

Fabrication and implementation of compact, low-power, three-dimensional,
Cockcroft-Walton photomultiplier tube power supplies

by

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Abstract

A photomultiplier tube high-voltage power supply was constructed using a "Free-Form" method of fabrication. The main goal of this project was to benchmark the performance of an experimental additive manufactured high-voltage power supply that is currently being investigated at Kansas State University. This is achieved through the comparison of non-traditional methods and material to traditional materials of the same circuit in a similar oriented geometry. A printed circuit board layout was considered to be insufficient for comparison due to the large differences in geometry compared to the 3-dimensional additive circuit. The method used to provide high-voltage and proper dynode stage biasing was a half-wave Cockcroft-Walton voltage multiplier. The 3-dimensional orientation was achieved through the Free-Form process with surface mount devices connected end-to-end or stacked together to form 3-dimensional shapes using temporary scaffolding and supports. This construction method used a low component-count design that was developed in an earlier phase of the project. The Free-Form method along with the previously designed circuit helped achieve a minimal package footprint while offering reliable biasing to the dynode stages.

This work includes an in-depth description of the Free-Form construction methods used to produce the 3-dimensional circuit along with electrical characteristic testing, and spectral analysis results. A comparison for size and weight was made between the prototypes and the commercially available E11807-01 resistive divider base. A performance comparison was made using an external +5V supply for the prototypes and an external NHQ 103M high-voltage power supply for the E11807-01. The electrical characteristic measurements included dynode stage voltages, photocathode regulation, photocathode voltage stability, and power consumption. Spectral analysis was conducted using the following check sources, ^{137}Cs , ^{60}Co ,

and ^{22}Na . The prototypes and the E11807-01 were tested using a CsI(Na) crystal attached to an R11265U series photomultiplier tube.

A total of two prototypes were produced using the Free-Form fabrication method. The final bulk dimensions for prototype A are 2.99 x 2.78 x 0.75 cm with a weight of 7.73g. Prototype B's final bulk dimensions are 2.98 x 2.77 x 0.87 cm with a weight of 8.7g. The final dimensions of the additive manufactured printed experimental power supply that is being benchmarked are 2.99 x 2.77 x 0.65 cm with a weight of 8.36g. A 38.8% reduction in volume and a 34.7% reduction in weight was achieved through the Free-Form fabrication method when compared to the E11807-01 resistive divider. The photocathode voltage regulation values about its set point achieved for each prototype were +0.36% -0.60% for prototype A, +0.35% -0.83% for prototype B, and $\pm 0.68\%$ for the printed prototype. The maximum power consumption of each prototype while driving the photomultiplier tube were 53.41 mW for both prototype A and B and 69.53 mW for the printed prototype. The energy resolution's measured for the full Cs-137 energy peak using a CsI(Na) crystal were 6.949% for prototype A, 7.851% for prototype B, 6.93% for the printed prototype, and 6.855% for the E11807-01.

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Dedication

This work is dedicated to my mother, Tammy Phalen, my late father Michael Tompkins, along with my brother and twin sister, Christopher and Jessica Tompkins. Thank you for your continued support throughout the years.

Chapter 1

Introduction

1.1 Motivations

A research team at Kansas State University has been developing and constructing a high-voltage power supply (HVPS) for the Hamamatsu R11265U series photomultiplier tube (PMT) through several non-traditional techniques. The circuit design for the HVPS being constructed was developed in previous work conducted by the research team. In that work, several circuit revisions were made to reduce the component volume and optimize the high-voltage output and regulation using a Cockcroft-Walton (CW) voltage multiplier to supply voltage to the PMT.² A prototype constructed using a PCB was used to verify functionality prior to the start of the non-traditional circuit development.

A major design consideration of this HVPS circuit was its utilization of multi-axis orientation through the use of three-dimensional (3D) construction techniques. Moving from a two-dimensional (2D) design to 3D provides several benefits and advantages. One benefit is a total reduction in the volumetric footprint of the circuit. This allows for larger circuits to fit into smaller packages which increase the mobility of devices like the gamma ray spectrometer discussed in this paper. The addition of alternative 3D component connection traces is another benefit that reduces the need for long planar trace lengths and vias between com-

ponents. The non-traditional nature of the construction methods used allow for the removal of PCB layers, PCB vias, and interconnections. The removal of these sections, common on PCB, allow the packed electronics to accommodate irregular free space and achieve organic system form factors. Organic system form factors include any non-planar surface of a system assembly that would restrict other traditional fabrication methods.

The newly emerging capabilities of electronics using a 3D design and fabrication methods allow for a focus on reductions in size, weight, and power consumption (SWaP). The size and weight can be reduced through the optimization of electrical component orientation allowing a tighter packaged design with a reduction in the resulting chassis size and total weight. The possible orientations for the circuit design are increased with the addition of the third dimension which can be adapted to many use case scenarios. The power consumption can be reduced through the use of a compact 16-stage half-wave CW voltage multiplier circuit design with 3D orientation in mind. The CW is comprised of capacitors and diodes that provided boosted voltages along its stages while keeping low output current with good linearity for both DC and pulsed currents.³ A non-traditional circuit fabrication method using additive manufacturing is currently being investigated at Kansas State University with an additional fabrication method named Free-Form (FF), which uses solder and wire, being constructed to provide a benchmark to the performance of the non-traditional methods and materials.

The details in the work presented show an overview of the construction of a non-traditional circuit, the verification of the HVPS, the comparison of performance between a FF circuit and an additive manufactured printed circuit, and a comparison to a commercially available resistive divider developed for use with the R11265U PMT.

1.2 Prior Work

The utilization of a CW voltage multiplier to provide a PMT with the voltage required to operate has been implemented in various research and design projects. An early example is a base designed and constructed by a research team from Indiana University to be used with a FEU84-3 PMT.⁴ The base consisted of multiple PCB boards that were placed within a 3.8 cm diameter by 15.5 cm in length cylindrical housing. The 14 stage CW ladder provided voltage to 12 dynode stages while using a supply voltage of 15-16 V. The base was capable of reaching a photocathode voltage of 2023 V while consuming a maximum of 150 mW of power.⁴ Their design used traditional circuit construction methods which are not optimized to reduce overall SWaP of the final assembly. A low powered high voltage base for the KM3NeT deep sea neutrino telescope was developed by a research team at Nikhef. Their circuit used a basic CW voltage multiplier to run a 10 stage PMT while under restrictions to the size, load, voltage range, and ripple. The prototype was developed using traditional methods with the circular PCB boards having a 38 mm diameter.⁵ The sizing and operational constraints introduced initial SWaP reduction but the restrictions of traditional circuit design and construction impede further optimization. Progress for further reductions in SWaP were made by researchers from the Idaho National Engineering and Environmental Laboratory. A prototype CW board was developed to drive two PMTs using a basic CW voltage multiplier.⁶ The board took into account the components sizes and allowable operational parameters to enable the device to be hand held and battery operated. Low current was required to reliably run while using a battery along with the need to be small in size to aid in mobility and ease of use while hand held. These goals were achieved through the benefits of a CW ladder.⁶ The prototype was constructed using traditional methods with the final circuit placed on a PCB board like the previous examples. Further reduction in the SWaP of the circuit were achieved with the supply current measured to be less than 15 mA at a 4-6V input resulting in a max power consumption of 90 mW and the final dimensions being 25.4 x 88.9 mm.

All of the designs discussed above use a CW ladder to drive a PMT with the final circuits using PCB boards to function properly. The development of a similar circuit without the use of PCB boards has been in development by a group of researchers at Kansas State University for several years. The research team focused on designing a HVPS for use on an R11265U series PMT with the implementation of multi-axis circuit construction using additive manufacturing (AM) techniques. Several prototype variations were developed with the main goals of the finalized design being an optimized CW to supply dynode stage biasing, minimized volumetric size of the final circuit, and low power consumption at increased radiation count rates.²

1.3 Construction Goals

The main goal of the work presented include benchmarking the performance for an additive manufactured HVPS that is currently being investigated at Kansas State University. An additional goal was the construction of a fully functional HVPS using a CW voltage multiplier to drive the Hamamatsu R11265U PMT using a non-traditional construction method that reduce overall SWAP. The goal of the performance benchmark is to provide a comparison of the results between non-traditional methods and material of the additive manufacturing fabrication method to traditional materials of the same circuit in a similar oriented geometry using the FF fabrication method. A printed circuit board layout was considered to be insufficient for comparison due to the large differences in geometry compared to the additive circuit. These main goals along with fabrication restrictions include:

1. The non-traditional construction technique must consist of known and proven material to make the final FF circuit. Solder and wires are the approved materials for electrical connections. These serves as a comparison to the unproven materials used to make connections in the additive manufactured circuit.
2. The final stage of the CW voltage multiplier must reach between -700 to -1000 V to properly drive the PMT. The final set points range between -800 to -900V based on

the voltage used in the data sheet for the PMT.¹

3. The voltage bias on the 12 dynode stages must follow the voltage distribution ratio provided in the Hamamatsu R11265U Series data sheet. The voltage distribution ratio comes from the E11807-01 tapered divider socket assembly.¹
4. The final HVPS prototype must achieve reductions to the size, weight, and power consumption, even during low to high count rate environments.
5. The final device must fit within the recessed connection cavity on top of the PMT with little addition to the total height of the detector.
6. The energy resolution achieved by the HVPS must show no degradation to the intrinsic resolution typical for a CsI(Na) scintillator.

1.4 Main Contributions

The construction and verification of non-traditional high-voltage power supplies using electrical characteristic and gamma ray spectroscopy has made the following key contributions to the field of nuclear science:

1. A performance benchmark between an additive manufactured circuit using non-traditional materials to a similar 3-D oriented circuit using traditional material.
2. Developed a hybrid process to fabricate 3-dimensional circuitry to fit organic system form factors using proven material.
3. An operational R11265U series photomultiplier tube using a Cockcroft-Walton voltage multiplier and a non-traditional construction method using proven materials.
4. Proven electrical performance of the high-voltage power supply and performance for gamma ray spectroscopy.

Chapter 2

Background and Phase 1

2.1 Cockcroft-Walton Voltage Multiplier

The Cockcroft-Walton (CW) voltage multiplier is a well known circuit technique used to multiply direct current (DC) voltages using an alternating current input. This multiplication technique was developed by expanding upon the prior invention of a voltage doubler developed by Heinrich Greinacher⁷. The expansion on the voltage doubler took place in 1932 by John Cockcroft and Ernest Walton and was used to power a particle accelerator. Their multiplier stood 12 feet high reaching potentials over 700 kV with protons having energies of up to 710 kV⁸. The 1951 Nobel prize in Physics was awarded to both men for their work with the newly named Cockcroft-Walton voltage multiplier. Further expansion on this technique was made in 1976 by John Dickson where a "charge pump" circuit operating on clocked pulses was implemented converting the circuit into a DC-to-DC multiplier⁹. The CW voltage multiplier can come in two main configurations depending on the speed desired for multiplication. These configurations are the half-wave and full-wave with the main differences being that the full-wave requires more components, but uses both the positive and negative segments of the AC wave to double voltages faster¹⁰.

2.2 Photomultiplier Tubes

The ability to make measurements using light through light detection technology provide unique advantages over other detection methods³. Some advantages include the analysis of material or substances through nondestructive means, high detectability, and high speed properties. Many different fields benefit from this type of technology including medical diagnosis, biotechnology, and spectroscopy³. Light detection devices can be split between three categories which include the external photoelectric effect, internal photoelectric effect, and thermal. The external photoelectric effect is when electrons are emitted from the surface of a material when struck by light under a vacuum. The PMT utilizes this effect with wide use in medical and analytical instruments³.

The photomultiplier is a versatile type of detector used for the radiant energy in the electromagnetic spectrum range between ultraviolet and near infrared^{11;12}. A PMT operates on the basis of accelerating electrons through stages to achieve a sizable gain at the anode producing a measureable current. A typical PMT consists of a photocathode, dynode stages, and an anode with the entire assembly contained in a glass envelope under high vacuum¹³. This works through the emission of photoelectrons from the photocathode. These photoelectrons are accelerated and focused through an applied electric field into dynode stages. For each incident electron, several secondary electrons are emitted from the dynode. This emission of secondary electrons is repeated for each successive dynode stage. The secondary electrons emitted from the final dynode stage are then collected by the anode.¹ The typical amount of dynode stages for a PMT ranges from 10 to roughly 20¹³. A sizable gain of around 10^6 is achieved when the electrons reach the anode resulting in a measurable current signal^{11;13}.

The discovery of the photoelectric effect was made by Heinrich Hertz in 1887 providing evidence that there was a way to produce electrical signals from individual photons of light¹³. Later in the year 1935 members of the RCA, Iams and Salzberg, produced the single stage PMT and in 1936, RCA members Zworykin, Morton, and Malter produced a multistage

PMT¹¹.

2.2.1 R11265U Series and E11807-01

The R11265U series PMT is produced by Hamamatsu and is listed to be compact and light weight.¹ This model does not include a resistive divider circuit and has bare pin connections to the internal dynode stages. The divider socket assembly is sold separately with a choice between the E11807 standard divider and the E11807-01 tapered divider. The difference between the standard and the tapered divider is that the tapered divider's interstage voltage is increased in the latter stages. This is done to improve pulse linearity by helping overcome space charge effects that occur due to an increase in electron density between the electrodes caused by an increase in incident light. Numerical values for the voltage distribution ratios can be found in Table 2.1. Due to abundance of linear stages providing a better match

Table 2.1: *Voltage distribution ratio of the Standard and Tapered divider type for an input of -900 V.¹ The value of 3.3 under Dy1 for the tapered divider represents a ratio of 1:3.3 between K and Dy1. K: Cathode, Dy: Dynode, P: Anode*

Stage	K	Dy1	Dy2	Dy3	Dy4	Dy5	Dy6	Dy7	Dy8	Dy9	Dy10	Dy11	Dy12	P
Standard		2.5	1.3	0.8	0.8	1	1	1	1	1	1	1	1	0.5
Tapered		3.3	1.6	1	1	1	1	1	1	1	1	1	2.7	1.3

for the linear multiplication of a CW voltage multiplier, the E11807-01 tapered divider was chosen as the circuit for comparison in the designed circuit.²

The E11807-01 socket attaches directly on the top of the PMT inside a recessed region using the aid of a center pedestal. The pedestal acts as both a guide and structural support so both parts come together in the proper orientation. The PMT and tapered divider are depicted in Figure 2.1. The divider socket has two wires coming out of the opposite side that end in BNC connections. The red wire is used to connect to a HV supply and provide the divider with the HV used to drive the PMT. The black wire is connected to the anode and is designated as the signal output of the PMT. The internal connection pins on the E11801-01



(a) R11265U series PMT



(b) E11807-01 Voltage divider socket

Figure 2.1: The R11265U series PMT and the E11807-01 Tapered divider socket assembly. The center pedestal is shown on the PMT along with the key inside the E11807-01 for proper alignment and structural support. Golden connection pins attach the divider socket to the exposed pins on the PMT.

match up to the bare connection pins on the PMT. These lead to the photo-cathode, dynode stages, and anode of the PMT with a pin layout shown in Figure 2.2.¹

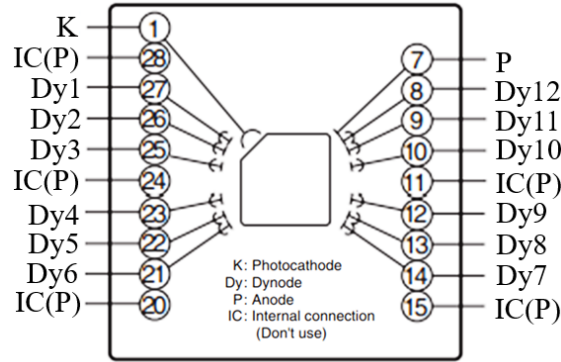


Figure 2.2: The pin layout for the R11265U series PMT showing the locations of the photo-cathode, dynode stages, internal connections, and anode.

2.3 Gamma-ray spectroscopy

The current pulse produced at the anode of the PMT can be used to take measurements for scintillation counting and gamma-ray spectroscopy. Some form of processing is typically applied to the raw signal to translate the current pulse into useful data. A common method

is to shape the pulse in a way where the pulse height is proportional to the detector pulse amplitude¹⁴. The pulse shaping process typically begins with feeding the raw pulses from the detector system into a preamplifier. This allows for the pulses to be extracted from the detector without degrading the intrinsic signal-to-noise ratio as long as the preamplifier's circuits are set with the detectors characteristics in mind¹⁵. Pulse shaping is then implemented in a different module without the restriction of needing to be in a relative close proximity¹⁵. Detectors, like the PMT, that produce relatively large signals in their outputs relaxes restrictions of noise contribution in the preamplifier and charge integration of the pulse at the detectors output and can be performed using inexpensive models such as a Model 113 or a Model 142IH¹⁵. Traditional methods implement an analog module, typically a shaping amplifier, to shape the charge integrated pulses from the preamplifier into a Gaussian shape. The height of the shaped pulses can then be read by a multi-channel analyzer to perform spectral analysis. More recent methods take in the preamplifier pulses and directly digitize them using a digitizer. These digitized pulses can then be processed with specific quantities of interest being extracted.¹⁶ The digital approach allows for the added benefits of accountable pulse-by-pulse differences, analysis of transient induced charge signals, reduction in dead time to hundreds of ns, and more¹⁶.

2.4 Circuit Design

The circuit designed during phase 1 by a previous research team at Kansas State University operates on a feedback loop with the PMT being supplied with high-voltage through the different stages of a half-wave CW ladder. The CW voltage is regulated through a set of electrical components with a micro controller altering the input stage of the CW ladder. The alteration on the input is carried through the ladder with the final stage being monitored as the feedback back into the micro controller. The full circuit can be seen in Figure 2.3 and is then split into several sections with more detail on their functionality and relation to one another being described below.

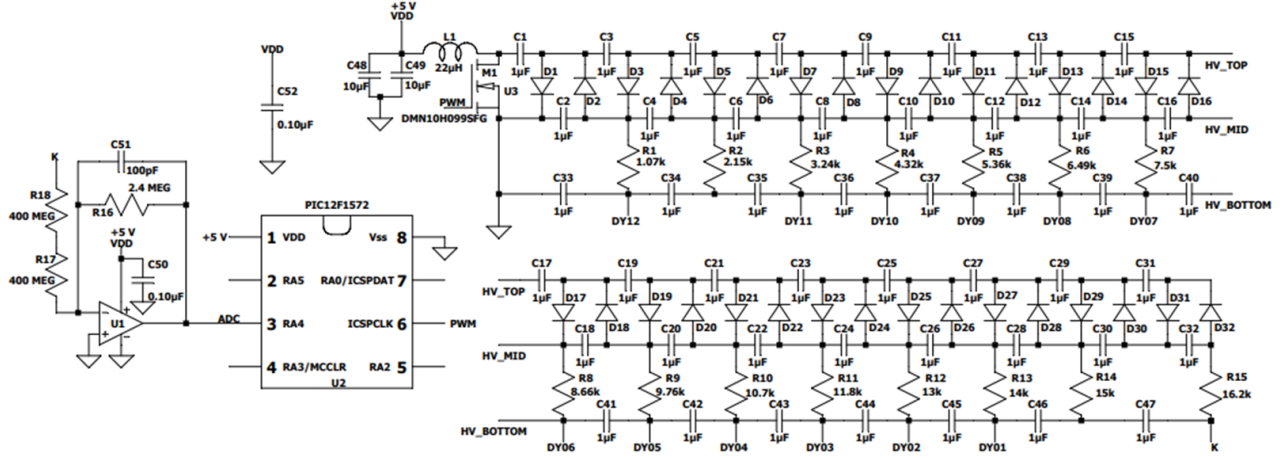


Figure 2.3: A full circuit diagram of the designed HVPS. Efforts were made to reduce the total amount of components needed to be placed, while keeping future 3D implementation in mind. The total number of components is 106.

2.4.1 Designed Front-End Feedback

The Front-End (FE) feedback section of the circuit shown in Figure 2.4 consists of 8 total electrical components with the main two being a micro-controller (MC) and an inverting operational amplifier. The HV from the final stage of the CW ladder is represented by the letter K and passes through the two 400M Ω resistors. These resistors connect into the inverting operational amplifier which feed into the ADC of the MC. This voltage being monitored as the feedback is compared to a coded set point. This comparison between the measured feedback voltage and the set point produces fluctuations in the duty cycle of a pulse-width modulation (PWM) produced by the MC.

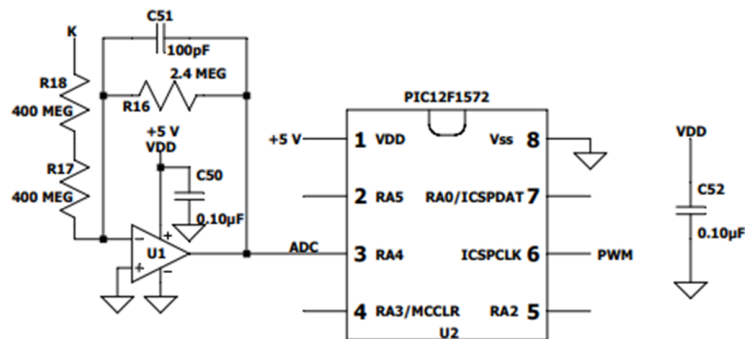


Figure 2.4: A circuit diagram of the feedback section of the HVPS. The Front-End feedback monitors the final CW stage voltage and regulates it around a specified set point.

2.4.2 Designed High-Voltage Supply

The fluctuation of the duty cycle produced from the feedback circuit feeds into a subsection of the HV supply circuit named the charge pump. The charge pump is shown in the top left of Figure 2.5 and includes 4 total electrical components which include two capacitors, an inductor, and a MOSFET. The PWM continuously flips the gate of the MOSFET at a fixed frequency of 151 kHz. The MOSFET causes the connected inductor to charge through the constant switching and results in large oscillatory current spikes to pump into the CW ladder. These oscillatory spikes provide the required AC voltage for the CW ladder to operate.

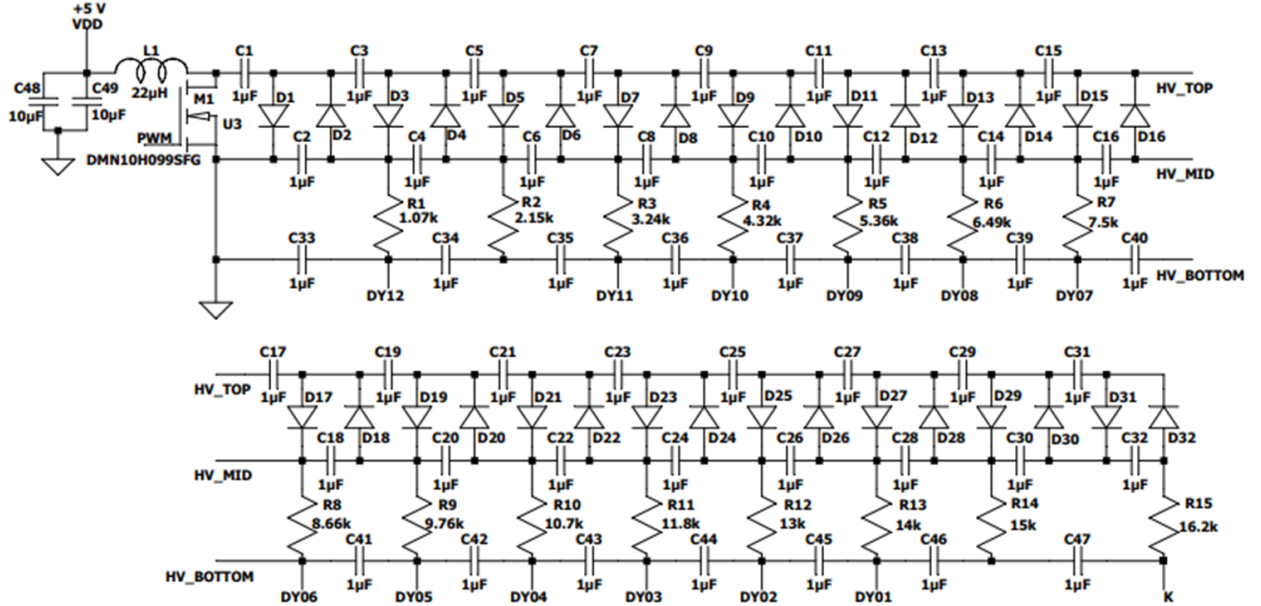


Figure 2.5: Circuit diagram of the high-voltage supply and charge pump. Includes the Cockcroft-Walton voltage multiplier and the charge pump attached to the first stage of the voltage multiplier.

The AC voltage applied by the charge pump enters the start of the CW ladder which is multiplied by each following stage. The voltage is multiplied through 16 total stages with the final stage voltage being connected to the feedback circuit through the two 400M Ω resistors. Of the 16 total stages, only 13 are used to provide the desired voltage biasing to properly run the PMT. The stages that are used for dynode biasing branch off into a line

of capacitors through different resistors that increase in their values the further up they are in the ladder. These additional resistors and capacitors filter and reduce voltage ripple that would degrade the signal produced in the PMT.² The points labeled DY12 and K have a separation of one CW ladder stage between other dynode stages to better fit the voltage distribution ratio of the tapered divider specified in the R11265U series data sheet.¹ The charge pump and the filtered CW ladder can be seen in Figure 2.5.

2.5 Additive Manufactured Circuit

Researchers at Kansas State University have been investigating the fabrication of a 3D circuit using additive manufacturing techniques. The HVPS circuit described above kept the end goal of additive manufacturing in mind with the next phase being the implementation of additive techniques to build the final power supply.² The fabrication methods implemented include the use of fused deposition modeling (FDM) to print the foundation material and the extrusion of conductive paste to produce the traces and connections between components.¹⁷

To construct an additive manufactured circuit with the desired parameters, specialized equipment was required. The nScript 3Dn-300 system was chosen based on its printing and 3D manufacturing abilities. The 3Dn series is described to be a factory in a tool that is advertised to be a high-precision motion platform for 3D manufacturing. The internal gantry platform consists of 1-5 tool heads with high-precision motors capable of 10nm resolution and up to 1 micron accuracy.¹⁸ The tool heads and internal equipment included on the 3Dn series are a hot end nFD pump, SmartPump 100, Real-Time Processing View, nScan Surface Mapping, UV Spot Curing Source, Pick and Place, and a milling bit.¹⁸ A picture of the 3Dn-300 system is shown in Figure 2.6.

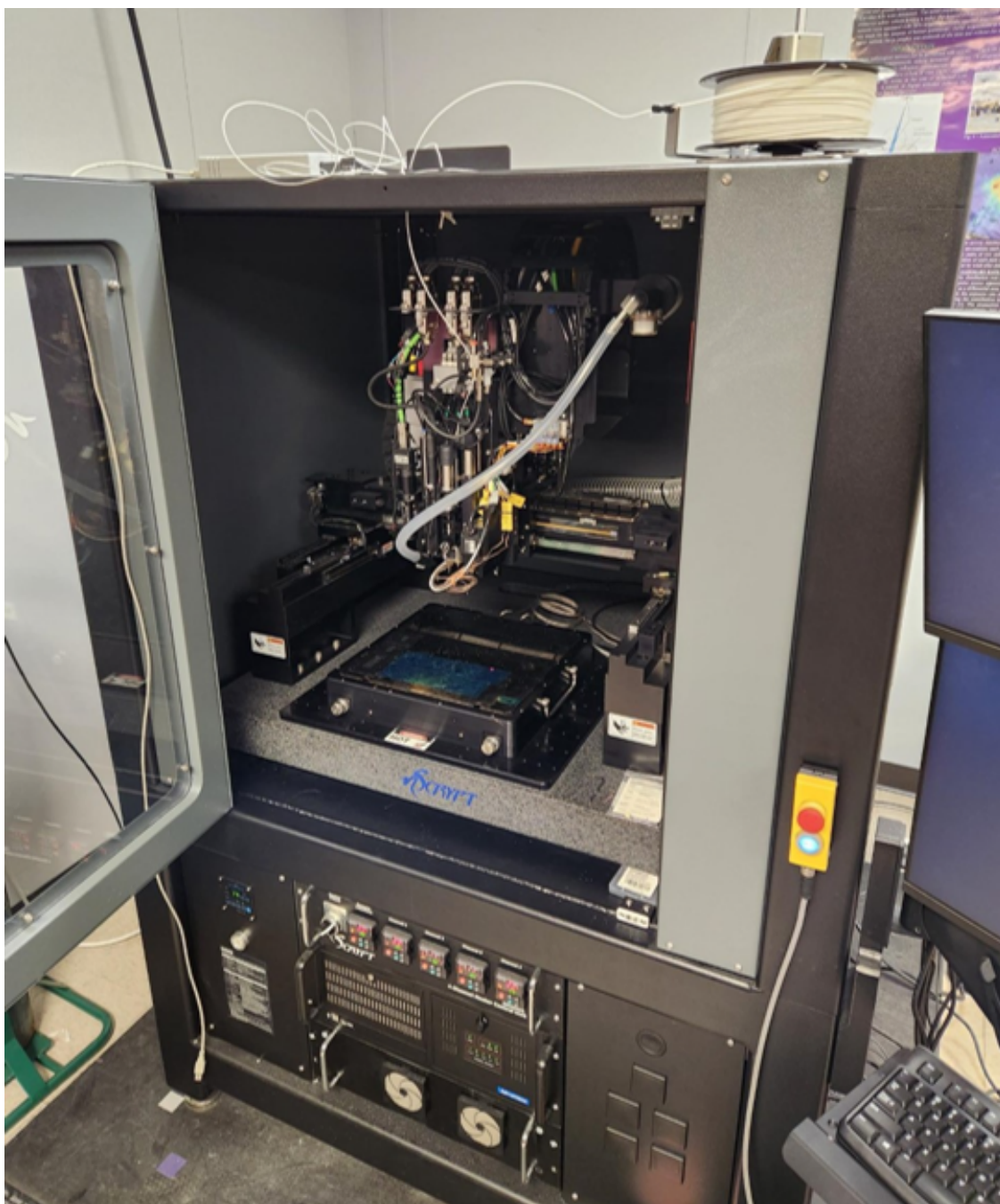


Figure 2.6: *The nScript 3Dn-300 system with a view of the gantry system with tool heads.*

The additive manufactured circuits were constructed alongside the Free-Form circuits. Each construction method used the same circuit described in section 2.4 along with the same electrical components. Any limitations or changes to the selected electrical components caused by shortages during COVID were applied to both construction methods to keep the comparison between the two consistent. An example of an additive manufactured printed HVPS prior to being placed in its printed enclosure is shown in Figure 2.7.¹⁷

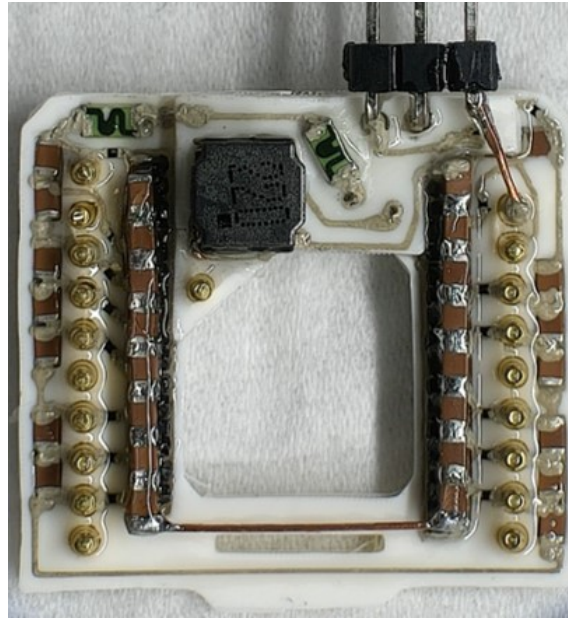


Figure 2.7: *Top down view of a printed prototype prior to being enclosed inside a printed housing.*

Chapter 3

Free-Form Construction Methods

3.1 3-dimensional circuit design

The circuit that was designed took 3D construction into consideration, but was verified using traditional methods on a PCB board. To transition to a non-traditional method, the circuit needed to be split into separate subsections that could be attached directly to each other once oriented properly. The method of connecting circuit components directly to each other is reminiscent of the point-to-point construction method commonly used prior to the use of PCBs. Point-to-point construction used the leads off of components to bridge between connections to reduce the need for additional wires. A modern example of this technique shows up in terminal strips or turret board's where the circuit is soldered to an electrical assembly.¹⁹ A more artistic and modern approach, similar to point-to-point, goes by the name of "Dead-Bug", "Air Wired", or "Manhattan Circuits". This style of circuit construction implements shorter connections by soldering directly between components or to a copper plate without the use of a PCB.²⁰ Additive manufactured circuit fabrication is being investigated to fabricate a form-factor free device system that implements 3D electronic to free-standing structures.²¹ Taking inspiration from these different circuit construction methods, temporary scaffolding was implemented to provide support to build up the 3D circuit where only proven materials could be used to make the connections. This construction method using

sections built off temporary supports was named Free-Form due to the implementation of a form-factor free design where electrical components were connected directly to each other and short lengths of wire were used to make longer interconnections. The first of these subsections built using the FF method was the CW voltage multiplier which was made into a sub-assembly hybrid component. This hybrid component was then used as the main structure to build the FF high-voltage supply circuit. The Front-End feedback and charge pump were the last subsection to be built using another form of temporary support in the form of alignment stencils. All of the sections were then placed in their final orientation and connected together resulting in the fully assembled FF HVPS.

3.2 Free-Form High-Voltage Supply Construction

The HV supply circuit section is a combination of CW voltage multipliers, filtration , and alignment pin connectors. Each of these subsections was built off of the previous stage using temporary scaffolding structures that consisted of rigs that would hold the parts in place and keep component spacing consistent while connections were made. Some rigs used heat resistant materials in the areas near where solder paste is dispensed and reflowed. The desired FF HV supply design and placement within the PMT is shown in Figure 3.1.

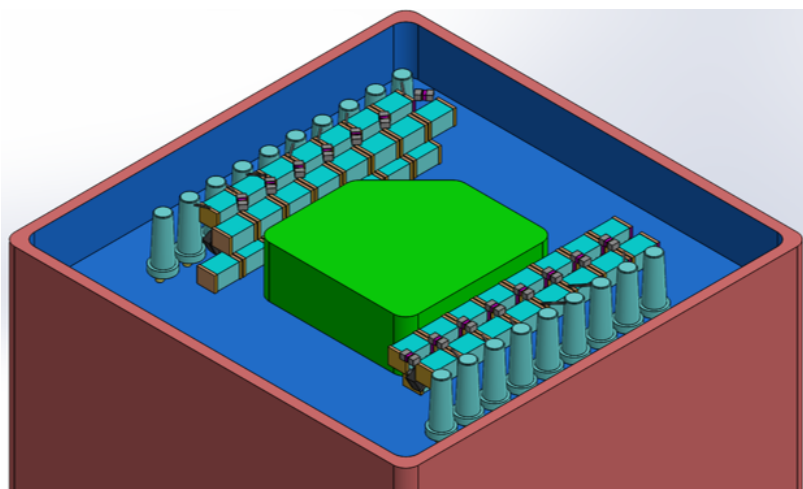


Figure 3.1: *The desired placement within the PMT for the high-voltage supply circuit. The space between the external pins and the central pedestal was used to improve volume utilization.*

3.2.1 Hybrid free-form Cockcroft-Walton Ladder

The half-wave CW ladder was designed to use itself as the scaffolding. Components were placed on top of one another and attached creating a voltage multiplier that could be treated as a single component. The FF CW voltage multiplier was labeled as hybrid part and was held in different orientations to act as a foundation to build off of to form sub-sections of the final circuit.

The ladders start as two lines of eight 0805 capacitors placed end-to-end inside channels of an aluminum rig to keep the spacing between capacitors consistent and to keep each line straight. Solder paste was used to connect the ends of the capacitors which provided structural integrity for diode placement. A line of capacitors being connected is shown in Figure 3.2. An MPP1 model manual pick-and-place machine from FORTEX was used to place the

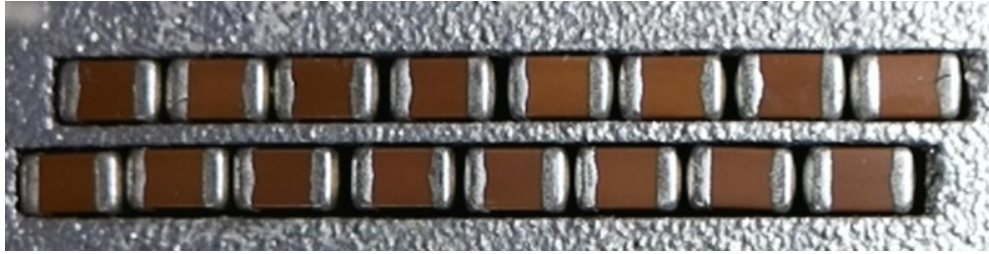


Figure 3.2: *Two lines of capacitors are placed inside channels of an aluminium rig to keep their shape constant.*

capacitors along with the 0402 diodes in the proper orientation to provide negative voltages on the increasing stages. A small amount of additional solder paste was dispensed on the connected capacitors to provide some adhesion for the diodes to stay in their respective places. This additional solder used with the previously connected capacitor lines allowed for the reduction of solder required to make the connections. Too little solder paste resulted in disconnections or misalignment of parts while excess solder resulted in shorts. A total of 16 diodes were placed to complete each hybrid CW ladder. After reflow, each ladder was visually inspected using the built in camera on the MPP1. Any flawed connections were manually adjusted, cleaned, and reinspected. The hybrid CW ladder was then removed from

the rig, cleaned thoroughly, and verified using a digital multi-meter at each diode.

Each hybrid ladder could provide 8 of the 16 stages needed to drive the PMT. This required two hybrid ladders for each HVPS with the ends connected to provide the increasing voltages at each stage between the two ladders. The reason for splitting the ladder into two sections was due spacing restrictions and dynode connection placement. The length of the full 16 stage ladder causes issues with the spacing within the recessed connection region on the PMT. Splitting the ladder in two allowed for better utilization of the space available while also placing the ladder stages closer to their respective dynode stage. The distance required to connect the ladder stages to their dynode stages was reduced to allow room for future filtration. A figure showing a finalized CW ladder is shown in Figure 3.3



Figure 3.3: *An eight stage CW hybrid ladder makes up half of the total 16 stage CW ladder required to run the PMT.*

3.2.2 High-Voltage filtration

The filtration for the CW ladder was optimized to have a cutoff frequency of 150 Hz at each connection to the dynode stage. This was accomplished by increasing resistor values along the ladder as the capacitance to ground decreased.² The reasoning for the inclusion of the filtering section was to further reduce additional ripple that is present in the voltage supplied to the dynode stages and to improve signal quality².

The filtration was constructed using the CW ladder hybrid component as the foundation along with temporary scaffolding used to hold parts in their place during connection. The

temporary scaffolding was made out of highly thermal resistant epoxy molded in the shape of a shallow trench used to hold capacitor lines and a deeper cavity used to hold the hybrid ladders on its side. Small 0402 sized resistors of varying values branch off from specific stages of the CW ladder and connect to another line of capacitors using solder paste. This secondary line of capacitors was constructed using the same aluminum rig used for the ladders. One hybrid CW ladder section contains 8 filter capacitors while the secondary hybrid ladder has 7 filter capacitors making up the 15 total required. The resistors were placed individually with their pads directly on the capacitors to form component-to-component connections minimizing the size and distance between parts. Parts were visually and electrically inspected for shorts and disconnections after all solder connections were made. An example of a pair of ladders with added filtration is shown in Figure 3.4. After validation, the temporary scaffolding was removed and the sub-section moved onto pin alignment and branching between the split ladders.

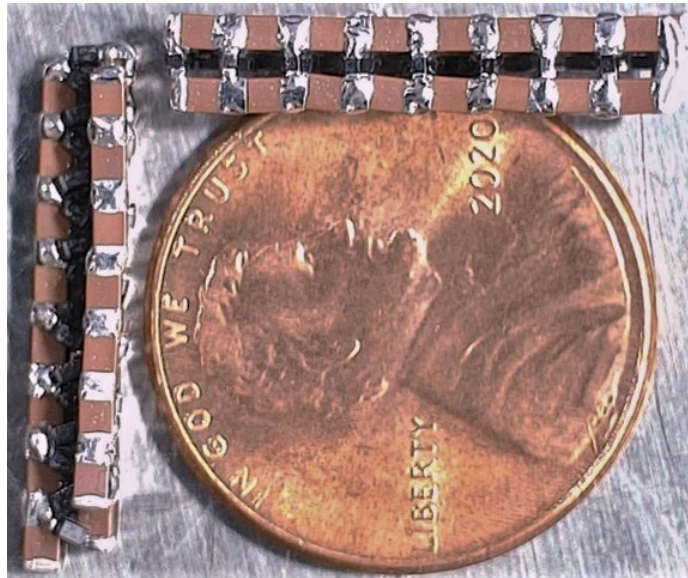


Figure 3.4: *A pair of CW ladders with resistors branching off select points to another capacitor line acting as filtration. This filtration reduces ripple and improves signal quality. A penny is used for a size comparison*

Another temporary support structure was used along with a slightly modified E678-19K pin alignment socket. This temporary support was also made using high temperature resistant epoxy and holds the ladder parallel to the pins with the filter capacitors branched

out at a 90° angle. The modified E678-19K socket had a side removed for better support placement and removal. The two ladder sections were placed and individually connected directly to the gold plated pins. Most of the connections were component-to-pin with little to no space between contact points. Several pins had longer distances to their respective capacitor and small copper wires were used to make the extended connections. After a visual inspection, the temporary supports were removed and the modified E678-19K alignment socket served as scaffolding holding the HV supply circuit in its final orientation. A layout for each pin on the aligned FF high voltage supply is shown in Figure 3.5.

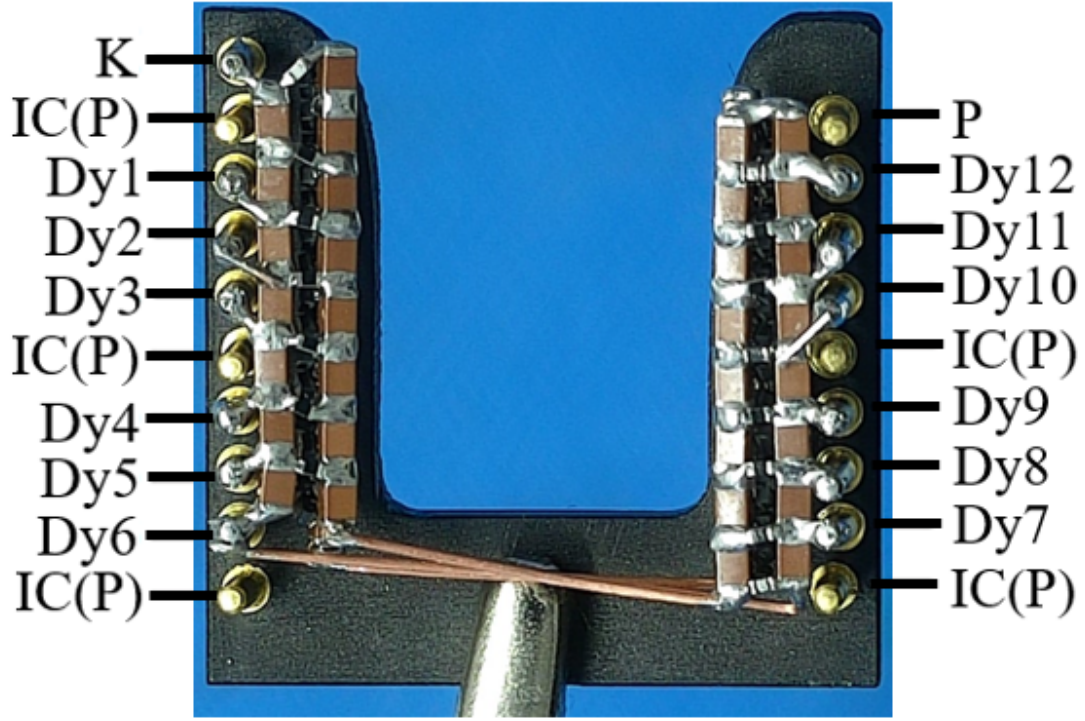


Figure 3.5: *The CW with filtration connected to the proper connection pins using an alignment pin socket for the R11265U series PMT.*

With the socket holding the high-voltage supply section in place the bottom ends of the ladders were connected to form a split full 16 stage ladder. Three copper wires were cut to length and attached to the top and bottom capacitors that make up the sides of the CW ladder and to the filter capacitor line. Another set of visual and electrical verification checks were taken using a digital multi-meter to ensure no accidental reflow occurred to the diode

and filtration connections. An example of a fully connected and verified high-voltage supply circuit is shown in Figure 3.6. All the temporary scaffolding used for the RC filtration

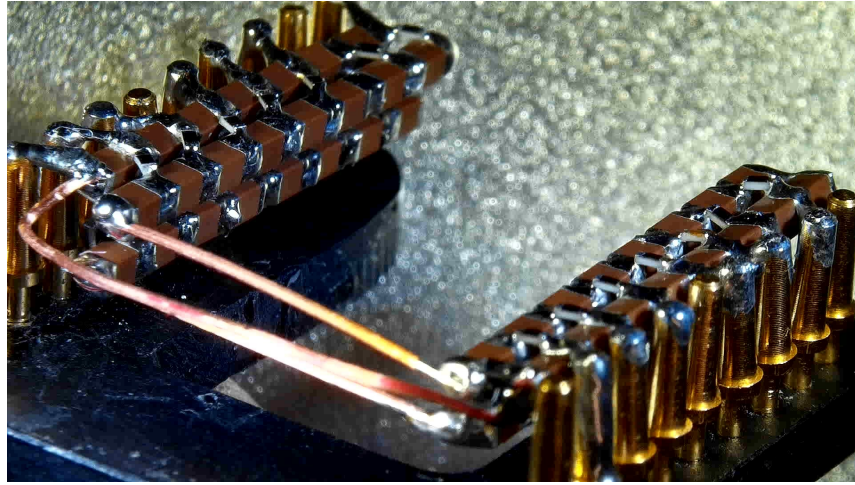


Figure 3.6: *An angled view of a verified FF high-voltage supply circuit. This section is now ready for connection to the front-end circuit to make up the HVPS.*

connections, filtered ladder alignment, and pin alignment is shown in Figure 3.7. Due to

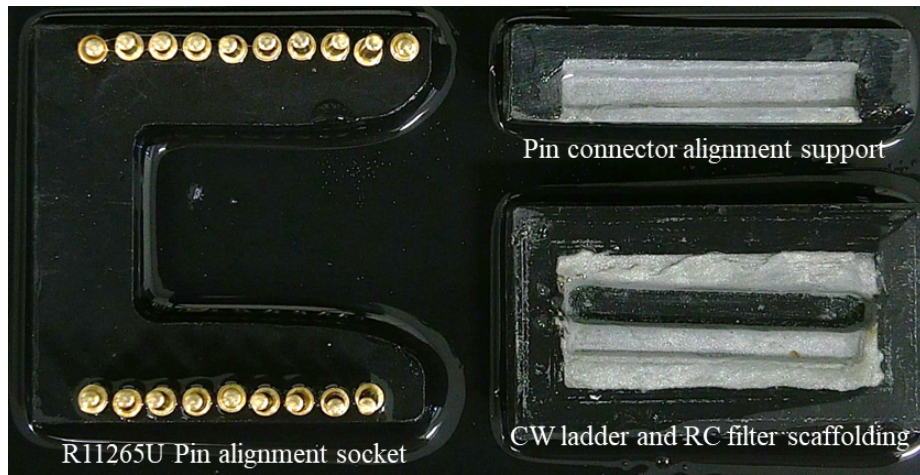


Figure 3.7: *A top-down view of the temporary scaffolding used for RC filtration connection, filtered ladder alignment, and pin alignment.*

the materials used, the temporary scaffolding could easily be remade, molded and shaped allowing for different orientations and multiple connection pathways to be explored.

3.3 Front-End Feedback

The FE feedback circuit was split into several layered subsections to properly fit within the remaining space inside of the PMT which is shown in Figure 3.8. These layers were then stacked and attached to the inductor to produce the full feedback circuit with the inclusion of the charge pump section. The subsection construction stages include the MC to MOSFET, the inverting operational amplifier with feedback resistors, and the charge pump.

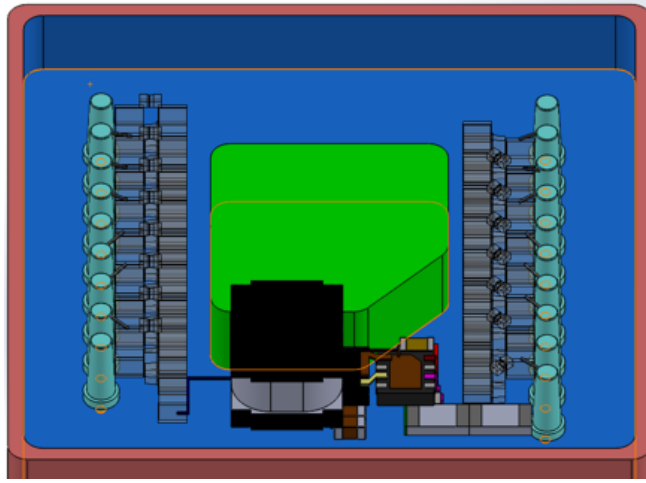


Figure 3.8: *Desired design and placement within the PMT for both the feedback and charge pump circuits.*

3.3.1 Front-End Stencils

The stencils used for the FE were made of thin stainless steel sheets typically used to spread solder paste across a PCB. Shapes were cut into these steel sheets to the size of the electrical components used to make up the sections of the FE circuit. The cut out regions took into account the sizing tolerances for each individual electrical component with the largest stated dimensions being used in the design. The sheet was then cut into smaller square parts with pin holes used for alignment purposes. Multiple square sections have the same design which allow several stencils to be stacked so larger components stay seated in their respective region. A design of the stencil sheet can be seen in Figure 3.9.

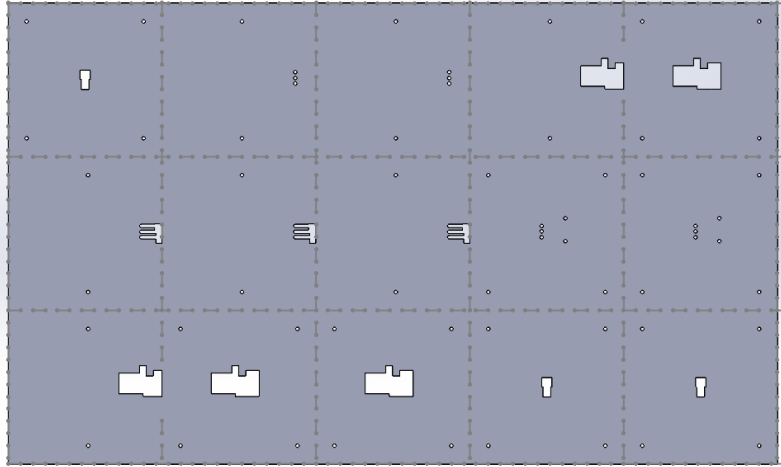


Figure 3.9: *Stainless steel stencils design used to hold the front-end components in place during construction.*

3.3.2 Front-End Micro-controller and MOSFET

The first layer of the FE includes a pre-programmed MC, MOSFET, and two capacitors. Two stencils were stacked on top of each other making a rig that holds all four components in place. A representation of a populated stencil is shown in Figure 3.10. Connections had little to no space between components, but the smaller pad sizes on the MOSFET and MC gave rise to issues using direct connection with just solder paste.

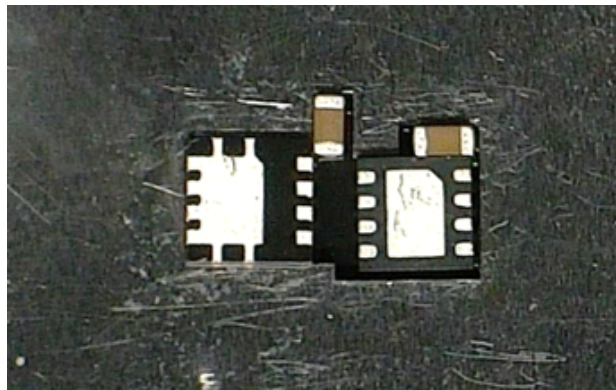


Figure 3.10: *An example of a populated stencil with the micro-controller, MOSFET, and capacitors in their respective locations.*

The implementation of 0.02 mm jump wire was used to improve the quality of connections. This wire was made into custom sized stranded wire able to make the required 3D shapes

to connect each component together. The thickness of the custom stranded wire could be change which eliminated accidental shorts between close connections commonly observed when using 27 AWG solid copper wire. The final diameter of the custom stranded wire was measured to be 0.43 mm in diameter or 28 AWG stranded wire. The process starts with a section of the custom wire being measured, shaped, and attached to the desired pads. The grounding between the components was connected through the large middle pad on the MC to reduce grounding issues. A set of thinner wires was connected to the MC pads required for programming. This allowed for updated code to be uploaded after the final assembly of the whole circuit. A fully connected example of the first layer is shown in Figure 3.11.

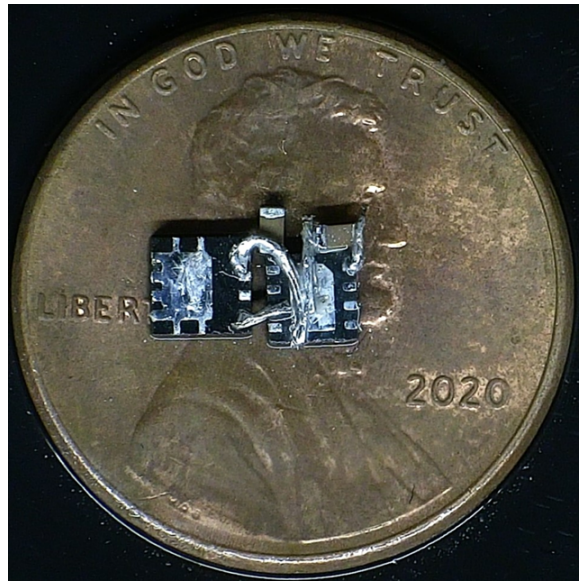


Figure 3.11: *Layer 1 of the front-end section. This layer includes the micro-controller, MOSFET, and two capacitors. Custom stranded 0.02mm jump wires were used to make connections. A penny is used as a sizing reference.*

Several revisions were made after receiving the stencils. Some of the smaller components, like the capacitors, were rearranged allowing for more direct connections. Further details will be discussed in the layer combination section 3.3.4.

3.3.3 Front-End Inverting Op-Amp

The second layer of the FE includes the inverting operational amplifier, a resistor capacitor pair, and the two $400\text{M}\Omega$ feedback resistors. The op-amp was treated as the central component with every other component branching off. The $2.4\text{M}\Omega$ resistor and 100 pF capacitor were stacked on top of one another and placed at the top edge of the op-amp. The two $400\text{M}\Omega$ resistors were attached end-to-end to one another and then placed directly above the 100 pF capacitor. The smaller sized components occasionally had movement issues while being connected. To minimize this issue, manual clamping was implemented through the use of small tweezers. Solder paste and thin custom stranded wires made the connections. A Solid Works rendering of the assembled circuit is shown in Figure 3.12. Slight changes were made after the stencil designs were received with the final iterations moving a capacitor from the first layer to the opposite end of the op-amp. This alteration is described in further detail below.

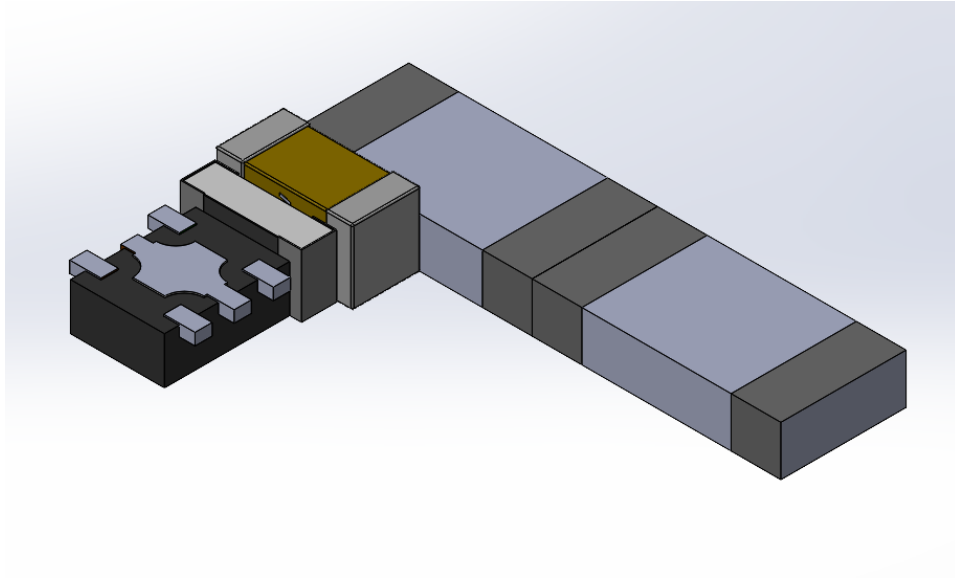


Figure 3.12: *A SolidWorks rendering of the second layer of the front-end circuit.*

3.3.4 Front-End Layering

The second layer was placed on top of the first forming the 3D FE circuit. To add structural support and help with the adhesion, DP-270 non-conductive epoxy was applied to the bottom of the op-amp and to the backside of the MC. The epoxy was also added to the gap between the MOSFET and MC to provide further mechanical support. Connections between the layers were made after allowing the epoxy to fully cure. Most of the connections lined up next to each other based on how the op-amp and MC were oriented during layer combination. Short stranded wired connections were used to complete the FE circuit. The completed FE circuit was then connected to the charge pump components after passing a visual and electrical inspection.

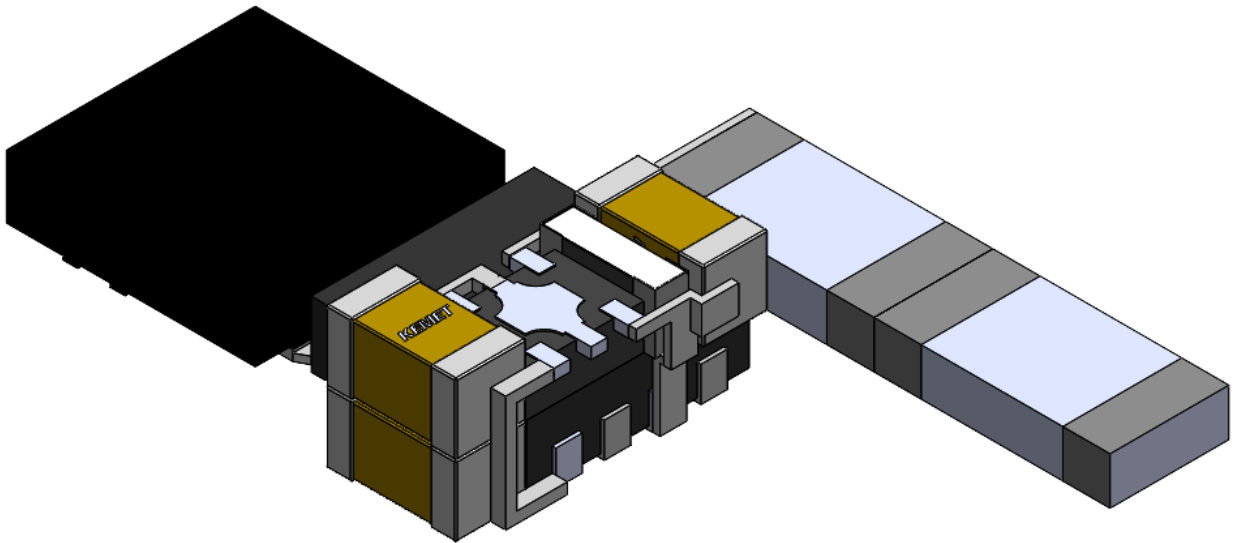


Figure 3.13: *A SolidWorks rendering of the combined front-end circuit with the mentioned altered placement of a capacitor.*

Several layer combination revisions were made with the placement of different components changing slightly. The two $0.10\mu\text{F}$ capacitors were rearranged to stack on top of one another to provide a more direct connection between the grounding pads of the op-amp, capacitors, and MC. This rearrangement also moved the op-amp back which resulted in shorter connections between itself and the MC. An example of the FE section is displayed in Figure

[3.13](#)

3.3.5 Front-End Charge Pump

With the layered 3D FE section completed the inductor and two $10\mu\text{F}$ capacitors were attached to form the charge pump that feeds the CW ladder. The large pad on the MOSFET was connected to one of the inductor pads with the spacing of this placement being crucial to allow this section of the circuit to properly fit within the gap between the split ladder portion of the high-voltage supply circuit. After insuring there were no shorts between the inductor and the MOSFET the other inductor pad was connected to two $10\mu\text{F}$ capacitors in parallel. These capacitors branched outwards from the inductor towards the op-amp. A top and bottom view of these connections are displayed in Figure 3.14.

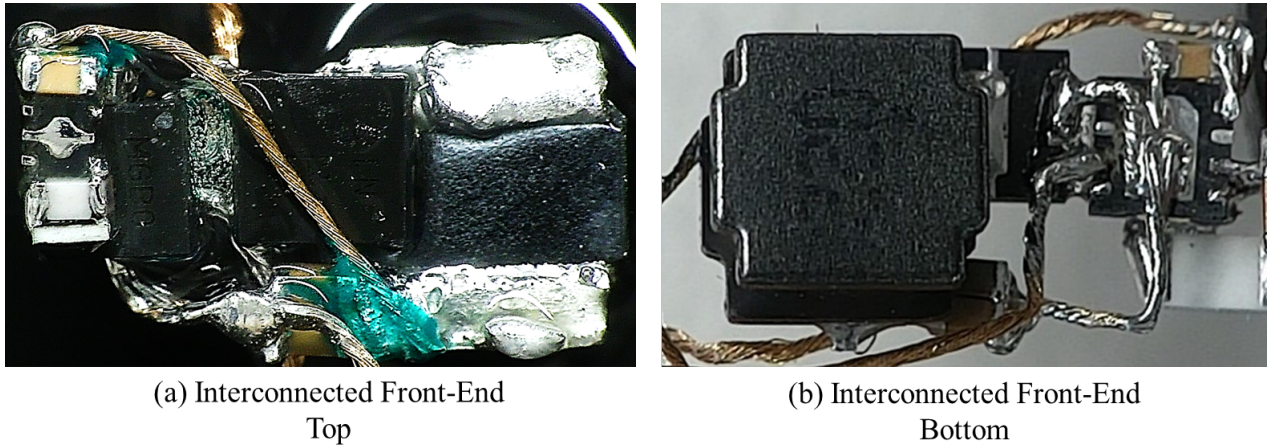


Figure 3.14: A top and bottom view of the combined front-end circuit attached to the charge pump. Top view is prior to the connection of the two $400\text{ M}\Omega$ resistors to the op-amp.

The ground connections for all of the FE components passed through the middle pad on the MC. A custom stranded wire connected to this central grounding pad and branched out to the charge pump capacitors that attached directly to the inductor. This wire then continued to extend past the capacitors for future external connections in the final assembly. The power line branched off from component connections that formed at the two $0.10\mu\text{F}$ capacitors near the op-amp and MC. Custom stranded wire started at these two capacitors and then passed over the MOSFET to the inductor pad where the two $10\mu\text{F}$ capacitors were attached. The power line also extended past the inductor for future connections.

3.4 Combined Circuit

The main foundation used for combining the separated sections of the circuit was the high-voltage supply while still attached to the E678-19K alignment socket. The FE circuit was placed on a flat elevated platform to better orient it to the high-voltage supply. Solid copper wire connected the inductor to the first stage of the CW ladder. This connection also stabilized the FE from moving during other connections. The ground connection for the ladder and filter capacitors were connected with custom stranded wire and extended past the inductor and met up with the grounding wire from the FE. The feedback resistors connected to the final stage pin of the CW ladder with the distance between the components being short enough to allow for a direct connection using a small amount of solder. A custom stranded wire connected to the anode pin for the future signal out connection in the final assembly. The elevated platform holding the FE in place was removed after the connections were verified electronically and visually. An example of the combined circuit is shown in Figure 3.15.

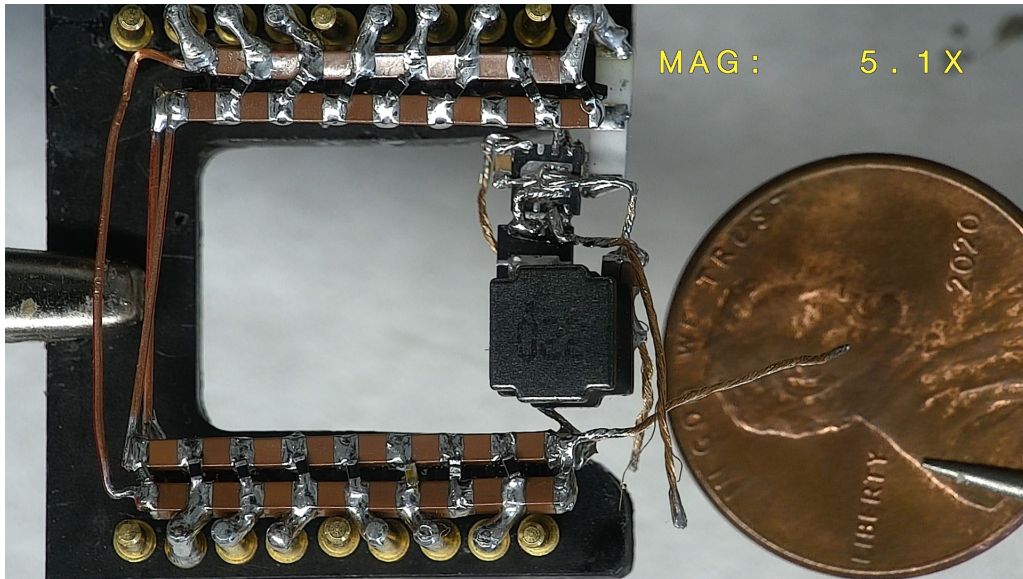


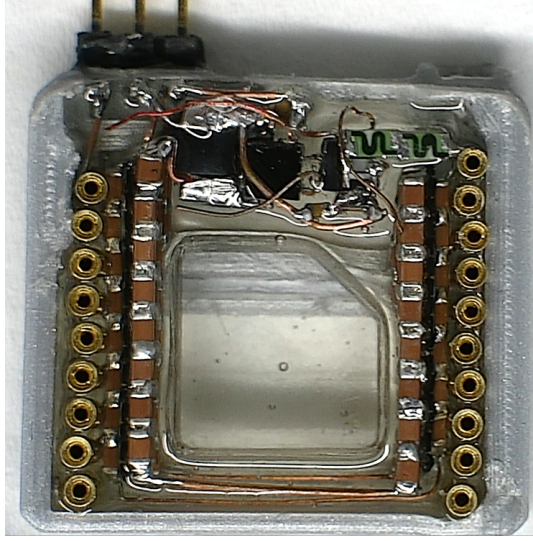
Figure 3.15: *A top view of the combined circuit excluding the additional stranded wire on the anode pin. A penny is included to provide a reference for the size of the assembly.*

The custom stranded wires seen near the lower right corner of the inductor were used to

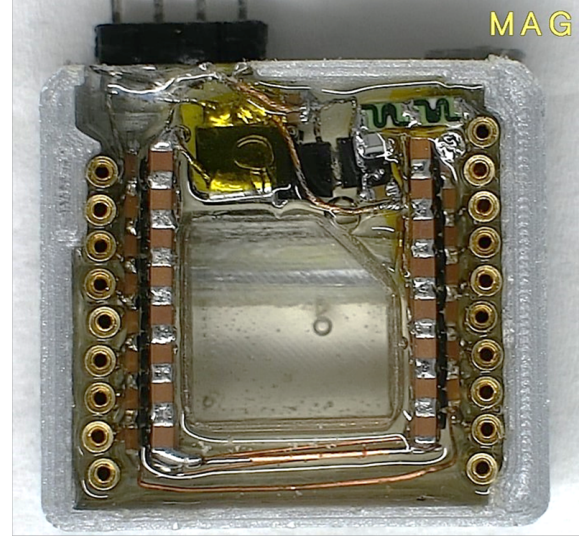
attach to the external connections for power, ground, and signal. Prototype B had an extra external connection to monitor the PWM from the MC. An example of this extra connection is present in Figure 3.15. The external connections were 90° header pins that were attached to a 3D printed enclosure that housed the final HVPS. The printed housing was designed to provide structural support during use and to minimize the final dimensions of the HVPS. The combined circuit was placed inside the printed housing and the connections to the power, ground, and signal out header pins were made.

Due to the FF construction of the circuit the only structural supports were the solder and wired connections. To provide additional strength and support, DP-270 non-conductive epoxy was used to back fill the housing around the HVPS. This provided structural strength to the devices while also preventing the combined circuit from arcing on itself during operation. To account for the space required by the central pedestal in the PMT, a water soluble PVA 3D printed pedestal was placed in the middle of the circuit. The DP-270 non-conductive epoxy filled the inside of the housing up to the flared rims of the golden pins. After curing for 24 hours the temporary pedestal was dissolved and the E679-19K alignment socket was removed. What was left was the final assembly of the FF HVPS to power an R11265U series PMT. Examples of the fully assembled HVPS's are shown in Figures 3.16 and 3.17.

A total of two HVPS were constructed with the differences between them being that prototype A included wired reprogramming connections and prototype B had an extra external connection to monitor the PWM of the MC. The additive manufactured or "printed" prototype, fabricated using the 3Dn-300HP system, was also constructed and housed in the same printed enclosure used for the two FF prototypes. The final bulk dimensions for prototype A were 2.99 x 2.78 x 0.75 cm with a bulk volume of 6.23 cm^3 . Prototype B had the final bulk dimensions of 2.98 x 2.77 x 0.87 cm with a bulk volume of 7.18 cm^3 . The printed prototype had the bulk dimensions of 2.99 x 2.77 x 0.865 cm with a bulk volume of 7.164 cm^3 . The bulk dimensions of the E11807-01 divider socket were 2.61 x 2.615 x 1.498 cm with a bulk

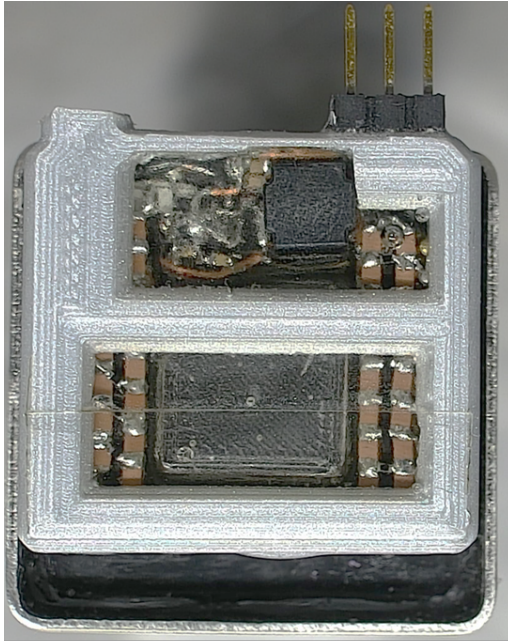


(a) Prototype A

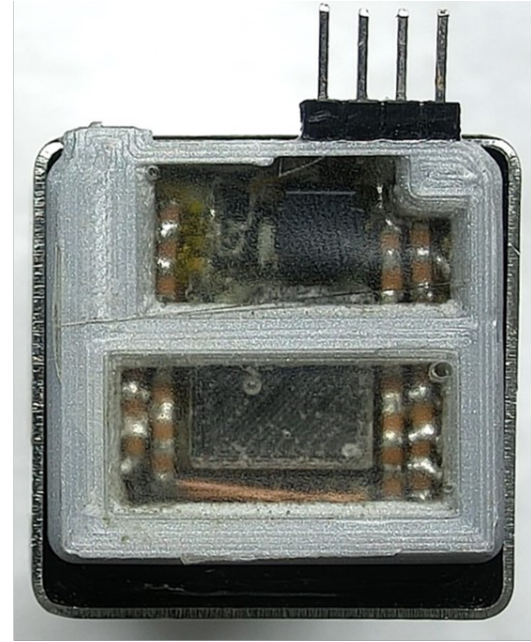


(b) Prototype B

Figure 3.16: *Bottom view of both fully enclosed FF HVPS prototypes.*



(a) Prototype A



(b) Prototype B

Figure 3.17: *Top view of both fully enclosed FF HVPS prototypes while attached to the top of the R11265U series PMT.*

volume of 10.20 cm^3 . This resulted in an overall volume reduction of 38.8% for prototype A, 29.7% for prototype B, and 29.7% for the printed prototype. The E11807-01 socket only includes the housing that contains the divider resistors while requiring an external high-

voltage source. The FF constructed prototypes, along with the printed prototype, include the high-voltage supply circuit and the control circuit while only requiring an external input of 5V. Each prototype is shown in Figure 3.18.

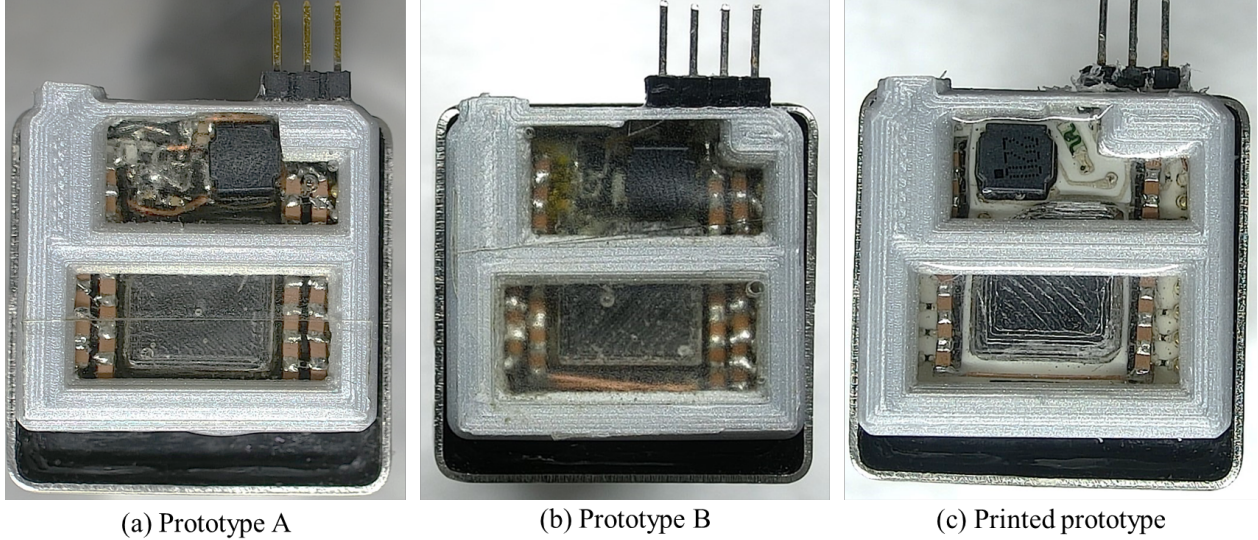
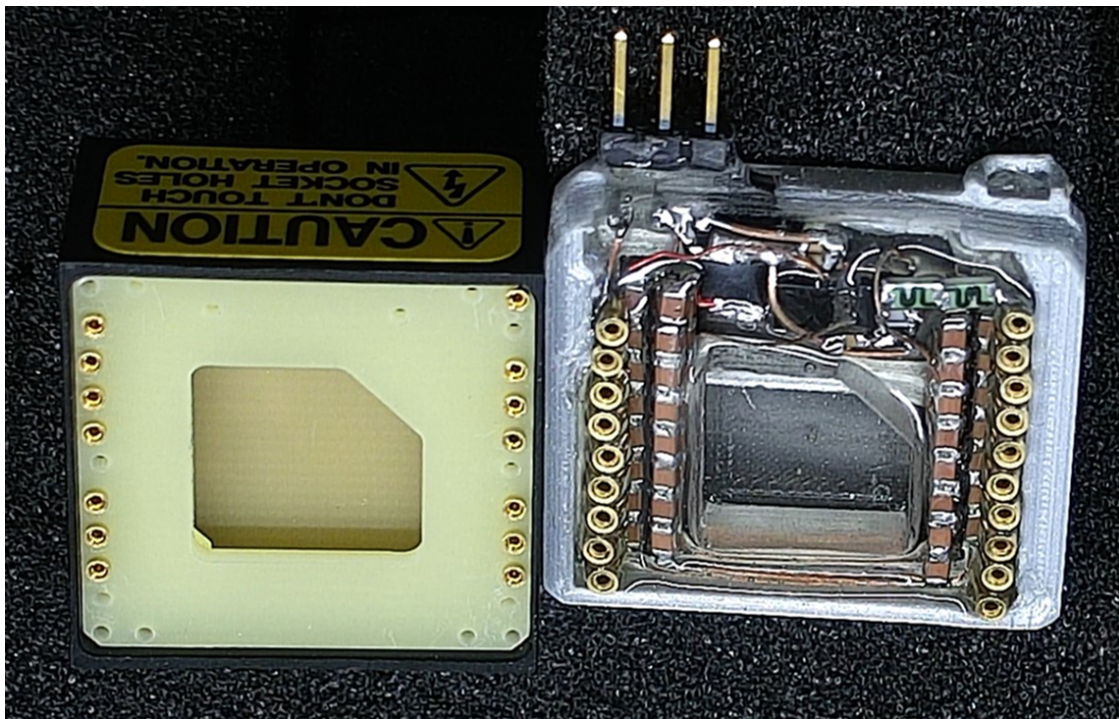


Figure 3.18: *Top view of all fully enclosed HVPS prototypes while attached to the top of the R11265U series PMT.*

The weights for each prototype were taken with prototype A weighing in at 7.73g, prototype B weighing 8.70g, and the printed prototype weighing 8.36g. The E11807-01 resistive divider was weighed without the BNC connectors and was 11.84 g. This resulted in a total weight reduction of 34.7%, 26.5%, and 29.4% for prototype A, prototype B, and the printed prototype respectively. A comparison between the E11807-01 and prototype A is shown in Figure 3.19.

The connection pins are visible on both the E11807-01 and prototype A. Fewer pins are used on the E11807-01 with disconnected holes taking their place due to specified interconnections on the R11265U series PMT¹. All prototypes required connection pins at all locations for proper attachment to the PMT without epoxy blocking the pins.



(a) E11807-01

(b) Prototype A

Figure 3.19: *An underside angled comparison of both the E11807-01 and Prototype A.*

Chapter 4

Measurements and Results

4.1 Electrical Characteristics

A set of electrical tests were conducted to characterize the functionality of the HVPS on and off the PMT. These tests include measurements of dynode stage voltages, photocathode voltage regulation, photocathode voltage stability, and power consumption. The testing set up is described in the subsections below along with their resulting measurements. Prototype A and the printed prototype were uploaded with the finalized code after tuning of the regulation around a set point. Prototype B had a previous version of the code prior to final tuning. It was unable to be updated due to the lack of reprogramming connections. A comparison between the E11807-01 resistive divider socket and all the prototypes is also provided when applicable.

4.1.1 Dynode Voltage Distribution Ratio

A total of 13 pins connect to stages on the CW ladder with the voltages increasing at each advancing stage. To measure the voltages at each of the 13 stages, the prototypes were probed while off of the PMT with a $25\text{M}\Omega$ load resistor to act as an intensive load on the circuit. This resistor value was chosen after taking current pulse measurements using a ^{137}Cs source. An average of this current pulse was used to represent a high count rate environment

and a large load on the HVPS. From this averaged current, a $25\text{M}\Omega$ resistor was selected to simulate the high intensity load. A 100X probe was used to measure the HV at each pin with the mean value monitored on an oscilloscope with a time scale of $2.5\mu\text{s}$. The voltages for the 13 stages were calculated for the E11807-01 resistive divider socket using the internal resistor network shown in Figure 4.1.¹ The calculation used a value of -840V as the HV

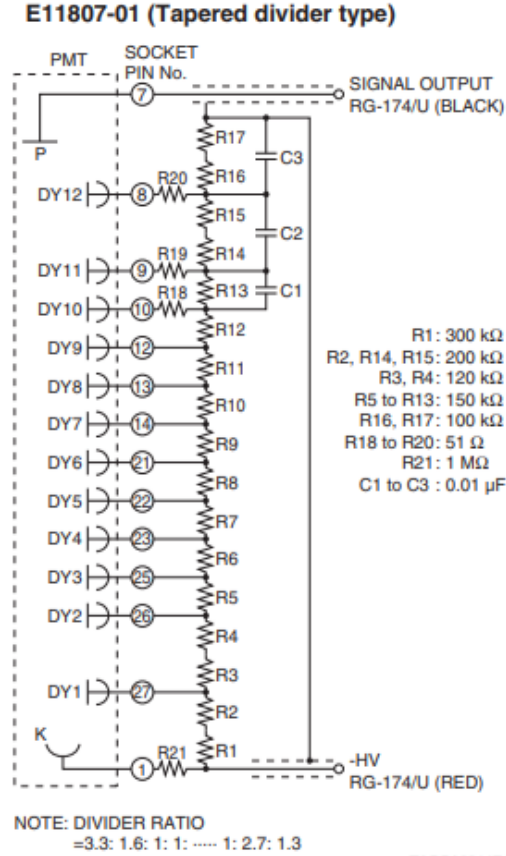


Figure 4.1: A circuit diagram of the E11807-01 showing the resistor network used to provide the biased voltages to each of dynode stages and the anode.

input to better match the anode voltages of the prototypes. Having the photocathodes set to similar voltages allowed for a better comparison between all stages. A plot of the voltages for all prototypes and the E11807-01 socket are shown in Figure 4.2. All bases share a linear section during the intermediate stages while having an increase in the voltage drop at both ends. All three prototypes have a lower voltage at the stages near the anode than that of the E11807-01 socket, but surpass the E11807-01 at stages 5 to 0. These plot points show some slight differences between the voltage bias levels at the different stages while keeping

the overall shape constant.

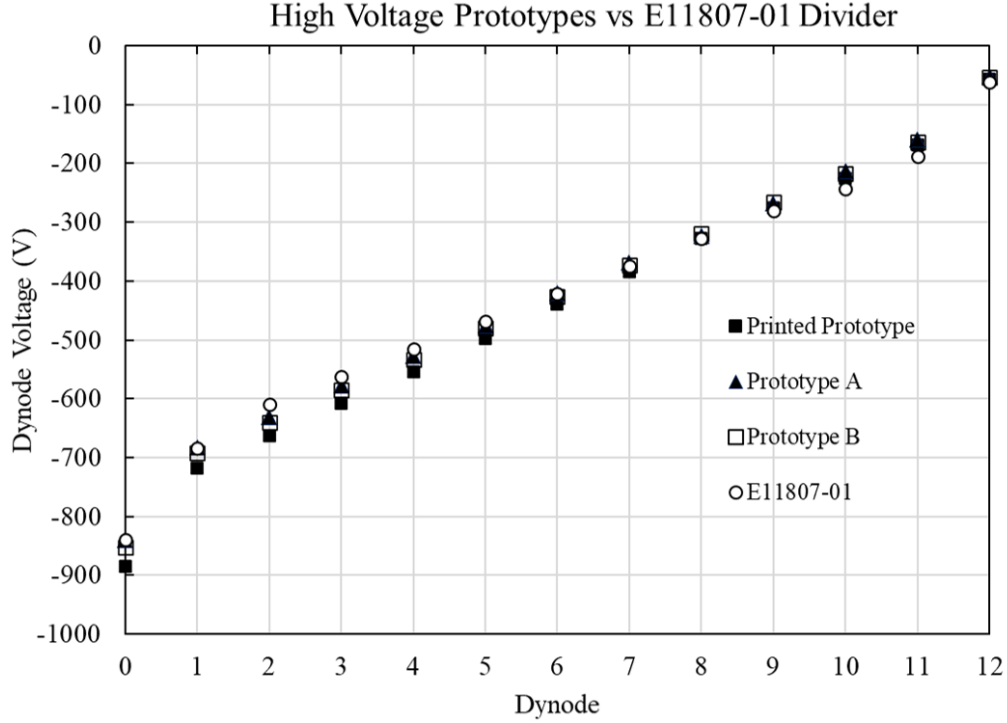


Figure 4.2: A plot of the voltages measured at each of the 13 stages for prototype A, prototype B, printed prototype, and the E11807-01 resistive divider.

4.1.2 Photocathode Voltage Regulation

The photocathode is located at the end of the CW voltage multiplier and receives the highest voltage out of all the stages in the PMT. This stage was the reference point for the feedback circuit to monitor and regulate the voltage at a selected set point. Any irregularities in the regulation will be largest at the photocathode due to it being the final stage of the voltage multiplier. To monitor the regulation, the photocathode was probed while off of the PMT with a $25\text{M}\Omega$ load resistor. With the oscilloscope set to DC coupling and a larger time scale of 250ms any fluctuations around the mean voltage were recorded using oscilloscope cursors. The cursor placements were determined by the largest voltage peaks above and below the mean measure voltage. While operating on a +5V input the photocathode mean voltage measured -835V with a percent fluctuation of +0.36% and -0.60% for Prototype

A. Prototype B had a mean voltage of -847 V with a percent fluctuation of +0.35% and -0.83%. The printed prototype had a mean voltage of -881 V with a percent fluctuation of $\pm 0.68\%$. The slight decreases in mean voltages are attributed to the larger time scale where more of the HV regulation was averaged. A photocathode regulation measurement wasn't recorded for the E11807-01 socket due to the HV being supplied by an external NHQ 103M benchtop HVPS.

4.1.3 Photocathode Voltage Stability

A measurement recording the stability of the photocathode was collected over an extended period of time to monitor any unintended changing trends of the final CW stage voltage. Trends where the voltage slowly changes over time would cause issues with the ability for the full detector system to operate properly. An example of poor operation quality would be unintended trending fluctuations in the voltage reducing the energy resolution during gamma-ray spectroscopy. The photocathode was probed while off of the PMT with the addition of the $25\text{M}\Omega$ load resistor. Measurements of the mean voltage were recorded from an oscilloscope in increments of 30 seconds over the course of an hour. These points were then plotted against their percent fluctuation from the total averaged voltage from the data set. Prototype A had an average voltage of -839 V with maximum fluctuations of +0.22% and -0.25%. Prototype B had an average voltage of -849 V with maximum fluctuations of +0.27% and -0.66%. The printed prototype had an average voltage of -884 V with maximum fluctuations of +0.148% and -0.19%. The stability plotted in Figure 4.3 is a good representation between the finalized tuned code uploaded to both prototype A and the printed prototype and a previous version of the code uploaded to prototype B. Both reach similar voltages but the stability of prototype A and the printed prototype is shown to be more consistent with voltage measurements hovering around the average. The resolution of the oscilloscope can be observed through the constant deviations observed. A stability measurement was not made for the E11807-01 socket due to the externally supplied HV which would have changing characteristics based on what type is used.

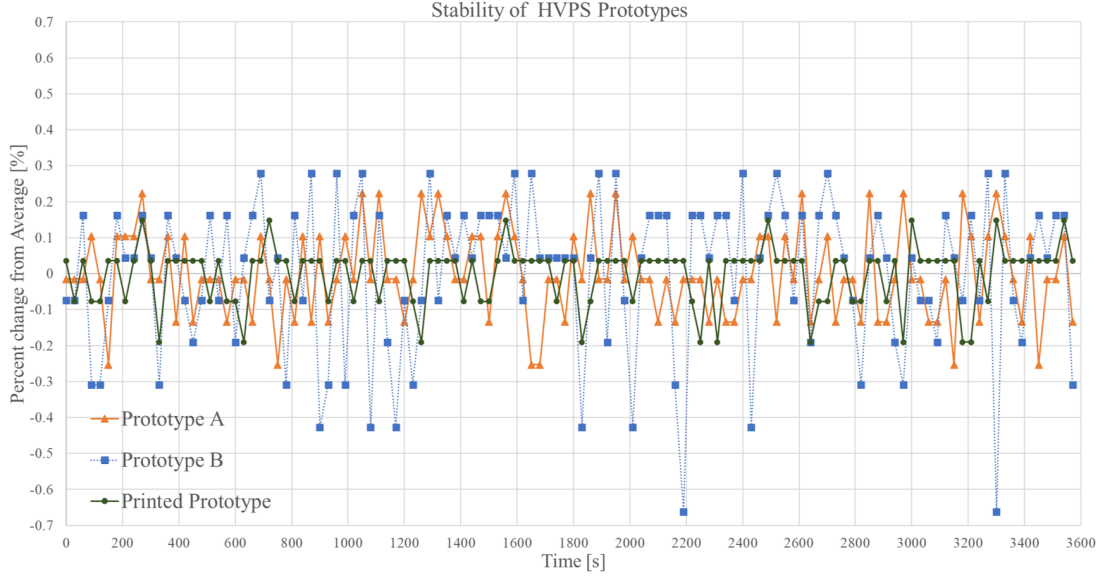


Figure 4.3: *A plot containing all prototypes with photocathode voltage fluctuation measurements made in 30 second increments over the course of an hour.*

4.1.4 Power Consumption

The power consumption of the HVPS was taken while attached to and driving the PMT detector assembly. The consumption of power from the prototypes was dependent on the amount of incident radiation that was seen by the scintillating crystal. The intensity was increased with the use of radioactive check sources stacked around or near the crystal. The incoming count rate (ICR) was monitored off of a CAEN pulse height analysis (PHA) desktop digitizer which calculated the amount of radiation that was being detected. The method to calculate a proper estimation of the ICR that the digitizer uses is a summation of the following events.

1. Events that are considered good that are going into an energy spectrum.
2. Events that are rejected by any user selections.
3. Events that are rejected through the time ordering algorithm of the software.
4. Events that are rejected due to saturation of the digitizer input stage
5. Pile up events that are counted twice. If there are two overlapping events within the

integration gate, there will be no trigger for the second one and an algorithm for pile up rejection will only tag the first one.

6. Poissonian event: Estimated lost events that occur during the Trigger Hold-Off time.

7. Poissonian event: Estimated lost events that occurred during a memory full condition

Further detail over the digitizer and the software used is provided in Section 4.2. All the check sources used to obtain the increasing ICR's are given in Table 4.1.

Table 4.1: *Check sources used to obtain incoming count rates for power consumption measurements.*

Check Source	Incoming Count Rates (cps)					
	100	1,000	15,000	43,000	100,000	175,000
^{137}Cs 10.00 μCi	-	X	X	X	X	X
^{137}Cs 1.08 μCi	-				X	X
^{137}Cs 1.00 μCi	-				X	X
^{137}Cs 0.259 μCi	-				X	X
^{109}Cd 1.04 μCi	-					X
^{109}Cd 1.03 μCi	-					X
^{109}Cd 1.00 μCi	-					X
^{65}Zn 1.14 μCi	-				X	X
^{65}Zn 1.00 μCi	-					X
^{22}Na 1.05 μCi	-					X
^{22}Na 1.00 μCi	-					X
^{60}Co 1.00 μCi	-					X
^{60}Co 0.949 μCi	-					X
^{57}Co 1.09 μCi	-					X
^{133}Ba 1.07 μCi	-					X
^{133}Ba 1.06 μCi	-				X	X
^{133}Ba 1.00 μCi	-				X	X
^{152}Eu 1.00 μCi	-					X
^{152}Eu 0.983 μCi	-					X

Measurements of the power consumption were made on a bread board that was monitoring the voltage drop of the 5V input across a 10 Ω resistor. The resistor was in series between the output of the 5V power source and the input of the prototype HVPS'. The voltages at

both ends of the resistor were monitored using 10X probes and the drop was measured using the math function on a oscilloscope. The power consumption was calculated using Equation 4.1 where the current is calculated using the voltage drop over the resistor.

$$Powerconsumption[mW] = 1000 * I * V = 1000 * \frac{\Delta V}{10\Omega} * 5V \quad (4.1)$$

These measurements were taken over a range of ICR levels and then plotted for all three prototypes with the plot shown in Figure 4.4.

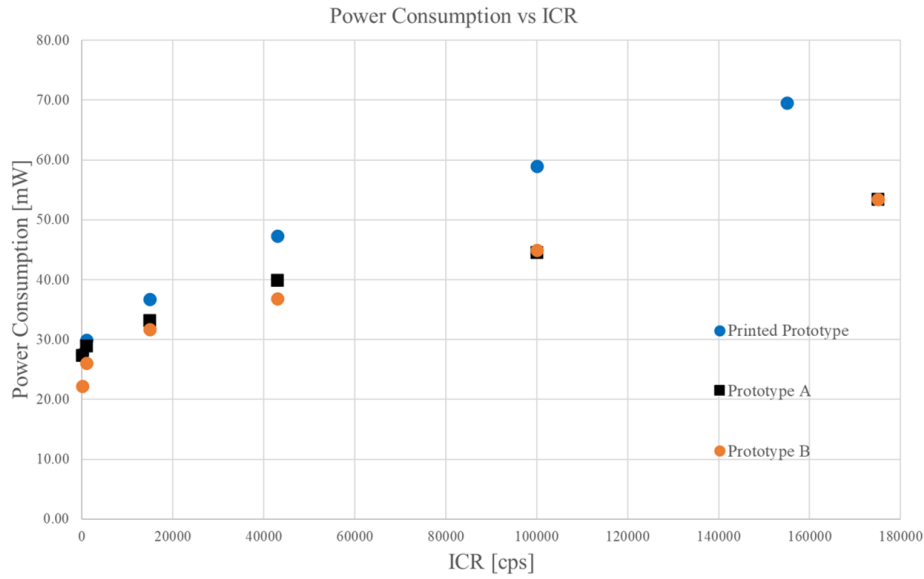


Figure 4.4: A plot of the prototype power consumption's based on the incoming count rate from a pulse height analysis digitizer.

The ICR ranges between a background measurement of 110 counts per second (cps) to just under 180,000 cps. The values for the lower count rates are slightly larger for prototype A than those of prototype B. Prototype A consumes between 23.13% to 8% more power during these low count rates ranging between 110 to 43,000 cps. The power consumption's between the two FF prototypes starts to align at 100,000 cps and continue up to the final ICR of 180,000 cps where both consume 53.4 mW. The power consumption of the printed prototype starts at a similar value at background with respects to prototype A, but starts to increase past both FF prototypes as the ICR increases. The maximum measured consumption for

the printed prototype was 69.53 mW at an ICR of 155,000 cps. The minimum no-load power consumption of the E11807-01 resistive divider was calculated using an input voltage of -900V and the total resistor sum of 2.69 M Ω with a value of 301 mW. This consumption is for the resistive divider alone without running the PMT. A comparison of the background power consumption of the prototypes to the no-load power consumption of the E11807-01 show a reduction of over 90%. The power consumption of a similar circuit using a 14-stage CW voltage multiplier to power a FEU84-3 PMT had a maximum power consumption of 150 mW. A comparison between the prototypes and this triple PCB board stack circuit show a reduction of 64.4% in maximum power consumption for prototype A and B and a 53.6% reduction for the printed prototype.

4.2 Radioisotope Spectroscopy

The fully assembled detector system was tested and evaluated using spectral analysis of various different check sources. The fully assembled detector system includes the scintillating crystal, R11265U series PMT, HV bases, and a prototype read-out board. Comparisons between the prototypes and the E11807-01 are shown in the resulting spectra. An evaluation of the overall spectra shape is made for each check source along with a comparison to the energy resolutions for the full energy peak of ^{137}Cs .

4.2.1 Scintillating Crystal

The scintillating crystal used for spectroscopy was a Cesium Iodide material activated with Sodium (CsI(Na)). This type of activated scintillating material has an wavelength emission maximum peak of 420nm.²² This emission peak matches well with the photocathode sensitivity of a bialkali PMT, which is the material used in the R11265U series PMT's.²² CsI(Na)'s photoelectron yield for gamma-rays is 85% of NaI(Tl) with a primary decay time of 630ns. A light output for CsI(Na) is 41,000 photons per Mev.²² The mechanical and thermal shock resistance of CsI(Na) is considered good making it well suited for harsh and

mobile environments.²³ The crystal is hygroscopic and is protected from moisture using a thin metal enclosure. The crystal along with the attached R11265U series PMT are shown in Figure 4.5.

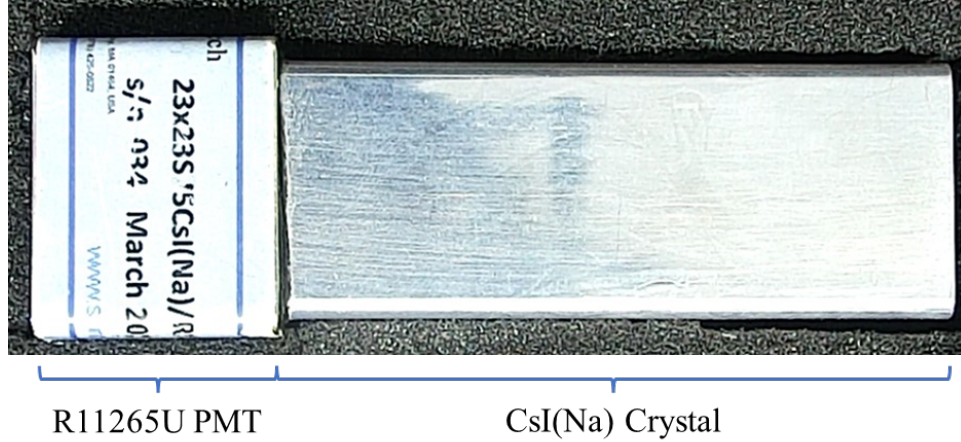


Figure 4.5: *The 1 inch x 1 inch x 3 inch CsI(Na) crystal encased in a metal housing attached to the R11265U series PMT.*

4.2.2 Digitizer

Signals from a PMT are typically fed through a preamplifier and a shaping amplifier to increase the magnitude of the signal pulse and to shape it into a Gaussian shape. A multi-channel analyzer (MCA) is then used to analyze the shaped pulses and place them into bins forming a spectrum. Another process that can be used to build spectra takes the analog pulses from the preamplifier and converts them into digital data through a device called a digitizer. The signals from the prototypes and the E11807-01 were fed into a preamplifier and then directed into a digitizer replacing the shaping amplifier and MCA. Based on the firmware type of the digitizer the pulses are analyzed by Pulse Shape Discrimination (PSD), Pulse Height Analysis (PHA), or Charge to Digital Converter (QDC)²⁴. The digitizer then runs through a PC using the provided software known as CoMPASS where the user can change parameters or view the data that has been digitized.

The firmware used for prototype A, prototype B, printed prototype, and the E11807-01

was the PHA firmware which is mainly used for high resolution spectroscopy²⁴. This digital approach of pulse height analysis synthesizes the process from the shaping amplifier all the way to the PC into a singular device known as a digitizer²⁴. Using this digitizer allows for new techniques based on field-programmable gate arrays to change the parameters of the readout based on the characteristics of the detector used. This allows different detectors to be used to detect different radiation while using the same hardware²⁴. The algorithm that is implemented in the multi channel analysis of this PHA digitizer is based on the Jordanov trapezoidal filter and is called Digital Pulse Processing for Pulse Height Analysis (DPP-PHA)²⁴. This filter has the ability to take the exponential decay signal produced by the preamplifier and transform it into a trapezoid. Proportionality to amplitude of the input pulse which is proportional to the energy deposited by the incident radiation inside the detector comes from the height of the flat top of this trapezoid²⁴. This trapezoid acts similar to a traditional shaping amplifier with the trapezoid having shaping time constants and needs calibration in respects to the pole-zero. An increase in resolution is achievable with the PHA digitizer through the use of longer shaping times, but this comes with the increased risk of more pile-up events²⁴. The trapezoid rise time has a correlation factor ranging between 2 to 2.5 which corresponds to the shaping time of a traditional set up²⁴.

Multiple settings needed to be optimized to properly setup the PHA digitizer to collect spectra. Multiple sets of analog to digital traces can be depicted using the waveform inspector provided in the CoMPASS software. Starting with the "DC offset", the baseline of the input signal is moved to cover the entire pulse and to avoid saturation²⁵. The trigger and timing filter is used to identify pulses from the input, generate a digital signal that identifies pulses, and calculate event times. To do this, a digital RC-CR² filter is performed and is optimized by setting the "fast discriminator smoothing" factor to 16. Next the "input rise time" is set and a bipolar signal is observed in the waveform inspector window. The peaks should be slightly curved and smooth without a flat top. The "threshold" is adjusted and moved to just above the noise of the RC-CR² to remove unwanted peaks in the lower bins²⁵. After optimizing both the DC offset and the trigger and timing filter the trapezoid can be

optimized for either low rate cases of up to a few hundreds of Hz or high rate cases of up to tens of kHz. A high rate case was chosen for the spectral analysis used for the prototypes and the E11807-01. To optimize for high rate cases the "trap. rise time" is typically reduced to a setting of 1-4 μs and the "trap. flat top" is set to 1 μs . During the optimization for each of the prototypes and the E11807-01 the trap. rise time was set to 5 μs and the trap. flat top was set to 3 μs . The top of the trapezoid is inspected in the waveform inspector to insure that it is flat. Settings can be adjusted from the suggested values to achieve the desired trapezoid. The peaking position "peaking time" and number of samples can also be adjusted based on the shape and flatness of the trapezoid if necessary²⁵. With the trapezoid optimized, the pole-zero is adjusted to try and remove any under or overshoot which will effect both the baseline of the trapezoid and the evaluation of the energy value²⁵. The issue of having either a flat trapezoid top or no over/undershoot occurred for both prototypes and the E11807-01. It was decided to prioritize the flatness of the trapezoid and allow slight over/undershoot with the settings tuned to minimize its effects on the final spectra.

4.2.3 Testing Setup

The optimization of the detector system was conducted in the final testing setup where spectra could be taken without the need to introduce additional equipment. The full testing setup consisted of the CsI(Na) crystal attached to the R11265U series PMT and either a prototype or the E11807-01 cap driving the PMT. The detector system was operated using a 5V input from a RIGOL DP832 programmable DC power supply for the prototypes or a -900V input from a NHQ 103M NIM module HVPS for the E11807-01. The raw pulses of the E11807-01 were connected directly to a BNC cable while the raw prototype pulses were connected through a small readout board to convert the header pin connection to BNC. These raw signals from the detector system were fed into the input of a ORTEC MODEL 113 preamplifier through a T-split BNC junction with a 10K Ω resistor in parallel. This resistor was added to the input to speed up the decay of the pulses and to alter their magnitude. The input capacitance of the preamplifier was set to 1000 pF. The magnitude of the out-

put pulses saturated the digitizer at higher energies causing issues encapsulating the 3 MeV range during radiation spectroscopy. To reduce the magnitude of the pulses being seen by the digitizer a 20 dB attenuator was attached in series to the output of the preamplifier. This reduction eliminated digitizer saturation and allowed the encapsulation of a 3 MeV range.

During measurements the detector system and the check source were set on top of the foam inside the Pelican case used to store the detector. The check source was placed 2 inches away from the middle of the broad side of the crystal and was held in place using small slits in the foam. A depiction of the typical setup is shown in Figure 4.6 with a front view and a top view used to show off all components used. The digitizer connected directly to a PC running

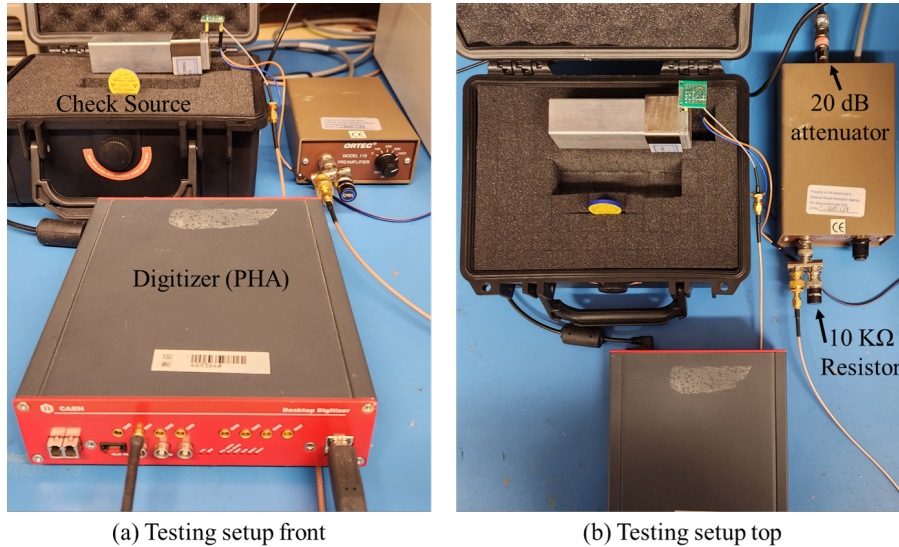


Figure 4.6: Testing setup used for spectral analysis with a ^{137}Cs check source placed 2 inches from the crystal and prototype B attached to the PMT.

the CoMPASS software through a USB connection. A total of 2048 bins was selected to be used for spectral analysis. Prior to check source measurements, the fine gain was adjusted through the software for each base. This moved the full energy peak of the ^{137}Cs check source near channel 450 which correlates to an energy nearing 662 keV when converted to a 3 MeV range. This peak adjustment reduces the magnitude of energy calibration required for the finalized spectra.

After tuning the fine gain, spectral data was recorded and exported for post processing in python. The first spectrum taken was a background measurement that was collected over the course of 30 minutes. This time was preset using the acquisition tab on CoMPASS. After a background measurement was recorded the resulting spectral plot was exported as a CSV file and multiple screen shots were saved using the built in screenshot tool on CoMPASS. A set of statistics of the spectrum are made available through CoMPASS which included incoming count rate, dead time, and pulse classification. The next set of spectra used several check sources. Each source was recorded separately using 6 minute intervals at the 2 inch distance described above and shown in Figure 4.6. The sources that were not currently being measured were placed outside of the testing room so they wouldn't contribute to the spectrum. The check sources used for spectral analysis were a 0.899 μCi ^{137}Cs , a 0.574 μCi ^{60}Co , and a 0.317 μCi ^{22}Na .

4.2.4 Spectral Analysis

Prior to the final tuning of the regulation code on prototype A the PSD digitizer was used to take early experimental spectral data. Several issues became apparent from this early stage spectra which included sections of the pulse being cut off in the waveform inspector, lower channel noise issues, and missing energy peaks at lower energies. To mitigate these issues further tuning of the regulation code was implemented along with reducing the magnitude of pulses through attenuation. The digitizer firmware was later switched to that of the PHA firmware to better analyze the pulses for spectral analysis with the user manual stating PHA was well suited for CsI.²⁴ All recorded spectra was collected after the optimization of PHA settings described in 4.2.2 and the uploading of the finalized tuned code to prototype A and the printed prototype.

A python script was used to perform post-processing of the PHA spectra by reading in the unfiltered CSV files that were exported from CoMPASS. The data contained in the unfiltered CSV file consisted of a time tag column, an energy column, and a flags column.

Additionally, a help file along with an info file titled "run" were generated by CoMPASS containing information for each of the separate spectral experiments. The python script read in the energies from the selected CSV and summed them up into an energy spectrum. The resulting spectrum produced by this summation of the energies looked identical to spectra observed through CoMPASS, but it had yet to be energy calibrated or count rate corrected. The check source spectra also contained background contributions which needed to be subtracted. Additionally the large amount of channels used resulted in rough spiked peaks throughout the spectra.

To smooth out the spectra, the original 2048 channels were rebinned down to 1024 total channels. The rebinned spectra was then divided by the run time stated in the INFO file to count rate correct the spectrum. The run file produced for each spectral acquisition kept the count rate correction consistent for the difference in time between the background measurement and check source measurements. An energy calibration was then performed through the use of 3 known energy peaks using both the ^{137}Cs and ^{60}Co spectra. The peaks used in the calibration from the Cs source were the Ba K shell X-ray at 32 keV and the 662 keV full energy gamma-ray peak. The peak used from the Co source was the 1.33 MeV full energy gamma-ray peak. The channel number of these peaks were recorded using the region of interest (ROI) tool provided in the CoMPASS software. The known energies of the peaks and their channel locations were plotted with a 2nd order polynomial trend line used to form a calibration equation. The multiple peaks along with the 2nd order polynomial calibration equation were used instead a single peak energy calibration to mitigate any non-linearity in peak location. This calibration was repeated and applied to all of the base specific spectra and converted the plots from channels vs counts per second (CPS) to energy vs CPS. After calibration the count rate corrected background spectrum was subtracted from the count rate corrected check source spectra. The post processed spectra of each base were then combined and fully plotted over the desired range of 3 MeV.

The combined background spectra is shown in Figure 4.7 and was used to perform back-

ground subtraction on the check source spectra. Each of the spectra from the prototypes and the E11807-01 are shown to reach the desired 3 MeV range. All three spectra are also shown to overlap with little deviation between each other.

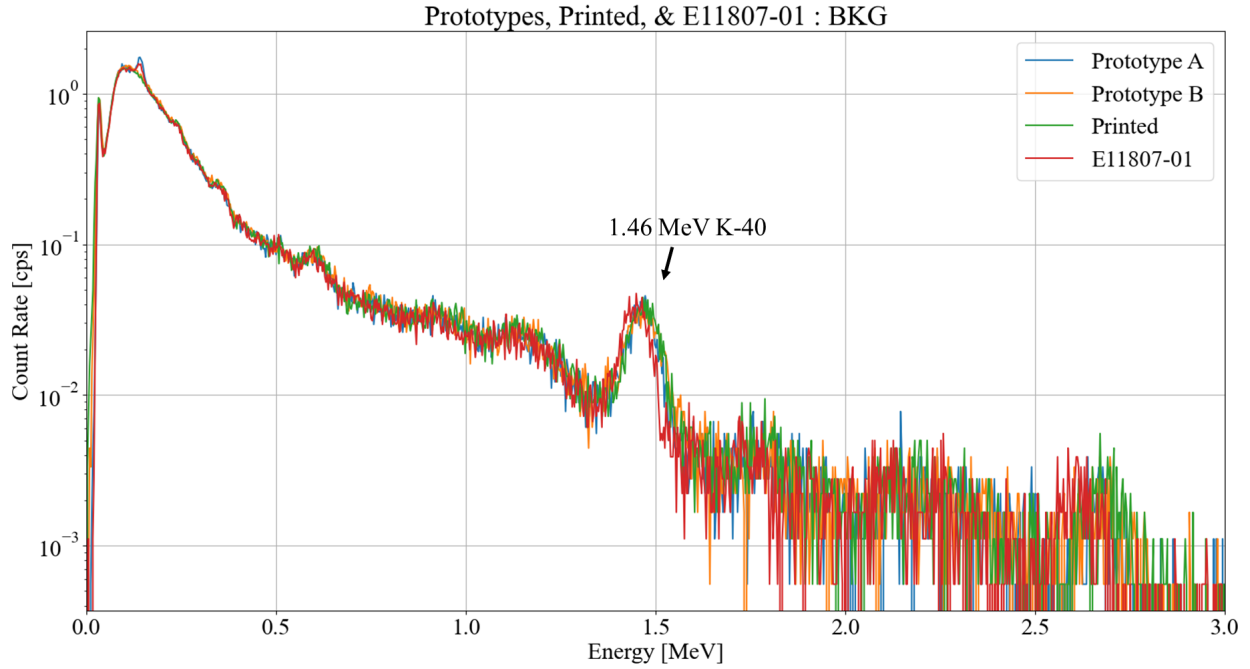


Figure 4.7: A plot containing count rate corrected background spectra of all prototypes and the E11807-01. Background was taken over the course of 30 minutes

A notable feature of background radiation shown in Figure 4.7 is the 1.46 MeV ^{49}K peak. This peak is a component of terrestrial background which is typically made of of ^{232}Th , ^{238}U , and ^{40}K . This grouping of isotopes is commonly known as KUT gamma rays. Other known contributors to background spectra are from radon gas and cosmic-rays. Only the ^{40}K peak is easily discernible from the spectra due to the intrinsic energy resolution of CsI(Na) crystals blending close energy peaks together.

The spectra shown in Figure 4.8 is the combination of the individual ^{137}Cs spectra from all three prototypes and the E11807-01. The spectra is count rate corrected, energy calibrated, and background subtracted. All four spectra are shown to overlap with little deviation at both the full energy 662 keV gamma-ray peak and the 32 keV X-ray peak. Slight deviation

is apparent along the Compton continuum with prototype B appearing to have a slight increase in the count rate for this region. The width of the full energy peak is slightly larger for prototype B when compared to the width for prototype A, printed prototype, and E11807-01.

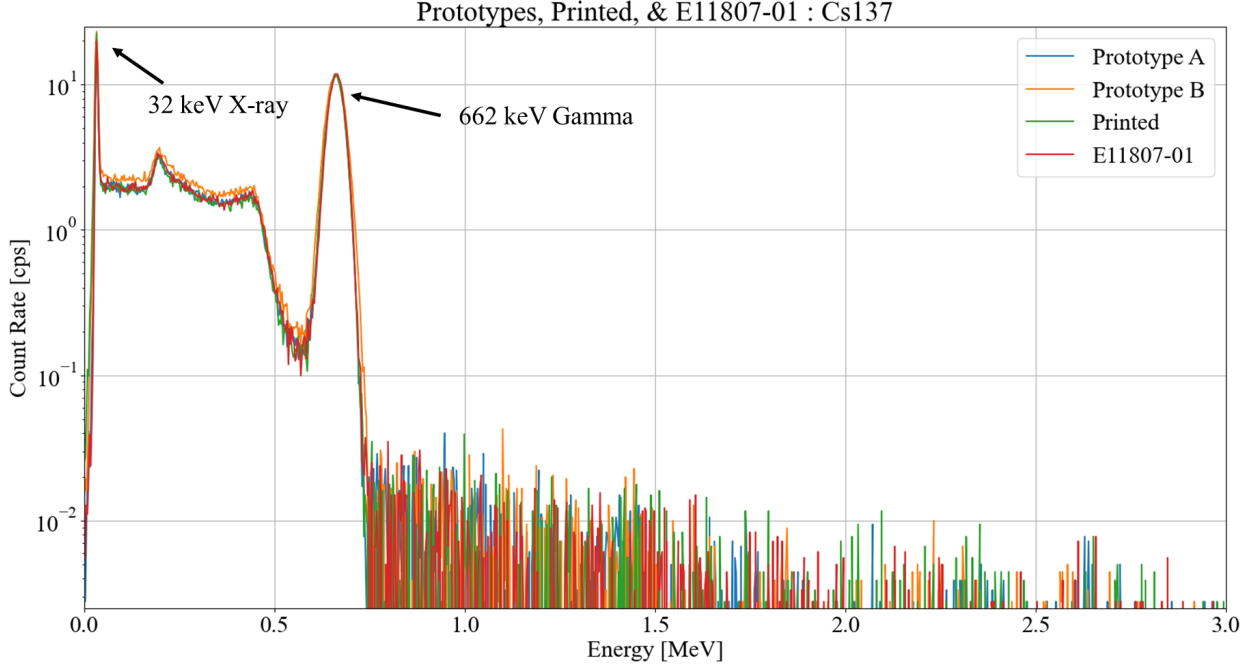


Figure 4.8: A plot containing count rate corrected and background subtracted ^{137}Cs spectra of all prototypes and the E11807-01. All ^{137}Cs spectra were taken over the course of 6 minutes

The energy resolution of the ^{137}Cs full energy peak for each base was measured using the CoMPASS provided ROI tool. The peak was selected and a Gaussian curve was fit over the region with a linear background fit being applied. From this curve, the ROI calculated the peak's centroid, the FWHM, the energy resolution, and several other measurements. An example of this ROI measurement for prototype A is shown in Figure 4.9. The equation calculating the energy resolution is shown in Equation 4.2.

$$\text{EnergyResolution}[\%] = \frac{FWHM}{\text{Centroid}} * 100 \quad (4.2)$$

The energy resolutions along with their error is provided in Table 4.2. The resolution for prototype A is 0.094% larger than that of the E11807-01 while prototype B is 0.996% larger

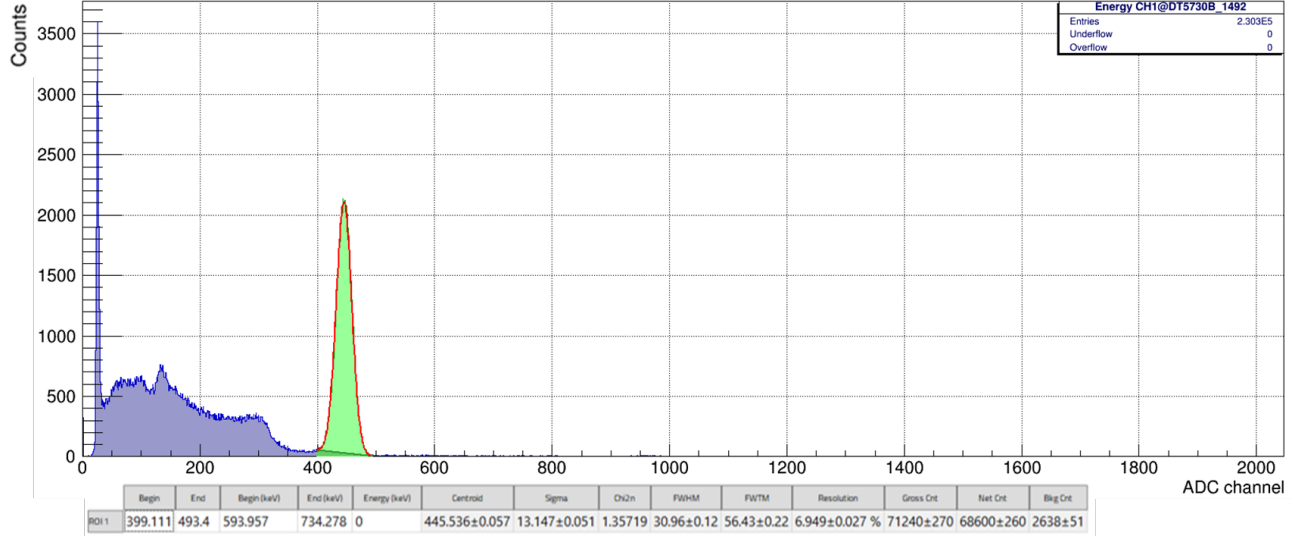


Figure 4.9: *Prototype A ROI measurement of a ^{137}Cs full energy peak using the spectra produced by the PHA digitizer on CoMPASS.*

and the printed prototype is 0.075% larger. A reason for the discrepancy between the energy resolutions of the prototypes are that the printed prototype was constructed with the tuned regulation code, prototype A was reprogrammable and had the tuned regulation code uploaded, and prototype B had a previous version of the regulation code that resulted in more fluctuation of its HV as shown in Figure 4.3.

Table 4.2: *Energy resolutions of the ^{137}Cs gamma-ray for all prototypes and E11807-01.*

Base	Energy Resolution	Error
Prototype A	6.949%	$\pm 0.027\%$
Prototype B	7.851%	$\pm 0.044\%$
Printed prototype	6.93%	$\pm 0.026\%$
E11807-01	6.855%	$\pm 0.029\%$

A combination of the individual ^{60}Co spectra from each of the bases is shown in Figure 4.10. Like the ^{137}Cs spectra shown in Figure 4.8 the ^{60}Co spectra have been background subtracted, count rate corrected, and energy calibrated. The features of all four spectra overlap with little deviation except for the edges of the full energy peaks. Due to the higher energy resolution of prototype B shown in Table 4.2 the gamma-ray peaks are depicted hav-

ing an increased width and less definition than those observed for prototype A, the printed prototype, and the E11807-01.

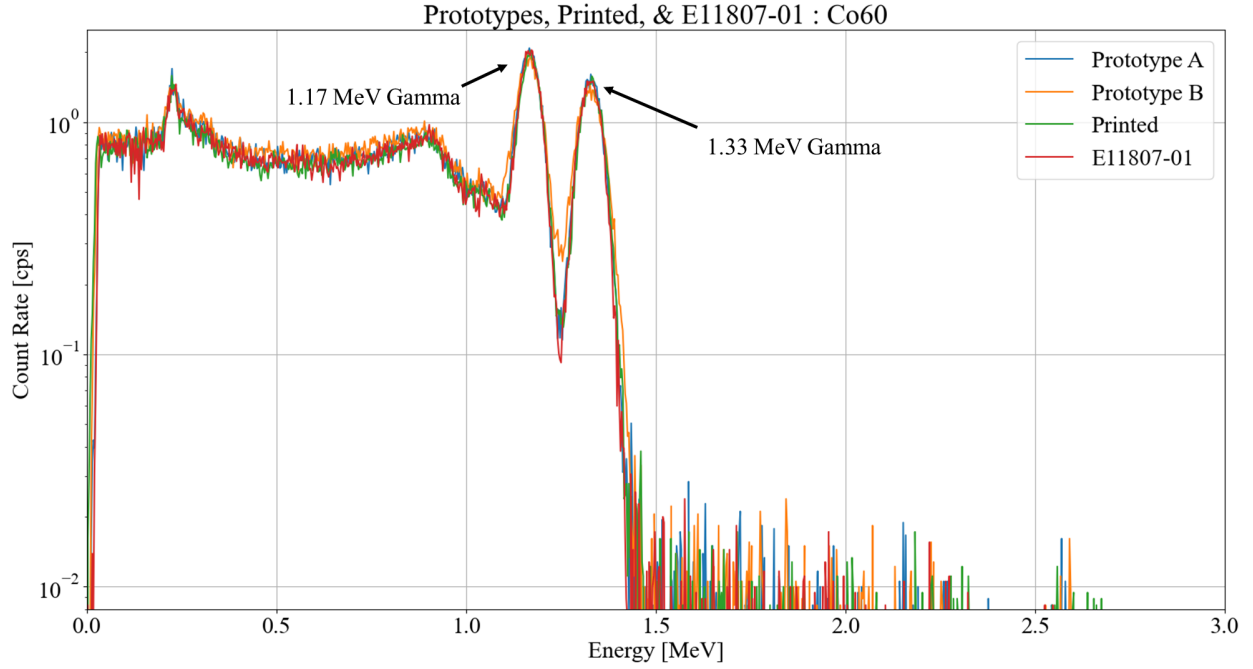


Figure 4.10: A plot containing count rate corrected and background subtracted ^{60}Co spectra of all prototypes and the E11807-01. All ^{60}Co spectra were taken over the course of 6 minutes

A feature that can be observed but is not depicted in the ^{60}Co spectra is the summation peak. The summation peak is the sum of both the 1.17 MeV gamma and the 1.33 MeV gamma resulting in a peak at an energy of 2.5 MeV. The direction of the two gamma's from the ^{60}Co source have no relation to one another and are isotropically emitted from the check source. This causes the probability of summed pulses being observed to be relatively small for the size of crystal used and the distance that the check source is from the crystal.

Figure 4.11 depicts the combination of the individual ^{22}Na spectra from the prototypes and the E11807-01. Like the check source spectra above the ^{22}Na spectra was background subtracted, energy calibrated, and count rate corrected. The ^{22}Na spectra contains 3 peak features with little deviation between each of the bases. Again the peaks from prototype B are slightly wider than those of prototype A, the printed prototype, and the E11807-01

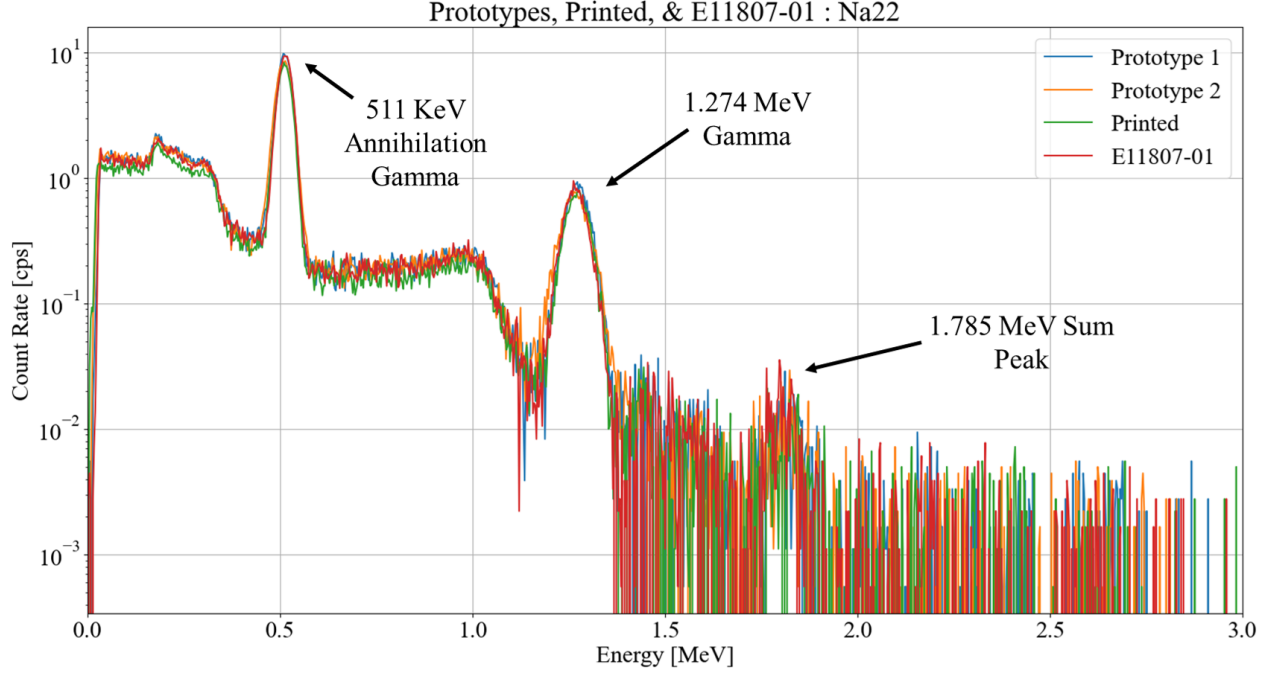


Figure 4.11: A plot containing count rate corrected and background subtracted ^{22}Na spectra of all prototypes and the E11807-01. All ^{22}Na spectra were taken over the course of 6 minutes.

due to the larger energy resolution. The three peak featured in the spectra are the 511 keV annihilation gamma, the 1.274 MeV gamma, and a 1.785 MeV summation peak. The 511 keV annihilation peak is a result of the electron capture beta+ decay. This beta + decay results in the emission of a positron and a neutrino where the positron can interact with an electron. The interaction between the electron and the positron results in an annihilation event with the emission of two 511 keV gamma rays 180° from each other. The resulting atom formed after the beta+ decay is an excited state of ^{22}Ne which then decays to its ground state through the release of the 1.274 MeV gamma ray. A summed peak of 1.785 MeV can occur as the combination of the annihilation gamma and the excitation gamma energies. The summation peak for ^{22}Na is more readily observed unlike the summation peak for ^{60}Co due to the increased likely hood that one of the emitted annihilation gamma-rays interacts in the crystal at the same time as the excitation gamma.

Chapter 5

Conclusion and Future work

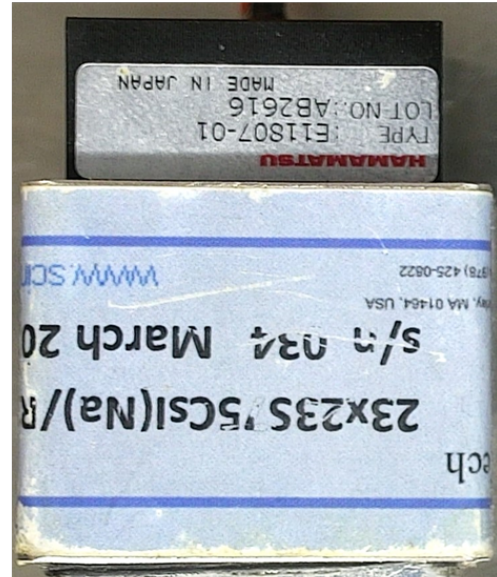
5.1 Conclusion

The two FF HVPS's served as a performance benchmark for the additive manufactured prototype that was fabricated alongside the efforts described in this work. The additive manufactured prototype employed a combination of additive and subtractive manufacturing techniques to produce a printed HVPS with electrical components seated in slots on an ABS plastic base.¹⁷ The traces and interconnections between components were made using CB028 conductive paste which was considered a non-proven material that was to be benchmarked by the proven materials listed above. Both 3D non-traditional fabrication techniques enabled the designed circuit to accommodate the irregular free space within the R11265U series PMT. Shown in Figure 5.1 is a comparison of the space utilized by the prototypes to the space utilized by the E11807-01. All three prototypes were enclosed in a printed housing and took up similar volume on the PMT.

Translating a circuit from a 2D planar design using a PCB to a 3D circuit using either construction method mentioned in this work offers many benefits but also introduces some complications. One of the main complications is probing parts of the circuit that are obstructed by the 3D geometry. As the circuit is constructed and subsequent sections are attached to each other some of the probe points become increasingly difficult to reach without



(a) Prototype on PMT



(b) E11807-01 on PMT



(c) Prototype and E11807-01

Figure 5.1: *The space utilized by the prototypes compared to the space utilized by the E11807-01.*

accidental probing or shorting different connections. This issue was mitigated by conducting visual and electrical check at every step to ensure each subsection had no issues prior to their connection to the main circuit. Another main issue is the lack of structural support in the FF circuit prior to potting in the protective housing. All connections were made through direct soldered or wired connections without any additional foundation keeping thing in place besides temporary scaffolding. This issue was reduced through the use of scaffolding during interconnections and was solved at the end with the encasement of the full circuit in a protective printed housing that was back filled with non-conductive epoxy. The final problem comes from the previous solution and it is the inability to repair the circuit after its placement in the protective housing. Once the non-conductive epoxy has set the circuit is completely sealed with no easy way to access defective parts.

From the dynode stage voltage measurements shown in 4.2, the printed prototype is capable of reaching voltages within the required range of -700 to -1000 V with a photocathode voltage of -884 V. The voltage distribution ratio, designed to follow the E11807-01's tapered divider, of the printed prototype shows no major deviations when compared to the FF prototypes besides having a larger voltage set point. The maximum regulation about the photocathode voltage set point is comparable to what is observed for prototype A with both having fluctuations at or below 0.68%. The results from the dynode voltage comparison and photocathode regulation show that a fabricated method using ABS plastic and CB028 conductive paste is a viable option to produce high-voltage electronics up to -1000 V.

The photocathode stability results shown in Figure 4.3 show that the printed prototype's photocathode voltage has no changing trend over an extended period of time. It also shows that the printed prototype has the smallest fluctuations about the mean voltage out of all the prototypes. The power consumption's of the printed prototype shown in Figure 4.4 are larger at every ICR level than those for either FF prototype. This increase in power consumption is mainly due to the higher voltage set point and is not considered a compromise of the fabrication method used in its construction. The energy resolutions of the ^{137}Cs gamma-ray

peak in Table 4.2 for the printed prototype and prototype A show no degradation to the intrinsic resolution of 7% typical for a CsI(Na) crystal. These comparisons show that the CB028 conductive paste deposited on the ABS base of the printed prototype performs similarly to the proven materials of solder and copper wire in this application of a high-voltage power supply for a PMT.

The increase in noise observed in the performance of prototype B compared to prototype A is believed to be a result of the first implementation of voltage regulation code uploaded to the MC and not a result of the materials used or the method of fabrication. The electrical and spectral results of prototype A show that it is capable of reaching high-voltages within the required range, has low fluctuations in the photocathode regulation, shows no changing trends in the photocathode voltage over an extended period of time, has low power consumption for low to high count rate environments, and shows no degradation to the intrinsic resolution of a CsI(Na) crystal. The results achieved by prototype A show that the FF method is also a viable fabrication technique to produce high-voltage power supplies for a PMT.

The FF technique is a viable high-voltage power supply fabrication option on its own due to its performance while providing the best volume utilization out of all the 3D manufacturing techniques discussed in this work. The labor involved with FF circuit construction isn't too intensive and is well suited for small batches of prototypes. The lack of a plastic base or a PCB allows for FF circuits to easily accommodate irregular free space and achieve organic system form factors more easily. Many of the connections in the FF circuit were reduced to lengths of zero through the use of component-to-component connections. Systems that require optimal volume utilization with a reduction to overall weight would greatly benefit from FF fabrication.

5.2 Future Work

Out of the two prototypes that were constructed using the FF method, only one was built to be reprogrammable. Thin wire was used to extend past the potting epoxy allowing a set of small clamps to connect to the micro-controller for programming. To improve future prototypes and to allow the ability for experimenting with different regulation code a different method for reprogramming is advised. It is recommended that the new connection method be in the form of internal pin sockets. This would allow for a more structurally secure and reliable connection without the risk of breaking wire that extrude from the underside of the base.

Further reduction to the size and weight of the prototypes could be achieved through the slight reductions in the protective printed housing placed over the FF circuit. The amount of epoxy used to add structure and strength to the enclosed prototype could be reduced to cover the upper half of the connecting pins instead of covering all the way to their flared base.

The power consumption of the prototypes could be reduced slightly by reducing the input voltage from 5V to 3.3V. Due to electrical component shortages during covid, the initial design used a MOSFET that could run as desired off of a 3.3V input. This could reduce the power consumption from the maximum 53.4 mW observed for both prototypes.

The construction of the hybrid CW ladders were conducted using a manual pick and place during the FF building process. Their assembly could be automated using a robotic pick and place along with a reflow oven. The settings used to reflow the solder paste would need to be optimized to reduce movement of the diodes on top of the capacitors. Using an automated process would speed up the construction and result in hybrid CW ladders that are more consistent in their features. The inclusion of the entire high-voltage supply section could be added to an automatic pick and place process with slight modifications to part placement and the use of different temporary scaffolding. Having parts stacking vertically with cutouts

keeping parts in place could allow for the entire high-voltage supply to be assembled and then reflowed in an oven. This would reduce the need for subsections to be connected in parts with some temporary supports being removed entirely.

It is recommended that the stencils used for the feedback section of the circuit be altered in some aspects to allow for increased restriction of the placed parts. These added restrictions could be implemented in the form of additional layers or overhangs to hold the smaller components in place during connections. The main issue that would be solved from this minor alteration is the surface tension of the reflowed solder paste can unintentionally envelop smaller components and drags them from their designated spot. Additionally, a more complex scaffolding system could allow for parts to be placed along with channels or tunnels being used to form solder or thin wired connections.

The use of some form of spot laser welding could be used to aid in the localized reflow of dispensed solder paste. The different orientations used in the construction of the HVPS and the spots where components branch off directly from one another would be improved with a more controlled localized reflow of solder paste. A quick localized reflow would reduce issues of accidental movement in nearby locations caused by the prolonged heat of a soldering iron that spreads through the circuit the longer it is used. This method could also be automated in some locations which could remove the need for large sections of temporary scaffolding.

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Appendix A

Reference Materials

Appendix A contains the full circuit schematic and bill of materials adapted from the previous work conducted in phase 1.^{[2](#)}

A.1 High-Voltage Power Supply and BOM

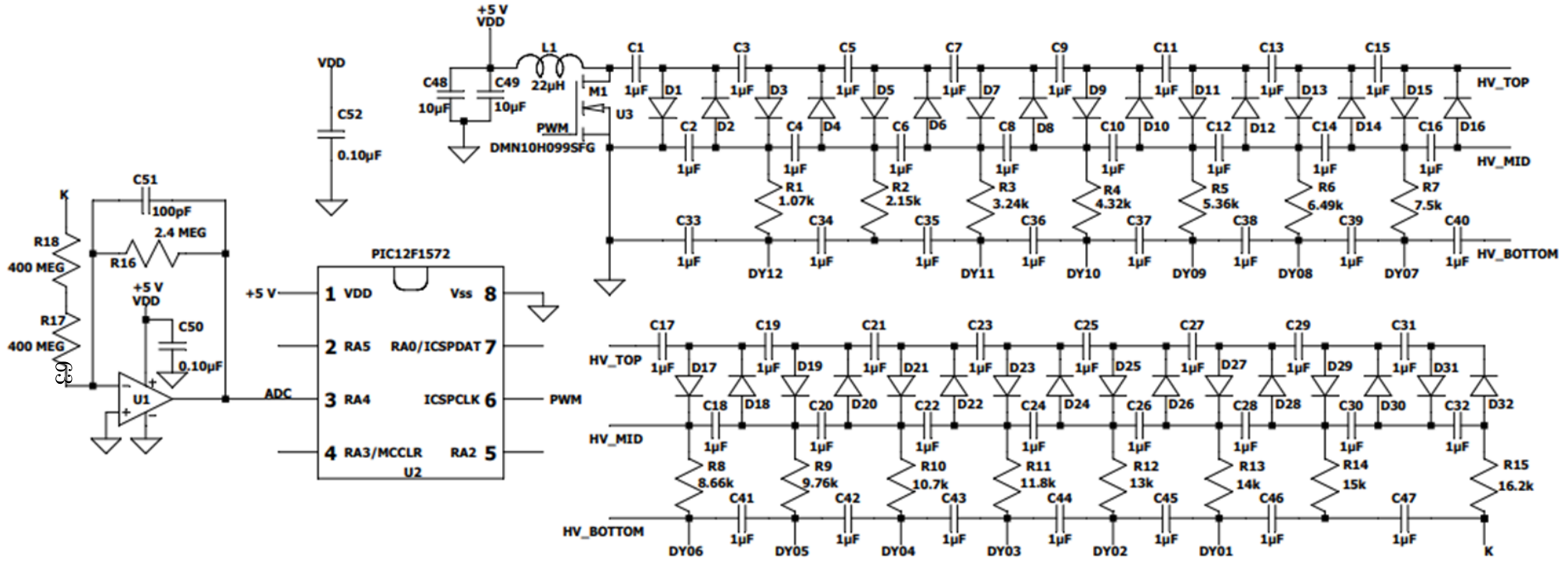


Figure A.1: Full circuit schematic for prototype using a half-wave Cockcroft-Walton ladder with charge pump and regulation.

Table A.1: *Bill of material for all prototypes.*

Name	Description	Designate	Quantity	Manufacturer	Part Number
100pF Capacitor	CAP CER 100PF 50V NP0 0603	C51	1	TDK Corporation	C1608NP01H101J080AA
0.10 μ F Capacitor	CAP CER 0.10 μ F 100V X7S 0805	C50, C52	2	KEMET	C0603C104J5RAC7867
1.0 μ F Capacitor	CAP CER 1.0 μ F 100V X7S 0603	C1-C47	47	TDK Corporation	C2012X7S2A105M125AE
10 μ F Capacitor	CAP CER 10 μ F 6.3V JB 0603	C48,C49	2	TDK Corporation	C1608JB0J106K080AB
Diode	100V 200mA (DC) Surface Mount SOD-523	D1-D32	32	Onsemi	1SS400T1G
22 μ H Inductor	FIXED IND 22 μ H 1.8A 89 M Ω SMD	L1	1	Würth Electronics	74404064220
PIC12F1572	PIC12F1272 Microcontroller IC 8-bit 32 MHz 3.5KB (2K x 14) FLASH 8-DFN (3x3)	U2	1	Microchip	PIC12F1572-I/MF
Op-Amp	IC OPAMP BU7445HFV-TR GP 1 CIRCUIT HVSOF5	U1	1	Rohm	BU7445HFV-TR
N-FET MOSFET	MOSFET N-CH 100V 4.2A POWERDI3333-8	U3	1	Diodes Incorporated	DMN10H099SFG

Table A.2: *Bill of material for all prototypes.*

Name	Description	Designate	Quantity	Manufacturer	Part Number
1.07k Ω Resistor	RES SMD 1.07 K Ω 0.1% 1/16W 0402	R1	1	Panasonic	ERA-2AEB1071X
2.15k Ω Resistor	RES SMD 2.15 K Ω 0.1% 1/16W 0402	R2	1	YAGEO	RC0402FR-072K15L
3.24k Ω Resistor	RES SMD 3.24 K Ω 0.1% 1/16W 0402	R3	1	YAGEO	RT0402BRD073K24L
4.32k Ω Resistor	RES SMD 4.32 K Ω 1% 1/16W 0402	R4	1	YAGEO	RC0402FR-074K32L
5.36k Ω Resistor	RES SMD 5.36 K Ω 1% 1/16W 0402	R5	1	YAGEO	RC0402FR-075K36L
6.49k Ω Resistor	RES SMD 6.49 K Ω 1% 1/16W 0402	R6	1	YAGEO	RC0402FR-076K49L
7.5k Ω Resistor	RES SMD 7.5 K Ω 5% 1/16W 0402	R7	1	YAGEO	RC0402FR-077K5L
8.66k Ω Resistor	RES SMD 8.66 K Ω 1% 1/16W 0402	R8	1	YAGEO	RC0402FR-078K66L
9.76k Ω Resistor	RES SMD 9.76 K Ω 1% 1/16W 0402	R9	1	YAGEO	RC0402FR-079K76L
10.7k Ω Resistor	RES SMD 10.7 K Ω 0.1% 1/16W 0402	R10	1	YAGEO	RT0402BRD0710K7L
11.8k Ω Resistor	RES SMD 11.8 K Ω 1% 1/16W 0402	R11	1	YAGEO	RC0402FR-0711K8L
13k Ω Resistor	RES SMD 13 K Ω 1% 1/16W 0402	R12	1	YAGEO	RC0402FR-0713KL
14k Ω Resistor	RES SMD 14 K Ω 0.1% 1/16W 0402	R13	1	YAGEO	RT0402BRD0714KL

Table A.3: *Bill of material for all prototypes.*

Name	Description	Designate	Quantity	Manufacturer	Part Number
15k Ω Resistor	RES SMD 15 K Ω 0.1% 1/16W 0402	R14	1	YAGEO	RT0402BRD0715KL
16.2k Ω Resistor	RES SMD 16.2 K Ω 1% 1/16W 0402	R15	1	YAGEO	RC0402FR-0716K2L
2.4M Ω Resistor	RES SMD 2.4 M Ω 1% 1/1W 0603	R16	1	YAGEO	AC0603FR-072M4L
400M Ω Resistor	RES SMD 400 M Ω 5% 1206	R17, R18	2	Vishay Dale	CRHV1206AF400MJNE5

Appendix B

Spectral Analysis Python Code

```
1 import matplotlib.pyplot as plt
2 import numpy as np
3 from os import listdir
4 from os.path import isfile, join
5 import os
6 import time
7 import datetime
8 import pandas as pd
9 plt.rcParams['font.family']='Times␣New␣Roman'
10 plt.rcParams['font.weight']='normal'
11 # plt.close('all')
12 %% Functions here
13 def read_list_mode(files_folder_dir, master_folder):
14     filenames = [f for f in listdir(files_folder_dir)
15                  if isfile(join(files_folder_dir, f))]
16     times = []
17     energies = []
18     energy_shorts = []
19     csv_files = []
20     info_files = []
21     real_times = []
```



```

22     for i in range(len(filenamees)):
23         if filenamees[i].endswith('.csv'):
24             csv_files.append(filenamees[i])
25         else:
26             pass
27     info_filenames = [f for f in listdir(master_folder)
28                       if isfile(join(master_folder, f))]
29     for i in range(len(info_filenames)):
30         if info_filenames[i].endswith('.info'):
31             info_files.append(os.path.join(master_folder,
32                                             info_filenames[i]))
33         else:
34             pass
35
36     for i in range(len(csv_files)):
37         file_dir = os.path.join(files_folder_dir, csv_files[i])
38         print('Current_list-mode_file:', file_dir, '\n')
39         df = pd.read_csv(file_dir, delimiter=';',
40                           usecols=['TIMETAG', 'ENERGY'])
41         timetag_temp = df.iloc[:,0].tolist() # channel number
42         energy_temp = df.iloc[:,1].tolist() # timetag
43         times.extend(timetag_temp)
44         energies.extend(energy_temp)
45
46     for j in range(len(info_files)):
47         info_data = open(info_files[j])
48         info_data_lines = info_data.readlines()
49         real_time_temp = info_data_lines[3]
50         real_time_temp = real_time_temp[-9:].split(':')
51         real_time_temp = (int(real_time_temp[0])*
52                           3600+int(real_time_temp[1])*
53                           60+int(real_time_temp[2]))
54         real_times.append(real_time_temp)

```

```

55     # note that all times are in picoseconds,the first timetag
56     # is the amount of time between the start of the measurement
57     # and the first count received
58     return times, energies, real_times
59 # note that all times are in ps, the first timetag is the amount of
60 # time between the start of the measurement and the first count received
61 def pulse_reader(pulse_folder):
62     filenames = [f for f in listdir(pulse_folder)
63                  if isfile(join(pulse_folder, f))]
64     csv_files = []
65     for i in range(len(filenames)):
66         if filenames[i].endswith('.csv'):
67             csv_files.append(filenames[i])
68         else:
69             pass
70     for i in range(len(csv_files)):
71         file_dir = os.path.join(pulse_folder, csv_files[i])
72         ptimes, psamples = np.loadtxt(file_dir, delimiter = ',',
73                                       usecols = [3,4], unpack=True)
74         ptimes = ptimes-np.min(ptimes) # fixes offset so times don't
75                                       # start as negatives
76
77     return ptimes, psamples
78
79 def rebin(input_spec, target_bins): # spectrum is in channels,
80                                     # not energy calibrated
81     rebinned_spec = np.zeros((target_bins,1))
82     intervals = int(np.floor(len(input_spec)/target_bins))
83     # print('Channel reduction factor from rebinning: ',intervals)
84     for i in range(target_bins):
85         rebinned_spec[i] = np.sum(input_spec[i*intervals:i*
86                                             intervals+intervals])
87     if len(input_spec)%target_bins != 0 and i==target_bins-1:

```

```

88         rebinned_spec[i] = rebinned_spec[i]
89         +np.sum(input_spec[(intervals*target_bins)-len(input_spec):])
90     return rebinned_spec
91
92     """ Start actual code here, begin with reading list mode data file
93     # Prototype 2 BKG
94     print('File reading started.\n')
95     lm_folder1 = (r"C:\Users\Samuel\Desktop\PMT_Data\2-8-23_FF6_PHA\2-8-23
        _FF6_Attenuation20dB_BKG\UNFILTERED")
96     lm_folder_master1 = os.path.dirname(lm_folder1)
97     lm_times1, lm_energies1, lm_run1 = read_list_mode(lm_folder1,
        lm_folder_master1)
98     save_name1 = 'Prototype_2-PHA-BKG-SpectraPlot.png'
99
100     start_len1 = 2048
101     bin_len1 = 1024
102
103     energy_spectrum1 = np.zeros((start_len1,1))
104     for i in range(len(lm_energies1)):
105         temp_val = int(lm_energies1[i])
106         energy_spectrum1[temp_val] += 1
107
108     energy_spectrum1 = rebin(energy_spectrum1, bin_len1)
109     energy_spectrum1 = np.divide(energy_spectrum1,lm_run1[0])# Count rate
        correct
110     print('The count rate for the entire spectrum is', np.round((np.sum(
        energy_spectrum1)),2), 'cps.\n')
111
112     x_list1 = np.linspace(0,bin_len1,bin_len1)
113     x_list1 = np.reshape(x_list1,(bin_len1,1))
114     en_cal1 = [0.00000021672, 0.0029823, 0.0033701]
115     # energy calibration is for a rebinned 1024 spectrum using xray and .662
        cs peaks and Co peak

```

```

116 for i in range(len(x_list1)):
117     x_list1[i] = (x_list1[i]**2)*(en_cal1[0]) + en_cal1[1]*x_list1[i]-
        en_cal1[2]
118
119
120 roi_start1 = 0.636 # left side of FWHM ROI in MeV
121 roi_mid1 = 0.6617 # middle of FWHM ROI peak in MeV
122 roi_end1 = 0.6879 # right side FWHM of ROI peak in MeV
123
124 en_res1 = 100*((roi_end1-roi_start1)/roi_mid1) # FWHM of peak in percent
125 # print('The energy resolution at 662 keV is', np.round(en_res1,2), '%.\n
        ')
126 x_coords1 = [roi_start1, roi_mid1, roi_end1]
127 y_coord1 = 5
128
129 # Plot the spectrum with ROI showing
130 fig1 = plt.figure(1)
131 plt.plot(x_list1, energy_spectrum1)
132 plt.xlabel('Energy [MeV]')
133 plt.ylabel('Count_Rate [cps]')
134 plt.xlim(0,3)
135 plt.title("Prototype_2-PHA-BKG")
136 plt.yscale('log')
137 plt.grid()
138 plt.savefig(os.path.join(lm_folder1,save_name1),dpi=600,bbox_inches = '
        tight')
139 plt.show()
140
141 ###
142 # Prototype 2 Cs137
143 lm_folder2 = r"C:\Users\Samuel\Desktop\PMT_Data\2-8-23_FF6_PHA\2-8-23
        _FF6_Attenuation20dB_Cs137\UNFILTERED"
144 lm_folder_master2 = os.path.dirname(lm_folder2)

```

```

145 lm_times2, lm_energies2, lm_run2 = read_list_mode(lm_folder2,
    lm_folder_master2)
146 save_name2 = 'Prototype_2-PHA-Cs137-SideView-SpectraPlot.png'
147
148 start_len2 = 2048
149 bin_len2 = bin_len1
150
151 energy_spectrum2 = np.zeros((start_len2,1))
152 for i in range(len(lm_energies2)):
153     temp_val = int(lm_energies2[i])
154     energy_spectrum2[temp_val] += 1
155
156 energy_spectrum2 = rebin(energy_spectrum2, bin_len2)
157 energy_spectrum2 = np.divide(energy_spectrum2, lm_run2[0]) # Count rate
    correct
158 BS2 = energy_spectrum2 - energy_spectrum1
159 print('The count rate for the entire spectrum is', np.round((np.sum(BS2))
    ,2), 'cps.\n')
160
161 x_list2 = np.linspace(0, bin_len2, bin_len2)
162 x_list2 = np.reshape(x_list2, (bin_len2, 1))
163 en_cal2 = [0.00000021672, 0.0029823, 0.0033701]
164 # energy calibration is for a rebinned 1024 spectrum using xray and .662
    cs peaks and Co peak
165 for i in range(len(x_list2)):
166     x_list2[i] = (x_list2[i]**2)*(en_cal2[0]) + en_cal2[1]*x_list2[i] -
        en_cal2[2]
167
168 roi_start2 = 0.6383 # left side of FWHM ROI in MeV
169 roi_mid2 = 0.6617 # middle of FWHM ROI peak in MeV
170 roi_end2 = 0.68389 # right side FWHM of ROI peak in MeV
171
172 en_res2 = 100*((roi_end2-roi_start2)/roi_mid2) # FWHM of peak in percent

```

```

173 print('The energy resolution at 662 keV is', np.round(en_res2,2), '%.\n')
174 x_coords2 = [roi_start2, roi_mid2, roi_end2]
175 y_coord2 = 12
176
177 # Plot the spectrum with ROI showing
178 fig2 = plt.figure(2)
179 plt.plot(x_list2, BS2)
180 plt.vlines(x_coords2, ymin=0, ymax=y_coord2)
181 plt.xlabel('Energy [MeV]')
182 plt.ylabel('Count Rate [cps]')
183 plt.xlim(0,3)
184 plt.title("Prototype 2-PHA-Cs137: Side View")
185 plt.yscale('log')
186 plt.grid()
187 plt.savefig(os.path.join(lm_folder2, save_name2), dpi=600, bbox_inches = '
    tight')
188 plt.show()
189
190 ###
191 # Prototype 2 Co60
192 lm_folder3 = r"C:\Users\Samuel\Desktop\PMT_Data\2-8-23_FF6_PHA\2-8-23
    _FF6_Attenuation20dB_Co60\UNFILTERED"
193 lm_folder_master3 = os.path.dirname(lm_folder3)
194 lm_times3, lm_energies3, lm_run3 = read_list_mode(lm_folder3,
    lm_folder_master3)
195 save_name3 = 'Prototype_2-PHA-Co60-SideView-SpectraPlot.png'
196
197 start_len3 = 2048
198 bin_len3 = bin_len1
199 energy_spectrum3 = np.zeros((start_len3,1))
200 for i in range(len(lm_energies3)):
201     temp_val = int(lm_energies3[i])
202     energy_spectrum3[temp_val] += 1

```

```

203
204 energy_spectrum3 = rebin(energy_spectrum3, bin_len3)
205 energy_spectrum3 = np.divide(energy_spectrum3, lm_run3[0])# Count rate
    correct
206 fig3 = plt.figure(3)
207 BS3 = energy_spectrum3 - energy_spectrum1
208 print('The count rate for the entire spectrum is', np.round((np.sum(BS3))
    ,2), 'cps.\n')
209
210 x_list3 = np.linspace(0,bin_len3,bin_len3)
211 x_list3 = np.reshape(x_list3,(bin_len3,1))
212 en_cal3 = [0.00000021672, 0.0029823, 0.0033701]
213 # energy calibration is for a rebinned 1024 spectrum using xray and .662
    cs peaks and Co peak
214 for i in range(len(x_list3)):
215     x_list3[i] = (x_list3[i]**2)*(en_cal3[0]) + en_cal3[1]*x_list3[i]-
        en_cal3[2]
216
217 # Plot the spectrum with ROI showing
218 fig3 = plt.figure(3)
219 plt.plot(x_list3, BS3)
220 plt.xlabel('Energy [MeV]')
221 plt.ylabel('Count Rate [cps]')
222 plt.xlim(0,3)
223 plt.title("Prototype 2-PHA-Co60: Side View")
224 plt.yscale('log')
225 plt.grid()
226 plt.savefig(os.path.join(lm_folder3,save_name3),dpi=600,bbox_inches = '
    tight')
227 plt.show()
228
229 ###
230 # Prototype 2 Na22

```



```

231 lm_folder4 = r"C:\Users\Samuel\Desktop\PMT_Data\2-8-23_FF6_PHA\2-8-23
      _FF6_Attenuation20dB_Na22\UNFILTERED"
232
233 lm_folder_master4 = os.path.dirname(lm_folder4)
234 lm_times4, lm_energies4, lm_run4 = read_list_mode(lm_folder4,
      lm_folder_master4)
235 save_name4 = 'Prototype_2-PHA-Na22-SideView-SpectraPlot.png'
236
237 start_len4 = 2048
238 bin_len4 = bin_len1
239 energy_spectrum4 = np.zeros((start_len4,1))
240 for i in range(len(lm_energies4)):
241     temp_val = int(lm_energies4[i])
242     energy_spectrum4[temp_val] += 1
243
244 energy_spectrum4 = rebin(energy_spectrum4, bin_len4)
245 energy_spectrum4 = np.divide(energy_spectrum4, lm_run4[0]) # Count rate
      correct
246 fig4 = plt.figure(4)
247 BS4 = energy_spectrum4 - energy_spectrum1
248 print('The count rate for the entire spectrum is', np.round((np.sum(BS4))
      ,2), 'cps.\n')
249
250 x_list4 = np.linspace(0, bin_len4, bin_len4)
251 x_list4 = np.reshape(x_list4, (bin_len4, 1))
252 en_cal4 = [0.00000021672, 0.0029823, 0.0033701]
253 # energy calibration is for a rebinned 1024 spectrum using xray and .662
      cs peaks and Co peak
254 for i in range(len(x_list4)):
255     x_list4[i] = (x_list4[i]**2)*(en_cal4[0]) + en_cal4[1]*x_list4[i] -
      en_cal4[2]
256
257 # Plot the spectrum with ROI showing

```

```

258 fig4 = plt.figure(4)
259 plt.plot(x_list4, BS4)
260 plt.xlabel('Energy [MeV]')
261 plt.ylabel('Count Rate [cps]')
262 plt.xlim(0,3)
263 plt.title("Prototype 2-PHA-Na22: Side View")
264 plt.yscale('log')
265 plt.grid()
266 plt.savefig(os.path.join(lm_folder4, save_name4), dpi=600, bbox_inches = '
    tight')
267 plt.show()
268
269 ###
270 # Prototype 1 BKG
271 lm_folder6 = r"C:/Users/Samuel/Desktop/PMT_Data/9-19-22_PHA/9-19-22_FF
    /9-19-22_FF3_Attenuation20dB_BKG/UNFILTERED"
272
273 lm_folder_master6 = os.path.dirname(lm_folder6)
274 lm_times6, lm_energies6, lm_run6 = read_list_mode(lm_folder6,
    lm_folder_master6)
275 save_name6 = 'Prorotype_1-PHA-BKG-SideView-SpectraPlot.png'
276
277 start_len6 = 2048
278 bin_len6 = bin_len1
279 energy_spectrum6 = np.zeros((start_len6,1))
280 for i in range(len(lm_energies6)):
281     temp_val = int(lm_energies6[i])
282     energy_spectrum6[temp_val] += 1
283
284 energy_spectrum6 = rebin(energy_spectrum6, bin_len6)
285 energy_spectrum6 = np.divide(energy_spectrum6, lm_run6[0]) # Count rate
    correct
286 fig6 = plt.figure(6)

```

```

287 print('The count rate for the entire spectrum is', np.round((np.sum(
    energy_spectrum6)),2), 'cps.\n')
288
289 x_list6 = np.linspace(0,bin_len6,bin_len6)
290 x_list6 = np.reshape(x_list6,(bin_len6,1))
291 en_cal6 = [0.00000021027, 0.0029382, 0.0033774]
292 # energy calibration is for a rebinned 1024 spectrum using xray and .662
    cs peaks and Co peak
293 for i in range(len(x_list6)):
294     x_list6[i] = (x_list6[i]**2)*(en_cal6[0]) + en_cal6[1]*x_list6[i]-
    en_cal6[2]
295
296 # Plot the spectrum with ROI showing
297 fig6 = plt.figure(6)
298 plt.plot(x_list6, energy_spectrum6)
299 plt.xlabel('Energy [MeV]')
300 plt.ylabel('Count Rate [cps]')
301 plt.xlim(0,3)
302 plt.title("Prototype 1-PHA-BKG: Side View")
303 plt.yscale('log')
304 plt.grid()
305 plt.savefig(os.path.join(lm_folder6,save_name6),dpi=600,bbox_inches = '
    tight')
306 plt.show()
307
308 ###
309 # Prototype 1 Cs137
310 lm_folder7 = r"C:/Users/Samuel/Desktop/PMT_Data/9-19-22_PHA/9-19-22_FF
    /9-19-22_FF3_Attenuation20dB_Cs137/UNFILTERED"
311
312 lm_folder_master7 = os.path.dirname(lm_folder7)
313 lm_times7, lm_energies7, lm_run7 = read_list_mode(lm_folder7,
    lm_folder_master7)

```

```

314 save_name7 = 'Prototype_1-PHA-Cs137-SideView-SpectraPlot.png'
315
316 start_len7 = 2048
317 bin_len7 = bin_len1
318 energy_spectrum7 = np.zeros((start_len7,1))
319 for i in range(len(lm_energies7)):
320     temp_val = int(lm_energies7[i])
321     energy_spectrum7[temp_val] += 1
322
323 energy_spectrum7 = rebin(energy_spectrum7, bin_len7)
324 energy_spectrum7 = np.divide(energy_spectrum7, lm_run7[0]) # Count rate
    correct
325 fig7 = plt.figure(7)
326 BS7=energy_spectrum7-energy_spectrum6
327
328 print('The count rate for the entire spectrum is', np.round((np.sum(BS7))
    ,2), 'cps.\n')
329
330 x_list7 = np.linspace(0,bin_len7,bin_len7)
331 x_list7 = np.reshape(x_list7,(bin_len7,1))
332 en_cal7 = [0.00000021027, 0.0029382, 0.0033774]
333 # energy calibration is for a rebinned 1024 spectrum using xray and .662
    cs peaks and Co peak
334 for i in range(len(x_list7)):
335     x_list7[i] = (x_list7[i]**2)*(en_cal7[0]) + en_cal7[1]*x_list7[i]-
        en_cal7[2]
336
337 roi_start7 = 0.637 # left side of FWHM ROI in MeV
338 roi_mid7 = 0.6617 # middle of FWHM ROI peak in MeV
339 roi_end7 = 0.687 # right side FWHM of ROI peak in MeV
340
341 en_res7 = 100*((roi_end7-roi_start7)/roi_mid7) # FWHM of peak in percent

```

```

342 # print('The energy resolution at 662 keV is', np.round(en_res7,2), '%.\n
    ')
343 x_coords7 = [roi_start7, roi_mid7, roi_end7]
344 y_coord7 = 15
345
346 # Plot the spectrum with ROI showing
347 fig7 = plt.figure(7)
348 plt.plot(x_list7, BS7)
349 # plt.vlines(x_coords7, ymin=0, ymax=y_coord7)
350 plt.xlabel('Energy [MeV]')
351 plt.ylabel('Count Rate [cps]')
352 plt.xlim(0,3)
353 plt.title("Prototype 1-PHA-Cs137: Side View")
354 plt.yscale('log')
355 plt.grid()
356 plt.savefig(os.path.join(lm_folder7, save_name7), dpi=600, bbox_inches = '
    tight')
357 plt.show()
358
359 ###
360 # Prototype 1 Co60
361 lm_folder8 = r"C:/Users/Samuel/Desktop/PMT_Data/9-19-22_PHA/9-19-22_FF
    /9-19-22_FF3_Attenuation20dB_Co60/UNFILTERED"
362
363 lm_folder_master8 = os.path.dirname(lm_folder8)
364 lm_times8, lm_energies8, lm_run8 = read_list_mode(lm_folder8,
    lm_folder_master8)
365 save_name8 = 'Prototype_1-PHA-Co60-SideView-SpectraPlot.png'
366
367 start_len8 = 2048
368 bin_len8 = bin_len1
369 energy_spectrum8 = np.zeros((start_len8,1))
370 for i in range(len(lm_energies8)):

```

```

371     temp_val = int(lm_energies8[i])
372     energy_spectrum8[temp_val] += 1
373
374 energy_spectrum8 = rebin(energy_spectrum8, bin_len8)
375 energy_spectrum8 = np.divide(energy_spectrum8, lm_run8[0])# Count rate
    correct
376 fig8 = plt.figure(8)
377 BS8=energy_spectrum8-energy_spectrum6
378 print('The count rate for the entire spectrum is', np.round((np.sum(BS8))
    ,2), 'cps.\n')
379
380 x_list8 = np.linspace(0,bin_len8,bin_len8)
381 x_list8 = np.reshape(x_list8,(bin_len8,1))
382 en_cal8 = [0.00000021027, 0.0029382, 0.0033774]
383 # energy calibration is for a rebinned 1024 spectrum using xray and .662
    cs peaks and Co peak
384 for i in range(len(x_list8)):
385     x_list8[i] = (x_list8[i]**2)*(en_cal8[0]) + en_cal8[1]*x_list8[i]-
        en_cal8[2]
386
387 # Plot the spectrum with ROI showing
388 fig8 = plt.figure(8)
389
390 plt.plot(x_list8, BS8)
391 plt.xlabel('Energy [MeV]')
392 plt.ylabel('Count Rate [cps]')
393 plt.xlim(0,3)
394 plt.title("Prototype 1-PHA-Co60: Side View")
395 plt.yscale('log')
396 plt.grid()
397 plt.savefig(os.path.join(lm_folder8,save_name8),dpi=600,bbox_inches = '
    tight')
398 plt.show()

```

```

399
400 ###
401 # Prototype 1 Na22
402 lm_folder9 = r"C:/Users/Samuel/Desktop/PMT_Data/9-19-22_PHA/9-19-22_FF
      /9-19-22_FF3_Attenuation20dB_Na22/UNFILTERED"
403
404 lm_folder_master9 = os.path.dirname(lm_folder9)
405 lm_times9, lm_energies9, lm_run9 = read_list_mode(lm_folder9,
      lm_folder_master9)
406 save_name9 = 'Prototype_1-PHA-Na22-SideView-SpectraPlot.png'
407
408 start_len9 = 2048
409 bin_len9 = bin_len1
410
411 energy_spectrum9 = np.zeros((start_len9,1))
412 for i in range(len(lm_energies9)):
413     temp_val = int(lm_energies9[i])
414     energy_spectrum9[temp_val] += 1
415
416 energy_spectrum9 = rebin(energy_spectrum9, bin_len9)
417 energy_spectrum9 = np.divide(energy_spectrum9,lm_run9[0])# Count rate
      correct
418 fig9 = plt.figure(9)
419 BS9 = energy_spectrum9 - energy_spectrum6
420 print('The count rate for the entire spectrum is', np.round((np.sum(BS9))
      ,2), 'cps.\n')
421
422 x_list9 = np.linspace(0,bin_len9,bin_len9)
423 x_list9 = np.reshape(x_list9,(bin_len9,1))
424 en_cal9 = [0.00000021027, 0.0029382, 0.0033774]
425 # energy calibration is for a rebinned 1024 spectrum using xray and .662
      cs peaks and Co peak
426 for i in range(len(x_list9)):

```

```

427     x_list9[i] = (x_list9[i]**2)*(en_cal9[0]) + en_cal9[1]*x_list9[i]-
        en_cal9[2]

428

429 # Plot the spectrum with ROI showing
430 fig9 = plt.figure(9)
431 plt.plot(x_list9, BS9)
432 plt.xlabel('Energy [MeV]')
433 plt.ylabel('Count Rate [cps]')
434 plt.xlim(0,3)
435 plt.title("Prototype 1-PHA-Na22: Side View")
436 plt.yscale('log')
437 plt.grid()
438 plt.savefig(os.path.join(lm_folder9, save_name9), dpi=600, bbox_inches = '
        tight')
439 plt.show()
440

441 ### Spectrum 11
442 # E11807-01 BKG
443 lm_folder11 = r"C:/Users/Samuel/Desktop/PMT_Data/9-19-22_PHA/9-19-22_Hama
        /9-19-22_Hama_Attenuation20dB_BKG/UNFILTERED"
444 lm_folder_master11 = os.path.dirname(lm_folder11)
445 lm_times11, lm_energies11, lm_run11 = read_list_mode(lm_folder11,
        lm_folder_master11)
446 save_name11 = 'Hama-PHA-BKG-SideView-SpectraPlot.png'
447

448 start_len11 = 2048
449 bin_len11 = bin_len1
450 energy_spectrum11 = np.zeros((start_len11,1))
451 for i in range(len(lm_energies11)):
452     temp_val = int(lm_energies11[i])
453     energy_spectrum11[temp_val] += 1
454

455 energy_spectrum11 = rebin(energy_spectrum11, bin_len11)

```



```

456 energy_spectrum11 = np.divide(energy_spectrum11,lm_run11[0])# Count rate
    correct
457 fig11 = plt.figure(11)
458
459 print('The count rate for the entire spectrum is', np.round((np.sum(
    energy_spectrum11)),2), 'cps.\n')
460
461 x_list11 = np.linspace(0,bin_len11,bin_len11)
462 x_list11 = np.reshape(x_list11,(bin_len11,1))
463 en_cal11 = [0.000000086333, 0.0029315, 0.0036015]
464 # energy calibration is for a rebinned 1024 spectrum using xray and .662
    cs peaks and Co peak
465 for i in range(len(x_list11)):
466     x_list11[i] = (x_list11[i]**2)*(en_cal11[0]) + en_cal11[1]*x_list11[i
    ]- en_cal11[2]
467
468 # Plot the spectrum with ROI showing
469 fig11 = plt.figure(11)
470 plt.plot(x_list11, energy_spectrum11)
471 plt.xlabel('Energy [MeV]')
472 plt.ylabel('Count Rate [cps]')
473 plt.xlim(0,3)
474 plt.yscale('log')
475 plt.grid()
476 plt.savefig(os.path.join(lm_folder11,save_name11),dpi=600,bbox_inches = '
    tight')
477 plt.show()
478
479 ###
480 # E11807-01 Cs137
481 lm_folder12 = r"C:/Users/Samuel/Desktop/PMT_Data/9-19-22_PHA/9-19-22_Hama
    /9-19-22_Hama_Attenuation20dB_Cs137/UNFILTERED"
482 lm_folder_master12 = os.path.dirname(lm_folder12)

```

```

483 lm_times12, lm_energies12, lm_run12 = read_list_mode(lm_folder12,
    lm_folder_master12)
484 save_name12 = 'Hama-PHA-Cs137-SideView-SpectraPlot.png'
485
486 start_len12 = 2048
487 bin_len12 = bin_len1
488 energy_spectrum12 = np.zeros((start_len12,1))
489 for i in range(len(lm_energies12)):
490     temp_val = int(lm_energies12[i])
491     energy_spectrum12[temp_val] += 1
492
493 energy_spectrum12 = rebin(energy_spectrum12, bin_len12)
494 energy_spectrum12 = np.divide(energy_spectrum12,lm_run12[0])# Count rate
    correct
495 fig12 = plt.figure(12)
496 BS12=energy_spectrum12-energy_spectrum11
497 print('The count rate for the entire spectrum is', np.round((np.sum(BS12))
    ,2), 'cps.\n')
498
499 x_list12 = np.linspace(0,bin_len12,bin_len12)
500 x_list12 = np.reshape(x_list12,(bin_len12,1))
501 en_cal12 = [0.000000086333, 0.0029315, 0.0036015]
502 # energy calibration is for a rebinned 1024 spectrum using xray and .662
    cs peaks and Co peak
503 for i in range(len(x_list12)):
504     x_list12[i] = (x_list12[i]**2)*(en_cal12[0]) + en_cal12[1]*x_list12[i
    ]- en_cal12[2]
505
506 roi_start12 = 0.637 # left side of FWHM ROI in MeV
507 roi_mid12 = 0.6617 # middle of FWHM ROI peak in MeV
508 roi_end12 = 0.687 # right side FWHM of ROI peak in MeV
509

```

```

510 en_res12 = 100*((roi_end12-roi_start12)/roi_mid12) # FWHM of peak in
    percent
511 # print('The energy resolution at 662 keV is', np.round(en_res12,2), '%.\n
    ')
512 x_coords12 = [roi_start12, roi_mid12, roi_end12]
513 y_coord12 = 13
514
515 # Plot the spectrum with ROI showing
516 fig12 = plt.figure(12)
517 plt.plot(x_list12, BS12)
518 # plt.vlines(x_coords12, ymin=0, ymax=y_coord12)
519 plt.xlabel('Energy [MeV]')
520 plt.ylabel('Count Rate [cps]')
521 plt.xlim(0,3)
522 plt.title("E11807-01-PHA-Cs137: Side View")
523 plt.yscale('log')
524 plt.grid()
525 plt.savefig(os.path.join(lm_folder12, save_name12), dpi=600, bbox_inches = '
    tight')
526 plt.show()
527
528 ###
529 # E11807-01 Co60
530 lm_folder13 = r"C:/Users/Samuel/Desktop/PMT_Data/9-19-22_PHA/9-19-22_Hama
    /9-19-22_Hama_Attenuation20dB_Co60/UNFILTERED"
531 lm_folder_master13 = os.path.dirname(lm_folder13)
532 lm_times13, lm_energies13, lm_run13 = read_list_mode(lm_folder13,
    lm_folder_master13)
533 save_name13 = 'Hama-PHA-Co60-SideView-SpectraPlot.png'
534
535 start_len13 = 2048
536 bin_len13 = bin_len1
537

```

```

538 energy_spectrum13 = np.zeros((start_len13,1))
539 for i in range(len(lm_energies13)):
540     temp_val = int(lm_energies13[i])
541     energy_spectrum13[temp_val] += 1
542
543 energy_spectrum13 = rebin(energy_spectrum13, bin_len13)
544 energy_spectrum13 = np.divide(energy_spectrum13,lm_run13[0])# Count rate
    correct
545 fig13 = plt.figure(13)
546 BS13 = energy_spectrum13-energy_spectrum11
547 print('The count rate for the entire spectrum is', np.round((np.sum(BS13))
    ,2), 'cps.\n')
548
549
550 x_list13 = np.linspace(0,bin_len13,bin_len13)
551 x_list13 = np.reshape(x_list13,(bin_len13,1))
552 en_cal13 = [0.000000086333, 0.0029315, 0.0036015]
553 # energy calibration is for a rebinned 1024 spectrum using xray and .662
    cs peaks and Co peak
554 for i in range(len(x_list13)):
555     x_list13[i] = (x_list13[i]**2)*(en_cal13[0]) + en_cal13[1]*x_list13[i
    ]- en_cal13[2]
556
557
558 # Plot the spectrum with ROI showing
559 fig13 = plt.figure(13)
560 plt.plot(x_list13, BS13)
561 plt.xlabel('Energy [MeV]')
562 plt.ylabel('Count Rate [cps]')
563 plt.xlim(0,3)
564 plt.title("E11807-01-PHA-Co60-Side View")
565 plt.yscale('log')
566 plt.grid()

```

```

567 plt.savefig(os.path.join(lm_folder13,save_name13),dpi=600,bbox_inches = '
    tight')
568 plt.show()
569
570 ###
571 # E11807-01 Na22
572 lm_folder14 = r"C:/Users/Samuel/Desktop/PMT_Data/9-19-22_PHA/9-19-22_Hama
    /9-19-22_Hama_Attenuation20dB_Na22/UNFILTERED"
573 lm_folder_master14 = os.path.dirname(lm_folder14)
574 lm_times14, lm_energies14, lm_run14 = read_list_mode(lm_folder14,
    lm_folder_master14)
575 save_name14 = 'Hama-PHA-Na22-SideView-SpectraPlot.png'
576
577 start_len14 = 2048
578 bin_len14 = bin_len1
579 energy_spectrum14 = np.zeros((start_len14,1))
580 for i in range(len(lm_energies14)):
581     temp_val = int(lm_energies14[i])
582     energy_spectrum14[temp_val] += 1
583
584 energy_spectrum14 = rebin(energy_spectrum14, bin_len14)
585 energy_spectrum14 = np.divide(energy_spectrum14,lm_run14[0])# Count rate
    correct
586 fig14 = plt.figure(14)
587 BS14=energy_spectrum14-energy_spectrum11
588 print('The count rate for the entire spectrum is', np.round((np.sum(BS14))
    ,2), 'cps.\n')
589
590
591 x_list14 = np.linspace(0,bin_len14,bin_len14)
592 x_list14 = np.reshape(x_list14,(bin_len14,1))
593 en_cal14 = [0.000000086333, 0.0029315, 0.0036015]

```

```

594 # energy calibration is for a rebinned 1024 spectrum using xray and .662
      cs peaks and Co peak
595 for i in range(len(x_list14)):
596     x_list14[i] = (x_list14[i]**2)*(en_cal14[0]) + en_cal14[1]*x_list14[i
      ]- en_cal14[2]
597
598 # Plot the spectrum with ROI showing
599 fig14 = plt.figure(14)
600 plt.plot(x_list14, BS14)
601 plt.xlabel('Energy [MeV]')
602 plt.ylabel('Count_Rate [cps]')
603 plt.xlim(0,3)
604 plt.title("E11807-01-PHA-Na22: Side View")
605 plt.yscale('log')
606 plt.grid()
607 plt.savefig(os.path.join(lm_folder14, save_name14), dpi=600, bbox_inches = '
      tight')
608 plt.show()
609
610 %%
611 # Combined Spectra BKG
612 fig16 = plt.figure(16) # Plots several spectra
613 plt.xlabel('Energy [MeV]')
614 plt.ylabel('Count_Rate [cps]')
615 plt.xlim(0,3)
616 plt.yscale('log')
617 plt.grid()
618 plt.plot(x_list6, energy_spectrum6)
619 plt.plot(x_list1, energy_spectrum1)
620 plt.plot(x_list11, energy_spectrum11)
621 plt.rcParams.update({'font.size': 22})
622 plt.rc('axes', labelsiz=22) # fontsize of the x and y labels
623 plt.title("Prototypes & E11807-01: BKG")

```

```

624 plt.legend(loc="upper_right", labels=('Prototype_1', 'Prototype_2', '
      E11807-01'))
625 #plt.savefig(os.path.join(lm_folder,save_name8),dpi=600,bbox_inches = '
      tight')
626 plt.show()
627
628 ###
629 # Combined Spectra Cs137
630 fig17 = plt.figure(17) # Plots several spectra
631 plt.xlabel('Energy [MeV]')
632 plt.ylabel('Count_Rate [cps]')
633 plt.xlim(0,3)
634 plt.yscale('log')
635 plt.grid()
636 plt.plot(x_list7, BS7)
637 plt.plot(x_list2, BS2)
638 plt.plot(x_list12, BS12)
639 plt.rcParams.update({'font.size': 22})
640 plt.rc('axes', labelsiz=22) # fontsize of the x and y labels
641 plt.title("Prototypes_&_E11807-01:_Cs137")
642 plt.legend(loc="upper_right", labels=('Prototype_1', 'Prototype_2', '
      E11807-01'))
643 #plt.savefig(os.path.join(lm_folder,save_name8),dpi=600,bbox_inches = '
      tight')
644 plt.show()
645
646 ###
647 # Combined Spectra Co60
648 fig18 = plt.figure(18) # Plots several spectra
649 plt.xlabel('Energy [MeV]')
650 plt.ylabel('Count_Rate [cps]')
651 plt.xlim(0,3)
652 plt.yscale('log')

```

```

653 plt.grid()
654 plt.plot(x_list8, BS8)
655 plt.plot(x_list3, BS3)
656 plt.plot(x_list13, BS13)
657 plt.rcParams.update({'font.size': 22})
658 plt.rc('axes', labelsiz=22)    # fontsize of the x and y labels
659 plt.title("Prototypes_&_E11807-01:_Co60")
660 plt.legend(loc="upper_right", labels=('Prototype_1', 'Prototype_2', '
        E11807-01'))
661 #plt.savefig(os.path.join(lm_folder, save_name8), dpi=600, bbox_inches = '
        tight')
662 plt.show()
663
664 ###
665 # Combined Spectra Na22
666 fig19 = plt.figure(19) # Plots several spectra
667 plt.xlabel('Energy_[MeV]')
668 plt.ylabel('Count_Rate_[cps]')
669 plt.xlim(0,3)
670 plt.yscale('log')
671 plt.grid()
672 plt.plot(x_list9, BS9)
673 plt.plot(x_list4, BS4)
674 plt.plot(x_list14, BS14)
675 plt.rcParams.update({'font.size': 22})
676 plt.rc('axes', labelsiz=22)    # fontsize of the x and y labels
677 plt.title("Prototypes_&_E11807-01:_Na22")
678 plt.legend(loc="upper_right", labels=('Prototype_1', 'Prototype_2', '
        E11807-01'))
679 #plt.savefig(os.path.join(lm_folder, save_name8), dpi=600, bbox_inches = '
        tight')
680 plt.show()

```