Signal Amplification from Photomultiplier Tubes

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Abstract

Understanding hadron structure is an important goal of modern nuclear physics. Exclusive reactions with neutral final states play an important role in allowing one to probe universal features of generalized parton distribution and to verify their formalism in thus far unexplored regimes. The Jefferson Lab 12 GeV upgrade provides the energies needed for precision neutral particle cross-section measurements in Hall C. A new $PbWO_4$ spectrometer provides a simple and economical option for neutral particle ID. As particles traverse the calorimeter's 1116 $PbWO_4$ blocks, scintillation occurs, which can be detected by 19-mm photomultiplier tubes (PMT's). The resulting signals are processed in a data acquisition system. Depending on module resolution, processing signals from these relatively small PMT's can be challenging. PMT's are sensitive enough to count single photons. However, the pulse heights for single photons and double photons are often indistinguishable. One way to address this problem is to amplify the PMT signal. We designed and constructed a prototype comparing the amplification provided by a typical LM741 operational amplifier (abbreviated as *op amp*) to a 595-THS3202D fast op amp. While both amplifiers are capable of adequate gain, the 741 is inadequate for the amplification of fast pulses from the PMT's.

1 Background

1.1 Photomultiplier Tubes

Photomultiplier Tubes (PMT's) are used in many types of modern electronic equipment as well as numerous kinds of particle detectors. The PMT's basic operating principle is based upon the photoelectric effect. The photoelectric effect occurs when a sufficiently energetic photon strikes the surface of a material, causing an electron to be ejected.

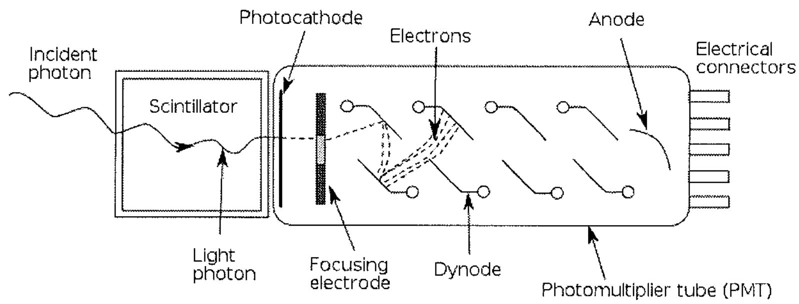

Figure 1: Photomultiplier tube with its main parts: photocell and electron multiplier. A photomultiplier's basic function is to detect single photons. Photo Source: `http://en.wikipedia.org/wiki/File:Photomultipliertube.svg`

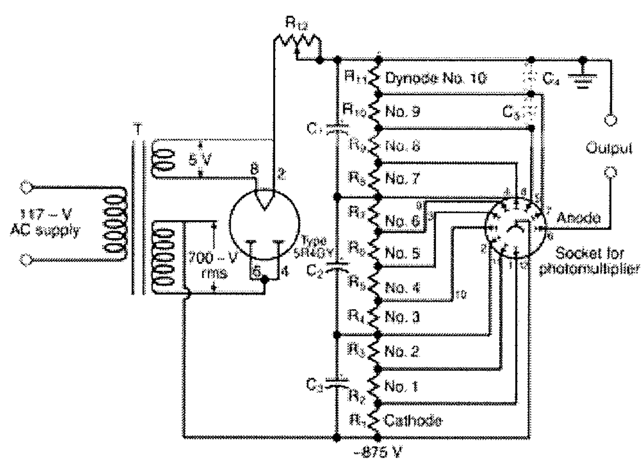

Figure 2: Schematic diagram of a photomultiplier with its dynodes tapped to different voltages on a potential divider. Photo Source: `http://cord.org/cm/leot/course04_mod08/8_fig20.jpg`

The resulting electron is then accelerated by a series of *dynodes* raised to a high potential (usually between 1.0 kV and 3.0 kV). The accelerated electron strikes the dynodes causing additional electrons to be ejected by secondary emission. A cascade effect occurs, producing a pulse comprised of thousands of released electrons from the dynodes. The signals produced by a photomultiplier tube are measurable, however the signal may not be sufficiently large to discern single photons from multiple photons. As a result, our group studied plausible amplifiers for amplifying the signals from a photomultiplier. Our two choice amplifiers were the 741 Operation Amplifier and the 595-THS3202D high speed operational amplifier.

Before the PMT signal of interest (related to the events sought) is run through an amplifier, it is first amplified above its intrinsic noise by increasing the applied voltage. The gain G of a PMT is calculated by the equation,

$$G = \prod_{i=1}^{N} k_i V_i^{\alpha} = K V_{\text{ht}}^{N\alpha} \tag{1}$$

The value N is the number of dynode stages. k_i's are constants associated with the ith dynode, and V_i is the voltage applied to the ith dynode. V_{ht} is the overall voltage applied to the tube. K is a constant that depends on the dynode materials and the voltages between each dynode and α is a value somewhere between 0.6 and 0.8. Equation 1 can be found from [1, p.2-6].

1.2 Solid State Amplifiers

The 741 op amp was a natural candidate for amplification of signals due to its low cost, low maintenance requirements, ease of use, and availability. The 741 op amp is a common component in electronic devices. The device was originally called an *operational amplifier* because an op amp can be configured to perform operations on signals. An op amp can be configured to add, subtract, multiply and divide signals. It is also capable of integrating and differentiating signals.

Solid state amplifiers (and integrated chips in general) are known as *active components*. An active component relies on a power source (usually DC power) to operate. When using an active component as a part of a circuit, special considerations and precautions must be taken. The first source of concern when dealing with a solid state amplifier is its power source. In order for an amplifier to function properly, its power source must be steady DC. As such power supplies are often regulated with other electronics to ensure a steady power source.

In order to understand op amps, we will introduce the relevant terminology. An amplifier makes use of its power source to amplify a signal. The amount by which a signal is amplified is referred to as the *gain*. The gain is calculated by,

$$\text{Gain} = \frac{\text{Voltage Output}}{\text{Voltage Input}} \tag{2}$$

To calculate gain in decibels (dB),

$$\text{Gain in dB} = 20 \log_{10} \left| \frac{\text{Voltage Output}}{\text{Voltage Input}} \right| \tag{3}$$

The speed at which an op amp responds is referred to as its *slew rate*. The slew rate is specified in terms of V/s or more commonly V/μs. It is the slew rate that determines what signals can be amplified based on the amplifier gain and the signal frequency. Ideally an op amp will have infinite slew rate, infinite bandwidth, infinite open-loop gain, infinite input impedance, and zero output impedance. Since electronic components are rarely ideal, experimental physics must take into account every non-ideal aspect. As a general rule of thumb the closer to ideal the component is the more expensive it is.

The 595-THS3202D fast op amp is an integrated chip that contains two op amps in one package. The operational amplifiers in our experiment were set up as inverting op amps as shown in Figure 3.

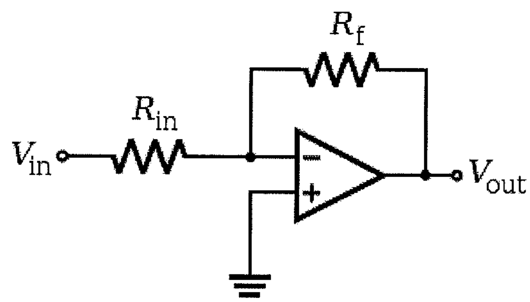

Figure 3: The is a simple inverting amplifier. Its output tends to be more stable than that of the non-inverting amplifier. A non-inverting amplifier can behave as an oscillator if special precautions are not taken.

1.3 Voltage Feedback Amplifier vs. Current Feedback Amplifier

When building an amplifier, it is important to consider whether the amplifier is a current feedback or voltage feedback amplifier. A voltage feedback amplifier bases its voltage output on the difference of voltages on the input terminals. A current feedback amplifier bases its output on the differences in current flowing in the input terminals. A current feedback op amp will become unstable if no minimum resistance is placed in series with the input terminal according to references [2] and [3]. No resistor is required between the non-inverting input and ground. A voltage feedback op amp does not have this limitation.

1.4 Why Amplify?

The bane of all electronic devices is electronic noise. A photomultiplier is no exception. A PMT has its own intrinsic noise. In addition the amplifier device will possess intrinsic noise and so will the data acquisition system (DAQ) for recording pulses from the PMT. The noise from each device has a unique statistical distribution corresponding to the amplitude of noise which should be distinguishable from the distribution of the event of interest. This may be optimized by increasing the intrinsic gain of the PMT and the amplifier, such that the events are distinguishable from the overall noise, but retaining most of amplifier dynamic. This information is contained in reference [1].

2 Experimental Setup

2.1 Experimental Question

When dealing with low signal levels, every electronic component matters. Relying upon the specifications of the manufacturers is an unwise practice that can lead to many false conclusions and artifacts. It is absolutely crucial to confirm that every electronic device is up to the assumed specifications. In our experiment we examine the amplification properties of the LM741 op amp and the 595-THS3202D fast op amp.

Our experiment evaluates whether or not the LM741 op amp can be used to amplify fast pulses from photomultiplier tubes. The pulses coming from the PMT are generally 4 nanoseconds to 20 nanoseconds. Should it be possible an LM741 op amp can be used in place of a 595-THS3202D fast op amp, cost could be greatly reduced.

2.2 Amplifier Design

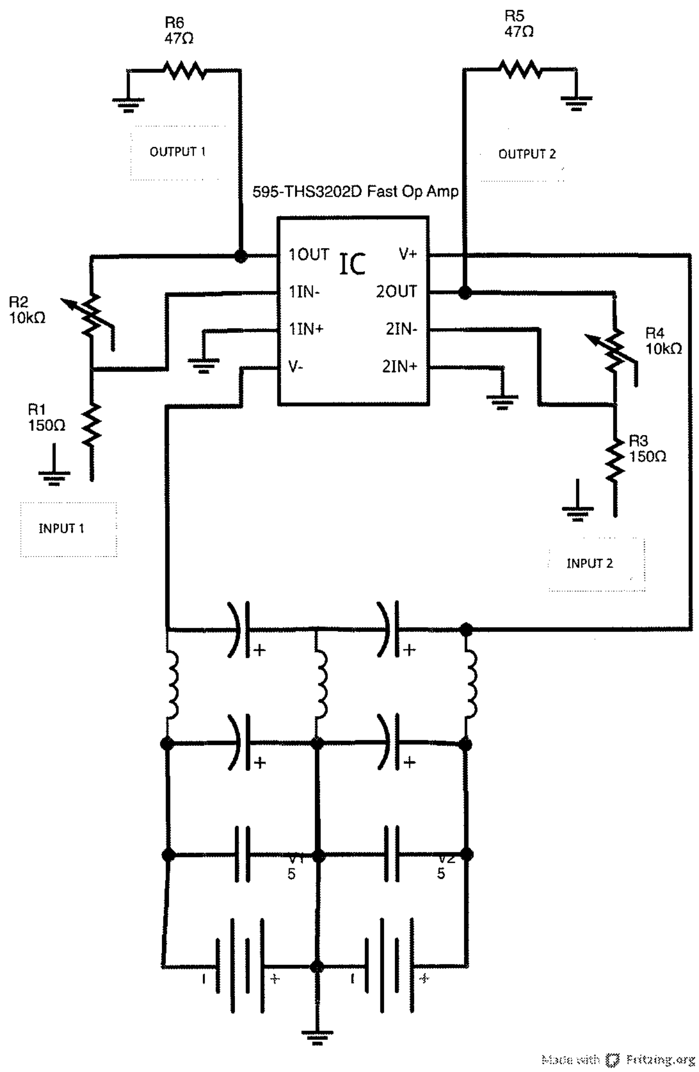

Figure 4: The power supply in this schematic is represented as two 5 volt sources. However, the actual power supply used in the amplifier module is a RECOM RAC06-05DC switching power supply. The inductors and capacitors represented in the diagram are additionally used for filtering the power supply.

2.3 Power Supply

As shown in the schematic caption, the power supply used was a RECOM RAC06-05DC switching power supply. Switching power supplies, by their very nature have high frequency intrinsic noise that may be present in the DC output. Switching power supplies are typically used in digital devices such as cell phones and computers. A switching power supply is much smaller than a regular power supply because the frequency of the input signal is greatly increased, which allows much smaller transformers and filter capacitors.

Switching power supplies are appropriate for certain digital applications due to their intrinsic noise immunity. For these reasons, the switching power supply was filtered. This particular power supply takes an input of 120 volts 60 Hz AC, and produces a 10 volt supply with +5, -5, and 0, terminals.

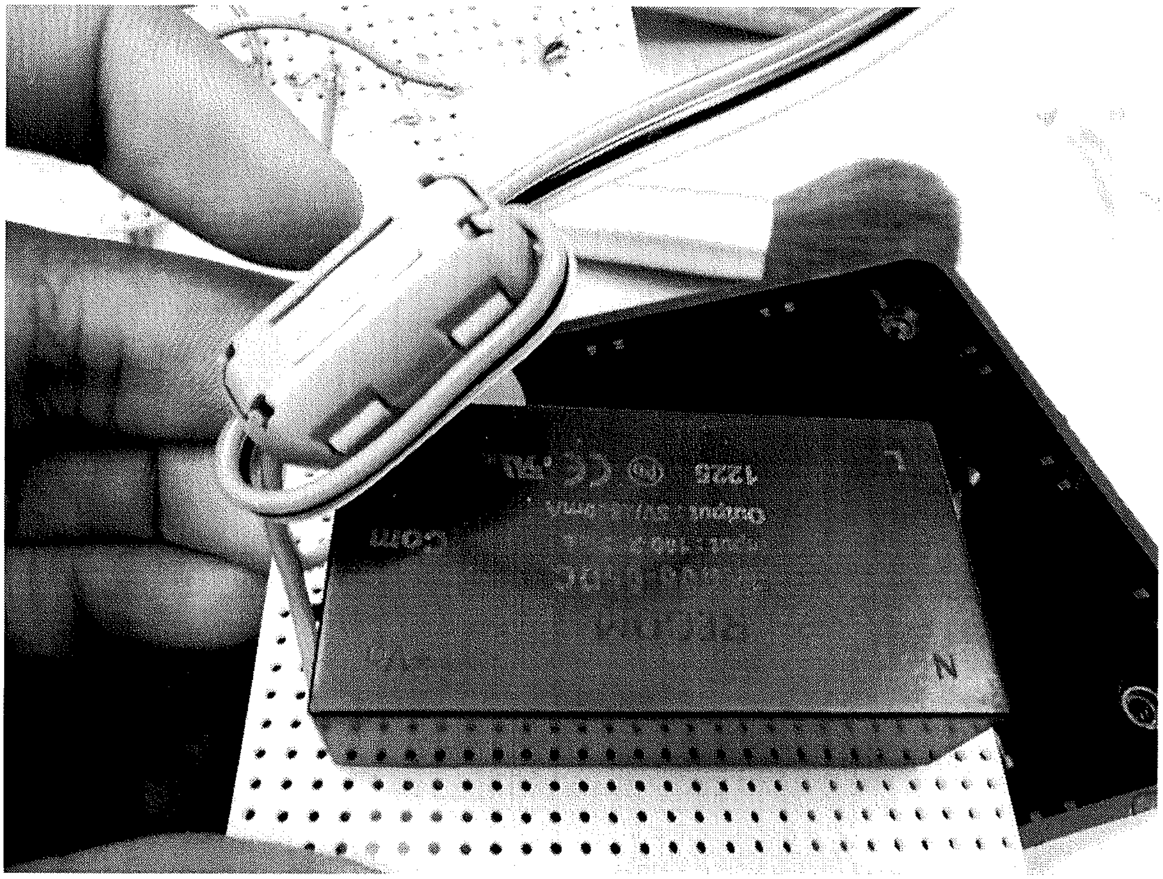

Figure 5: The wires are wrapped through a ferrite core in order to suppress the high frequency noise from the power supply due to the increased impedance at these frequencies. Without this ferrite bead, noise can contaminate the amplifier power supply.

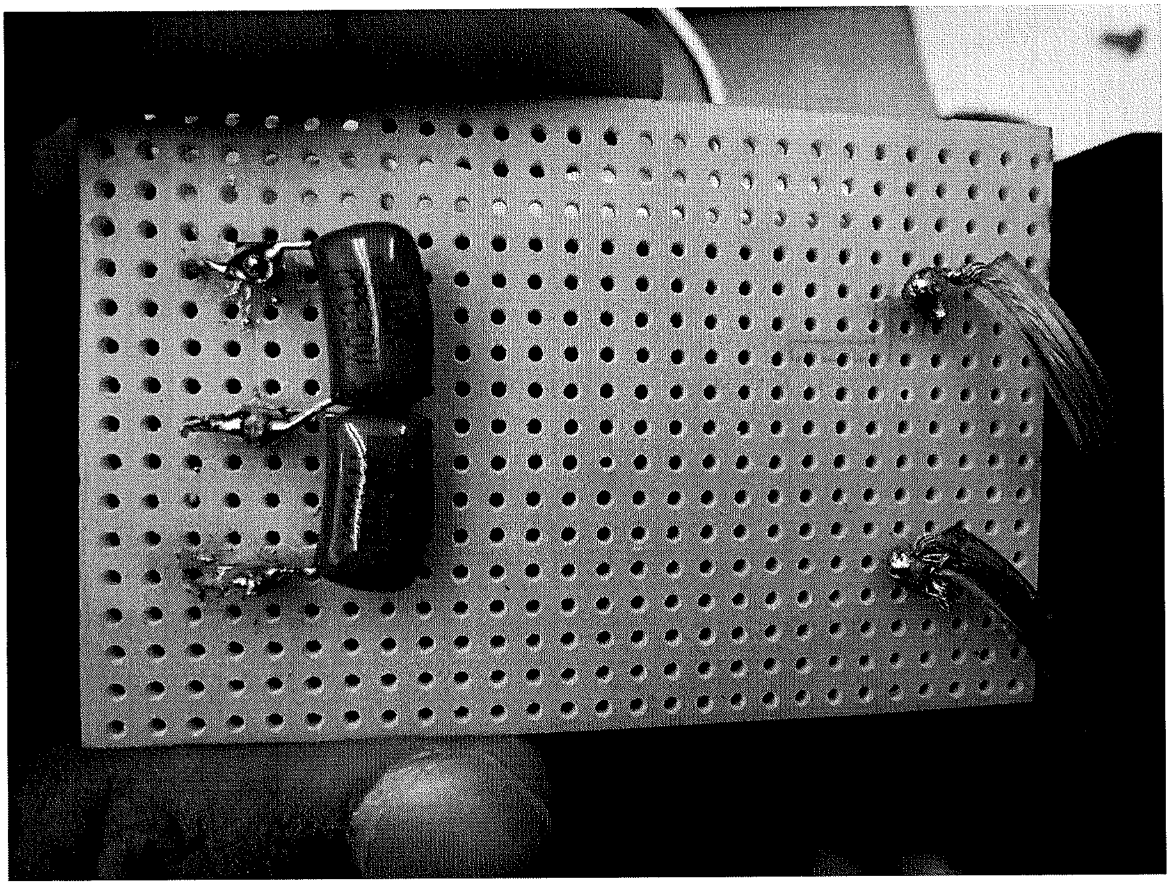

Figure 6: Two polyester bypass capacitors are placed in parallel with the power supply to bypass high frequency noise. During the testing phase of this project, a residual 10 kHz interference was observed in the power supply output despite all the filtering techniques. In order to remove the interference, two electrolytic 2200 μF capacitors (35 volts) were placed in parallel with the output. The polyester bypass capacitors were left in place for reasons discussed in the text.

In Figure 6, the polyester capacitors are also in parallel with two 2200 μF (35 volts) electrolytic capacitors. Both sets of capacitors are left in place, because the polyester capacitors have a much lower inductance than the electrolytic capacitors. This high inductance would cause signals much higher than 10 kHz to appear on the power supply, because the impedance of an inductance (L) to a signal of frequency (f) equals $2\pi f L$. The higher the frequency the higher the impedance. If the impedance becomes too high, the high frequency signal will appear as a voltage across the capacitors, since the bypass will not be adequate.

2.4 Amplifier Board Layout

The fast amplifier was assembled on the perf board, and designed to be modular and compact. This board with the electronic components is the main core of the amplifier module we built. The orange capacitors on the left are tantalum capacitors used for filtering the power supply. Tantalum capacitors are used in this design due to their very low inductance. Low inductance is an important consideration when attempting to filter high frequency power supply ripple (interference).

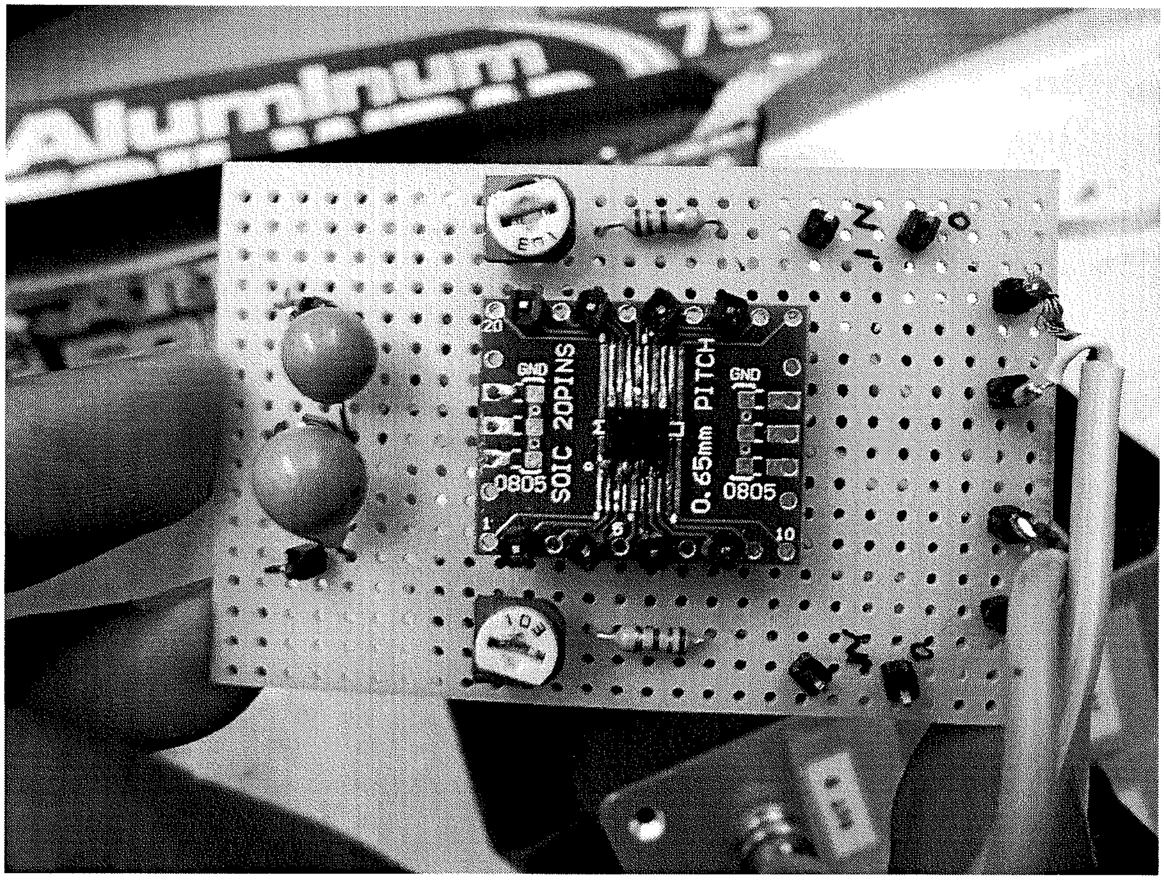

Figure 7: The 595-THS3202D fast op amp was mounted on a perf board with both channels connected to circuits that allow the amplifier gain to be adjusted appropriately. The blue variable resistors marked "103" are two 10 kΩ potentiometers that allow the gain to be adjusted for each individual channel. The two orange capacitors on the left are tantalum capacitors used for filtering the power supply.

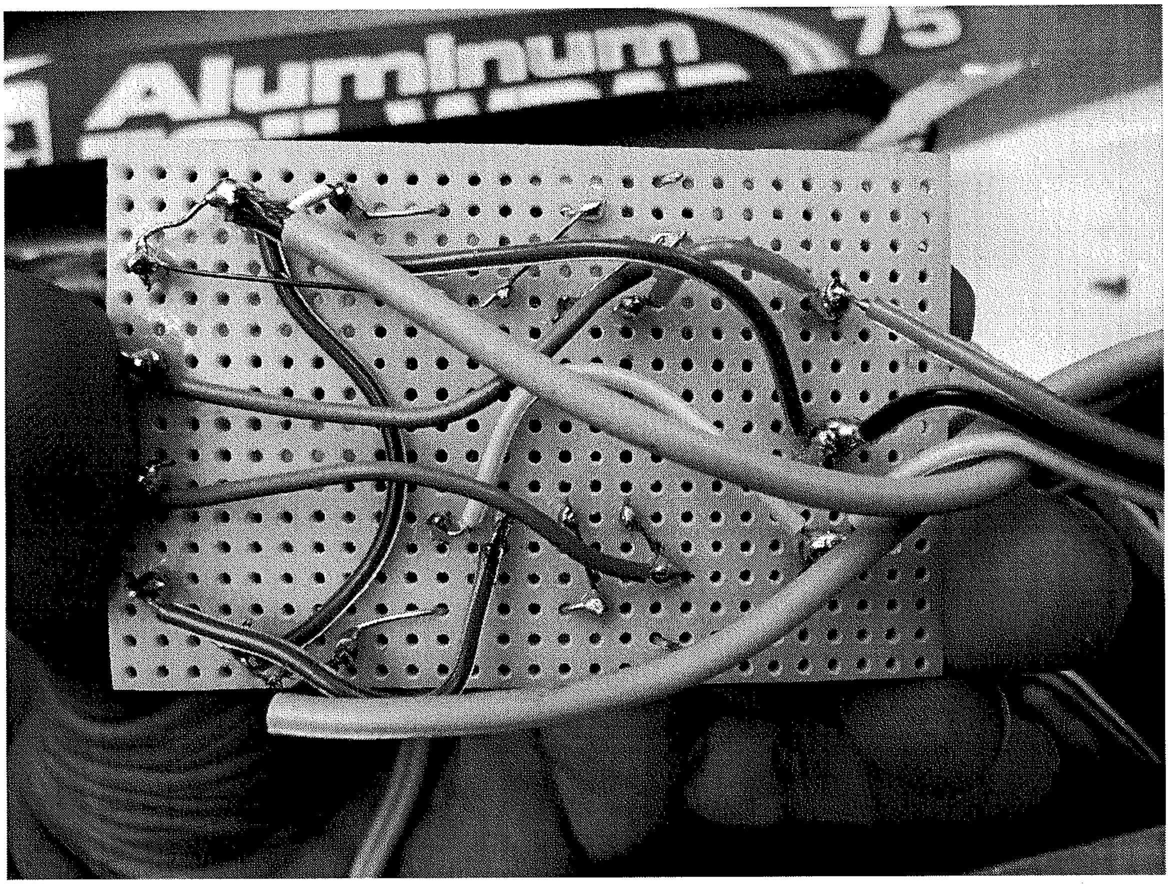

Figure 8: Underside of the amplifier board, clearly showing the connections. The green and black wires are connected to the power supply ground. The white wires are negative supply voltage and the red wires are the positive supply voltage. The thicker white shielded cables are connected to the input and output signals. The length of the shielded cables were later reduced to prevent pickup of excessive noise.

2.5 Input/Output Signal Layout

The input and output leads were designed as BNC connectors that were fixed to an aluminum grounding plate. The ground from the BNC male and female connectors were not soldered to the aluminum grounding plate. Instead the grounds are screwed to the aluminum plate by the hexagonal nut present on the BNC jacks themselves. The output leads are loaded with 47 Ω resistors to match the impedance of a 50 Ω cable or oscilloscope input. The impedances are matched as best as possible to prevent reflected pulses.

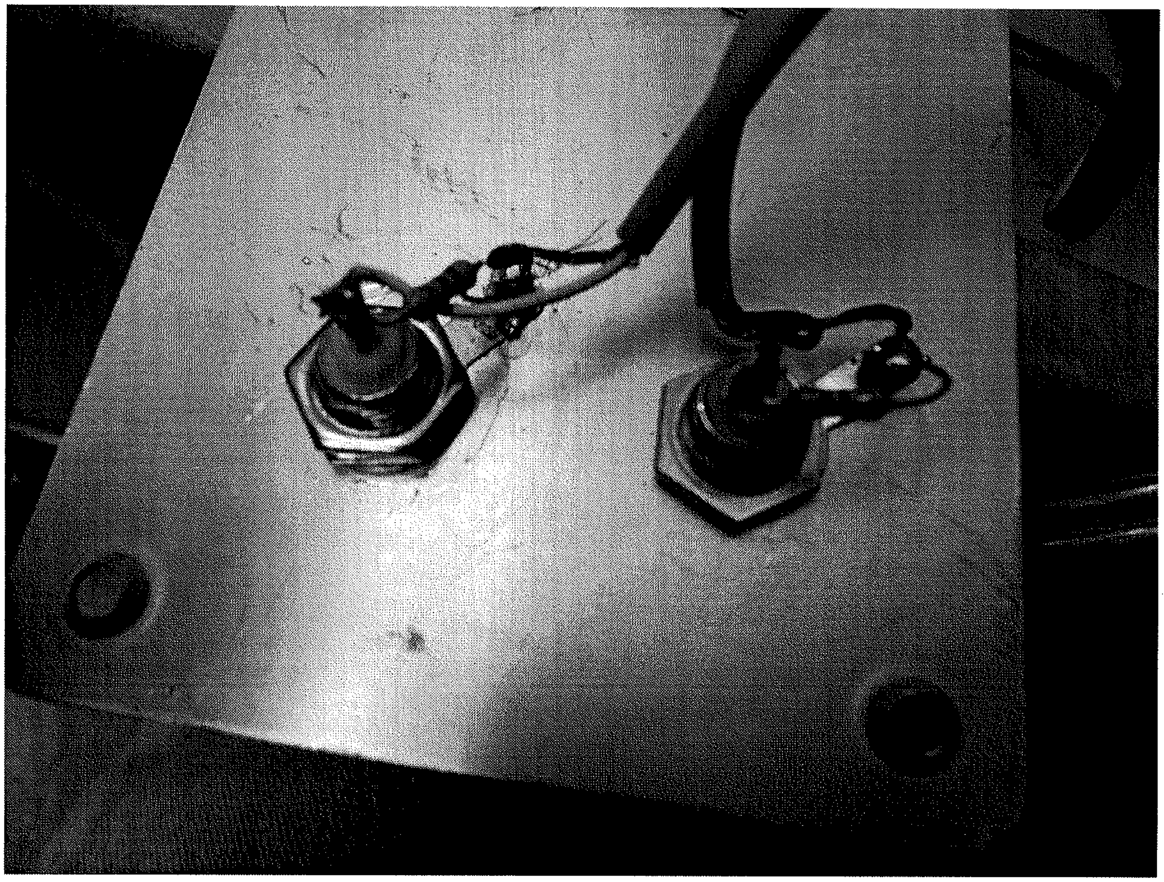

Figure 9: Output BNC jacks are loaded with 47 Ω resistors to prevent reflected pulses in anticipation of a 50 Ω coaxial cable. They are connected to shielded cables to reduce background electromagnetic noise that could be introduced into the output.

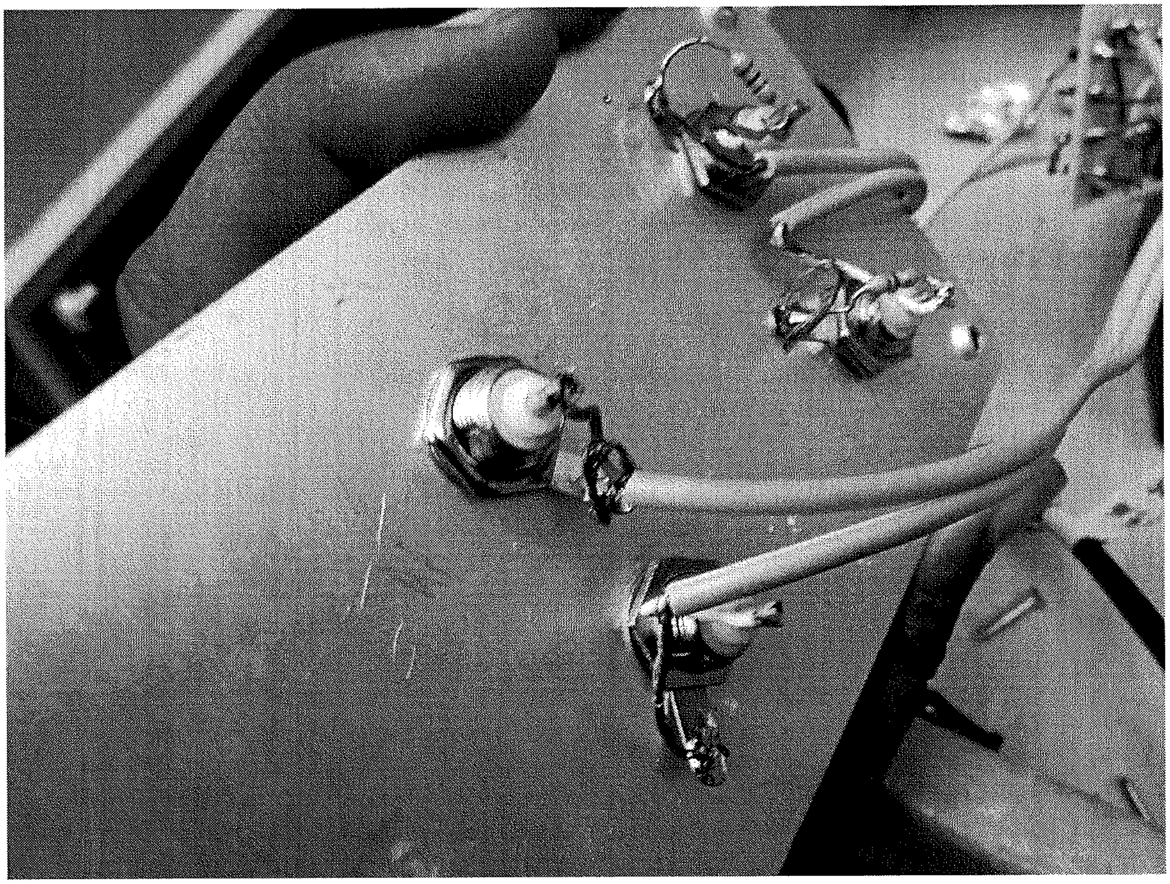

Figure 10: BNC input and output jacks that are connected to the aluminum grounding plate.

3 Experiment

3.1 LM741 Op Amp

The LM741 op amp was tested using an input signal from an Instek Function Generator model GFG-8216A. The output signal was measured using a BK Precision 20 MHz Oscilloscope model 2120B. The LM741 op amp was mounted on a bread board. It was supplied with two Duracell Alkaline 9 volt batteries configured to create a bipolar power supply. The signal had dropped by over 20 dB when the frequency approached 1.1992 MHz. This preliminary test shows that the LM741 amplifier has an inadequate bandwidth for use in photomultiplier tubes. No further tests were performed on the LM741 due to the results of the preliminary test.

3.2 595-THS3202D Fast Op Amp

The 595-THS3202D fast op amp was tested using an input signal from an Intstek Function Generator model GFG-8216A. Its output was measured using a BK Precision 20 MHz Oscilloscope model 2120B. This first test was a frequency sweep test. The amplifier was soldered on a perf board. It was powered with a RECOM RAC06-05DC switching power supply that was filtered with two 1000 pF polyester capacitors in parallel with two 2200 μF electrolytic capacitors. In addition the supply was filtered with a ferrite core that the supply leads were wrapped through. On the perf board the supply was again filtered with two tantalum capacitors.

3.3 Noise Test

By measuring the amplifier output with the no input signal (the input is shorted as an additional measure), we have found that there is approximately 3 mV of intrinsic amplifier noise. The signal coming from the PMT is typically around 10 to 20 mV.

3.4 Frequency Sweep Test

The frequency sweep test used an Instek Function Generator model GFG-8216A as an input. The output was measured using a BK Precision 20 MHz Oscilloscope model 2120B.

Frequency (Hz)	Input Voltage (V)	Output Voltage (V)	Absolute Gain	Gain (dB)
1006.1	1.20	-2.90	2.42	7.66
1099.8	1.20	-2.90	2.42	7.66
1199.6	1.19	-2.90	2.44	7.74
1299.8	1.19	-2.90	2.44	7.74
1399.8	1.19	-2.90	2.44	7.74
1500.2	1.21	-2.90	2.40	7.59
2000.1	1.15	-2.95	2.57	8.18
2501.4	1.13	-2.95	2.61	8.33
3002.0	1.10	-2.98	2.71	8.66
3511.4	1.10	-2.93	2.66	8.51
4005.1	1.10	-2.95	2.68	8.57
5009.5	1.12	-2.91	2.60	8.29
5998.7	1.12	-2.95	2.63	8.41
7011.9	1.13	-2.93	2.59	8.28
8010.2	1.11	-2.92	2.63	8.40
9010.1	1.13	-2.93	2.59	8.28
10074	1.13	-2.92	2.58	8.25
11072	1.12	-2.92	2.61	8.32
12092	1.12	-2.91	2.60	8.29
13013	1.11	-2.92	2.63	8.40
14045	1.10	-2.95	2.68	8.57
15079	1.11	-2.95	2.66	8.49
17000	1.11	-2.92	2.63	8.40
19055	1.12	-2.91	2.60	8.29
21021	1.11	-2.91	2.62	8.37
23100	1.10	-2.91	2.65	8.45
30098	1.11	-2.91	2.62	8.37
40185	1.10	-2.90	2.64	8.42
50002	1.10	-2.92	2.65	8.48
60072	1.12	-2.93	2.62	8.35
70149	1.10	-2.92	2.65	8.48
80239	1.11	-2.93	2.64	8.43
90526	1.11	-2.90	2.61	8.34

100410	1.09	-2.97	2.72	8.71
200120	1.10	-2.95	2.68	8.57
300430	1.10	-3.01	2.74	8.74
400390	1.09	-3.00	2.75	8.79
501080	1.05	-3.00	2.86	9.12
600450	1.09	-3.02	2.77	8.85
701790	1.05	-3.00	2.86	9.12
807250	1.05	-3.05	2.90	9.26
906430	1.09	-3.00	2.75	8.79
1002900	1.10	-3.05	2.77	8.86
1503000	1.09	-3.00	2.75	8.79
2004700	1.05	-3.00	2.86	9.12
2506500	1.02	-3.00	2.94	9.37
3002900	1.03	-3.00	2.91	9.29
3114300	1.04	-3.00	2.88	9.20

Table 1: The function generator was able to measure its own output signal frequency with an accuracy of up to five significant figures. The dB gain values were calculated by applying the function $20\log_{10}(\text{gain})$.

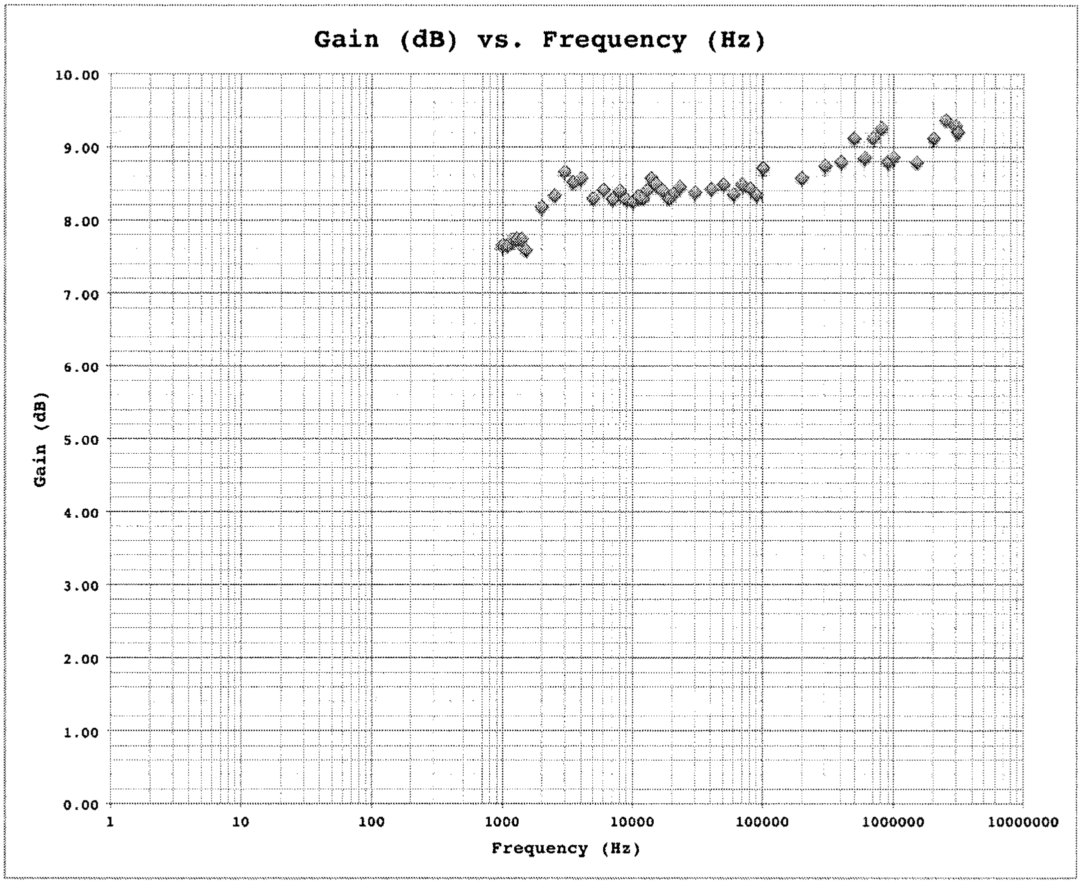

Figure 11: Bode Plot of the amplifier gain is shown above. The function generator used was only capable of 3.1143 MHz.

The slight upward trend in Figure 11 (the Bode Plot) is believed to be the result of the frequency response of the function generator used or more likely inaccuracies in the data recording process. The data recorded to create this plot was recorded from an analog oscilloscope. Data recorded from the analog oscilloscope may not be nearly as accurate as data recorded from a digital oscilloscope.

3.5 Pulse Generator Test

The pulse generator test used an Avtech AV-1030-C pulse generator as the signal input. The output was measured using a Tektronix TDS 5104 Digital Phosphor Oscilloscope. This scope was used because its fast response time was crucial in the success of the experiment, in addition the oscilloscope was capable of capturing the data from the screen (which was very convenient). The following images are from the screen captures from the oscilloscope.

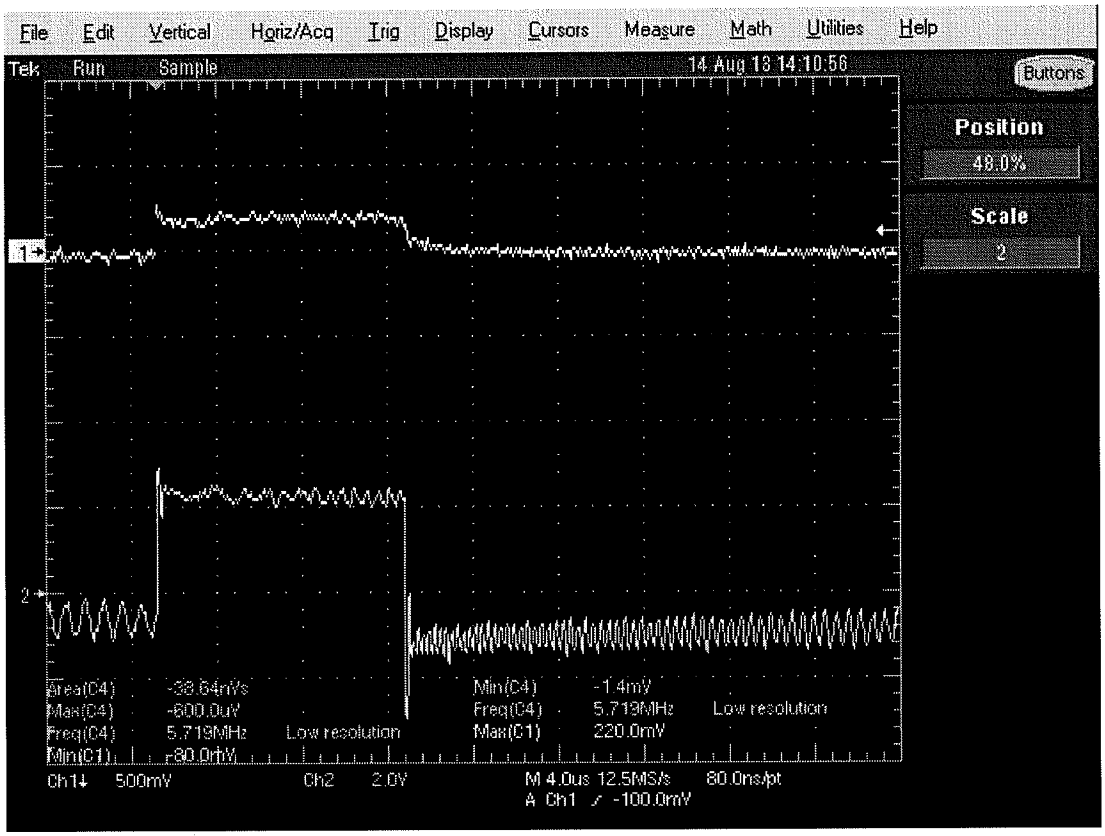

Figure 12: 10 μs pulse being amplified by the 595-THS3202D amplifier. The orange trace is the original signal input the blue trace is the amplified pulse. The orange trace is on a scale of 500 mV per division. The blue trace is on a scale of 2.0 V per division. The damped oscillations on the blue trace are a result of reflected pulses. The impedances were not matched on the input of the amplifier module and the 50 Ω impedance on the pulse generator output.

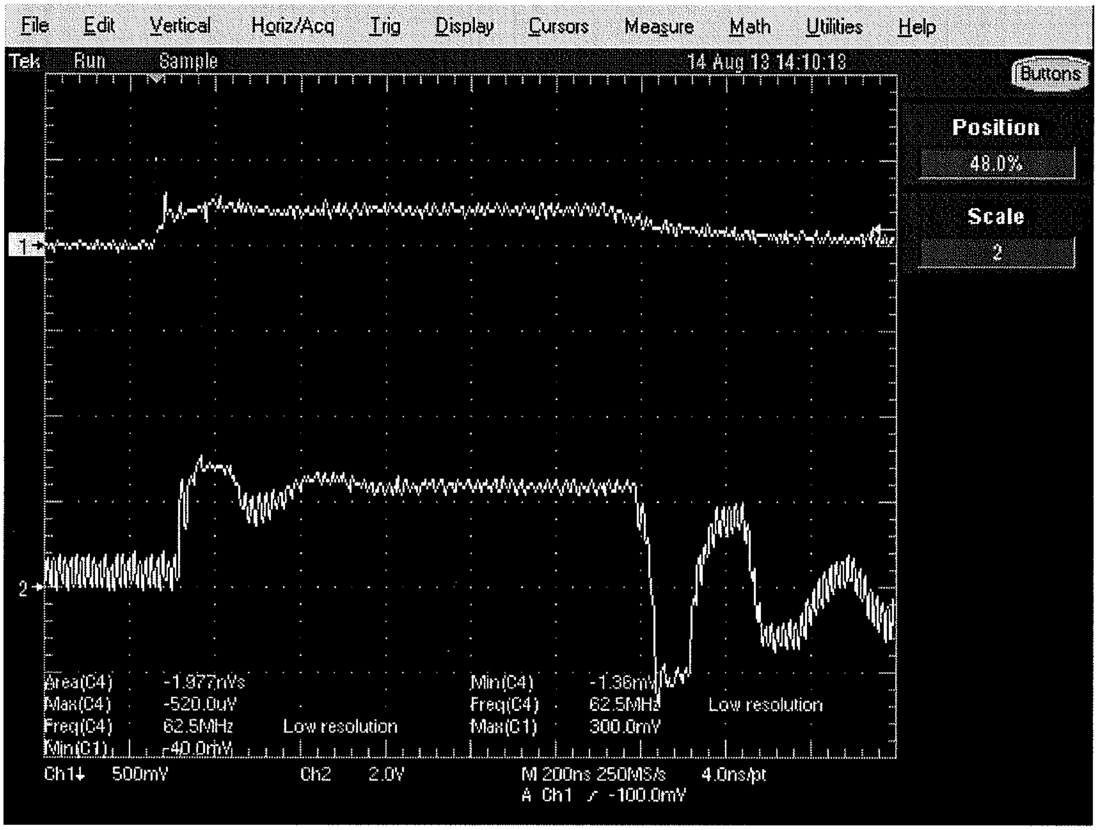

Figure 13: 1 μs pulse being amplified by the 595-THS3202D amplifier. The orange trace is the original signal input the blue trace is the amplified pulse. The orange trace is on a scale of 500 mV per division. The blue trace is on a scale of 2.0 V per division. The damped oscillations on the blue trace are a result of reflected pulses. The impedances were not matched on the input of the amplifier module and the 50 Ω impedance on the pulse generator output.

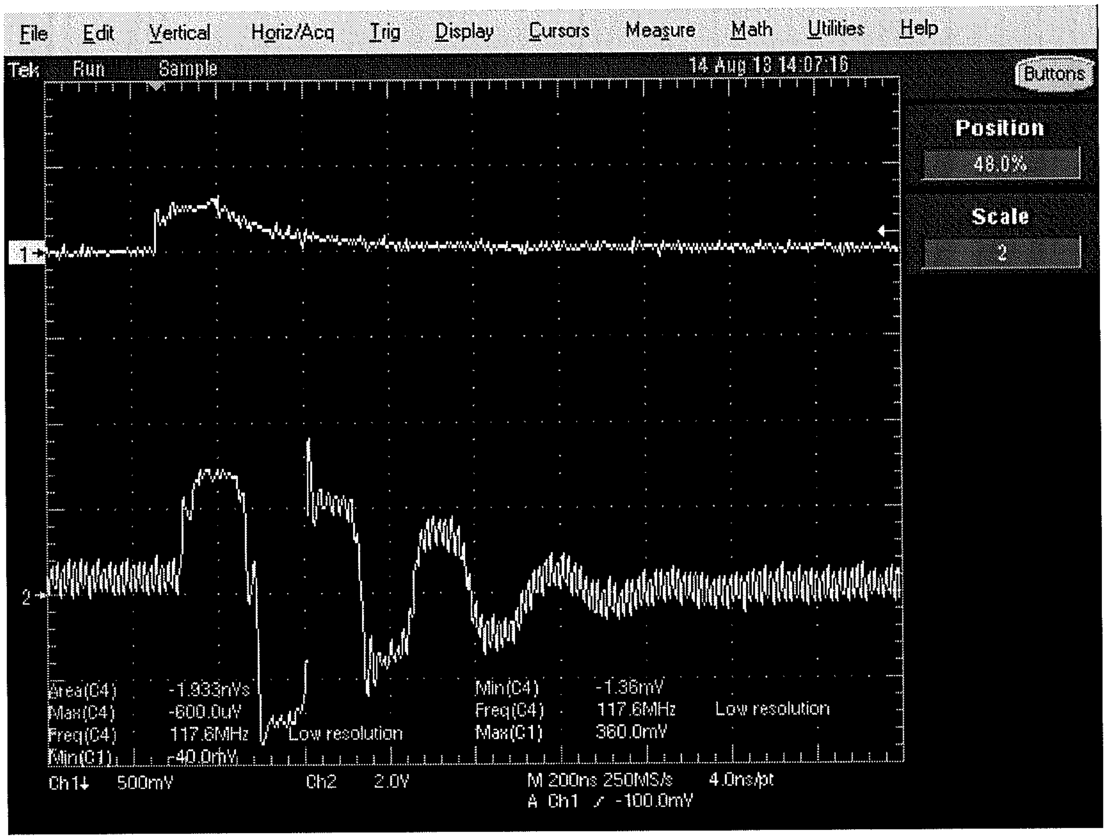

Figure 14: 100 ns pulse being amplified by the 595-THS3202D amplifier. The orange trace is the original signal input the blue trace is the amplified pulse. The orange trace is on a scale of 500 mV per division. The blue trace is on a scale of 2.0 V per division. The damped oscillations on the blue trace are a result of reflected pulses. The impedances were not matched on the input of the amplifier module and the 50 Ω impedance on the pulse generator output.

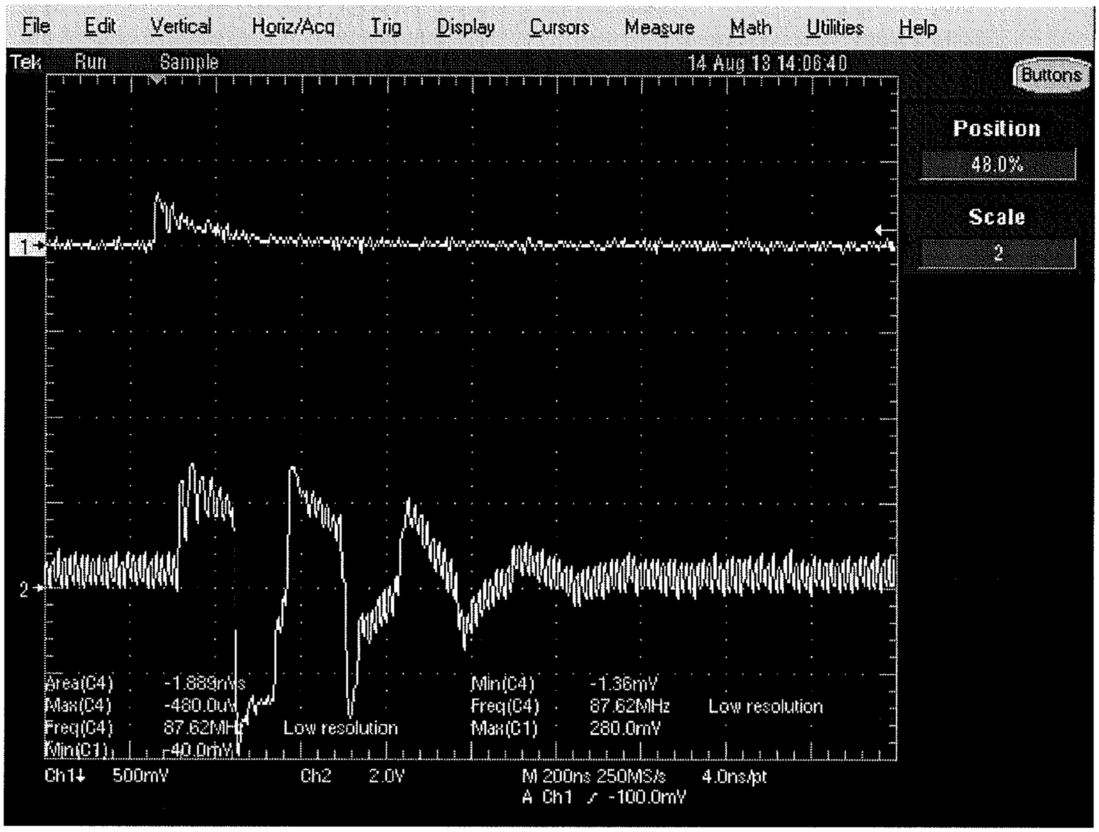

Figure 15: 15 ns pulse being amplified by the 595-THS3202D amplifier. The orange trace is the original signal input the blue trace is the amplified pulse. The orange trace is on a scale of 500 mV per division. The damped oscillations on the blue trace are a result of reflected pulses. The impedances were not matched on the input of the amplifier module and the 50 Ω impedance on the pulse generator output.

4 Conclusion

From the frequency sweep and pulse generator, we conclude that the amplification provided by the 595-THS3202D fast operational amplifier is adequate for use in photomultiplier tubes. The amplifier bandwidth is adequate for particle physics experiments that may be performed in Jefferson Laboratories. Preliminary tests indicate the LM741 operational amplifier is not adequate for use in the amplification of PMT signals.

Acknowledgments

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References

[1] Philips Photonics. (1994). *Photomultiplier Tubes: Principles & Applications.* Philips Photonics.

[2] Karki, James. (November, 1998). *Voltage Feedback vs. Current Feedback Op Amps.* Texas Instruments.
Retrieved from `http://www.ti.com/lit/an/slva051/slva051.pdf`
Literature Number: SLVA051

[3] Mancini, Ron. (2008). *Op Amps for Everyone.* Texas Instruments.
Retrieved from `http://www.ti.com/lit/ml/sloa080/sloa080.pdf`
Literature Number: SLOD006A

[4] Texas Instruments. (September, 2002 revised January, 2010). *2-GHz, Low Distortion, Dual Current-Feedback Amplifiers.* Texas Instruments.
Retrieved from `http://www.mouser.com/ds/2/405/slos242f-199119.pdf`
Literature Number: SLOS242F