DRAFT
Design Notes
and
Cost Estimate
for the proposed
BigBite Cerenkov Detector

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1 Design Goals

This document describes the Cerenkov detector we plan to use for the upcoming Hall A neutron d_2 experiment (E06-014). The inclusive nature of that experiment makes the addition of the Cerenkov counter for pion and proton rejection critical for the low energy bins. The design goal for E06-014 is a conservative pion rejection factor of 500:1. When coupled with a 20:1 rejection ratio from the shower/preshower, a total rejection factor of 10^5 should be achievable.

It is understood that the Cerenkov detector will become part of the "standard" electron detector package for BigBite to the benefit of all subsequent experiments involving that spectrometer.

2 Mechanical Design

The Cerenkov detector will be installed into the gap between the front and back wire chambers in the BigBite electron detector stack. The current design has been developed to fit in this location with minimal changes to the existing frame. This fixes the maximum depth of the tank to 60 cm. The front profile has the dimensions of the sensitive region of the rear wire chamber in order to match the solid angle of the existing detector stack. Figure 1 shows a diagram with the outer dimensions for the Cerenkov detector overlaid on an engineering drawing of the BigBite detector stack.

2.1 Optics

Cerenkov radiation emitted by relativistic particles will be collected in 10 spherical focusing mirrors tiled in a 5x2 arrangement at the back of the tank. Each of those primary mirrors focuses light into a 5” PMT by way of a flat secondary mirror located towards the front of the tank. This configuration allows the PMTs to be positioned away from the BigBite fringe field and provides a relatively compact design that can be installed in the existing BigBite detector frame with minimal modifications. One of the challenges in designing the optics for this device was accommodating a side-effect of BigBite’s exceptionally large momentum bite. The larger bend angle of low momentum particles results in their associated Cerenkov radiation being focused higher on the PMT surface than that of high-momentum particles.

When the ray-trace simulation was run using Monte Carlo’d trajectories for 0.6, 1.0, and 1.4 GeV/c electrons[*] produced in the target cell, tracked through the BigBite magnet (1.2 Tesla field), and into the detector stack we found the resulting Cerenkov light formed a vertical band roughly 7–8” tall in the plane of each PMT surface. Simply increasing diameter of the PMT becomes untenable as background rates and PMT cost rise rapidly as the photocathode diameter increases. The simplest solution was to install a conical collar extending 10 cm out from the 5” PMT surface with a final diameter of 9”. This simplified Winston cone improves the geometric ray collection efficiency of the associated PMT to $>$ 95% and allows the Cerenkov sensitivity to remain relatively flat for particles with momentum above 0.6 GeV/c. Note that length of the focal band at the PMT is largely driven by the low-energy (short-orbit) end of the momentum acceptance. For example, the separation between the mean focal point for the 1.0 and 1.4 GeVȩlectrons is roughly 1/4–1/5 that of the separation between the 0.6 and 1.0 GeV focal points for a BigBite field of 1.2 T.

Figure 2 shows a model of the proposed Cerenkov detector showing mirrors, PMTs, and simple Winston cones. The primary spherical mirrors are 31 cm wide by 41 cm tall with a radius of 116 cm (focal length: 58 cm). The flat secondary mirrors are 20 cm wide by 24 cm tall.

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[*] Those electron energies bound the kinematic region of interest to E06-014.

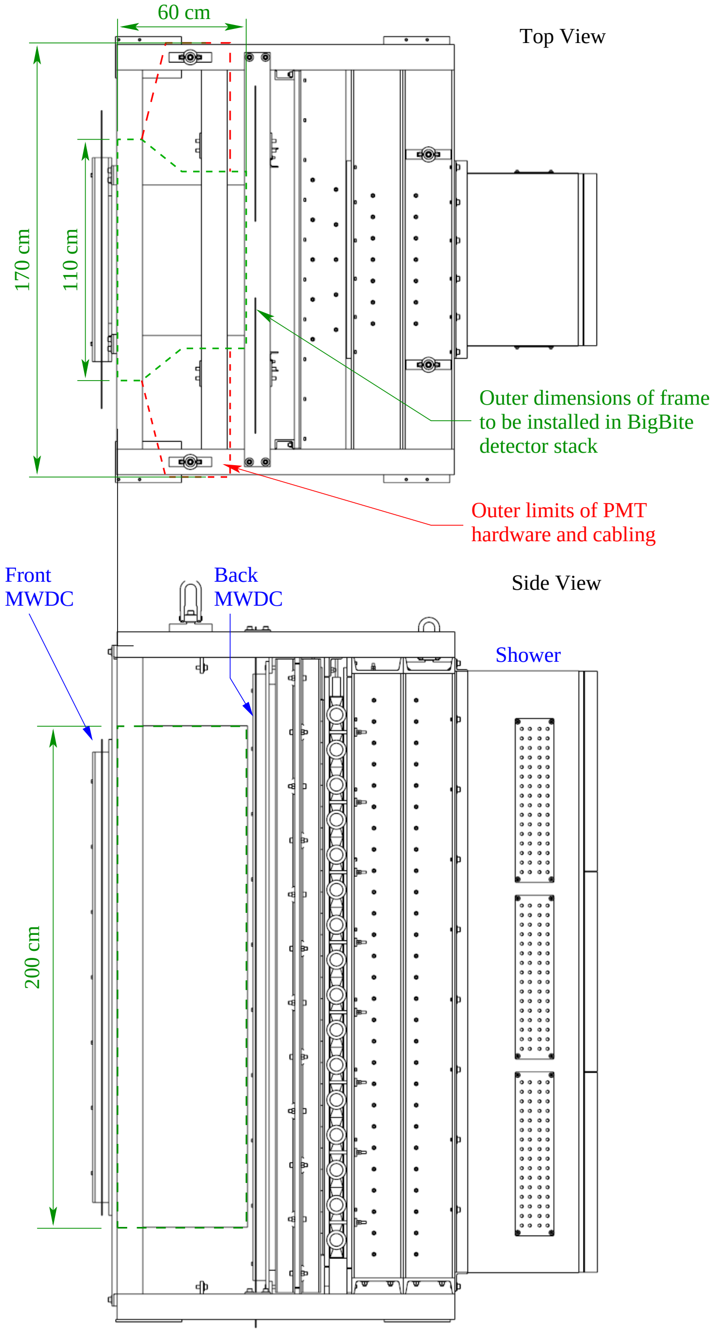


Figure 1: Diagram of the BigBite detector stack with an overlay of the proposed Cerenkov detector's outer dimensions.

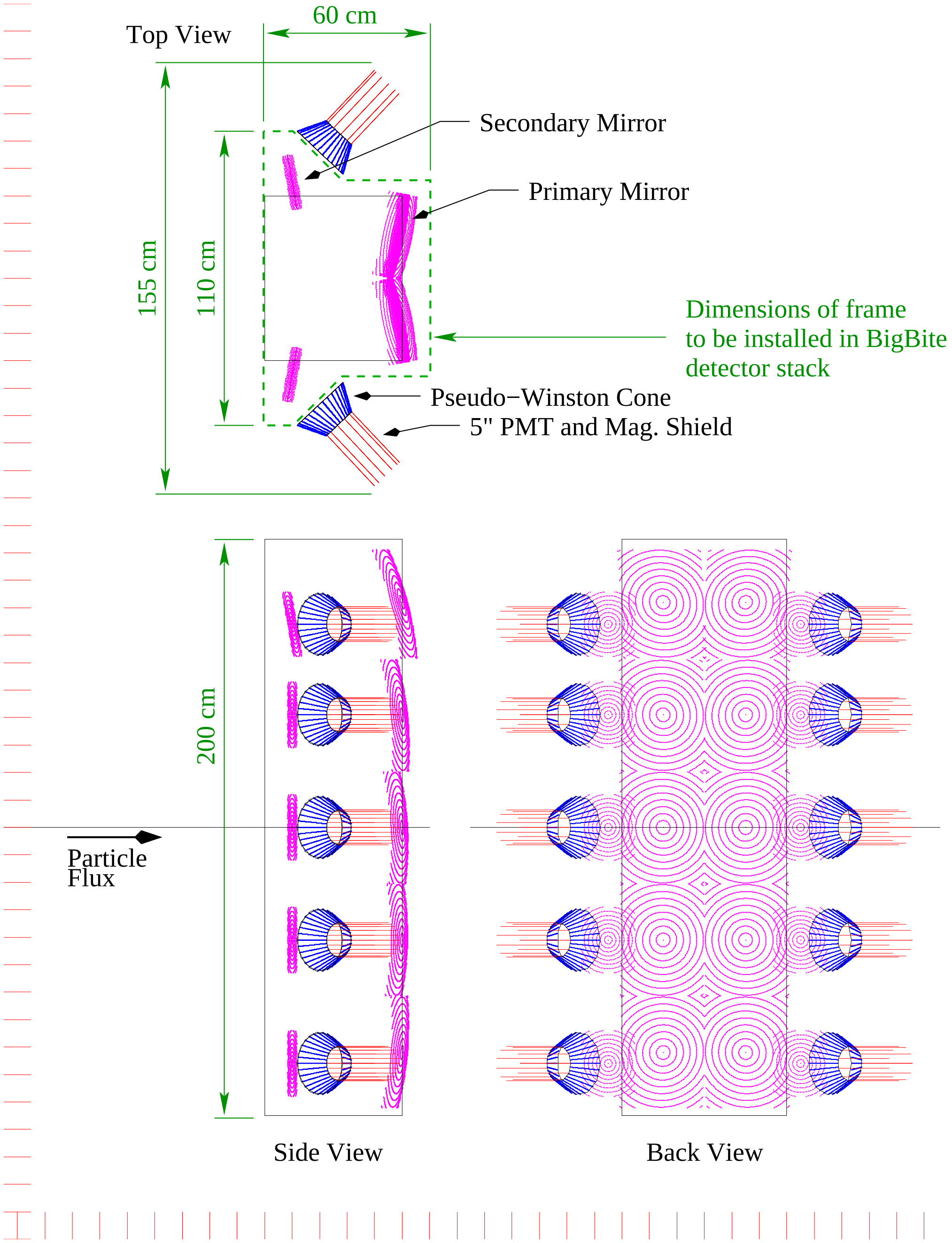


Figure 2: Model of the proposed Cerenkov detector showing mirrors (magenta), PMTs (red), and the simplified Winston cones (blue).

3 Ray trace simulations

Figure 3 shows a ray-trace with the current configuration. Colors map to ray/object classifications as follows:

- yellow → initial photon emitted by an relativistic electron,
- blue → reflected photon,
- the red cylinders with the flared ends represent PMTs with the attached Winston cone.

The blue dots on the back view indicate points where rays reflect off a mirror. The yellow dots indicate the projected impact points of photon rays on the back-plane (*i.e.* if the mirrors were not present). Photons hits on the PMT photo-cathode are shown in the 10 small circles to the right and left of the back-view projection. Rays that hit the Winston cone and get reflected onto the PMT are shown as green dots. Rays that only involve the primary and secondary mirrors are colored blue. The green "spray" evident in the upper- and lower portions of the Winston cone (back-view) respectively correlate to rays from the lowest (0.6 GeV/c) and highest (1.4 GeV/c) momentum electrons involved in this simulation.

4 Anticipated Performance

Our preferred choice of Cerenkov radiator is C_4F_{10} at 1 atm. This material is non-flammable, non-toxic, odorless, and does not require special handling to remain a gas at room temperature. It is currently in use in Cerenkov devices in both Hall B and Hall C at Jefferson Lab. Its index of refraction is 1.0015 giving a pion threshold of 2.5 GeV/c. Assuming a 40 cm track length in the radiator, our calculations predicts a mean PMT response of 14 measured photo-electrons (p.e.'s) per electron with a conventional Burle 8854 5" PMT. This estimate includes the PMT quantum efficiency, PMT window transparency, and is multiplied by a factor of 0.7 to accommodate a cumulative 10% loss at each mirror and the window coupling the PMT to the gas tank (Fig. 4). As a cross-check on the above calculation, the performance of the current Hall A short Cerenkov (a similar design) was scaled to correct for the different path-length and radiator gas. The resulting estimate of 12 p.e.'s for the BigBite Cerenkov configuration is consistent with the earlier independent calculation.

Table 1 lists the characteristics of several gases along with an estimated p.e. yields for the commonly used 5" Burle 8854 PMT and for a quartz-window PMT (modeled after a 3" Photonis XP4318). Due to the heavy UV weighting of the Cerenkov spectrum, a quartz-window PMT has a significant advantage over a typical "UV glass" PMT like the Burle.

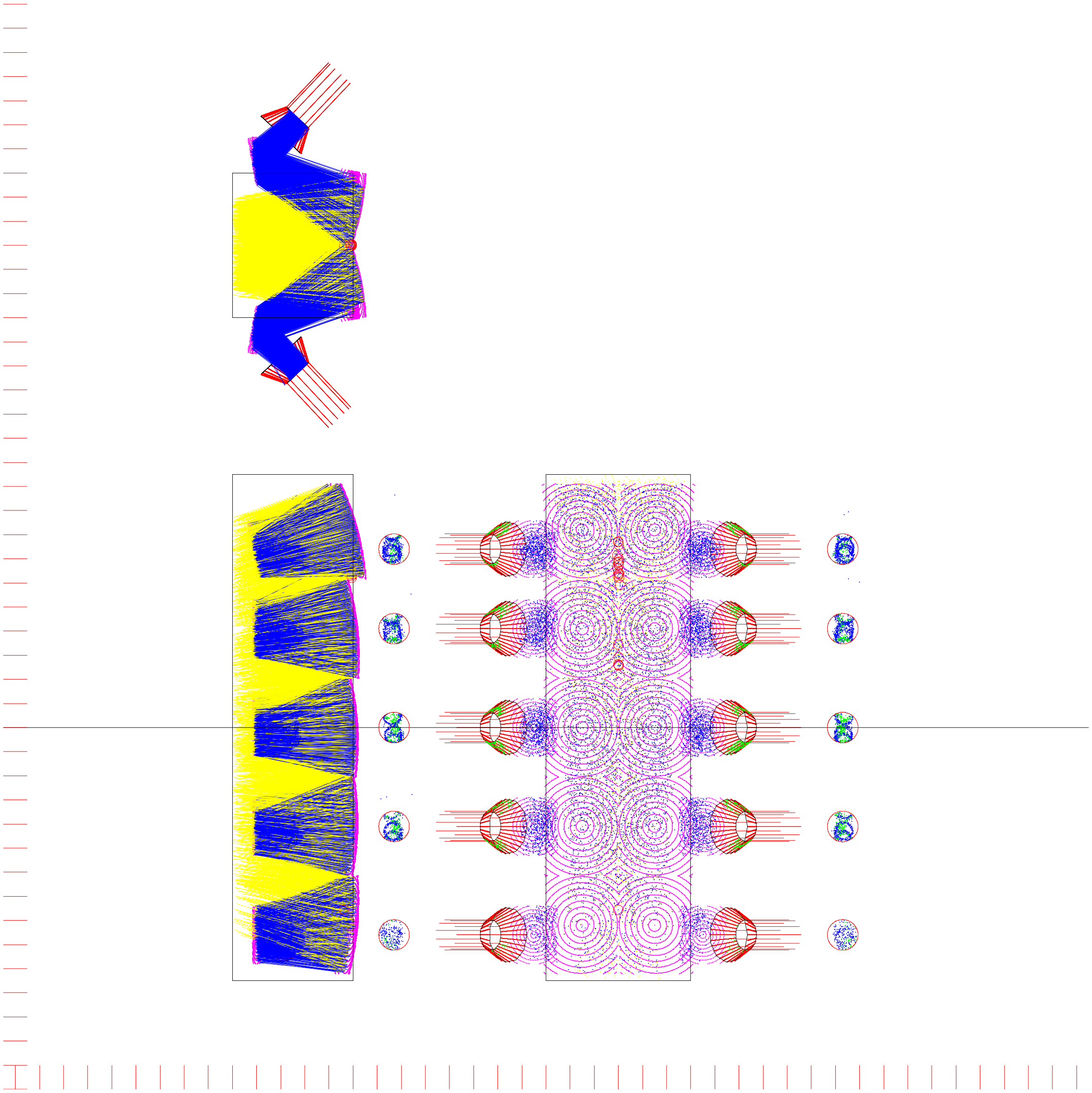


Figure 3: Ray trace of the Cerenkov optics for incident electrons with energies 0.6, 1.0, and 1.4 GeV. Incident electrons (not shown) emit Cerenkov photons (yellow) which are incident on the primary mirrors. The reflected rays are shown in blue. Photon hits on the PMT photo-cathode are shown in the 10 small circles to the right and left of the back-view projection. Rays that hit the Winston cone and get reflected onto the PMT are shown as green dots. Rays that only involve the two principle mirrors are colored blue.

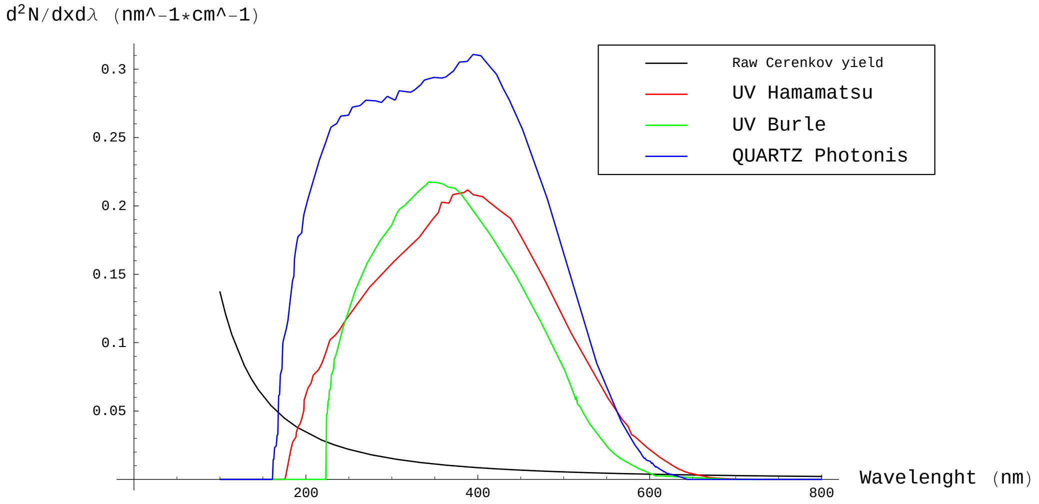


Figure 4: Differential photo-electron (p.e.) yield per wavelength (in nm) per unit distance in radiator (in cm). The three colored curves represent the quantum efficiencies (q.e.) of three characteristic 5” PMTs ((i.e.) p.e.’s per photon). The black curve is the raw Cerenkov differential photon yield. Integrating the product of the Cerenkov yield and the q.e. gives a first-order estimate of the PMT response to an electron track in the radiator.

Table 1: Options for the radiator gas at 1 atm. The number of detected photo-electrons (p.e.'s) assumes a 40 cm track through the gas and includes the effects of PMT quantum efficiency, absorption losses in the radiator, and has been scaled down by a factor of 0.7 to accommodate losses at the mirrors and PMT surface.

Gas	n	e^- thr. (MeV/c)	π thr. (MeV/c)	Detected p.e.'s Burle 8854	Detected p.e.'s Quartz PMT
N_2	1.0003	21	5926	3.2	5.4
CO_2	1.0004	17	4671	5.4	9
Freon12	1.0011	11	2984	11	16*
C_4F_{10}§	1.0015	9	2522	14	25
PMT Cost				\$4–6k†	\$2.5k‡

§A July 2006 quote for C_4F_{10} put the cost at US\$145 per kg in bulk (1 kg liquid = 100 liters gas at STP).

*Freon12 absorbs UV light with $\lambda < 230$ nm reducing the advantage of the UV transparent quartz PMT.

†Informal estimate from Photonis/Burle rep (Aug 2006). The 8854 model is undergoing a (re-)design phase.

‡Quote for Photonis XP4508B (Aug 2006). A performance-equivalent Electron Tubes model 9823B was quoted at \$5460. (Quartz window), and \$3534. (UV glass model).

The high number of registered p.e.'s will allow an aggressive online threshold (3–4 p.e.'s) to be applied which should remove virtually all of the 1–2 p.e. background noise while triggering on $> 98\%$ of the electron tracks (with a healthy margin of error).

4.1 Wavelength Shifter

We also have the materials needed to add a wavelength shifter to the PMT face to convert some fraction of the far-UV photons to something within the PMT sensitivity envelope. This typically results in a 20–30% increase in the number of p.e.'s registered by the PMT, although getting the coating 'just right' is a bit of an art. This would allow us to switch to an alternate radiator gas such as Freon12 ($n = 1.0011, p_\pi^{\text{thresh}} = 3\,\text{GeV}$) with a minimal impact on the Cerenkov performance.

4.2 Magnetic Shielding for the PMTs

During G_{E_n} (E02-013) a bare (no scintillator) 3" PMT was made light-tight and mounted on the sided of the BigBite detector stack at a location approximating the position of the PMTs in the current design (Fig. 5).

The BigBite fringe field at that location was measured to be ≈ 11 Gauss along the PMT axis. However, the remnant field inside the mu-metal shield (which happened to be for a Burle 8854) was < 0.02 Gauss. We also observed that the shielded PMT performance was independent of its alignment to the fringe field, confirming that a conventional mu-metal magnetic shield will be sufficient.

4.3 Background rates

Several measures of background rates in the 3" PMT were taken under production conditions (with the pol. ^{3}He target) during the latter portion of the G_{E_n} experiment. When the PMT was mounted on the upstream side of the BigBite detector stack (with no shielding from background radiation), single p.e. rates were observed to be on the order of 14 kHz/μA. Shielding the PMT from the room with 1" of aluminum reduced the rate to roughly 7 kHz/μA. Increasing the threshold to the 3 p.e. level dropped the rate to 1.8 kHz/μA.

These data were used to estimate the rates for the d_2^n/Transversity experiments by

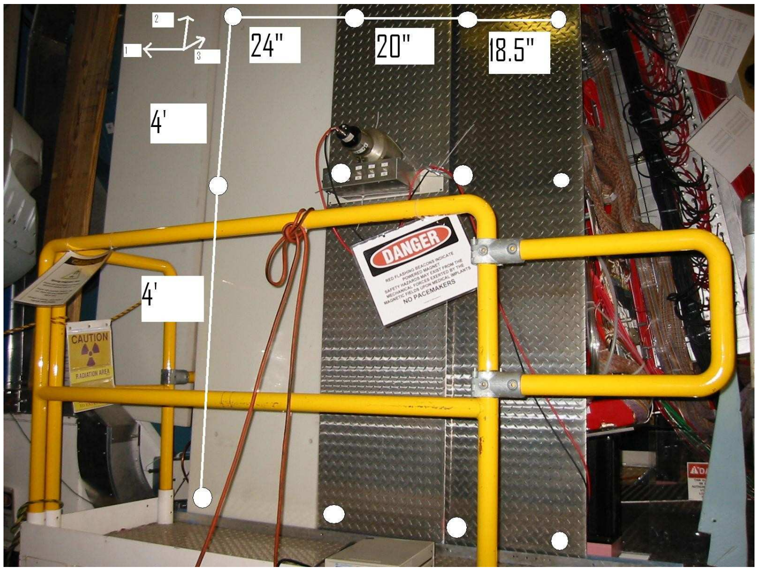
- scaling up by a geometric factor of $(5/3)^2$ to account for the additional "active area" of the 5" PMT,
- scaling up by an additional factor of two to account for the different kinematic conditions between the G_{E_n} test and the $\theta = 30^\circ$ Transversity setup (which will have the highest backgrounds).

This suggests we should anticipate background rates of roughly 10 kHz/μA (40 kHz/μA) for a threshold of ≥ 3 p.e. (≥ 1 p.e.). For a 10 μA beam this means a Cerenkov trigger rate of $\approx 100\,kHz$ per PMT.

For a simple single-arm trigger consisting of the Cerenkov ANDed with a 10 kHz shower/preshower trigger (this rate was < 3 kHz for G_{E_n}) , this would suggest a random background trigger rate contribution of roughly 1000 Hz for a 100 ns coincidence window. This is a manageable worst case scenario. A more complicated trigger that takes advantage of the segmentation in the Cerenkov and the shower trigger is being considered. Such a segmented trigger would reduce the randoms rate by a factor of 5–10. These rates have been computed using conservative values and should be an upper bound. In any case, if the backgrounds are worse than are estimated here, then the rates in the MWDCs should be the limiting factor.

5 Gas Handling

Care will be taken in the design and construction of the Cerenkov frame to make sure that it is hermetically sealed. Prior to an experiment the tank will be purged with nitrogen to



Units: Gs(Gauss)

1	2	3.7	2.5	1.3
2	0.04	10.3	2.8	1.75
3	21	9.4	2.68	1.4

1	-25	1.2	2.2	0.9
2	45	11	3.9	1.76
3	41	11.6	4.1	1.86

1	0.98	1,24	0.8	1.1
2	2.3	2.1	1.3	0.89
3	-2.4	0.9	1.2	0.8

Probe axis is indicated by (1,2,3) which reference a RH coord system with '1' pointing towards the target, parallel to the floor (see upper-left in photo).

Field INSIDE mu-metal shield for PMT strapped to shield plate was < 0.02 G for all directions. Probe was located 2” inside shield (see figure on lower-left).

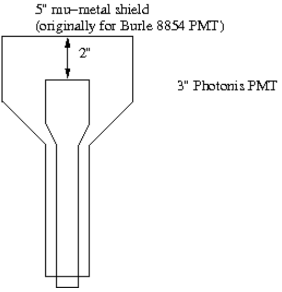


Figure 5: Photograph showing the location of the bare (no scintillator) PMT mounted on the upstream side of the BigBite detector stack during G_{E_n}. Magnetic field measurements were taken up against the shielding at the indicated points. The plastic (white) and Al panels were leaned up against the BigBite frame to shield the wire chambers from low energy background. The PMT being tested is tied to the make-shift shelf clamped to the Al plate in the center of the frame.

Table 2: Atmospheric pressure variations for the Newport News area. The pressure load is in units of kg-force per meter^2.

Period	Pressure variation	Pressure load
Average Daily	1 kPa (0.6 kPa typical)	102 kgf/m^2
Yearly (2005–6, peak-peak monthly scale)	3 kPa	306 kgf/m^2
Yearly (2005–6, maximum)	8 kPa	510 kgf/m^2

remove water vapor and oxygen. Then a C_4F_{10} bottle will be connected and the tank will be slowly filled with the upper vent open until C_4F_{10} can be visually observed spilling from the vent on the top of the tank. A single fill will require roughly 1800 liters of gas based on the preferred design in which the Cerenkov tank is sized to house the PMTs inside the gas volume.

FermiLab experiment E907 used a C_4F_{10} gas Cerenkov with a similar design (3400 liter volume, PMTs located inside the gas tank). They used a pressure compensating gas system that maintained a slight overpressure in their tank. Excessive overpressure in the tank was relieved by venting into the atmosphere. Underpressures were dynamically corrected using an automated control valve coupled with a differential pressure meter monitoring the gauge pressure at the top of the tank. A separate differential pressure transducer was used to measure the weight of the C_4F_{10} column between the top and bottom of the tank. Their average gas consumption rate was roughly 28 liters/day (1 ft^3/day). This rate is consistent with calculations using average daily atmospheric pressure variation and the ideal gas law.

Managing the gas pressure in the BigBite tank will be accomplished using a similar design. If we assume an average 1 kPa daily fluctuation in atmospheric pressure then the associated gas consumption for an 1800 liter volume may be estimated to be roughly 18 liters/day. At US$1.45/liter that corresponds to $26/day.

A common storm can result in a pressure change at a rate of 2.5 kPa/hour while a 100 year storm can result in a drop of 8 kPa/hour. The associated flow rates of 900 to 2400 sccm[†] need to be taken into account (assuming an STP volume of 1800 liters).

Table 2 lists atmospheric pressure variations for the Newport News area.

5.1 Monitoring

Leakage of the C_4F_{10} during a run will readily show itself as a drop in the mean number of p.e.'s per electron from the (estimated) 14 to down to something approaching the 3–4 p.e.'s for nitrogen. Such a reduction in amplitude will also appear in the upper PMTs first as the

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[†] Standard cm^3 per minute (STP).

C_4F_{10} will naturally concentrate at the bottom of the tank. The combination should provide a clear online signal of gas leakage before it becomes a problem. The weight of the gas column measured by a differential pressure transducer can be used as a rough measure of the gas content in the tank that does not require monitoring Cerenkov detection efficiencies. Alternate/additional methods of monitoring the gas purity in the tank are being investigated. In particular, a cheap ultrasonic sound velocity system could be used as a density monitor at the top of the tank.

6 Cost Estimate

The engineering work and dimensioned shop drawings are being produced by Ed Kaczanowicz (Temple University). Ed has already completed the equivalent work for the SANE Cerenkov for use in Hall C. We plan to recycle the design of some of the smaller, more complicated components (such as the gimballed mirror mounts) in the BigBite design to reduce overhead where possible.

We are currently evaluating whether it is feasible to increase the width of the Cerenkov tank to $\approx 170\,\mathrm{cm}$ and mount the PMTs inside the C_4F_{10} volume. The width *can* be accommodated within the BigBite frame, although it may require at least one of the “wings” to be attached from the side after the rest of the assembly is installed from the front of the existing detector frame. The benefits include eliminating the need for the 10 quartz optical windows that couple the PMTs to the interior of the tank (saving $6000), a minor increase in light collection efficiency by reducing unwanted reflective interfaces, and eliminating potential degradation of the PMT performance by insulating it from the helium rich atmosphere surrounding the target without the additional overhead of nitrogen buffering the PMTs. Due to those advantages, enclosing the PMTs within gas volume is our preferred solution.

Table 3 presents a cost estimate for the proposed detector. The first four items are baseline components that will need to be purchased or built from scratch. We hope to source used PMTs through arrangements with our collaborators to defray the total cost. Given the relatively small number required (12) we do not expect locating adequate PMTs to be a problem.

The minimal capital outlay for the base items is estimated to be **$66k**. This omits the Winston cones (at the cost of reduced performance for electrons below 0.8 GeV/c), the Quartz windows (PMTs will be installed inside the tank), and presumes we will use existing PMT hardware. These items could be added or upgraded at a later date to enhance the Cerenkov performance for subsequent experiments.

Table 3: Cost estimate for the BigBite gas Cerenkov. The top four items comprise the base cost. The PMT cost is listed, but we hope to source the tubes from existing components. The Quartz windows will not be required in the preferred design.

Component	Units	Cost/unit	Sub-total
Cerenkov frame/mounting hw/fittings			\$30k
Primary Mirrors (spherical)	10+2	\$2000	\$24k
Secondary Mirrors (flat)	10+2	\$1000	\$12k
Pseudo-Winston Cones[†]	10+2	\$500	\$6k
PMT, base, μ-metal shield (**Quartz**)[‡]	10+2	\$2500	\$30k
Quartz optical windows[*]:	10+1	\$500	\$6k
C_4F_{10} gas: (cost/fill[§])		\$2600	—
Daily consumption (atm. press. fluctuations)		\$26/day	—

[†] May be omitted for purposes of E06-014 at the cost of a significant loss in efficiency for the lowest energy bins.

[‡] Quartz-face PMTs result in almost a factor of two more detected photons versus a UV-glass PMT.

[*] Not required if the PMTs can be installed inside the tank (preferred option).

[§] A fill is estimated to be 1800 liters priced at US\$1.45/kg (1 kg liquid = 100 liters gas at STP).