A Counting Data Acquisition System for Measuring Parity Violation Asymmetry in Deep Inelastic Scattering

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Abstract

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An experiment measuring the parity violating asymmetry in deep inelastic scattering was completed at the Thomas Jefferson National Accelerator Facility in experimental Hall A. From this asymmetry one can extract a combination of the quark weak axial charge with a factor of five improvement in precision over world data. To achieve this, asymmetries at the 10^{-4} level were measured. A highly specialized data acquisition (DAQ) system with intrinsic particle identification (PID) was developed and utilized. The DAQ system of this experiment is presented here with an emphasis on understanding of its PID performance, deadtime effect, and the capability of measuring small asymmetries.

Key words: Jefferson Lab; Hall A; PVDIS; DAQ
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1 Introduction

The Parity Violating Deep Inelastic Scattering (PVDIS) experiment E08-011 was completed in December 2009 at the Thomas Jefferson National Accelerator Facility (JLab). The goal of this experiment [1,2] is to measure to a high precision the parity

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violating asymmetry in deep inelastic scattering of a polarized electron beam on an unpolarized liquid deuterium target. This asymmetry is sensitive to a combination of the quark weak axial charge $2C_{2u} - C_{2d}$, where $C_{2q} = 2g_V^e g_A^q$ with $q = u, d$ indicating an up or a down quark, g_V^e is the electron vector coupling and g_A^q is the quark axial coupling to the Z^0 boson.

For electron inclusive scattering from an unpolarized target, the electromagnetic interaction is parity conserving and is insensitive to the spin flip of the incoming electron beam. Only the weak interaction violates parity. Taking the difference of the left-handed and right-handed electron scattering cross-sections, one can isolate the parity violating contribution. The parity violating asymmetry for deep inelastic electron scattering from a deuterium target, A_{PV}, can be written as

$$A_{PV} \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \left(-\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)\left(2g_A^e Y_1 \frac{F_1^{\gamma Z}}{F_1^\gamma} + g_V^e Y_3 \frac{F_3^{\gamma Z}}{F_1^\gamma}\right) , \tag{1}$$

where Q^2 is the negative of the four-momentum transfer squared, G_F is the Fermi weak coupling constant, α is the fine structure constant, Y_1 and Y_3 are kinematic factors, and x is the Bjorken scaling variable. In the quark parton model,

$$F_1^{\gamma Z} = \sum g_V^q Q_q \left[q(x) + \bar{q}(x)\right] \tag{2}$$

$$F_3^{\gamma Z} = \sum g_A^q Q_q \left[q(x) - \bar{q}(x)\right] \tag{3}$$

$$F_1^{\gamma} = \frac{1}{2}\sum Q_q^2 \left[q(x) + \bar{q}(x)\right] \tag{4}$$

where Q_q is the electric charge of quarks and $q(x)$, $\bar{q}(x)$ are quark distribution functions. Rewriting $g_{A(V)}^e g_{V(A)}^q$ as $C_{1(2)q}$, and assuming $R^\gamma = R^{\gamma Z} = 0$, one has $Y_1 = 1$ and

$$A_{PV} = \left(\frac{3G_F Q^2}{\pi\alpha^2\sqrt{2}}\right) \times \frac{2C_{1u}[1 + R_C(x)] - C_{1d}[1 + R_S(x)] + Y_3(2C_{2u} - C_{2d})R_V(x)}{5 + R_S(x) + 4R_C(x)} , \tag{5}$$

where $R_{V,C,S}$ are related to quark distributions. The magnitude of the asymmetry is in the order of 10^{-4}, or 10^2 parts per million (ppm) at $Q^2 = 1$ (GeV/c)^2. The tree-level Standard Model effective weak coupling constants $C_{1,2q}$ are

$$C_{1u} = 2g_A^e g_V^u = -\frac{1}{2} + \frac{3}{4}\sin^2\theta_W \ , \ \ C_{2u} = 2g_V^e g_A^u = -\frac{1}{2} + 2\sin^2\theta_W \ ,$$
$$C_{1d} = 2g_A^e g_V^d = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W \ , \ \ C_{2d} = 2g_V^e g_A^d = \frac{1}{2} - 2\sin^2\theta_W \ ,$$

with θ_W the weak mixing angle. The goal of JLab E08-011 is to measure the PVDIS asymmetries to a statistical precision of $3-4\%$ and a systematic uncertainty of $<3\%$, and under the assumption that hadronic physics corrections are small, to extract from these asymmetries the effective coupling constant combination $(2C_{2u}-C_{2d})$. The magnitude of the asymmetries is expected to be 90 and 170 ppm for the two measured kinematics of $Q^2 = 1.1$ and 1.9 (GeV/c)^2, respectively. To achieve the required precision, event rates up to 500 kHz are expected. Although this is not the first time the PVDIS asymmetries are measured, the only preceeding PVDIS measurement was carried out at SLAC [5,6] about 35 years ago, with a $\approx 9\%$ statistical and a $\approx 9\%$ systematic uncertainties. The increased precision of this experiment required better controls of all systematic uncertainties.

The experiment used a 100 μA polarized electron beam with a polarization of approximately 90% and a 20-cm long liquid deuterium target. The two High Resolution Spectrometers (HRS) [3] were used to detect scattered electrons. Similar to other deep inelastic scattering experiments, the main challenge of the measurement is to separate electrons from charged pion background due to electro- or photoproductions. While the standard HRS detector package and data acquisition (DAQ) system routinely provide a high particle identification (PID) performance, they are based on full recording of the detector signals and are limited to event rates up to 4 kHz. This is not sufficient for the high rates expected for the experiment. The HRS DAQ will be referred to as "standard DAQ" hereafter. For previous JLab parity violation experiments focusing on elastic scattering from nuclear or nucleon targets, integrating DAQs could be used because elastic scattering typically is not contaminated from other charged particle backgrounds. For the SLAC PVDIS experiment, an integrating DAQ was used with the input being the leadglass detector signals. However, about 2% of the integrated signal was from the pion background. This is comparable to our statistical uncertainty and a better data collection method must be found.

2 DAQ Overview

The design goal of the new DAQ is to count event rates up to 1 MHz with hardware-based PID. The following detectors in the HRS were used: two scintillator planes provided the main trigger, while a CO_2 gas cherenkov counter and a double-layered lead glass provided particle identification information. The standard tracking detector (the vertical drift chamber) was turned off during production data taking because it may not endure the expected high event rates.

For the gas cherenkov detector and the double-layered lead glass counter, a full recording of their output ADC spectrum is not feasible at the expected high rate. Instead their signals are passed through discriminators and logic units to form preliminary electron and pion triggers. These preliminary triggers are then combined

with the scintillator triggers and cherenkov signals from the standard DAQ to form the final electron and pion triggers, which are then sent to scalers to record the event counts and form asymmetries. Particle identification is fulfilled by the use of discriminators for both the lead-glass and the cherenkov counters and proper settings of their thresholds.

For HRS the two layers of the leadglass counter are called "preshower" and "shower" detectors, respectively. The preshower blocks in the Right HRS (the spectrometer located to the right side of the beamline when viewed along the beam direction) has 48 blocks arranged in a 2×24 array, with the longest dimension of the blocks aligned perpendicular to the particle trajectory. For the two blocks in each row, only the ends facing outward are read out by photo-multiplier tubes (PMTs) and the other ends of the two blocks were facing each other and not read out. Therefore the preshower detector had 48 output channels. All preshower blocks were individually wrapped to prevent light leak. The preshower and the shower detectors in the Left HRS are similar to the preshower detector on the Right HRS except that for each detector there are 34 blocks arranged in a 2×17 array. The shower detector in the Right HRS had 75 blocks arranged in a 5×15 array with the longest dimension of the blocks aligned along the trajectory of scattered particles. PMTs are attached to each block of the Right shower detector on one end only, giving 75 output channels.

In order to reduce the amount of electronics needed and to avoid high electronic background, the leadglass blocks in both the preshower and the shower detectors were divided into 6 (8) groups for the Left (Right) HRS, with each group consisting 8 blocks. On the Right HRS only 60 of the 75 shower blocks were used while the 15 blocks on the edge were not included in the DAQ. The reduction on the HRS acceptance due to not using these side blocks is negligible. Signals from the 8 blocks in each group were added using a custom-made analog summing unit (SUM8), then passed to discriminators. The geometry and the position of each preshower group was carefully chosen to match those of the corresponding shower group to maximize electron detection efficiency. On the Left HRS adjacent groups in both preshower and shower had overlapping blocks, while for the Right HRS only preshower blocks were overlapping. To allow overlapping between adjacent groups, signals from preshower blocks on the Right HRS and from both preshower and shower blocks on the Left HRS were split into two identical copies using passive splitters. Grouping of the leadglass blocks is shown in Fig. 1.

A schematic diagram for the DAQ electronics for the Right HRS is shown in Fig. 2. The electron and pion triggers were formed by passing shower (SS) and preshower (PS) signals or their sums, called total shower (TS) signals, through discriminators with different thresholds. For electron triggers, logical ANDs of the preshower discriminator and the total shower discriminator outputs were formed. For pion triggers only one set of discriminators on the TS signals were used. These signals were then combined with the signal from scintillators and the gas cherenkov (called

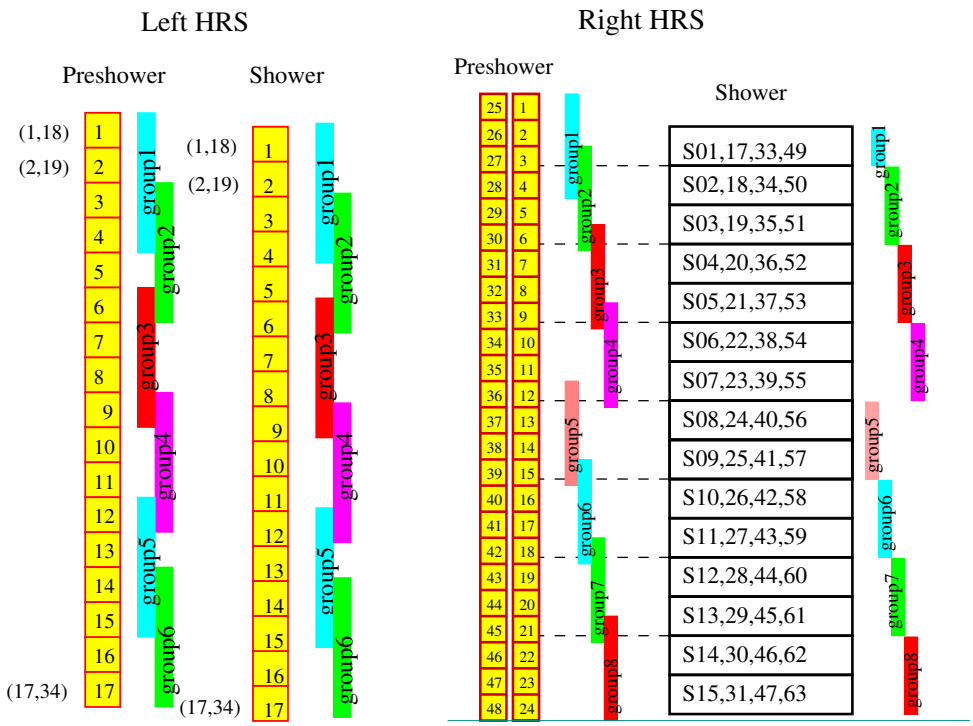

Fig. 1. Grouping scheme (side-view) for the double-layered lead glass counters for the Left and the Right HRS. Scattered particles enter the detector from the left. The colored vertical bars represent the range of each group.

electron or pion "VETO" signals) to form electron or pion triggers for each shower and preshower group. The electron or pion triggers from all six (eight for the Right HRS) groups were then ORed together to form the global electron or pion triggers for the Left (Right) HRS. All triggers – electron and pions from each group, as well as the final global triggers – were counted using scalers.

In order to study the counting deadtime of the DAQ, two identical paths of electronics were constructed. The only difference between the two paths is in the discriminator output width, set at 30 ns and 100 ns for the narrow and the wide paths, respectively. Since scaler counting is free of deadtime effect and the output width of all logic modules were set to 15 ns, the deadtime of the DAQ for each group is dominated by those from the discriminators.

The SUM8 modules used for summing all lead glass signals also served as fan-out modules, providing exact copies of the input PMT signals. These copies were sent to the standard HRS DAQ, hence the standard DAQ remained fully functional. During the experiment, data were collected at low rates using reduced beam currents with both DAQs functioning, such that a direct comparison of the two DAQs can be made. The vertical drift chambers were used during these low rate DAQ studies. Outputs from all discriminators, signals from the scintillator and the gas cherenkov, and all electron and pion triggers were sent to fastbus TDCs (fbTDC) and were recorded in the standard DAQ. Data from these fbTDCs were used to

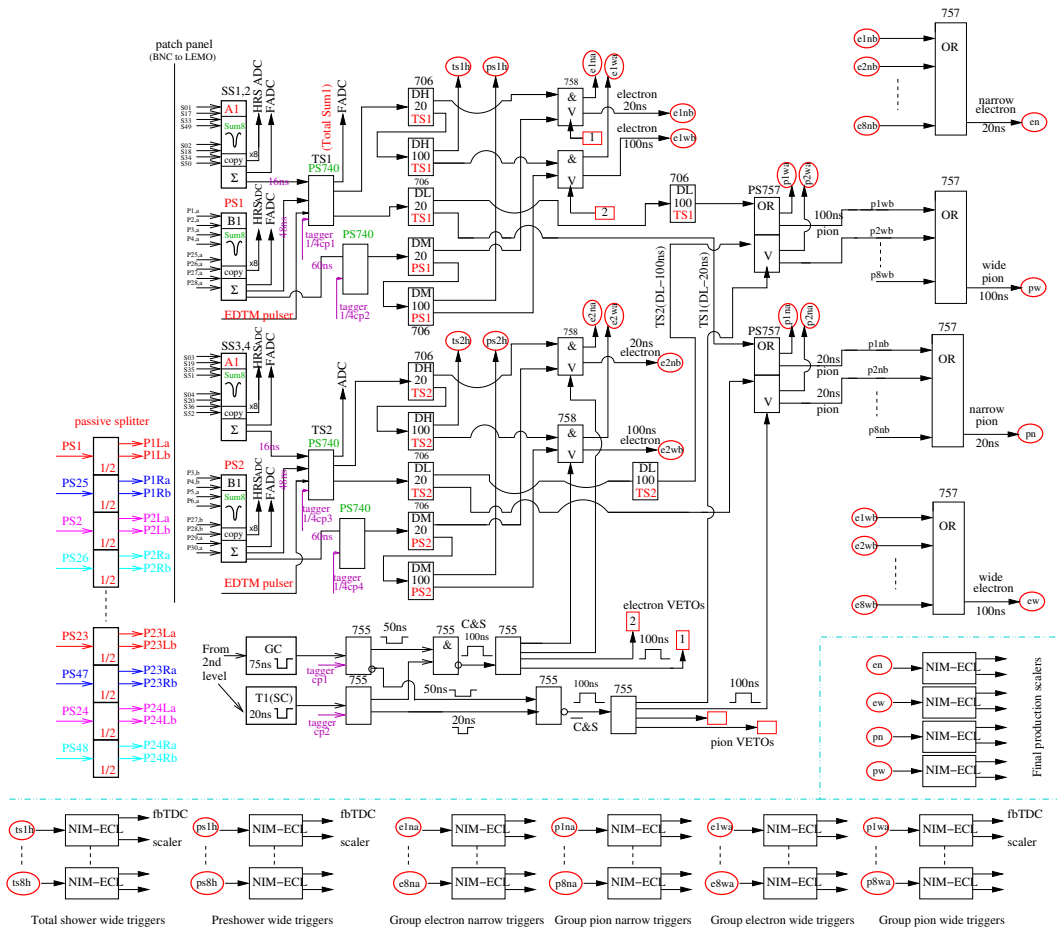

Fig. 2. Electronics diagram for the Right HRS DAQ used by the PVDIS experiment. The Sum8's, discriminators and logic modules for two groups are shown, as well as the location of the tagger signal, setup of the VETO circuit using the scintillator and the gas cherenkov signals, the logic units for combining triggers from all eight groups into final triggers, and the scalers. Electronics for the Left HRS are similar except the units related to grouping.

align signals in timing before and throughout the experiment. They also allow the study of the cherenkov or lead-glass performance for the new DAQ triggers.

Full sampling of analog signals were done using Flash-ADCs (FADCs) at low rates intermittently during the experiment. For one group on the left and one group on the right HRS, the preshower and shower SUM8 outputs, the intermediate logical signals of the DAQ, and the output electron and pion triggers were recorded. These FADC data provide inputs and cross checks for the DAQ performance study.

3 DAQ PID performance

PID performance of the DAQ system were studied at low beam currents using fbTDC signals along with ADC spectrum of all detector signals recorded by the

standard DAQ. Figure 3 shows the preshower vs. shower signals for group 2 on the Left HRS. A comparsion between no fbTDC cut and with cut on the fbTDC signal of the electron wide trigger from this group clearly shows the hardware PID cuts.

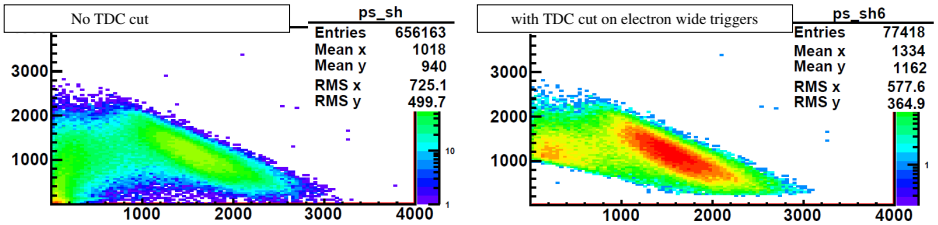

Fig. 3. Preshower vs. Shower ADC spectrum (sum of 8 blocks each) for group 2 on the Left HRS, without fbTDC cut (left) and with cut on the group 2 electron wide trigger fbTDC signal (right). It clearly shows the hardware cuts on the preshower and the total shower signals, indicating the DAQ is selecting the correct events as electrons. The cuts can be adjusted by changing the discriminator thresholds. The events near the vertical axis, around ADC channels (200,1000), are electrons that deposited energy in overlapping blocks between group 2 and group 1 (or group 3) and are recorded by the other group.

Electron efficiency and pion rejection factors of the lead glass counter on the Left HRS are shown in Fig. 4 as functions of the vertical hit position of the particle in the preshower detector. PID performance on the Right HRS is similar. Electron efficiency from wide groups are slightly higher than narrow groups because there is less event loss due to timing mis-alignment when taking the coincidence between the preshower and the total shower discriminator outputs. Variations in the electron efficiency across the spectrometer acceptance effectively change the kinematics (Q^2) of the measurement. For this reason, data were taken daily during the experiment to monitor the DAQ PID performance and corrections are applied to data.

Combined with the ≈ 200 pion rejection factor of the gas cherenkov counter, the total pion rejection was above 10^4. With the parity violation asymmetry of pion production being no larger than that of scattered electrons, the uncertainty in the final asymmetry results due to pion contamination is negligible compared to the $3-4\%$ statistical uncertainty.

4 DAQ Deadtime Study

Deadtime is the amount of time after an event during which the system is unable to record another event. Identifying exact width of the deadtime is always a challenge in counting experiments. Comparison between the narrow and the wide paths helps to diagnose the deadtime. In addition, dividing lead glass blocks into groups help to greatly reduce the deadtime loss in each group compared to summing all blocks together and forming only one final trigger.

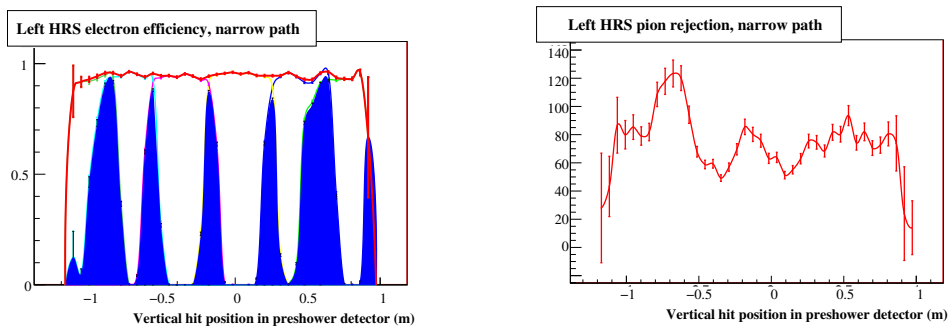

Fig. 4. Electron detection efficiency (left) and pion rejection factor (right) vs. vertical (dispersive) hit position of the particle in the preshower detector for the narrow electron triggers in the Left HRS. A one-hour run was used in this evaluation. For electron efficiencies, the total efficiency is shown by the red curve, while blue shaded area indicates events that are recorded by the two adjacent groups. The average electron efficiency across the detector for this one-hour run is $(94.626 \pm 0.002)\%$ and the averge pion rejection factor is 75.3 ± 1.1. The error bars are statistical only. PID performance for the wide path and the Right HRS are similar.

As shown in Fig. 2, the deadtime of the DAQ has three components:

(1) The "group" deadtime: deadtime due to discriminators and logical AND modules used to form group triggers;
(2) The "veto" deadtime: deadtime from electronics that used scintillator and cherenkov signals to form the "gate" signals which were sent to the AND module of each group to form group electron and pion triggers.
(3) The "OR" deadtime: deadtime due to the logical OR module when combining all group triggers.

The final deadtime is a combination of all three. In order to evaluate the DAQ deadtime, a full-scale simulation was developed as follows: The analog signals for preshower, shower, scintillator and gas cherenkov as recorded by ADCs from low-current runs are fed into the simulation as inputs. The simulation takes into account all electronics and delay cables of the DAQ and calculate digital outputs from discriminators, all AND and OR modules. For the preshower and shower SUM8 outputs, FADC data were used to determine the time constant (width) for group 3 on the left HRS and group 4 on the right HRS (???).

Evaluation of the group deadtime is tested by the tagger measurement described below.

4.0.1 Group Deadtime Measurement

In order to study the deadtime in details, a high rate pulser signal ("tagger") was mixed with all preshower and total shower signals using analog summing modules, see Figs. 2 and 5. In the absence of all detector signals, a tagger pulse produces

without loss an electron trigger output, and a "tagger-trigger coincidence" pulse between this output and the delayed tagger – the tagger itself with an appropriate delay to account for the DAQ response time. When high-rate detector signals are present, however, some of the tagger would not be able to trigger the DAQ due to deadtime. The relative loss in the tagger output w.r.t. the tagger input has two components:

(1) The count loss R_o/R_i: when a detector PMT signal precedes the tagger signal by a time interval δt shorter than the DAQ deadtime but longer than the delayed tagger pulse width, the tagger signal is lost and no coincidence output is formed;

(2) The pileup fraction p: when a PMT signal precedes the tagger signal by a time interval δt shorter than the delayed tagger signal width, there would be coincidence output between the delayed tagger and the electron output triggered by the detector PMT signal. If δt is less than the DAQ deadtime (which is true for this experiment), the tagger itself is lost due to deadtime and the tagger-trigger coincidence is a false count and should be subtracted. In the case if δt is longer than the DAQ deadtime (not true for this experiment but could happen in general, the tagger itself also triggers a tagger-trigger coincidence but in this case, there are two tagger-trigger coincidence events, both recorded by the fbTDC if working in the multi-hit mode, and one is a false count and should be subtracted.

The pileup effect can be measured because the delay between the coincidence output and the input tagger would be smaller than when the electron output is caused by the tagger. This effect is illustrated in Fig. 5 and contributes to both I_1 and I_2 region of the fbTDC spectrum.

The fractional loss of tagger events due to DAQ deadtime is evaluated as

$$D = 1 - (1 - p)(R_o/R_i), \tag{6}$$

where R_i is the *i*nput tagger rate, R_o is the *o*utput tagger-trigger coincidence rate, and $p = (I_1 + I_2)/I_0$ is a correction factor for pileup effects (see Fig. 5 for definition of $I_{0,1,2}$). The pileup effect was measured using fbTDC spectrum for electron narrow and wide triggers for all groups. Results for the deadtime loss D are shown in Figs. 6 and 7 and compared with simulation. Different beam currents between 20 and 100 μA were used in this dedicated deadtime measurement.

Although the deadtime is a characteristic of the DAQ system and should not change with time, the exact decomposition into the count loss R_o/R_i and the pileup p depends on timing constants t_1 and W, shown in Fig. 5. Therefore, drifting in timing alignment and output width could affect the relative contribution from count loss vs. pileup effect, but not the group deadtime results.

The slope of the tagger loss vs. event rate gives the value of group deadtime in seconds, as shown in Figs. 6 and 7, for group 3 on the left HRS and group 4 on

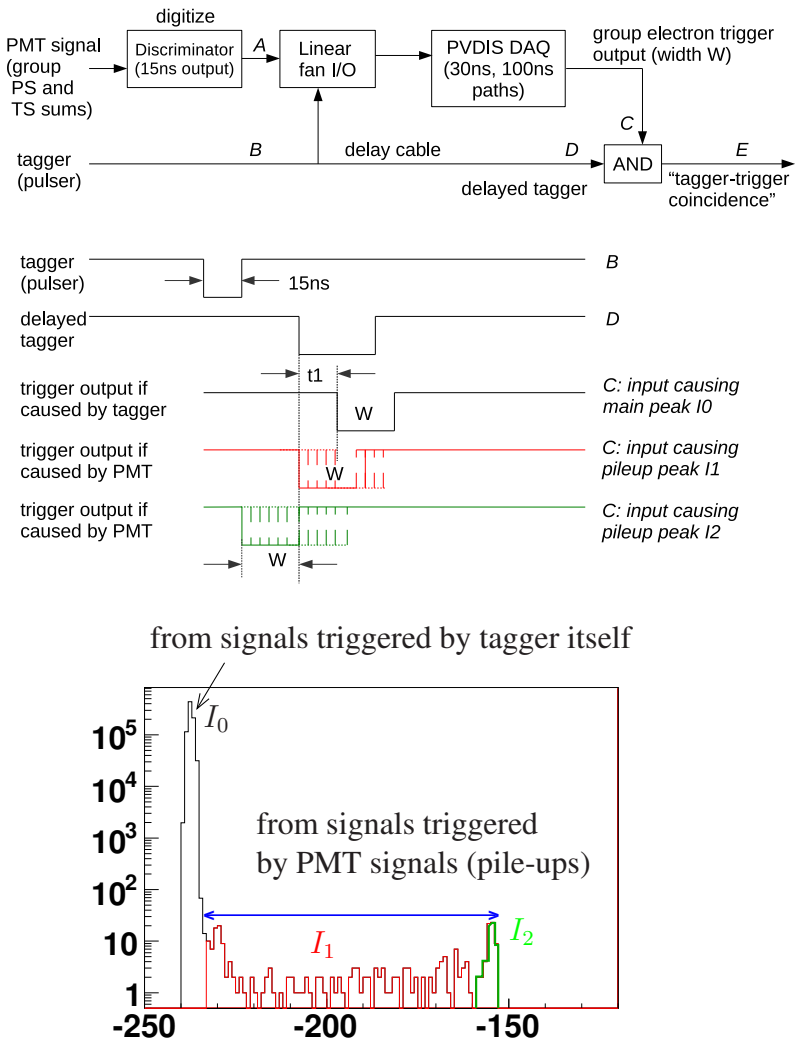

Fig. 5. Top: schematic diagram for the tagger setup and signal timing sequence. Bottom: fbTDC spectrum for the relative timing between tagger-trigger coincidence and the input tagger, in 0.5 ns. The fbTDC module works in the multi-hit mode. Two different scenarios are shown: 1) Main peak I_0: when there is no PMT signal preceding the tagger, the tagger triggers the DAQ and forms a tagger-trigger coincidence. 2) Pileup events I_1 and I_2: when there is a PMT signal preceding the tagger by a time interval shorter than the delayed tagger width, the PMT signal triggers the DAQ and forms a tagger-trigger coincidence signal with the delayed tagger.

the right HRS, respectively. These data are compared with results from the simulation. One can see that the deadtime for the wide path is approximately 100 ns as expected. The deadtime for the narrow path, on the other hand, is dominated by the input PMT signal width (typically 60-80 ns) instead of the 30-ns discriminator width. The simulated deadtime for the narrow path is smaller than data. This could be because we do not have enough FADC data to determine the time constant of

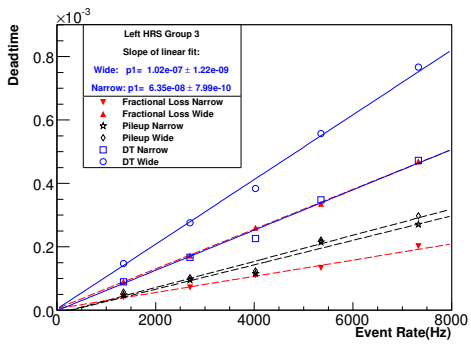

Fig. 6. Deadtime loss in percent vs. event rate from the tagger method for group 3 on the Left HRS. Left: actual deadtime loss from tagger measurements; Right: simulated deadtime loss of the tagger. The tagger count loss (blue) and the pileup correction (green) are shown separately. Results of the linear fit (p_1) shows the measured or simulated group deadtime in seconds. These data were taken (or simulated) at a Q^2 of 1.9 (GeV/c)^2. Group 3 is from the central blocks of the lead-glass counter and has the highest rate among all groups.

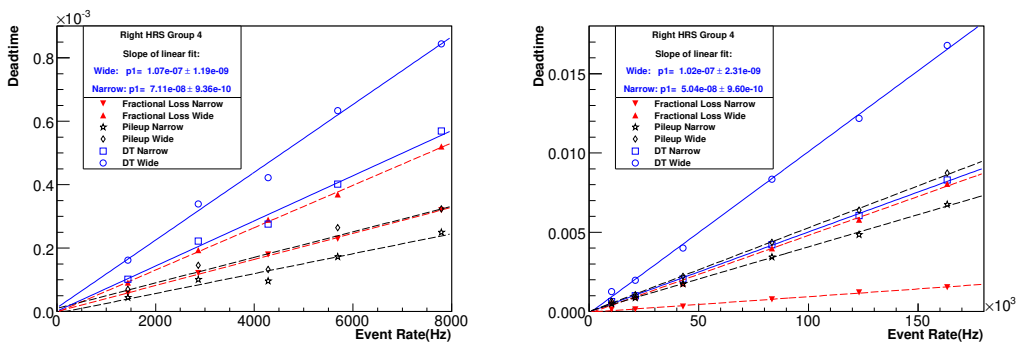

Fig. 7. Deadtime loss in percent vs. event rate from the tagger method for group 4 on the Right HRS. Left: tagger data; Right: simulation. These data were taken (or simulated) at a Q^2 of 1.9 (GeV/c)^2. Group 4 is from the central blocks of the lead-glass counter and has the highest rate among all groups. See Fig. 6 caption for details.

all 8 lead glass block signals of this group, neither do we have FADC data on the timing alignment between these blocks. There is also inconsistency between tagger data and simulation in the decomposition of count loss vs. pileup effects. This could be due to drifting in timing alignment and DAQ output width, and measurements of these parameters were done only at the end of the experiment.

4.0.2 Total Deadtime Evaluation

Although the deadtime loss of each group was measured using tagger signals, the dominating term in the total deadtime is from the veto electronics because the total trigger rate from scintillators and gas cherenkov is much higher than individual group rate. The difference in total loss between narrow and wide path is thus smaller than that in their group deadtimes. Simulation for the veto deadtime was compared

with FADC data and the agreement was found to be at 20% level.

There is no direct measurement of the OR deadtime. The effect of the logical OR module, however, is quite straightforward and can be calculated analytically.

The simulated deadtime loss of the global electron triggers is shown in Fig. 8. This loss provides a direct correction to the measured asymmetry. The deadtime corrections to the final asymmetry results are $(\pm)\%$ and $(\pm)\%$, for $Q^2 = 1.9$ and 1.1 (GeV/c)^2, respectively.

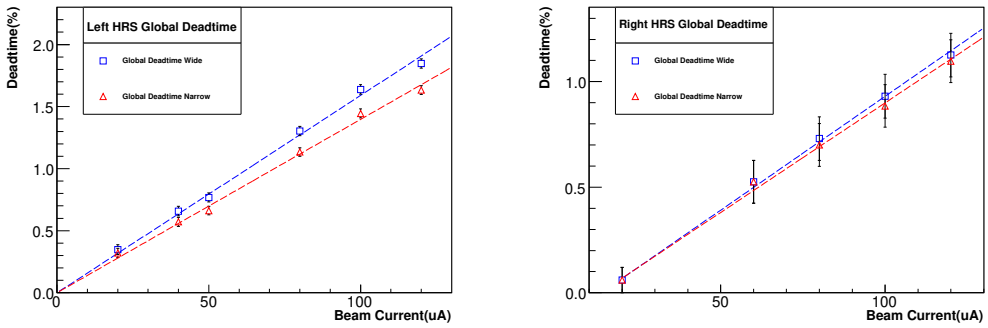

Fig. 8. Simulated deadtime loss of the global electron trigger for the left (left) and the right (right) HRS. Results of the linear fit (p_1) is the simulated total deadtime in seconds.

4.1 Asymmetries

The physics asymmetries sought for in this experiment are 90 and 160 ppm, for the two Q^2 values, respectively. The measured asymmetries are about 10% smaller due to beam polarization. To understand the systematics of the asymmetry measurement, a half-wave plate (HWP) was inserted in the beamline to flip the laser helicity in the polarized source during half of the data taking period. The measured asymmetries flip sign for each beam HWP change and the magnitude of the asymmetry remain consistent within statistical error bars. The asymmetries are formed from event counts of each beam helicity pair (one pair has 33-ms of helicity plus and 33-ms of helicity minus beam), normalized by the beam charge. Figure 9 shows the pair-wise counting asymmetry from about 80% of the total data sets of this experiment. The different HWP states have already been corrected. One can see that the asymmetry spectrum agrees to four orders of magnitude with Gaussian distribution expected from purely statistical fluctuations.

4.2 Conclusion

A scaler-based counting DAQ with hardware-based particle identification was successfully implemented in the 6 GeV PVDIS experiment at Jefferson Lab. Asymme-

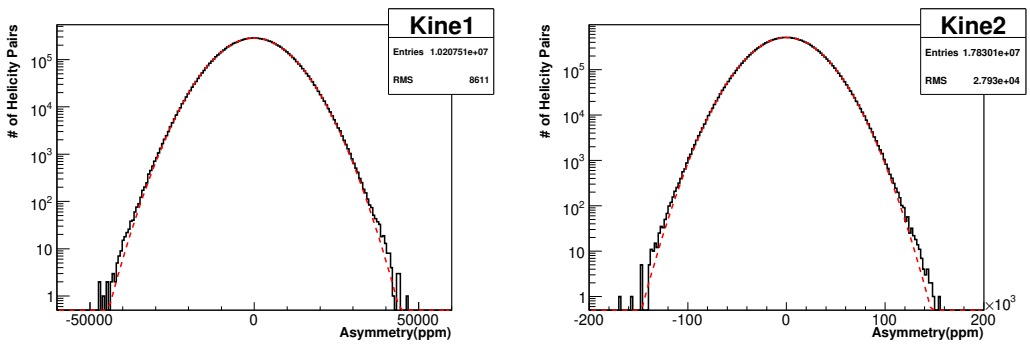

Fig. 9. Blinded counting asymmetry in ppm for the global electron narrow trigger for $Q^2 = 1.1$ and $Q^2 = 1.9$ (GeV/c)^2. Data for $Q^2 = 1.1$ (GeV/c)^2 were collected only on the Left HRS and the whole data set is shown. Data for $Q^2 = 1.9$ (GeV/c)^2 were taken on both Left and Right HRSs and only the Right HRS data set is shown, which accounts for about 80% of the total statistics.

tries measured by the DAQ follow Gaussian distributions as expected from purely statistical measurements. Particle identification performance of the DAQ were measured during the experiment and corrections are applied to the data on a day-to-day basis. DAQ deadtime was calculated from a full-scale timing simulation and results are well understood. Compared to the $(3-4)\%$ statistical uncertainty, systematic uncertainties from the new DAQ contribute to an negligible amount - they are not negligible! quote a number! to the final asymmetry results.

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