FADC/FPGA and Scaler Algorithm for DIS-Parity DAQ

August 25, 2005

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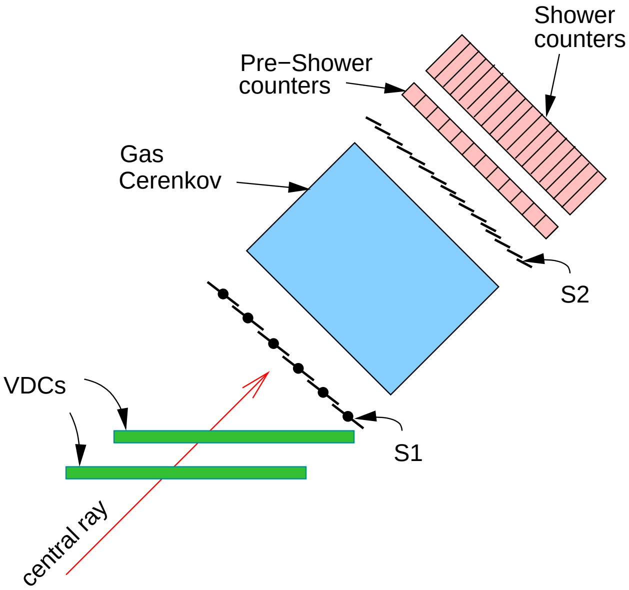
The FADC/FPGA setup and algorithm for DIS-parity (E05-007) DAQ are described in section I. Section II is dedicated to the design and algorithm of the scaler DAQ. It is a working document and the final version will be used for the first FADC prototype and the first scaler DAQ prototype design. The document is written based on the right HRS structure but can also be applied to the left HRS with some modifications.

1 FADC/FPGA DAQ

1.1 FADC Inputs

The detector package on the right HRS is shown in Fig. 1. Five detectors will be used: Two scintillator planes S1, S2, CO_2 gas Cerenkov detector, Preshower detector and the Shower detector. A total of 182 PMT signals will be input to FADCs. Also sent to the FADC will be the helicity signal.

Figure 1: Detector package on right HRS (sideview). “Central ray” shows the trajectory of particles from the spectrometer. Vertical drift chambers (VDC) will not be used for high rate running.



1. The first scintillator plane S1 is made of six thin plastic scintillator bars oriented horizontally. Each bar is viewed by two PMTs, one on the left and one on the right side (12 PMT

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signals, Rs1.la[i] and Rs1.ra[i][2]);

2. 10 PMT signals from the gas Cerenkov detector (Rcer.a[i]);
3. The second scintillator plane S2 is made of sixteen thin plastic scintillator bars oriented horizontally. Similar to the S1 plane, each bar is viewed by two PMTs, one on the left and one on the right side (32 PMT signals Rs2.la[i] and Rs2.ra[i]);
4. The Preshower detector is made of 48 lead glass blocks arranged in 2 columns (horizontal) and 24 rows (vertical). Each block is viewed by one PMT (48 PMT inputs Rps.a[i]).
5. The Shower detector is made of 80 lead glass blocks arranged in 5 columns (horizontal) and 16 rows (vertical). Each block is viewed by one PMT (80 PMT inputs Rsh.a[i]).
6. The helicity signal.

1.2 Triggering

Two scintillator planes S1 and S2 will be used for triggering. The geometry of these two detectors are shown in Fig. 2. We define a good "S-ray" event as follows:

- If a PMT signal exceeds the threshold (e.g. 10 above the pedestal), this PMT is considered to be "fired";
- If both the left and the right PMT of a paddle i (i from 0 to 5 for S1 and from 0 to 15 for S2) are fired, this paddle is considered to be fired;
- If paddle i in S1 and paddle j in the S2 plane are fired, and if i and j satisfy the following: we say an "S-ray trigger" is formed.

Table 1: "S-ray" conditions of S1 and S2 plane paddles.

If S1 i is	and S2 j is one of the following
0	0,1,2,3,4,5
1	2,3,4,5,6,7
2	4,5,6,7,8,9
3	6,7,8,9,10,11
4	8,9,10,11,12,13
5	10,11,12,13,14,15

1.3 Algorithm for extracting integrated area of a PMT pulse

The output of a PMT is a pulse that can be described as [1]

$$V(t) \quad = \quad -A_0 \frac{e^{-\frac{t}{\tau_S}} - e^{-\frac{t}{\tau}}}{\tau - \tau_S} \qquad (1)$$

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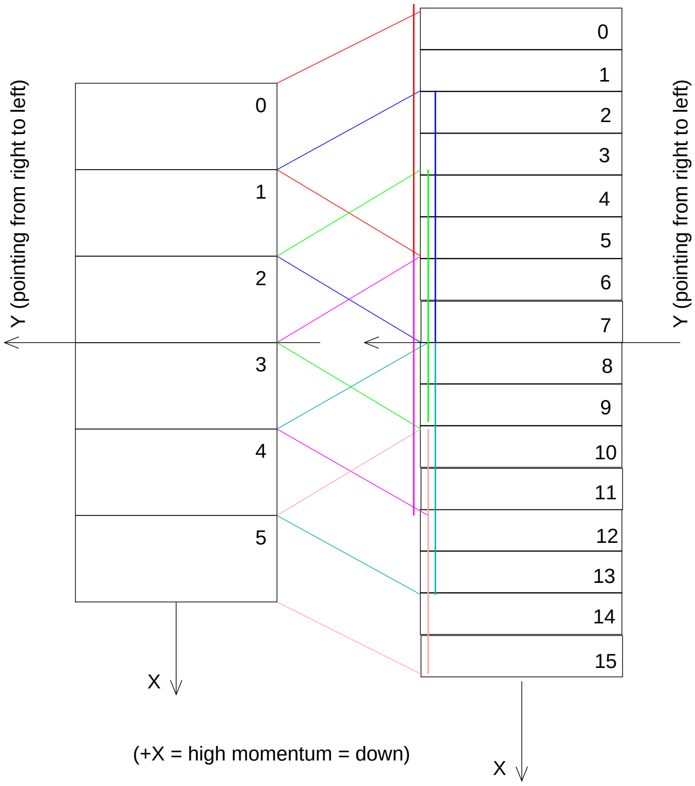
[2] Some denominations of the regular HRS DAQ are used here but are not to be confused with that used by the Analyzer/ROOT. For example, each element of Rs1.la[i] here describe the voltage of the PMT pulse vs. time for the i^{th} scintillator bar in the S1 plane, i.e. it is actually a 2D array Rs1.la[i][t].

Figure 2: Position of scintillator bars in the S1 (left) and the S2 (right) plane. X and Y axises are for the detector coordinator system. Different color coding shows the condition for forming an “S-ray” trigger. For example, if bar 0 in S1 is fired, and one of the bars 0-5 in the S2 plane is also fired (connected to bar 0 in S1 by red lines), we say an S-ray trigger is formed.



for $t \neq \tau_S$. Here τ_S is the decay time of the detector and τ describe the time constant of the PMT. A_0 is the total integrated area of the pulse. The maximum of the pulse and the time it occurs are

$$t_{max} = \frac{\tau_S \tau}{\tau - \tau_S} \ln(\frac{\tau}{\tau_S}) \tag{2}$$

$$V|_{t_{max}} = \frac{A_0}{\tau_S} (\frac{\tau}{\tau_S})^{-\frac{\tau}{\tau - \tau_S}} \tag{3}$$

Figure 3 shows the shape of PMT pulses from Shower, Preshower and Cerenkov of an event recorded by a 12-bit 100MHz FADC unit during the hypernuclear experiment in June. The decay time were extracted for these detectors, as shown in table 2. Here we assume the PMT has a time constant of 20 ns.

The integrated area of a PMT pulse should be extracted as follows:

1. Once an S-ray trigger is formed, first the pedestal for each channel in Preshower, Shower and Cerenkov is calculated by averaging 10 samples (100 ns window for a 100 MHz or 40 ns window for a 250 MHz sampling rate) BEFORE the trigger occurs:

$$Rps.ped[i] = \frac{1}{100\text{ns}/t_S} \sum_{t=t_0-100\text{ns}}^{t_0-1\text{ns}} Rps.a[i][t] \; i = 0...47$$

   with t_0 the time of the trigger, t_S the sampling time of FADC (10ns for 100MHz sampling rate and 4ns for 250MHz). Similar for Shower and Cerenkov;

Figure 3: PMT pulse shape recorded by a 12-bit 100MHz FADC module: Shower detector (single block, top left), Preshower detector (sum of two adjacent blocks, top right), and Gas Cerenkov detector (sum of all 10 PMTs, bottom left).

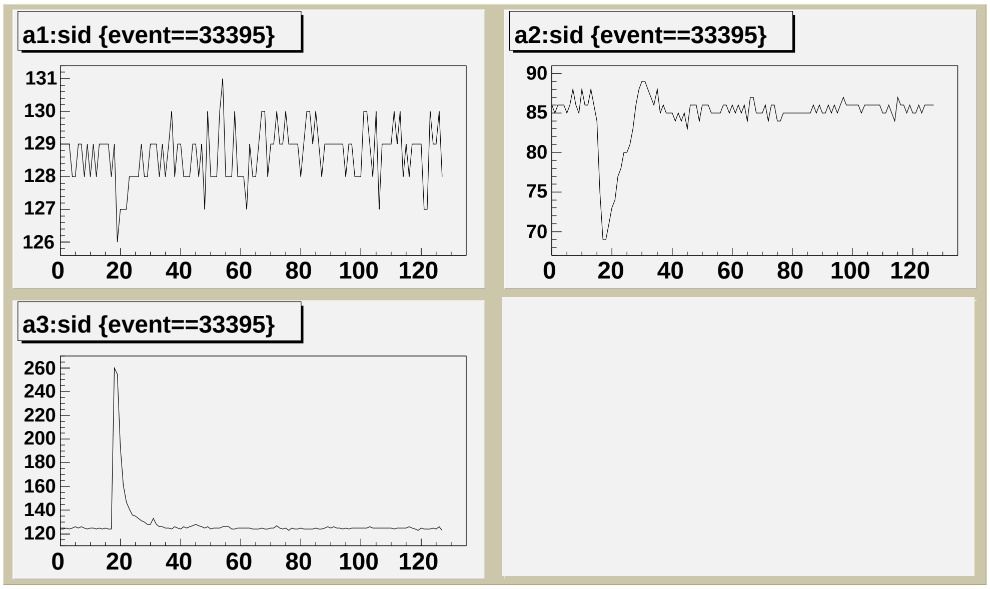


Table 2: Decay time of HRS-R detectors and PMT pulse width: FWH(T)M = "Full Width at Half (Tenth) Maximum". t_{max} is where the pulse maximum occurs and can be considered as the pulse rise time..

Detector	τ_S (ns)	τ (ns)	t_{max} (ns)	average FWHM (ns)	average FWTM (ns)
Preshower/Shower	32	20	25	62.42	126.09
Gas Cerenkov	1.67	20	4.5	19.25	52.15

2. If a rapid variation is found among 10 samples before the trigger (indicating an event preceding the current trigger), 10 samples during a time window from 250 to 350ns AFTER the trigger are used to calculate the pedestal:

$$Rps.ped[i] = \frac{1}{100\mathrm{ns}/t_S} \sum_{t=t_0+260\mathrm{ns}}^{t_0+350\mathrm{ns}} Rps.a[i][t]$$

3. If both time windows appear to have an event, the averaged value of pedestals from previous events is used.

4. If an ADC channel has stable pedestal (drift < 5 mV), then its pedestal do not need to be extracted for each event. Rather it can be extracted for every (e.g.) 10 events and be read out for monitoring purpose.

5. When there is no pileup, the integrated area is calculated as the sum of FADC sample minus the pedestal for a 50 ns (120 ns) time window for Cerenkov (Preshower/Shower) detectors, respectively:

$$\begin{aligned} Rcer.area[i] &= \sum_{t=t_0}^{t_0+50\mathrm{ns}} \Big(Rcer.a[i][t] - Rcer.ped[i]\Big), \;\; i = 0...9 & (4) \\ Rps.area[i] &= \sum_{t=t_0}^{t_0+120\mathrm{ns}} \Big(Rps.a[i][t] - Rps.ped[i]\Big), \;\; i = 0...47 & (5) \\ Rsh.area[i] &= \sum_{t=t_0}^{t_0+120\mathrm{ns}} \Big(Rsh.a[i][t] - Rsh.ped[i]\Big), \;\; i = 0...79 & (6) \end{aligned}$$

6. The integrated area is then corrected for the gain of the PMT, unless the gain matching was already satisfied by adjusting the high voltage of all PMTs. Gain correction factors A_i^{det} can be obtained by comparing ADC spectra of all PMTs. Or in the simplest case, corrections factors from previous experiments can be used:

$$\begin{aligned} Rcer.area_c[i] &= A_i^{cer} Rcer.area[i], \;\; i = 0...9 & (7) \\ Rps.area_c[i] &= A_i^{ps} Rps.area[i], \;\; i = 0...47 & (8) \\ Rsh.area_c[i] &= A_i^{sh} Rsh.area[i], \;\; i = 0...79 & (9) \end{aligned}$$

7. In addition to the integrated area, the maximum pulse height V_{max} will also be recorded;

$$\begin{aligned} Rcer.Vmax[i] &= \max_{t=t_0}^{t_0+60\mathrm{ns}} |Rcer.a[i][t] - Rcer.ped[i]|, \;\; i = 0...9 & (10) \\ Rps.Vmax[i] &= \max_{t=t_0}^{t_0+100\mathrm{ns}} |Rps.a[i][t] - Rps.ped[i]|, \;\; i = 0...47 & (11) \\ Rsh.Vmax[i] &= \max_{t=t_0}^{t_0+100\mathrm{ns}} |Rsh.a[i][t] - Rsh.ped[i]|, \;\; i = 0...79 & (12) \end{aligned}$$

8. For Cerenkov detector, the sum of integrated area from all 10 PMTs (after gain correction) is calculated as:

$$Rcer.sum_c = \sum_{i=0}^{9} Rcer.area_c[i] \,. \qquad (13)$$

Calcultions for integrated area for pileup events will be discussed in the next section.

9. For Preshower and Shower detectors, the sum of PMTs from each segment will be calculated in a similar manner. Fragmentation of these two detectors will be described in the next section.

1.4 Pileups, Pulse Separation, and Analysis of the Preshower/Shower Detector Signals

1.4.1 Pileups where the second pulse occurs after the maximum of the first pulse

If two “S-ray” triggers occur in less than a 60 ns interval, the Preshower and Shower pulses of these two events will pileup on each other. And if the two triggers occur in less than a 20 ns interval, the gas Cerenkov PMT signal will also pileup. If the 2nd pulse starts after the t_{max} of the first pulse, the integrated area of two pulses can be separated by two methods:

1. Method #1

   (a) The integrated area of the first pulse will be calculated from its V_{max} (recorded by the FADC), τ and τ_S (extracted from pulse shape analysis as in table 2) and Eq. (3);

   (b) The sum of integrated area of two pulses will be extracted from the FADC;

   (c) The integrated area of the second pulse will be calculated by subtracting (a) from (b).

   However, one can see that if pileups do not occur in all ADC channels, then there is ambiguity in whether the pulse in no-pileup channels correspond to the 1st or the 2nd pulse in the pilup channel. One solution is to compare the timestamp of each trigger to the timestamp of each ADC sampling, which might require a long on-board processing time. Another solution is to correct each ADC sampling by its gain first, then add the gain-corrected pulse of all channels of one detector or segmented detector (10 for Cerenkov, 14 for each Preshower segment and 15 for each Shower segment) together, and calculate the integrated area, which is in a different order than the procedure described in section 1.3. This way the pileup is likely to occur in the summed pulse even if only a portion of the channels have pileuped pulses.

2. Method #2
   Here we try to record the previous pulse and subtract it from current pulse:

   (a) For each S-ray event, the pulse height $V_{max,1}$ and a timestamp t_1 are recorded for each channel. Here t_1 is the timing of the S-ray trigger, or alternatively can record $t_{max,1}$, the time when $V_{max,1}$ occurs, since the pulse shape of each channel will be well known from pulse shape analysis;

   (b) If the 2nd S-ray event (t_2) occurs later than $t_{max,1}$ but before the first pulse decay to its 1/10 maximum, the area of the previous pulse can be calculated using Eq. (1):

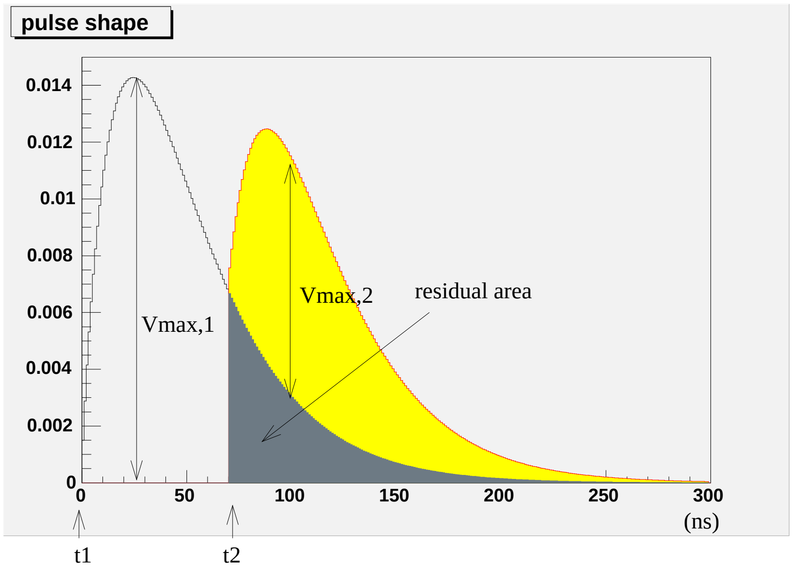
   $$\begin{aligned} residual\ area_1 &= \int_{t_2-t_1}^{\infty} V(t)\mathrm{d}t = -\frac{A_{0,1}}{\tau-\tau_S}[\tau_S e^{-\Delta t/\tau_S} - \tau e^{-\Delta t/\tau}] \\ &= \frac{V_{max,1}}{\tau-\tau_S}\frac{\tau^{\frac{\tau}{\tau-\tau_S}}}{\tau_S^{\frac{\tau_S}{\tau-\tau_S}}}\left[\tau_S e^{-\Delta t/\tau_S} - \tau e^{-\Delta t/\tau}\right] \end{aligned} \tag{14}$$

   Note that we have used Eq. (3) and have defined $\Delta t = t_2 - t_1$. The equation may look cumbersome but can be simplified if τ and τ_S are known and if we use a lookup table, for example table 3.

Table 3: Residual area A_{res} of a Preshower or Shower pulse after $\Delta t > t_{max} \approx 25$ ns. A_{res}/A_0 is the fraction of residual area to total area, and A_{res}/V_{max} is giving for a 250MHz sampling FADC. For the pulse shape $\tau = 20$ ns and $\tau_S = 32$ ns were used.

Δt (ns)	A_{res}/A_0	A_{res}/V_{max}	Δt (ns)	A_{res}/A_0	A_{res}/V_{max}	Δt (ns)	A_{res}/A_0	A_{res}/V_{max}
28	0.7006	12.2683	64	0.2930	5.1297	100	0.1059	1.8549
32	0.6445	11.2856	68	0.2629	4.6028	104	0.0942	1.6495
36	0.5902	10.3352	72	0.2355	4.1241	108	0.0837	1.4660
40	0.5385	9.4284	76	0.2108	3.6903	112	0.0744	1.3021
44	0.4896	8.5724	80	0.1884	3.2983	116	0.0660	1.1560
48	0.4438	7.7713	84	0.1682	2.9449	120	0.0586	1.0258
52	0.4013	7.0270	88	0.1500	2.6267	124	0.0520	0.9099
56	0.3620	6.3395	92	0.1337	2.3409	128	0.0461	0.8067
60	0.3260	5.7078	96	0.1190	2.0846	132	0.0408	0.7150

Figure 4: Separation of pileup events. The residual area of the first pulse is calculated using its maximum height and the known pulse shape, and is then subtracted from the total area to obtain the integrated area of the second pulse.



(c) The integrated area of the 2nd pulse can then be calculated correctly by subtracting residual area of the previous pulse from the total area of the 2nd pulse obtained from FADC samples.

(d) The height of the 2nd pulse should be the maximum of $V_2(t) - V_1(t)$ where $V_1(t)$ is the residual of the 1st pulse and can be calculated from Eq. (1). To reduce processing time we will only record the area of the 2nd pulse.

1.4.2 Pileups with very short intervals

If the 2nd pulse starts before the t_{max} of the first pulse, we see that there is no safe and easy way to separate the two pulses, since V_{max} of the first pulse cannot be extracted from FADC readings. Consider 1 MHz events rate, the possibility of such pileups in the Shower and Preshower detector is 1 MHz×25ns=2.5%. To reduce such pileup events, we fragment the Preshower and the Shower detector into four sections, as shown in Fig. 5. This will reduce the "inseparable pileups" to 0.6%.

Even though we cannot separate such pile-ups, it is possible to study their effects. We will discuss about it in section 1.5.1.

1.4.3 Fragmentation of Preshower and Shower Detectors

Signals from the Preshower and the Shower detector are analyzed as follows:

1. The integrated area of pulses from all PMTs will be calculated following the procedure described in section 1.3, and gain corrected;
2. Sum of integrated area from blocks in each segment is calculated

$$Rps.frag.sum_c[j] = \sum_{i=frag_j} Rps.area_c[i], \;\; j = 0, 1, 2, 3 \tag{15}$$

$$Rsh.frag.sum_c[j] = \sum_{i=frag_j} Rsh.area_c[i], \;\; j = 0, 1, 2, ...7 \tag{16}$$

   where $frag_j$ describes the four segments of each detector.

3. The segment which gives the highest sum will be taken:

$$Rps.sum_c = \max_{j=0,1,2,3}(Rps.frag.sum_c[j]) \tag{17}$$

$$Rsh.sum_c = \max_{j=0,1,2,3}(Rsh.frag.sum_c[j]) \tag{18}$$

1.5 PID

Once an "S-ray" trigger occurs and the summed integrated pulse areas from Cherenkov, Preshower and Shower detectors are extracted, the event is identified as follows:

- If the three sums satisfy electron cuts:

$$Rps.sum_c > T_{ps}, \; Rsh.sum_c > T_{sh} \tag{19}$$

$$Rsh.sum_c + C \times Rps.sum_c > T_{tsh} \tag{20}$$

$$Rcer.sum_c > T_{cer} \; . \tag{21}$$

Figure 5: Position of lead glass blocks in the Preshower (left) and Shower (right) plane. X and Y are for the detector coordinator system. Different colors show fragmentations of the detector. In order to reduce cross-board communication, each segment contains less than 16 blocks so that can be kept within one FADC board (16 channels).

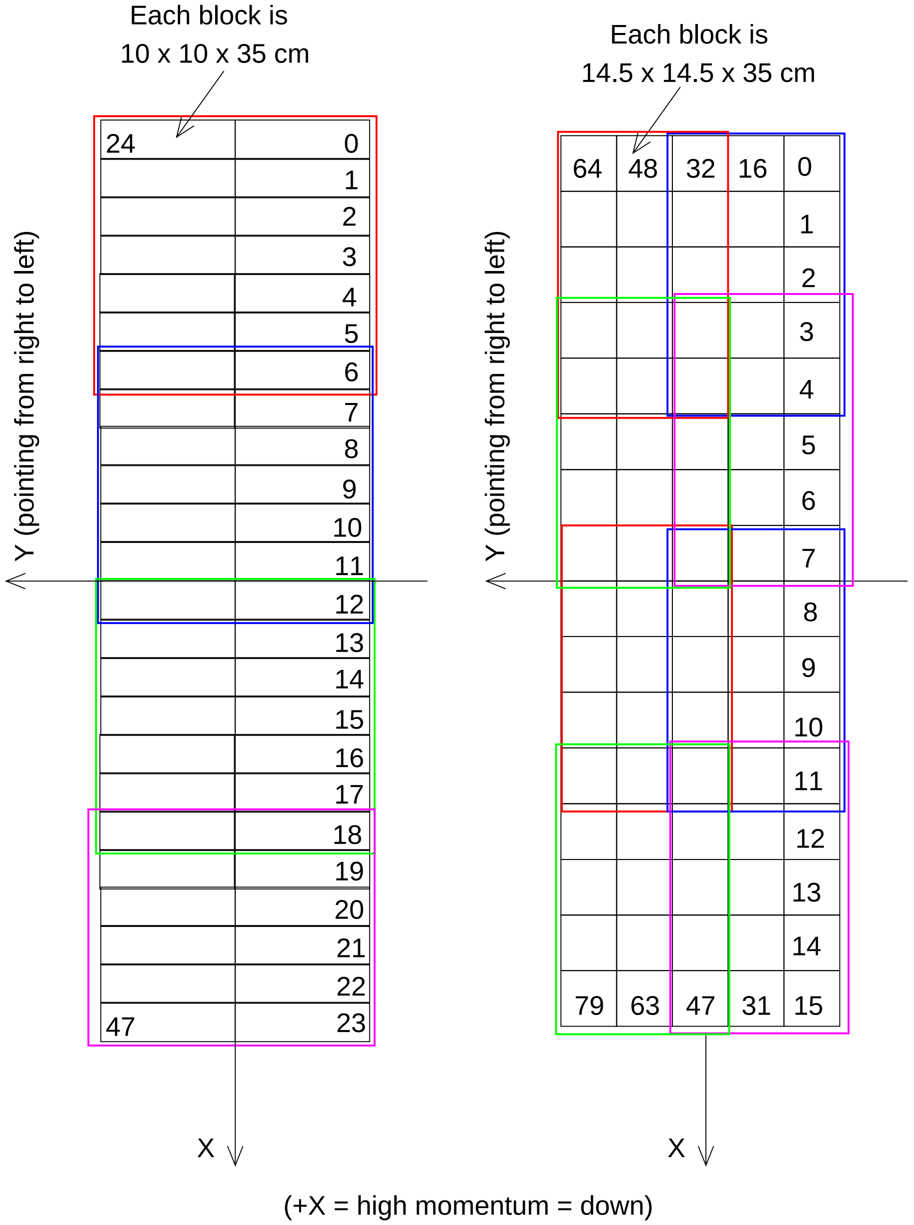
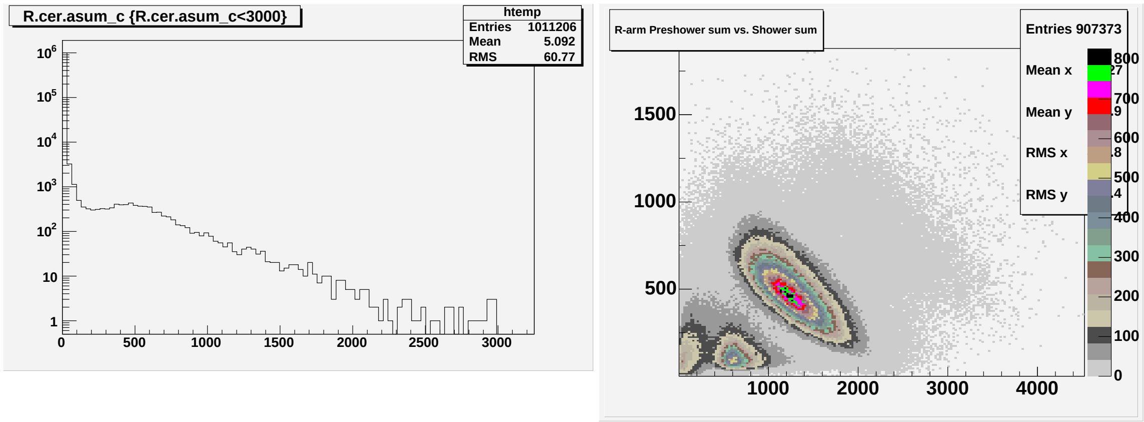


Figure 6: Gas cherenkov (left), Preshower and Shower ADC sums (right) from a typical run. Electrons and pions show clearly as two blobs in the Preshower/shower plot.



where T_{det} is the threshold in Preshower (ps), Shower (sh) yields and the sum of the two "Total Shower" (tsh), the event is identified as a good electron event; Typical threshold values are: $T_{sh} = 200$, $T_{ps} = 50$, $C = 2.0$, $T_{tsh} = 1600$ and $T_{cer} = 400$. However the numbers depend on the sampling rate of the FADC so may change proportionally.

- If the three sums satisfy pion cuts (total of five cuts), the event is identified as a good pion event:

$$Rps.sum_c > 50, \; Rps.sum_c < 150 \tag{22}$$

$$Rps.sum_c > 450, \; Rps.sum_c < 800 \tag{23}$$

$$Rcer.sum_c = 0 \; . \tag{24}$$

  Again the thresholds will change with the FADC sampling rate.

1.5.1 PID for pileup events with $t_2 < t_{max,1}$

All pileup events can be divided into four types: 1) e-e pileups, 2) $e - \pi$ and $\pi - e$ pileups; and 3) $\pi - \pi$ pileups. $\pi - \pi$ pileup events can be abandoned by checking the signal in Cerenkov detector, since pions usually do not generate Cerenkov light. $\pi - e$ and $e - \pi$ events are likely to be identified as one good electron event, since the integrated area in Shower and Preshower sums will be slightly shifted to larger values due to pion's energy deposit, but will not be distorted much and thus still satisfy electron cuts. The pions of $e - \pi$ or $\pi - e$ pileups should be abandoned. Events with $e - e$ pileups should be studied and corrected carefully, since loss of electron counts is rate-dependent and will cause a direct uncertainty to the asymmetry we measure. Identification of $e - e$ pileups can be done using very high threshold cuts (twice the values given above), and the total number of electrons is obtained by: $n_{e,tot} = n_e + 2n_{e,high}$ where n_e is number of events passing electron cuts but not high threshold electron cuts, and $n_{e,high}$ is number of events passing high threshold electron cuts. $e - e$ inseparable pileups will occur at $< 0.5\%$ level.

1.6 FADC Outputs

We assume that the maximum readout speed of FADC is (40-50) MBytes/sec, the FADC has 10 bit resolution thus the integrated sum can be recorded in 3 Bytes (10 bit × 40 samples ×

16 channels at most); We give below several options of FADC outputs, in the order of low to high priority:

1. Must readout: Number of electrons, pions, and electron pileups (from high threshold cuts), tagged by the beam helicity, once per run (a few Bytes?);
2. An “ntuple” containing Shower sum, Preshower sum and Cerenkov sum, 9 Bytes/event, 9 MBytes/sec for 1 MHz rate; Or
3. An “ntuple” containing the summed integrated area (3 Bytes) and maximum pulse height (2 Bytes) from Shower, Preshower and Cerenkov, 15 Bytes/event, 15 MBytes/sec for 1 MHz rate;
4. One-dimensional histograms of all PMT signals. It is preferred to make one histogram for each PMT (182 histograms). Assuming each run is 1 hour long, each histogram will take 3 Byte/bin × 1024 bin = 3 KByte. The total volume of 182 histograms is 546 KBytes/run. This should not be a problem for readout because all histograms will be readout only once at the end of each run. However on-board memory might be a limitation.
5. Histogram of pedestals for each channel, to monitor detector stability. Assuming pedestals do not drift more than 50 mV (10 bins for a 10-bit FADC) in the worst case, each histogram requires 10 bin×(1+4) Bytes/bin=50 Bytes and the total volume is about 10 KBytes. Here 4 Bytes is for the bin content (maximum number of events for a 1 MHz rate and 1 hour run) and 1 Byte is for the bin value (actual pedestal value in mV). Again this will be read out only once per run and should not cause a problem on the readout speed. An alternative way is to calculate on-board the mean and RMS value of each pedestal, if the memory is a problem.

   The outputs above add up to about 15 MBytes/sec. We see that there is room for reading out full samples:
6. Assuming each ADC sample contains 4 Bytes (including 2 Bytes of data, 1 Byte of time stamp, and 1 Byte of spare for whatever is needed) and we record a window of 200 ns (50 samples) for each event, we obtain 200 Bytes/channel×182 channels × 1 MHz = 36.4 KBytes. Using a readout limit of 40 MBytes/sec, we can read out full samples at a rate of about 600 Hz.

1.7 Number of FADC Boards Required

Assuming each board has 16 channels, we need one for S1, one for S2, one for Cerenkov, four for Preshower, and eight for Shower. This adds up to a total of 15 boards and should be fit in one crate. Note that the Preshower and Shower need more than (48+80)/16=8 boards because of the overlapping between their fragments.

2 Scaler DAQ

2.1 Scaler Inputs and Triggering

The inputs and triggering (forming of the S-ray) are the same as the FADC system as described in sections 1.1 and 1.2.

2.2 Algorithm for summing detector PMTs

For scaler DAQ, the gain of all PMTs in each detector must be matched by adjusting their high voltages. Then the sum of 10 PMTs in the Cherenkov detector is formed. For Shower and Preshower detectors, sum of each fragments of the detector is formed. Unlike FADCs, we do not separate pileup events.

2.3 PID

The summed PMT outputs are sent to discriminators for PID. The logic is the same as described in section1.5, except that the cuts will be equivalently applied to the pulse height, not the integrated area, though the two sets of cuts can be related to each other using Eq. (3). For Shower and Preshower, sum of each fragment is compared with electron and pion cuts and an OR among fragments is formed.

2.4 Outputs

The outputs of the scaler system will be number of electrons, pions, and high threshold electrons identified by PID cuts, each tagged by the beam helicity. They will be read out once per run.

References

[1] W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, 2nd Ed., Sprinter-Verlag Berlin Heidelberg, 1994.