, 3/4, 3/3 and 2/3 plane. The trigger used in the DAQ is discussed in Section 3.9.3. The background corrected charge normalized yield aggregated over all strips distinguishes between the various

Figure 6.2

Scaler mode yield of runs with 15 run average

trigger type used for that data set. Here green, magenta and blue represent 2/4, 3/4 and 2/3 plane trigger respectively. When we require a coincidence of signals from more than one plane, the inefficiency of the added planes participating in the trigger formation further suppress the final yield. We thus see a change in yield as we change the trigger. In order to isolate the modification in yield due to change in trigger, we can compare the yield of accumulation mode data to the scaler mode data, since the scaler data is not affected by trigger condition. The ratio of accumulator to scaler mode yields is discussed in Section 6.1.3.

A change of gate width (Section 3.9.2) also leads to changes in the yield, but all of the main experiment was run at a fixed gate width of 300 ns, hence this did not contribute to any of the observed variations in yield. Similarly, the discriminator threshold and the high voltage to the detector were not changed throughout the data taking period, hence was not responsible for any variation in yields.

### 6.1.1.2 Operating condition

A change in the running condition in the experimental hall, or at the hardware level is responsible for several of the above variations. The changes in operating conditions in the order of importance are; variation of laser power, variation of overlap between laser and electron beams, change in detector position.

Figure 6.3

#### Beam current through Run-2

Only quartets with current above 20uA and laser cycles with no beam trips were used in the analysis. Figure 6.3 shows the mean value of current in a run. In this plot, the red markers show the mean of current above the limit of  $20\mu A$ , while the blue markers show the beam current during the good laser cycles that were marked by no beam trips.

The dipole field was responsible for the overlap between electron and laser beam. This field also analyzes the Compton electrons and hence can affect the position of the Compton edge. Figure 6.4 shows the variation of the dipole current during the period of Run-2. The

nominal dipole field was  $\sim 0.544$  T and the variation of 0.6 A in beam current seen in this plot caused a variation of the order of 0.003 T in the dipole field. We also had trim coils on the dipole on which the current varied by up to 0.4% due to fluctuations in its power supply.

Figure 6.4

Dipole current in Chicane through Run-2

Apart from the change in Compton edge due to change in Compton dipole field, several times, we changed the vertical position of electron detector, resulting in a change in the location of the Compton edge (CE) in the recorded spectrum. Since the plotted yield is a sum over all the illuminated strips, a change in CE will result in change of overall rate recorded in a data set. Figure 6.5 shows the manual changes in the detector position. Due to a readout error, we could not record this data for the last period appearing blank in this plot.

The above changes can lead to changes in the CE. The variation of CE through the running period is depicted in Figure 6.6. The Y axis shows the Compton edge as obtained in the two parameter fit to extract electron beam polarization. There were variations in the Compton edge also because of changes in beam position.

Figure 6.5

Detector position measured with respect to an arbitrary reference

### 6.1.2 Time normalized yield

The electronic noise contribution to the yield scales with time. If the current remains constant over the laser on and off periods, this noise contribution is naturally subtracted as shown in Equation (5.2) of Section 5.1.1. For low current runs, the yield from noise is a significant fraction of the total yield and has to be explicitly subtracted from the laser on and off yields.

Figure 6.6

Compton edge variation through Run-2 averaged over each slug

Figure 5.3 in Section 5.1 shows the time normalized signal rate recorded in the accumulation mode. The background subtracted physics rate (blue squares), the background rate (red circles) and the electronic noise rate (black triangles) were obtained by adding over the signal rate from all strips of the run. The runs in the range 23200 - 24200 were with the trigger condition of 3/4 plane, hence the noise rate is most suppressed. As expected, the Compton and background rates do not change significantly with trigger condition.

The trigger inefficiency correction factors for a run are determined by the aggregate scaler rate in a run and hence the correction factors plotted in Figure 6.7 follow the same trend as the scaler rate in Figure 6.2. As expected the correction due to trigger inefficiency was largest for the runs with maximum rates where the correction amounted to  $\sim 6\%$  increase of the corresponding rates.

Figure 6.7

Trigger inefficiency correction factors, averaged over 15 runs

### 6.1.3 Ratio of triggered yield to scalers

The triggered data (accumulation mode) was gated off during helicity transition periods. The scalers measured the total yield from the detector strips and were unchanged by changes in trigger condition and mostly reflect the true total event rate on the detector including the electronic noise, secondary electrons etc. These components are suppressed in the triggered data.

Figure 6.8 shows the ratio of the charge normalized, yield measured in accumulation mode to that measured in scaler mode. This should be unaffected by changes in beam current, Compton edge, beam - laser overlap etc; because each of these changes affects both the data collection modes. This is a good diagnostic of the overall behavior of the data. As can be seen, the ratio is overall the same for a given trigger type. The plot shows three color markers representing data with different trigger type 2/4 plane (green), 3/4 plane (magenta) and 2/3 plane (blue).

Figure 6.8

Ratio of yield from triggered data to scalers

## 6.2 Asymmetry

With the background and noise corrected Compton yield we form an asymmetry (Section 5.2) for each strip. The increasing strip number denotes increasing distance from the unscattered electron beam and hence an increasing  $\rho$  ( $\frac{E'}{E'_{max}}$ ). Using the 64 strips of the electron detector in the Hall-C setup, we were able to sample the Compton asymmetry from a little before the zero crossing, up to the Compton edge as shown in Figure 6.9. The strip at the Compton edge detects Compton scattered electrons that have undergone an energy loss,  $\Delta E = E - E' \sim 46 \text{ MeV}$ , each subsequent strip represents a reduction in the  $\Delta E$  by  $\sim 0.6 \text{ MeV}$  per strip. Here  $E$  and  $E'$  are the energy of unscattered and Compton scattered electrons.

As already discussed in Section 3.9.1, the scaler data is ungated during helicity reversal hence is diluted with yield from the period of helicity transition. The helicity was reversed at a frequency of  $\sim 960 \text{ Hz}$ , using  $\leq 70 \mu\text{s}$  for reversal of helicity. From this we can expect a dilution of  $\sim 5\%$ . The asymmetry for a  $\sim 1$  hour run in scaler mode is shown in Figure 6.10. The relative difference in the asymmetry between the accumulator and scaler mode is shown in Figure 6.11 (only strips beyond the zero crossing are shown for clarity).

Figure 6.9

Typical asymmetry measurement using accumulation data

Figure 6.10

Typical asymmetry measurement using scaler data

This shows the approximately constant difference in asymmetry because of the dilution from events collected during the helicity reversal period. In this plot, we have shown a linear fit of the relative difference from a strip after the zero crossing up to the Compton edge<sup>1</sup>. A relative difference of 0.057 is consistent with the dilution expected from the helicity reversal period.

Figure 6.11

Relative difference in asymmetry of accumulation and scaler data

### 6.2.1 Background asymmetry

In this section we discuss the asymmetry of the laser off yield. The laser off yield is used to subtract the physics background (due to beam halo, Bremsstrahlung etc) from the laser on yield in order to obtain the Compton yield (Section 5.1). The laser off asymmetry represents the asymmetry of the physics background and was consistent with zero for most runs. Figure 6.12 shows one such case of the background asymmetry from a typical hour long run. In this plot, the red line shows a constant fit of the asymmetry in each strip.

<sup>1</sup>This was necessary to avoid division by zero in this ratio

This fit is used to assign a value of background asymmetry ( $A_{bgd}$ ) for each run. When the background asymmetry thus determined is plotted for the whole run, we get Figure 6.13.

Figure 6.12

A representative background asymmetry

For part of the run, we had a finite amount of laser light stored in the cavity during the nominal laser off period, giving non-zero asymmetry to the data used for background subtraction. The effect of a finite background asymmetry on the measured Compton asymmetry is given by:

$$A_{exp} = A_{raw} + \text{dilution} \times A_{bgd} \quad (6.1)$$

where  $A_{exp}$ ,  $A_{raw}$  and  $A_{bgd}$  are the measured Compton asymmetry, the raw (true) asymmetry and the background asymmetry respectively.

The background asymmetry is consistent with zero over the entire period, with the largest value within 0.006. Due to high signal to background ratio i.e small dilution factor, the effect of a non-zero background asymmetry is significantly suppressed in our setup. We

Figure 6.13

### Background asymmetry for Run-2

took two test runs to evaluate the effect of leakage on the background. In one of these runs, the light entering the cavity was physically blocked ensuring no leakage, while the second run had the light leakage problem (referred as 'no flipper' run). The difference in the yield added over all strips between these two runs came out to  $2.02 \pm 0.03 \text{ Hz}/\mu\text{A}$ . Since the Compton edge was at strip 50 for this run range, hence the above rate would translate into  $0.046 \text{ Hz}/\mu\text{A}$  per strip up to the Compton edge. Figure 6.16 shows this value using a linear fit of the difference between the two yields <sup>2</sup>.

Using a neighbouring run with same CE to estimate a typical Compton yield we get a dilution factor of  $\sim 0.0035$ . Therefore, even if the background asymmetry grows as large as 0.01% (3 times larger than the maximum measured value), the raw asymmetry is changed by 0.000035. Using 0.04 as the maximum Compton asymmetry the effect of

<sup>2</sup>laser light physically blocked and not blocked

Figure 6.14

Histogram of  $A_{bgd}$

Figure 6.15

Histogram of  $\chi^2$  in  $A_{bgd}$  determination

Figure 6.16

Difference in yield between runs with laser light physically blocked

the background asymmetry is 0.09%. Note that the maximum background we record is  $\leq 0.004\%$ .

As mentioned in Section 5.1, a fixed cut on the laser power spectrum was used to define the laser-off period. Laser power of 1800 units or lower was considered as laser off (see Figure 5.1).

### 6.2.2 Fitting the asymmetry

Fitting the theoretical shape to the experimental asymmetry as described in Section 5.2.7, we extract the polarization from each run (typically one hour long). A typical extraction of polarization using a two parameter fit, is shown in Figure 6.17. The two parameters are polarization and floating Compton edge. The sign of polarization, which changes based on whether a half wave plane (HWP) is in the path of the beam or not, is also accounted for by the fit. Figure 6.17 and Figure 6.18 show the case of the fit with the insertable half wave plane in and out respectively.

Figure 6.17

Typical polarization extraction using two parameter fit with HWP in

Figure 6.18

Typical polarization extraction using two parameter fit with HWP out

The quality of fit between theoretical asymmetry and the measured asymmetry as described in Section 5.2.7 is represented by the  $\chi^2$  per degree of freedom for the fit used to extract polarization. This is histogrammed in Figure 6.19 for all data sets of Run-2. As seen from this, the mean of the fit is a little larger than 1.3.

Figure 6.19

Histogram of  $\chi^2$  per degree of freedom

Another measure for the fit quality is the residue of the fitted theoretical and experimental asymmetry. Figure 6.20 shows the fit residue from an hour long run. The red line represents the linear fit of the fit residue from each strip. Using this value of linear fit as the fit-residue for each run, the fit residue of data in Run-2 was consistent with zero as can

be seen in the histogram of the residual for period of Run-2 and has a mean consistent with zero.

Figure 6.20

Residual of Compton asymmetry fit to data

We did not find any correlation between the fit quality vis-a-vis the  $\chi^2$  or the residuals with the respective yield in the run. This rules out the possibility of any bias being introduced in the analysis due to the beam current variations or any possible change in individual detector strip efficiency.

### 6.3 Polarization

Polarization is one of the fit parameters in the two parameter fit described in the preceding section. The statistical uncertainty quoted with this polarization is the uncertainty in the respective fit parameter. The extraction for individual runs as described in Section 6.2.2 is used to get a polarization for each 1 hour long run. Figure 6.23 shows the polarization thus extracted for each run with its statistical uncertainty.

Figure 6.21

Histogram of fit residue for runs

Figure 6.22

Histogram of  $\chi^2$  in residue determination

Figure 6.23

Plot of extracted polarization throughout Run-2

The initial goal regarding the statistical power of the Compton polarimeter was to achieve  $< 1\%$  statistical uncertainty from one hour of data. Figure 6.24<sup>3</sup> shows the mean statistical precision achieved during Run-2 from each hour long data set. The mean of this histogram is 0.64.

Figure 6.25<sup>4</sup> shows a scatter plot of the polarization Vs its statistical uncertainty returned by the fit. The plot shows the expected behavior that the polarization and its extracted uncertainty are not correlated.

Nominally, the laser cycle comprised of 60 s of laser on and 30 s of laser off. But this definition of laser cycle was changed a few times during Run-2. In the laser cycle analysis we maintain a count of the number of laser cycles used while throwing out any laser cycle with a beam trip. The Figure 6.26<sup>5</sup> shows that the statistical uncertainty of the polarization

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<sup>3</sup>for all the runs reported

<sup>4</sup>uncertainty returned by the fit

<sup>5</sup>and number of laser cycles used

Figure 6.24

Histogram of statistical uncertainty for the extracted polarization

Figure 6.25

Plot showing no correlation between polarization and the uncertainty

reduces with increasing number of laser cycles used. This correlation plot clearly indicates two distinct data clusters. The lower cluster representing the majority of runs is from laser cycles with periods set to 60 s for on and 30 s for off. The other laser cycle definitions used were 50 s on and 25 s off, as well as, 90 s on and 45 s off. The second cluster with slightly higher uncertainty for the same number of laser cycles, is from runs with 50 s for laser on and 25 s for laser off.

For plots in this section, we have excluded the runs with less than 2 good laser cycles which maps to  $\sim 1.5\%$  statistical uncertainty on polarization and are not representative of the typical hour long run.

Experience at JLab has shown that certain configuration changes at the polarized source have the potential to impact the polarization. These, along with other major changes that could potentially affect the Compton polarimeter are marked in Figure 6.27. In this plot, the blue markers show the absolute value of polarization averaged over 15 runs, irrespective of the HWP state. The dashed lines show the event marker. The various events marked in this plot are color coded as per the following list:

- red: change in laser spot on the cathode crystal to create beam
- magenta : photo-cathode reactivation
- blue: new horizontal wien state
- green: change in Compton laser helicity state
- yellow: other changes introduced for a limited time.

The yellow markers representing other changes included change in orbit lock for beam laser overlap, change of beam energy, transverse beam polarization, large charge asymmetry etc.

Figure 6.26

Plot showing correlation between statistical uncertainty on polarization

Figure 6.27

Major event markers during Run 2

The jumps in the beam polarization are directly correlated with the operations at the polarized electron source when the laser spot is displaced to illuminate a different spot on the photo-cathode in order to continue delivering beam. We notice that on each of the red (spot move) markers, there is a hint of an effect and on each of the magenta (re-activation) markers there is a significant jump in beam polarization. The beam spot on the cathode crystal used for beam generation is changed when we measure a lower quantum efficiency. These significant variations in the beam polarization demonstrates that the continuous measurement provided by the Compton polarimeter is a necessity. The exact reason for the significant rise or fall in polarization due to spot change and reactivation is not clear though a brief discussion is provided in Chapter 2.

We did not find any non statistical variation in the value of extracted beam polarization with change in the state of Compton laser helicity. These are marked with green dashes in Figure 6.27. Here, we also do not see the change in electron beam helicity state, changed via the Wien flipper (blue dashed lines).

Additionally, we intend to perform a relative comparison of the results from the photon detector, when they become available.

#### **6.4 Cross calibration between Møller and Compton Polarimeters**

The Møller and Compton polarimeters work on entirely different principles and have completely different systematics, so we chose to compare the respective measurements keeping every other possible parameter fixed. Earlier attempts to study the beam polarization simultaneously using different polarimeters at JLab found a difference  $> 1\sigma$  between

the different polarimeters [24]. The difference was attributed to poorly understood systematic uncertainties of the different polarimeters.

A set of Compton measurements sandwiched by Møller measurements were carried out at the same beam current to cross calibrate the two polarimeters in Hall C.

With lower beam currents, the measurement in the Compton polarimeter is hampered by poor statistics. On the other hand, increasing the beam current causes the systematics on the Møller measurement to rise due to target heating. We found an optimal value of the beam current by checking the maximum current at which the Hall C Møller polarimeter works without the heating effect becoming dominant (Section 2.5.2). This was found to be  $4.5 \mu A$ . The optics parameters used to transport the electron beam through the Compton chicane were slightly different from those used to reach the Møller target. So even though the beam for both Compton and Møller measurements went through the magnetic chicane, the laser-table lock was released in the case of Møller. This became necessary because the operators were unable to establish the beam position on Møller target while keeping the trajectory through the Compton chicane with the laser-table lock. The regular Møller measurements were anyways made without going through the chicane. Other than these minor differences, rest of the beam optics was kept same for both the measurements.

Figure 6.28 <sup>6</sup> shows the polarization extracted from the Compton measurements during the cross calibration. We have plotted it with the adjacent high current data with no known change potentially affecting the beam polarization. The data clusters with high current before and after the low current runs were averaged separately and listed in Table 6.4

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<sup>6</sup>along with neighboring high current runs and Møller average

to observe any variation within the short period between these runs. In this plot, the polarization extracted from Compton polarimeter at low current is shown in blue while that obtained from Møller polarimeter is in black. In this plot the inner error bar shows the statistical uncertainty while the outer error bar shows the total uncertainty given by the quadrature sum of statistical and systematic uncertainties.

On similar lines, the background asymmetry of these runs are plotted in Figure 6.29 to show the behaviour of background asymmetry for high current and low current data. It should be noted that the effect of any finite background asymmetry becomes more significant at lower current. The effect of background asymmetry was estimated in Section 6.2.1 for high current runs. Figure 6.30 shows the fit residue for the above polarization extraction.

Here we present a table with the final averaged polarization from Møller and Compton as is relevant to this comparison study. The preliminary laser cycle averaging study finds that the measurements do not agree within one standard deviation of statistical uncertainty of the measurement. Note that the high current ( $I = 180 \mu A$ ) and low current ( $I = 4.5 \mu A$ ) Compton measurements are consistent with each other within one standard deviation.

The polarization extracted from the two beam polarimeters were still consistent with each other within the total uncertainty of the measurements.

## 6.5 Results for Qweak

Since the Qweak experiment will calculate asymmetry for every slug, the slug based polarization is a natural way for Qweak to use the Compton results. Figure 6.31 shows the

Figure 6.28

Polarization measured at  $4.5\mu\text{A}$

Figure 6.29

Background asymmetry for the Compton measurements

Figure 6.30

Fit residue of Asymmetry fit used to extract the polarization



Table 6.1

Mean polarization measurements during cross calibration

| Measurement type             | Mean polarization (%) | Statistical uncertainty | Total uncertainty |
|------------------------------|-----------------------|-------------------------|-------------------|
| Compton (at $I = 180\mu A$ ) | 86.92                 | 0.15                    | 0.47              |
| Møller (at $I = 4.5\mu A$ )  | 86.54                 | 0.14                    | 0.72              |
| Compton (at $I = 4.5\mu A$ ) | 87.44                 | 0.71                    | 0.84              |
| Compton (at $I = 180\mu A$ ) | 87.16                 | 0.29                    | 0.53              |

value of polarization averaged over each slug. The runs with HWP in, leading to a positive polarization are shown in red while that with HWP out, leading to negative polarization are shown in blue. The inner error bar represents the statistical precision while the total error bar is the quadrature sum of the statistical and systematic uncertainty (0.85%). In this plot, we have also superimposed the results for Møller with its statistical and systematic (0.70%) uncertainty added in quadrature.

## 6.6 Conclusion and Future Possibility

We were able to continuously monitor the electron beam polarization through the half of run1 and whole of Run-2 data collection periods of the QWeak experiment without being invasive. The online monitoring was done at the same beam current at which the QWeak experiment was collecting physics data. The use of radiation hard diamond micro-strip

Figure 6.31

Polarization averaged over each slug

detector gave us an energy resolution of  $\sim 0.6$  MeV and using the custom electronics made at TRIUMF we were able to achieve a statistical precision of  $\sim 0.6\%$  during an hour long data run. We have carried out extensive study to understand the systematic uncertainties from the data acquisition, the instrument as well as the analysis method to assign the final systematic contribution. We have constrained it at  $0.85\%$  in the absolute polarization measurement.

To use the polarimeter after the JLab energy upgrade, the magnetic chicane will need to be re-organized with a vertical offset of 2.3 cm (compared to Table 2.1). For an energy of 11 GeV, the maximum asymmetry of  $4.1\%$  currently will change to  $32\%$ , hence making the measurement easier. Using the same magnet, the Compton edge electrons will be 37 mm away from the main beam compared to the current 17 cm distance from the main beam. The detectors, QWAD boards along with other data acquisition hardware and software can be directly used even after the energy upgrade without any changes. These along with the

experience of building the currently working polarimeter from scratch makes the 12 GeV polarimetry in Hall-C a promising endeavour.

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