Determination of the weak charge of the proton through parity violating asymmetry
measurements in the elastic $e+p$ scattering

By

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A Dissertation
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
in Applied Physics
in the Department of Physics and Astronomy

Mississippi State, Mississippi

December 2014

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2014

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Title of Study: Determination of the weak charge of the proton through parity violating asymmetry measurements in the elastic e+p scattering

Pages of Study: 269

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The Qweak experiment has taken data to make a 2.5% measurement of parity violating elastic e+p asymmetry in the four momentum transfer region of 0.0250 (GeV/c)^2 . This asymmetry is proportional to the weak charge of the proton, which is related to the weak mixing angle, $\sin^2(\theta_W)$. The final Qweak measurement will provide the most precise measurement of the weak mixing angle below the Z^0 pole to test the Standard Model prediction. A description of the experimental apparatus is provided in this dissertation. The experiment was carried out using a longitudinally polarized electron beam of up to 180 microampere on a 34.5 cm long unpolarized liquid hydrogen target. The Qweak target is not only the world's highest cryogenic target ever built for a parity experiment but also is the least noisy target. This dissertation provides a detailed description of this target and presents a thorough analysis of the target performance. Statistical analysis of Run 1 data, collected between Feb - May 2011, is done to extract a blinded parity violating asymmetry of size $-299.7 \pm 13.4 \text{ (stat.)} \pm 17.2 \text{ (syst.)} \pm 68 \text{ (blinding) parts-per-billion}$.

This resulted in a preliminary proton's weak charge of value 0.0865 ± 0.0085 , a 9% measurement. Based on this blinded asymmetry, the weak mixing angle was determined to be $\sin^2(\theta_W) = 0.23429 \pm 0.00211$.

DEDICATION

To my family.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my advisor Prof. Jim Dunne for giving me the wonderful opportunity to be a part of the Qweak collaboration and for all the support and guidance I have received over the years. I am immensely grateful to my on-site advisor Greg Smith, who showed by example how to be a thorough researcher. His patience, meticulousness and encouragement have always inspired me to perform better. I am wholeheartedly thankful to David Mack for guiding me through various analysis and simulation projects and for providing detailed insights that have helped me grow as a physicist. Thank you to Silviu Covrig for his huge contribution in designing the Qweak target and also for the expert guidances I received in various target related work. I would like to thank Prof. James Birchall for teaching me the trades of Qweak GEANT3 Monte-Carlo simulations. I am thankful to my committee members for their time and effort to go through my dissertation and provide me with fruitful corrections.

I would like to thank Mark Pitt, Dave Gaskell, Dave Armstrong and Roger Carlini for their invaluable insights to various analysis projects discussed in my dissertation. It has been a very enriching experience working with various people from the Qweak collaboration. I am grateful to my fellow graduate students and postdocs for helping me in various research projects. I especially want to thank Katherine Myers, Scott MacEwan, Jeong Han Lee, Jiawei Mei, Rakitha Beminiwatha, Buddhini Waidyawansa, Amrendra Narayan, Em-

manouil Kargiantoulakis and Wade Duvall for promptly helping me with various simulation and analysis issues. I have learned so much from you all, thank you for always being so helpful. I would like to thank my former roommates and colleagues Don Jones, Luwani Ndukum and Nuruzzaman for their help and support both on and off the lab endeavors.

Qweak wouldn't have been possible without dedicated work from a lot of individuals. I want to extend my sincere thanks to the Dave Meekins, Chris Keith and James Brock from Jlab target group and Hall C technicians for their help in my various target related undertakings and also for their unwavering support to make the Qweak target a big success. A big thanks to Paul King and the entire data quality group for making data available for analysis. I would like to thank Aja, Safalta, Manoj, Urvashi, Rajneesh, Dinesh, Pashupati and Rashmi for all the encouragement you gave to see me through the graduate school. I would also like to thank Connie Vaughn and Susan Galloway for helping me with various administrative work to make my stay in Virginia as comfortable as it could have been.

Finally, I would like to thank the department of energy for providing funding to my research. The work presented in this dissertation was supported by DOE grant number DE-FG02-04ER41330 and DE-FG02-07ER41528.

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CHAPTER 1

THEORY

1.1 Matter, Particles and the Standard Model

“By convention there is color,

By convention sweetness,

By convention bitterness,

But in reality there are atoms and space”

-Democritus (circa 400 BCE)

The quest to understand what matter is made of is one of the oldest undertakings in human history. Democritus, often cited as the father of the modern science, conjectured the indivisibility of atoms, which he believed were the building blocks of matter. However, very little progress was made until the beginning of the 19th century when John Dalton propounded his famous atomic theory (1802). He proposed that physical matter was made of atoms combined in whole number ratios. Almost a century later (1898) J.J. Thompson discovered that cathode rays consist of fundamental particles: the electrons. The first quarter of the 19th century saw an unprecedented development in both theoretical and experimental particle physics. Albert Einstein laid the foundation of quantum mechanics early in 1905

with his wave-particle theory on the photoelectric effect. Rutherford found experimental evidence of a positive nucleus in 1911 and proposed the famous Rutherford's model of atoms. Improvements over Rutherford's model were made by Bohr in 1913. Bohr's model limited electrons in an atom to discrete radii which explained emission lines in atomic spectra. Significant achievements like the wave-particle duality by Louis de Broglie (1923), the uncertainty principle by Werner Heisenberg (1925) and the wave equation by Erwin Schrödinger (1925-1926) laid the framework of the quantum mechanics. On the experimental front, James Chadwick discovered the neutron (1932) and parity violation was observed (1957) in ^{60}Co by Chien-Shiung Wu shortly after it was predicted (1956) by Tsung-Dao Lee and Chen Ning Yang. Muon and solar neutrinos were discovered in 1964 and 1967 with the latter being one of the biggest puzzles in particle physics. Meanwhile, the quark model was proposed (1964) by Murray Gell-Mann and George Zweig and evidence of the first quarks was found in 1969 by Jerome Friedman, Henry Kendall, and Richard Taylor. In 1967, Steven Weinberg, Sheldon Glashow (collaboration) and Abdus Salam (independently) unified the weak and the electromagnetic interactions in their famous electroweak theory. Consequently, the Standard Model of particle physics was formulated which has had an enormous success in explaining and predicting several phenomena. Discovery of the charmed quark (1974), tau lepton (1975) and bottom (1977) quark, W and Z bosons (1983), top quark (1995), tau neutrino (2000) and more recently the Higgs boson (2013) firmly cemented the effectiveness of the Standard Model (SM).

As shown in Figure 1.1 [1], the SM consists of two families of matter: quarks and leptons and a family of force carriers. Both quarks and leptons come in three generations.

The first generation of matter is what the visible universe is made of. The exotic matter formed by the second and third generation of quarks and leptons is found in high energy collisions, in the particle colliders or in cosmic events like supernova. Both quarks and leptons are fermions with spin of 1/2. Force carriers that mediate interactions (strong, electromagnetic and weak) are bosons with spin 1.

Figure 1.1

The Standard Model of particle physics.

The Standard Model of particle physics showing three generations of matter, gauge bosons and the Higgs boson. Gravity still remains excluded.

The SM is based on the gauge groups $SU(3) \otimes SU(2) \otimes U(1)$. $U(1)$ denotes the symmetry group of the electromagnetic interaction where the fermions act as singlets and interact by exchanging one boson, $SU(2)$ for the weak interaction where the left handed

fermions act as pairs mediated by three bosons and SU(3) for the strong interaction where the fermions act as triplets mediated by eight bosons.

The SM has had some glaring shortcomings; notably the omission of gravity, charge-parity violation, dark matter and dark energy. The neutrinos have been found to have non-zero mass as opposed to the SM prediction and can change flavors via oscillations [2]. The very success of the SM in predicting various experimental observables also makes it possible to test the SM with very precise measurements of the parameters within the standard model.

1.2 Symmetry and spontaneous symmetry breaking

A symmetry can be understood as a transformation which leaves the Lagrangian and the action of the system invariant. If $\phi(x)$ is a scalar field and $\phi^*(x)$ its complex conjugate then the solutions to

$$\mathcal{L} = -\partial^\mu \phi^* \partial_\mu \phi - m^2 \phi^* \phi \quad (1.1)$$

are the equations of motion given by

$$\begin{aligned} \partial^2 \phi - m^2 \phi &= 0, \\ \partial^2 \phi^* - m^2 \phi^* &= 0. \end{aligned} \quad (1.2)$$

A global transformation of the fields as

$$\phi'(x) = e^{i\alpha} \phi(x), \quad \phi'^*(x) = e^{-i\alpha} \phi^*(x). \quad (1.3)$$

leaves the equations of motion unchanged as

$$\partial^2 \phi' - m^2 \phi' = e^{i\alpha} (\partial^2 \phi - m^2 \phi) = 0. \quad (1.4)$$

The Lagrangian and the action (S) are invariant under this transformation, i.e.,

$$\mathcal{L}(\phi', \partial_\mu \phi') = \mathcal{L}(\phi, \partial_\mu \phi), \quad S[\phi'] = S[\phi] \quad (1.5)$$

thus making this transformation a symmetry.

A symmetry is broken by an external force which appears as an additional term(s) in the Lagrangian or in the equations of motion whereas a spontaneously broken symmetry has no such term(s). The equations of motion and the Lagrangian still remain the same in the latter case. Consider a common example of a rod which has rotational symmetry. Applying force transversely to one end bends the rod and breaks the symmetry. However, applying force longitudinally leads to the buckling of the rod in one of the many directions possible which still follow the original equations of the motion (i.e., spontaneously breaks the symmetry). All arbitrary ground states have the lowest energy (degenerate) and their physical states are related to each other by rotation (symmetric transformation).

1.2.1 Global and local symmetries

A global symmetry is exhibited by parameter(s) that remain unchanged at every point in space-time under some transformation. For example, α in Equation 1.3 does not depend on location. The rotational symmetry is an example of global symmetry where all the points undergo the same amount of transformation. The phase transformation discussed in Section 1.2 is also a global symmetry. Here, the phase of the fields transform by the same amount in space-time.

A local symmetry is the one which has a space-time dependent parameter. For example, if the angle of rotation changes at different points of space-time then it is a local symmetry

(i.e., not all the points undergo the same transformation). Also, if the phase depends on space-time then the Lagrangian is no longer an invariant ($\mathcal{L}(\phi, \phi^*) \neq \mathcal{L}'(\phi', \phi'^*)$) under a local phase transformation. The Lagrangian invariance can however be restored by introduction of an additional field in the Lagrangian such that $\mathcal{L}(\phi, \phi^*, A) \longrightarrow \mathcal{L}'(\phi', \phi'^*, A')$.

Consider a Lagrangian of a complex scalar field ϕ as

$$\mathcal{L} = \partial_\mu \phi \partial^\mu \phi^* - V(\phi) \quad (1.6)$$

where

$$V(\phi) = \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2 \quad (1.7)$$

is the potential term. The kinetic term is invariant under global U(1) transformation i.e, $\phi'(x) = e^{i\alpha} \phi(x)$, and the Lagrangian will be invariant if the potential term is invariant under the U(1) transformation also. For example, a potential of the form $V(\phi) = (\phi \phi^*)^2$ makes the Lagrangian invariant under a global U(1) transformation. However, under a local gauge transformation the kinetic term is not invariant since the derivative will act on the time varying component adding extra term(s) in the Lagrangian. The local invariance is maintained by imposing a new gauge field to the Lagrangian. This field has the following gauge transformation:

$$A_\mu \longrightarrow A_\mu + \frac{1}{q} \partial_\mu \alpha(x) \quad (1.8)$$

where q is the charge of the field and also appears in the covariant derivative that replaces the normal derivative as

$$D_\mu = \partial_\mu - iqA_\mu. \quad (1.9)$$

A_μ also has a gauge invariant dynamical term $F_{\mu\nu}F^{\mu\nu}$ where

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad (1.10)$$

is the field strength of the new gauge field. The gauge invariant U(1) Lagrangian is now given by

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + D_\mu\phi D^\mu\phi^* - V(\phi) \quad (1.11)$$

which is the Lagrangian of quantum electrodynamics.

1.3 Electro-Weak theory and the Higgs mechanism

Electro-Weak theory is a gauge theory of combined electromagnetic (U(1)_Y) and weak (SU(2)) interactions. The Lagrangian for electro-weak theory is given by

$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{fermion} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa} \quad (1.12)$$

where

$$\mathcal{L}_{gauge} = \frac{1}{2}W_{\mu\nu}^a W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \quad (1.13)$$

$$\begin{aligned} \mathcal{L}_{fermion} = \sum_f \bar{\psi}_f i\gamma^\mu \left(\partial_\mu + i\frac{g'}{2}Y B_\mu + i\frac{g}{2}\tau_a W_\mu^a \right) \psi_f \\ + \sum_f \bar{\psi}_f i\gamma^\mu \psi_f \left(\partial_\mu + i\frac{g'}{2}Y B_\mu \right) \end{aligned} \quad (1.14)$$

$$\mathcal{L}_{Higgs} = (D_\mu\phi)^\dagger(D^\mu\phi) - \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2 \quad (1.15)$$

where the covariant derivative

$$D_\mu = \left(\partial_\mu + i\frac{g'}{2}Y B_\mu + i\frac{g}{2}\tau_a W_\mu^a \right) \quad (1.16)$$

and $\mu^2 < 0, \lambda > 0$. Higgs field is a SU(2) complex doublet with isospin $t = 1/2$ and weak hypercharge $y_\phi = 1$ and of the form

$$\phi(x) = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \quad (1.17)$$

ϕ^+ has charge $Q^f = +1$ ($t_3 = +1/2, y_\phi = 1$) whereas ϕ^0 has charge $Q^f = 0$ ($t_3 = -1/2, y_\phi = 1$). In matrix form, this can be written as

$$\begin{aligned} Q^f \cdot \phi(x) &= \left(T_3 + \frac{Y}{2} \right) \phi(x) = \left[\frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \right] \phi(x) \\ &= \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \phi(x). \end{aligned} \quad (1.18)$$

The potential in Equation 1.7 has a minima at

$$\phi^\dagger \phi = \frac{-\mu^2}{2\lambda} \quad (1.19)$$

Choosing the vacuum state to be

$$\phi(0) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu \end{pmatrix}, \quad \nu^2 = \frac{-\mu^2}{\lambda} \quad (1.20)$$

makes $Q^f \cdot \phi_0 = 0$. This is done to ensure the photon remains massless as the electromagnetic gauge group U(1) generated by Q^f remains unaffected by the Higgs mechanism.

In the absence of gauge interactions the spontaneously broken global symmetry would give three massless Goldstone bosons and a massive Higgs field. However, in the presence of the gauge fields, the fields can be written as unitary gauge of the form

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + \rho(x) \end{pmatrix}. \quad (1.21)$$

The Higgs Lagrangian can now be re-written as

$$\begin{aligned}
\mathcal{L}_{Higgs} = & \frac{1}{2}(\partial_\mu \rho)^2 - \frac{1}{2}m_\rho^2 \rho^2 - \lambda \nu \rho^3 - \frac{\lambda}{4}\rho^4 \\
& + \frac{1}{2}m_W^2(W_\mu^1 W^{\mu 1} + W_\mu^2 W^{\mu 2}) \\
& + \frac{\nu^2}{8}(g' B_\mu - g W_\mu^3)(g' B^\mu - g W^{3\mu}) \\
& + \text{interaction terms}
\end{aligned} \tag{1.22}$$

The result is a neutral massive Higgs field ρ with mass $m_\rho^2 = 2 \lambda \nu^2$ and massive vector fields W^1 and W^2 with mass $m_W = \frac{1}{2} g \nu$. The charged bosons are given by

$$W^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp i W_\mu^2) \tag{1.23}$$

and

$$W_\mu^1 W^{\mu 1} + W_\mu^2 W^{\mu 2} = 2 W_\mu^+ W^{\mu -}. \tag{1.24}$$

The quadratic term contains the fields B_μ and W_μ^3 . Upon diagonalization by defining

$$Z_\mu = \frac{g W_\mu^3 - g' B_\mu}{\sqrt{g^2 + g'^2}} \tag{1.25}$$

and

$$A_\mu = \frac{g' W_\mu^3 + g B_\mu}{\sqrt{g^2 + g'^2}} \tag{1.26}$$

the quadratic term is reduced to $\frac{1}{2}m_Z^2 Z_\mu Z^\mu$ where

$$m_Z = \frac{1}{2} \nu \sqrt{g^2 + g'^2}, m_A = 0 \tag{1.27}$$

are the masses associated with the fields Z_μ (Z boson) and A_μ (photon). The weak mixing angle is defined as

$$\tan \theta = \frac{g'}{g}, \cos \theta = \frac{m_W}{m_Z} \tag{1.28}$$

such that the fields are given as

$$\begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & -\sin \theta_W \\ \sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix}. \quad (1.29)$$

Fermions also get their masses in the SM from the coupling of the Higgs field with the fermion field via Yukawa coupling. The Yukawa Lagrangian is given by

$$\mathcal{L}_{Yukawa} = -G_e \overline{(\nu_e, e^-)}_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} e_R^- \quad (1.30)$$

+ hermitian conjugate + similar terms for muon and tau fields.

The Yukawa terms are invariant under both $SU(2)_L$ and $U(1)_Y$. The Lagrangian under the unitary gauge

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + \rho(x) \end{pmatrix} \quad (1.31)$$

becomes

$$\mathcal{L}_{Yukawa} = -\frac{G_e \nu}{\sqrt{2}} \overline{e^-} e^- - \frac{G_e \nu}{\sqrt{2}} \rho \overline{e^-} e^-. \quad (1.32)$$

The first term gives the mass of the electron

$$m_e = \frac{G_e \nu}{\sqrt{2}} \quad (1.33)$$

and the second term is the remaining Yukawa coupling. In this way, all other fermions get their masses but neutrinos remain massless. In general,

$$m_f = \frac{G_i \nu}{\sqrt{2}} \quad (1.34)$$

where $f = u, d$ or any other fermion.

1.4 Weak charge of the proton

The interaction Lagrangian can be written as [3] ,

$$\begin{aligned}
\mathcal{L}_{fermion} = & \sum_f \bar{\psi}_f \left(\partial_\mu - m_f - g \frac{m_f H}{2M_W} \right) \psi_f \\
& - \frac{g}{2\sqrt{2}} \sum_f \bar{\psi}_f (\gamma^\mu (1 - \gamma^5) (T_+ W_\mu^+ + T_- W_\mu^-)) \psi_f \\
& - e \sum_f Q^f \bar{\psi}_f \gamma^\mu \psi_f A_\mu \\
& - \frac{g}{2 \cos \theta_W} \sum_f \bar{\psi}_f \gamma^\mu (g_V^f - g_A^f \gamma^5) \psi_f Z_\mu
\end{aligned} \tag{1.35}$$

where T_+ and T_- are the weak isospin raising and lowering operators in the weak charged-current interaction (second) term given by

$$T_\pm = T_1 \pm iT_2. \tag{1.36}$$

For small four momentum transfer squared i.e., $Q^2 \ll M_W^2$ this term is reduced to the effective four-fermion contact interaction with the Fermi constant given by $\frac{G_F}{\sqrt{2}} = \frac{1}{2\nu^2} = \frac{g^2}{8M_W^2}$. The third and the fourth terms give the electromagnetic and weak neutral-current interaction respectively (Figure 1.2) where e is the electromagnetic charge of a positron and g_V^f and g_A^f are the vector and axial-vector couplings defined as

$$g_V^f = T_f^3 - 2Q^f \sin^2 \theta_W \tag{1.37}$$

and

$$g_A^f = T_f^3. \tag{1.38}$$

Figure 1.2

Feynman diagrams for the tree level interactions between a polarized electron and a proton.

The electromagnetic interaction (left) is mediated via the exchange of a virtual photon whereas a Z boson is exchanged during neutral-weak interaction (right).

Also at low momentum transfer in electron-hadron and electron-electron scattering, the parity violating Lagrangian terms of the four-fermion interactions are given by [3]

$$\mathcal{L}_v^e = \frac{G_F}{2} \sum_i (C_{1i} \bar{e} \gamma_\mu \gamma^5 e \bar{q}_i \gamma^\mu q_i + C_{2i} \bar{e} \gamma_\mu e \bar{q}_i \gamma^\mu \gamma^5 q_i) \quad (1.39)$$

and

$$\mathcal{L}_e^e = \frac{G_F}{2} C_{2e} \bar{e} \gamma_\mu \gamma^5 e \bar{q}_i \gamma^\mu q_i + C_{2i} \bar{e} \gamma_\mu e \quad (1.40)$$

where C_{1i} and C_{2i} are weak vector quark couplings defined by

$$C_{1i} = -\frac{1}{2} g_V^f \quad (1.41)$$

$$C_{2i} = \frac{1}{2} g_A^f (1 - 4 \sin^2 \theta_W). \quad (1.42)$$

The weak charge of the proton (Q_W^p) is defined as

$$Q_W^p = -2(2C_{1u} + C_{1d}) \quad (1.43)$$

where the subscripts u and d pertain to the up and the down quark respectively. Similarly, the weak charge of the neutron is given by

$$Q_p^N = -2(C_{1u} + 2C_{1d}). \quad (1.44)$$

In general,

$$Q_W^p = -2(C_{1u}(2Z + N) + C_{1d}(Z + 2N)). \quad (1.45)$$

Table 1.1

EM and weak charges of the up and down quarks, proton and neutron.

	EM Charge	Weak Charge	
u	2/3	$1 - 8/3 \sin^2 \theta_w$	$-2 C_{1u}$
d	-1/3	$-1 + 4/3 \sin^2 \theta_w$	$-2 C_{1d}$
P (uud)	1	$1 - 4 \sin^2 \theta_w$	$-2(2 C_{1u} + C_{1d})$
N (udd)	0	-1	$-2(C_{1u} + 2C_{1d})$

At tree level, the weak charges can be written as a function of the weak mixing angle (θ_W). The fourth column gives the respective weak charges in terms of weak vector quark couplings C_{1u} & C_{1d} .

1.5 Electron-proton scattering and form factors

Scattering polarized electrons off proton targets is a way to probe the weak interaction. Electron-proton scattering is dominated by the electromagnetic interaction and there is really no direct way of identifying whether the scattering was the result of the neutral weak interaction or not. However, due to the interference of the electromagnetic and weak neutral amplitudes one gets an observable via the parity violating asymmetry. This section

discusses how the proton's weak charge can be determined by studying electron-proton scattering.

1.5.1 Electromagnetic Form Factors

The amplitude of the tree level electromagnetic interaction is given by

$$\mathcal{M} = \frac{1}{Q^2} j^\mu J_\mu \quad (1.46)$$

where Q^2 is the four momentum transfer squared, and

$$j^\mu = -e \overline{\psi}_e(k') \gamma^\mu \psi_e(k) \quad (1.47)$$

is the electron current and J_μ is the nucleon current. J_μ can be written in its most general form that encompasses Lorentz covariance and parity and time reversal invariance [4] as

$$J_\mu = e \overline{u}_N(p') \left[\gamma_\mu F_1(Q^2) + \frac{i \sigma_{\mu\nu} q^\nu}{2m_N} F_2(Q^2) \right] \quad (1.48)$$

where F_1 and F_2 are Q^2 dependent form factors called the Dirac and Pauli form factors, respectively. Also commonly used are the Sachs form factors which are linear combinations of F_1 and F_2 and given by

$$G_E^{\gamma,Z}(Q^2) = F_1^{\gamma,Z}(Q^2) - \tau F_2^{\gamma,Z}(Q^2), \quad (1.49)$$

$$G_M^{\gamma,Z}(Q^2) = F_1^{\gamma,Z}(Q^2) + F_2^{\gamma,Z}(Q^2), \quad (1.50)$$

where $\tau = (\frac{Q}{2m_N})^2$ is a kinematic factor and G_E and G_M are the electric and magnetic form factors respectively. When $|\mathbf{Q}|^2 \ll m_N^2$, i.e., when the nucleon recoil is insignificant, G_E and G_M are the Fourier transforms of the nucleon's electric and magnetic moment

distributions, respectively in the infinite momentum frame. In the limit $Q^2 \rightarrow 0$, $G_E(0)$ is the net charge and $G_M(0) = \frac{\mu}{e/2m_N}$ is the net magnetic moment of the nucleon. For the proton and the neutron,

$$G_E^p(0) = 1, G_M^p(0) = \mu_p = 2.79 \quad (1.51)$$

$$G_E^n(0) = 0, G_M^n(0) = \mu_n = -1.91.$$

Furthermore, the mean square electric and magnetic charges are related to G_E and G_M as follows:

$$\begin{aligned} \langle r_E^2 \rangle &= -6 \left(\frac{dG_E^p(Q^2)}{dQ^2} \right)_{Q^2=0}, \\ \langle r_M^2 \rangle &= -6 \left(\frac{dG_M^p(Q^2)/\mu_p}{dQ^2} \right)_{Q^2=0}. \end{aligned} \quad (1.52)$$

These form factors have been well studied in electron-proton scattering experiments using hydrogen targets and by measuring cross section given by the Rosenbluth formula [5]

$$\left(\frac{d\sigma}{d\Sigma} \right)_{lab} = \frac{\alpha^2}{4E^2 \sin^4(\frac{\theta}{2})} \frac{E'}{E} \left(\frac{(G_E^p)^2 + \tau(G_M^p)^2}{1 + \tau} \cos^2 \frac{\theta}{2} + 2\tau(G_M^p)^2 \sin^2 \frac{\theta}{2} \right). \quad (1.53)$$

Here, θ is the lab scattering angle, E and E' are the incident and scattered electron energy respectively. At low Q^2 , G_E^p , G_M^p and G_M^n are found to follow the dipole function

$$G_D(Q^2) = \left(1 + \frac{Q^2}{0.71} \right)^{-2} \quad (1.54)$$

where Q^2 is in GeV. The form factors are

$$\begin{aligned} G_E^p &= G_D, \\ G_M^p &= \mu_p G_D, \\ G_M^n &= \mu_n G_D. \end{aligned} \quad (1.55)$$

G_E^n and G_M^n can not be directly measured due to the lack of a free neutron target. They can, however, be less precisely accessed by subtracting the proton contribution in electron-deuteron scattering or by scattering neutrons off the atomic electrons. G_E^n is approximated by the Galster parameterization [6]

$$G_E^n = \frac{-\mu_n \tau G_D}{1 + 5.6\tau} \quad (1.56)$$

and is constrained by $G_E^n(0) = 0$.

1.5.2 Neutral Weak Form Factors

Figure 1.2 also shows the weak interaction between an electron and a proton via the exchange of a Z boson in an electron-proton scattering process. The amplitude for this interaction is given by

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} j^{Z\mu} J_\mu^Z \quad (1.57)$$

where

$$j^{Z\mu} = \bar{\psi}_e \gamma^\mu (g_V^e - g_A^e \gamma^5) \psi_e \quad (1.58)$$

is the electron current and

$$J_\mu^Z = \bar{\psi}_p \left(\gamma_\mu F_1^Z(Q^2) + \frac{i\sigma_{\mu\nu} q^\nu}{2m_p} F_2^Z(Q^2) + \gamma_\mu \gamma^5 G_A^Z \right) \psi_p \quad (1.59)$$

is the proton current with three form factors. G_A^Z is the axial form factor and F_1^Z , F_2^Z are the weak neutral form factors. These form factors can be written as the sum of form factors over the light quark flavors weighted by electromagnetic (Q^f) and weak charges (g_V^f, g_A^f).

$$G_{E,M}^{p,\gamma} = \sum_{f=u,d,s} Q^f G_{E,M}^f, \quad (1.60)$$

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$$G_{E,M}^{p,Z} = \sum_{f=u,d,s} g_V^f G_{E,M}^f, \quad (1.61)$$

$$G_A^{p,Z} = \sum_{f=u,d,s} g_A^f G_A^f. \quad (1.62)$$

Substituting Q^f , g_V^f and g_A^f one gets

$$G_{E,M}^{p,\gamma} = \frac{2}{3} G_{E,M}^u - \frac{1}{3} (G_{E,M}^d + G_{E,M}^s), \quad (1.63)$$

$$G_{E,M}^{p,Z} = \left(1 - \frac{8}{3} \sin^2 \theta_W\right) G_{E,M}^u - \left(1 - \frac{4}{3} \sin^2 \theta_W\right) (G_{E,M}^d + G_{E,M}^s), \quad (1.64)$$

$$G_A^{p,Z} = -G_A^u + G_A^d + G_A^s. \quad (1.65)$$

Invoking isospin symmetry, which assumes the properties of up (down) quarks in the proton being the same as down (up) quarks in the neutron, one gets

$$G^{u,p} = G_{E,M}^{d,n}, G^{d,p} = G_{E,M}^{u,n}, G^{s,p} = G_{E,M}^{s,n}. \quad (1.66)$$

The form factors of the neutron can now be written similarly to those of the proton above.

The neutral weak form factors of the proton and the neutron are then written in terms of the electromagnetic form factors as

$$G_{E,M}^{p,Z} = (1 - 4 \sin^2 \theta_W) G_{E,M}^{p,\gamma} - G_{E,M}^{n,\gamma} - G_{E,M}^s, \quad (1.67)$$

$$G_{E,M}^{n,Z} = (1 - 4 \sin^2 \theta_W) G_{E,M}^{n,\gamma} - G_{E,M}^{p,\gamma} - G_{E,M}^s, \quad (1.68)$$

$$G_A(Q^2) = G_A(0) \left(1 + \frac{Q^2}{M_A^2}\right)^{-2} \quad (1.69)$$

where $G_A(0) = -1.267 \pm 0.004$ and $M_A = 1.00 \pm 0.02$ GeV from [7],[8].

1.6 Parity Violation

A parity transformation inverts the spatial co-ordinates (i.e., $\mathcal{P}(x,y,z) = (-x,-y,-z)$). Until 1956 it was believed that all the known interactions were invariant under parity transformation. Familiar expressions of gravitational and electromagnetic forces which depend on the distance between the particles remain unchanged under the parity transformation. However, the weak interaction was found to violate parity i.e., the behavior of the weak interaction in the mirror worlds was different. For example, a screw with right handed threads advances in the direction of the thumb (say +Z direction) upon rotation. However, in a mirror world the same screw would have left handed threads and while the direction of rotation remains the same, the screw advances in -Z direction. If a screw were to have only right (left) threaded grooves then the right (left) handedness would be an intrinsic property of a screw. In other words, a particle with an intrinsic spin and a given handedness will behave differently in the mirror world, thus violating parity. Helicity reversal is thus equivalent to a parity transformation. This handedness for electrons is denoted by the term helicity defined as

$$h = \mathbf{s} \cdot \hat{\mathbf{p}} \quad (1.70)$$

where a positive (negative) helicity denotes a right (left) handed electron. Parity violation in beta decay was proposed in 1956 by T.D. Lee and C.N. Yang and almost immediately discovered by C.S. Wu *et. al.* in ^{60}Co [9]. Wu measured an asymmetry in the number of electrons emitted when the magnetic field was changed. In scattering experiments polarized electrons are scattered from unpolarized proton targets. The helicity of the electrons is then reversed which gives rise to an asymmetry discussed next.

1.6.1 Parity Violating Asymmetry

If $\mathcal{M}^\gamma$ and $\mathcal{M}^Z$ are the electromagnetic and weak neutral amplitude then the total electron-proton scattering cross section is proportional to the the square of the sum of these amplitudes.

$$\sigma_{total} \propto |\mathcal{M}^\gamma + \mathcal{M}^Z|^2. \quad (1.71)$$

Different cross sections are obtained when the helicity states of the incoming electrons are altered between left and right. This is because of the parity violating nature of the weak interaction which changes the value of $\mathcal{M}^Z$ depending on the helicity state of the electron. The difference in the cross sections is defined as the parity-violating asymmetry and is given by

$$A_{PV}^{ep} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \quad (1.72)$$

where the subscripts L (R) denote the left (right) helicity state of the incident electrons. In terms of the amplitudes the parity violating asymmetry can be written as

$$A_{PV}^{ep} = \frac{|\mathcal{M}^\gamma + \mathcal{M}_{\mathcal{R}}^Z|^2 - |\mathcal{M}^\gamma + \mathcal{M}_{\mathcal{L}}^Z|^2}{|\mathcal{M}^\gamma + \mathcal{M}_{\mathcal{R}}^Z|^2 + |\mathcal{M}^\gamma + \mathcal{M}_{\mathcal{L}}^Z|^2}. \quad (1.73)$$

A carefully worked out expression of this parity violating asymmetry in terms of Sachs form factor is given by [10]

$$A_{PV}^{ep} = \left[\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \right] \left(\frac{\epsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1 - 4\sin^2\theta_w)\epsilon' G_M^\gamma G_A^Z}{\epsilon(G_E^\gamma)^2 + \tau(G_M^\gamma)^2} \right) \quad (1.74)$$

where $\tau = Q^2/4M^2$, $\epsilon = [1 + 2(1 + \tau)\tan^2(\theta/2)]^{-1}$, $\epsilon' = \sqrt{\tau(1 + \tau)(1 - \epsilon^2)}$ are the kinematic variables and $Q^2 \equiv -q^2 > 0$ is the four momentum transfer squared. In the limit $Q^2 \rightarrow 0$, $G_E^Z = 1 - 4\sin^2\theta_W$ or the proton's weak charge. Using expressions 1.67-1.69,

1.72 can be re-written in terms of electromagnetic, weak neutral and strange form factors of the proton and the neutron as

$$A_{PV}^{ep} = - \left[\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \right] (A_p + A_n + A_s + A_e) \quad (1.75)$$

where

$$A_p = 1 - 4 \sin^2 \theta_W = Q_W^p \quad (1.76)$$

$$A_e = Q_W^e \frac{\epsilon G_E^{\gamma p} G_E^{\gamma n} + \tau G_M^{\gamma p} G_M^{\gamma n}}{\epsilon (G_E^{\gamma p})^2 + \tau (G_M^{\gamma n})^2} \quad (1.77)$$

$$A_s = Q_W^s \frac{\epsilon G_E^{\gamma p} G_E^s + \tau G_M^{\gamma n} G_M^s}{\epsilon (G_E^{\gamma p})^2 + \tau (G_M^{\gamma p})^2} \quad (1.78)$$

$$A_n = Q_W^n \frac{\epsilon' G_A^{Zp} G_M^{\gamma p}}{\epsilon (G_E^{\gamma p})^2 + \tau (G_M^{\gamma p})^2}. \quad (1.79)$$

Here Q_W^f is the weak charge of the fermion f . A simpler equation for A_{PV} now reads as

$$A_{PV}^{ep} = - \frac{G_F}{4\pi\alpha\sqrt{2}} [Q^2 Q_W^p + F(Q^2, \theta)] \quad (1.80)$$

where $F(Q^2, \theta)$ is the total hadronic part of the parity violating asymmetry. Furthermore, at small forward scattering angles and low momentum transfer ($\theta \rightarrow 0, Q^2 \rightarrow 0$), $\epsilon \rightarrow 1$ and $\tau \rightarrow 1$. A_{PV}^{ep} can now be written as

$$A_{PV}^{ep} = - \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} [Q_W^p + Q^2 B(Q^2)] \quad (1.81)$$

where the B term is the hadronic form factor term. The size of the asymmetry at $Q^2 \sim 0.025 \text{ (GeV/c)}^2$ and assuming $Q_W^p \sim 0.007$ is about 2×10^{-7} .

The next chapter will describe the experimental setup to measure this parity violating physics asymmetry. Chapter 3 describes the target system, which was the primary hardware

responsibility of this author, used in the Qweak experiment. Chapter 4 will present Monte-Carlo simulation work done by this author. A detailed statistical analysis for the extraction of the physics asymmetry from the measured asymmetry will be discussed in chapter 5. The determination of the proton's weak charge will be done in chapter 6.

CHAPTER 2

THE QWEAK APPARATUS

2.1 Overview

Figure 2.1

Schematic of elastic scattering of polarized electrons from a proton target.

An electron with energy (E) and momentum ($\mathbf{p}$) scatters off a proton conserving the total energy of the system. E' and $\mathbf{p}'$ are the energy and momentum of the electron after scattering. The energy transfer in the process $\nu = E - E'$ and the three momentum transfer $\mathbf{q} = \mathbf{p} - \mathbf{p}'$. Then the four momentum transfer $Q^2 \equiv -q^2 = -(\nu^2 - \mathbf{q}^2) \geq 0$. $S(\pm)$ are the opposite electron helicity states and θ is the scattering angle.

The Qweak experiment has measured the parity violating asymmetry (A_{PV}) in elastic electron proton scattering at very small four momentum transfer squared (Q^2). This was done by scattering longitudinally polarized electrons of opposite helicity states off an unpolarized liquid hydrogen target and measuring the cross sections of elastically scattered

electrons (Figure 2.1) at $Q^2 = 0.025 \text{ (GeV/c)}^2$. This gives rise to an asymmetry given by Equation 1.72.

As shown in Equation 1.81, the weak charge of the proton (Q_W^P), to first order, is proportional to the parity violating asymmetry. A precision determination of Q_W^P entails precise measurements of the parity violating elastic $\vec{e}p$ asymmetry, the beam polarization and the four momentum transfer squared while simultaneously suppressing and measuring the backgrounds, false asymmetries and various systematic effects. The hadronic contribution to the asymmetry, $B(Q^2, \theta)$, is small at our kinematics and is constrained by the previous Parity Violating Electron Scattering (PVES) data on hydrogen, deuterium and helium at Q^2 up to 0.63 (GeV/c)^2 . To determine Q_W^P to 4% combined statistical and systematic uncertainties it was proposed to constrain the total error on the asymmetry to 2.5% [10].

Measuring a very small expected asymmetry ($\sim -220 \text{ ppb}^1$) with a very high precision ($\sim 5 \text{ ppb}$) poses enormous challenges on restricting statistical and systematic errors. To carry out such a precision experiment it was required to have

- High detected rates of elastically scattered electrons. This was achieved by producing polarized electrons at the highest beam current ever used by any experiment at Jefferson lab on the world's highest power cryogenic target to date.
- Low noise from the target and the electronics used in the experiment. The Qweak target despite being the highest power is also the least noisy cryogenic target ever used in a parity-violation experiment. Custom built low noise electronics were used in all measurements performed by the experiment to provide a large signal to noise ratio. The detectors themselves were built to operate in a harsh radiation environment and yet provide stable response over a wide solid angle acceptance.
- Systematic errors suppressed and well measured. This was accomplished by minimizing and correcting for helicity correlated beam property changes, backgrounds

¹parts per billion

from target cell windows and other sources. Precision polarimetry yielded sub-percent level polarization measurements.

- Precise measurement of Q^2 . This was done by using suitable collimators and by precisely measuring the beam energy and the scattering angle of elastically scattered electrons using a dedicated system of various tracking detectors.

Figure 2.2 shows a CAD layout of a partially shielded Qweak apparatus which was installed in Hall C of Jefferson lab in Newport News, Virginia. The experiment ran in two modes: current or integrating mode and counting or event mode. The beam current was as high as $180\ \mu\text{A}$ in the integrating mode and as low as $100\ \text{pA}$ in the event mode. In both the operational modes the scattered electrons passed through a series of three collimators which defined the acceptance. A magnetic field then bent and focused the scattered electrons by about 14° on to the detectors. Integrating mode used Čerenkov quartz bar detectors to measure the asymmetry, and counting mode used drift chambers, trigger scintillators and the Čerenkov quartz bars to measure the scattering angle and Q^2 of elastically scattered electrons. Several beam line devices were used to monitor beam energy, current, position and polarization.

After almost a decade of planning and preparations, the commissioning of the experiment started in July of 2010 followed by the Commissioning Run and two active data taking periods: Run 1 (Feb 2011- May 2011) and Run 2 (Nov 2011- May 2012). The operating parameters for the Run 1 of the Qweak experiment are shown in Table 2.1. The major components of the experiment are described in the upcoming sections.

Figure 2.2

CAD drawing of the Qweak apparatus.

Partial shielding is shown along with major components. See text for details.

Table 2.1

Basic Run 1 parameters

Parameter	Value
Beam Energy	1160 MeV
Beam Polarization	88 %
Target thickness	34.4 cm
Average scattering angle	7.9°
Scattering angle acceptance	5.8° - 11.6°
ϕ acceptance	49% of 2π
Solid Angle	$\Delta\Omega = 43$ msr
Acceptance averaged Q^2	$0.025 (\text{GeV}/c)^2$

2.2 Continuous Electron Beam Accelerator Facility (CEBAF)

Figure 2.3

Schematic of the CEBAF and the experimental halls.

CEBAF of Jefferson lab is a re-circulating linear accelerator based on superconducting radio frequency (RF) technology to accelerate electrons. Prior to the ongoing upgrade to double the energy, the maximum energy electrons could be accelerated to was close to 6 GeV. The accelerator consists of two accelerating regions called the LINACs (Linear Accelerators) and two bending regions each with 4 or 5 recirculating arcs (see Figure 2.3 [11]). The beam could then be delivered to one or all three experimental halls. Electron beam accelerated to 1.16 GeV was delivered for the Qweak experiment.

2.2.1 Polarized electron source

Polarized electrons in CEBAF are produced from strained-superlattice gallium arsenide (GaAs) by photoproduction using a circularly polarized laser. In an unstrained GaAs semiconductor, electrons in the valence band can be optically pumped to the conduction band. The electrons in the conduction band still need about 4 eV of energy to escape the crystal lattice. Coating the surface of GaAs, which otherwise has positive electron affinity, with Cesium gives negative electron affinity to the crystal [12]. Strained GaAs consists of a layer of GaAsP grown in between two layers of GaAs. This layer of GaAsP exerts mechanical strain on its neighboring GaAs layers due to lattice mismatch, perturbing the lattice potential. The mechanism of photo-production of polarized electrons from GaAs using a polarized laser beam is shown in Figure 2.4 [11].

The use of strained-superlattice GaAs boosted electron polarization from 75% (for only strained GaAs) to >85%. The strained-superlattice GaAs also increased the Quantum efficiency (QE, probability of electron emission per photon) to about 0.8%. The laser spot on the photocathode was moved when the QE at a particular spot fell below 0.3%.

The strained-superlattice GaAs photocathode was placed at the end of an inverted insulator inside a vacuum chamber ($10^{-10} - 10^{-11}$ Torr) [13]. Upstream to the gun chamber was a preparation chamber to prepare samples without deteriorating the vacuum in the gun chamber. This load locked inverted electron gun was operated at 130 kV (the nominal operating point was 100 kV prior to Qweak) for the experiment. The photocathode lifetime was prolonged by reducing ion back bombardment and field emission, and by improving the transmission through the injector apertures at high beam currents. During Run 2 of the

Figure 2.4

Schematic of energy levels in GaAs.

Unstrained GaAs has degenerate $P_{3/2}$ states with $\pm\frac{1}{2}$ and $\pm\frac{3}{2}$ spin states. The solid and dashed lines indicate optical excitation with left or right circularly polarized photons respectively. In a strained GaAs crystal the degeneracy of the $P_{3/2}$ state is broken and only transitions from $m_j = \pm\frac{3}{2} \rightarrow m_j = \pm\frac{1}{2}$ are allowed. Electrons of opposite helicity are emitted when photons of opposite circular polarization are incident on the strained crystal.

experiment the laser spot size was changed to $800\text{ }\mu\text{m}$ from $500\text{ }\mu\text{m}$ to enhance the lifetime of an illuminated spot by as much as 2.5 times and also to reduce space charge forces.

Figure 2.5

Schematic of the CEBAF laser table.

Hall C uses a fiber laser of wavelength 1560 nm whose frequency is then doubled to 780 nm . The polarized beam combining cube (PCC) combines lasers from all three halls before the Pockels cell (PC). The PC changes the linear polarization of the laser beams to circular polarization. Pseudo random helicity signals control the high voltage switch of the Pockels cell and flip the circular polarization of the incident laser beam 960 times a second. The insertable half wave plate (IHPW) and rotatable half Wave plate (RHWP) were used to minimize helicity correlated false asymmetries.

Figure 2.5 shows a schematic of the CEBAF laser table. Three independent circularly polarized laser beams, each at a repetition frequency of 499 MHz and offset in phase by 120° for each of the three halls, were incident on the photocathode. The laser beams are initially linearly polarized and it is only after they pass through the Pockels cell that they gain circular polarization. A Pockels cell is aligned such that its birefringent axis is at an angle of 45° to the laser beam axis. The birefringence of the Pockels cell is proportional

to the applied electric field (2.5 kV) which can be reversed to change the helicity of the photoelectrons produced. The helicity signal in the form of a pulse of 0 V or 1 V acts as a switch to reverse the polarity of the applied electric field to the Pockels cell. Based on the helicity signal (0 V or 1 V) the circular polarization of the laser beam changes (right or left) thus controlling the helicity (negative or positive) of the photoelectrons. A new helicity switch was installed for the Qweak experiment to flip the helicity at 960 Hz [13] instead of the nominal 30 Hz. This signal produced a helicity pattern of four states (+ − − + or − + + −) called a quartet where the first and the last state had the same helicity. The first window in any quartet was chosen pseudo-randomly by a 30-bit pseudo random number generator to ensure cancellation of the ~ 40 ppb false asymmetry generated by the helicity signal marking the start of a quartet. The reported helicity signal was further delayed by 8 patterns than the actual helicity signal to cancel any electronic pickup in the counting house.

Linearly polarized laser light passed through an insertable half wave plate (IHWP) that flipped the polarization by 180° , reversing the polarization of the laser beam that reached the Pockels cell. Data were taken with about every eight hours of IHWP in followed by about eight hours of IHWP out configuration. Each such eight hour block of data is called a slug. Data from IHWP in and out configurations were averaged to monitor and remove Helicity Correlated Beam Asymmetries (HCBA). The Rotatable Half Wave Plate (RHWP) is another birefringent control to minimize HCBA. A RHWP minimizes HCBA by rotating the incident polarization axes such that they are at an angle of 45° to the analyzing power of the photocathode for each of the two states of the PC.

Additionally, there were two Wien filters and two solenoids in the injector which precessed the electron spin before the beam was delivered to the experimental Hall. The static electric and magnetic fields in a Wien filter let the electrons pass without any deflection but precess their spin around the magnetic field. The electron beam sees the vertical and the horizontal Wien filters respectively which align the spin of the beam in the required orientation. The two solenoids after the vertical Wien filter can each add about 45° of rotation to the electron spin. This setup can serve as a slow helicity reversal by switching the direction of rotation induced by the solenoids. The Wien flip (right to left or vice versa) took several hours hence was done only about once a month to cancel out helicity correlated beam spot size effects in the measured asymmetry.

The size of tolerable errors on helicity correlated beam properties for the experiment and the measured values for Run 1 are shown in Table 5.3. A small amount of linear polarization in the laser beam creates false asymmetries like charge asymmetry (unequal amount of charge in opposite helicity states). Active charge feedback was run continuously to minimize charge asymmetry during the entire experiment to meet the goal of < 0.1 parts per million (ppm) for the charge asymmetry.

Position feedback was not run actively in the experiment. Adiabatic damping (decrease in beam emittance during acceleration) in the accelerator, which was used in previous parity-violation experiments like G0 [14] and Happex [15], was not efficient enough to limit helicity correlated position differences at the target within the specs of the experiment. Therefore, a manual feedback system using helicity magnets was used in the injector for position feedback. With the help of these magnets the position differences were can-

celed out to acceptable limits by moving the beam vertically and horizontally in a helicity correlated manner. The injector also made use of custom built, low noise 18 bit Analog-to-Digital Converters (ADCs) designed and built at TRIUMF [16] for the Qweak experiment to read out the injector data at 960 Hz of helicity reversal.

2.2.2 RF cavities and beam acceleration

After acceleration to 62 MeV in the injector, the polarized electron beam was then transported to the superconducting RF LINACs. Each LINAC had 20 cryomodules capable of accelerating the electrons up to 548 MeV (during Qweak) and with five passes a final energy of 6 GeV could be achieved. Each cryomodule had eight 5 or 7 cell cavities made from pure Niobium. Each cavity was about 0.5 m long and could provide an average accelerating gradient of about 7.5 MV/m. 5 kW klystrons generated RF at 1497 MHz that propagated through a waveguide to the cavities. The entire beam with electrons of various energies and freshly injected 62 MeV electrons were accelerated to maintain the same phase in the beam. The Qweak experiment mostly received one pass beam except for a brief period at the start of the Run 2 when two pass beam was delivered.

2.3 Beam line monitors

Both the magnitude and the position of the polarized electron beam had to be known within tight specs of the experiment (see Table 5.3). This was accomplished by using a large number of precision devices in the injector, transport lines and in the experimental hall to monitor beam current and positions.

2.3.1 Beam Charge Monitor (BCM)

The Qweak experiment needed a linear, precise, and low noise measurement of the beam charge incident at the target. The main detector signals were charge normalized to nullify the fluctuations in the signal due to the changes in the beam current. To serve this purpose, six cavity type BCMs were installed in the beamline. BCM 1 & 2 used analog receivers and were used in the Run 1. The other 4 BCMs utilized digital receivers which were not ready until Run 2. One of these cavities: BCM 8, was the primary BCM used in Run 2 for charge normalization of the main detector signal. These cylindrical stainless steel cavities were used in resonant TM 010 mode at 1497 MHz such that the signal output of the cavity was proportional to the beam current in the cavity. They were placed in ambient housing maintained at 110 °F. For the beam currents in the range of 1-180 μA the BCMs were calibrated against a Parametric Current Transformer device [17] called the Unser monitor, whereas for the low beam current measurements (10 nA - 1 μA) a Faraday cup was used. Unfortunately, the Unser monitor offset is subject to slow drifts, and so can not be used continuously for normalization whereas the Faraday cup can only be used invasively while stopping beam to the other Halls. The Unser monitor was calibrated for absolute current measurements before the experiment and the BCMs were calibrated periodically using the Unser during the experiment. During a BCM calibration, beam was ramped in steps of 20 μA from zero with a beam off period in between any two beam ramp periods, with each beam on and off period lasting about 1.5 minutes. The beam off periods are vital for they provide the linear offset of the Unser monitor and the beam on periods give the slope of the BCM response vs. the Unser response for the BCM calibrations.

The contribution of the beam current measurement to the main detector asymmetry width was measured by the size of the width of the differences of the charge asymmetries of the two nominally identical BCMs. This difference is referred as the *BCM double difference* (BCMDD). In this BCMDD variable, the correlated signal component cancels out leaving only the uncorrelated monitor noise. The difference of the asymmetry of BCM 1 & 2 had a width of about 110 ppm (Run 1) whereas it was only about 60 ppm for BCM 7 & 8 (Run 2). Ideally, the BCMDD width should be zero but the presence of noise and non-linearity in the BCM chain (monitor & electronics) give rise to a non-zero width. The effect of this width is the enlargement of the main detector asymmetry width; measured to be about 235 ppm during Run 1 and ~ 225 ppm during the Run 2.

2.3.2 Beam Position Monitor (BPM)

Twenty four Switched Electrode Electronics (SEE) BPMs [18] were used in the injector beamline and twenty three along the Hall C line to monitor the beam position. A SEE BPM is a cylindrical cavity with four antennae rotated to 45° from the vertical in the plane perpendicular to the beam direction. These antennae pick up the RF signals from the incoming electron beam, the amplitudes of which are proportional to the beam position. The signals from the four antennae are then used to determine the beam position. A weighted combination of five BPMs upstream of the target was used to calculate the beam positions and angles at the target. A sixth BPM 3c12X, placed at the highest dispersive region of the arc, was often used as a monitor of beam energy change. Data collected during the Qweak experiment indicated the position resolutions of these SEE BPMs was about $1\mu\text{m}$

[19]. More accurate beam positions were provided by super harp scanners [20]. A super harp has three wires that are moved across the path of the beam and can only be used in beam currents $\simeq 6 \mu\text{A}$.

2.3.2.1 Beam energy

The absolute beam energy measurement was done using the beamline monitors and arc (bending region) dipoles. The eight dipoles in an arc were energized with quadrupoles in this region turned off and the super harps upstream (BPM 3c07) & downstream (BPM 3c17) of the maximum dispersive region (BPM 3c12) provided the beam positions. The dispersion during the energy measurements was 12 cm/% and 4 cm/% otherwise. The momentum is then given by

$$p = \frac{e}{\Delta\theta} \int Bdl \quad (2.1)$$

where θ is the bending angle through the Hall C arc and $\int Bdl$ is the magnetic field over the electron path. The measurements done during the Run 1 gave an average of $1160.4 \pm 1.7 \text{ MeV}$.

2.4 Beam Polarimetry

The uncertainty in the beam polarization is one of the most challenging systematics for the Qweak experiment. With the goal of less than 1% uncertainty in the polarization measurement, two independent polarimetry schemes were used: Møller polarimetry and Compton polarimetry.

Figure 2.6

Schematic of the Basel- Hall C Møller polarimeter.

Only quadrupole magnets Q1, and Q3 were used in the Qweak experiment, Q2 was installed as a part of the 12 GeV upgrade program. See text for details.

2.4.1 Basel-Hall C Møller polarimeter

The Hall C Møller polarimeter [21] is based on the Møller scattering of a polarized electron beam from the electrons in a polarized target. This is a well-understood device which has delivered reliable polarization measurements at the percent level in Hall C for almost two decades. The polarimeter consists of a superconducting solenoid that produces a magnetic field of 3.5 T which polarizes atomic electrons in a thin iron foil out of the plane normal to the beam direction. In addition, the polarimeter has a series of movable collimators, magnetic quadrupoles and electron detectors (Figure 2.6).

The cross section of the interaction is given by

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_0} \left[1 + P_t^{\parallel} P_b^{\parallel} A_{zz}(\theta) \right] \quad (2.2)$$

where $P_t^{\parallel}$ & $P_b^{\parallel}$ are the polarization of the target and beam respectively, $A_{zz}(\theta)$ is the analyzing power, and $\frac{d\sigma}{d\Omega_0}$ the unpolarized cross section. An asymmetry ($A_{Møller}$) was formed as the ratio of the difference and the sum of the cross sections at the opposite beam polarization states and is equal to

$$A_{Møller} = A_{zz}(\theta) P_t^{\parallel} P_b^{\parallel} \quad (2.3)$$

The analyzing power, expressed in terms of the center of mass angle is

$$A_{zz}(\theta) = -\sin^2 \theta \frac{(8 - \sin^2 \theta)}{(4 - \sin^2 \theta)^2} \quad (2.4)$$

For $\theta = 90^\circ$ $A_{zz}(\theta) = -7/9$.

The saturating magnetic field provided a known, longitudinal polarization of about 8% averaged over all the atomic electrons in the target foil. The foil was oriented normal to

the direction of the polarized electron beam. The quadrupoles Q1 and Q2 were used to horizontally focus and defocus the Møller electrons, and collimators were used to select scattered electrons at a particular kinematics ($\theta_{CM} \sim 90^\circ$). Finally, the scattered electrons were detected in coincidence using a set of scintillation counter hodoscopes and lead glass counters placed on opposite sides of the beam line. The beam polarization can be extracted precisely ($\lesssim 1\%$ uncertainty) once the target polarization, acceptance and the asymmetry are known.

The Møller polarimeter was used 2-3 times a week in both IHWP in and out configuration and each measurement lasted several hours. However, the Møller polarimeter was invasive to the main measurement and could only be used at beam currents $< 2 \mu\text{A}$. To have non-invasive, continuous polarization measurements at high beam currents a Compton polarimeter was also developed specifically for this experiment to augment the information from the Møller.

2.4.2 Compton polarimeter

The Hall C Compton polarimeter bent the polarized electron beam ~ 57 cm vertically to a Compton laser table using dipole chicane magnets D1 and D2 (see Figure 2.7). The laser table consisted of a 10 W (532 nm) continuous wave green laser locked to a Fabry-Pérot cavity with gain $\simeq 200$ and a half wave plate to produce circularly polarized photons.

Figure 2.7

Schematic of Hall-C Compton polarimeter.

The blue line is the electron beam and the red curve is Compton scattered photons.

The polarized electron beam Compton scattered from the circularly polarized laser light in the cavity. An asymmetry was formed as

$$A_{measured} = \frac{N_L - N_R}{N_L + N_R} \quad (2.5)$$

where N_L and N_R were the detector rates measured in the opposite laser beam polarization states. The backscattered photons and electrons were measured in separate detectors to give two quasi-independent measurements of the beam polarization. Dipoles D3 and D4 bent the beam back to the beamline.

A lead-tungstate (PbWO_4) crystal, water cooled to 14°C , was used to detect the photons that underwent Compton scattering with the incoming electron beam. The photon detector was unusually sensitive to the beam tune and provided a very limited amount of useful data.

The Compton scattered electrons were spatially separated from the unscattered beam by dipole D3 and detected by four radiation hard diamond micro-strip electron detectors

right in front of D4. The maximum electron displacement and the location of the Compton edge (maximum energy transferred by a photon during a Compton scattering) were at 17 mm and 23 mm respectively from the beam path of 1.16 GeV electrons. This required radiation hard detectors that could perform in a harsh radiation environment of ~ 2.5 kRad/hr. These diamond plates were artificially grown using chemical vapour deposition (CVD) [22]. Each detector, on the side facing scattered electrons, had a set of 96 metal strips with a pitch of $200\text{ }\mu\text{m}$ ($180\text{ }\mu\text{m}$ metal and the rest gap) and the opposite side had only a metal electrode ($100\text{ }\mu\text{m}$ thick successive depositions of Ti, Pt and Au) covering the entire diamond surface [23]. The 48 even and 48 odd strips were connected separately to two high density connectors [24]. The detector assembly sat in vacuum and at an angle of $\sim 10.2^\circ$ to the vertical such that each detector plane was normal to the incoming scattered electrons. A motion system lowered the assembly within 7 mm of the main electron beam and retracted into a shielded garage when not in use. During the operation, a bias voltage of -400 V was given across each detector plane and the signals were fed to a custom built chain of 48 low noise pre-amplifiers, shaping amplifiers and discriminators also called Qweak Amplifier Discriminator (QWAD) cards [16]. The processed signals from the QWADs were then handled by the CEBAF online data acquisition (CODA, see section 2.14).

The energy of the Compton scattered electron was determined from the location (distance) of the electron hit in one of the 96 strips and the detector location. QED provides precise values of the Compton asymmetry [25] as a function of momentum. Asymme-

Figure 2.8

Preliminary polarization values from the Compton electron detector.

The relative shift in the Møller and Compton polarization was due to a faulty quadrupole in the Møller polarimeter.

try was experimentally determined using Equation 2.5. Fitting the calculated asymmetry A_{QED} to the measured asymmetry $A_{measured}$ gives the electron polarization P_e as

$$A_{measured} = P_e P_\gamma A_{QED} \quad (2.6)$$

where P_γ is the laser polarization.

The electron detector was commissioned in Run 1 and has polarization measurements only from April 2011, towards the end of Run 1. However, it provided a continuous measure of the absolute beam polarization from that point on, accurate to $\lesssim 0.6\%$ (statistical) per hour. Typical polarizations of 87% were reported during the experiment (Figure 2.8 [26]) and comparison with Møller polarization measurements helped identify issues with the Møller polarimeter in Run 1. More details on the Compton electron detector design, commissioning and performance can be found in Amrendra Nayaran's thesis [27].

2.5 Beam modulation

Changes in the beam properties (transverse position, angle and energy) at the time scale of the helicity reversal can induce false asymmetries in the detectors. These changes were suppressed in the injector and by the 8-fold azimuthal symmetry of the detectors, and any remaining HCBA was measured and corrected in the asymmetry data. The correction is given by

$$A_{false} = - \sum_i \frac{\partial A}{\partial \chi_i} \Delta \chi_i \quad (2.7)$$

where $\frac{\partial A}{\partial \chi_i}$ are the sensitivities of the measured detector asymmetries to the helicity correlated beam parameters: i = positions (X, Y), angles (X', Y') and energy (E) at the target, and $\Delta \chi_i$ are the measured helicity correlated beam parameter differences.

Detector sensitivities can be determined from natural beam motion or by driven beam motion. For the former, the beam positions, angles and energy at the target can be used as independent variables to extract sensitivity slopes. This is essentially a linear regression method where the measured asymmetry assumes linear dependence on the beam positions, angles, and energy to extract the sensitivity slopes. From the slopes and the differences of helicity correlated beam parameter differences, the correction to the measured asymmetry can be determined using Equation 2.7.

The same can be done by deliberately changing the beam parameters (X, Y, X', Y' & E) independently to determine the detector sensitivities. The driven motion system can yield more accurate detector sensitivities to the beam parameters because they can be highly correlated, and may not be fully decoupled by linear regression of natural beam motion. In the Qweak experiment beam modulation was done using air-core dipoles for the position and angle modulation and an RF cavity for the energy modulation. GEANT3 simulations of the main detector energy sensitivity done by this author are presented in Section 4.3.

The beam modulation was actively run for most of Run 1 and 2. Each cycle of driven motion parameter modulation took about 320 seconds: 4s for each parameter modulation followed by a gap of about 50 s for reconfiguration. Each five parameter beam modulation cycle took 6.25%/cycle of the production running time. The Run 1 HCBA corrections used in this dissertation are based on natural beam motion and will be discussed later in detail in Section 5.2.1.5. More details on the beam modulation and analyses can be found in Joshua Hoskins' dissertation [28].

2.6 Target

One of the most challenging aspects of the experiment was the liquid hydrogen target. A 35 cm long liquid hydrogen target was designed [29],[30] for the experiment to operate at an incident beam current up to 180 μA and simultaneously limit the target noise to less than 50 ppm, making the Qweak target the world's highest power and the least noisy cryogenic target. Also, a set of dummy targets of various thicknesses were used to measure the background and to carry out other ancillary measurements. A detailed description of the elements of the Qweak target system and the measured performance is given in Chapter 3.

2.7 Collimator system

The guiding principles for the collimator design were to minimize the uncertainty in Q_w^p [31] as well as to suppress backgrounds from reaching the detectors, ultimately selecting elastically scattered electrons in the angular range of $6^\circ - 12^\circ$ onto the detectors. A set of three collimators (Figure 2.9): two clean up collimators surrounding a defining collimator, was used in the experiment.

Each collimator was made of Pb (95.5%) and Sb (4.5%) with eight symmetric apertures. The first collimator was 15.24 cm thick and centered 74.25 cm downstream of the liquid hydrogen target center. The center of the acceptance defining 15 cm thick collimator was placed 271.64 cm downstream of the target center. It had eight apertures of area $\sim 400 \text{ cm}^2$ each. The downstream face of this collimator defined the angular acceptance of 4% of π in theta and 49% of 2π in phi i.e., scattering angle of $6^\circ - 12^\circ$ and a solid angle of 43 msr

Figure 2.9

CAD drawing of the Qweak triple collimator system.

Beam direction is from right to left. Part of the target scattering chamber is shown on the right of the first collimator. Also shown are the upstream luminosity monitors, horizontal drift chambers, part of the magnet and lead lintels in it, and shielding blocks (in yellow).

at the main detectors. The third collimator was 11.2 cm thick and was placed 381.9 cm downstream of the target center. The first and third collimators had apertures larger than the second collimator so as not to define the acceptance.

2.8 Co-ordinate System & Magnetic Spectrometer

The Qweak co-ordinate system is described in Figure 2.10. The Qweak Toroidal (QTor) magnetic spectrometer was used to focus the elastically scattered electrons emerging from the collimators onto the main detector. A power supply provided 8.9 kA of current at 123 V to produce a $\int Bdl \sim 0.89$ T-m seen by the scattered electrons. The magnet coils were placed in 8 symmetric octants. The first fiducial measurements and field mapping of the spectrometer was done at MIT-BATES [32] (Figure 2.11:left). It was disassembled, sent to Jlab where it was reassembled (Figure 2.11:right) and the upstream half of the magnet was mapped again.

The magnetic field bent the lower energy inelastic electrons radially away from the main detector bars and low momentum particles with positive charge were bent inwards and were prevented by the detector hut (Section 2.10) from reaching the main detectors. Low energy Møller electrons that made it through the collimator openings were easily swept away by the magnetic field. The electron profile entering the magnet from the collimator system was focused radially but defocused azimuthally, hence a moustache shaped electron envelope 10 cm tall and 200 cm wide was incident on each of the main detectors (Figure 2.12).

Figure 2.10

The Qweak co-ordinate system.

Two rectangular co-ordinate systems were used in the experiment: a local one for the main detectors and a global one for everything else. The right handed global co-ordinate system had its origin at the center of the Qweak Toroidal (QTor) magnetic spectrometer, with its X axis to beam left, Y axis vertically up and Z axis along the beam direction. The local co-ordinate system also had its origin at the QTor center. The main detector plane was 570.625 cm downstream of QTor center. In the local coordinate system, X axis was radially outward from the beamline and Y axis along the length of the bar and Z axis along the beam direction. Main detectors (MDs) were placed in eight octants named from 1 to 8. Each octant had its corresponding MD bar i.e., beam left octant had MD1. Photomultiplier tubes (PMTs) at the end of each MD bar were named $\pm$ as shown. QTor also had eight coils (not shown in the figure) which were labeled from 2 to 9. Coil 2 was placed in between octant 3 and 4 ($\phi = 102.5^\circ$) and the numbering of coils increased clockwise. Two rotatable tracking packages named package 1 and package 2 were parked in octant 1 and octant 5 respectively. These packages were retracted out of the acceptance during the current mode operations but inserted in during the event mode running.

Figure 2.11

The Qweak toroidal magnetic spectrometer.

Left: Being mapped at MIT. Right: In Hall C.

Since the detectors were immobile except over a limited range for initial manual alignment, the magnetic field of the spectrometer had to be changed to focus either elastic or inelastic electrons on to the detectors. This was done by setting the spectrometer at 8921 A for the elastic and at 6700 A for the inelastic running in Run 1. For the Run 2 the beam energy was changed to 1158 MeV so the spectrometer was run at 8900 A for the elastic asymmetry measurements.

While the QTor performed well during the entire running period of the Qweak experiment it was occasionally plagued with diode and transistor failures, water leakage in the power supply and other regulation control problems. One such operational failure cost about a month of running early in Run 1. Analyses have revealed that there were periods when the spectrometer current briefly changed on its own by $\sim 0.3\%$ during Run 2 chang-

ing yields in the main detector by $\sim 8\%$, but these changes had negligible impact on the asymmetry measurement.

2.9 Main detectors

A set of eight radiation hard synthetic quartz bars at a fixed radius around the beamline formed the main detector system (Figure 2.12:left). Two Spectrosil 2000 bars [33], non-scintillating and low luminiscent, of dimensions $100 \times 18 \times 1.25$ cm were glued with UV transparent SES-406 [34] to form a single 2 m long main detector bar. The bars were at a radius of 335 cm from the beam line in a Ferris wheel-like aluminum support frame located 5.78 m downstream of the target.

Čerenkov radiation is produced in a medium when the speed (v) of a particle in the medium exceeds the speed of light. A cone of light is emitted with a defined Čerenkov polar angle ($\theta_c(E)$) given by

$$\cos \theta_c(E) = \frac{1}{\beta \eta(E)} \quad (2.8)$$

where $\eta(E)$ is the index of refraction of the medium as a function of energy of the emitted photon and $\beta = \frac{v}{c}$. For fused silica the index of refraction is 1.488 at 300 nm. Čerenkov threshold is when $\theta_c = 0$, i.e., $\beta = \frac{1}{\eta} = 0.672$ and the Čerenkov threshold energy is given by

$$E_{th} = \sqrt{p^2 + m_e^2} = \sqrt{(m_e \gamma \beta)^2 + m_e^2} = m_e \sqrt{\frac{n^2}{n^2 - 1}} = 0.69 \text{ MeV} \quad (2.9)$$

where p is the electron momentum and m_e is the mass of the electron at rest. At Qweak kinematics, the scattered electrons that reach the quartz bars have $p \sim 1100$ MeV, $\beta \simeq 1$, hence the Čerenkov angle

$$\theta_c = \cos^{-1} \left(\frac{1}{\eta\beta} \right) = 47.78^\circ. \quad (2.10)$$

It was found during Run 1 that the neutral background was much higher than expected (~ 10 times) and so 2 cm thick lead tiles were installed in front of the main detector bars. The Pb pre-radiators effectively quenched the signal from low energy neutral backgrounds. The $\vec{e}p$ elastic electrons created electromagnetic showers in the pre-radiators boosting the signal in the main detector, but at the price of worse detector resolution from statistical fluctuations in the shower.

Figure 2.12

The main detector system.

Left: CAD layout of MD system in the Ferris wheel looking downstream. MD1 is in beam left octant. MD9 is a background detector and is discussed in Section 2.9.1. Right top: Actual main detector bars with lead tiles. Right bottom: Profile of scattered electrons on MD7.

Both ends of each main detector bar had 20 cm long, 1.25 cm thick and 18 cm wide lightguides, also made of Spectrosil 2000 and coupled to a 130 mm, model 9312WKB photo multiplier tube (PMT). Each PMT [35] had a multialkali S20 (Na2KSb:Cs) photocathode, UV transmitting glass windows and 10 stages of high gain, high stability SbCs dynodes. The PMTs were sensitive to light in the wavelength range of 200-900 nm with a maximum quantum efficiency of about 23% at 270 nm ([36] pg 121). GEANT4 [37] simulations predicted ~ 260 photoelectrons would be produced per event by the 1.16 GeV electron beam in the quartz bar. However, only 80 - 100 photoelectrons per event were observed during the experiment. The PMTs had bases that were interchanged between high gain (low rate) counting mode or low gain (high rate) current mode. The gain for a current mode base was set to ~ 200 with the pre-radiators and that for a counting mode base was of $\mathcal{O} 10^6$. Each main detector assembly was housed in an aluminum casing to check any possible movement/slip of the bars. The low noise electronics chain for the main detectors is discussed in Section 2.13. The integrated rate at the detectors was maximum (6.4 GHz total) when the QTor current was 8921 A with $180 \mu\text{A}$ of beam current on the 35 cm liquid hydrogen target.

QTor scans were done by varying the spectrometer current which changed the electron profiles and thus the signals in the main detector bars. GEANT3 [38] simulations of current & event mode QTor scans were done by this author and a detailed comparison of the simulations with data is given in Section 4.2 and 4.4.2.1.

2.9.1 Background Detectors

A full main quartz detector, identical to its eight MD counterparts, and named as main detector 9 (MD9) was used to monitor neutral background asymmetry. During Run 1 MD9 was placed horizontally on the beamline but moved downstream of MD5 with the outer radii of MD9 very close to the inner radii of MD5 for Run 2. At this location MD9 saw almost the same background as its neighboring MD5.

Three dark boxes, each containing a PMT identical to the MD1-9 PMTs, a low gain current mode base and a LED were used as auxillary detectors to monitor electronics noise. The third dark box also had a fused silica plate (analogous to a MD light guide) glued to the PMT in the same fashion as the lightguides were glued to the PMTs in the MDs. The first dark box detector (aux001) was placed in a fixed beam right location in the Ferris wheel platform close to the quartz scanner but out of the nominal scattered electron acceptance. This detector provided a small low noise signal (~ 1.25 ppb/hr) as a reference to the noise level in the MD electronics chain. The second auxillary detector (aux002), placed between MD5+ and MD6- PMTs during the commissioning Run, monitored PMT background. The third detector (aux003) was placed between MD8+ and MD1- PMTs to monitor PMT + lightguide background. Later in Run 1 (March 2011), the second and the third auxillary detectors were moved (see Figure 2.13) to the superelastic region downstream of the MD3. Complete information on the main detector fabrication can be found in Peiqing Wang's doctoral dissertation [36].

Figure 2.13

Auxillary background detectors.

Top left (right) shows placement of second (third) auxillary detectors during the commissioning period. They were moved to a new position as shown in the bottom during early Run 1.

2.10 Shielding

The detectors were heavily shielded against the neutral background in the experimental hall. A high density (2.7 g/cm^3) wall of concrete containing barite (BaSO_4) reinforced with stainless steel rebar with eight wide apertures (Figure 2.14) formed the upstream wall of an hermetically enclosed hut built to shield the quartz detectors, Region III vertical drift chambers, trigger scintillators and the focal plane scanner from the room background. The remaining walls and ceiling of the detector shield hut were formed from normal concrete shielding about 4' thick.

Simulation studies revealed that the Møller electrons which have high rates could interact with the defining collimator and produce a large neutral background, which if unchecked would reach the main detectors [39]. This led to the addition of eight collimators called lintels in between adjacent coils of the QTor. The lintels blocked the direct line of sight from the inner edge of the defining collimator to the main detectors.

Some parts of the beamline were also shielded to minimize the background on the detectors. A 14.9 mm diameter tungsten plug was installed in the center of the first collimator to shield electrons scattered off in small angles (1° - 4°) which would otherwise interact with the beamline to produce more backgrounds. The water cooled tungsten plug tremendously suppressed the existing beamline background but in turn produced secondary backgrounds as the charged particles interacted with the tungsten plug. To mitigate this, a 12" long and 2" thick lead donut was installed around the beam pipe in the region between the second and the third collimator. The beamline inside the detector hut was also shielded by a 2" thick lead box starting from the shield wall to the downstream end of the main

Figure 2.14

CAD drawing of the Qweak apparatus with the high density shielding wall.

Sky blue represents the scattered electron profile originating from the target and reaching the main detectors.

detectors (up to $Z = 622.6$ cm from the QTor center). The bare portion of beamline inside the detector hut also had a stack of lead bricks to make a shield of about 8" thick on the sides, 2" on the top and 1" on the bottom.

2.11 Luminosity Monitors

Two sets of Čerenkov detectors, made from the same Spectrosil 2000 [40] as the main detectors, were used as luminosity monitors [41] in the experiment. A set 4 of luminosity monitors (upstream lumis, Figure 2.15:left) were strategically placed on the upstream face of the primary collimator to detect $\sim 5^\circ$ scattered Møller electrons. The signal was read out by two PMTs at opposite ends of each upstream luminosity monitor. A second set of 8 downstream lumis [41] (Figure 2.15:right) was placed 17 meters downstream of the target to detect small angle (0.5°) Møller and elastically scattered electrons. These lumis were placed in special cups built in the beampipe of diameter 60 cm and within 13 cm of the beamline. Only one PMT per detector was used to read out the signal in downstream lumis. The active detector area of an upstream lumi was $7 \text{ cm} \times 25 \text{ cm} \times 2 \text{ cm}$ and that for a downstream lumi was $3 \text{ cm} \times 5 \text{ cm} \times 2 \text{ cm}$. Air-core light guides transported light from the quartz to 2 inch Hamamatsu R375 phototubes [42] with quartz windows in photodiode mode. The upstream and downstream lumis saw rates of about 133 GHz and 100 GHz of scattered electrons respectively.

The upstream lumis were less sensitive to the beam parameter changes than the downstream lumis and were supposed to monitor target density fluctuations. The downstream lumis were meant to monitor helicity correlated beam properties as well as to provide a

Figure 2.15

The luminosity monitors.

Left: Upstream luminosity monitors. Right: Downstream luminosity monitors.

null asymmetry monitor with much smaller statistical uncertainty than the main detectors. However, the lumis did not behave well as the noise levels were rather large and time dependent. The downstream lumis mainly saw effects from raster modulation which enlarged their measured asymmetry width to a point where they no longer had asymmetry width smaller than the main detectors. Thus, the lumis were used neither as target density fluctuation monitors nor as null asymmetry monitors but were used to help estimate the neutral background. Additional details regarding the lumis can be found in John Leacock's doctoral dissertation [41].

2.12 Tracking system

For elastic $\vec{e}p$ scattering, the four momentum transfer squared (Q^2) is given by

$$Q^2 = \frac{4E^2 \sin^2 \theta/2}{1 + 2\frac{E}{M} \sin^2 \theta/2} \quad (2.11)$$

where E is the incident beam energy, θ is the scattered electron laboratory angle and M is the mass of the proton. A dedicated tracking system was commissioned to measure θ and determine Q^2 with $< 0.5\%$ uncertainty. Also, the tracking measurements helped determine the detector bias due to light yield variation over the length of the quartz bar. The quartz main detectors were used in high gain event (counting) mode during the tracking measurements. Additional detector systems, namely the Region II Horizontal Drift Chambers (HDCs), the Region III Vertical Drift Chambers (VDCs), and the Trigger scintillators (TS) were used to carry out the tracking measurements at low beam currents (50 pA- 50nA). The HDCs were located immediately downstream of the defining collimator while the VDCs were located in between the QTor and the main detectors. The HDCs with intrinsic spatial resolution of $\sim 250 \mu\text{m}$ were used to determine the vertex location in the target and the scattering angle to $\sim 0.6 \text{ mrad}$. The VDCs had position resolution of $266 \mu\text{m}$ ([43] pg. 98) and were used primarily to determine the Q^2 variation across each of the main detector bars. Tracks in the HDCs and VDCs were matched to determine the trajectory of the electrons after passing through the magnetic field. The TS were placed in between the MD and the VDCs and were used in dilution and background studies. Both chamber systems consisted of a pair of packages placed in opposite octants. The packages could be rotated to other octants saving the need to having three extra pairs of packages. They were inserted

into the acceptance only during the tracking measurements and were retracted during the current mode operation. A small quartz scanning device [44] was installed on a moveable frame in front of octant seven. The scanner ran at all beam currents. Used in both counting mode and integration mode the scanner mapped the rates over the entire quartz bar, providing a way to tie the low current and high current detector performance together. Details on the VDC, the TS and the performance of the tracking system can be found in [43], [39] and [44] respectively.

2.13 Electronics & Data acquisition (DAQ)

Custom low noise electronics were designed and built by TRIUMF and the DAQ was setup differently for the current mode and the tracking mode. In current mode operation, the low-noise current-to-voltage preamplifiers of the main detectors converted the DC anode current coming from the low gain bases of the PMTs to a voltage signal of around 6V. The voltage signal was then fed to the integrators where it was digitized by 18-bit Analog-to-Digital Converters (ADCs) [16] sampling at 500 kHz.

The trigger for the current mode was the Macro Pulse Signal (MPS) sent by the injector. This signal gated detector and beam monitor signals to only sample and integrate the signal during the T_{stable} period. The $\sim 70 \mu s$ T_{settle} period in between adjacent helicity states was necessary to let the Pockels cell stabilize, which reduced helicity correlated false asymmetries. Figure 2.16 shows a schematic of the signal processing time sequence. Additional internal delays of $43 \mu s$ ($T_{ADC \text{ Delay}}$) and $10 \mu s$ were set during each helicity

Figure 2.16

Helicity trigger and data read-out in integrating mode.

sampling period to allow internal processing, allowing only the signal in the shaded region to be sampled and integrated.

These timing gates result in read-out of 89% of the signal in each helicity state. 260 channels from the MD and beamline monitors were fed to the custom built low noise ADC [16] (named as VQWK-ADC) modules which were mounted into five Read-Out-Controllers (ROCs). Data were collected at the rate of 7-8 MB/s during current mode by the CEBAF Online Data Acquisition (CODA) system.

The event mode data acquisition was also handled by CODA. The event mode DAQ could simultaneously handle multiple triggers from the Region II scintillator paddles, Region III trigger scintillators, Čerenkov quartz bars, Focal plane scanner and a variable clock signal (usually 10 Hz) to replace the helicity signal. Signals from the high gain event mode bases fitted to the PMTs of the main detectors, the R II & III drift chambers, TS and the focal plane scanner were fed into the front-end electronics of charge sensitive ADCs (QDCs), pipeline Time-to-Digital Converters (named F1 TDCs) [45] and scalars. With the

event rate in a single scintillator as low as ~ 100 Hz for 50 pA of beam current and as high as ~ 50000 Hz for 20 nA of beam current it was of utmost importance to manage the event rate without increasing the computer dead-time (the event mode DAQ could run at a maximum of 6 kHz with a computer dead-time of 99%). This was managed by using pre-scales to scale down the input rate to 1-2 kHz in order to achieve a reasonable computer dead-time. Thorough details on the Qweak DAQ can be found in Rakitha Beminiwatha's [46] and Buddhini Waidyawansa's [19] dissertations.

CHAPTER 3

TARGET

3.1 Overview

A high luminosity ($\sim 2 \times 10^{39} s^{-1} \text{ cm}^{-2}$) liquid hydrogen (LH2) target was built for the Qweak experiment to measure a ~ -220 ppb asymmetry with a precision of ~ 5 ppb. Collimation of the scattered beam was done for precise measurements of Q^2 , which restricted target length to 35 cm. Liquid hydrogen packs more than 25 times more atoms in the length available than gaseous hydrogen does. Very pure (99.999%) hydrogen can be obtained commercially at reasonable price. However, achieving a high luminosity also requires using high beam current on the target. A high beam current deposits a large amount of heat in the target and can induce noise in the asymmetry measurements due to the changes in the density of the liquid near the helicity reversal rate. The challenge has always been to balance the amount of current (power) a cryogenic target could take without significantly contributing to the systematic uncertainties due to the target density fluctuations. Table 3.1 shows properties of various liquid hydrogen targets used in different parity violation experiments. The Qweak target represents the highest power and the least noisy LH2 target ever built.

Table 3.1

Table of properties of liquid hydrogen targets used in various parity-violation experiments.

	$p/T/\dot{m}$ psia/K/(kg/s)	L cm	P/IE W/ μ A/GeV	Power W/cm ³	D mm	$\Delta\rho/\rho$ %	$\delta\rho/\rho$ ppm
SAMPLE [47]-[48]	25/20/0.6	40	700/40/0.2	396	2	1	<1000 @ 60 Hz
HAPPEX [15]	26/19/0.1	20	500-35-55/3	76	$5 \times 5, 6 \times 3$	-	100 @ 30 Hz
PV-A4 [49]-[50]	25/17/0.3	10	250/20/0.854	310	1.7	0.1	392 @ 50 Hz
E158 [51]	21/20/1.8	150	700/12/48	467	1	1.5	<65 @ 120 Hz
G0 [14]	25/19/0.3	20	500/40-60/3	346	2×2	<1.5	<238 @ 30 Hz
Qweak [52]	35/20/1	35	2500/180/1.1	375	4×4	<1.6	<50 @ 960 Hz

p - pressure, T - temperature, $\dot{m}$ - mass flow rate, L - length, P - beam power on the target, I - maximum beam current, E - beam energy, D - beam spot size, $\Delta\rho/\rho$ - target density reduction, $\delta\rho/\rho$ - size of target density fluctuation at given helicity reversal frequency.

3.2 Design Criteria

A 35 cm long liquid hydrogen target was designed to provide an integrated rate of 6.4 GHz at 180 μ A of incident beam current. One of the most challenging constraints was to limit the target noise contribution to the asymmetry measurement below 50 ppm. This was very important to limit the additional time required to achieve the statistical goals of the experiment to $< 5\%$. To maintain a stable loop temperature of 20 K at such high beam current, a heat exchanger was required to transfer up to 3 kW of heat away from the liquid hydrogen. Also a heater was necessary to balance the heat load (up to 3 kW) when there was no beam at the target and to regulate the temperature at 20 ± 0.02 K at all times. It was calculated that a centrifugal pump that would deliver a differential pump pressure of about 1.2 psid was required to maintain the desired 1.1 kg/s flow in the loop. The flow requirement was determined by extensive computational fluid dynamics (CFD) simulations.

3.3 Target loop

A closed loop (SA-213 SS tube) of 3" outer diameter (0.062" wall) containing an aluminum alloy cell, a high power heater, a centrifugal pump, and a hybrid heat exchanger formed the primary Qweak target (Figure 3.1). The loop had hydrogen and helium supply and return lines. The entire loop was supported by a long 8" diameter pipe that had limited vertical and horizontal motion.

About 57 liters of liquid hydrogen, maintained at 20.00 K and 35 psi, was recirculated in the loop in about 4 s. A flow of 1.1 kg/s (15 liter/s) of the liquid was directed in the

Figure 3.1

The Qweak target loop.

A- the liquid hydrogen cell, B- the high power heater, C- the centrifugal pump, D- the hybrid heat exchanger, E- the dummy target ladder, F- the vertical motion system. Red and blue arrows denote the flow direction of LH2. Green arrows denote the flow directions of the coolants. Beam direction is transverse to the flow direction in liquid hydrogen cell. The dummy target ladder was attached underneath the liquid hydrogen cell. The cell is rotated 90° to make the flow pattern visible.

transverse direction across the beam. The pressure head was 11 m (1.1 psi at 72 kg/m³). The entire loop except the cell was wrapped in 25 layers of super-insulation¹ to minimize the radiative heat transfer from the surrounding vacuum chamber to the cryogenic target loop. Temperature sensors were installed at various locations of the loop (see Section 3.7). The pressure in the loop was monitored using various pressure sensors in the gas panel. Also, the polarized electron beam which otherwise has an intrinsic diameter of $\sim 200 \mu\text{m}$ was uniformly spread (rastered) to a square of size 3.5 - 4 mm using ~ 25 kHz triangular waveforms produced by iron-free magnets upstream of the target [53]. This decreased the areal power density at the target and was imperative for safety considerations as an unrastered beam could damage the target cell windows and exacerbate the target noise. The major components of the target are shown in Figure 3.1

3.3.1 Coolant Requirement & Supply

A beam of 180 μA deposited about 2100 W of power in the target from the ionization losses in the two 0.005" thick aluminum windows ($\rho = 2.699 \text{ g/cm}^3$, $dE/dX = 2.032 \text{ MeV/g/cm}^2$) and 35 cm thick liquid hydrogen ($\rho = 0.0723 \text{ g/cm}^3$, $dE/dX = 4.653 \text{ MeV/g/cm}^2$). Bremsstrahlung loss in the liquid hydrogen was about 46 MeV but did not contribute to the target heating. Heat loads in LH2 from various sources are shown in Table 3.2.

To meet this enormous ($\sim 3 \text{ kW}$) demand of target cooling power, which had never been required by any previous experiment at Jefferson lab, liquid helium coolant from the

¹A multilayer insulator made up of a reflective layer (e.g., aluminized mylar) with a low thermal conducting spacing layer.

Figure 3.2

Schematic of coolant lines & recovery heat exchanger.

Typical pressure, temperature and flow rate of coolants during the experiment are shown. CHL and ESR provide coolant coolants to the target. 4 K coolant coming out of the target was sent to the recovery heat exchanger before returning to the CHL. Joule Thompson (JT) valves were used to control the flow of the coolants.

Table 3.2

Target heat loads.

Source	Value (W)
Beam Power in LH ₂	2075
Beam Power in Cell Windows	23
Viscous heating	177
Radiative losses	150
Table Heater	40
Pump Motor	150
Reserve heater power	260
Total Heat Load	2874

The estimated uncertainty on the final heat load is 10%.

Central Helium Liquefier (CHL) was used for the first time in Hall C along with gaseous helium from the End Station Refrigerator (ESR). About 40.53 g/s of Helium from ESR (at 12.06 atm and 14.8 K) and about 13.7 g/s from CHL (at 2.2 atm and 5.02 K) were supplied to the target with the latter also being used to cool down the superconducting magnet in the Møller polarimeter. Typical operational parameters are shown in Figure 3.2.

Independent return lines collected coolants at 20.31 K but at different pressures (3.09 atm for 15 K flow and 1.38 atm for 4 K flow). The existing 4 K return line was coaxial to the 4 K supply line and carried 5 K helium from the superconducting magnets. However, having 20 K flow through the pre-existing coolant lines would have raised the supply temperature of 4 K helium. To avoid the necessity and the corresponding cost of having a new transfer line for 4 K return, the space for the nitrogen shield in the existing transfer line was used for 4 K helium return. This had the additional benefit of providing a more effective shield. A recovery heat exchanger was built for the experiment to recover the enthalpy of

the returning 4 K coolant which would otherwise have been wasted. The return line of 4 K went to the recovery heat exchanger to help with 15 K cooling at the ESR.

3.3.2 Heat Exchanger

The heat exchanger was designed to serve a dual purpose: to liquify the gaseous hydrogen in the loop to 20 K and to maintain the loop temperature at 20 K by transferring heat from the liquid hydrogen. Two sources of coolants; 15 K helium at 12 atm & 4 K helium at 3 atm, made it possible to provide the required cooling power which was otherwise impossible to obtain from either of the coolant supplies alone. The flow rates of the coolants were optimized to draw about 1.2 kW of the total cooling power from the 15 K supply and the rest from 4 K supply. Utilizing coolant at 4 K could prove detrimental for hydrogen freezes at 13.8 K, hence the supply from the two coolant sources were managed so as not to freeze hydrogen in the heat exchanger.

The heat exchanger had three layers of finned copper tubes in three sections wound on a cylindrical aluminum mandrel of diameter 3.62 " (92 mm) as shown in Figure 3.3. A 1/2 " copper tube having 1/4 " fins with 16 fins/inch was used to form each layer. There were perforated sheets in between the adjacent layers and the sections were brazed together. As shown in Figure 3.3 (left), the layers of each section were connected to ensure a similar pressure drop in each element (coil).

The 4 K supply circulated through two layers of the heat exchanger and all three layers had coolant running in the direction opposite to the hydrogen flow. The central cylinder acted as a baffle to force the hydrogen to flow through the coils.

Figure 3.3

Hybrid heat exchanger.

Left: A drawing of the cross section of the hybrid heat exchanger. Right: CAD drawing of the same. 15 K supply goes in from the left in the blue colored coil while 4 K goes to the other two coils in the direction opposite to the flow of hydrogen.

The differential pressure loss due to this heat exchanger was estimated using the Darcy-Weisbach formula [54]. At a mass flow rate of 1.08 kg/s of 20 K liquid hydrogen, the net loss was predicted to be 0.22 psi, not including the sudden change in the flow velocity at the narrow ends of the heat exchanger. It was required that the device be built by an ASME code machine shop so a stamped hybrid heat exchanger with the above specifications was built and delivered by Meyer Tool, Chicago.

3.3.3 High Power Heater

The target loop had a 3 kW capacity resistive heater to balance the heat load and maintain the loop temperature at 20.00 ± 0.02 K at all times including even when the beam was off or when solid targets were positioned in the beam. The heater design determined the surface area of the resistive wire (13 AWG Nichrome) that would provide power (Q)

of 2500 W without boiling liquid hydrogen. At 35 psi liquid hydrogen boils at 23.597 K. The required surface area is given by

$$Q = \bar{h}A_{wire}\Delta T \quad (3.1)$$

where $\bar{h}$ is the average heat transfer coefficient for the wire array, A_{wire} is the total surface area of the wire and ΔT is the difference between the boiling and loop temperature. Four layers of wire were bundled around crossed 1/16" thick G10 boards as shown in Figure 3.4. The layers formed in-line rather than staggered arrays to minimize the pressure drop in the heater. The innermost and the outermost layers were connected in series, as were the two intermediate layers, such that the two series of layers had the same wire length. Those two series were then connected in parallel. The resistive wire had resistance of 0.128 Ω /ft, diameter (D) of 72 mil and a total length of 11.5 m. Each layer had 23 rows separated by a gap of $X_l = 2D$ and each layer was at a distance of $X_t = 3.6D$ from the next layer.

Additionally, slots were machined in between the adjacent holes to enhance the flow of liquid. However, refined computational fluid dynamics (CFD) calculations using ANSYS' FLUENT found the slots unnecessary and a spare heater was built with only 92 mil diameter holes. To deliver a heat load of 2.5 kW while keeping the temperature of liquid on contact below the boiling point the length required was only 8 m. The total resistance of the heater was measured at the joint of the wires from the two parallel series of layers. The resistance was determined by connecting it to a DC power supply and submerging it in liquid nitrogen. By varying the voltage and measuring the current, the resistance was de-

Figure 3.4

High power heater during fabrication.

terminated from the slope of I vs. V curve. This gave a resistance of $1.33 \, \Omega$, greater than the optimum resistance ($1.2 \, \Omega$) for the Sorensen 3 kW 60 VDC power supply. The maximum power this heater could provide with the 60 VDC was about 2700 W. During Run 2, when we used $180 \, \mu\text{A}$ of beam current, it became clear that we required more heater power to minimize temperature oscillations after beam trips. Hence, a new 4 kW 80 VDC power supply was then used for the remainder of the experiment. The heater was housed in a 3" pipe opposite to the heat exchanger leg in an 11" section with conflat flanges as shown in Figure 3.5.

The pressure drop at the heater was estimated by the following equation:

$$\Delta p = \frac{f N_L G_{max}^2}{2 g_c \rho_{h2}} \approx 0.27 \, \text{psi} \quad (3.2)$$

where f is the friction factor, N_L is the number of rows in the heater, and

$$g_c = 1 \, \text{kg} \cdot \text{m} / \text{N} \cdot \text{s}^2. \quad (3.3)$$

Figure 3.5

Drawing of the high power heater placement.

$$G_{max} = U_{max} \rho h_2 \quad (3.4)$$

where U_{max} is the maximum fluid velocity through the heater. The friction factor [55] has the form:

$$f = 0.176 + 0.32 \frac{X_l}{D} \left(\frac{X_t}{D} - 1 \right)^{-n_f} Re_f^{-0.15} \quad (3.5)$$

where the exponent is $n_f = 0.43 + 1.13D/X_l$ and $Re_f = 4.8 \times 10^4$ is the Reynolds number for the geometry used. For our flow speeds, the friction factor had a value of 0.084.

3.3.4 Pump

The pump for the Qweak target was designed to deliver a mass flow rate of 15 L/s and a head of 1.3 psi while limiting the viscous heating below 10% of the beam power (2.1 kW) at 180 μ A. A pump head is simply the maximum vertical height (h) a liquid can be pumped by a given pump. The pressure developed by the pump is then $P = h\rho g$ where ρ

is the specific gravity of the liquid and g is the acceleration due to gravity. The choice of a pump impeller is given by the specific speed

$$N_s = N \frac{\sqrt{Q}}{H^{0.75}} = 1805 \quad (3.6)$$

for $N = 1800$ rpm, $Q = 230$ gpm, and $H = 37.4$ ft. This value of N_s implies a centrifugal pump which delivers a high head but is of moderate capacity. Since the viscous heating is proportional to the cube of the fluid velocity, the loop pipes were designed to have a diameter of 3 " which corresponds to a fluid velocity of 3.3 m/s and ultimately limited the viscous heating to 177 W.

A centrifugal pump for the Qweak target was built to meet these specifications by Jefferson lab target group's Dr. David Meekins. One of the major design constraints of the pump was to avoid cavitation. Cavitation occurs in low pressure/suction regions of the pump creating cavities or bubbles in the liquid being pumped. A particular common type is vane passing syndrome. This occurs when there is a very small gap between the outer diameter of the impeller and the cutwater (an imaginary circle drawn from the shaft centerline and tangent to the tip of the volute lip(s) [56]) which causes an increase in the velocity of the liquid followed by decrease in fluid pressure. When this pressure falls below the liquid vapor pressure, one gets vaporization. The collapsing bubbles can damage the volute and if they escape into the high pressure region, they cause noise and vibration in the system. Cavitation lowers the pump capacity, head, and efficiency. This can be prevented by keeping an impeller tip to cutwater clearance of 4% or 6% of the impeller diameter for

diameter $< 14''$ or $> 14''$ respectively. Cavitation can also be mitigated by operating the system at a pressure much greater than the vapor pressure.

Another design constraint was to have the pump within the scattering chamber so that it could be moved with the target, i.e., a submersible pump was needed. A race car turbocharger of aluminum 356.0 cast with suitable geometry was adapted to this task. Conflat flanges were welded to the volute, which allowed the pump motor housing to connect to the loop pipes (Figure 3.6). The impeller with 12 blades had outlet (r_2) and inlet (r_1) radii of 7.1 cm and 5.4 cm and the height (h_2) at the outlet radius was 1.4 cm. The angles between the impeller blades to the tangent of the outer and inner impeller circumferences were $\beta_2 = 50^\circ$ and $\beta_1 = 5^\circ$ respectively. At the expected capacity of 15 L/s and 30 Hz ($\omega = 188$ radians/s) of rotational speed, the slip is given by

$$\sigma = 1 - \frac{\sqrt{\sin(90^\circ - \beta_2)}}{Z^{0.70}} = 0.86 \quad (3.7)$$

where Z is the number of blades. The head was estimated using [57]

$$H = \frac{\sigma(\omega r_2)^2 - r_2 \omega Q \tan(90^\circ - \beta_2)}{2\pi g r_2 b_2} = 12.5 \text{ m} \quad (3.8)$$

where $g = 32.2 \text{ ft/s}^2$.

A 1 hp (746 W) Baldor motor powered the pump. The explosion proof motor had AC induction inverter duty of 230 V and 2.8 A. The motor had a shaft diameter of 0.625'' and 0.875'' on either side of the rotor. The motor housing was custom built with 316L stainless steel (SS) to accommodate the pump. One end of the motor's shaft was connected to the pump and the other end to a tachometer. Champion hybrid ceramic bearings [58] replaced the motor's original bearings to withstand the cryogenic conditions. The 1.3125''

Figure 3.6

Centrifugal pump.

Left: Impeller in the volute. Right: Pump motor during the pump fabrication. Conflat flanges are not shown.

bearings made up of Si_3N_4 were used in SS races and graphite impregnated vespel retainers. A few turns of 0.252" diameter copper tube carrying 20 K helium return coolant was wound around the pump motor housing to help keep it cool. An Elite microsystems drive controller [59] was used to control the motor.

3.3.5 Cell

The most important component of the Qweak target was the cell, which housed liquid hydrogen for interaction with the polarized electron beam. It was equally challenging to build an extended 35 cm long cell that would take up to $180 \mu\text{A}$ of beam current (2.1 kW of power) and yet offer minimum noise due to changes in the target density. The cell was designed using computational fluid dynamics (CFD) simulations by Silviu Covrig (Jlab). CFD simulations were run to determine an optimum cell geometry that offered minimum

boiling at the windows and along the beam axis. A conical cell with flow transverse to the beam direction was found to meet the design criteria. The cell had an inlet manifold to redirect the flow of liquid in four regions: two regions towards the windows where the fluid velocity would be the highest to mitigate heating due to the beam and two along the beam axis as shown in Figure 3.7. Fluent simulations for this model predicted about 0.8% of reduction in the density but no boiling in the bulk liquid as the beam traversed the cell. However, the windows were predicted to have hot spots where the power density was estimated to be at least an order of magnitude greater than in the liquid. This made it necessary to have windows as thin as possible, but within the operationally safe limits.

Figure 3.7

Schematic of the liquid hydrogen cell

Blue arrows show the flow direction of liquid hydrogen in the cell. Actual cell block is in faint outline. Red arrow shows the beam direction.

Figure 3.8

CFD simulation of fluid velocity in the target cell.

Flow is from right to left and beam direction is from bottom towards top of the page. Velocity is highest at the cell windows to mitigate boiling.

The cell, at room temperature, was 37.85 cm long from the upstream window flange to the downstream window flange [60]. The length of liquid hydrogen in the cell was estimated to be 343.6 ± 0.05 mm [60]. The Run 1 beam entrance window, at the end of a cylinder of internal diameter 0.875" (22.2 mm), was 4.14 ± 0.04 mil thick whereas that for Run 2 was 4.07 ± 0.04 mil thick. The beam exit windows were rather complicated: The Run 1 exit window had a 1" thick flange of outer diameter 12" (305 mm) and an inner diameter of 6.83" (173 mm). The thickness inside the flange's inner diameter dropped to 0.025" (0.635 mm) on a machined surface with a radius of curvature of 10" (254 mm). A 4.98 ± 0.11 mil thick nipple of diameter 15 mm was machined at the center of the Run 1 exit window. The beam exited the cell from this nipple, while the electrons with scattering angle up to 14 degrees traversed the thicker part. The Run 2 exit window had a nipple of

Figure 3.9

Target cell windows after Run 1.

The beam exit windows (lower left or top right) had a sturdy layer of black unknown substance. These windows were replaced for Run 2.

thickness 5.35 ± 0.12 mil. Thickness measurements of the cell windows are discussed in Appendix A. The manifolds were welded to the cell and the windows were screwed with titanium bolts. Each cell was leak checked at a pressure of 150 psi. The target cell and windows were made of an aluminum alloy Al 7075-T6, the constituent metals and their % composition by weight are given in the Table 3.3.

3.4 Solid Targets

A carefully designed ladder containing dummy aluminum targets, optics target foils, hole targets and nuclear targets was attached to the bottom of the hydrogen cell. The hydrogen cell had a flat bottom where the top plate of the solid target ladder was bolted. The attached surfaces were coated with a thermal compound to facilitate better heat transfer. The dimensions of the solid target ladder were $11.45'' \times 7.5'' \times 14.46''$ with the longest dimension being along the beam axis to place the dummy aluminum targets in the same Z positions as the windows of the hydrogen cell. The frames were designed to provide maximum thermal contact to promote heat transfer at high beam currents from the solid targets, and to avoid interference with the acceptance of the scattered electrons from the upstream targets.

As shown in Figure 3.10, the ladder had sculpted squares of size $0.590''$ in the beam facing (upstream) side of the upstream and downstream frames of thickness $0.75''$. The opposite (downstream) side of these squares had threaded vaults $0.5''$ deep to allow $1.52''$ thick threaded aluminum pipes to press the targets against the frame. The distance between these adjacent pockets' center was $1.574''$. A washer was used in between a target

Table 3.3

Elements in the aluminum alloy by % used to make the target cell windows.

	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ti+Zr	Ni	Total
IN	89.72	0.06	0.12	1.7	0.01	2.5	0.19	5.7	0.04	0.04	-	100.08
OUT	-	0.08	0.14	1.5	0.04	2.6	0.19	5.9	0.02	-	0.0002	10.47

IN and OUT are the beam entrance and exit windows respectively.

Figure 3.10

Run 1 solid target ladder.

Various targets are labeled based on their names (e.g., 2% Aluminum) and types (e.g., 2×2 hole target). Labels in yellow boxes are the names of platinum resistance thermometers.

and a screw and the same thermal compound was used around the edges of the target and the washer for better thermal contact. The targets were cleansed with ethanol to remove impurities including oils from human contact. The centers of the hole targets were carefully aligned and were used to center the hydrogen cell and other dummy targets. Foils containing optics targets (explained later) were fastened to the bottom arms.

Solid targets were installed in six rows and three columns in the ladder plus two more rows of optics foil positions. Aluminum targets were used to study the background. The thickness varied to benchmark radiative corrections, but were typically 4 mm to reduce the time to make those measurements and to match the 4% thickness of the liquid hydrogen target. All the aluminum dummy targets were made from the same material used to make the beam entrance and exit windows for the hydrogen cell. In order to minimize the background measurement time, the aluminum targets sustained high beam currents (60 - 120 μA). They were placed close to the hydrogen cell to help take away the heat generated by interaction with the beam. Hole targets were located in all three columns in the upstream face and in the middle column in the downstream face. This system allowed us to center the target on the electron beam and determine the pitch, roll and yaw of the extended system. Less frequently used targets (e.g., carbon and pure Al) were used in various systematic studies. Five foil aluminum optics targets were placed at a distance of 8 cm from each other and these targets were used in tracking measurements to check vertex reconstruction. Thicknesses and areas were carefully measured for these carbon and aluminum solid targets, the details of which can be found in Appendix A.

Early in Run 1 a less frequently used dummy DS 2 % Al target melted as a result of poor thermal contact with the heat sink. Prior to Run 2 several spare dummy targets were installed in the dummy target ladder as a backup should any target melt. The top plate was re-designed to improve thermal contact between the hydrogen cell and the DS dummy targets, and the frames holding optics targets were replaced to avoid interference with the spare dummy targets.

3.5 Motion Mechanism

The Qweak target had a unique two axis motion system: horizontal (X , transverse to the beam direction) and vertical (Y), to move to different target positions accurately and reproducibly bearing a load of about 10 kN. A linear actuator: Thomson TC5 series electric cylinder (TC5-T41V-100-10B-600-MF1-FS2-B) [61], attached to the top plate of the scattering chamber provided 500 mm of vertical motion. The vertical lifter plate (Figure 3.11) and two vertical lifter rails (THK LM guide rails, model number HSR85-A) of lengths 39" were attached to the linear actuator. Another plate attached to the vertical lifter plate held a 62" long and 1/8" thick pipe with a diameter of 8" to support the target loop. This pipe was thermally isolated from the loop to prevent heat transfer from the pipe to the loop when the target had liquid hydrogen. It was estimated that only 4 W of heat was transferred by a pipe 8" in diameter and 1.5 m long. The actuator was controlled by an IDC S6961 stepper motor controller [62].

Horizontal motion was provided by two additional rails (THK LM guide rails, model number HSR35-M1A) of length 13.5" and an actuator (THK LM guide actuator model

Figure 3.11

Target motion mechanism.

Left: The top plate with vertical and horizontal motion mechanisms being assembled. Right: A CAD drawing of the top plate viewed from above.

number KR46) located on the underneath the vertical lifter plate (Figure 3.11). These rails and actuator provided 86 mm of horizontal motion to the 8" pipe and the target loop beneath. A Phytron VSS-UHVC Cryo stepping motor [63] was used to move the actuator in the vacuum.

Both motion systems had a 24 VDC brake, along with two pairs of limit switches, a home switch, and hard stops. Each system also had a linear resistive encoder to calibrate and regulate the motion system.

3.6 Scattering Chamber

A chamber from the SAMPLE [64] experiment was modified to use as the Qweak scattering chamber. The chamber had dimensions of 38" $\times$ 34" $\times$ 67.9" and was made of 1" thick 6061-T6 aluminum. A cylindrical Hall C standard pivot chamber (4.14' long and 3.75' in diameter) sat on top of this rectangular chamber connected by a cylindrical transition piece. The entire target loop hung from the top plate of the Hall C standard pivot target scattering chamber. The HKS splitter magnet stand supported the entire scattering chamber assembly [29].

The SAMPLE chamber had a 20" port where the electron beam entered the scattering chamber. A 16" extended stroke aluminum gate valve was placed on the downstream side of the SAMPLE chamber. The gate valve was open during data taking periods and was closed to help ensure personnel safety in the experimental hall and to isolate the cryotarget from the downstream beamline. Next to the downstream end of the gate valve was a vacuum window (Figure 3.12) made of Al 2024-T4 immediately upstream of the first col-

Figure 3.12

Vacuum window.

Vacuum window with spokes in a wagon-wheel configuration inside the scattering chamber (not shown).

limator. The thin spoked regions passed the scattered electrons out of the vacuum window and were only 0.035" thick. A 1060 gallon steel tank, called the dump tank, was also connected to the scattering chamber by a pipe of 6" diameter. This tank would collect hydrogen gas in the event of cell rupture or hydrogen leakage, in order to keep the scattering chamber sub-atmospheric in the event of such an accident.

3.7 Loop Instrumentation & Controls

The target loop's temperature and pressure were monitored by a set of temperature sensors placed at various locations in the loop, and pressure transducers at the gas panel in the experimental hall. Various control systems were provided to the trained target operators

to ensure smooth operation of the target, to change the target positions, to act swiftly and appropriately during any adverse scenario and to log the events.

3.7.1 Temperature and Pressure Sensors

Four pairs of calibrated Cernox CX-1070-SD-4D temperature sensors [65] were installed at the following locations to monitor the temperature of liquid hydrogen: the hydrogen cell manifold inlet, heater inlet, heater outlet and manifold outlet. These sensors monitored temperatures in the range of 0-100 K with a precision of 0.016 K. A pair of CX-1070 SD-4L temperature sensors were installed at the pump out location to monitor target warm up and cool down. These sensors mapped a range of 4 K - 325 K with the same precision stated above. Each pair had a redundant sensor in case one failed due to radiation damage or any other cause. The sensors were mounted on G10 rods attached to a ten pin CeramTec 10236-02-CF feedthrough. Push-pin connectors were used in the electrical feedthroughs and a 1.33 " mini-conflat seal held these feedthroughs. The sensors reached about halfway into the 3 " diameter loop plumbing. 36 AWG kapton insulated copper wires made the electrical connections and heat shrink tubing covered the feedthrough connectors for better insulation (Figure 3.13: left). A Kelvin connection (4 wire sensing) was made for each temperature sensor so that the wires resistance had negligible effect on the measurements. Similar temperature sensors were placed at 4 K and 15 K supply and return line across the heat exchanger (Figure 3.13 Right). Additional pairs of temperature sensors were placed before and after the Joule-Thompson (JT) supply valves for each coolant service.

Figure 3.13

Temperature sensors.

Left: A temperature sensor assembly. Right: Helium coolant temperature sensors in various parts of the heat exchanger.

The dummy target ladder had less accurate Cernox Pt-103 [65] temperature sensors epoxied in holes drilled at various points in the ladder (Figure 3.10). The temperature of the horizontal motion table was also monitored to keep it above 300 K. The temperature sensors were read out by Lakeshore 218S [66] temperature monitors. Each monitor could read eight sensors with an accuracy of 0.001 K.

Pressures in the loop and in the coolant lines were monitored using NoShok 625-100A-1-1-8-9 pressure transducers [67].

3.7.2 Target Controls

A combination of manual and automated hardware and software controls were implemented to ensure safe operation of the Qweak target. A Fast Shut Down (FSD) condition was set on pump head (differential pressure across pump) which turned off the beam in the event of pump failure. During late Run 1 an unrastered beam of 5 μA was accidentally delivered to the target briefly but without any damage to the cell. To avoid recurrence of any such incident a FSD was set on the raster size when the hydrogen target was in the beam. This would cut off the beam if an unrastered beam was attempted to be delivered to the hydrogen target.

A Proportional-Integral-Differential (PID) loop was used to control the high power heater (HPH). The PID loop altered the heater power output based on the beam current reading on a beam charge monitor as well as one of the liquid hydrogen temperature sensors (pump outlet). The PID maintained the loop at 20.00 ± 0.02 K during stable operation and at 20.00 ± 0.15 K during a beam ramp when the incident beam power varied over a 2 kW

range. The HPH was manually operated during Input-Output Controller (IOC) hangs or when problems arose with the main HPH power supply. This was done by switching to an auxiliary power supply, connected in parallel with the main supply, the output of which was controlled by a potentiometer dial in the Hall C counting room. An independent 4 K heater, also on a PID loop, was triggered by the manifold-in temperature sensor. The 4 K heater kicked in if the manifold inlet temperature fell below 17 K. The 4 K supply JT valve was also regulated by a PID loop. This PID closed the 4 K JT supply valve by 2%/min if the manifold-in temperature fell below 16 K. This was the last resort to prevent the liquid hydrogen from freezing if the target operator failed to take other mitigation steps.

Figure 3.14

Target GUI

Most of the target electronics were placed in the racks in the experimental hall, away and shielded from the direct radiation. The target IOC was however placed in a VME crate up in the racks close to the Hall C counting room. Signal input and output from different target components was handled by Greenspring ADIO modules. An Ethernet cable connected the IOC to a monitoring computer. This computer had a Linux based operating system which supported Experimental Physics and Industrial Control System (EPICS) and its extensions. A Motif Editor and Display manager (MEDM) Graphical User Interface (GUI) was used to control and monitor the target. The primary GUI is shown in Figure 3.14. A number of StripTools were constantly run to monitor loop temperatures, pressures, currents and voltages to the power supply, etc. An Alarm Handler (ALH) was used to provide warnings of unfavorable condition in the target loop or refrigeration system. The target GUI was developed to be a one stop GUI to monitor essential non-target components like the QTor power supply, ion chamber rates etc. Data from target components were logged in EPICS databases. Various target control components like the VME crate with the IOC, the target computer, the temperature and pressure readouts, the pump tachometer and the JT valve controls were connected to Un-interruptible Power Supplies (UPS) for safe operation of the target during a power outage.

3.8 Measured Target Performance

Numerous measurements performed to assess the individual and overall performance of the entire target system will be discussed next.

Figure 3.15

Loop temperature variation as a function of beam current.

Shown in green is the loop temperature and the beam current is in red.

3.8.1 Temperature Stability

The liquid hydrogen target was maintained at a nominal temperature of 20 K and pressure of 35 psia. When the beam suddenly tripped off there was an excess of 2.1 kW of cooling power on the target, which was well balanced by the high power heater. A PID loop lowered the heater output once beam was ramped back up in steps of about 5 $\mu\text{A/s}$. Each such step lasted for about 5 seconds and the liquid had damped temperature oscillations with a maximum initial amplitude of 0.15 K (see Figure 3.15) for about 3 minutes after reaching the maximum current of 180 μA . Once the oscillations died out the loop temperature remained fairly stable within 0.02 K. A stability cut was implemented in the data analysis to filter data taken during beam trips and ramps.

3.8.2 Pump

The cryogenic pump was run at a nominal frequency of 28.5 Hz to avoid noise pickup at 30 Hz. Early in the commissioning run (October 2010) the pump failed and upon inspection it was found that the teflon retainer in the upper bearing had failed presumably due to overheating. New ceramic bearings with a SS race and graphite impregnated vespel retainer replaced the failed bearings. Also, a small flow of the liquid hydrogen to the bearings was maintained to help keep the bearings cold. The pump then ran without any failure for the rest of the experiment but the heat load in the target increased by about 150 W [68] after the bypass was created. There were several pump trips during Run 1 which were mainly due to sudden current drops in the pump motor, but the recovery process was short and swift (less than a minute) and did not cause any major problems to the experiment.

3.8.2.1 Pump Head

The pump head was explicitly measured to be 1.10 ± 0.1 psid at 30 Hz of pump speed by an Omega Engineering PX771A-300WCDI differential pressure transducer. Measurements from an Orange Research 1516-S1073 0-5 psid differential pressure gauge placed at opposite ends of the pump in the hydrogen supply and return lines also confirmed the same pump head.

3.8.2.2 Mass Flow Rate

Liquid hydrogen mass flow rate was calculated by measuring the power dissipated and the temperature difference in liquid hydrogen as it passed through the high power heater at the given pressure. The power deposited by the heater is given by

$$\dot{Q} = \dot{m}C_p\Delta T \quad (3.9)$$

where $\dot{m}$ is the mass flow rate, C_p is the specific heat at constant pressure and ΔT is the temperature difference before and after the liquid entered the heater. The heater power was obtained as a product of current and voltage from the heater's power supply. Values of temperature, pressure and heater power were taken from records in EPICS. Temperature offsets in different thermometers were removed by taking the differences of temperatures during a beam on and a beam off period. If $\dot{Q}_1$, T_{1A} and T_{1B} are the heater power, inlet manifold temperature and heater outlet temperature respectively during a beam on period then

$$\dot{Q}_1 = \dot{m}C_p(T_{1A} - T_{1B}) \quad (3.10)$$

and similarly for a beam off period

$$\dot{Q}_2 = \dot{m}C_p(T_{2A} - T_{2B}). \quad (3.11)$$

The mass flow rate is given by

$$\dot{m} = \frac{\dot{Q}_1 - \dot{Q}_2}{C_p(T_{1A} - T_{1B} - T_{2A} + T_{2B})}. \quad (3.12)$$

The mass flow rate was measured at various times in both Run 1 and Run 2 and the results are plotted in Figure 3.16. The plot shows the measured mass flow rates at various points during the experiment with an average of 1.31 ± 0.32 (kg/s). An error of 10 % of the measured value was assigned to the error in heater power measurement.

Figure 3.16

Mass flow rate measurements.

3.8.2.3 Pump Efficiency

The pump efficiency can be estimated as [69]

$$\eta = 0.94 - 0.08955 \left[\frac{Q(\text{gpm})}{N(\text{rpm})} \left(\frac{3.56}{\epsilon(\mu\text{m})} \right)^2 \right]^{-0.21333} - 0.29 \left[\log \left(\frac{2286}{N_s} \right) \right]^2. \quad (3.13)$$

where Q , N , N_s and ϵ are the capacity, shaft speed, specific speed and estimated surface roughness of the loop respectively. For measured value of $Q = 230$ gpm, $N = 1800$ rpm, and $N_s = 1805$ and $\epsilon \sim 10 \mu\text{m}$, $\eta = 72\%$.

3.8.3 Heat Exchanger Performance

For a heat exchanger, the log mean temperature coefficient is given by

$$\Delta T_{LM} = \frac{T_{ho} - T_{ci} - (T_{hi} - T_{co})}{\ln \left(\frac{T_{ho} - T_{ci}}{T_{hi} - T_{co}} \right)} \quad (3.14)$$

and this is related to the heat transfer coefficient (U) as

$$U = \frac{m_{He} \cdot c_P^{He} \cdot (T_{co} - T_{ci})}{\Delta T_{LM}} \quad (3.15)$$

where the indices hi , ho , ci , co denote the temperatures of hydrogen in, out and coolant in and out respectively. The Qweak target loop had only one sensor each to monitor coolant inlet and outlet temperatures. The temperature sensor on 15 K return line died early during Run 1 and the rest were not well calibrated to extract a meaningful heat transfer coefficient using the relations above. However, the heat transfer rate and the coolant out temperatures can be estimated from a knowledge of mass flow rate and the coolant and hydrogen in temperatures.

The relations,

$$C_{He} = (\dot{m}c_P)_{He} \quad (3.16)$$

$$C_{LH2} = (\dot{m}c_P)_{LH2}$$

give C_{max} and C_{min} . Define

$$C_r = \frac{C_{min}}{C_{max}} \quad (3.17)$$

$$NTU = \frac{U}{C_{min}} \quad (3.18)$$

where NTU stands for the number of heat transfer units and U is the heat transfer coefficient in the units of (W/K). The effectiveness of a counterflow heat exchanger is given by [70]

$$\epsilon = \frac{1 - \exp[-NTU(1 - C_r)]}{1 - C_r \exp[-NTU(1 - C_r)]}. \quad (3.19)$$

The total heat transfer rate can now be calculated as

$$Q = \epsilon C_{min}(T_{hi} - T_{ci}) \quad (3.20)$$

and the outlet temperatures of helium and hydrogen are respectively given by [70]

$$T_{co} = T_{ci} + \frac{Q_{He}}{C_{He}} \quad (3.21)$$

$$T_{ho} = T_{hi} - \frac{Q_{LH2}}{C_{LH2}}. \quad (3.22)$$

The heat transfer coefficient can be estimated from the geometry of the heat exchanger by using the following relation [70]:

$$\frac{1}{U} = \frac{1}{h_{He}A_{He}} + \frac{1}{h_{LH2}A_{LH2}} \quad (3.23)$$

where A is the total area available for the heat transfer and

$$h = 0.023 \frac{C_p G^{0.8} \eta^{0.2}}{D_e^{0.2} P_r^{0.6}} \quad (3.24)$$

where G is the mass flow per unit area of the flow, η the fluid's dynamic viscosity, D_e the wetted perimeter and P_r is the Prandtl number. Using the above relation, heat transfer coefficients were estimated as $U_{15K} = 548 \text{ W/K}$ and $U_{4K} = 323 \text{ W/K}$.

Owing to the complex geometry of the counterflow heat exchanger used, the following assumptions were made to simplify further calculations:

- Liquid hydrogen is distributed uniformly over all the three 4 K and 15 K coolant loop windings.
- Heat transferred by one coolant loop is independent of the other two.
- 4 K He supply is evenly divided in two 4 K loops inside the heat exchanger. i.e., both the loops have identical geometry and the same mass flow rate.
- The temperature of liquid hydrogen entering the heat exchanger is maintained at 20 K by the PID loop.

Results obtained using relations 3.18, 3.20 and 3.21 are shown in Table 3.4.

Table 3.4

Calculated values of NTU , ϵ , Q and T_{out} for the Qweak heat exchanger.

	15 K	4 K	LH2
NTU	2.45	5.78	-
ϵ	0.909	0.996	-
Q (W)	1023	836	-
T_{out} (K)	19.54	19.95	19.75

The total heat transferred by the Qweak heat exchanger was determined to be 2696 W. The temperature of liquid hydrogen coming out of the heat exchanger can also be calculated using the simple relation

$$\dot{Q} = \dot{m}C_p(T_{in} - T_{out}) \quad (3.25)$$

where $\dot{Q}$ is the power delivered by the high power heater. Assuming $T_{in} = 20$ K, T_{out} was determined to be 19.75 K.

3.8.4 Liquid Hydrogen Target Performance

The statistical error on the measured asymmetry per quartet is $\frac{\sigma_A}{\sqrt{N}}$ where σ_A is the asymmetry width per quartet and N is the number of quartets. (Refer to Section 5.1 for details on measured asymmetry.)

In-beam operations of the target involve effects like bulk density reduction and density fluctuations in the liquid hydrogen. Whenever there is beam on the target, the bulk density of liquid hydrogen decreases, reducing the effective length of the target and hence the total main detector yield. Density fluctuations can occur in the liquid hydrogen owing to the change in beam properties like position, size and intensity of the incident beam or due to the changes in the circulation speed of liquid hydrogen. If density fluctuations occurred over a time interval comparable to the helicity reversal frequency then they tend to change the measured asymmetry widths. Helicity reversal was done at 960 Hz instead of the usual 30 Hz used previously at Jefferson lab to minimize the effects due to the target density fluctuations. A quartet pattern was used to cancel linear drifts in the measured yield (see Appendix B). An attempt to understand the effect of helicity reversal frequency

and the ordering of MPSes within a quartet on the measured target noise to the asymmetry will be discussed in Section 3.8.4.5. Significant fluctuations in the density mean a large asymmetry width, hence requiring a longer running time to achieve the same precision on the asymmetry measurements. The Qweak target was designed to have effects due to density fluctuations on the measured asymmetry width per quartet to be $\lesssim 50$ ppm at nominal running condition of $180\mu\text{A}$ of beam current, $4 \times 4 \text{ mm}^2$ raster size and 30 Hz of pump speed. Discussed next are the independent ways the target density fluctuation effects on the measured asymmetry widths were studied.

3.8.4.1 Boiling results

Figure 3.17

MD yield variation with target pump speed.

Figure 3.17 shows the change in the main detector yield at two pump speeds but at the same beam current and same raster size. The large drops in yield at a pump speed of 12

Hz is assumed to be caused by bubble formation in the liquid hydrogen target. This yield variation results in the enlargement of the asymmetry width. The asymmetry width is also dependent on the beam spot size on the target. Figure 3.18 shows the change in asymmetry width for different raster sizes used at 150 μA of beam current and a pump speed of 30 Hz. Similar changes in asymmetry width were observed when the intensity of the beam on target was changed as discussed in Section 3.8.4.2.

Figure 3.18

MD asymmetry width variation with raster size.

Main detector asymmetries (in ppm) at different raster sizes at 150 μA of beam current and 30 Hz of pump speed. Notice enlargement of the asymmetry width with smaller raster sizes.

Changes in the measured asymmetry widths are good indicators of target density fluctuations where the dynamic equilibrium of the target is temporarily unsettled. Density

fluctuations were observed and measured when either of the beam current, pump speed, beam spot size, helicity reversal frequency and the loop temperature were changed. A model was used to explain the changes in the asymmetry widths with the change in either of the variables mentioned above. Define

$$\sigma_T^2 = \sigma_S^2 + \sigma_B^2 \quad (3.26)$$

where σ_T is the total measured asymmetry width, σ_S is the statistical asymmetry width per quartet and σ_B is the boiling width due to target density fluctuations. Target contributions to the total asymmetry width were calculated assuming the change in widths were mainly due to the changes in the target's properties. The dependence of σ_B on the beam current, pump speed, beam spot size, helicity reversal frequency and the loop temperature is discussed next.

3.8.4.2 Beam Current Scan

Separate runs were taken at a fixed raster size of $3.5 \times 3.5 \text{ mm}^2$ and pump frequency of 30 Hz but at different beam currents as one way to characterize target density fluctuations. This study was done during the commissioning period when the nominal main detector asymmetry width was around 250 ppm. The asymmetry widths at various beam currents were linearly regressed against beam position and angles. A non-linear fit of the form

$$\sigma_{MD}^2 = \left(\frac{a}{\sqrt{I}} \right)^2 + \left(\frac{b}{I} \right)^2 + (cI^3)^2 + d^2. \quad (3.27)$$

where I is the beam current and a , b , c and d are the fit parameters was used in Figure 3.19 to describe the current dependence of the main detector asymmetry width (blue boxes).

From the fit, $a = 2985.5$, $b = 6153.1$, $c = 1.242 \text{ E-05}$ and $d = 85 \text{ ppm}$.

Figure 3.19

Beam current scan.

Variation of asymmetry width (blue boxes) at different beam current with fixed raster of size $3.5 \times 3.5 \text{ mm}^2$ 28.5 Hz of pump speed is shown. The dashed black curve is the fit (Equation 3.27) to the data. The red points are boiling widths due to the target and the solid red curve is the boiling curve (Equation 3.28).

The model assumes the total asymmetry width is from statistics (first term), beam current normalization (second term), density fluctuations (third term), all of which are dependent on the beam current, and a current independent fourth term. The statistical width is inversely proportional to the square root of the beam current or the number of quartets. This includes counting statistics (200 ppm including the 70 μ s settle time associated with the helicity reversal) and detector resolution (92 ppm). The width due to the beam normalization is inversely proportional to the current and was about 50 ppm at 180 μ A. The fourth term in the fit is independent of the beam current and represents the excess noise which was about 85 ppm. The fit gives a cubic power dependence of boiling width on the beam current. Thus,

$$\sigma_B = \sqrt{(cI^3)^2} \quad (3.28)$$

and $\sigma_B = 59$ ppm at 169 μ A of the beam current, 3.5×3.5 mm² of raster area and 30 Hz of pump speed. Despite the apparent increase in the boiling width with an increase in the beam current the total asymmetry width decreases. This is because of the number of quartets increase with an increase in the beam current reducing the statistical and charge normalization width. The net effect is the reduction of the total asymmetry width at high beam currents (i.e., the increase in the boiling width is very small compared to the decrease in statistical width). Later in the experiment, it was found that the total main detector asymmetry width decreased after better shielding of the main detector system and with new beam current monitor electronics, reducing the excess noise substantially.

3.8.4.3 Pump Speed Scan

The effect of pump speed on target density fluctuations was studied in late Run 1 (May 2011). A slower circulation caused by a decrease in the fan speed allowed an element of liquid hydrogen to remain in the beam path longer. This caused large density fluctuations in the target which lead to the enlargement in the asymmetry widths at lower pump speeds. The total asymmetry width increased by about 9% when the pump speed was lowered from nominal 28.5 Hz to 12 Hz.

MD asymmetry width variation with the pump speed was described by a fit of the form

$$\sigma_{MD}^2 = a^2 + \frac{b^2}{F^c} \quad (3.29)$$

where F is the pump speed in Hz, and $a = 233$, $b = 1889$ and $c = 2.288$. The fit is shown by the dotted blue curve in Figure 3.20. The first term in the fit would have been the total asymmetry width had there been no density fluctuations in the target. The second term in the fit predicts that the target noise width falls off almost inversely with the pump speed at the given conditions i.e.,

$$\sigma_B = \sqrt{\frac{1889^2}{F^{2.288}}}. \quad (3.30)$$

$\sigma_B = 41$ ppm at 169 μA of the beam current, 4×4 mm² of raster area and 28.5 Hz of pump speed.

Figure 3.20

Pump speed scan.

Variation of asymmetry width at different pump speeds with fixed raster of size $4 \times 4 \text{ mm}^2$ and $169 \mu\text{A}$ of beam current is shown. The dashed blue curve is the fit to the data given by Equation 3.29. The red points are boiling widths due to the target and the solid red curve is the boiling curve given by Equation 3.30.

3.8.4.4 Raster Size Scan

This study was done to understand the raster size dependence of the MD asymmetry. The variation of the MD asymmetry width with the square raster sizes at constant beam current of 182 μA and pump frequency of 28.5 Hz was studied using a model of form

$$\sigma_{MD}^2 = a^2 + \frac{b^2}{X^c} \quad (3.31)$$

where X is the raster size in mm, $a = 226$ ppm, $b = 1216$ and $c = 4.748$ are the fit parameters. The fit is shown by dotted black curve in Figure 3.21.

Spreading the beam area reduced the incident power areal density and thus reduced boiling at the target windows. The spread had to be small enough to ensure that the beam did not interact with the tungsten plug downstream in the first collimator, which had an aperture of only 14.9 mm. The fit model in Figure 3.21 assumes the target density fluctuation comes from the raster size raised to some exponent and not specifically from the raster area. As seen from the fit, the freely floating exponent on the raster size is not 2^2 which corresponds to the raster area. From the fit,

$$\sigma_B = \sqrt{\frac{1216^2}{X^{4.748}}}. \quad (3.32)$$

which gives $\sigma_B = 46$ ppm at 180 μA of the beam current, $4 \times 4 \text{ mm}^2$ of raster area and 28.5 Hz of pump speed.

All the three different ways of measuring the target noise width can be combined to give an empirical formula for target noise width with varying beam current (I), pump frequency (F) and raster size (X) as

$$\sigma_B(X, I, F) = \left[1.3 + \left(\frac{19.4}{X(\text{mm})} \right)^{2.37} \right] \times \left(\frac{I(\text{A})}{169} \right)^3 \times \left(\frac{28.5}{F(\text{Hz})} \right)^{1.14} \text{ ppm.} \quad (3.33)$$

Figure 3.21

Raster size scan.

Variation of asymmetry width with different square raster sizes at $182 \mu\text{A}$ of beam current and pump speed of 28.5 Hz is shown. The fit (dotted black) to the data is given by Equation 3.31. The red points represent boiling widths and the solid red curve is the boiling width curve from Equation 3.32.

At $4 \times 4 \text{ mm}^2$ of raster size, 28.5 Hz of pump frequency and 180 μA of the beam current, the target noises derived from all three independent studies have a good agreement within 5 ppm.

3.8.4.5 Target Noise Dependence on Helicity Reversal Frequency

A pump speed scan under conditions similar to the one described in section 3.8.4.3 was done at the helicity reversal frequency of 480 Hz instead of the nominal 960 Hz used during the rest of the experiment. The same functional form as described in Equation 3.29 was used to fit the variation of the MD width with pump speed. From the fit (solid blue curve) shown in Figure 3.22, $a = 168.6 \text{ ppm}$, $b = 8085$ and $c = 2.95$ which gave

$$\sigma_B = \sqrt{\frac{8085^2}{F^{2.95}}}. \quad (3.34)$$

Using this relation, $\sigma_B = 58 \text{ ppm}$ at 169 μA of beam current, $4 \times 4 \text{ mm}^2$ of raster area and 28.5 Hz of pump frequency at 480 Hz helicity reversal frequency.

Fast Fourier Transforms (FFT) of normalized main detector yields indicated increased noise at frequencies less than 50 Hz helicity reversal frequency as shown in Figure 3.23. Data from the 960 Hz pump speed scan described in Section 3.8.4.3 were reanalyzed to mimic various helicity reversal rate conditions. This was done by taking charge normalized yields from a continuous chain of MPSes during a stable time period where the MD yield was not fluctuating and by rearranging them to generate asymmetry distributions and their widths.

MPS helicity windows were re-arranged without regard for the helicity states, so the asymmetry formed was not a physics asymmetry. Since the objective of this study is to

Figure 3.22

Boiling at 480 Hz of helicity reversal frequency.

Variation of asymmetry width at different pump speeds with fixed raster of size $4 \times 4 \text{ mm}^2$ and $169 \mu\text{A}$ of beam current at 480 Hz of helicity reversal is shown. The solid blue curve is the fit to the data. The red points are boiling widths due to the target and the dashed red curve is the boiling curve.

Figure 3.23

Fast Fourier transform (FFT) spectrum of main detector 1 negative tube yield.

(a) $20\ \mu\text{A}$ of beam current on liquid hydrogen (b) $180\ \mu\text{A}$ of beam current on liquid hydrogen (c) $120\ \mu\text{A}$ of beam on aluminum (d) $76\ \mu\text{A}$ of beam current on carbon. FFTs of solid targets are flat as they should be. At $180\ \mu\text{A}$ of beam current there is a $1/f$ tail in hydrogen data but not at $20\ \mu\text{A}$. This suggests that target noise at high beam currents is predominantly at smaller frequencies, and motivates the decision to employ faster helicity reversal in this experiment.

look at the effects on the asymmetry width, the asymmetry itself does not matter. Since each MPS is reversed at 960 Hz, two consecutive MPSes can be taken as a single unit reversed at 480 Hz, four consecutive MPSes as a single MPS at 240 Hz and so on. If $Y_1, Y_2, Y_3, Y_4, Y_5, Y_6, Y_7, Y_8$ are the normalized yields corresponding to the consecutive helicity windows then they can be combined in two ways to form an asymmetry at the same mimicked helicity reversal frequency. The asymmetry at 480 Hz can be written as

$$A(480)_{QRT} = \frac{(Y_1 + Y_4) - (Y_2 + Y_3)}{(Y_1 + Y_4) + (Y_2 + Y_3)}. \quad (3.35)$$

which is equivalent to the experimental asymmetry and as

$$A(480)_{Pair} = \frac{(Y_1 + Y_2) - (Y_3 + Y_4)}{(Y_1 + Y_2) + (Y_3 + Y_4)}. \quad (3.36)$$

The only difference in the above two expressions is the way the MPSes are ordered. It is shown later that there is a difference in the asymmetry widths derived from these two orderings of the same sequence of helicity windows. Similarly, the asymmetry at 240 Hz can be written as

$$A(240)_{QRT} = \frac{(Y_1 + Y_2 + Y_7 + Y_8) - (Y_3 + Y_4 + Y_5 + Y_6)}{(Y_1 + Y_2 + Y_7 + Y_8) + (Y_3 + Y_4 + Y_5 + Y_6)} \quad (3.37)$$

and

$$A(240)_{Pair} = \frac{(Y_1 + Y_2 + Y_3 + Y_4) - (Y_5 + Y_6 + Y_7 + Y_8)}{(Y_1 + Y_2 + Y_3 + Y_4) + (Y_5 + Y_6 + Y_7 + Y_8)} \quad (3.38)$$

and so on for other mimicked helicity reversal frequencies at $f = 160, 120, 96, 80, 60, 40, 30, 20$ and 15 Hz respectively.

Figure 3.24

Asymmetry widths for 'QRT' vs. 'Pair' ordering at different mimicked helicity reversal frequencies.

Asymmetry widths for both ‘QRT’ and ‘Pair’ patterns were then extracted as shown in Figure 3.24. The procedure was repeated to mimic asymmetry widths at various pump speeds. Then, a pseudo pump speed scan was done by fitting mimicked asymmetry widths against pump speeds at a given mimicked helicity reversal frequency. The fit gave the target boiling width at that mimicked helicity reversal frequency. Doing the same for every mimicked helicity frequency, one can estimate the dependence of the target boiling contribution on the helicity reversal rate. Figure 3.25 shows $1/f^{0.4}$ variation of the boiling width with the helicity reversal frequency (f). It also provides strong evidence that the ‘QRT’ ordering suppresses noise better than the ‘Pair’ ordering.

3.8.4.6 Target Noise Dependence on Loop Temperature

The variation of the measured asymmetry width at different loop temperatures and pump speeds was also studied. It was assumed that any change in the measured asymmetry widths due to the changes in loop temperatures ought to be caused by the target. The loop temperature was varied from 19 K to 22 K at 35 psia and the pump speed was varied to measure the effects of density fluctuations at each temperature.

The top plot in Figure 3.26 shows the variations of measured asymmetry widths at different pump speeds and loop temperatures. The same fit model as described in Equation 3.29 was used to extract the fit parameters which were in turn used to extract σ_B at different loop temperatures like in Equation 3.30. The lower plot in Figure 3.26 shows a strong suppression of target density fluctuations with greater sub-cooling of the liquid

Figure 3.25

Boiling results at various helicity reversal frequencies.

Shown are the fits to the boiling widths from 'QRT' (solid-red) and 'Pair' (dotted black) ordering. Blue boxes show the actual measurements done at those helicity reversal frequencies.

Figure 3.26

Effect of sub-cooling of liquid hydrogen.

Top: Asymmetry widths at different loop temperatures and pump speeds. Dotted curves are the fits to the data. Bottom: Values of boiling widths (colored points) at different loop temperature and pump speeds. Solid curves describe the evolution of σ_B . See text for details.

hydrogen. Sub-cooling caused σ_B to drop from 127 ppm at 22 K to 38 ppm at 19 K for the pump speed of 28.5 Hz.

3.8.4.7 Bulk Density Reduction

The main detector response to the changes in the beam current was studied in various beam current ramps on liquid hydrogen and solid targets (Al, C). A decrease in the main detector yield was anticipated as the magnitude on the incident beam current on the liquid hydrogen increased. This is expected because higher beam current deposits more heat on the target thereby reducing the density and hence the effective length of the target seen by the beam, resulting in the decrease of the main detector yield. Once the fluid reaches dynamic equilibrium then there should be no more change in the main detector yield. However, the yield changes observed were not always in the right direction, i.e., yield increased in some cases as shown in Figure 3.27 which is unphysical.

A similar trend of yield variation was seen on the solid targets whose yields should essentially be immune to the changes in the beam current. This erratic behavior can be attributed to the incorrect subtraction of the main detector pedestal or the improper calibration of the beam current monitors or luminescence or perhaps decay of radioactive activity in the main detector shield hut. A detector pedestal is simply the yield of the detector when there was no beam in the experimental hall and can come from the remnant background or activity. Ratios of the main detector yields from hydrogen and aluminum data were taken for the same current range to eliminate the effects of improper beam current calibration. This ratio ought to take out the unphysical increase in the yield if it was coming from the

Figure 3.27

Yield changes in liquid hydrogen and aluminum targets.

A negative slope of $\sim 1\%$ over $100 \mu\text{A}$ was anticipated based on CFD calculations. An increase in the yield is unphysical. The numbers in the legend refer to the run numbers from which the data are taken.

Figure 3.28

Ratios of liquid hydrogen yield to that of aluminum.

A flat response was expected. The increase in the ratio is unphysical. See text for details.

charge normalization of the detector yield. Unfortunately, the ratio still showed the same behavior with a change of $\pm 0.8 \%$ per $100 \mu\text{A}$ of beam current. It was concluded that the bulk density reduction is no greater than 1.6% but the limitation imposed by the non-linearity of the apparatus made it impossible to extract the exact value. The experiment is immune to these effects because at high beam currents (i.e., $>150\mu\text{A}$), the non-linearity is very small.

3.9 Summary

The above sections have described the design and performance analysis of the world's highest power liquid hydrogen target. The target met its design goal to limit the asymmetry width contribution due to target density fluctuations below 50 ppm. The success of CFD calculations for the first time to design a target cell to reduce target density fluctuations has opened a new way of designing future target cells. It has been realized that the CFD calculations can be refined to estimate or improve performance of other components like the heater or the heat exchanger. Several independent techniques were developed to accurately estimate σ_B . It has been shown that a higher helicity reversal frequency helped reduce σ_B . This is encouraging for future precision parity experiments like Moller [71] which aims to run at higher helicity reversal frequency and has even tighter constraints on σ_B than Qweak had. Sub-cooling the liquid hydrogen was also found to be very effective in suppressing σ_B , something that can prove highly beneficial to the future experiments. In short, the Qweak target can be taken a successful prototype for future precision experiments.

CHAPTER 4

MONTE-CARLO SIMULATIONS

4.1 Overview

Monte-Carlo simulation studies using GEANT3 were a part of my contributions to the experiment. GEANT3 is a powerful simulation tool developed at CERN and is based on FORTRAN. GEANT3 optimized for the QWeak experiment (QWGEANT3) was used extensively in development and design of the collimators, location of the main detectors and in determining the optimum magnetic field. Extensive background studies were done using QWGEANT3, the details of which can be found in Katherine Myers's dissertation [39]. The simulation studies presented in this section are based on the Qweak Run 1 geometry. This includes the location of experimental elements based on pre-Run 1 surveys with the target cell of length 34.5 cm, $3.5 \times 3.5 \text{ mm}^2$ or $4 \times 4 \text{ mm}^2$ beam raster size, the "2007" magnetic field map and the beam energy of 1160 MeV. A rather large beamline background was found during the commissioning run. Consequently, lead (Pb) tiles of dimensions $200 \text{ cm} \times 22 \text{ cm} \times 2 \text{ cm}$ were placed in front of the main detector bars ($200 \text{ cm} \times 18 \text{ cm} \times 1.25 \text{ cm}$). The addition of the Pb pre-radiators suppressed the low energy background by about a factor of 3 and increased the photo electron yield by about a factor of 6-7, for an increase in signal to noise ratio of ~ 20 .

4.2 Main Detector Signal

The main detector signal was simulated using standard Qweak event generators. These generators calculated cross sections, asymmetries and Q^2 distribution based on the type of reactions (elastic or inelastic scattering etc.). Events were generated within the raster dimensions randomly along the length of the target volume and within angular ranges of $\Delta\theta = 2.5^\circ - 19.5^\circ$ and $\Delta\phi = \pm 17^\circ$, which cover the acceptance of the main detector 1 (beam left). The electrons are assigned random scattering energy as shown in Equation 4.8. Energy losses were calculated as the electrons propagated through the target and other “*active elements*” described in the QWGEANT3 geometry. Both the pre-radiator and the quartz bar were defined in the simulation as “active detectors” and each particle reaching an active detector was registered as a hit. Information like particle type, energy etc. of a hit were recorded for every hit in each active detector. The simulated rate at a detector is given by [39]

$$R = \frac{\mathcal{L} \cdot \Delta\theta \cdot \Delta\phi \cdot N_d}{N_t} \quad (4.1)$$

where $\mathcal{L}$ is the luminosity for the liquid hydrogen target, N_d and N_t are the number of detected and thrown particles respectively. Each event was weighted by its cross section. Particles with velocities $\beta > \frac{1}{\eta}$, where η is the refractive index of the quartz, produce Čerenkov light in the main detector quartz bars. An empirical model ([39] pg. 88) was used to estimate light production per particle (electron, positron or photon) in the quartz bar. Signal in the detector was simulated as

$$\text{Signal}_{sim} = R \times \langle N \rangle \quad (4.2)$$

where R is the rate at the pre-radiator and $\langle N \rangle$ is the average photoelectrons per particle at the quartz bar. Summing over all the particle types gave the total signal at the quartz bar.

A QTor scan was simulated by calculating the total signal using the above formula at various QTor currents by this author. Elastic $\vec{e}p$, $\vec{e}Al$, inelastic $\vec{e}p$, $\vec{e}Al$, and quasi-elastic $\vec{e}Al$ event generators were used to estimate the total signal in the main detector as shown in Figure 4.1. Signals from π^- production and from Møller scattering were not included.

At the elastic peak, about 96% of the total signal is from the elastic $\vec{e}p$ process, about 3.6% from the $\vec{e}Al$ scattering and about 0.5 % from the inelastic $\vec{e}p$ and $\vec{e}Al$ combined. Simulated signals were then compared to the actual main detector yields measured during a QTor scan at identical beam currents. The measured yields were corrected for the neutral (and therefore QTor current independent) beamline background corresponding to $\sim 0.2\%$ at the nominal elastic setting of 8921 A. The current mode data (in the units of $V/\mu A$) was then scaled by a factor of 40339 to match the value of simulation (arbitrary unit) at 8921 A. Figure 4.2 [72] shows a very good agreement between simulated (and scaled) signal and measured yields for most part of the elastic region (peak and tail down to 7500 A). However, the results from the simulations and data disagree by about 10% at the Delta resonance (6700 A of QTor current) and the discrepancy systematically increases below 6700 A of QTor current as shown in Figure 4.2. This discrepancy in simulated and measured yields can be due to omission of π^- production on the proton, non-linearity of the main detector or due to improper treatment of large energy loss radiative processes in the elastic tail.

Figure 4.1

Simulation of QTor signal.

Simulated signals in arbitrary unit (a.u.) from the elastic e-p (red), the elastic e-Al (blue), the inelastic e-p (green) and the quasi-elastic e-Al (magenta) processes are shown. The last three are multiplied by 10 to enhance visibility in the plot. Contributions from primary & secondary electrons, positrons and photons are included.

Figure 4.2

Comparison of simulated data with measured current mode data.

Measured yield was scaled to match simulated yield at 8921 A of QTor current. A sharp rise in the measured signal below 2000 A of QTor current is due to low energy electrons from Møller scattering (not yet included in simulation).

4.2.1 Inelastic Dilution Factor

Extraction of the parity-violating elastic $\vec{e}p$ asymmetry in principle needs subtraction of the parity violating inelastic asymmetry from the measured asymmetry. This is done by subtracting the product of the inelastic asymmetry and the inelastic dilution factor (fraction of the inelastic signal in the elastic signal) from the measured elastic asymmetry, and will be discussed more in Section 5.10.2. The dilution of the elastic signal due to only inelastic signals (inelastic electron-proton or inelastic electron-aluminum) cannot be measured directly and is solely determined by properly benchmarked simulations. The simulations described in the previous section were used to determine the inelastic dilution factor as

$$f_{\text{inelastic}} = \frac{\text{Inelastic signal}}{\text{Total signal}} \quad (4.3)$$

at various QTor currents (see Figure 4.3). Dilution of the elastic signal by inelastic processes at the elastic peak was found to be very small i.e., 0.02 ± 0.0005 (stat.) %.

For the inelastic asymmetry, the dilution however is $1 - f_{\text{inelastic}}$ at 6700 A which is about 73% from Figure 4.3. But, as discussed earlier, there is about 10% discrepancy between simulated and measured data at the inelastic peak which makes the estimation of the dilution factor of 73% at the inelastic peak slightly less accurate. Parity violating inelastic asymmetry at the Δ resonance is extracted by subtracting the product of parity violating elastic asymmetry and the dilution from the elastic tail at the inelastic peak. Therefore, it is important to reduce this disparity for correct interpretation of the parity-violating inelastic asymmetry.

Figure 4.3

Inelastic dilution factor as a function of QTor current.

Red lines point to the inelastic dilution factor at the nominal elastic running point of QTor at 8921 A.

4.3 Main Detector Energy Sensitivity

Asymmetry corrections due to changes in helicity-correlated beam energy changes were the largest false asymmetry corrections, and will be discussed in the next chapter. Energy sensitivity was determined by linear regression on natural beam motion and also by deliberately changing the beam energy. Energy sensitivity was determined by this author from simulation by varying the beam energy from -2% to +1% of the nominal 1.160 GeV. The total light yield from the elastic $\vec{e}p$ process was simulated at various beam energies using relation 4.2. A second order polynomial

$$Y = p_0 + p_1 E + p_2 E^2 \quad (4.4)$$

where p_0 , p_1 and p_2 are the fit coefficients and E is the beam energy was fit near the region of interest ($E = 1.160$ GeV) to extract the fit parameters: p_0 , p_1 and p_2 (see Figure 4.4). Equation 4.4 was then differentiated with respect to E and then normalized to convert dY/dE to $\frac{dY/dE}{dE/E}$, hence dimensionless units of ppm/ppm.

Energy sensitivities at various QTor currents were estimated using this procedure based on Run 1 conditions. Figure 4.5 shows a net negative energy sensitivity at the nominal operating point of QTor current (8921 A), which decreases with an increase in magnetic spectrometer current.

An increase in the QTor current changed the acceptance of the main detector system, bending more of the electron profile scattered from the upstream window of the liquid hydrogen cell on to the main detector bars. A lower nominal field was deliberately chosen

Figure 4.4

Determination of energy sensitivity.

Simulated light yield variation for $\vec{e}p$ scattering with beam energy (blue points) is shown. The red curve is a second order polynomial fit to these points.

Figure 4.5

Comparison of energy sensitivities from simulation and measurements.

Sensitivities were determined by linear regression on natural beam motion (red circles) and by modulation of energy (green triangles). Both simulation (blue boxes) and data suggest a decrease in energy sensitivity with an increase in QTor current. Note: A 1% increase in QTor current moved the scattered beam envelope radially outward by ~ 1 cm.

to reduce the number of electrons scattered off the upstream window from reaching the main detectors.

Figure 4.6

Energy sensitivity variation with MD octants.

Left: Octant dependence of the energy sensitivity. An average energy sensitivity of -7.55 ± 0.33 ppm was seen in this run, but with a ± 5 ppm/ppm variation across the bars. Right: Typical shape of the energy sensitivity for the eight octants without octant dependence.

Early in Run 1, a dipole shape of energy sensitivity was noticed in the MD system (Figure 4.6:left) [73]. In an ideally symmetric MD system, all the eight detectors should have the same energy sensitivity, more or less as that shown in Figure 4.6:right. The observed variation of energy sensitivity suggested a possibility of misalignment of the MD bars such that the scattered electron profiles reached the individual bars at different radii [74].

Figure 4.7

Simulated variation of energy sensitivity with MD bar.

A one cm net displacement of the MD was not enough to explain the observed magnitude of energy sensitivity.

Simulations were done by this author to check if a net MD displacement was causing the observed pattern. Displacing the entire MD array to the left by a cm produced a similar dipole pattern of energy sensitivity (Figure 4.7), the magnitude of which was about half of the observed value. Hence, this relatively large simulated misalignment was not able to explain the energy sensitivity in Figure 4.6:left. Different studies and survey results also ruled out the possibility of having more than half a cm of misalignment in the entire MD system. Witness plates [75] and Region III tracking data both independently confirmed that the MD system was aligned to its nominal radius well within 0.5 cm. Later, this variation of the energy sensitivity was explained, to a great extent, by residual dispersion¹ of the electron beam at the target. It was also found that the energy modulation affected X_{tgt}

¹Changes in X and Y position of the beam at the target due to energy changes in the beam.

and Y_{tgt} [76] movement during energy modulation cycles, i.e., energy modulation affected position at the target causing a dipole shape in the energy sensitivity.

4.4 Electromagnetic Radiative Correction

Electrons lose energy in the target mainly via the continuous process of ionization and the discrete process of Bremsstrahlung. Effects of radiative losses due to the electromagnetic interaction must be included to correct the measured asymmetry data. This section discusses the need for such a correction and two approaches used by the author to determine a radiative correction factor for Wien 0 and Run 1.

Figure 4.8

Schematic of radiative energy loss in elastic electron-proton scattering.

IB emission can occur before or after scattering, hence the terms *ISR* and *FSR* (see text). The circle represents a zoomed in scattering vertex. Points A and A' represent points infinitesimally close to the scattering vertex before and after scattering.

Emission of real or virtual photons reduces the energy of the electrons in the target medium. This radiation (see Figure 4.8) can be emitted due to:

- the interaction of the incident electron with the scattering nucleus. This causes emission of real photons before or after and the process is termed internal Bremsstrahlung (*IB*) emission. Initial state radiation (*ISR*) affects the Q^2 and the asymmetry of the interaction whereas the final state radiation (*FSR*) reduces the total available energy after scattering, thereby changing the acceptance of scattered electrons in the detectors.
- the interaction of the incident electron with nuclei other than the scattering nucleus before and after the actual scattering. Real photons are emitted in what is commonly known as external Bremsstrahlung (*EB*) emission.

The measured asymmetry needs to be corrected for the effects due to *IB* and *EB*. The radiative correction factor, R_{RC} is defined as

$$R_{RC} = \frac{A_{Tree}}{A_{Rad}} \quad (4.5)$$

where A_{Tree} is the asymmetry calculated without considering energy loss via radiation. In other words, only ionization energy loss is taken into account while calculating A_{Tree} . A_{Rad} , however, includes contributions from both *IB* and *EB* in addition to the ionization energy loss. Hence, R_{RC} gives a measure of the change in the measured asymmetry due to radiative processes. R_{RC} can be estimated within the framework of GEANT3 as it provides reliable energy loss routines for both ionization and *EB* energy losses, and reliable assumptions can be made to estimate *IB* energy losses. The next two subsections discuss two ways of estimating R_{RC} and have been used for corrections in Wien 0 [52] and Run 1 (this dissertation).

4.4.1 R_{RC} for Wien 0

The radiative correction factor for Wien 0 was determined using the available energy approach. Available energy is defined as the net energy an electron has just before scat-

tering and is calculated by subtracting energy losses from various processes like ionization and bremsstrahlung. The elastic $\vec{e}p$ generator in the standard QWGEANT3 randomly selects a point along the target length of the specified target as the scattering vertex. Energy loss up to this point is calculated by GEANT3 routines, with user input to turn on and off certain energy loss processes like ionization, EB , multiple scattering, etc. The net energy at the scattering vertex (energy at A in Figure 4.8) is then used to determine the asymmetry and Q^2 . The zeroth order cross section is modified to account for IB at the scattering vertex and the second order correction in α (fine structure constant) is given by Equation 8.81 in [77]

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_0 \left(1 - \frac{2\alpha}{\pi} \ln \left[\frac{E}{k_{cut}} \chi(Q^2) \right] \right) \quad (4.6)$$

where E is the electron vertex energy (corresponding to energy at A in Figure 4.8) and k_{cut} is the elastic infrared cut-off energy.

$$\chi(Q^2) = \ln \left(\frac{Q^2}{m_e^2} - 1 \right) \quad (4.7)$$

where m_e is the rest mass of the electron. For the Qweak kinematics, where $k_{cut} \ll E$, the reduced energy (at point A') corresponding to the corrected cross section is given by [78]

$$E_{A'} = E_A \times \left[1 - \exp \left(-RNDM \times \frac{\pi}{2 \times \alpha \times \chi(Q^2)} \right) \right] \quad (4.8)$$

where $RNDM$ is a random number. The difference in the energy at A and A' gives the total IB . In this model, an IB photon is assumed to be collinear with the outgoing electron such that the emitted photon does not affect Q^2 but changes the acceptance of the scattered

electron. However, the total IB is not divided into ISR and FSR making it impossible to identify if an IB photon was emitted before or after scattering.

The following cases were simulated to study the effects of various radiative losses to the asymmetry :

- Case Ia: Energy loss from ionization and EB up to point A in Figure 4.8 were calculated using standard GEANT3 routines. The net energy (total energy minus energy lost) was then used in the calculations of the asymmetry (A_{Rad}^{EB}) and Q^2 at point A.
- Case Ib: From the same simulation output file (ntuple) for Case Ia, energy at point A with energy loss only from ionization was calculated using $E = 1160 - dE/dX \times t$ where t is the distance between the upstream end of LH2 and the randomly selected scattering vertex. This energy was used to calculate A_{Tree} and Q^2 at point A.
- Case II: Taking energy loss from EB and $1/2 IB$ at point A, the asymmetry and Q^2 were calculated.
- Case III a: Simulated Q^2 and the asymmetry with ionization, EB and IB all turned on.
- Case III b: Taking the ntuple from Case III a, energy at A with energy loss only from ionization and IB was calculated as $E = 1160 - dE/dX \times t - (E_A - E_{A'})$ where E_A and $E_{A'}$ are the energies at A and A' respectively. Using this energy, the Q^2 and the asymmetry (A_{Rad}^{IB}) were simulated.

It should be noted that going from case I to III, the net energy loss increased. As a result, Q^2 was reduced as shown in Figure 4.9. It was found necessary to have all three cases simulated inside a single simulation because separate simulations, even with the same random seed, produced different number of events at the detector.

The corrections due to EB and IB are defined as

$$R_{EB} = \frac{A_{sim}^{Tree}}{A_{sim}^{EB}} \quad (4.9)$$

which is the ratio of asymmetries from case Ib and Ia. Similarly,

$$R_{IB} = \frac{A_{sim}^{Tree}}{A_{sim}^{IB}}. \quad (4.10)$$

Figure 4.9

Q^2 variation with pre-scattering energy.

Pre-scattering energy is defined as the energy at point A of Figure 4.8. Shown are the values of Q^2 for various cases described above.

Depolarization due to radiative energy loss was found negligible ($<0.11\%$) for elastic scattering [79]. $R_{depol.} = 1.0011$. The results of the above mentioned studies are shown in Table 4.1

Table 4.1
Radiative correction summary for Wien 0

Case	$\langle Q^2 \rangle$ (GeV/c) ²	Elastic asymmetry (ppm)	Correction factors
I a: Ionization + EB	0.0249	0.2202	$R_{EB} = 1.0040$
I b: No rad.	0.02501	-0.2211	
II: Ionization + EB+ IB	0.02475	0.2189	$R_{IB} = 1.0117$
III a: Ionization + EB+ IB	0.0246	0.2174	
III b: Ionization + IB	0.02471	-0.2185	

Putting together all the corrections, the total radiative correction factor was calculated as

$$R_{RC} = R_{EB} \times R_{IB} \times R_{depol} = 1.017 \pm 0.005 \quad (4.11)$$

where the error bar is to account for the fact that this method can not separate contributions from ISR and FSR, and hence R_{IB} is a slight overestimation of the correction factor we need.

4.4.2 R_{RC} for Run 1

As a check to Wien 0 result, a more sophisticated approach used for the G0 experiment [80] was implemented. This approach is based on Tsai's [81] prescription of the radia-

tive correction. Original codes from the G0 experiment were modified for Qweak by this author, the details of which are discussed next.

In this approach, the energy at the scattering vertex is calculated by a separate sub-routine within the QWGEANT3 simulation framework. The energy at the scattering vertex minus the ionization losses at the target entrance window and liquid hydrogen is given by

$$E_s = 1160(MeV) - \left(\frac{dE}{dZ}\right)_{Al} \times t_{Al} - \left(\frac{dE}{dZ}\right)_{LH2} \times t_{LH2} \quad (4.12)$$

where Z is the location of randomly chosen scattering vertex location, $(\frac{dE}{dZ})_{Al}$ and $(\frac{dE}{dZ})_{LH2}$ are respectively ionization energy loss in Al and LH2, and t_{Al} and t_{LH2} are respectively the thicknesses of aluminum and liquid hydrogen traversed by the beam before scattering, respectively. This ensures the beam undergoes the same energy loss in various simulations of A_{Tree} and A_{Rad} . Elastically scattered electrons will have an energy of

$$E' = \frac{E_s}{1 + 2\frac{E_s}{M} \sin^2(\theta/2)} \quad (4.13)$$

where θ is the scattering angle and M is the mass of the proton.

A_{Tree} is calculated using E_s and θ , and has no corrections due to radiative effects. To calculate A_{Rad} the energy spectrum is divided into a peak and a tail region. An event is said to be in the peak region if its energy E_p is within 1 MeV of an elastically scattered electron energy (E') at that point, i.e., $\Delta E \simeq 1$ MeV. The choice of 1 MeV is arbitrary as long as the difference between the cross sections at the energies E_s and $E_s - R\Delta E$ is less than 10% [81]. $R\Delta E$ is the maximum amount of energy that can be taken away by the radiated photons,

$$R \equiv \frac{\omega_s}{\omega_p}. \quad (4.14)$$

ω_s and ω_p are the maximum energies of the photons that can be emitted in the direction of the incident and the scattered electron respectively and are defined as

$$\omega_s = \frac{1}{2} \frac{u^2 - M_p^2}{M - E_p(1 - \cos \theta)} \quad (4.15)$$

and

$$\omega_p = \frac{1}{2} \frac{u^2 - M_p^2}{M + E_s(1 - \cos \theta)}. \quad (4.16)$$

u^2 is the missing mass squared given by

$$u^2 = 2m_e^2 + M_p^2 + Q^2 + 2M_p(E_s - E_p). \quad (4.17)$$

The radiatively corrected peak cross section is given by modified² Equation 2.16 in [81]

$$\frac{d\sigma_{peak}}{d\Omega} = G(\theta, t_{H2}) \frac{d\sigma_{unrad}}{d\Omega} e^{\delta} \left(\frac{R\Delta E}{E_s} \right)^{bt} \left(1 - \frac{\xi}{\Delta E} \right) \quad (4.18)$$

where $\frac{d\sigma_{unrad}}{d\Omega}$ is the unradiated cross section. ξ is a parameter in Landau straggling given by Equation 2.5 in [81].

$$\xi = 0.154 \frac{Z}{A} T X_0 \quad (4.19)$$

where T is the target thickness in radiation length and X_0 is unit radiation length in gm/cm².

$G(\theta, t_{H2})$ is given by Equation 2.17 in [81] as

$$G(\theta, t_{H2}) = 1 + 0.5772 b_{H2} t_{H2} + \frac{\alpha}{\pi} \left[\frac{1}{6} \pi^2 - \Phi \cos^2 \left(\frac{\theta}{2} \right) \right]. \quad (4.20)$$

The last term in Equation 4.20 is the Schwinger correction term and Φ is the Spence function defined as

$$\Phi(x) = \int_0^x \frac{-\ln |1-y|}{y} dy. \quad (4.21)$$

²A correction term due to EB losses after actual scattering is not included here as it is already included in GEANT3.

The term $bt = b_{H_2}t_{H_2} + b_{Al}t_{Al}$ where t_{H_2} is the length of liquid hydrogen, in terms of radiation length, from the upstream window to the scattering vertex and t_{Al} is the length of the upstream window also expressed in radiation length. The factor b is nearly equal to $\frac{4}{3}$ and is given by

$$b = \frac{4}{3} \left[1 + \frac{1}{9} \frac{(Z+1)}{(Z+\eta)} \ln (183 Z^{-1/3})^{-1} \right] \quad (4.22)$$

where Z is the atomic number and

$$\eta = \frac{\ln(1440 A^{-2/3})}{\ln(183 Z^{-1/3})} \quad (4.23)$$

is the term due to bremsstrahlung emission and A is the atomic weight.

The events which have $E_p < E' - \Delta E$ will have radiated a large amount of energy and thus will be in the tail region. The tail cross section involving corrections for ionization, internal and external bremsstrahlung and virtual photons is given by modified Equation 3.1 in [81] as

$$\begin{aligned} \frac{d\sigma_{tail}}{d\Omega dE_p} = v_s^{b(t+t_r)} & \left[\left(\frac{d\sigma_{el}(E_s - \omega_s)}{d\Omega} \right) \frac{M + (E_s - \omega_s)(1 - \cos \theta)}{M - E_p(1 - \cos \theta)} \right. \\ & \left. \left((t + t_r) \frac{b}{\omega_s} \phi(v_s) + \frac{\xi}{2\omega_s^2} \right) + \frac{d\sigma_{el}(E_s)}{d\Omega} \left(bt_r \frac{1}{\omega_p} \phi(v_p) \right) \right] \end{aligned} \quad (4.24)$$

where

$$v_s = \frac{\omega_s}{E_s}, \quad (4.25)$$

$$v_p = \frac{\omega_p}{E_p + \omega_p} \quad (4.26)$$

and

$$t_r = \frac{1}{b_{H_2}} \frac{\alpha}{\pi} \left[\ln \left(\frac{Q^2}{m_e^2} - 1 \right) \right] \quad (4.27)$$

is the length of the equivalent radiator and ' t ' is the total radiation length of the target.

Equation 4.24 takes into account the combination of cases where a scattered electron might

have emitted a bremsstrahlung photon before or after the scattering in which case the energy before scattering will be $E_s - \omega_s$ and E_s respectively. Q^2 and the asymmetry in the tail region are formed by weighting the corresponding Q^2 or asymmetry with their corresponding cross sections as [80]

$$A_{tail}^{Rad} \left[\frac{d\sigma_{tail}}{d\Omega dE_p} \right] = v_s^{b(t+t_r)} \left\{ \left[A_{PV}(E_s - \omega_s) \frac{d\sigma_{el}(E_s - \omega_s)}{d\Omega} \right] \frac{M + (E_s - \omega_s)(1 - \cos \theta)}{M - E_p(1 - \cos \theta)} \right. \\ \left. \left[t(1 - D_{tot}^{ext}) + t_r(1 - D_{tot}^{int}) \frac{b}{\omega_s} \phi(v_s) + \frac{\xi}{2\omega_s^2} \right] + A_{PV}(E_s) \frac{d\sigma_{el}(E_s)}{d\Omega} \left(bt_r \frac{1}{\omega_p} \phi(v_p) \right) \right\} \quad (4.28)$$

where $A_{PV}(E_s - \omega_s)$ is the asymmetry of the electrons which emit photons of energy ω_s prior to the scattering, D_{tot}^{ext} is the total depolarization in LH2 and Al due to *EB* [80], [82] and D^{int} is depolarization due to *IB* [80], [83].

4.4.2.1 Results

Six million events were thrown in each of the simulation cases described below to extract $A_{T_{ree}}$ and A_{Rad} .

- Case I : Includes only E_s to calculate the asymmetry and Q^2 , no corrections for *IB* or *EB*. This gives $A_{T_{ree}}$.
- Case II : Includes only ionization correction to the asymmetry and Q^2 . Result should and does match with result from Case I.
- Case III : Includes ionization and *EB* corrections to the asymmetry and Q^2 .
- Case IV : Includes ionization and *IB* corrections to the asymmetry and Q^2 .
- Case V : Includes all ionization, *EB* and *IB* corrections to the asymmetry ($A_{Rad.}$) and Q^2 .

Table 4.2 shows the Q^2 and asymmetry results for the various cases mentioned above.

Unlike the procedure used in Wien 0, this procedure has a better handle on *IB* and all

Table 4.2

Results from the Tsai based radiative correction for Run 1.

Case	$\langle Q^2 \rangle (GeV/c)^2$	Asymmetry (ppm)
Tree level	0.02493	-0.2211 (A_{Tree})
Ion. correction only	0.02493	-0.2212
Ion. + EB corrections	0.02486	-0.2204
Ion. + IB corrections	0.02480	-0.2199
Ion. + EB + IB corrections	0.02472	-0.2190 ($A_{Rad.}$)

the corrections including depolarization can be calculated at the same time. Using Equation 4.5, $R_{RC} = 1.0096 \pm 0.0012$ (stat.).

The predictions of this Tsai based model were further investigated by comparing elastic $\vec{e}p$ rates at different Qtor currents to the rates from standard QWGEANT3 simulations and rates from event mode data [84] as shown in Figure 4.10. The simulated rates are obtained only from elastic $\vec{e}p$ scattering whereas the data contain all possible interactions. There is a 2-3% agreement between both the simulations and the data at the elastic peak, which is dominated by elastic $\vec{e}p$ scattering. Simulated rates from both models fall short of the measured rates in the tail region, partly because processes other than elastic $\vec{e}p$ scattering are not included in the simulations. The Tsai based model gives a slightly smaller (8%) disagreement with the data compared to the standard QWGEANT3 rate (10%) at QTor current of 6700 A (inelastic peak).

The effect of varying the size of the elastic window was studied by setting $\Delta E = 1$ MeV and 2 MeV. For $\Delta E = 2$ MeV, $R_{RC} = 1.0161 \pm 0.0012$. The elastic $\vec{e}p$ rate predicted at the elastic peak for the $\Delta E = 2$ MeV window was found to be about 15% smaller

Figure 4.10

MD rates from simulation and measured event mode data.

Sim 1 (blue triangles) is from the standard Qweak simulation, *Sim 2* (red inverted triangles) is from the Tsai based model and event mode data is shown by the black curve. The vertical dashed magenta line points to the nominal QTor running point of 8921 A. See text for details.

than the measured rate. It was found that the elastic cross section changed by more than 10% outside the $0.8 < \Delta E < 1.2$ MeV window, the reason for which is not very well understood. The difference in the central values of R_{RC} at $\Delta E = 1$ and 2 MeV is taken as an additional error. Hence, for Run 1 $R_{RC} = 1.0096 \pm 0.0065$.

CHAPTER 5

ANALYSIS

This chapter presents a detailed description of the analysis and extraction of the parity violating physics asymmetry (A_{PV}^{ep}) from the measured raw asymmetry. All the asymmetry results presented in this chapter have an additive blinding factor discussed later in Section 5.13. Examples will be given on criteria for data selection and correction procedures.

5.1 Experimental Asymmetry

Integrated MD raw signals ($Y_{raw}^{+/-}$) from the Qweak ADC's were corrected for beam off (pedestal) signals (Y_{ped}) and then normalized by the beam current ($I_{beam}^{+/-}$) as follows [46]:

$$Y^{+/-} = \frac{(Y_{raw}^{+/-} - Y_{ped})g}{N} / I_{beam}^{+/-} \quad (5.1)$$

where g is the ADC gain to convert ADC counts to volts, and N is the number of samples per MPS in the $2 \mu s$ window [46]. Normalized yields were calculated for every MPS window of a quartet to form a PMT asymmetry, defined as ([46] pg. 88)

$$A_{PMT} = \frac{(Y_1^+ + Y_4^+) - (Y_2^- + Y_3^-)}{(Y_1^+ + Y_4^+) + (Y_2^- + Y_3^-)} \quad (5.2)$$

where $Y_i^{+/-}$ are the MPS yields in a quartet in a given PMT. The main detector (MD) asymmetry used in this thesis was exclusively calculated as the average of the asymmetries from all 16 PMTs, to ensure gain mismatches between the PMTs do not increase the false asymmetries [85]. False asymmetries due to various electronic leakages were found to be very small, details of which can be found in ([19] chapter 5).

The following sections will discuss data quality and various corrections to the experimental asymmetry to obtain the A_{PV}^{ep} using Equation 5.42.

5.2 Run 1 Data Quality Overview

Data used in this analysis were collected between February-May 2011. The size of this data set is about 9 times the size of the data set used in the first Qweak publication of the proton's weak charge [52]. There were five Wien periods (1-5) and 95 slugs (42-136) in Run 1 (see Table 5.1). A slug contains about 8 hours of data. Slugs 135-136 were omitted from this analysis because they have very few data and thus have large statistical errors of about 7 times the size of asymmetry. The next few subsections offer a preliminary look at Run 1 data at the runlet¹ level and offer cuts based on the properties of various asymmetry and beam line monitors. For visualization purposes, some of the plots are binned at the slug or Wien level.

5.2.1 Basic Data Quality Cuts

Several global data quality cuts were implemented in the Qweak analyzer. These include cuts on hardware read-out errors and beam modulation data. BPM, BCM and

¹about 4-5 minutes of data. A run has about 12 runlets and is about an hour long.

Table 5.1

Wien numbering, Wien states, slug ranges and number of slugs in each HWP state per Wien.

	Wien	Wien flip	Slug Range	Number of IN/OUT slugs
	0	Right	31-40	4/6
Run 1	1	Left	42-58	9/8
	2	Right	59-80	11/11
	3	Left	81-98	9/9
	4	Right	99-116	8/10
	5	Left	117-136	10/10
Run 2	6	Right	137-155	10/9
	7	Left	156-171	8/8
	8	Left	172-225	27/27
	9	Right	226-306	41/40
	10	Right	307-321	7/8
Total				144/146

There is also an additional ‘g-2’ flip in Run 2.

Čerenkov detector related cuts were used to remove quartets with BPM signal saturations, ADC errors, low current and unstable beam periods (beam trips) and large fluctuations in the main detector yields ([46] pg. 90). All the analysis and plots presented herein contain data from runlets labeled as ‘good’ in Run1Pass5b database and have $|\text{charge asymmetry}| < 10$ ppm. Slug 63 was found to have a large asymmetry regression correction (1.7 ppm) and was dropped from the analysis. Additional potential cuts will be discussed in subsections to follow.

5.2.1.1 Pedestal Survey

Helicity correlated pedestal differences provide information about any potential pickup of the helicity signal into the ADCs, as well as the electronics noise level. The former is

given by the mean in a distribution of helicity correlated pedestal differences and the latter is provided by the RMS width. Leakage of the helicity signal can potentially be a source of false asymmetry in the detectors. For example, $0.01 \mu\text{V}$ of helicity correlated signal difference in the main detector signal (typically $\sim 6 \text{ V}$) could introduce a false asymmetry of $\frac{0.01 \mu\text{V}}{6 \text{ V}} = 1.7 \text{ ppb}$. The main detectors and the BCMs, the two most important monitors to measure asymmetry, showed helicity signal pickup was less than 1 ppb for the entire experiment [86]. The level of electronics noise, given by the width of the distribution, was found to be stable around $25 \mu\text{V}$ for the main detectors, corresponding to $\sim 4 \text{ ppm}$ of electronic noise for typical MD signals. Helicity pickup in the luminosity monitors was also found to be less than 1 ppb.

Figure 5.1

Pull distribution for all Qweak detector channels and beamline monitors.

Data are from the pedestal runs taken during the Qweak experiment. The black curve is the Gaussian fit. The ostensibly non-zero mean is probably statistical and corresponds to roughly $0.1 \pm 0.06 \text{ ppb}$.

Because many channels were examined in many pedestal runs, it was of no surprise to find a few that were non-zero by 3-4 σ off the mean. A pull plot is helpful in evaluating data points that pull the mean of the distribution. Define the pull variable as,

$$\sigma(Ped)_{i,j,k} = \frac{\langle P \rangle_{i,j,k}}{Error_{i,j,k}} \quad (5.3)$$

where $\langle P \rangle$ is the mean helicity correlated pedestal difference and the indices i, j and k denote channel number, run number and IHWP state respectively. Figure 5.1 shows a gaussian distribution of $\sigma(Ped)_{i,j,k}$ for all Qweak detector channels.

Five minute pedestal runs were taken every shift (8 hours) and at every no beam period. Pedestal files were updated regularly. Pedestals were subtracted from the detector yields (Equation 5.1) so as not to cause significant non-linearity². For example, a 120 mV pedestal error would cause a $\frac{120mV}{6V} \sim 2\%$ non-linearity. The main detector pedestal subtracted signal mean was found to be around 1 mV for the entire experiment resulting in a non-linearity from pedestal errors of $< \frac{1mV}{6V} = 0.02\%$. More details about this study can be found in [86].

5.2.1.2 Stability of Main Detector Yield

PMTs at the ends of each detector bar were occasionally roughly gain matched by adjusting the high voltages during the experiment and then more accurately matched offline. Raw yields were normalized by the beam current using relation 5.1. The software-matched yields were stable within 5%. Approximately 1-2% hour-scale oscillations from temperature drifts in the experimental hall are seen in the main detector yields. A typical PMT

²The software offsets used for BPM's and BCM's are not the beam-off pedestals but rather the result of careful fits. This is because RF signal processing can be highly non-linear for small signal amplitudes.

yield over the entire Run 1 is shown in Figure 5.2. There is no evidence of beam scraping in the form of large spikes.

Figure 5.2

Normalized yield of MD 7 positive PMT through Run 1.

Each dot represents a runlet. Red lines separate five Wien periods.

5.2.1.3 Beamline Background Detectors' Yield

Soft background was monitored using a set of dedicated background detectors (MD9, PMTONL, PMTLTG) outside the elastic electron envelope as well as the upstream luminosity monitor (US lumi). Positions of the first three detectors were changed during Run 1 as mentioned in section 2.9.1. Most of the dilution from these soft backgrounds is consistent with the electrons scattering in the target and striking the downstream beamline [39].

Figure 5.3

Yields of various background detectors during Run 1.

The jump in PMTLTG and PMTONL yields is due to the changes in their location. Vertical red lines mark the boundaries of Wiens 1-5. All background detectors show relatively stable yields, including a few percent change due to temperature oscillations.

This is loosely referred to as the ‘beamline background.’ The US lumi was critical for the beamline background correction of the regressed asymmetry and will be discussed later in section 5.5. Yields of all four background detectors were studied in both locations during Run 1. The high voltages were adjusted only after the move to prevent saturation. Yields of PMTLTG, PMTONL and MD9 fluctuated about 5 % in both locations whereas [87] that of US lumis fluctuated by about 10% through Run 1. No visible increase in the background yield was seen when the beam raster size was changed from 3.5 mm to 4 mm. The stability of the background detectors’ yield is strong evidence that there was no serious scraping by the electron beam which might have temporarily increased the soft background dilution.

5.2.1.4 Charge Asymmetry

The charge asymmetry (A_q) measurement is critical since the yield-based asymmetry in Equation 5.2 can be shown to be [88]

$$A_{\text{PMT}} = A_{\text{signal}} - A_q. \quad (5.4)$$

Corrections for charge asymmetries were typically 200 - 1000 ppm per quartet, much larger than any other correction.

The A_q for a BCM is defined as

$$A_q = \frac{(I_1^+ + I_4^+) - (I_2^- + I_3^-)}{(I_1^+ + I_4^+) + (I_2^- + I_3^-)} \quad (5.5)$$

where $I_i^{+/-}$ are the beam currents as measured by a BCM in a quartet. An active charge feedback system was used to help suppress the charge asymmetry [46].

Figure 5.4

Histogram of mean charge asymmetry for all the runlets in Run 1

Data are weighted by MD error and are not sign corrected for Wien and HWP flips.

Figure 5.4 shows the distribution of the Run 1 A_q with a mean of -135.6 ppb. To prevent rare runlets with very large $|A_q|$ from having a significant effect on the Run 1 charge asymmetry, only runlets having $|A_q| < 10$ ppm were used in the analyses.

Charge asymmetries were measured by both BCM 1 and 2 and their average was studied in [89]. Errors on BCM 1, 2 and the charge asymmetries were derived from the BCM resolution. The resolution of a BCM was determined through the width of the differences of the charge asymmetries or BCMDD as given by

$$\begin{aligned} \delta A_q(BCM1/2) &= \frac{\delta(BCMDD)}{\sqrt{2}} \\ \delta A_q(charge) &= \frac{\delta(BCMDD)}{2}. \end{aligned} \tag{5.6}$$

where ‘ δ ’ denotes the rms of the distribution.

Figure 5.5 shows that the charge feedback almost always gave a large negative average A_q . Wien and HWP sign flips helped suppress the overall charge asymmetry but the scatter in the sign corrected charge asymmetries was still large enough to yield a relatively large average. As shown in Figure 5.6, the net effective charge asymmetry for $\langle \text{IN}, -\text{OUT} \rangle^3$ in Run 1 was -68 ± 3 ppb. It is however encouraging that the A_q as measured by BCM 1 & 2 roughly agree given that no correction has been made for differential position sensitivities in the two BCMs.

Figure 5.5

Charge asymmetry through Wiens 1-5.

Charge asymmetries in IN (blue boxes) and OUT (red circles) half wave plate states for Wiens 1-5. Data are not corrected for Wien or HWP flips which would have obscured the fact that the charge asymmetry was systematically negative.

³sign corrected physics asymmetry. See Section 5.3 for details.

Figure 5.6

Charge asymmetry measurements during Run 1.

Shown are the values for $\langle \text{IN}, -\text{OUT} \rangle$ charge asymmetry as measured by BCM 1 and 2. There is apparently good agreement between BCM1 (blue boxes) and BCM 2 (green triangles) within statistical errors. The solid black line represents the average charge asymmetry. Data are sign corrected for HWP and Wien flips.

5.2.1.5 Linear Regression

Multivariate linear regression schemes were implemented to determine sensitivity slopes and to correct for the false asymmetries created by helicity correlated beam property differences. The regressed asymmetry is given by $A_{reg} = A_{raw} + A_{false}$.

$$A_{false} = - \sum_i \frac{\partial A}{\partial \chi_i} \Delta \chi_i \quad (5.7)$$

where $\frac{\partial A}{\partial \chi_i}$ are the sensitivities of the measured detector asymmetry and $\Delta \chi_i$ are helicity correlated beam parameter differences (X/Y positions and angles, energy and sometimes charge). A detailed discussion of various linear regression schemes on the natural beam motion for the Qweak experiment is presented in Section 5.4.

5.2.1.6 Detector Sensitivities

Detector sensitivities to the respective IV's were determined from a runlet. Only data with beam current $> 100 \mu\text{A}$ were included to extract sensitivity slopes from the linear regression. Sensitivities varied from slug-to-slug as shown in Figure 5.7. Typical sensitivities for the IV's used in the “5+1” linear regression scheme can be found in Table 5.2. Some of the observed changes can perhaps be attributed to large drifting residual dispersion at the target, changes in beam spot location (either deliberate or in the form of tiny slow drifts), changes in the fast raster size, or the beam probing the target window curvature a little differently after a target-out/target-in change.

There were correlations between energy and position/angle sensitivities. For example, there was a negative correlation between X and X' , and Y and Y' , sensitivities as shown in Figure 5.8 [90]. Charge sensitivity was negative but not too large with the exception of

Figure 5.7

MD sensitivities from “5+1” linear regression scheme.

Sensitivities are weighted by their statistical error. Points in blue and red respectively denote IN and OUT half wave plate states. The green vertical lines mark the boundaries of five Wien periods. See Section 5.4 for a discussion on various linear regression schemes.

some runlets which have a non-linearity of $\simeq 35\%$. It was recently shown by simulation that the apparent charge sensitivity was strongly biased by the effect of correlated BCM noise between the MD asymmetry and the charge asymmetry [91]. The changes in apparent charge sensitivity are mainly due to changes in the charge asymmetry width, and to a lesser extent to variation in the BCM resolution. Correction of the apparent charge sensitivities for this effect is in progress. Values of the detector sensitivities by slug and by Wien can be found in [92].

Table 5.2

Straight average over Run 1 of the “5+I” MD sensitivities to the helicity correlated beam parameters.

MD sensitivity to	Value
X position(ppb/nm)	0.06 ± 0.001
X angle (ppb/nrad)	11.28 ± 0.05
Y position (ppb/nm)	0.14 ± 0.001
Y angle (ppb/nrad)	1.27 ± 0.03
Energy (ppm/ppm)	$-4.63 \pm 3.31\text{E-}03$
Charge (ppm/ppm)	$-0.03 \pm 1.71\text{E-}05$

5.2.1.7 Helicity correlated beam property differences

Helicity correlated beam position, angle, energy and charge differences were studied in [93] and more recently in [94]. BCM 1 and 2 were used to monitor beam charge while BPMs 3h07a, 3h07b, 3h07c, 3h09, 3h09b and 3c12 were employed for the other beam parameters.

Figure 5.8

Slug level correlation of position and angle sensitivities for the “5+1” linear regression.

The errors associated with these variables were determined from the monitor resolutions as opposed to the statistical errors. A single BPM has a resolution of $1 \mu\text{m}$ per quartet and by error propagation, resolutions of target position and angle IV's were determined to be $0.98 \mu\text{m}$ and $0.13 \mu\text{rad}$ per quartet, respectively [95]. Using the nominal dispersion of $4.1 \text{ cm}/\%$ at BPM 3c12, the energy resolution was determined to be 0.42 ppm per quartet. From N quartets, the errors determined from monitor resolutions were

$$\begin{aligned} \delta(X/Y) &= \frac{0.98 \mu\text{m}}{\sqrt{N}} \\ \delta(X'/Y') &= \frac{0.13 \mu\text{rad}}{\sqrt{N}} \\ \delta E &= \frac{0.42 \text{ ppm}}{\sqrt{N}} \end{aligned} \tag{5.8}$$

about one order of magnitude smaller than the naive errors based on the beam jitter widths.

Table 5.3

Measured helicity correlated beam parameter differences for Run 1.

Parameter	Spec for the entire experiment	Run 1 $\langle IN, -OUT \rangle$	Run 1 $\frac{\langle IN \rangle + \langle OUT \rangle}{2}$
ΔX (nm)	<2	5.21 ± 0.05	-21.36 ± 0.05
$\Delta X'$ (nrad)	<30	-0.04 ± 0.007	-1.2 ± 0.007
ΔY (nm)	<2	-4.64 ± 0.055	-11.85 ± 0.055
$\Delta Y'$ (nrad)	<30	0.22 ± 0.007	-0.51 ± 0.007
ΔE (ppm)	<0.001	-0.003 ± 0.00002	-0.009 ± 0.00002
A_q (ppm)	<0.1	-0.07 ± 0.003	0.02 ± 0.003

The differences use respective monitor resolutions as errors. The average is weighted by regressed MD errors. The column labeled $\langle IN, -OUT \rangle$ includes sign flips for HWP and Wiens. The column labeled $\frac{\langle IN \rangle + \langle OUT \rangle}{2}$ includes sign flips for Wiens only.

Table 5.3 shows the weighted mean of helicity correlated beam property differences during Run 1 along with the specifications for the entire experiment. The differences (x_i) were weighted by the regressed main detector asymmetry errors (σ_i) as

$$\langle \Delta_P \rangle = \frac{\sum_{i=1}^N \frac{x_i}{\sigma_i^2}}{\sum_{i=1}^N \frac{1}{\sigma_i^2}} \quad (5.9)$$

and the error on the weighted mean is given by

$$\sigma_P = \frac{\sqrt{\sum_{i=1}^N \frac{\delta_i^2}{(\sigma_i^2)^2}}}{\sum_{i=1}^N \frac{1}{\sigma_i^2}} \quad (5.10)$$

where δ_i are errors on differences. When $\sigma_i = \text{constant}$, this equation reduces to the familiar expression

$$\sigma_P = \frac{\delta_i}{\sqrt{N}}. \quad (5.11)$$

Figure 5.9

Helicity correlated beam parameter differences during Run 1

Data are weighted by their own errors. The vertical black lines mark the boundaries of Wiens 1-5. See text for details.

Figure 5.9 shows the slug level helicity correlated beam parameter differences. Even though the differences are sometimes large for IN or OUT slugs, there is generally fair cancellation in $\langle \text{IN}, -\text{OUT} \rangle$ overall but not for $(\frac{\langle \text{IN} \rangle + \langle \text{OUT} \rangle}{2})$ in Wiens 4 and 5. See Section 5.3 for a discussion on $\langle \text{IN}, -\text{OUT} \rangle$ and $\frac{\langle \text{IN} \rangle + \langle \text{OUT} \rangle}{2}$.

Numerical results are given in Appendix C for each Wien for $\langle \text{IN}, -\text{OUT} \rangle$, $\frac{\langle \text{IN} \rangle + \langle \text{OUT} \rangle}{2}$, $\langle \text{IN} \rangle$ and $\langle \text{OUT} \rangle$. Because the sensitivities are not constant, the precise Run 1 averages in Table 5.3 are not as useful as one might expect. They do, however, make it clear that with non zero $\langle \text{IN}, -\text{OUT} \rangle$ differences with $\sim 100\sigma$ significance, there is tremendous room for improvement using feedback.

5.2.1.8 Regressed MD Asymmetry Width

The width of the regressed MD asymmetry is a clear indicator of the health of the MD signal chain. It is normally dominated by statistics with contributions from target density fluctuations and BCM resolution. A comparison of the MD asymmetry width before and after “5+1” linear regression is shown in Figure 5.10. The trivial dependence of the MD asymmetry width on the beam current can be approximately removed by the following scaling relation:

$$\sigma_{Scaled}^{MD} = \sigma_{Regressed}^{MD} \sqrt{\frac{I_{beam}}{180}}. \quad (5.12)$$

The properly regressed, scaled MD asymmetry width should be fairly constant.

Figure 5.10 [96] shows un-regressed (raw), regressed, and scaled (regressed) asymmetry width. Some runlets have unusually large unregressed widths. Linear regression almost always reduced the quartet level asymmetry width by about 2 ppm in a runlet. The scaled

Figure 5.10

Asymmetry widths through Wiens 1-5 of Run 1.

Red triangles are for unregressed, blue triangle for “5+1” regressed and green circles are “5+1” regressed, and scaled asymmetry widths. See text for details.

Figure 5.11

Regressed and scaled MD rms widths by slug.

“5+1” regressed MD rms scaled using Equation 5.12. Scaling is done to remove beam current dependence in the regressed asymmetry width. Stable MD asymmetry widths suggest absence of extra noise in the measurements. See text for details on the jump in the asymmetry width towards the end of Wien 3 and beginning of Wien 4.

widths were fairly stable around 229 ppm except for a brief period more easily seen in Figure 5.11. The jump in MD asymmetry width towards the end of Wien 3 and in the beginning of Wien 4 was apparently due to poor beam conditions that produced a BCMDD of ~ 300 ppm instead of the nominal ~ 90 ppm. Even after interrupting the beam supply to Hall A, which was then running at a high beam current, the surge in BCMDD width persisted [97]. A beam tuning in the accelerator the next day returned the MD asymmetry widths back to the nominal (~ 245 ppm) [98].

With a regressed asymmetry width cut of $\sigma_{MD}^{reg} < 255$ ppm, the Run 1 $\langle \text{IN}, -\text{OUT} \rangle = -233.06 \pm 11.63$ ppb. This represents a 1.05 ppb difference in the central value in $\langle \text{IN}, -\text{OUT} \rangle$ without this additional cut (see Table 5.8). This difference is assigned as a cut dependent systematic error on the regressed asymmetry, i.e., $|dA_{msr}_{\text{cut}}| = 1.05$ ppb.

5.3 Linear Regression Corrections

The many linear regression schemes available for the Qweak experiment can broadly be classified into charge vs. no charge, pair BPMs vs. target BPMS, and BPM 3c12 based target energy vs. 3c12 BPM variables. Table 5.4 lists all linear regression schemes [99] with clear distinction between schemes containing no-charge and charge.

The regression correction is defined as

$$\Delta A = A_{reg} - A_{raw} \quad (5.13)$$

where A_{reg} and A_{raw} are respectively the linearly regressed and raw (unregressed) asymmetry. Figure 5.12 shows ΔA by slug. Equation 5.7 gives the net linear correction which in principle is the net false asymmetry. Regression corrections were made at the runlet

Table 5.4

Linear regression schemes for the Qweak experiment.

Scheme	Position & Angle IVs	Energy IV	Charge IV	Other IV
Std.	qwk_target	qwk_energy	-	-
Set 5	bpm 9b+4, bpm 9b-4	bpm_3c12X	-	-
Set 7	bpm 9+4, bpm 9-4	bpm_3c12X	-	-
Set 11	qwk_target	bpm_3c12X	-	-
Set 12	qwk_target+4X	bpm_3c12X	-	-
Set 13	qwk_target	bpm_3c11X	-	-
“5+1”	qwk_target	qwk_energy	qwk_charge	-
Set 3	qwk_target	bpm_3c12X	qwk_charge	-
Set 4	qwk_target	qwk_energy	qwk_bcm5	-
Set 6	bpm 9b+4, bpm 9b-4	bpm_3c12X	qwk_charge	-
Set 8	bpm 9+4, bpm 9-4	bpm_3c12X	qwk_charge	-
Set 9	qwk_target	bpm_3c12X	qwk_charge	asym_uslumi_sum
Set 10	qwk_target	qwk_energy	qwk_bcm6	-

level using Equation 5.7 and then averaged to get slug-level corrections. Slug-level corrections were weighted by the regressed main detector asymmetry error to get the Wien level corrections for each beam parameter. Results from both the “5+1” and the standard linear regression schemes are summarized in Table 5.5. ‘Comb’ plots showing corrections for all beam parameters are shown in Appendix D.

Although additional corrections will be made, the quality of the linear regression is suggested by

- χ^2/dof of average sign corrected asymmetry ($\langle \text{IN}, -\text{OUT} \rangle$) through Run 1. $\langle \text{IN}, -\text{OUT} \rangle$ is the physics asymmetry (with a fixed blinding offset), which should essentially be the same for all the data sets since the polarization correction was small.
- average of all the asymmetries without accounting for sign changes due to HWP and Wien flips $\frac{\langle \text{IN} \rangle + \langle \text{OUT} \rangle}{2}$. Physics and false asymmetries that flip sign with HWP and Wien flips average to zero in this metric, leaving largely what is called the null asymmetry. A non-zero resultant asymmetry means presence of false asymmetries

Figure 5.12

“5+1” linear regression corrections by slug for Wiens 1-5.

Blue and red circles denote HWP IN and OUT slugs respectively.

that were not removed by linear regression alone. The blinding offset cancels exactly in $\frac{\langle IN \rangle + \langle OUT \rangle}{2}$.

Table 5.5

Summary of the “5+1” and the standard linear regression corrections for Run 1.

	$\langle IN, -OUT \rangle$ (ppb)		$\frac{\langle IN \rangle + \langle OUT \rangle}{2}$ (ppb)	
	Value	Error	Value	Error
Wien 1	2.11 (0.94)	1.05 (1.03)	-1.57 (-1.75)	1.06 (1.03)
Wien 2	-6.41 (-2.61)	0.53 (0.47)	-5.89 (-0.36)	0.54 (0.48)
Wien 3	13.21 (9.55)	1.03 (0.87)	-14.13 (-15)	1.04 (0.90)
Wien 4	10.08 (16.17)	1.52 (1.43)	-4.13 (-1.09)	1.55 (1.44)
Wien 5	6.15 (7.50)	1.50 (1.41)	-62.99 (-43.11)	1.55 (1.47)
Run 1	-0.18 (1.74)	0.40 (0.36)	-10.26 (-5.61)	0.40 (0.37)

Results for the standard linear regression scheme are shown in parantheses. Note the relatively large correction in Wien 5 for $\frac{\langle IN \rangle + \langle OUT \rangle}{2}$.

A rather large null asymmetry was seen in linearly regressed Run 1 data, potentially due to incomplete removal of false asymmetries by the linear regression. $\langle IN, -OUT \rangle$ averaged at different timescales showed wildly varying fit probability (probability that an observed χ^2 exceeds the value χ^2 by chance, even for a correct model [100]) as shown in Table 5.6. Data averaged at the slug level had almost zero probability, whereas data averaged at Wien level or slug pairs had non-negligible fit probabilities. A slug pair was formed by averaging two consecutive slugs with proper sign corrections. The extremely low slug

ensemble fit probability indicates the presence of slowly drifting offset-like asymmetries which are removed by slug-pair or higher averaging. These slug-level offsets are removed later in post-regression (Section 5.4.1). The “5+1” linear regression scheme is used for further data analysis in this dissertation.

Table 5.6

Fit probability of <IN, -OUT > for different time averaging through Run 1.

Binning	Probability	
	Raw	Regressed “5+1”
Wiens	0.033	0.096
Slug Pairs	4.84E-03	0.173
Slugs	1.20E-09	5.75E-06

5.4 Linear Regression Scheme Dependence

A comparison of results from various linear regression schemes applied to the Run 1 data is shown in Table 5.7 and Figure 5.13.

Previous studies have shown no difference between the two ‘3c12X’ based energy variable. This is confirmed by Table 5.7 with only 0.3 ppb difference between *Std.* and *Set 11*, and 0.5 ppb between “5+1” and *Set 3*.

Regression schemes with charge have better χ^2/dof as shown in Table 5.7 (ignoring *Set 9*) and *Set 8* has the smallest χ^2/dof (hence the highest probability). There is a 2-3 ppb negative correction when charge is included. This is close to the expected correction for the charge asymmetry i.e., charge correction $\sim$ - charge sensitivity $\times$ charge asymmetry =

Table 5.7

Comparison of $\frac{\langle IN \rangle + \langle OUT \rangle}{2}$ and $\langle IN, -OUT \rangle$ from various linear regression schemes.

Reg. scheme	$\frac{\langle IN \rangle + \langle OUT \rangle}{2}$ (ppb)	$\langle IN, -OUT \rangle$ (ppb)	χ^2/dof	Probability (%)	Comments
Off	-37.95 ± 11.62	-231.93 ± 11.57	2.62	3.31	
Std.	-52.33 ± 11.60	-229.99 ± 11.55	2.11	7.64	target BPMs
Set 5	-53.67 ± 11.60	-229.32 ± 11.55	1.93	10.28	pair BPMs
Set 7	-53.71 ± 11.60	-230.43 ± 11.55	2.01	9.02	pair BPMs
Set 11	-52.28 ± 11.60	-230.29 ± 11.55	2.17	6.91	target BPMs
5+1 (Std. + Q)	-58.12 ± 11.60	-232.01 ± 11.54	1.97	9.64	target BPMs
Set 3 (Set 11 + Q)	-57.62 ± 11.59	-232.46 ± 11.53	2.04	8.53	target BPMs
Set 6 (Set 5 + Q)	-58.92 ± 11.59	-232.61 ± 11.54	1.94	10.15	pair BPMs
Set 8 (Set 7 + Q)	-60.67 ± 11.59	-232.54 ± 11.54	1.81	12.44	pair BPMs
(Set 9	-41.28 ± 12.11	-213.93 ± 12.04	2.22	6.43)	lumi asym.
(Set 10	-50.76 ± 11.49	-226.3 ± 11.44	1.97	9.59)	BCM 6

The reduced χ^2 , & probability are for Wien level $\langle IN, -OUT \rangle$ are listed. *Off* means no regression and *Q* stands for charge. See text for details.

Figure 5.13

Comparison of various linear regression schemes.

The vertical red line separates no charge vs. charge regression schemes. The bottom plots show the probabilities for various linear regression schemes at the Wien level (left) and the slug-pair level (right).

- $(-0.0256) \times (-60)$ ppb = -1.5 ppb. There is a difference of ~ 2 ppb in net correction from charge (“5+1”) vs. no charge (*Std.*) regression schemes. This ambiguity is assigned as a systematic error on linear regression scheme dependence in this analysis.

Position and angle IVs used in various schemes have different resolutions depending on the number of BPMs used and their spacing. For example, the “5+1” uses the target BPM formed by a combination of BPMs (‘3h07a’, ‘3h07b’, ‘3h07c’, ‘3h09’ and ‘3h09b’) whereas *Set 8* uses pair BPMs (‘9+4’ and ‘9-4’) only. The locations of BPMs used in *Set 8* spanned twice the distance in the beamline as did the target BPMs. Hence, *Set 8* has better angle resolution than the “5+1”. However, the “5+1” has better position resolution as it has more BPMs. Probabilities in Table 5.7 indicate that pairs of BPM (‘9,4 or 9b,4’) give a better result than the target BPMs. This may be because the target BPM has poorer angle resolution.

Set 9 gave a much larger (18 ppb) correction than any of the other regression schemes. It was a tentative scheme to correct for beamline background, and will not be discussed further. *Set 10* uses BCM 6 as an independent variable. BCM 6 was being commissioned during Run 1, hence any result involving BCM 6 will not be included in the analysis.

5.4.1 Residual correlations

If linear regression was done right then the false asymmetries from the beam parameter differences would be completely removed. This was shown to be true at the quartet level [101], which is where the linear regression corrections are first applied. However, the sensitivities from natural beam jitter may suffer systematic errors. The fact that the MD

Figure 5.14

Residual correlations in the main detector asymmetry.

Plots of residual MD asymmetry vs. measured helicity correlated beam property differences for “5+1” regression with the first order polynomial fit. $\Delta X'$ has a highly significant residual correlation at 5σ .

width gets narrower with regression is encouraging but errors may exist. Even though there was no residual correlation at the quartet level for the “5+1” regressed data [101], a non-zero residual correlation was found at higher time averaging scales like runlets or slugs.

The residual asymmetry for a slug was calculated by subtracting the physics asymmetry with appropriate sign from the total slug asymmetry as follows:

$$\text{Residual asymmetry} = \text{Asymmetry} - \text{sign} \times \langle \text{Regressed asymmetry} \rangle . \quad (5.14)$$

The residual MD asymmetry was found to be highly correlated with helicity correlated beam parameter differences [102] for the “5+1” as well as other schemes that use natural beam motion to extract sensitivity slopes, and *dithering* that uses deliberate beam motion [103].

In Figure 5.14 there is a highly significant residual correlation (5σ) in $\Delta X'$, the rest may be due to cross-correlation with X' . A post regression correction was applied on a slug-to-slug basis to the regressed asymmetry (A_{reg}) to correct this correlation. Define the post regression asymmetry as

$$A_{\text{post reg.}}^{(1)} (\text{ppb}) = A_{reg} (\text{ppb}) - 25.88 (\text{ppb/nrad}) \times \Delta X' (\text{nrad}) \quad (5.15)$$

where 25.88 (ppb/nrad) is the X' slope from the fit in Figure 5.14 and $\Delta X'$ is slug averaged X' difference. A post regression correction as described above removed residual correlations from beam position, angle and energy differences (see Figure 5.15). Correlation to charge still existed, revealing the presence of uncorrected errors at the $\simeq 50$ ppb level

Figure 5.15

Post-regression correction.

Shown are the plots of residual correlation of MD asymmetry with beam parameter differences after correcting charge using Equation 5.16. See text for details.

for many slugs and the null asymmetry was still more than 2 sigma away from zero. A correction to the charge of the form

$$A_{msr} \text{ (ppb)} = A_{\text{post reg.}}^{(1)} \text{ (ppb)} - 0.166 \text{ (ppb/ppb)} \times \Delta Q \text{ (ppb)} \quad (5.16)$$

where 0.166 (ppb/ppb) is the residual charge slope after $\Delta X'$ correction and ΔQ is the charge difference gives the post regression corrected asymmetry A_{msr} . Both these post-regression corrections helped nullify residual correlations as shown in Figure 5.15. Table 5.8 gives the null and physics asymmetries, and χ^2/dof (in parentheses) for regression and post-regression (residual correlation corrected) asymmetries. After post regression corrections, the Run 1 null asymmetry moved to zero within 1.7σ . The χ^2/dof for individual Wiens and Run 1 overall also improved after these corrections. It is more appropriate and consistent to regress all variables simultaneously, an effort which is in progress.

The net post-regression correction is

$$A_{msr}(\text{post-reg}) = 12.2 \pm 6.1 \text{ ppb} \quad (5.17)$$

with a conservative 50% error to account for the need of such correction to the data.

The fact that the χ^2/dof for Wiens 2 and 5 improved with post-regression while Wiens 1, 3 and 4 stayed approximately the same suggests it is not the case that the linear regression is working correctly and we are being fooled by a large false asymmetry in Wien 5 from a hidden independent variable. The simplest explanation is that our linear regression based on natural jitter is sometimes woefully inadequate.

Table 5.8

Null and physics asymmetries for regression and post-regression corrections.

Wiens	Regression $\frac{\langle IN \rangle + \langle OUT \rangle}{2}$ (ppb)			Post-regression $\frac{\langle IN \rangle + \langle OUT \rangle}{2}$ (ppb)			Regression $\langle IN, -OUT \rangle$ (ppb)			Post-regression $\langle IN, -OUT \rangle$ (ppb)		
	Mean	Error		Mean	Error		Mean	Error		Mean	Error	
1	-76.99	28.31		-52.23	28.31		-277.13 ($\chi^2/\text{dof} = 1.79$)	27.84		-271.52 ($\chi^2/\text{dof} = 1.72$)	27.84	
2	10.82	23.98		12.27	23.98		-238.19 ($\chi^2/\text{dof} = 1.15$)	23.98		-218.74 ($\chi^2/\text{dof} = 0.98$)	23.98	
3	-27.59	25.55		-24.79	25.55		-222.26 ($\chi^2/\text{dof} = 1.37$)	25.55		-202.69 ($\chi^2/\text{dof} = 1.32$)	25.55	
4	-59.74	26.90		-22.25	26.90		-253.14 ($\chi^2/\text{dof} = 2.00$)	26.87		-229.00 ($\chi^2/\text{dof} = 1.99$)	26.87	
5	-149.45	25.46		-22.44	25.46		-178.95 ($\chi^2/\text{dof} = 2.77$)	25.24		-186.96 ($\chi^2/\text{dof} = 0.52$)	25.24	
Run 1	-58.12	11.59		-19.77	11.59		-232.01 ($\chi^2/\text{dof} = 1.97$)	11.54		-219.78 ($\chi^2/\text{dof} = 1.43$)	11.54	

 χ^2/dof for $\langle IN, -OUT \rangle$ are shown in parentheses.

5.5 Beamline Background Correction

Although the asymmetry of the beamline background was expected to be only of order 0-2 ppb, the US lumi, which were used as the background monitor, saw ppm-level asymmetries. These asymmetries resemble helicity correlated beam asymmetries in that they do not flip sign with HWP changes.

Figure 5.16

Determination of beamline background correction slope.

Slugs 49 and 107 had unusually large US lumi asymmetries of 18 and -46 ppm respectively, and are excluded in this and all corresponding Run 1 data analysis. See text for details.

The significant non-zero correlation between the fully regressed (including post-regression) main detector asymmetry (A_{MD}) and the US lumi asymmetry (A_{US})⁴ is used to correct for the beamline background without needing to know the beamline dilution in either the MD

⁴See Appendix F for plots on US lumi sensitivities and regression corrections.

or the US lumi. The procedure to obtain the correction slope is outlined in [104] and the steps are described next [105].

The slug level MD and USlumi asymmetries and their errors, used in Figure 5.16, were weighted by the regressed MD errors. The slope in Figure 5.16 is taken as the beamline background correction factor C_{US}^{MD} , i.e., $C_{US}^{MD} = 16.2 \pm 6$ (stat.) ppb/ppm. This correction factor is 3.6 times larger than the Wien 0 correction factor (4.5 ppb/ppm based on dilution measurements of the tungsten shutter study [106]). To account for this difference, a 50% systematic error (8 ppb/ppm) is assigned to the C_{US}^{MD} . Hence,

$$C_{MD}^{US} = 16.2 \pm 6.2(stat.) \pm 8(syst.) \text{ ppb/ppm.} \quad (5.18)$$

C_{MD}^{US} needs further work including a final post-regression for the US lumi and possibly a simulation to see if halo electrons can scatter from the target entrance tube and reach the MD. The contribution of the correlated target and BCM noise to C_{MD}^{US} was found to be negligible [107].

The beamline background correction was done on a slug by slug basis by subtracting the product of C_{US}^{MD} and A_{US} from A_{MD} . The beamline asymmetry

$$\langle A_{US} \rangle = -639 \pm 13.8 \text{ ppb} \quad (5.19)$$

such that the net beamline correction is

$$\Delta A_{BB} = -C_{MD}^{US} \times \langle A_{US} \rangle = 10.35 \pm 6.4 \text{ ppb.} \quad (5.20)$$

The error on $\langle A_{US} \rangle$ is the statistical error on the US lumi.

5.5.1 Beamline Dilution

The beamline dilution factor is required to extract A_{PV}^{ep} (see Section 5.14.) The beamline dilution factor determined for the Wien 0 f_{BB} (Wien 0) = 0.00193 ± 0.00064 [108]. Since the correction factor, C_{MD}^{US} , for Run 1 was found to be 3.6 times that of Wien 0, it is assumed that the f_{BB} for Run 1 is 3.6 times that of Wien 0 as well. This gives,

$$f_{BB}(\text{Run 1}) = 0.007 \pm 0.002. \quad (5.21)$$

5.6 Beam Polarization Correction

The measured data need to be corrected for the fact that the longitudinal beam polarization was not 100%. While the Qweak experiment had two independent polarimeters (Møller & Compton), only the Møller polarimeter was functional for the majority of the Run 1. Detailed analysis of the beam polarization is underway for both polarimeters. For the purpose of this dissertation, the beam polarization correction was done based on the Møller polarimeter measurements done during Run 1. Based on these measurements, Wiens 1 and 2 were assigned a very preliminary beam polarization of $87 \pm 2 \%$ and Wiens 3-5, $89 \pm 2 \%$. [109]. A conservative error bar of 2% is assigned to account for all the systematic and statistical errors on the polarization measurements. The total error is expected to be significantly smaller than 2%, once finalized.

The beam polarization correction was done by dividing the beamline background corrected regressed asymmetry (includes post-regression corrections as well) by the beam polarization (P). This implies a change in the main detector weighting, i.e., weighting

changes from $\frac{1}{\sigma_{MD}^2}$ to P^2/σ_{MD}^2 . A small effect was found on the probabilities for various binnings after the polarization correction [110].

5.7 Summary of Run 1 Data with Level I corrections

So far, the level I corrections (linear regression, post-regression, beamline background and polarization corrections) have been discussed. These are defined to be point to point corrections which could affect the χ^2/dof and hence the probability. The level II corrections (remaining background and experimental bias) that do not change with time will be discussed later. A pull distribution of all the slug level asymmetries with level I corrections is shown in Figure 5.17. The slug-level pull distribution is a fairly stringent test since unknown false mechanical asymmetries are not averaged away by HWP sign reversals. The few 2-3 sigma slugs are possibly consistent with being statistical fluctuations.

The probability improves significantly for all time averages (slugs, slug-pairs and Wiens) with level I corrections, as shown in Table 5.9. More detailed comparisons of the raw (un-regressed) and the level I corrected null and physics asymmetries are given in Table 5.10 and plotted in Figure 5.18. See Appendix E for more details.

Figure 5.17

Pull plot of slug asymmetries after level I corrections.

The red curve is a constrained Gaussian fit with zero mean and unit RMS. The slugs in Wien 5 (magenta), which were at ± 3 sigma before post-regression are now within ± 1 sigma. See text for details.

Table 5.9

Statistical Summary of Run 1 for three time binnings.

	Raw (Pol.)			Corrected (Level I corrected)		
	Asym (ppb)	χ^2/dof	Probability	Asym (ppb)	χ^2/dof	Probability
Wien	-261.4 $\pm$ 13.17	2.65	0.03	-238.6 $\pm$ 13.14	0.32	0.87
Slug-pair	-261.4 $\pm$ 13.17	1.64	4.84E-03	-238.6 $\pm$ 13.14	0.96	0.55
Slugs	-261.4 $\pm$ 13.17	2.17	1.16E-09	-238.6 $\pm$ 13.14	1.20	0.09

Raw data are corrected for longitudinal beam polarization.

Figure 5.18

Null and physics asymmetry through Run 1.

Raw data are the measured yield-based asymmetries, without any corrections. Corrected data have level I corrections and appropriate signs for Wien and HWP flips. See text for details

Table 5.10

Null and physics asymmetries before and after level I corrections.

	Raw $\frac{\langle IN \rangle + \langle OUT \rangle}{2}$ (ppb)		Corrected $\frac{\langle IN \rangle + \langle OUT \rangle}{2}$ (ppb)		Raw $\langle IN, -OUT \rangle$ (ppb)		Corrected $\langle IN, -OUT \rangle$ (ppb)	
Wiens	Mean	Error	Mean	Error	Mean	Error	Mean	Error
1	-75.76	28.38	-41.99	31.81	-279.04	27.91	-253.36	31.29
2	32.07	24.04	23.71	26.94	-193.35	24.03	-242.19	26.94
3	-0.38	25.64	-34.63	29.37	-247.17	25.64	-222.63	29.37
4	-55.66	26.96	-21.91	30.92	-268.31	26.93	-253.98	30.89
5	-107.69	25.52	-15.12	29.26	-189.00	25.31	-223.77	29.02
Run 1	-37.95	11.62	-15.60	13.20	-231.90	11.57	-238.60	13.14

The errors are statistical only.

5.8 Transverse Asymmetry

The longitudinally polarized (P_L) electron beam had traces of transverse polarization (P_T). The symmetry of the main detectors largely suppressed leakage of $P_T A_T$ into the apparent $P_L A_{PV}$, where A_T is the transverse asymmetry. Residual transverse polarization in the longitudinally polarized beam can be determined by fitting the regressed asymmetry of all the eight main detector bars with the following function:

$$A_i = -A_T \times [P_V \cos(\phi_i) - P_H \sin(\phi_i)] + C \quad (5.22)$$

where $i = 1-8$, P_V and P_H are respectively the residual vertical and horizontal transverse polarization, $\phi = (\frac{\pi}{4})(i-1)$ and C is predominantly $P_L A_{PV}$. A_T was explicitly measured in dedicated full transverse polarization measurements and was determined to be -4.8 ± 0.6 ppm [19]. The above equation has parity conserving components from the transverse po-

Figure 5.19

<IN, -OUT> longitudinal plus transverse asymmetry during for Wiens 1-5.

Fits in the plots are of the form described in Equation 5.22. See text for details.

larization which vary as $\cos(\phi)$ and $\sin(\phi)$, plus a ϕ -independent component from $P_L A_{PV}$ in combination with a potential false asymmetry from $P_T A_T$ due to broken MD symmetry.

Figure 5.19 shows the octant variation of the $\langle \text{IN}, -\text{OUT} \rangle$ asymmetry with a fit given by Equation 5.22. Separate fits to the data in IN and OUT slugs can be found in [90]. The fit parameters P_V and P_H , in principle, give the residual vertical and horizontal transverse polarization.

Figure 5.20

Preliminary values of the residual transverse polarization during Wiens 1-5.

Data are sign corrected for Wien and HWP flips. The horizontal blue and green lines are the fits to the data. Values in Wien 4 and 5 might not all be due to transverse leakage. See text for details.

From Figure 5.20, a net residual $P_V = 0.64 \pm 0.32 \%$ and $P_H = 0.89 \pm 0.29 \%$ were determined in linearly regressed Run 1 parity violating asymmetry data. While it is not

clear how much, it is assumed that some contribution to the observed residual transverse polarization is also due to the helicity correlated beam property (position, angle, energy) differences. These P_T extractions are very preliminary as the data used have not been post-regressed. The large P_V and P_H values in Wien 4 and 5 (see Figure 5.20) might shrink after the post-regression correction.

For this analysis, these values of P_V and P_H are interpreted as upper bounds on the transverse leakage. The transverse leakage (ΔA_T) is assumed to be zero with an uncertainty bounded by the maximum of $|C_V \times P_V| + |C_H \times P_H|$. Taking $C_V = 0.008 \pm 0.072$ ppm and $C_H = 0.004 \pm 0.064$ ppm from [19] (Equation. 7.7), $dA_T^{\text{leakage}} = 0.82$ ppb.

5.9 Summary of Systematic Uncertainties on the Regressed Asymmetry

The statistical uncertainty on the “5+1” linear regression itself was determined to be 0.4 ppb as shown in Table 5.5 and from Section 5.2.1.8, $|dA_{msr_{\text{cut}}}| = 1.05$ ppb. A systematic uncertainty of 2 ppb, i.e., $|dA_{msr_{\text{regscheme}}}| = 2$ ppb, is applied to the regressed asymmetry based on the difference in the size of the correction for charge vs. no charge linear regression schemes as discussed in Section 5.4. Additional systematic uncertainties due to potential transverse polarization leakage ($|d\Delta A_T^{\text{leakage}}| = 0.82$ ppb) and due to $\sim 1\%$ non-linearity in the MD signal chain ($|dA_{msr_{\text{non-lin}}}| = 2.2$ ppb) are applied. In principle, the residual correlations discussed in Section 5.4.1 should have been zero and the reason why that is not the case is still being investigated. An uncertainty of 50% of the size of the post-regression residual correlations correction is assigned to the regressed asymmetry i.e., $|dA_{msr_{\text{post-reg}}}| = 6.1$ ppb.

5.10 Other Background Corrections

Background for the Qweak experiment is defined as any source of signal in the detectors other than that due to $\vec{e}p$ elastically scattered electrons. Four major sources of background were identified in the experiment: aluminum window, inelastic scattering, beamline background, and other neutral background. Two numbers are needed to subtract a background contribution: the asymmetry of the background and the fraction of the background in the elastic signal (also known as the dilution factor). Beamline background correction was done on a slug-by-slug basis so that the effect on the χ^2/dof of the slugs could be examined. The net beamline background correction is 10.3 ± 6.4 ppb and the beamline dilution factor and asymmetry are given in Section 5.5.1. Sources of the remaining three backgrounds and measurements of their asymmetries and dilution factors are discussed in the subsequent subsections.

5.10.1 Aluminum Window Background

The aluminum window background came from the liquid hydrogen target windows. Even though the cell windows were made as thin as possible and the magnetic field was set to suppress scattered electrons from the upstream window, the aluminum⁵ window background is the biggest source of background. Dedicated runs were taken on dummy aluminum window targets, mostly on a 4% radiation length dummy which was placed at the same position along the beamline as that of the downstream window of the liquid

⁵Note that the windows were not strictly made of aluminum but rather an alloy with about 90% aluminum (See Table 3.3 for chemical composition of the windows).

hydrogen cell. Data on a 2% upstream Al target data were also taken to understand the upstream window background.

Window background corrections, allowing for the fact that there was an upstream window, underwent an analysis procedure, similar to the published Wien 0 analysis (i.e, no post-regression). The measured aluminum asymmetry was corrected for beam polarization, neutral background (to be discussed) and radiative effects in the nuclear target. The parity violating $\vec{e}Al$ asymmetry was determined to be [39]

$$A_{Al} = 1.7581 \pm 0.1818 (stat.) \pm 0.1795 (syst.) + 0.0376 (model) \text{ ppm} \quad (5.23)$$

where ‘*model*’ refers to the model dependent uncertainty for radiative correction. A reduction of statistical uncertainty is expected with more data taken during Run 2 under analysis.

The dilution factor associated with the aluminum windows was measured explicitly by measuring rates from the empty liquid hydrogen target cell. The dilution factor is then the ratio of rates from empty to full target. In absence of liquid hydrogen (empty target), the electrons scattered from aluminum windows have higher energies due to lack of ionization loss in liquid hydrogen. This changes the acceptance of electrons scattered from the empty cell and a model was developed to account for the change in the rate due to change in acceptance. The dilution factor for the aluminum asymmetry was determined to be

$$f_{Al} = 0.03226 \pm 0.0001 (stat.) \pm 0.0004 (syst.) + 0.0021 (model) \quad (5.24)$$

where ‘*model*’ refers to the model dependent uncertainty for rate correction in the empty target.

5.10.2 Inelastic Background

Background from inelastic scattering off liquid hydrogen and aluminum windows was also present. The parity violating asymmetry from the $W \sim 1232 \text{ (MeV/c)}^2$ region was measured by running the experiment at a QTor current of 6700 A, which focused the $\Delta(1232)$ peak onto the main detector bars. This asymmetry was corrected for elastic radiative tail dilution, aluminum windows,⁶ and neutral backgrounds. The fully corrected inelastic asymmetry was determined to be [41]

$$A_{inelastic} = -3.020 \pm 0.970 \text{ ppm.} \quad (5.25)$$

Inelastic dilution was determined using simulations as described in Section 4.2.1. Since the simulated rates were about 10% smaller than the measured rates at the inelastic peak, a preliminary uncertainty of 100% is assigned to the inelastic dilution factor. Hence,

$$f_{inelastic} = 0.0002 \pm 0.0002. \quad (5.26)$$

5.10.3 Neutral Background

Neutral background, also known as *QTor transport channel neutral background*, is different from the beamline background discussed in Section 5.5. Neutral backgrounds consist mainly of photons but can have very small fractions of neutrons that were produced by scraping of collimator edges and the shield wall apertures by the scattered electrons as they were bent by the QTor field. Assuming the scraping was primarily due to electrons that had undergone Møller scattering, an asymmetry of magnitude zero with a highly conservative

⁶This is done to avoid double counting the inelastic background from Al which is included in the Al window subtraction

error of 0.2 ppm was assigned. The dilution factor associated with this asymmetry was estimated as the difference between total dilution due to neutral background and dilution due to beamline background as measured in separate studies [111]. Another 100% error bar is assigned to this dilution factor pending further analysis. Thus, for neutral background, asymmetry and dilution are given by

$$A_{neutral} = 0.00 \pm 0.200 \text{ ppm}, \quad (5.27)$$

$$f_{neutral} = 0.0019 \pm 0.0019. \quad (5.28)$$

5.11 Experimental Bias Correction

The experimental bias corrections include (1) electromagnetic radiative corrections (discussed in Section 4.4.2), (2) detector bias correction, (3) acceptance correction, and (4) Q^2 correction. The electromagnetic radiative correction factor was determined to be

$$R_{RC} = 1.0096 \pm 0.0065. \quad (5.29)$$

Detector bias correction pertains to the fact that light collection and average Q^2 in the main detector bars vary across the length of the bar [112]. A “*light weighting*” was done to account for this non-uniformity in light yield. Simulations were run in GEANT4 optimized for the Qweak tracking system with and without the “*light weighting*” correction. The detector bias correction was then defined as

$$R_{Det} = \frac{A_{no-bias}^{sim}}{A_{bias}^{sim}} \times \delta Q^2 = 0.987 \pm 0.007 \quad (5.30)$$

where δQ^2 is the change in Q^2 in these simulations and is added as an extra correction for reasons described in [46] (Appendix D-8).

Another correction relevant to the experimental bias is the acceptance correction. The main detectors accept a significant range in Q^2 and the result is quoted at an average Q^2 . This correction maps the average of the elastic ep asymmetry at all the Q^2 s to the asymmetry at average Q^2 as follows:

$$A_{Tree}(< Q^2 >) = R_{Acc} < A_{Tree}(Q^2) > \quad (5.31)$$

where R_{Acc} is the acceptance correction factor determined by simulations [113] to be

$$R_{Acc} = 0.980 \pm 0.010. \quad (5.32)$$

A final correction is done for the bias in determining the central Q^2 [114]. The correction factor is [52]

$$R_{Q^2} = 1.000 \pm 0.030. \quad (5.33)$$

The total experimental bias correction is given by

$$R_{tot} = R_{RC} \times R_{Det} \times R_{Acc} \times R_{Q^2} = 0.9765 \pm 0.0323 \quad (5.34)$$

5.12 Q^2 and Effective Kinematics

To describe the Qweak kinematics, one needs the effective average energy, average scattering angle, average Q^2 , and average asymmetry at that energy. Despite significant progress, the final determination of the Q^2 by the Qweak tracking group is ongoing. Simulations at the elastic peak have been benchmarked by the experimental data (see Section 4.2). The Q^2 for the published Wien 0 result [52] and this dissertation has been determined from simulations by this author [112] to be

$$< Q^2 >_{Tree} \equiv < Q^2 >_{tree}^{sim} = 0.02450 \pm 0.0006 \text{ (GeV/c)}^2 \quad (5.35)$$

where $\langle Q^2 \rangle_{Tree}$ is the tree level acceptance averaged Q^2 determined without any radiative effects. Effects of radiative losses are convoluted in R_{other} as an effective correction.

The average effective energy was determined from GEANT3 simulations [115], [15] using the relation

$$E_s = \left\langle E_{beam} - \frac{dE}{dz} \cdot Z \right\rangle = 1155 \pm 3 \text{ MeV} \quad (5.36)$$

where $E_{beam} = 1160 \text{ MeV}$ is the beam energy, $\frac{dE}{dz}$ is ionization loss per unit length in the target and Z is the length traveled by an electron in the target before scattering, chosen randomly by GEANT3.

The acceptance averaged effective scattering angle is defined by [115], [15]

$$\cos(\theta_{eff}) = \frac{1 - \frac{\langle Q^2 \rangle_{tree}}{2E_s^2} \left(1 + \frac{E_s}{M}\right)}{1 - \frac{\langle Q^2 \rangle_{tree} \cdot E_s}{2E_s^2 \cdot M}} \quad (5.37)$$

i.e.,

$$\langle \theta_{eff} \rangle = 7.90^\circ \pm 0.30^\circ \quad (5.38)$$

where M is the proton's rest mass.

5.13 Note on Blinding Factor for Run 1

This section will discuss how hydrogen data were blinded in the Qweak experiment. Separate blinding numbers were used to blind Wien 0 (unblinded and now published), Run 1 and Run 2 data. Unblinding of Run 1 and 2 data is a possibility in the Spring of 2015. The blinding offset applied to the raw asymmetry in Run 1 was assigned a value within a $\pm 60 \text{ ppb}$ box. Eligibility for blinding of hydrogen data was determined at the runlet level, by looking at EPICS values of target position (liquid hydrogen), temperature (18-22

K), pressure (20-35 psi) and beam current ($> 1 \mu\text{A}$) at the target. Any runlet outside the prescribed limits (shown in parentheses) for those parameters was not blinded. Data taken on aluminum was not blinded. Blinding sign was determined by Wien and HWP states as shown in Table 5.11. Formalism on extraction of the A_{PV}^{ep} is discussed next.

Table 5.11

Blinding sign (+/-) based on HWP and Wien states.

HWP	Wien Flip		
	Right	Left	Horizontal
IN	-	+	-
OUT	+	-	+

5.14 Parity Violating Physics Asymmetry

The measured asymmetry (A_{msr}), with a blinding offset, can be written in terms of the physics asymmetry (A_{PV}^{ep}) and other background asymmetries as

$$A_{msr}^{blinded} = (1 - f_{total}) P A_{PV}^{ep} + f_{BB} C_{MD}^{US} < A_{US} > + P f_{Al} A_{Al} + P f_{neutral} A_{neutral} + P f_{inel.} A_{inel.} + B_{offset} \quad (5.39)$$

where f_i 's are the background fractions in the main detector signal, and

$$f_{total} = f_{BB} + f_{Al} + f_{neutral} + f_{inel.} \quad (5.40)$$

is the total dilution from various backgrounds. BB denotes beamline background. The average upstream lumi asymmetry is assumed to be of mechanical origin, that which does not change sign with polarization. The other backgrounds, i.e., aluminum, neutral, and

inelastic, are due to physics processes which have polarization (P) associated with them.

Once the blinding factor with appropriate sign is revealed, it should be added/subtracted

from $A_{msr}^{blinded}$ to get A_{msr} i.e.,

$$A_{msr} = A_{msr}^{blinded} \pm B_{offset}. \quad (5.41)$$

Analysis from this point onwards assumes a zero B_{offset} and an error bar will be assigned

for that. Equation 5.39 can now be rewritten as

$$A_{PV}^{ep} = \frac{R_{tot}}{1 - f_{total}} \left[\frac{A_{msr} - C_{MD}^{US} \langle A_{US} \rangle}{P} - f_{Al} A_{Al} - f_{neutral} A_{neutral} - f_{inel} A_{inel} \right]. \quad (5.42)$$

Partial errors on Equation 5.42 can now be written as

$$\begin{aligned} dA_{PV}^{ep}|_{A_{msr}} &= R_{tot} \times \frac{1}{P} \times \frac{1}{1 - f_{total}} \times dA_{msr} \\ dA_{PV}^{ep}|_P &= R_{tot} \times \frac{A_{msr} - C_{MD}^{US} \langle A_{US} \rangle}{1 - f_{total}} \times \frac{dP}{P^2} \\ dA_{PV}^{ep}|_{R_{tot}} &= \frac{A_{msr} - C_{MD}^{US} \langle A_{US} \rangle}{P} - \sum_1^3 f_i A_i \times \frac{dR_{tot}}{1 - f_{total}} \\ dA_{PV}^{ep}|_{C_{MD}^{US}} &= R_{tot} \times \frac{1}{P} \times \frac{1}{1 - f_{total}} \times \langle A_{US} \rangle \times dC_{MD}^{US} \\ dA_{PV}^{ep}|_{\langle A_{US} \rangle} &= R_{tot} \times \frac{1}{P} \times \frac{1}{1 - f_{total}} \times C_{MD}^{US} \times d\langle A_{US} \rangle \\ dA_{PV}^{ep}|_{A_i} &= R_{tot} \times \frac{1}{1 - f_{total}} \times f_i \times dA_i \\ dA_{PV}^{ep}|_{f_{BB}} &= R_{tot} \times \left[\frac{A_{msr} - C_{MD}^{US} \langle A_{US} \rangle}{P} - \sum_1^3 f_i A_i \right] \times \frac{df_{BB}}{(1 - f_{total})^2} \\ dA_{PV}^{ep}|_{f_i} &= R_{tot} \times \left[\frac{A_{msr} - C_{MD}^{US} \langle A_{US} \rangle}{P} - \sum_1^3 f_i A_i - A_i(1 - f_{total}) \right] \\ &\quad \times \frac{df_i}{(1 - f_{total})^2} \end{aligned} \quad (5.43)$$

where the summation on index ‘ i ’ is extended over the sum of the products of aluminum, neutral and inelastic background dilutions f_i and asymmetries A_i .

5.15 Results and Summary

Figure 5.21 and Table 5.12 show asymmetries and corrections to obtain A_{PV}^{ep} from blinded A_{raw} . The raw asymmetry is corrected for false asymmetries using linear regression and a post regression correction is applied to nullify the residual correlations to the helicity correlated beam parameter differences. This gives A_{msr} (assuming blinding offset subtraction) which is then corrected for the beamline background and the result is normalized by the beam polarization. Subsequent subtraction of the aluminum, neutral and inelastic asymmetry components from the A_{msr} and multiplication by the experimental bias factor R gives the A_{PV}^{ep} . The blinded parity violating $\vec{e}p$ asymmetry, with the blinding offset error⁷ is

$$A_{PV}^{ep} (< Q^2 >_{Tree}) = -299.7 \pm 13.4 \text{ (stat.)} \pm 17.2 \text{ (syst.)} \pm 68 \text{ (blinding) ppb.}$$

Uncertainties obtained using relations from Equation 5.43 are detailed in Figure 5.22 and Table 5.13. The statistical and systematic errors are similar in magnitude at this stage of the analysis. The top priorities are to reduce the uncertainties on aluminum asymmetry and on the beamline background correction.

⁷The blinding offset error on 60 ppb box is 68 ppb due to $1/P$ correction.

Figure 5.21

Asymmetries and corrections to get A_{PV}^{ep} from A_{raw} .

Asymmetries are shown in magenta and corrections in blue. The polarization correction ($1/P$) is expressed as an additive correction for convenience. The blinding offset error is not included.

Figure 5.22

Breakdown of individual error contributions to A_{PV}^{ep}

The errors shown are obtained using relation 5.43. The statistical error is shown in the orange bar (leftmost) and the total systematic error in the black bar. The dotted horizontal red line represents proposed final error goal. The total error is shown in the magenta bar (rightmost). $A_{msr-syst}$ is dominated by the error on post-regression. Refer to Table 5.13 for actual values. The blinding offset error is not included.

Table 5.12

Asymmetries and additive corrections.

Source	Asymmetries and additive corrections (ppb)	
	Value	Error
A_{raw}	-231.9	11.6
Regression	12.2	6.5
Trans.	0.0	0.8
Non-lin.	0.0	2.2
A_{msr}	-219.8	11.5
BB	12.0	7.5
Pol.	-30.5	5.7
Al	-57.8	9.6
Neutral	0.0	0.7
Inelastic	0.6	0.6
Exp. bias corr	-4.1	9.9
$A_{PV}^{ep} (< Q^2 >_{Tree})$	-299.7	21.7

Shown in bold are asymmetries, the rest are corrections.

Table 5.13

Breakdown of error contributions to the A_{PV}^{ep} from relation 5.43.

Source	Contribution to dA_{PV} (ppb)
$A_{msr}(\text{stat.})$	13.4
$A_{msr}(\text{syst.})$	3.8
Pol	5.7
A_{Al}	8.5
f_{Al}	4.5
$A_{neutral}$	0.4
$f_{neutral}$	0.6
$\langle A_{US} \rangle$	0.3
C_{MD}^{US}	7.5
f_{BB}	0.7
$A_{inel.}$	0.2
$f_{inel.}$	0.6
Det bias	2.1
EM rad. corr.	1.9
Acceptance corr.	3.1
Q^2 corr.	9.0
Total systematic error	17.2
Total stat. + syst. error	21.7

Note: the blinding offset error is not included.

CHAPTER 6

INTERPRETATION AND RESULTS

A blinded parity-violating physics asymmetry, $A_{PV}^{ep} (< Q^2 >_{Tree}) = -299.7 \pm 13.4$ (stat.) ± 17.2 (syst.) ± 68 (blinding) ppb was determined using Run 1 data from the Qweak experiment. Since the data will not be unblinded by the time this dissertation is completed, the results presented in this chapter are very preliminary and are strictly for updating Run 1 analysis priorities. This chapter will highlight the steps followed in the first determination of the weak charge of the proton [52] and provide a preliminary measurement of the proton's weak charge based on the asymmetry presented above. An alternative way of calculating the proton's weak charge by estimating hadronic contributions can be found in [46]. Blinding offset error will be neglected in the calculations to follow.

6.1 Electroweak Radiative Corrections

Effects like vacuum polarization, loops and box diagrams contribute to higher order corrections, which effectively lead to the variation of the couplings (EM, weak or strong) with Q^2 , also known as the running of the coupling constants. The proton's weak charge at tree level in the SM is given as

$$Q_W^p(SM) = 1 - 4 \sin^2 \hat{\theta}_W(0) \quad (6.1)$$

where $\sin^2 \hat{\theta}_W(0)$ is the proton's weak charge at $Q^2 = 0$.

Figure 6.1

Box diagrams for electroweak radiative corrections.

In the modified minimal subtraction ($\overline{MS}$) renormalization scheme, the weak mixing angle at $Q^2 \rightarrow 0$ is predicted based on the precisely measured value of the weak mixing angle at the Z^0 pole [3]. The Feynman diagrams for the electroweak radiative corrections that result in the running of the weak mixing angle as a function of energy in the $\overline{MS}$ scheme are shown in Figure 6.1. The $Q_W^p(SM)$ at $Q^2 = 0$, including higher order corrections, is given by [116],

$$Q_W^p(SM) = [\rho_{NC} + \Delta_e] \times [1 - 4\sin^2 \hat{\theta}_W(0) + \Delta'_e] + \square_{WW} + \square_{ZZ} + \square_{\gamma Z} \quad (6.2)$$

where $\rho_{NC} = 1 + \Delta_\rho$ [117] renormalizes the ratio of neutral to charged current interaction strengths at low energies, Δ_e and Δ'_e respectively are electron vertex and external leg corrections to the axial-vector Zee and γee couplings [118], and $\square_{WW}, \square_{ZZ}, \square_{\gamma Z}$ are the corrections from the box diagrams as those in Figure 6.1. The amplitudes of the precisely known, purely weak $\square_{WW}$ and $\square_{ZZ}$ give about 26% and 3% correction to Q_W^p ,

respectively. The size of the corrections for the various terms in Equation 6.2 are given in Table 6.1. The only energy dependent term is the $\square_{\gamma Z}$ piece. Its contribution at the Qweak kinematics has been carefully calculated by various authors to ever greater precision using dispersion relations [118], [119]. The energy dependent vector and axial vector components of $\square_{\gamma Z}$ are shown in Figure 6.2 from [120].

Figure 6.2

Energy dependence of $\square_{\gamma Z}$.

Real part of the $\square_{\gamma Z}$ showing energy dependent axial vector (blue band) and axial (red band) and old energy independent (green band) parts are shown. Vertical dotted line shows the Qweak energy.

Table 6.1

Values of the electroweak radiative corrections in Equation 6.2.

Correction	Value
Δ_e	-0.00116 [116]
Δ'_e	-0.00142 [116]
$\square_{WW}$	0.018317 [116]
$\square_{ZZ}$	0.001926 [116]
$\square_{\gamma Z}(0)$	0.0044 [121]
ρ_{NC}	1.00833 [116]

6.2 Determination of the Weak Charge of the Proton

The proton's weak charge is extracted by combining the existing parity violating electron scattering asymmetry data on hydrogen, deuterium and helium up to $Q^2 = 0.63 \text{ (GeV/c)}^2$ including the asymmetry measured by the Qweak measurement. A detailed discussion on the procedure can be found in [122] and [52].

All of the hydrogen data points were corrected for the energy dependence of the gamma-Z box diagram as determined in [120]. A correction for the Q^2 dependence of the gamma-Z box diagram outlined in [123] using form factors described in [124] was also applied. The E and Q^2 dependence of the $\square_{\gamma Z}$ corrections to the Qweak asymmetry are found to be very small. Together they amount to a change of $-0.0126 \pm 0.0008 \text{ ppm}$ ([120], [123] and [52]) in the asymmetry at $Q^2 = 0.025 \text{ (GeV/c)}^2$. A global fit was done to the data with five free parameters: the weak vector quark couplings (C_{1u} and C_{1d}), the strange charge radius ρ_s and magnetic moment μ_s , and the isovector axial form factor. C_{1u} and C_{1d} are (half)

the weak charges of the u and d quarks, ρ_s and μ_s to the strange quark form factors $G_E^s = \rho_s Q^2 G_D$ and $G_M^s = \mu_s G_D$. Varying the dipole mass λ in the dipole form

$$G_D = \left(1 + \frac{Q^2}{\lambda}\right)^2 \quad (6.3)$$

over the range of $0.7 < \lambda(\text{GeV}/c)^2 < 2.0$ shifted Q_W^p only by ± 0.001 as reported in [52].

The correction and the corresponding uncertainty contribution from the iso-scalar axial form factor was found to be negligible [125]. Using data with the largest available Q^2 or θ in the global fit did not yield any significant difference above $Q^2 > 0.25 (\text{GeV}/c)^2$ [52].

The resulting asymmetry fit is of the form $A(Q^2, \theta)$. To better visualize the fit, the θ dependence was removed by calculating the reduced asymmetry as,

$$A_{PV}^{reduced} = A_{PV}^{measured} - [A_{calc}(\theta, Q^2) - A_{calc}(0, Q^2)] \quad (6.4)$$

where $A_{calc}(\theta, Q^2)$ was determined using Equation 1.74 and the results of the fit. The reduced asymmetry (Figure 6.3) can now be written in a simpler form

$$\frac{A_{PV}}{A_0} = Q_W^p + Q^2 B(Q^2, \theta = 0) \quad (6.5)$$

where $A_0 = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]$. The reduced asymmetries for all the data used in the global fit were then plotted as a function of Q^2 as shown in Figure 6.3. The intercept of the fit ($Q^2 = 0$) gives the proton's weak charge as

$$Q_W^p (\text{Qweak} + \text{PVES}) = 0.0870 \pm 0.0085.$$

Note that this result is blinded and strictly very preliminary.

Figure 6.3

Global fit to extract the proton's weak charge.

Result of the global fit (solid black curve) of the reduced asymmetries shown with points rotated to the forward angle limit is shown. The yellow band represents the uncertainty in the fit. The SM prediction is shown by a small black arrow. The blinded reduced asymmetry derived in this dissertation is shown in red. The blue dotted line shows the result of not including the Q_{weak} point in the fit. **Note: This result is blinded.**

6.3 Weak Charge of the Neutron

As shown in Equation 1.45, the weak charge for any fermion can be written in terms of C_{1u} , C_{1d} , N and Z . For ^{133}Cs ($Z = 55$ and $N = 78$), the weak charge is given by $55 Q_W^p + 78 Q_W^n$ which is proportional to $C_{1u} + 1.12 C_{1d}$. Thus, the atomic parity violation (APV) result of ^{133}Cs [126] better constrains the iso-scalar weak vector charges. Using the most recent correction [127] on ^{133}Cs APV, and the Q_W^p (Qweak + PVES) result, the weak quark vector couplings can be determined with higher precision from a fit as shown in Figure 6.4. This experiment (Qweak) provides the second equation needed to extract the two unknowns: C_{1u} and C_{1d} .

This procedure has already been implemented in [52] to make the first determination of the C_{1u} and C_{1d} as well as the weak charge of the neutron. For this analysis, using the same procedure, the values obtained for the weak quark vector couplings are

$$C_{1u} = -0.1940 \pm 0.0039,$$

$$C_{1d} = 0.3448 \pm 0.0038.$$

Using these couplings, the weak charges of the proton and the neutron are determined to be

$$Q_W^p = 0.0865 \pm 0.0085, \tag{6.6}$$

$$Q_W^n = -0.9910 \pm 0.0081.$$

These blinded results are 2σ away from the SM predictions but should not be scientifically interpreted because of the large blinding box.

Figure 6.4

Constraints on the weak vector quark couplings C_{1u} and C_{1d} .

The plot shows iso-scalar vs. iso-vector fit using APV data on ^{133}Cs (the green band) and the world PVES (the blue ellipse) data including the blinded Qweak result presented in Section 6.2. Combining the APV result with the PVES data gives the red ellipse. The outer and inner ellipses are drawn at 95% and 65% confidence level respectively. The black line is the SM prediction as a function of $\sin^2 \theta_W$ in the $\overline{MS}$ scheme. The black dot is the SM prediction based on $\sin^2 \theta_W = 0.23116$. **Note: This result is blinded.**

6.4 The Weak Mixing Angle

Equation 6.2, combined with values from Table 6.1 can be re-written as

$$\sin^2 \theta_W = \frac{1}{4} \left[1 + (-0.00142) - \frac{Q_W^p - 0.018317 - 0.001926 - 0.0044}{1.00833 + (-0.00116)} \right]. \quad (6.7)$$

Using the value of Q_W^p from Equation 6.6 in Equation 6.7, one gets,

$$\sin^2 \theta_W = 0.23429 \pm 0.00211.$$

It should be remembered that the A_{PV}^{ep} used in calculations of the weak charges of the proton and neutron, and the weak mixing angle is a blinded asymmetry. These values are bound to change once the blinding offset is released which can potentially change the central value of the reported asymmetry. However, the blinding uncertainty has not been included in these analyses, so the uncertainties in the extracted values for C_{1u} , C_{1d} , Q_W^p , Q_W^n , and $\sin^2 \theta_W$ reflect what we expect to be the final uncertainties from the Run 1 data. The observed two sigma difference from the SM asymmetry can solely be due to this blinding offset and the readers should not draw any scientific conclusions from the values calculated in this chapter or from the preliminary plots shown. The existing measurements shown in Figure 6.5 are from the atomic parity violation on Cesium (APV) [126], SLAC E-158 [51], deep inelastic neutrino-nucleus scattering (NuTeV) [128], and from Z^0 pole asymmetries (LEP+SLC) [129].

Figure 6.5

The running of the weak mixing angle in the $\overline{MS}$ scheme.

The solid black curve is the running of $\sin^2 \theta_W$ in the $\overline{MS}$ scheme, the thickness of which gives its uncertainty at any point. The ‘Wien 0’ result is from only 4% of the total unblinded data taken by the Q_{weak} experiment. Anticipated final uncertainty on $\sin^2 \theta_W$ is shown in green. **Note: This result (black box) is blinded.**

6.5 Implications of the Qweak Measurement

The final result of the full Qweak experiment is expected after Spring of 2015. It will be the most precise measurement of the parity-violating $\vec{e}p$ at a very small Q^2 . Using the procedures discussed in this chapter, the Qweak experiment can then provide the most precise measurement of the weak charges of the nucleons and the weak vector quark couplings. This will further constrain the iso-scalar and the iso-vector coupling combinations for the future experiments. With its final precision, the Qweak experiment will provide a stringent test of the SM.

A significant discrepancy between the Qweak result and the SM prediction could signal a new unexplored branch of physics. The new physics could be described by some models in the forms of the SM extensions. As discussed in [116], these extensions can include neutral gauge bosons (Z'), leptoquarks, super symmetry (SUSY) loops or R-parity violating (RPV) SUSY interactions.

Even if the final Qweak result agrees with the SM, the results will put tight constraints on the mass reach for the new physics. The model independent mass reach at 95% confidence level (2σ) is given by

$$\frac{\Lambda}{g} \equiv \frac{1}{\sqrt{2\sqrt{2}G_F\Delta Q_W^p}} = 2.0 \text{ TeV} \quad (6.8)$$

where g is the coupling constant associated with the new physics, G_F is the Fermi constant and ΔQ_W^p is the error on $Q_W^p = 0.0080$ from this analysis (not including the blinding error). Taking $g = 1$, an agreement between the SM prediction and the final Qweak result would rule out, at 95% confidence level, any new physics or new particles below 2.0 TeV. Finally,

using the coupling constant i.e., $g = 4\pi$ favored in [130] and [131], the mass reach from the blinded results presented in this dissertation is 24.5 TeV.

6.6 Future Work

The blinded A_{PV}^{ep} determined in this dissertation has the error bar three times smaller than the published Wien 0 result. The dominant systematic errors, as shown in Table 5.13 are due to Q^2 , A_{Al} , C_{MD}^{US} and f_{Al} . While often the errors are assigned generously, there is a plenty of room for further improvement in these areas. For the first time in the experiment, a post-regression correction was done based on the work done by this author and the benefits of doing so have been discussed in Section 5.4.1. A more rigorous understanding and solution to the residual correlations is expected in the days to come. It remains to be seen whether the collaboration decides to implement the Tsai based radiative correction model for other physics processes like inelastic $\vec{e}p$, elastic $\vec{e}Al$ scattering. A consistent radiative correction model for all the interactions might be useful given the fact that there still exists an unexplained $\sim 8\%$ discrepancy in the measured and simulated signals at the $N \rightarrow \Delta$ peak.

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APPENDIX A

SOLID TARGET MEASUREMENTS

A.1 Introduction

This Appendix describes work done by Greg Smith, Jim Dunne, Silviu Covrig and this author to measure basically the mass, area and thicknesses of various solid targets. The goal of these measurements was to accurately and precisely determine the areal densities of various dummy aluminum and carbon targets and thicknesses of the liquid hydrogen cell windows used in the Qweak experiment. The cell window thicknesses are an integral part of Monte-Carlo simulation that describes target geometry. Areal densities are required to estimate the rate from the cell windows, and to benchmark simulations and data for aluminum and carbon targets. The sections below will discuss how the areal densities and thicknesses of the solid targets were measured. A special technique to measure the cell windows' thickness using gamma attenuation will also be discussed. Tools used in these measurements are shown in Figure A.1.

A.2 Solid Target Areal Density Measurements

Areal density for a solid target can be determined by measuring the mass (m) and the area (A) of a target as

$$\rho_A = \frac{m}{A}. \quad (\text{A.1})$$

A.2.1 Mass Measurements

Masses were measured using a precision Denver Instruments M220 scale [132] in a semi-clean temperature controlled room. The calibration of the device was verified using standard weights before and after the mass measurements were taken, but not after every single mass measurement. The device specification claims a precision of 0.1 mg, but in

Tools

Figure A.1

Various tools used in areal density measurements.

practice, a precision (σ_m) of 0.3 mg was established after several measurements. The sliding doors in the scale were opened only to insert the target, and were shut closed during the actual measurements, to eliminate effects from air currents. The scale was used only after a couple of hours after it was turned on, allowing the device to sufficiently warm up. The scale was zeroed before a set of N measurements. N measurements of the mass of the same target were taken and averaged to get a final weighted mean mass. The uncertainty of the weighted mean mass was assigned to be either $\sigma_m/\sqrt{N}$ or the standard deviation of the N measurements, whichever was greater.

A.2.2 Area Measurements

Areas of solid targets were measured using a Mitutoyo ToolMakers Microscope (TMM) [133] (see Figure A.1) which has a precision of 0.25 microns. This precision was not achieved due to the imperfections of the edges. Some targets had beveled edges which gave different areas for the opposite sides (see Figure A.2:left), while some even had chamfered corners which made it very hard to pinpoint a vertex for measurements or to repeat measurements.

Three areas were measured for each face (6 per target) as shown in Figure A.2(right): the top, middle and the bottom. For every set of measurement of four vertices for four corners, a fifth measurement of the first vertex was done as a check for repeatability of vertices. The difference in the first and the fifth measurements, which basically are for the same point, was used to estimate an uncertainty in the area measurements.

Area was determined using the general formula for any convex quadrilateral given by

$$A = \frac{1}{4} \sqrt{4p^2q^2 - (a^2 + c^2 - b^2 - d^2)^2} \quad (\text{A.2})$$

where a, b, c, d are the sides, and p and q are the diagonals of the quadrilateral derived from the measured vertices.

It was found that the first and the fifth (repeat) measurement disagreed by about 0.6 mil in average. The standard deviation (dV_x, dV_y) of the differences ($\Delta V_x, \Delta V_y$) from N measurements of the same target was used as input to a Monte-Carlo study, to estimate the effect of the differences on ΔA (error on the area). In this study, all four vertices were moved randomly from their measured positions within $\pm dV_i$, where $i = x, y$ to obtain new areas. This was repeated about 1000 times and the standard deviation of the distribution was assigned as the error on the area measurement for each target. Areas calculated using Equation A.2 were weighted by this error. Calculations done to estimate the area lost due to chamfers showed that the lost areas were typically about 30 ppm and were thus neglected.

A.3 Solid Target Thickness Measurements

Thicknesses of the dummy targets were measured using several devices. A Starret micrometer [134] with a 6 mm diameter spindle and flat contact surfaces (see Figure A.1) was used initially. This device measures the thickest part of the target with a precision of ~ 0.25 mil. The Mitutoyo digital micrometer [133], on the other hand, has a rounded spindle that can measure a point with a precision of 0.15 mil. Hence, the Mitutoyo micrometer was used in all the dummy target thickness measurements.

Thicknesses of the solid targets were not really needed for the determination of the areal density, but were measured to cross check the results obtained by measuring mass and area by combining with the volume density (see Section A.4). All the targets were cleaned with ethanol and dried before any measurements were made. Direct human contact was avoided by using gloves to handle the targets.

Thickness measurements were mostly done in the central region where the rastered beam interacted with the target. The surfaces of the dummy targets had scratches and thickness varied by about a negligible 0.03%.

A.4 Volume Density Measurements

The goal of this measurement was to accurately measure the volume densities to the solid targets and then combine these results with the thickness measurements described in Section A.3 to obtain an independent result for the areal density of the solid targets.

If W_{air} and W_{water} are the weights of the solid targets in air and water respectively, then the buoyant force is given by

$$F_{\text{buoyant}} = W_{\text{air}} - W_{\text{water}} = \rho_{\text{water}} \cdot V \cdot g \quad (\text{A.3})$$

where ρ is the density, V is the volume and g is the specific gravity. Equation A.3 can be re-written in terms of the density of the target as

$$\rho_{\text{target}} = \rho_{\text{water}} \frac{W_{\text{air}}}{W_{\text{air}} - W_{\text{water}}}. \quad (\text{A.4})$$

Ultra pure ‘high performance liquid chromatography’ (HPLC [135]) grade water was used to precisely determine ρ_{water} .

A setup similar to the one described in [136] was developed in a temperature controlled room. When the target was lowered in the target holder submerged in the ultra pure water using a clean forceps (to avoid potential contamination by handling), it took a few minutes for the torsional oscillations of the thin wire supporting the target holder to dampen. It was found that the scale drifted by about 0.1 mg/ 10 minutes and the mass measurements done over a longer period of time were subject to this drift. This introduced additional uncertainties in the measurements to a point where it was no longer possible to obtain the precise measurements (precise relative to the m/A measurements) for the volume and hence the areal density measurements. It was thus decided not to pursue these measurements but to rely on the precise measurements explained in Section A.2.2.

A.5 Cell Windows Thickness Measurements

The liquid hydrogen cell windows were machined from a bigger piece of Al alloy, making it impossible to use a Mitutuyo micrometer on the entrance and exit windows (i.e., where the beam actually entered and exited). Initial measurements of the entrance and the exit windows were done using a Hall effect gauge [137] (see Figure A.1), aka Magna Mike 8500. This device has a $1/16''$ ball at the tip, which measures thickness to a precision of 0.3 mil. Pre-Qweak measurements thus had larger uncertainties and it was decided to make another set of more precise measurements using a different technique after the experiment was over and when the windows were considered radiologically safe to make quick short measurements.

Figure A.3

Target cell windows.

Top: Upstream window (left) cut off to punch out the entrance window (right).
 Bottom: The exit window (left) punched out to get exit window and four thicker dummy targets (right) for α and t measurements. All the punched parts were carefully labeled and stored in a radiologically controlled area.

The stem of the entrance windows were cut using a metal cutter, about an inch from the upstream end (see Figure A.3) to make it easier for micrometer measurements. The part of the entrance and exit windows (for both Run 1 and 2) were punched out using a mechanical press. This enabled us to take micrometer measurements at various points in the punched windows. A custom built die was used so as not to deform the actual windows. Rehearsals were done on spare windows that were not used in the experiment. The spare windows did not show any sign of deformation as proved by the same thickness measured with a micrometer before and after punching. The punched out parts had low levels of radiological activity considered safe to be handled by hands. The punched entrance windows showed a variation of thickness by about 1%. The non-uniformity in curved exit windows' thicknesses was up to 2.3%, highlighting the difficulty in machining a curved surface. A more precise measurement of the cell window thicknesses was planned by using a gamma attenuation technique discussed in the next section.

A.6 Gamma Attenuation Measurements

This project was motivated by the success of a similar project done for the Primex experiment [136]. The goal of this project was to determine the linear attenuation coefficient α of the Al alloy used in the target cell windows and then to use it to determine the cell windows' thicknesses (t).

Radiation passing through matter gets attenuated in intensity by a factor $\exp(-\alpha t)$. Knowing the intensity before (I_0) and after (I) the radiation passes through the matter of thickness t , one can get the linear attenuation coefficient by using the relation

$$I = I_0 \exp(-\alpha t). \quad (\text{A.5})$$

Spare dummy targets of thicknesses 1-2 mm were available to be used in determination of α for the entrance windows. These dummies were from the same batch of the alloy that was used to build the upstream windows. No spare alloy material existed that could be used for the exit windows. It was decided to punch out thicker parts (~ 20 mil) of the downstream windows to use them for the determination of α (see Figure A.3). The thicknesses of the entrance and exit windows, which we wanted to measure precisely, were about 4-5 mil.

A.6.1 Source Selection

A gamma source with emission lines between 10-30 keV was required to provide $\sim 50\%$ attenuation for 0.01 cm (4 mil) - 0.2 cm thick aluminum. Americium (Am-241) was found to be readily available with two gamma peaks at 13.95 and 17.74 keV. Though Am-241 has a 60 keV gamma peak too, it was found unsuitable for the thicknesses we were trying to measure. This is because attenuation is very little at 60 keV for a 0.01 cm thick target and we would have to wait a significantly longer time to acquire a good amount of statistics. Am-241, in a circular pillbox of diameter of one inch was loaned out by the radiation control (RADCON) department at Jefferson lab for these measurements. The nominal activity of this source was 64 μCi .

A.6.2 Collimators

Painted lead blocks were cut and drilled to use as collimators and a source holder (see Figure A.4). The lengths and diameters of the collimators were designed assuming a large angular acceptance of the detector and a very small gap between the source and the collimator. Two collimators of length $1/2''$ each and two others of $1''$ each were drilled with drill bits of size $3/32''$ and $1/16''$, making a total of four collimators. The central part of the Pb block had a 6 mm deep and 25.4 mm diameter hole to snugly fit the Am-241 source. This block not only kept the source stationary but also shielded the environment from the radiation. The opening of the hole in the block was kept close to the collimator.

Two additional collimators were made by drilling $1/16''$ thick Pb sheets once it was found that the activity of the entrance and exit target windows was not negligible. One of these was used as a collimator and placed on top of the source sink, covering the source, while the other was attached on one side of the metal plate, which held the target on the other side. This meant that the X-ray beam only saw a very small area (as permitted by a 2 mm diameter collimator hole) of the entrance/exit windows and the X-rays coming out of the target were also collimated by the second collimator. The far end of the cylindrical extension tube of the detector was kept very close to the second collimator. Alignment was done by moving the collimators in X and Y until the maximum rate from the source was measured in the detector. Dummy targets and thin windows were then inserted and removed without disturbing the alignment. Typically the rates in all the measurements were < 300 Hz.

Figure A.4

A lead block showing markings for cutting into five blocks.

Four pieces were cut out from left and right of this block to make four collimators. A hole was drilled in the remaining central block to hold the source. See text for details.

A.6.3 Motion System

A two stage motion system was borrowed from Hall A. The setup had plates with holes to mount the target. The motion system had two linear actuators, controlled by a Velmex NF90 stepper motor controller [138] and was connected to a computer via an RS-232 interface. The motion was found to be reproducible within a mm.

A.6.4 Detector

The measurements were initially planned to be done with a sodium iodide (NaI) detector. The detector material was enclosed in a cylindrical aluminum housing 12 cm in diameter and 9.4 cm long [139]. Perhaps because of the large size of the detector and small size of the source, the signal to noise ratio was very small which made it virtually impossible to identify gamma peaks within 10 - 20 keV range from Am-241.

Amptek XR 100 CR [140], a low energy photon detector, was found to provide the required resolution. The Amptek XR 100 CR has a Si-PIN detector with an area of $2.4 \text{ mm} \times 2.8 \text{ mm}$, and provides an energy resolution of 220 eV FWHM with standard $12 \mu\text{s}$ shaping time [140]. The entire detector assembly is only about five inches long. However, since the detector was originally used in vacuum X-ray detection, it came with a standard conflat compression O-ring port and about a foot long cylindrical tube attached to it. The far side of the cylindrical tube had a beryllium (Be) window to keep the vacuum inside the tube intact. It was verified that the thermoelectric cooler in the assembly was keeping the active detector components (Si-PIN photodiode and input FET) at the manufacturer's recommended working temperature of $\sim 245 \text{ K}$.

Figure A.5

Experimental setup for gamma attenuation measurements.

The top middle figure shows the schematic for the measurement. Top left picture shows the detector with its vacuum extension tube, top right picture shows source (red pillbox) in the source sink and the collimators (blue). The bottom picture shows the entire assembly with a two stage motion system. See text for details.

The detector had a custom pre-amplifier and a multichannel analyzer (MCA) of its own and had options for turning on/off pileup rejection and the rise time discrimination circuit. All the measurements were taken with these optional circuits ON. The MCA for the detector was connected to a computer via a serial port and a custom control software (ADMCA 2.0 [141]) was used for data acquisition. The MCA also had a live visual display of the spectrum. The detector was calibrated using an iron (Fe-55) source which has distinct 5.9 keV and 6.49 keV gamma peaks. The entire experimental setup is shown in Figure A.5

A.6.5 Analysis

Non-negligible cosmic background peaks below 10 keV were found when the detector was left running for a couple of hours in the room. A software threshold was set to collect data only above 10 keV. The rate from the background above 10 keV was almost zero, so the measurements taken were not influenced by the cosmic background.

The punched windows were still radioactive from their exposure to the electron beam. Backgrounds from the remnant radioactivity were also studied by measuring the rates with the detector only looking at (1) the active windows only (one window at a time), and (2) at the windows plus source combination. Spectra from both cases are shown in Figure A.6. A background peak at the tail of 13.95 keV peak (from Am-241) was found in a sea of background from window activity (see Figure A.6). As shown in Figure A.6 the Am-241 spectrum shifted right when the targets (active windows) were put in the gamma beam to measure their thickness, compared to the spectrum when no target was put in.

Figure A.6

Spectra from Am-241 source and cell window.

Spectra from (1) Am-241 only (faint green outline) and (2) Am-241 and exit window (filled red region). Note the shift in the centroid of the peaks when in (2). A small satellite peak from window activity is also seen. The quadratic background level is much higher in (2) compared to (1). The other unlabeled peaks are from Am-241.

Pile-up in the MCA or Compton scattering of photons in the target were ruled out as the total rate at the detector with both source and active windows in was less than 100 Hz. The deadtime associated with these measurements were found to be very small ($<1\%$). Also, the pile-up rejection circuit was active and naively one would expect a shift of the spectrum to the left (towards smaller energy) if the photons lost energy via Compton scattering. The shift was not as visibly distinct in the entrance windows (both Run 1 and 2) as compared to the exit windows. It is noteworthy that the activity was higher in the downstream windows than in the upstream ones. Moreover, the downstream face of the Run 1 exit window has a pronounced dark spot where the beam penetrated it, of unknown origin.

Measurements were taken in three different modes: (1) with source only (2) with source and a thicker dummy and (3) with source and thin punched windows. The first two measurements give α while the first and the last give the thickness by using α . Spectra were obtained for three different cases for all entrance and exit windows. The measured spectra were fit with gaussian peaks and a quadratic background. The fit background was subtracted from the measured data before the peaks were fit. While fitting data from the active windows, the background peak was also subtracted by fitting the background peak as well (see Figure A.7). The gaussian fit was then integrated to get the number of counts under both 13.95 keV and 17.74 keV peaks. α and t were then determined using these counts by using relation A.5.

Figure A.7

Fitting of the peaks after quadratic background subtraction.

The two peaks of energy 13.95 keV and 17.74 keV are from Am-241. A small peak from the radioactive window can be seen at the bottom of 13.95 keV peak. Two other peaks adjacent to 17.74 keV are from Am-241 as well. The fitting routine was used to fit all peaks at once.

A.6.6 Conclusions

The fit results gave two different thicknesses for 13.95 and 17.74 keV peak, thickness from 17.74 keV peak always being higher than from 13.95 keV peak for reasons unknown. This difference was up to 0.5 mil for the entrance windows and up to several mil for the exit windows. The difference did not go away when a spare window of thickness comparable to the radioactive entrance windows was used. The 17.74 keV peak was used as a sanity check of the results obtained from the 13.95 keV peak, which clearly failed in these measurements.

The thicknesses acquired using the 13.95 keV peak did not always agree with the Mitutuyo micrometer measurements within the precision of the micrometer. It was inconclusive whether this difference was real, possibly due to ~ 0.3 mil cavity in the alloy, or not. The measurements were also found to be irreproducible and thus it was concluded that these results could not be trusted. It still remains unclear whether these strange results are related to the detector in some way or to the residual radioactivity in the windows or both. It is hoped that any such future measurements shall be done well before the windows see any electron beam.

A.7 Results

A summary of the thickness measurements of the entrance and exit windows using Mitutuyo micrometer are shown in Table A.1.

A summary of thicknesses, masses, areas, and areal densities for various aluminum and carbon targets used in the Qweak experiment are listed in Figure A.8 [142].

Run	Tgt Pos.	US or DS	What	Mean Mitutoyo Thk (mm)	Stdev Mitutoyo Thk (mm)	Mean Weight (gm)	Stdev Weight (gm)	Mean Area (in^2)	Stdev Area (in^2)	Mean Flip Area diff	Mean Split avg(in&out) Split (%)	Mean p(areal)/thk Vol. Dens. (g/cm^3)	Mean rho(areal) (g/cm^2)	Stdev rho(areal) (%)	Mean X0 (%)
1	1	DS	Al dummy	1.7725	0.00435	3.0957	0.00013	0.9824	0.00012	3.617%		2.7556	0.4884	0.0125%	2.033%
1	2	DS	Al dummy	7.1188	0.00169	12.4173	0.00010	0.9569	0.00006	0.578%	0.2642%	2.8253	2.0113	0.0063%	8.371%
1	3	DS	Al dummy	3.5878	0.00109	6.2518	0.00007	0.9586	0.00005	0.670%	0.1133%	2.8185	1.0112	0.0058%	4.208%
1	4	DS	thin C	0.9973	0.00227	1.0606	0.00012	0.9729	0.00007	0.254%	0.0527%	1.6967	0.1692	0.0136%	0.397%
1	6	DS	Be slab 3/3	6.1054	0.00337	7.0570	0.00030	0.9643	0.00008	0.000%	0.0000%	1.8616	1.1366	0.0099%	1.746%
1	12	US	C	3.1716	0.00104	4.5234	0.00015	0.9990	0.00016	0.055%		2.2129	0.7018	0.0168%	1.645%
2	1	DS	Al dummy	1.8637	0.00082	3.2494	0.00010	0.9646	0.00008	0.066%	0.0000%	2.8015	0.5221	0.0089%	2.173%
2	2	DS	Al dummy	7.1980	0.00143	12.5669	0.00009	0.9642	0.00007	0.052%	0.0023%	2.8066	2.0202	0.0070%	8.408%
2	3	DS	Al dummy	3.6828	0.00083	6.4214	0.00010	0.9642	0.00008	0.053%	0.0000%	2.8028	1.0322	0.0092%	4.296%
2	4	DS	C	3.1876	0.00182	4.5312	0.00012	0.9991	0.00010	0.000%	0.0000%	-	0.7030	0.0105%	1.648%
2	6	DS	Al dummy	3.6678	0.00568	6.4232	0.00021	0.9648	0.00012	0.030%		2.8134	1.0319	0.0124%	4.295%
2	12	US	thin C	0.9973	0.00227	1.0606	0.00012	0.9729	0.00007	0.254%	0.0527%	1.6967	0.1692	0.0136%	0.397%
2	16	US	spare Al dmy	3.5954	0.01982	6.2740	0.00052	0.9584	0.00015	0.104%		2.8223	1.0147	0.0176%	4.223%
2	17	US	spare Al dmy	1.8033	0.01198	3.1369	0.00042	0.9638	0.00012	0.417%		2.7976	0.5045	0.0180%	2.100%
1 & 2	10	US	Pure Al (5/4)	1.0149	0.00045	1.7318	0.00013	0.9524	0.00007	6.991%	0.0000%	2.7623	0.2803	0.0117%	1.167%
1 & 2	13	US	Al dummy	0.8812	0.00055	1.5243	0.00009	0.9627	0.00005	0.147%	0.0519%	2.7850	0.2454	0.0079%	1.021%
1 & 2	14	US	Al dummy	3.6030	0.00102	6.2940	0.00010	0.9599	0.00005	0.153%	0.0433%	2.8201	1.0161	0.0056%	4.229%
1 & 2	15	US	Al dummy	1.7987	0.00070	3.1359	0.00009	0.9664	0.00005	0.072%	0.0283%	2.7963	0.5030	0.0065%	2.093%

Mean volume density of Al dummies 2.8038 +/- 0.0195g/cm^3
Mean volume density of US Al dummies 2.8043 +/- 0.0162g/cm^3
Mean volume density of DS Al dummies 2.8034 +/- 0.0228g/cm^3

Figure A.8

Summary table of solid target thicknesses.

Table A.1

Average cell window thicknesses as measured by Mitutuyo micrometer.

	Entrance window		Exit window	
	Mean (mil)	Error (mil)	Mean (mil)	Error (mil)
Run 1	4.14	0.044	4.98	0.114
Run 2	4.07	0.038	5.35	0.118

APPENDIX B
YIELD DRIFT

B.1 Yield drifts

Consider a quartet of form $+- -+$ and let V_0 , V_{phys} , and V_d be the constant offset, physics yield, and linear drift in the yield per unit time respectively. Assuming the helicity windows are created at time in arbitrary units t , $3t$, $5t$ and $7t$ such that the time interval between any two consecutive helicity states is always the same ($2t$ in this case), the total PMT yield for the four helicity states in the given quartet can be written as,

$$\begin{aligned} V_1 &= V_0 + V_{phys} + V_d t, \\ V_2 &= V_0 - V_{phys} + 3V_d t, \\ V_3 &= V_0 - V_{phys} + 5V_d t, \\ V_4 &= V_0 + V_{phys} + 7V_d t. \end{aligned} \tag{B.1}$$

Asymmetry from a quartet is given by

$$A(\text{quartet}) \equiv \frac{(V_1 + V_4) - (V_2 + V_3)}{(V_1 + V_4) + (V_2 + V_3)} = \frac{4V_{phys}}{4V_0 + 16V_d t} \simeq \frac{V_{phys}}{V_0} \tag{B.2}$$

assuming $V_0 \gg V_d t$. Similarly, asymmetry from a pair $(+-)$ is given by

$$A(\text{pair}) \equiv \frac{V_1 - V_2}{V_1 + V_2} = \frac{2V_{phys} - 2V_d t}{2V_0 + 4V_d t} = \frac{2V_{phys}}{2V_0 + 4V_d t} - \frac{2V_d t}{2V_0 + 4V_d t} \simeq \frac{V_{phys}}{V_0} - \frac{V_d t}{V_0}. \tag{B.3}$$

A potential V_d of magnitude 1%/10 sec (1000 ppm/sec) after a beam trip would create a false asymmetry of 2 ppm ($t = 2/1000$ sec for a pair, hence $V_d t = 2$ ppm) if pairs were used instead of quartets.

APPENDIX C

HELICITY CORRELATED BEAM PARAMETER DIFFERENCES

C.1 Helicity correlated beam parameter differences

This appendix summarizes the results of study on helicity correlated beam parameter differences for Run 1. The six parameters studied are : qwk_targetX/Y, qwk_targetX/Yslope, qwk_energy and qwk_charge. Listed are the tables with $\langle IN, -OUT \rangle$, $\frac{\langle IN \rangle + \langle OUT \rangle}{2}$, $\langle IN \rangle$ and $\langle OUT \rangle$ values of these parameters. Each table has six data columns as described below:

- Columns 1-2 : Straight averages and errors of runlets without Wien sign correction.
- Columns 3-4 : “mdallpmtavg” error weighted averages and errors of runlets without Wien sign correction.
- Columns 5-6 : “mdallpmtavg” error weighted averages and errors of runlets with Wien sign correction.

		<IN,-OUT>						
		No wt/ No W. sign		MD wt/ No W. sign		MD wt/ W. sign		
		Mean	Error	Mean	Error	Mean	Error	Units
Run I	X	-11.4837	0.0523	-11.1932	0.0548	5.2109	0.0548	nm
	X'	-0.3041	0.0068	-0.2160	0.0071	-0.0442	0.0071	nrad
	Y	8.1437	0.0523	7.3662	0.0548	-4.6441	0.0548	nm
	Y'	-0.0074	0.0068	-0.1645	0.0071	0.2197	0.0071	nrad
	E	0.00218	0.00002	0.00463	0.00002	-0.00322	0.00002	ppm
	Aq	0.0459	0.0031	0.0870	0.0030	-0.0682	0.0030	ppm
Wien 1	X	-0.3333	0.1153	0.3730	0.1400	0.3730	0.1400	
	X'	-0.2021	0.0150	-0.1989	0.0182	-0.1989	0.0182	
	Y	19.4747	0.1153	19.6684	0.1400	19.6684	0.1400	
	Y'	0.8468	0.0150	0.8519	0.0182	0.8519	0.0182	
	E	-0.00007	0.00005	-0.00011	0.00006	-0.00011	0.00006	
	Aq	-0.0056	0.0072	-0.0115	0.0087	-0.0115	0.0087	
Wien 2	X	-16.7262	0.1113	-17.1316	0.0894	17.1316	0.0894	
	X'	0.0823	0.0145	0.0498	0.0116	-0.0498	0.0116	
	Y	11.4731	0.1113	11.0905	0.0894	-11.0905	0.0894	
	Y'	-0.4673	0.0145	-0.4202	0.0116	0.4202	0.0116	
	E	0.01221	0.00005	0.01222	0.00004	-0.01222	0.00004	
	Aq	0.0873	0.0066	0.1051	0.0052	-0.1051	0.0052	
Wien 3	X	-20.6375	0.1110	-20.8329	0.1401	-20.8329	0.1401	
	X'	-0.6947	0.0144	-0.6998	0.0182	-0.6998	0.0182	
	Y	-4.5461	0.1110	-5.3152	0.1401	-5.3152	0.1401	
	Y'	-0.3245	0.0144	-0.3465	0.0182	-0.3465	0.0182	
	E	0.00229	0.00005	0.00265	0.00006	0.00265	0.00006	
	Aq	0.0167	0.0083	0.0042	0.0101	0.0042	0.0101	
Wien 4	X	-2.7147	0.1261	-10.2314	0.1316	10.2314	0.1316	
	X'	-0.0936	0.0164	-0.6033	0.0171	0.6033	0.0171	
	Y	20.3864	0.1261	10.6350	0.1316	-10.6350	0.1316	
	Y'	0.3880	0.0164	-0.1986	0.0171	0.1986	0.0171	
	E	-0.00211	0.00005	-0.00381	0.00006	0.00381	0.00006	
	Aq	0.1156	0.0060	0.1492	0.0058	-0.1492	0.0058	
Wien 5	X	-1.9689	0.1185	0.9567	0.1437	0.9567	0.1437	
	X'	-0.0450	0.0154	0.0509	0.0187	0.0509	0.0187	
	Y	-5.4676	0.1185	-5.7486	0.1437	-5.7486	0.1437	
	Y'	-0.3505	0.0154	-0.3422	0.0187	-0.3422	0.0187	
	E	0.00195	0.00005	0.00217	0.00006	0.00217	0.00006	
	Aq	0.0252	0.0062	0.0627	0.0075	0.0627	0.0075	

Figure C.1

Run 1 <IN, -OUT> for the helicity correlated beam parameter differences.

		<IN+OUT>						
		No wt/No W. sign		MD wt/ No W. sign		MD wt/ W. sign		
		Mean	Error	Mean	Error	Mean	Error	Units
Run I	X	-5.5875	0.0523	-1.9883	0.0548	-21.3616	0.0548	nm
	X'	0.0593	0.0068	0.2695	0.0071	-1.1968	0.0071	nrad
	Y	17.3808	0.0523	15.5360	0.0548	-11.8450	0.0548	nm
	Y'	0.5363	0.0068	0.3944	0.0071	-0.5071	0.0071	nrad
	E	-0.00082	0.00002	0.00237	0.00002	-0.00930	0.00002	ppm
	Aq	-0.1200	0.0031	-0.1364	0.0031	0.0249	0.0031	ppm
Wien 1	X	4.5337	0.1158	4.1191	0.1414	4.1191	0.1414	
	X'	-0.0116	0.0151	-0.0154	0.0184	-0.0154	0.0184	
	Y	10.3072	0.1158	9.6008	0.1414	9.6008	0.1414	
	Y'	0.3523	0.0151	0.3281	0.0184	0.3281	0.0184	
	E	-0.00059	0.00005	-0.00063	0.00006	-0.00063	0.00006	
	Aq	-0.1462	0.0072	-0.1369	0.0088	-0.1369	0.0088	
Wien 2	X	2.5518	0.1116	3.8711	0.0895	-3.8711	0.0895	
	X'	0.5665	0.0145	0.6341	0.0116	-0.6341	0.0116	
	Y	7.2172	0.1116	7.4029	0.0895	-7.4029	0.0895	
	Y'	-0.2751	0.0145	-0.3290	0.0116	0.3290	0.0116	
	E	0.00936	0.00005	0.01024	0.00004	-0.01024	0.00004	
	Aq	-0.0395	0.0066	-0.0840	0.0052	0.0840	0.0052	
Wien 3	X	13.3192	0.1111	14.4270	0.1402	14.4270	0.1402	
	X'	0.5471	0.0144	0.5735	0.0182	0.5735	0.0182	
	Y	-0.6583	0.1111	0.0869	0.1402	0.0869	0.1402	
	Y'	0.1034	0.0144	0.1176	0.0182	0.1176	0.0182	
	E	-0.00279	0.00005	-0.00270	0.00006	-0.00270	0.00006	
	Aq	-0.1100	0.0085	-0.1064	0.0101	-0.1064	0.0101	
Wien 4	X	51.0517	0.1261	48.1467	0.1341	-48.1467	0.1341	
	X'	2.9374	0.0164	2.8626	0.0174	-2.8626	0.0174	
	Y	69.8754	0.1261	66.6344	0.1341	-66.6344	0.1341	
	Y'	3.4870	0.0164	3.4172	0.0174	-3.4172	0.0174	
	E	0.01088	0.00005	0.01091	0.00006	-0.01091	0.00006	
	Aq	-0.1513	0.0061	-0.1799	0.0060	0.1799	0.0060	
Wien 5	X	-99.3939	0.1197	-100.2714	0.1454	-100.2714	0.1454	
	X'	-3.7427	0.0156	-3.7619	0.0189	-3.7619	0.0189	
	Y	0.1625	0.1197	-1.2362	0.1454	-1.2362	0.1454	
	Y'	-0.9860	0.0156	-1.0439	0.0189	-1.0439	0.0189	
	E	-0.02095	0.00005	-0.02072	0.00006	-0.02072	0.00006	
	Aq	-0.1528	0.0063	-0.1747	0.0075	-0.1747	0.0075	

Figure C.2

Run 1 $\frac{\langle IN \rangle + \langle OUT \rangle}{2}$ for the helicity correlated beam parameter differences.

		IN						
		No wt/No W. sign		MD wt/ No W. sign		MD wt/ W. sign		
		Mean	Error	Mean	Error	Mean	Error	Units
Run I	X	-17.0199	0.0737	-13.2560	0.0790	-16.9506	0.0790	nm
	X'	-0.2453	0.0096	0.0636	0.0103	-1.2858	0.0103	nrad
	Y	25.3646	0.0737	23.4839	0.0790	-16.9327	0.0790	nm
	Y'	0.5240	0.0096	0.2447	0.0103	-0.3064	0.0103	nrad
	E	0.00137	0.00003	0.00709	0.00003	-0.01287	0.00003	ppm
	Aq	-0.0841	0.0046	-0.0640	0.0046	-0.0406	0.0046	ppm
Wien 1	X	3.7460	0.1554	3.9230	0.1856	3.9230	0.1856	
	X'	-0.2126	0.0202	-0.2122	0.0241	-0.2122	0.0241	
	Y	28.7488	0.1554	27.9428	0.1856	27.9428	0.1856	
	Y'	1.1637	0.0202	1.1346	0.0241	1.1346	0.0241	
	E	-0.00060	0.00007	-0.00065	0.00008	-0.00065	0.00008	
	Aq	-0.1395	0.0097	-0.1320	0.0117	-0.1320	0.0117	
Wien 2	X	-14.3423	0.1525	-13.1700	0.1280	13.1700	0.1280	
	X'	0.6115	0.0198	0.6988	0.0166	-0.6988	0.0166	
	Y	18.2154	0.1525	18.6665	0.1280	-18.6665	0.1280	
	Y'	-0.7243	0.0198	-0.7569	0.0166	0.7569	0.0166	
	E	0.02095	0.00006	0.02270	0.00005	-0.02270	0.00005	
	Aq	0.0494	0.0091	0.0169	0.0075	-0.0169	0.0075	
Wien 3	X	-7.8097	0.1542	-6.9772	0.1943	-6.9772	0.1943	
	X'	-0.1678	0.0200	-0.1490	0.0253	-0.1490	0.0253	
	Y	-5.1801	0.1542	-5.2318	0.1943	-5.2318	0.1943	
	Y'	-0.2249	0.0200	-0.2336	0.0253	-0.2336	0.0253	
	E	-0.00040	0.00006	0.00005	0.00008	0.00005	0.00008	
	Aq	-0.1132	0.0130	-0.1115	0.0150	-0.1115	0.0150	
Wien 4	X	48.3807	0.1785	47.1879	0.2071	-47.1879	0.2071	
	X'	2.8463	0.0232	2.8106	0.0269	-2.8106	0.0269	
	Y	90.3217	0.1785	90.1026	0.2071	-90.1026	0.2071	
	Y'	3.8780	0.0232	3.8768	0.0269	-3.8768	0.0269	
	E	0.00878	0.00007	0.00920	0.00009	-0.00920	0.00009	
	Aq	-0.0698	0.0096	-0.0771	0.0095	0.0771	0.0095	
Wien 5	X	-115.0740	0.1806	-114.8240	0.2210	-114.8240	0.2210	
	X'	-4.3040	0.0235	-4.2929	0.0287	-4.2929	0.0287	
	Y	-5.2827	0.1806	-7.1760	0.2210	-7.1760	0.2210	
	Y'	-1.4726	0.0235	-1.5476	0.0287	-1.5476	0.0287	
	E	-0.02189	0.00008	-0.02175	0.00009	-0.02175	0.00009	
	Aq	-0.1476	0.0094	-0.1381	0.0114	-0.1381	0.0114	

Figure C.3

Run 1 $\langle IN \rangle$ for the helicity correlated beam parameter differences.

		OUT						Units
		No wt/No W. sign		MD wt/ No W. sign		MD wt/ W. sign		
		Mean	Error	Mean	Error	Mean	Error	
Run I	X	5.8448	0.0743	9.2794	0.0761	-25.7726	0.0761	nm
	X'	0.3640	0.0097	0.4754	0.0099	-1.1077	0.0099	nrad
	Y	9.3970	0.0743	7.5880	0.0761	-6.7573	0.0761	nm
	Y'	0.5486	0.0097	0.5442	0.0099	-0.7078	0.0099	nrad
	E	-0.00300	0.00003	-0.00234	0.00003	-0.00572	0.00003	ppm
	Aq	-0.1558	0.0042	-0.2088	0.0041	0.0904	0.0041	ppm
Wien 1	X	5.3213	0.1718	4.3152	0.2133	4.3152	0.2133	
	X'	0.1893	0.0223	0.1814	0.0277	0.1814	0.0277	
	Y	-8.1343	0.1718	-8.7413	0.2133	-8.7413	0.2133	
	Y'	-0.4592	0.0223	-0.4784	0.0277	-0.4784	0.0277	
	E	-0.00057	0.00007	-0.00060	0.00009	-0.00060	0.00009	
	Aq	-0.1528	0.0106	-0.1418	0.0132	-0.1418	0.0132	
Wien 2	X	19.4459	0.1629	20.9121	0.1250	-20.9121	0.1250	
	X'	0.5215	0.0212	0.5695	0.0163	-0.5695	0.0163	
	Y	-3.7810	0.1629	-3.8608	0.1250	3.8608	0.1250	
	Y'	0.1742	0.0212	0.0990	0.0163	-0.0990	0.0163	
	E	-0.00223	0.00007	-0.00223	0.00005	0.00223	0.00005	
	Aq	-0.1284	0.0095	-0.1849	0.0072	0.1849	0.0072	
Wien 3	X	34.4482	0.1600	35.8313	0.2021	35.8313	0.2021	
	X'	1.2620	0.0208	1.2961	0.0263	1.2961	0.0263	
	Y	3.8635	0.1600	5.4055	0.2021	5.4055	0.2021	
	Y'	0.4317	0.0208	0.4688	0.0263	0.4688	0.0263	
	E	-0.00518	0.00007	-0.00546	0.00008	-0.00546	0.00008	
	Aq	-0.1069	0.0108	-0.1013	0.0137	-0.1013	0.0137	
Wien 4	X	53.7226	0.1783	49.1054	0.1704	-49.1054	0.1704	
	X'	3.0285	0.0232	2.9145	0.0222	-2.9145	0.0222	
	Y	49.4291	0.1783	43.1662	0.1704	-43.1662	0.1704	
	Y'	3.0960	0.0232	2.9577	0.0222	-2.9577	0.0222	
	E	0.01298	0.00007	0.01262	0.00007	-0.01262	0.00007	
	Aq	-0.2328	0.0076	-0.2826	0.0073	0.2826	0.0073	
Wien 5	X	-83.7138	0.1572	-85.7187	0.1891	-85.7187	0.1891	
	X'	-3.1814	0.0204	-3.2309	0.0246	-3.2309	0.0246	
	Y	5.6077	0.1572	4.7035	0.1891	4.7035	0.1891	
	Y'	-0.4995	0.0204	-0.5402	0.0246	-0.5402	0.0246	
	E	-0.02001	0.00007	-0.01968	0.00008	-0.01968	0.00008	
	Aq	-0.1579	0.0082	-0.2113	0.0098	-0.2113	0.0098	

Figure C.4

Run 1 $< OUT >$ for the helicity correlated beam parameter differences.

APPENDIX D

COMB PLOTS FOR LINEAR REGRESSION CORRECTIONS

D.1 Comb plots

These plots show corrections for each helicity correlated beam parameter differences used in the “5+1” linear regression.

Figure D.1

<IN, -OUT> corrections by Wien for all IV's in the "5+I" linear regression.

Figure D.2

$\frac{\langle IN \rangle + \langle OUT \rangle}{2}$ corrections by Wien for all IV's in the "5+I" linear regression.

Figure D.3

$\langle IN \rangle$ corrections by Wien for all IV's in the “5+I” linear regression.

Figure D.4

$\langle OUT \rangle$ corrections by Wien for all IV's in the “5+I” linear regression.

APPENDIX E

RUN 1 CORRECTIONS SUPPLEMENT

E.1 Run 1 corrections

This appendix contains histograms and a table of regression, post-regression, beamline background, polarization and finally level I corrections for all slugs in Run 1. The corrections are defined in the order they are applied to the data as following:

- Regression correction = regressed (“5+1”) asymmetry - raw asymmetry.
- Post-regression correction = post-regressed asymmetry - regressed asymmetry.
- Beamline background correction = beamline background corrected asymmetry - post-regressed asymmetry.
- Polarization correction = beam polarization corrected asymmetry - post-regressed asymmetry.
- Level I correction = asymmetry with regression, post-regression, beamline background and polarization corrections - raw asymmetry.

Figure E.1

Histograms of corrections (top to bottom) leading up to level I corrections for Run 1.

Table E.1

Run 1 <IN, -OUT> asymmetries, and associated χ^2/dof and probabilities for raw and regressed data with various corrections.

		Asymmetry	χ^2/dof	Prob.
Raw	Wiens	-231.9 ± 11.57	2.62	0.033
	Slug-pairs	-231.9 ± 11.57	1.64	0.005
	Slugs	-231.9 ± 11.57	2.17	0.000
Reg.	Wiens	-232 ± 11.54	1.97	0.096
	Slug-pairs	-232 ± 11.54	1.20	0.173
	Slugs	-232 ± 11.54	2.02	0.000
Post-reg.	Wiens	-219.8 ± 11.54	1.43	0.222
	Slug-pairs	-219.8 ± 11.54	1.10	0.293
	Slugs	-219.8 ± 11.54	1.30	0.032
BB	Wiens	-209.4 ± 11.54	0.33	0.861
	Slug-pairs	-209.4 ± 11.54	0.96	0.551
	Slugs	-209.4 ± 11.54	1.20	0.092
Pol.	Wiens	-250.5 ± 13.14	1.28	0.277
	Slug-pairs	-250.5 ± 13.14	1.09	0.318
	Slugs	-250.5 ± 13.14	1.29	0.034
Level I	Wiens	-238.6 ± 13.14	0.26	0.903
	Slug-pairs	-238.6 ± 13.14	0.95	0.566
	Slugs	-238.6 ± 13.14	1.20	0.095

Data are binned at slug, slug-pair and Wien level.

APPENDIX F

US LUMI SENSITIVITIES AND CORRECTIONS

F.1 US lumi sensitivities and corrections

This appendix has plots of “5+1” sensitivities and linear regression corrections for the upstream lumis. US lumi asymmetry correction (ΔA) is defined as the difference between the regressed and raw asymmetry.

Figure F.1

Slug averaged “5+1” US lumi sensitivities by Wiens.

The vertical green lines mark the boundaries of the five Wien periods.

Figure F.2

Slug level “5+1” US lumi asymmetry corrections by Wiens.

Blue circles represent HWP IN and red circles denote HWP OUT slugs.