Overview of MWPC Construction for the Charged Pion Polarizability Experiment (CPP) at Jefferson Lab

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Abstract
This document provides many of the construction details for the MWPCs built for the CPP experiment at JLab. Test results obtained at UMass are also presented. Additional details on construction and detector testing can be obtained from electronic laboratory notes maintained by and available from the authors.

1. Overview

Early in the development of the CPP proposal it was realized that rejection of Bethe-Heitler muon pairs at a level sufficient for the proposed experiment wasn't possible with the standard GlueX setup. At that point it was decided to pursue the development of an auxiliary detector system that could be installed on the GlueX platform downstream of FCAL. π/μ PID would be accomplished using FCAL, which provides for a modest level of π/μ PID, and the auxiliary detector. At the $\approx$ 3 GeV particle energies of the CPP experiment, π/μ PID is problematic because β's are nearly equal for pions and muons, and charged pions don't readily produce showers in lead glass. At these energies charged pions are typically absorbed on heavy nuclei with the emission of several neutrons and protons, the latter at energies at or below threshold for Cherenkov light emission in lead glass. After considering several options, including the use of scintillator arrays, it was decided to build a system of MWPCs with iron absorbers stacked between the chambers. The iron absorbers have a total hadronic interaction length sufficient to stop all the charged pions in the iron, whereas sufficiently thin to allow muons to continue through the MWPCs and iron absorbers. Eight chambers are being constructed for the CPP experiment, and 6 chambers will be used in data taking.

The table below summarizes many of the important details of the MWPCs constructed for the CPP experiment.

Parameter	Value
sensitive area	60 x 60 inch^2
sense wire pitch	0.4 inch
wire plane to cathode plane distance	0.4 inch
size of central deadened region	10 x 10 cm^2
wire arrangement	planar, with field wires between sense wires

Parameter	Value
sense wire diameter	20 µm
field wire diameter	.003” non-central region, .004” central region
sense wire voltage	typically +1800 volt
field wire voltage	ground
cathode plane voltage	ground
operating gas	90:10 argon:CO_2 by volume, flowing at 5 cc/s
typical chamber gain	$\approx 100{,}000$
maximum drift time	$\approx 570\ ns$
number of electronic channels per chamber	144

2. MWPC prototyping efforts

Detector prototyping started almost immediately after approval of the experiment by PAC 40. The prototyping effort went through three phases prior to starting construction of the 8 CPP chambers.

First phase: We started by constructing several small chambers, approximately 6” × 6”, with 6 or fewer sense wires. 3-D printing was used for producing the chamber planes, and PCBs were designed for the chamber mounted preamps. The preamps are discussed in the electronics section of this report. SMA connectors were used for signal readout. Garfield studies were used for optimizing the drift cell design, the primarily the minimization of charge collection time.

Fig. 2.1 Full-scale prototype MWPC mounted on the platform behind FCAL for a beam test.

Second phase: Building on what we learned from the phase 1 prototypes, we built a 24 channel “medium scale” prototype, approximately 12” × 12”. The objective was to finalize the design of the 24 channel electronics preamp PCB, which would be used in the full scale detectors. The detector uses a multi-pin connector which is compatible with the JLab FADC125. This prototype detector was extensively used for cosmic ray drift time and chamber plateau studies. Details of these studies are given in the section on MWPC testing.

Third phase: The last phase was the construction of a full scale detector with the parameters given in the table above. The chamber utilizes 6 of the 24 channel preamp boards developed for the second phase prototype. The full scale prototype chamber was constructed at UMass and transported to JLab for a beam test in early 2018. Fig. 2.1 shows the prototype detector in Hall D mounted at the end of the platform behind FCAL for the test run. After the test the detector was removed from the beam line, and is still located in Hall D.

3. Overview of MWPC mechanical construction

A schematic cross-sectional view of a chamber is shown in Fig. 3.1. A chamber is built onto two aluminum honeycomb plates of size 64” × 64”. The aluminum facing on the plates is 1/16” thick. Internal to the honeycomb plate there’s an aluminum bar of cross sectional area 2” × 0.5” that goes around the edge of the plate. Thru-holes were drilled through the outer edge of the *Wire Frame plate* (bottom plate in Fig. 3.1) and tapped for 1/4-20 machine screws. The same pattern of thru-holes, c’sinked, were drilled through the outer edge of the *Spacer Frame plate* (top plate in Fig. 3.1). 1/4-20 allen-head flat-head screws are used to secure the two detector halves together. The G10 slats and electronic PCBs were epoxied to the honeycomb plates using a 2 hour set epoxy, Loctite EA E-120HP. An o-ring (ordered from McMaster-Carr, part # 7643K71, 0.07" dia. soft viton, A55 durometer) provides a gas seal between the two chamber plates.

Fig. 3.2 shows a photo of a honeycomb plate. At the center of the plate the manufacturer drilled a 2 inch diameter hole through the aluminum facing plates for the photon beam to pass through. We also removed the internal aluminum honeycomb from these holes.

The G10 slats were cut to size by the supplier, and Fig. 3.2 shows a photo of the slats as they came from the supplier. The UMass machine shop did all of the final machining for the G10 slats, including the cutting of thru-holes, o-ring grooves, and trimming the G10 slats to length as needed. Details of the honeycomb plate and G10 slat designs are shown in Appendix A.

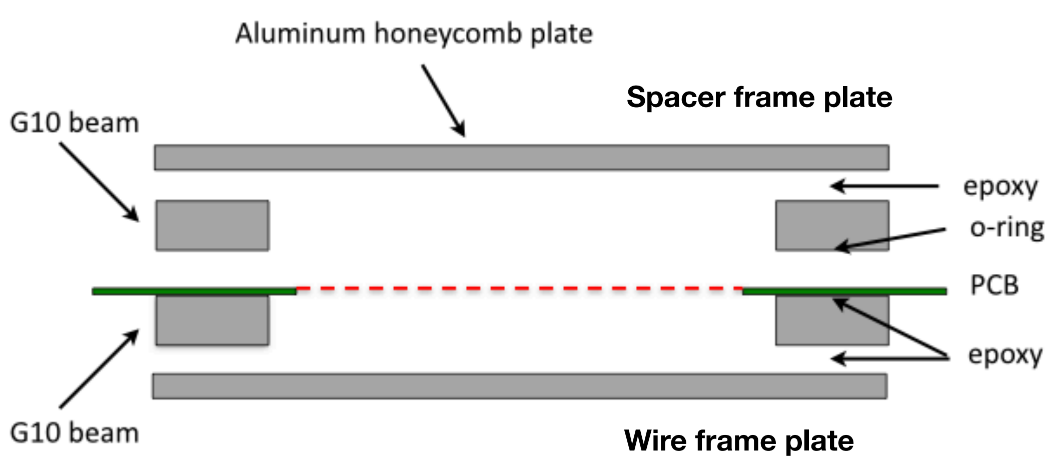


Fig. 3.1 Schematic view of the MWPC construction and assembly.

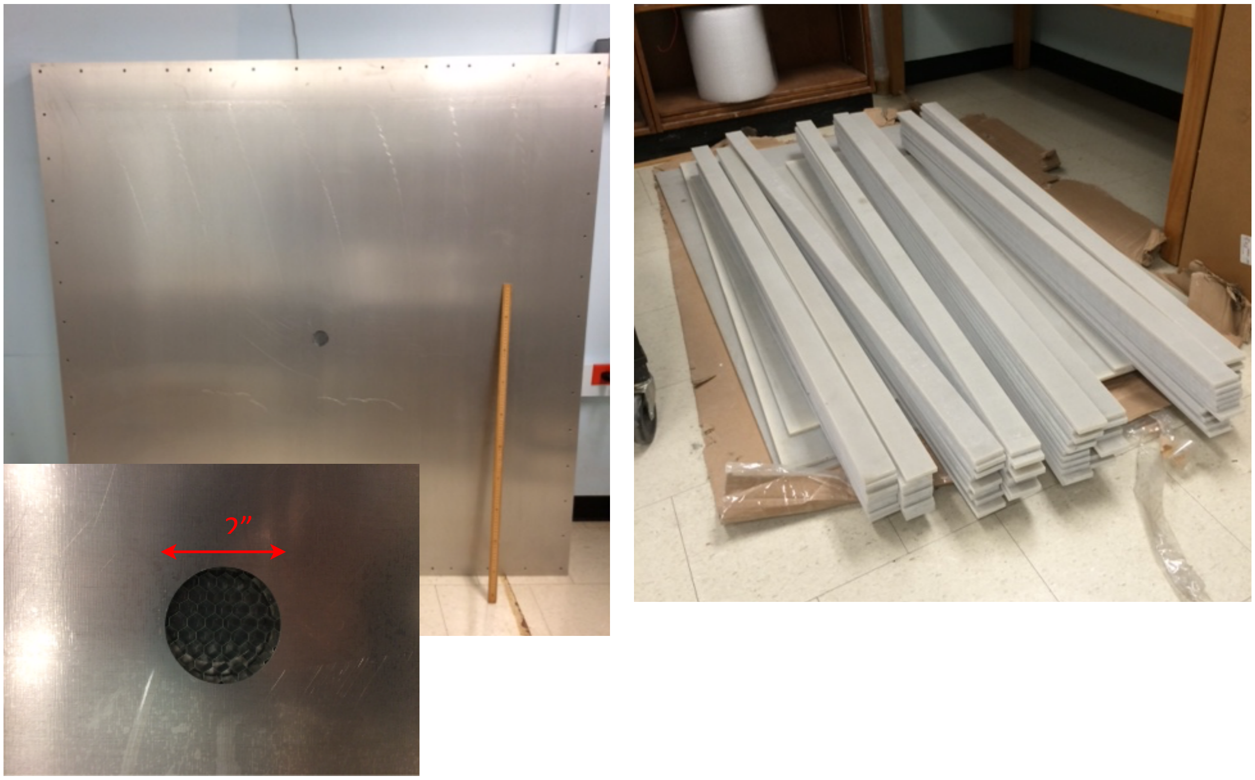


Fig. 3.2. Left, photo of honeycomb plate, with closeup photo of the central hole. Right, the G10 slats as they came from the supplier prior to machining at UMass.

4. Assembly of the wire planes and spacer planes

• *Epoxying the G10 slats to the honeycomb plates*

The aluminum plates were “roughed” up with 220 grit sandpaper on the 2” margin of the plate to give the epoxy a better grip to the aluminum plate. The epoxy was applied onto the G10 slates (not onto the plate), and special care was taken to lay down the correct amount of epoxy so that the epoxy thickness was 5 mil. This required repeated application of epoxy to the slat then weighing the epoxy gun to determine how much epoxy had been applied. The first two slats laid down onto a plate were the “short” beams, each of which were held in position with two gauge pins. The gauge pins were coated with dish soap so that they could be removed after the epoxy had set using a vise-grip wrench. After the short beams were epoxied onto the plate, the two “long” beams were epoxied onto the plate. Seven clamps were applied to each slat to hold the beams in position.

• *Epoxying the Preamp and HV PCBs to the Wire Frame “short” beams*

The issue with the PCBs is that they came slightly oversized from the PCB manufacturer (this is typical), and each PCB had to be individually trimmed to size. The procedure was to “tile” the

PCBs onto the wire frame, and then use a 72” long ruler marked with 10 mil divisions to determine how much material on PCB left and right should be removed. The PCBs were trimmed on a router table using brass shims to carefully control the amount of material shaved off. After the PCBs were trimmed, the PCBs were epoxied to the Wire Frame short beams using our standard epoxying procedure. To hold the PCBs in position and to push them down to the desired height on the Wire Frame, a 6 ft stainless steel beam was placed on top of the preamp (and HV) PCBs, and clamps on the left and right sides of the steel beam pushed the beam down onto the Wire Frame. The overall registration of the field wire and sense wire pads to the required 0.2” wire spacing (0.4” sense wire spacing) was quite good for nearly all of the preamp and HV PCBs.

- *Attachment of thin aluminum windows*

Central thin window: A 2” diameter hole was bored through the center of the honeycomb plates for passage of the photon beam. On the interior surface of the plates the hole was patched over using a 3” diameter aluminum foil patch with thickness 0.6 mil to provide a gas seal. The patch was bonded to the plate by laying down a circular ring of epoxy just inside the 3” diameter of the patch, then interior to the epoxy ring laying down at 12, 3, 6, and 9 o’clock a small blob of conductive epoxy (MG Chemicals silver conductive epoxy). The aluminum patch was placed onto the plate, a 5 mil plastic sheet of the same diameter placed on top of the foil, then a rubber roller (used for applying wallpaper) was used to roll the patch flat. Afterwards the plastic sheet was removed, and cleanup was with acetone and ethanol.

X-ray port: For testing and gain matching the detectors, we installed a thin window on the spacer plane so that an x-ray source (^{55}Fe) can be used to trigger a sense wire. A 0.25” diameter hole was bored through the spacer plane, and a 1” aluminum patch was placed over the hole on the interior surface of the spacer frame to provide a gas seal. The patch was bonded with conductive epoxy (not regular epoxy) to the honeycomb plate. Looking from the preamp side of the detector with the preamp electronic components up, counting from the left side of the chamber the x-ray port is centered over the 12th wire of the 2nd preamp card. This is the 60th sense wire counting from the left of the chamber. The x-ray port is at the mid-point of this wire.

5. Wire stringing

The MWPCs were strung in a class 10,000 clean room at UMass. The clean room workers wore Tyvek “bunny” suits with attached hoods and boots. When in contact with internal surfaces of a chamber, or when working on the electronics, the workers also wore gloves. Wire stringing commenced by attaching two 3/4” diameter “Acme” threaded rods, 6’ long with a thread spacing of 0.1”, to the two ends of the Wire frame. Brackets attached to the edges of the Wire frame were used to hold the Acme rods in position, and there was also a supporting bracket mounted at the mid-point of the frame to support the Acme rod, as there’s a significant gravitational sag if not supported at the mid-point. Height adjustment screws in the left, right and center brackets allowed us to bring Acme rod to the proper height relative to the top of the Wire frame. Hex nuts on the Acme rod on the outside and inside of the left and right support brackets allowed us to slide the rod left or right and then lock-in the horizontal position of the Acme rods.

We would typically string 3 “guide wires” over the Acme rods as a preliminary step to positioning the rods. The 3 guide wires, usually field wires, are brought to the correct height with fine adjusters on the extreme left, center and right hand sides of the Wire Frame. Once the Acme rods were brought to the correct height relative to the wire frame, the rods were shifted left or right to align the guide wires to the plated thru-holes in the center of the field wire pads. When both rods were in position the hex nuts on the Acme rods were used to lock the rods into position.

Wire stringing outside of the central 10 sense wire region of the chamber:
Tensioning weights were attached to the wires, and then the wires were laid over the ≈ 6” excess length of the Acme rod positioned to one side of the Wire frame. During the process of playing out sense wire from the spool, the sense wire was pulled through a clean room rag (lint free polyester) soaked in 200 proof ethanol to clean the wire. We didn’t use this cleaning procedure for the field wires. The 20 μm gold plated tungsten sense wires were tensioned at 25 g, and the 3 mil “silver coat” beryllium copper field wires were tensioned at 80 g tension. Calculations show that a sense wire tension of 25 g is several times the minimum tension needed for electrostatic stability, i.e. the tension needed to cancel out electrostatic forces that tend to pull sense wires out of their equilibrium positions. The field wire tension of 80 g was chosen so that both sense wires and field wires follow the same catenary under the force of gravity. Clean room workers used smooth rods to carry the wires from the Acme rod to the Wire Frame solder pads so that the wires were under a constant tension.

Wire stringing pattern in the central 10 sense wire region of the chamber:
Recall that the chambers will be positioned on the beam line downstream of FCAL with the photon beam going through detector center. For this reason it is necessary to deaden the central 10 cm × 10 cm region of the chamber to ionizing radiation. For the GlueX FDCs (forward drift chambers) copper electroplating was used to build up the sense wire diameter in the central region of the chamber to approximately 100 μm. In this case the wire radius is larger than the critical radius for the onset of multiplicative gas gain, and the detector in this region has no sensitivity to ionizing radiation. Early on in the development of the MWPCs at UMass we also investigated the electroplating technique, without success. We found a reasonable solution is to fit conductive carbon fiber tubes of size 0.71 mm OD × 0.28 mm ID × 10 cm long to the 10 central sense wires of the chamber.

The carbon fiber tubes are "slippery" and don't stay in position along the sense wire if the chamber is tilted, and therefore must be bonded to the wire. For bonding we investigated the use of (i) a conductive carbon based paint and (ii) "super glue" (Gorilla brand). Generally we found the carbon paint difficult to use, producing a fragile and unreliable bond. The bond with super glue was excellent, and in testing we often found that holding a tube with one hand and pulling on the wire bonded to the tube with the other hand, the wire would often break under load before slipping out of the tube. Application was with a “0 Round” fine tip artists paint brush. Resistance measurements from the center of the carbon tube to the grounded end of the wire yielded similar resistances for different bonding: (i) about 100 Ω for both ends bonded with carbon paint, (ii) about 130 Ω for one end bonded with carbon paint and the other end with super-glue, and (iii) about 150Ω for both ends bonded with super-glue. These are difficult measurements to do, and we estimate the error to be as much as $\pm 50\Omega$. Because of the much stronger bond and similar electrical conductivities, we used super-glue for bonding the carbon fiber tubes to the sense wires.

When examining the carbon fiber tubes under a microscope we found that the tubes often have loose carbon fibers that extend outward for as much as several mm. This was a serious problem in the initial development of the first full scale prototype detector. In this case the wayward carbon fibers at +HV shorted to adjacent field wires at ground. The solution was to sand down the carbon tubes with 1000 grit "Wetordry" sand paper, and then wash the tubes off with ethanol and a lint free polyester wipe (clean room quality) prior to installation. We also sanded a "bevel" onto both ends of the tubes so there wouldn't be any sharp points on the tubes. The polished carbon fiber tubes were inspected under a microscope prior to installation in the chamber. When taking these precautions for the 8 CPP chambers there wasn't a single instance of a carbon fiber tube shorting to ground. This is a total of 80 sense wires with bonded carbon tubes.

The disadvantage to using relatively large diameter carbon tubes for wire deadening is the affect that it has on wire capacitance. Standard MWPC references show that sense wire capacitance has a weak dependence on wire diameter, and for most MWPC designs it's barely a consideration. However in the case of the 0.71 mm diameter carbon tubes the change in capacitance relative to 25 μm diameter bare wires is considerable, roughly a factor of $\times 2$ higher than for a bare wire. Multiplicative gas gain cannot occur on the carbon tubes, that's not possible because the surface electric field is orders of magnitude lower than the field needed for the onset of an avalanche. The concern is that the carbon tubes increase the capacitance of *adjacent bare sense wires,* i.e. those without carbon tubes, which can lead to unstable operation for those wires. The detailed analytical calculation we have for the sense wire, field wire, and cathode plane capacitances assumes an infinite array of wires, and therefore doesn't allow for a test of this effect (see *Particle Detection with Drift Chambers*, by Blum, Riegler, and Rolandi, for details of the calculation). To make sure this isn't a problem we ran GARFIELD studies with the specific sense and field wire configuration in the central region. The studies didn't find a significant change in capacitance for the adjacent bare sense wires; apparently the field wires do a very good job of electrically isolating sense wires from adjacent sense wires. There was an increased capacitance for field wires adjacent to sense wires with carbon tubes.

The sense wires with 10 cm carbon tubes were tensioned at 50 g because of the significant weight carried by these wires. 50 g tension is near the elastic limit for 25 μm tungsten wire. Because the field wires adjacent to the carbon tubes have increased capacitance, we used a slightly larger field wire diameter of 4 mil, versus 3 mil elsewhere, to reduce the electric field strength at the surface of the field wire. The 4 mil field wires were tensioned at 60 g so that the catenary shape followed by the field wires approximated the catenary shape followed by the sense wires.

6. Electronics

• *Preamp electronics PCB*

To minimize expense and the use of connectors, which can produce noise due to bad grounding, components for the preamps were surface mounted onto the same PCBs epoxied to the G10 slats, and that the field and sense wires are soldered to. The design for the preamp PCB was developed in our first and second phase prototypes: it's a relatively standard trans-impedance amplifier, a.k.a current-to-voltage converter, on a double sided PCB. The trans-impedance gain is set to 20k to get reasonable pulse height for cosmic ray signals. Six preamp boards are used per MWPC, with 24 channels per preamp board. The op-amp used is the TI OPA657, which has a gain bandwidth product of 1.6 GHz. Usually the issue in designing electronics like this is preventing the op-amps from oscillating, and special care was taken to stabilize the +5V and -5V low voltage inputs to the op-amp with filtering capacitors. A schematic for the preamp is shown in Fig. 6.1. Since we use the JLab FADC125 for reading out the chambers, the output of the preamp should be differential. One solution for converting the single ended output from the op-amp to differential output is to use a line receiver IC with differential output. For us there are disadvantages in doing this: increased current draw, and making the PCBs taller (longer in the wire direction). For these reasons we decided to use a passive transformer to generate differential output from the preamp. We used the MABAES0060 transformer, advertised to have a usable frequency range from 300 kHz to 200 MHz, part # 1465-1317-6-ND at Digikey. For the connection to the signal cable we used the 24 channel connector that was spec'd by Fernando Barbosa. A photo of the preamp PCB is shown in Fig. 6.2.

• *HV biasing PCB*

The sense wires are biased to +HV through PCB cards on the side of the chamber opposite from the preamp PCBs. Each sense wire is connected in parallel to the +HV source through its own 1 MΩ current limiting resistor. A photo of the HV biasing PCB is shown in Fig. 6.3.

• *Description of grounding, LV distribution and shielding*

Field wire grounding: grounded on both the preamp PCB and HV PCB ends of the wire.

Preamp PCB grounding: Fig. 6.4 is a photo of the "bottom" side of the preamp PCB. From top to bottom in this image the three long horizontal strips are busing for +5V, ground (the tinned trace), and -5 V to the six preamp PCBs. Copper braid is used to connect adjacent preamp PCBs. To minimize current draw and possible LV drops across the detector, LV for the 3 left preamp PCBs are not connected to LV for the 3 right preamp PCBs. Grounds for all the preamp PCBs are connected.

The grounding scheme described here was perfectly adequate for prototypes operating at UMass, and for the full scale prototype (shown in Fig. 2.1) operating at UMass and the JLab EEL building. However, when transported into Hall D the electronics on the full scale prototype would oscillate, particularly for the central preamp PCBs. Although it was possible to discern minimum ionizing particles in the chamber, clearly there was a problem in how the preamp PCBs were grounded. With hindsight we now realize the 60" long ground busing on the bottom of the preamp PCBs (see Fig. 6.4) acts less like a grounding connection and more like a transmission line. The solution has been to connect ground strips for all of the preamp PCBs through heavy gauge copper wire to the honeycomb plates. We do a similar treatment on the HV PCBs. In the UMass lab we see a reduction in noise with this grounding arrangement. We plan to test the chamber electronics in Hall D once the MWPCs have been moved to JLab.

We will also plan to have an enclosure made from 1/32" aluminum surround the preamp PCBs to help reduce noise. Fig. 6.5 shows a photo of the prototype enclosure that was constructed at UMass. Knockouts in the enclosure allow us to cable up the preamp electronics, connect LV, and ground the preamp PCBs to the Wire Frame plate with heavy gauge copper wire. Fig. 6.6 shows the effect of the enclosure on output signals. Details of the measurement are provided in the figure caption. The enclosure seems to be effective in reducing noise.

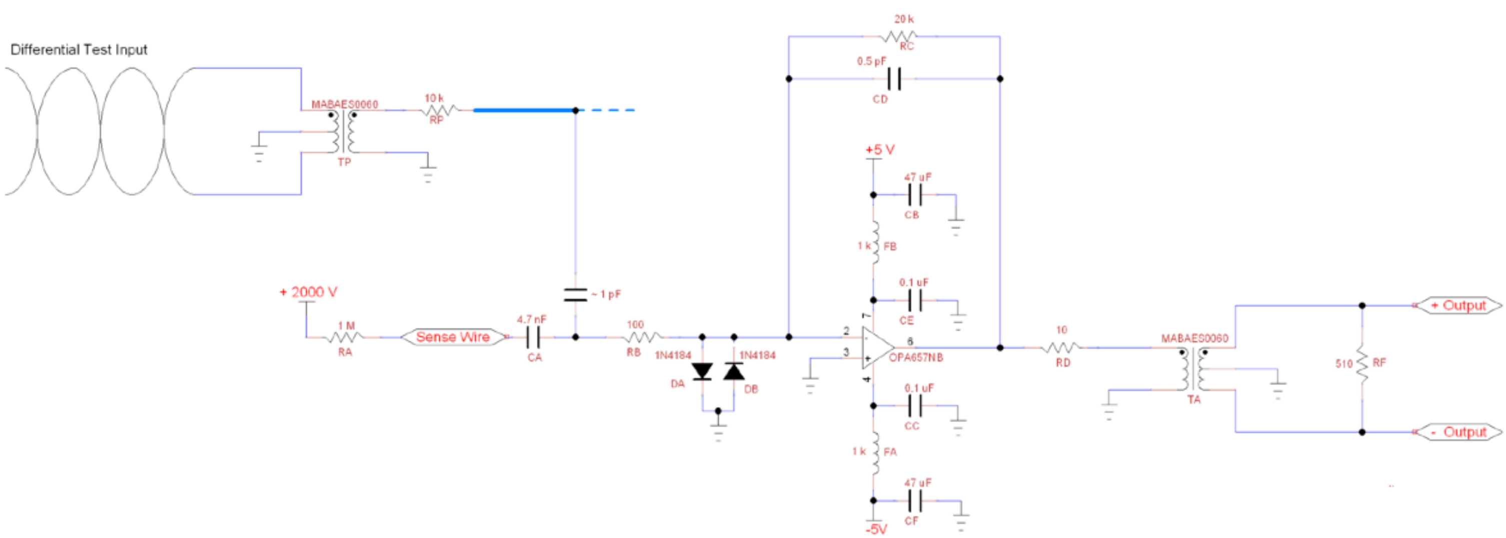


Fig. 6.1 Schematic of the preamp electronics.

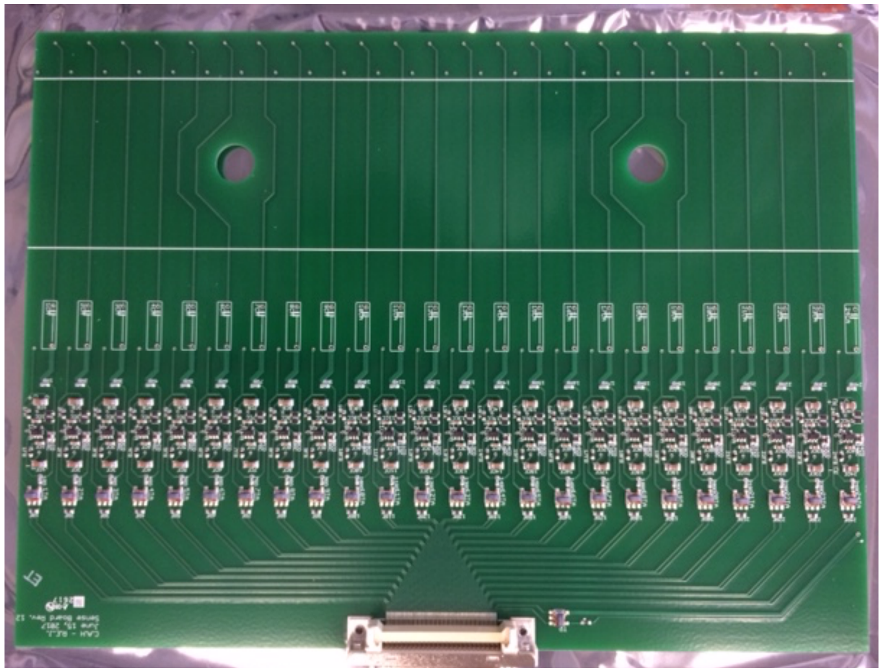


Fig. 6.2. Photo of the “top” side of the preamp PCB.

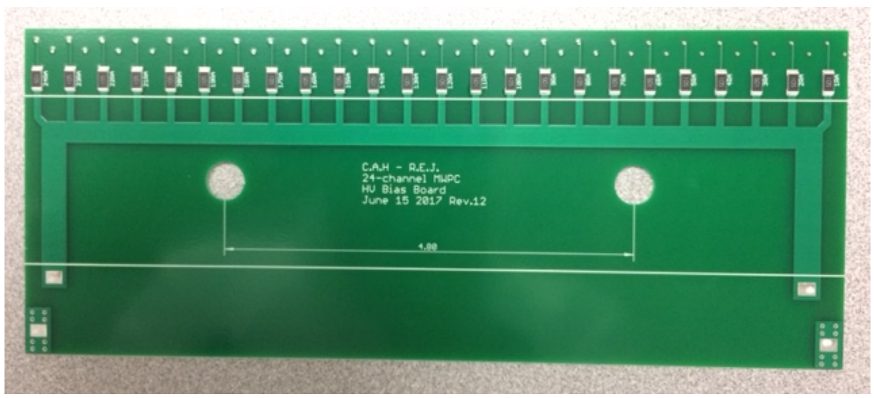


Fig. 6.3. Photo of the HV biasing PCB.

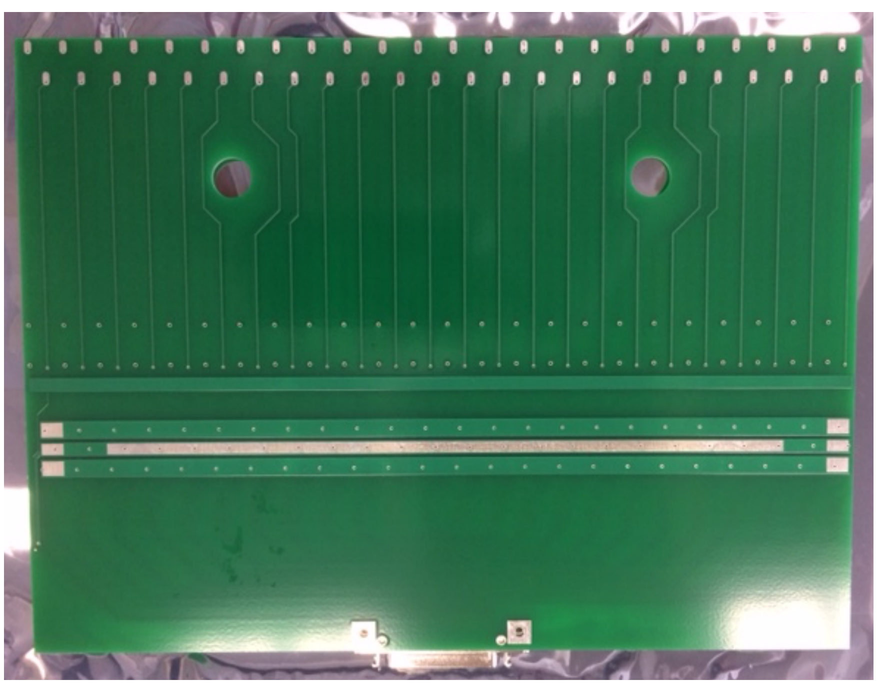


Fig. 6.4. Photo of the “bottom” side of the preamp PCB.

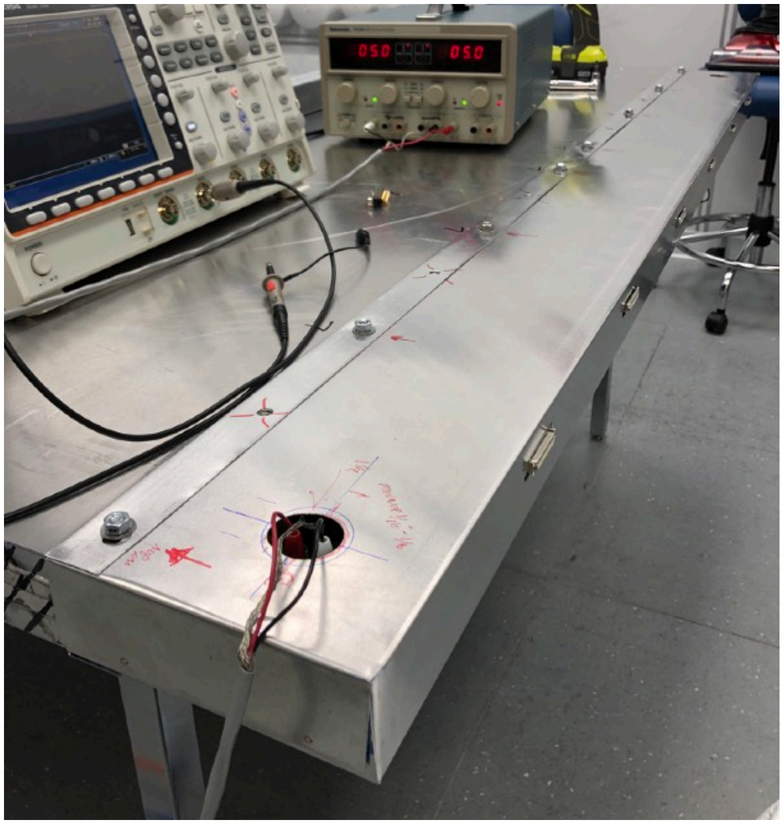


Fig. 6.5. Photo of the prototype preamp enclosure.

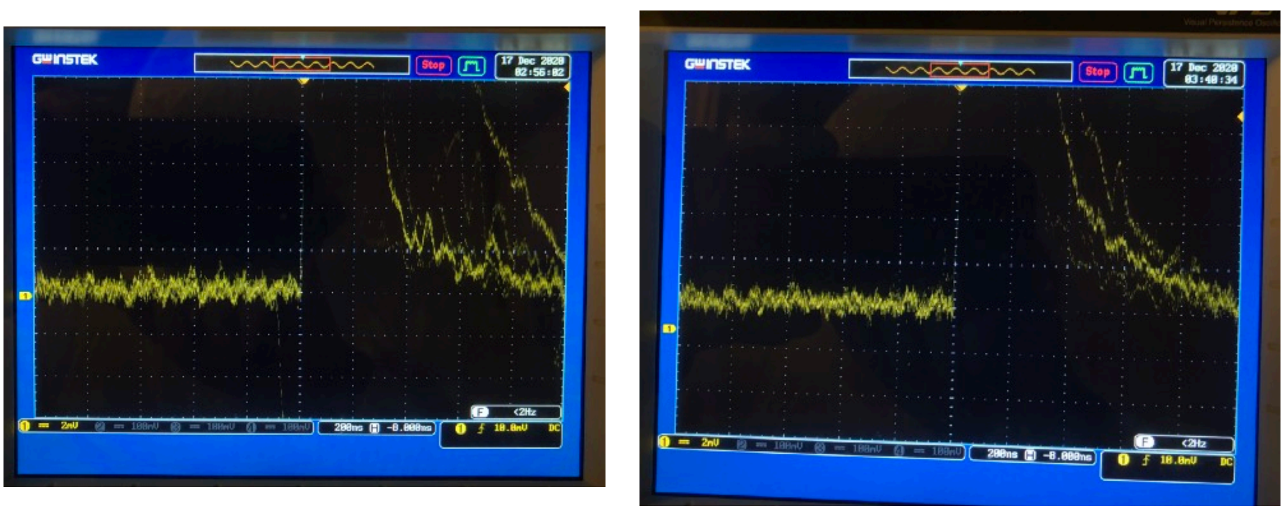


Fig. 6.6. The left photograph is a screen shot of a cosmic ray signal in the MWPC without the preamp enclosure. These images were taken with a scope probe touching the positive terminal of the output transformer, and scope trigger set at 10 mV. The vertical scale is 2 mV/div, the horizontal scale is 200 ns/div. The leading edge of the cosmic ray signal is at scope center. Peak amplitude for the cosmic signal is off scale and is not displayed on the scope. Noise during the 1 μs interval preceding the cosmic signal is approximately 1 mV peak-to-peak. The right photograph is with the preamp enclosure. In this case the noise appears to be smaller, approximately 0.5 mV peak-to-peak.

7. Completing MWPC assembly

• *Finishing up the Wire frame after wire stringing*

Because we use sanded down G10 slats to get thickness variation at the required level of a few mil, the surface of the G10 is rough and doesn't provide a good gas seal for the o-ring. To get a smooth, glassy surface on the G10 we painted the G10 slats with a 1:2 mixture by weight of epoxy:acetone. Only the portion of the G10 slat in contact with the o-ring was painted, a band approximately 1/4" wide going around the entire wire frame plate, including over the preamp and HV PCBs. We also applied this "paint" to the o-ring groove on the Spacer Frame.

Installed on the Wire Frame: 2 SHV connectors; 6 LV banana plugs (2 for ground, 2 for +5V, and 2 for -5V); screws for securing the edge connectors to the PCBs; copper braid for busing +5V, ground, and -5V to adjacent preamp PCBs; HV jumper wire for busing HV to adjacent HV PCBs; grounding cables for the preamp PCBs; grounding cables for the HV PCBs.

• *Cleaning the Spacer and Wire Frames*

Cleaning the Spacer Frame is straightforward; we place the frame on the table in the clean room and wipe it down with a lint free polyester rag (clean room quality) soaked in 200 proof ethanol. Having a high intensity lamp at a low angle of incidence also helped in allowing us to see lint and other contaminates on the frame.

Cleaning the Wire Frame is much more difficult because the sense and field wires limit access to the plate behind the wires. Unfortunately during the one week or longer time required to string a Wire Frame, lint, solder flux, and even bits of copper braid will drop onto the plate, and should be removed. We found the best way to do this is to mount the Wire Frame in the vertical position, allowing for close up visual inspection. Having a high intensity lamp at a low angle of incidence was also helpful to see contaminates. To remove stuff behind the wires we built a "straw tube" attachment for the hose of our HEPA vacuum cleaner, where the straw tube is sufficiently small in diameter to slip between wires. We would attach the straw tube to the vacuum cleaner hose, insert the straw tube between wires, and suck out any foreign objects. This is an effective although slow and tedious strategy for cleaning the Wire Frame plate. This process typically took about two hours.

• *Putting the completed Wire and Spacer Frames together*

The assembly steps can be summarized as follows:

(i) Place the Spacer Frame horizontal on the clean room table, insert the o-ring, and clean off the Spacer Frame.

(ii) At this point the Wire Frame is in the vertical position. Attach the two 78" inch "lifting bars" to the outside of the Wire Frame so it can be picked up and carried over the Spacer Frame. Thread thru from the outside of the Wire Frame two 1/4-20 screws on each of the 4 sides of the frame (8 screws total), the screws positioned near the mid-points of each side, and extending out of the inner surface of the frame by about 1/4". These screws are used for alignment when lowering the Wire Frame onto the Spacer Frame.

(iii) Two clean room workers lift the vertical Wire Frame by the lifting bars, rotate the Wire Frame horizontal, and carry the Wire Frame over the Spacer Frame on the clean room table.

Then slowly lower the Wire Frame onto the Spacer Frame, watching frame alignment at the corners nearest to them, feeling for the 1/4-20 screws to drop into the corresponding thru-holes on the Spacer frame.

(iv) Once the Wire Frame is on top of the Spacer Frame, the 8 alignment screws are removed, and all of the fastening screws and hex bolts (the latter needed for securing the preamp enclosure to the MWPC) are hand threaded from the bottom of the Spacer Frame. When all the fasteners are in position, the following pattern is used for tightening the screws: side #1 tightens the 2 screws nearest the mid-point of that side, side #3 does the same, side #2 does the same, and side #4 does the same. Then the pattern is repeated, tightening the 2 screws just to the outside of the screws previously tightened. This pattern repeats until all the fasteners have been tightened.

(v) Thread the gas line connectors onto the Wire .

• *Applying Humiseal:*

After the chamber was assembled, Humiseal was applied by paint brush and dropper to the tinned exposed HV surfaces on the preamp PCBs. The surfaces of concern are leads and solder pads for the HV blocking capacitors on both the top and bottom sides of the PCBs. The PCB signal trace leading from the chamber interior to the external HV blocking capacitor is also at +HV, however the trace is covered with green solder mask, and we don't view that area as a problem when running the MWPC in high humidity atmosphere.

8. MWPC testing

• *Tests using the "medium scale" prototype detector*

Studies of the wire chamber geometry and electronics were carried out during all three phases of detector prototyping (see section 2 for a description of these detectors). Most of the quantitative studies used the phase II prototype, the so called "medium scale" prototype. This detector has one preamp PCB card, 24 sense wires, and an edge connector compatible with a cable that can connect to the FADC125. This detector currently resides in a storage cabinet in the Hall D counting room (see D. Lawrence or R.Miskimen for details). For these studies we brought a FADC125 to UMass from JLab along with all of it's ancillary electronics (VXS crate, ...). Fig. 8.1 shows the detector setup at UMass. For setting up a cosmic ray trigger we used a 2" diameter NaI detector.

The goal for the studies was to obtain drift time spectra and relative efficiency measurements. The CPP chambers could have a significant background load of e^+e^- and x-rays hitting the chambers (see our ERR response for quantitative estimates of these rates), and for that reason we decided to run the MWPCs at a relatively modest gain of 100,000. MWPC gain depends on two factors, the gas mixture and HV. In the early stages of MWPC development we investigated three chamber gases: (i) Ar:CO_2 90:10, (ii) Ar:CO_2 80:20, and (iii) Ar:CO_2:CF_4 88:2:10. Argon:CO_2 mixtures are fairly standard MWPC gases, and mixes that include CF_4 (freon) have been commonly used on ATLAS and other detectors to obtain faster drift velocities, a potential advantage for CPP.

The chamber gain was calibrated using the 5.9 keV x-ray line from ^{55}Fe. The gain calibration assumes the x-ray is absorbed on argon with emission of an electron by the photo-electric effect, and knowledge of the average ionization energy for argon. Working in this approximation you can calculate the number of primary electrons produced in the chamber gas by the ^{55}Fe x-ray, N_p. The observed charge in the preamp signal is given by this expression,

$$\frac{1}{R_T}\int V(t)dt = Q_{out}$$

where R_T = 20k is the trans-impedance gain of the preamp, and V(t) is output voltage from the preamp. The time integral of the MWPC waveform for the ^{55}Fe x-ray was measured by a variety of methods, charge sensitive ADC, oscilloscope, and FADC125, and they all gave fairly consistent results as long as the tail of the signal was included in the integration. The chamber gain is given by this expression:

$$gain = \frac{Q_{out}}{eN_p}$$

Details of the gain calibration procedure using the phase I prototypes and a charge sensitive ADC are contained in a report by Michael Roberts, a UMass grad student. The report can be obtained from the authors by request.

Fig. 8.2 shows the results of relative efficiency measurements at fixed gain of 100,000 as a function of the threshold voltage for the signal. Results are shown for the three gas mixtures. Although the gains are identical for the plots, the chamber voltages are different, being lowest for the 90:10 mixture and highest for the freon mixture. Since all three gases are running at the same gain, it's expected that the onset to the efficiency plateau should occur at approximately the same voltage threshold. The data in Fig. 9.2 demonstrate this, with all three distributions showing a "knee" at the same threshold voltage of 23 mV.

Fig. 8.3 shows the drift spectra for the three chamber gases. The CF_4 mixture has the shortest maximum drift time, approximately 440 ns; Ar:CO_2 90:10 has the next shortest drift time, approximately 570 ns; and Ar:CO_2 80:20 has the longest drift time, approximately 970 ns. Since the CF_4 mix has a maximum drift time only 23% shorter than the 90:10 mix, we viewed the difference between maximum drift times as not significant. There are also large negatives to the use of CF_4 in the chamber gas, including CF_4 being expensive, smelly, possibly corrosive, incompatibility with the Hall D CDC mixing panel, (probably) not being allowed to vent the chamber gas into the hall, and CF_4 being bad for the atmosphere. For these reasons we decided to use Ar:CO_2 90:10 for the MWPC gas.

• *Testing the MWPCs built for the CPP experiment*

Because of time constraints and because we had to ship the FADC125 system back to JLab at the start of physics operations in Hall D, it wasn't feasible to repeat the test program described above for the medium scale prototype for the eight MWPCs constructed for CPP. Given that global parameters such as detector efficiency and drift time distributions aren't expected to change in going from the medium scale prototype to the big detectors, detector checkout at UMass largely consisted of verifying operation for the 144 signal channels in a chamber. Tests included: (i) biasing the detector to its operating voltage of +1800 V, verifying chamber current as nominal, typically around 50 nA, without sparking or HV trips, and (ii) examining on a scope each of the 144 signal channels in the MWPC to verify good cosmic ray signals, and a scope trigger rate between 10 to 20 Hz as measured at the positive transformer output for a scope threshold set at 10 mV. Regarding the HV bias testing, we never had a case where the chamber current was abnormally high, where the chamber sparked or tripped the HV supply. These MWPCs tend to not do that.

Regarding individual sense wire testing, we found the vast majority of sense wires in a given MWPC to be fine and not requiring any "fix", typically about 98% of the wires. However, it wasn't unusual to observe 2 "bad" wires per newly constructed MWPC. *We never observed bad sense wires in the small or medium scale prototype detectors.* The difference might be that the prototypes have many fewer wires than the big detectors, 6 to 24 wires for the prototypes versus 144 in the big detectors, and the wire lengths are much shorter in the prototypes than the big detectors, 6" to 10" long in the prototypes versus 60" in the big detectors. As a consequence there's a much greater length of sense wire in the big detectors, and possibility of something going wrong. Generally we found bad sense wires to fall into three fault groups: (1) in about one occurrence per MWPC a "standard" sense wire has a self-sustaining discharge with signal rate up to several kHz, (2) in about one half of the MWPCs the one sense wire directly over the thin aluminum x-ray port on the chamber shows a similar discharge phenomena, and (3) in about one in 20 of the sense wires with bonded carbon tubes there's a similar discharge phenomena.

Our strategy for fixing sense wires was to remove and replace the bad sense wire and the two adjacent field wires. This was generally effective for the first and third sense wire fault groups described above.

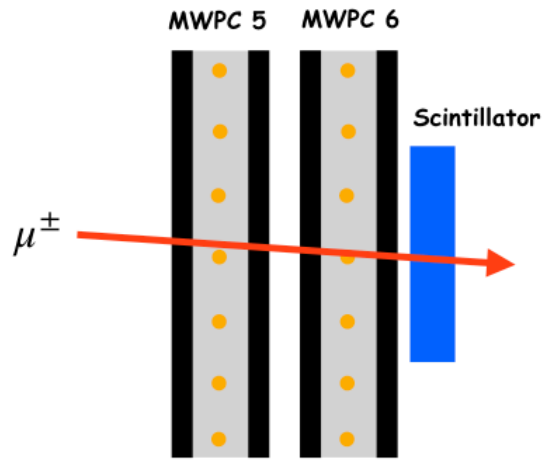
For the second wire fault group, where the sense wire directly over the thin aluminum x-ray port is noisy, the strategy wasn't effective. The problem wasn't observed on any of our prototype detectors, which complicates finding a solution. Polishing and cleaning the thin aluminum x-ray window, or even replacing the window didn't make a difference. What we found effective in reducing the noise rate was to run the chamber for 24 hours or longer at full HV of +1800V. After a long run at full HV noise on the wire would drop to approximately 100 Hz, allowing us to observe cosmic ray signals on the wire. We also observed the same effect for wires in the first and third sense wire fault groups, running for a long time at full HV would decrease the noise rate, allowing us to observe cosmic ray signals.

Wire replacement requires opening the detector, removing and replacing the bad wire(s), and then closing the detector. The breakdown of effort for two clean room workers is about one hour to open the detector, two hours to restring, and then 2 hours to close, about 5 hours total. Given the possibility of introducing additional problems into the chamber, or even breaking wires, and the considerable effort involved in doing this, our philosophy was to replace sense wires only if they are demonstrably not working, i.e. we can't see a cosmic ray signal on our lab scope.

- *Further MWPC testing at JLab*

When the eight CPP chambers have been transported to JLab there will be further opportunities for test measurements. A FADC125 based DAQ system is available in the JLab EEL building, and we'll have the capability to reproduce the studies we did for the medium scale prototype detector for the big chambers. We expect to deliver the first batch of four MWPCs to JLab in early summer, May to June 2021, and the second batch of four MWPCs to JLab in late summer, August to Sept. 2021.

To calibrate PID for the CPP measurement it will be important to measure the MWPC efficiency in situ during the experiment, particularly for muon tracks. To allow for this we're planning to install several long scintillator paddles behind the last two MWPCs. At the end of the stack of iron absorbers and MWPCs incident pions have largely been filtered out, and the rate is predominantly due to muons. The last two MWPCs will be installed with sense wires vertical, as will the scintillator paddles. As shown in the figure on the right, this allows us to define a coincidence between MWPC #5 and #6, and the scintillator paddle, providing a clean measurement of the MWPC detection efficiency. There is room behind the last MWPC for installing scintillators, and spare scintillator paddles are available from the GlueX TOF upgrade.



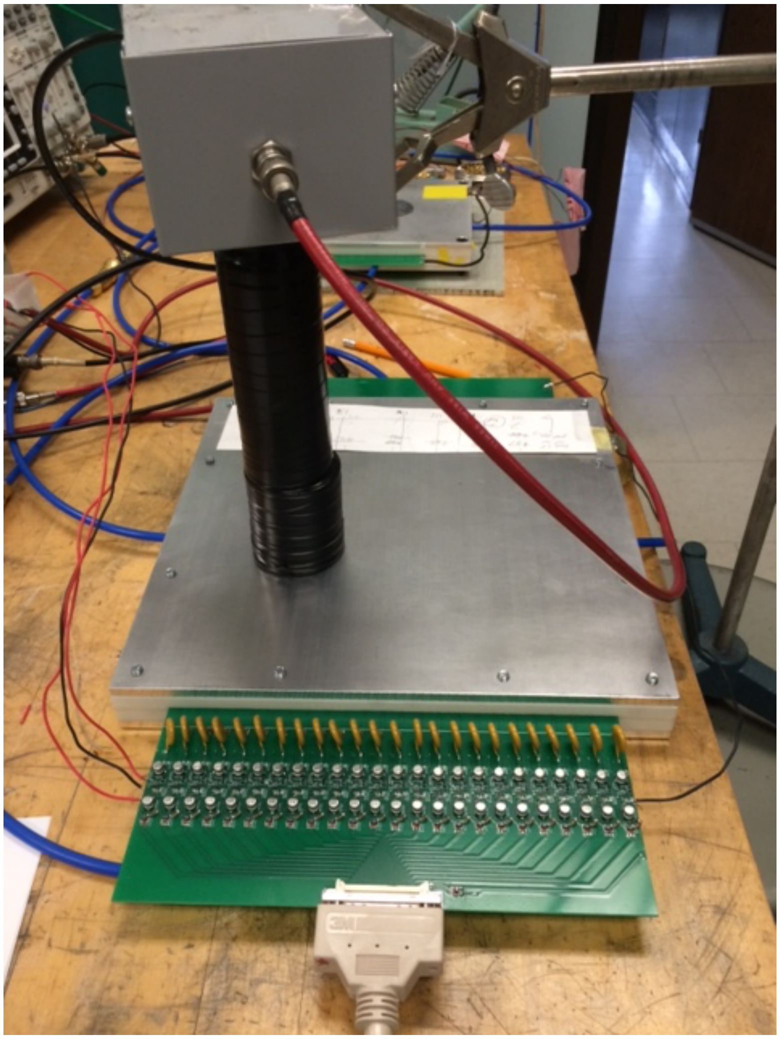


Fig. 8.1. Photograph of the “medium scale” prototype detector used for cosmic ray studies. The NaI detector used for triggering is shown above the MWPC. The cable attached to the preamp PCB goes to the FADC125.

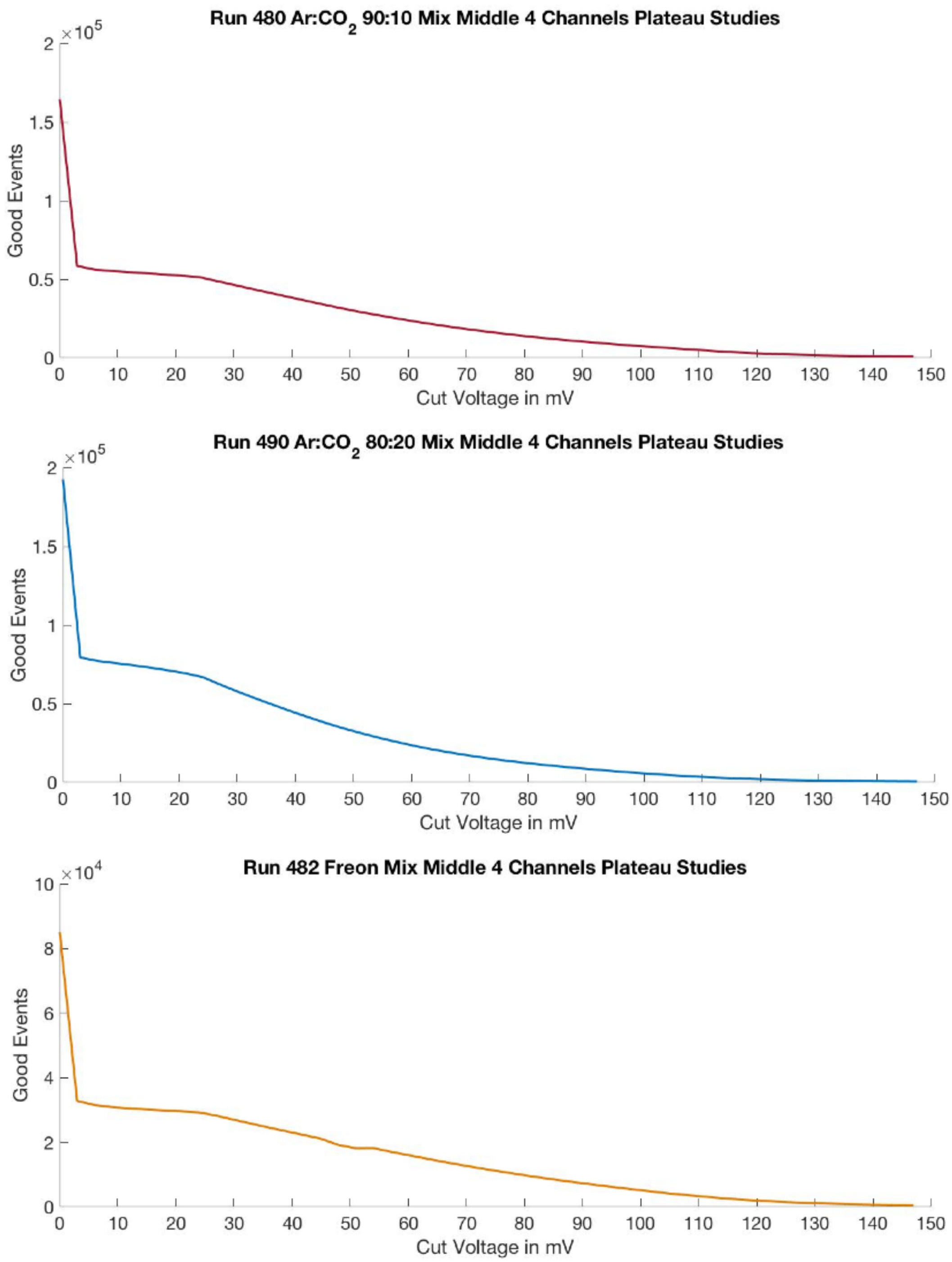


Fig. 8.2. Relative efficiencies for 3 MWPC gases. Top, $Ar:CO_2$ 90:10, middle $Ar:CO_2$ 80:20, and bottom $Ar:CO_2:CF_4$ 88:2:10. The horizontal axis is the threshold voltage for the signal in units of mV.

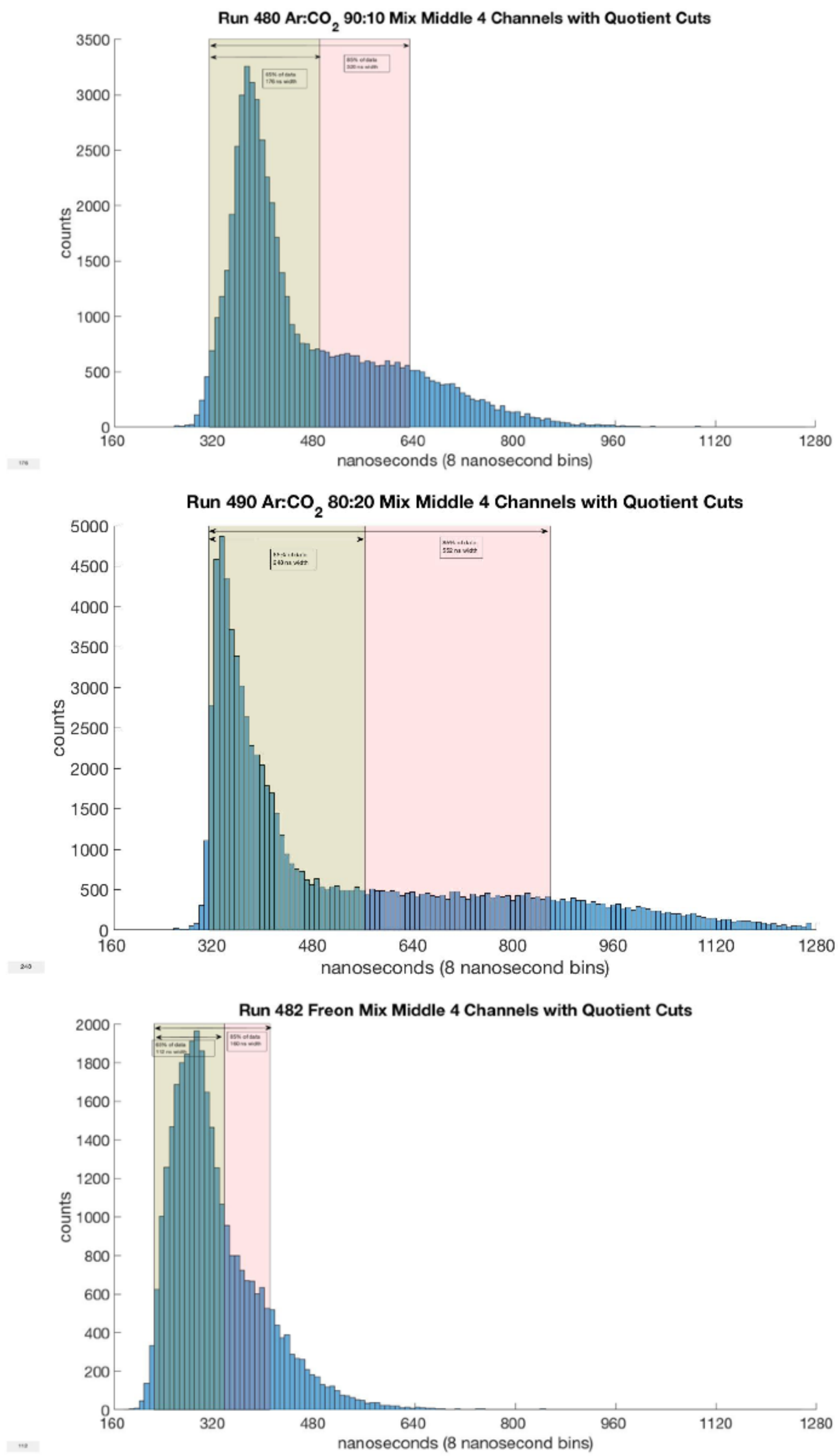


Fig. 8.3. Drift times for 3 MWPC gases. Top, $Ar:CO_2$ 90:10, middle $Ar:CO_2$ 80:20, and bottom $Ar:CO_2:CF_4$ 88:2:10. The horizontal axis is the drift time in ns.

9. Running the MWPCs at JLab

• *Gas*

The MWPC gas is argon:CO_2 mixed at 90:10 by volume, running at 5 cc/s into each chamber. The chambers are leaky because it's difficult to get a good gas seal between the o-ring and the rough G10 slats, and because the o-ring runs across signal traces on the preamp PCBs. For that reason it's better to run at a high flow rate (5 cc/s) than a low flow rate ($\approx$ 1 cc/s), a low flow rate risking diffusion of air into the chamber. Gas connections are made through Swagelok quick-connects on the chamber. Since we're running a non-explosive gas, our preference is to vent chamber gas into the room. Our experience using vent lines running to the outside has not been good; if outside pressure goes high relative to room pressure, then air will back into the chamber. In principle a "bubbler" on the exhaust line prevents this, although we've also heard stories of bubbler oil backing into chambers. Our strong preference is to vent chamber gas into the room. We recommend flushing gas through the chamber for at least 18 hours before turning on the HV.

• *Low voltage*

On the left and right sides of the preamp side of the MWPC there are three banana plugs for the low voltage connections; "black" for ground, "red" for +5V, and "white" for -5. The LV is segmented, there's a left and right side to the detector. *If you want to turn on all 144 channels, then you must supply +5V, -5V, and ground on both the left and right sides of the chamber.* Each LV channel draws approximately 1A, so the MWPC requires 2A at +5V, 2A at -5V, and a grounding connection. If you want to turn on just the left or right side of the detector, you can bias the LV connections on that side, leaving the other side unconnected.

• *High voltage*

The MWPC has two SHV connectors on the HV PCB side of the detector; you can supply +HV on either of the SHVs, they're connected and it makes no difference. The one exception is the "Arwen" detector, where an accident resulted in a HV PCB edge getting broken off, it has just one SHV. As discussed in section 8 on testing, the strategy for these chambers has been to operate at relatively modest gain, $\approx$ 100,000. For a gas mix of 90:10 argon:CO_2 this voltage turns out to be very close to +1800V. We typically ramp up HV at a rate of +10V/s, and limit current draw at 1mA. Once the chambers stabilize at +1800 V, the MWPCs draw about 50 nA as measured on a Bertan HV supply. Remarkably, we've never had an instance where one of these detectors has sparked on us. As noted previously, these chambers tend to not do that.

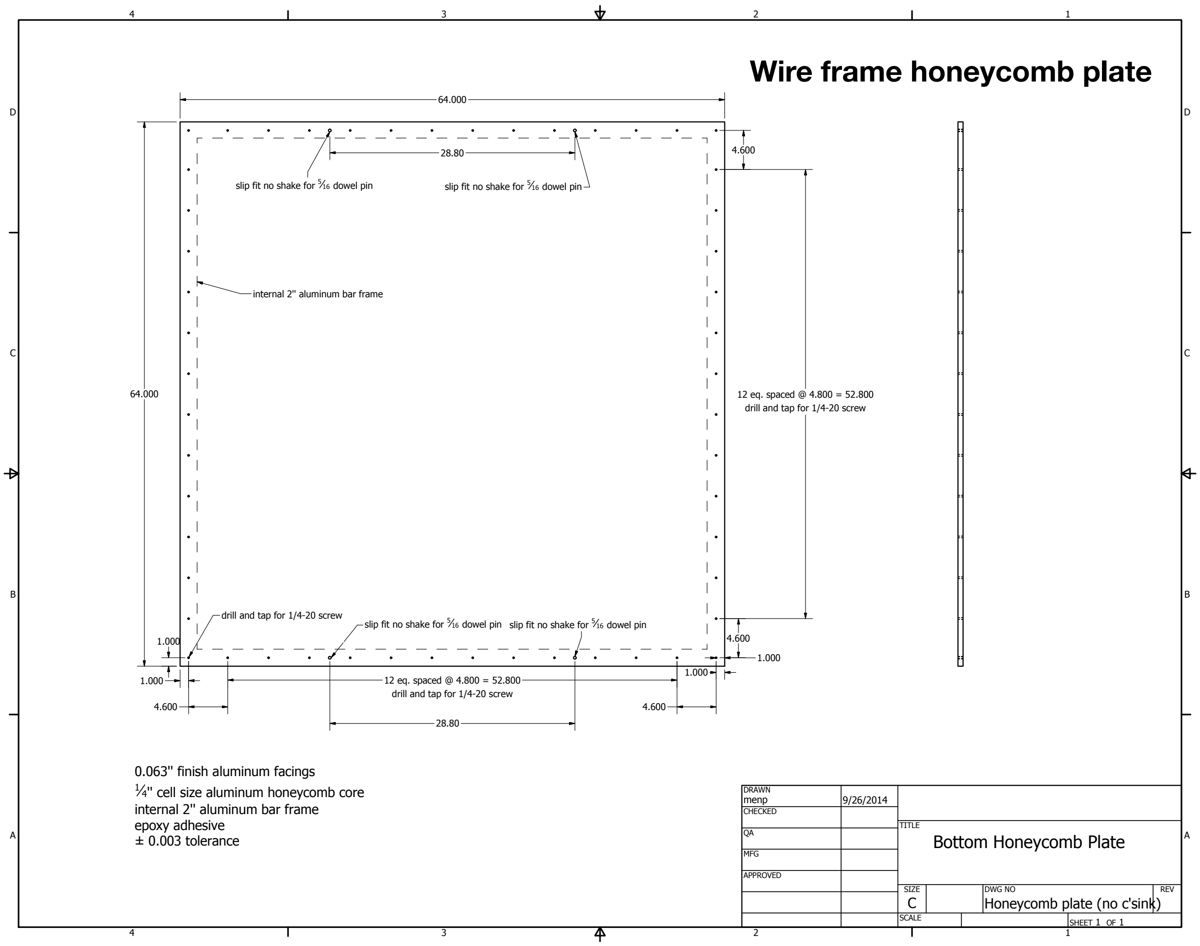
• *Gain matching to conditions at UMass*

A ^{55}Fe source can be used to calibrate the gain of the detector relative to what we observed at UMass. From the preamp PCB side of the chamber, counting from the left with electronic components in the up position, the port is centered over wire #12 on preamp PCB #2. If the MWPC is on a table with electronics up, then the x-ray port is on the bottom side of the detector. As noted in the section on MWPC testing, this wire is problematic for about one half of the MWPCs due to noise, apparently from the thin aluminum window over the port. Nevertheless, we believe it should be possible to discern a ^{55}Fe x-ray signal for all of the chambers. We saw a reduction in noise rate for this wire after running the chamber at full HV for 24 hours or longer. *At UMass, for HV of +1800 V and a 90:10 gas mixture, the median peak amplitude for the ^{55}Fe x-ray signal is approximately +250 mV as measured at the positive output terminal of the transformer using a scope probe. The same amplitude was observed for all of the MWPCs.* If the signal observed at JLab is significantly larger or smaller than this, it's likely the "90:10" gas mixture at UMass may not be exactly the same as the 90:10 gas mixture at JLab. We saw a similar effect when the full scale prototype detector was brought to JLab, resulting in a recalibration of the UMass gas flow tubes used for gas mixing. Our preference is for the chamber gain to be held at approximately 100,000. If the median peak amplitude as measured at JLab differs significantly from +250 mV, our suggestion is make adjustments in +HV to bring the measurement into agreement with +250 mV.

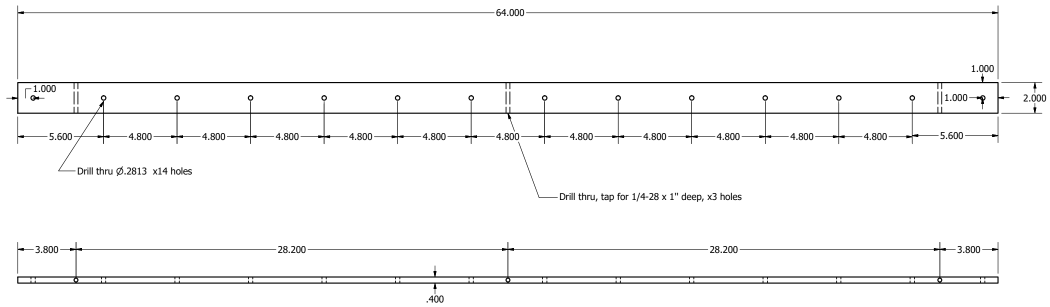
• *Electronics readout for bench tests*

To readout all 24 signal channels on a preamp PCB you'll need the signal cable built specifically for the CPP chambers, and most likely a DAQ system using the FADC125. Six of these signal cables were built for the CPP MWPC test in Hall D, and most likely the cables are still somewhere in Hall D (see Fernando Barbosa for information). If you only need to observe a single channel then a reasonable solution is to use a scope probe, probing either positive or negative output pins of the transformer, or the op-amp output pin (positive going signal). If the preamp electronics enclosure is mounted on the MWPC, then things are slightly more complicated. One solution is to attach the mating male connector to the chamber's female connector (this can be done with the enclosure on), and then probe output pins on the male connector with the scope probe. You'll need a connector map to know how connector pins correspond to wire # and the output polarity.

Appendix A: Honeycomb plate and G10 slat designs

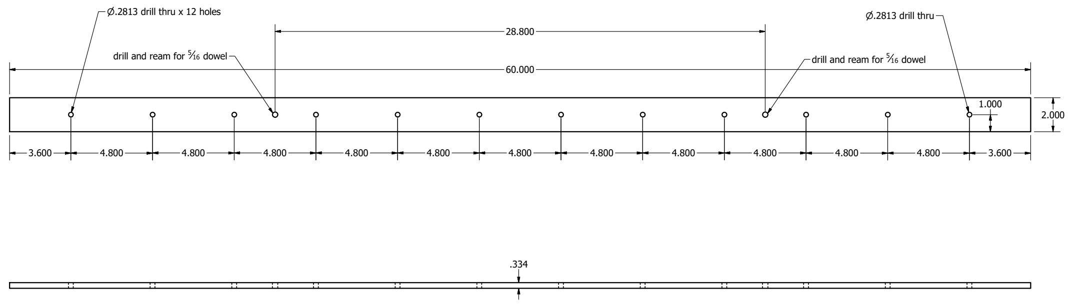


Wire frame slats



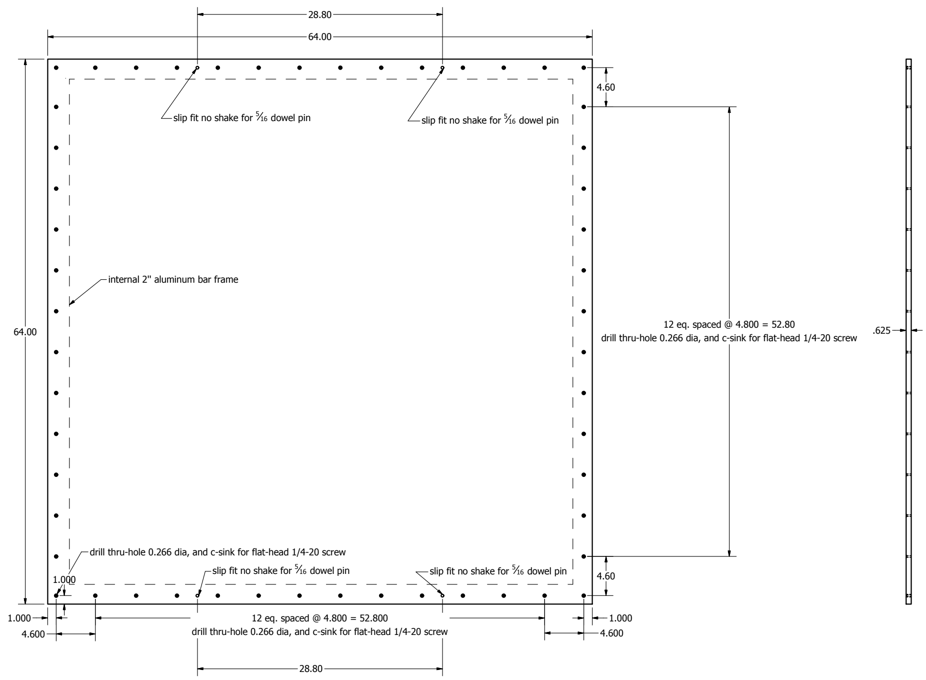
DRAWN A.S.	1/6/2016	2 required; material already cut to size; all dimensions in inches.
CHECKED A.S.	9/22/2017	TITLE
QA		MWPC Wire Beam Long
MFG		
APPROVED		SIZE C — DWG NO Wire beam long — REV 4
		SCALE — SHEET 1 OF 1

Wire frame slats



DRAWN A.S.	1/6/2016	2 required; material already cut to size; all dimensions in inches.
CHECKED A.S.	4/27/2017	TITLE MWPC Short Wire Beam
QA		
MFG		
APPROVED		SIZE C / DWG NO Wire beam short / REV 3
		SCALE / SHEET 1 OF 1

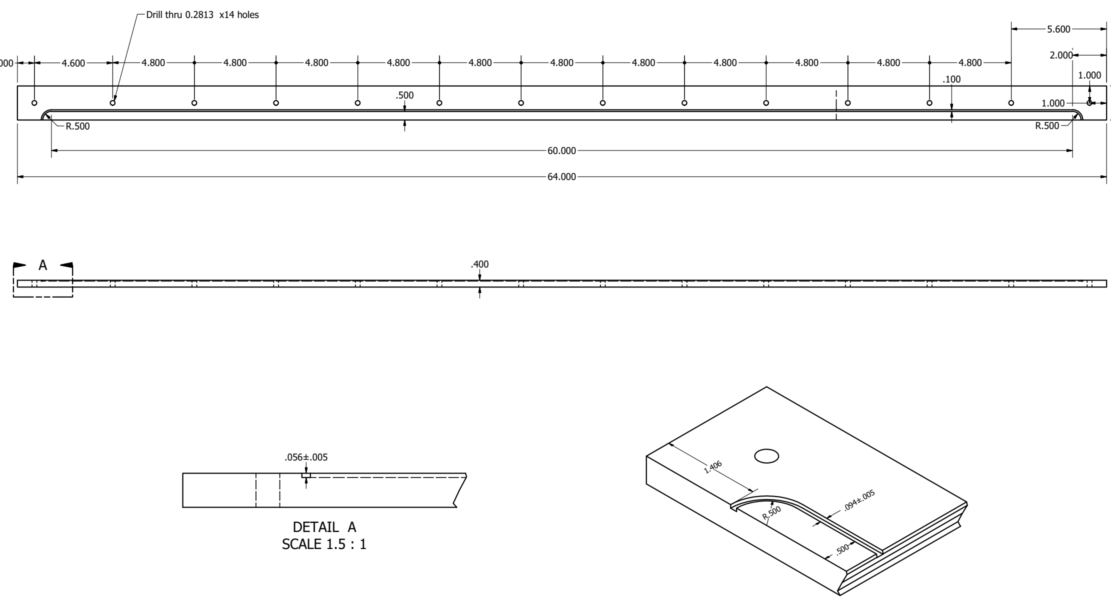
Spacer frame honeycomb plate



0.063" finish aluminum facings
1/4" cell size aluminum honeycomb core
internal 2" aluminum bar frame
epoxy adhesive
±0.003 tolerance

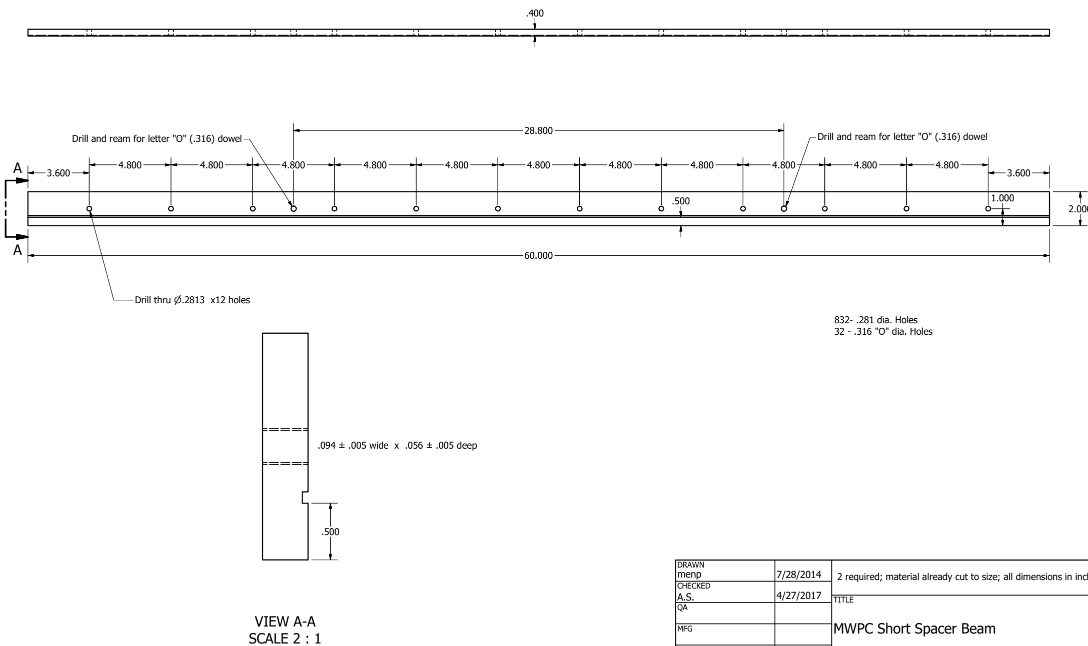
DRAWN menp	1/15/2016	
CHECKED		TITLE
QA		Top Honeycomb Plate
MFG		
APPROVED		
		SIZE C — DWG NO Honeycomb plate (c'bore) — REV
		SCALE — SHEET 1 OF 1

Spacer frame slats



DRAWN menp	7/28/2014	2 required; material already cut to size; all dimensions in inches.
CHECKED A.S.	4/27/2017	TITLE
QA		MWPC Long Spacer Beam
MFG		
APPROVED		
		SIZE C · DWG NO Spacer beam long · REV 3
		SCALE · SHEET 1 OF 1

Spacer frame slats



DRAWN menp	7/28/2014	2 required; material already cut to size; all dimensions in inches.
CHECKED A.S.	4/27/2017	TITLE
QA		MWPC Short Spacer Beam
MFG		
APPROVED		SIZE C · DWG NO Spacer beam short · REV 3
		SCALE · SHEET 1 OF 1