A Study of Transistorized Bases for the ARGUS PMT's

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October 30th, 2012

Abstract

In Run I of the SeaQuest experiment at Fermi National Lab, there was an indication that the photomultiplier tubes (PMT's) nearest to the target were not capable of handling periods of high-intensity, high-frequency signals from the hodoscopes. A prototype voltage divider design was chosen to improve the performance of these PMT's. These results indicate a 4x improvement in rate capability. The results also indicate a doubling of pulse amplitude, which may nullify the need for signal amplifiers for these PMT's.

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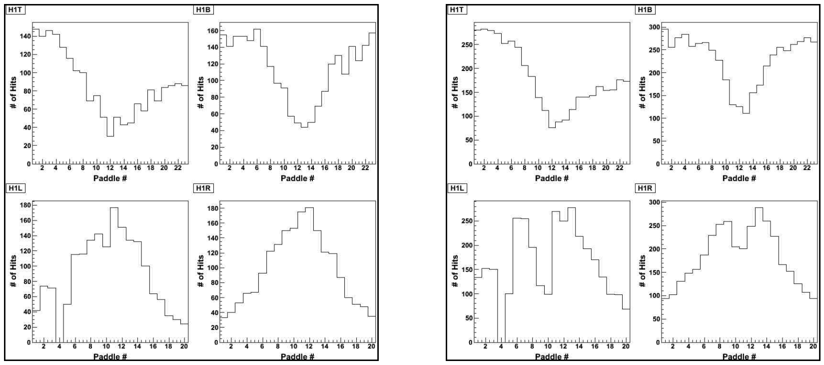


Figure 1: (Left) Histogram of hodoscope 'hits' in a typical event; (Right) Histogram of high-intensity event, with marked sagging in the middle of the y-measuring hodoscopes [3]

1 PMT Sagging

During Run I of SeaQuest, it was observed on April 17th that there appeared to be a drop in expected performance in the $y-$measuring hodoscopes (Figure 1).

These events occured under specific conditions:

- The sagging has been observed with the dimuon trigger, but not with a single-muon trigger.
- The sagging has been only observed in the "line of fire"
- The y-measuring PMT's are not used in the trigger

Two things can be derived from this. The first is that since the dimuon trigger is much more constrained, it is more sensitive to "splat" events, or RF buckets with high intensity. The result of these "splats" is pulses of light being channeled to the PMT's at an intensity and/or rate that the PMT is not capable of handling. This reasoning is consistent with the fact that such events don't make an appearance in the single-muon trigger events.

The second thing to note from this is that this sagging looks to only occur in the y-measuring PMT's, which are not used in triggering. This means that the sag in performance has not effected the Run I trigger, and has therefore caused no problem for Run I data. Regardless, optimally performing PMT's must be pursued, especially since it is the case that we will be experiencing higher intensity beam with Run II.

Further documentation on this issue can be found at the University of Illinois E906 Hardware TWiki [1], and further analysis on the PMT sag conditions by Markus Diefenthaler is soon to be found in an upcoming document.

The understood nature of this *"sag"* in performance is due to a destabilization in the voltage divider (PMT base) that holds each dynode stage at a specific voltage. When the PMT base destabilizes and is unable to maintain an appropriate voltage difference between dynode stages, this leads to inefficient performance of the PMT.

Here, we assemble a new base for our ARGUS PMT's (Philips XP-2008 or Photonis XP2072), test several variations, and compare their performance to the original PMT base and to some Hamamatsu PMT's.

2 PMT Bases

2.1 Terminology and Common Characteristics

Each base divides -1500±100V over the photocathode (K), ten dynode stages (D1-D10), and the anode (A). Some common features.

There are two currents that are discussed in this document are:

- **Signal Current** - This is the signal that passes over the anode, which is the end-result of the cascading secondary emission electrons from each dynode stage.
- **Bleeder Current** - This is the current through the voltage divider. It is termed the "bleeder" current since the compounding electrons in the signal current must be "bled" from the current through the voltage divider.

Throughout these voltage base designs, capacitors are commonly implemented in the latter dynode stages. These capacitors, when charged, are utilized when a large pulse of light induces a large signal current. When this happens, the capacitors help to replenish the charge on the dynode stages without requiring the charges to be drawn from the bleeder current, thereby keeping the voltage across the dynode stages more stable.

2.2 Original Base

This is the PMT base that is currently used with our ARGUS PMT's. It features capacitors of increasing capacitance along the last six stages, and steadily increases the voltage across the final four stages.

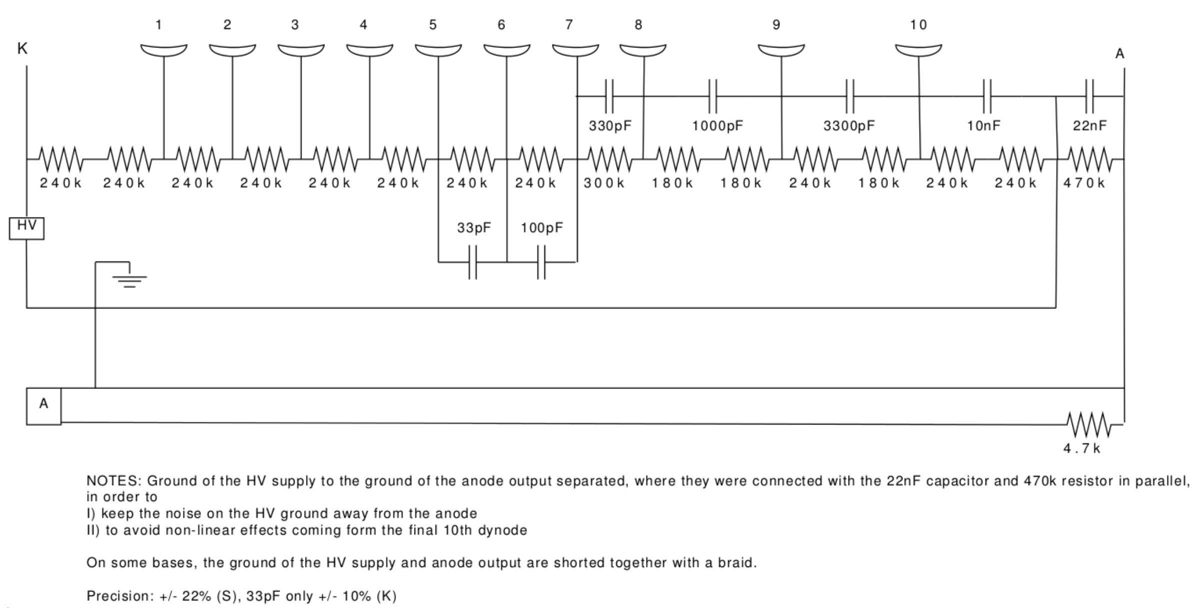


Figure 2: The original PMT base design.

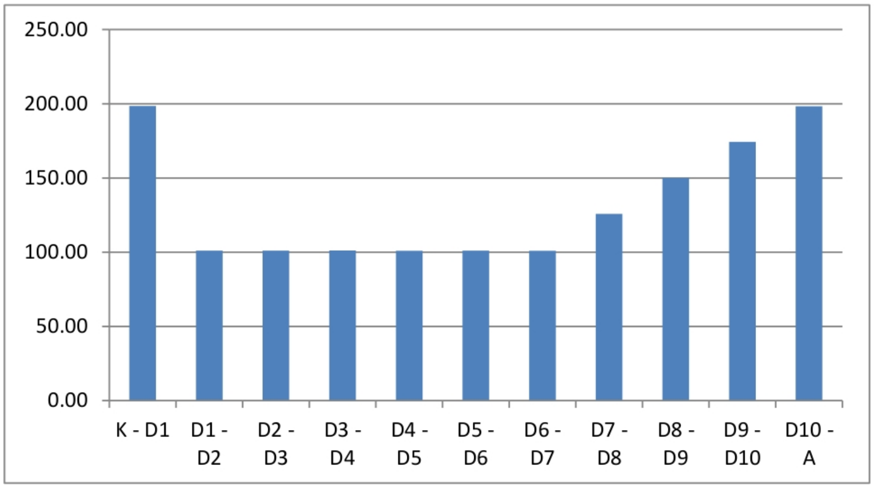


Figure 3: The (negative) voltage between subsequent stages for the original PMT base.

2.3 Prototype Base v1

This is the base design provided by Sten Hansen (Fermilab Particle Physics Division), designed in 2010 for the same model of PMT's for use at CERN.

Three important features of this design include:

- Lower resistance
- Parallel currents
- Transistors and diodes
- Flat distribution of voltage

The lower overall resistance of the voltage divider increases the bleeder current. This means that the base will be more capable of handing high-intensity/-rate events, as it will be better able to replenish the charges on each dynode stage in the case of a large signal. Typically, the larger the bleeder current, the larger the signal current can be without destabilizing the voltage divider.

At dynode six on Figure 4, we see that the current is split into two paths. The intent here is for the smaller current that goes through the series of $1M\Omega$ resistors maintains the voltage difference, and the larger current that freely passes through the transistors supplies the dynode stages with needed charge.

Transistors are introduced here to maintain the proper voltage division. If at any point the proper voltage drop across the gates of the transistors is not supplied (and thereby across the dynode stages), the source-to-drain current through the transistor is stopped until the proper gate voltage is restored. This helps to regulate the voltage across the dynodes, but if the charges lost to the signal current are not restored, the PMT will still eventually "sag" and fail.

The diodes are there to prevent the current from moving across the transistors improperly, and thereby preventing them from being damaged when powering the circuit on and off.

Also, the voltage across each stage, from D1 to A, are relatively flat. According to the specifications for the ARGUS photomultiplier tube, this is the recommended voltage configuration for maximum gain [2].

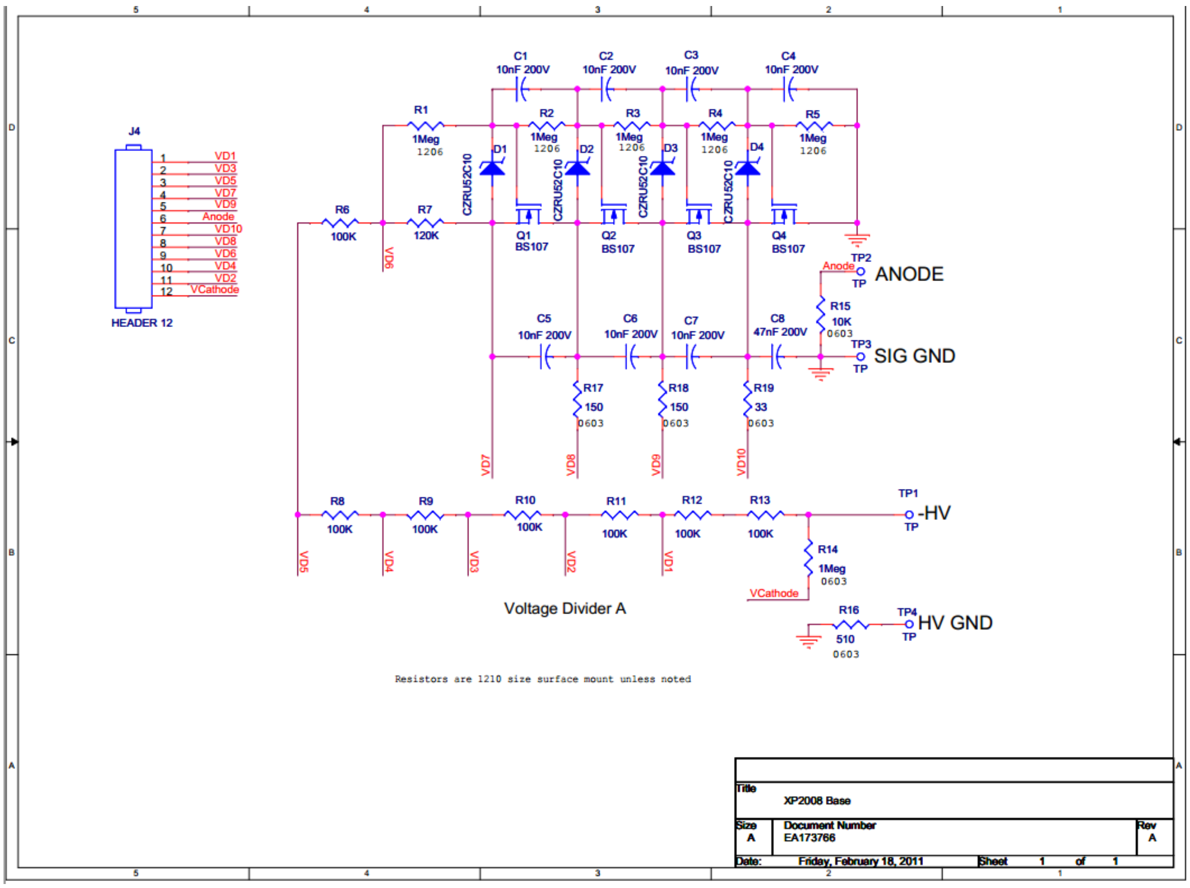


Figure 4: The Prototype v1 board.

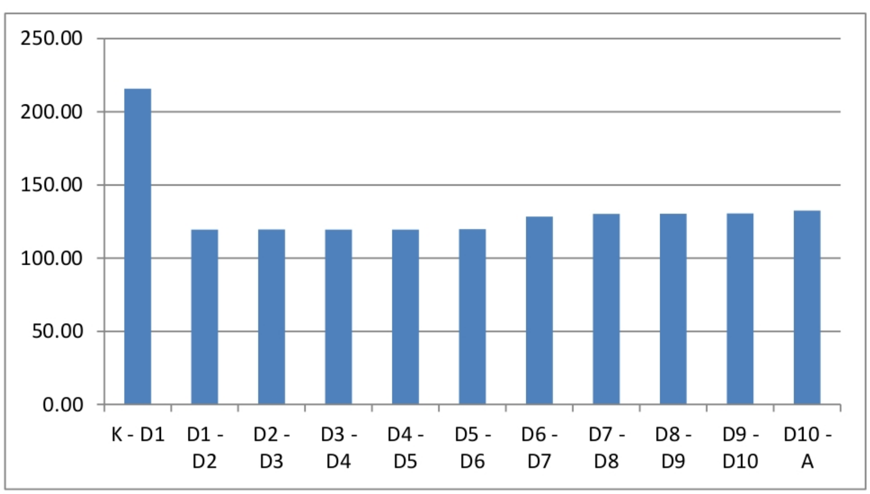


Figure 5: The (negative) voltage between subsequent stages for the Prototype v1 PMT base.

2.4 Prototype Base v2

The first modification made to the prototype board was to halve the resistance of each of the first six stages (R6-R13 on Figure 4) to increase the bleeder current. The voltage division remains unchanged from v1 (Figure 5).

2.5 Prototype Base v3

This modification to the v1 design "transistorized" the D5-D6 and D6-D7 stages in the case that the destabilization was occurring even at these earlier stages (Figure 6).

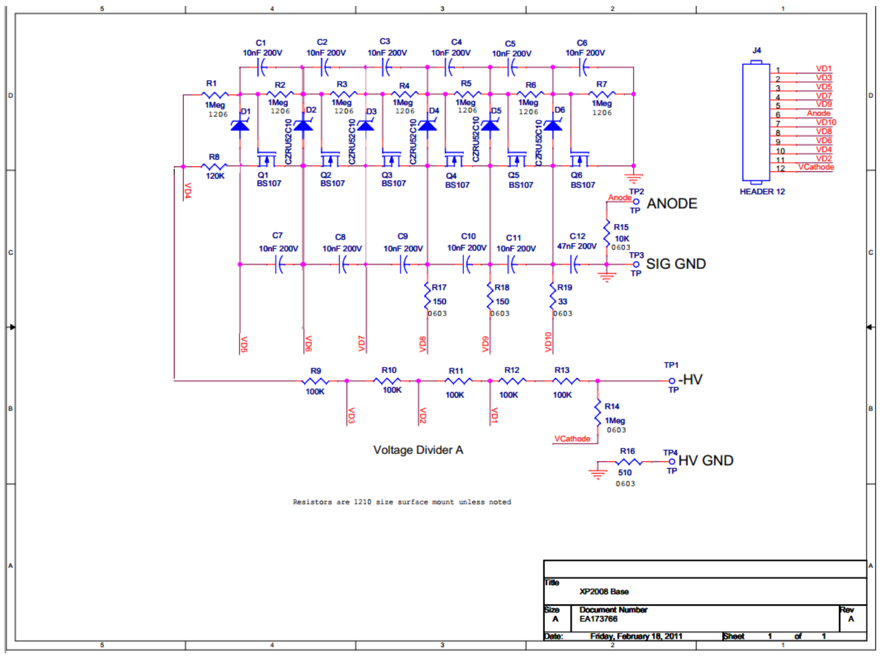


Figure 6: The Prototype v3 board: 3 more transistorized stages than the Prototype v1 design.

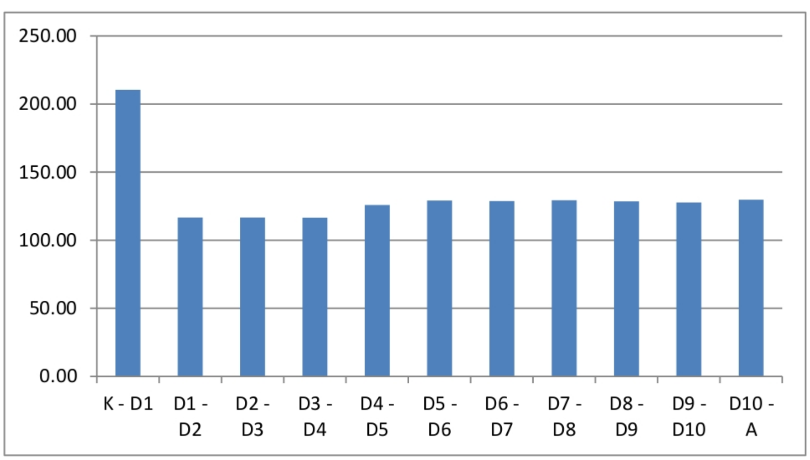


Figure 7: The (negative) voltage between subsequent stages for the Prototype v3 PMT base.

2.6 Prototype Base v4

Here, the resistance over the final stage (D10-A) was increased from $1M\Omega$ to $1.5M\Omega$ (R5 in Figure 4). This was done in case that the final batch of electrons needed help being "swept" to the anode with a higher voltage difference.

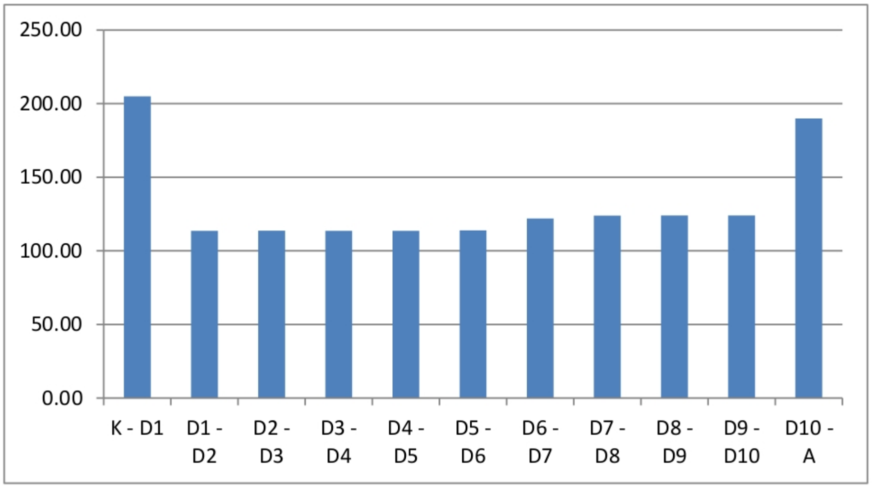


Figure 8: The (negative) voltage between subsequent stages for the Prototype v4 PMT base.

3 PMT Base Comparisons

There is a specific difficulty with the objective to increase the rate capability of our PMT's. This difficulty is that we do not have a target rate to attain. The rate and intensity that caused the original PMT+base to sag is difficult to ascertain (see section 2.1), and even if it was exactly known, it would be difficult to match the intensity with an experimental setup. In addition, the beam conditions for Run II are yet unknown.

As a result, the objective in these tests is to *compare* the performance of the same PMT using different bases.

Due to the effects of using different PMT's, temperature changes, and humidity, the behavior can be quite variable. For this reason, one can only reasonably compare results within each test, and not across different tests. Each was performed on different days, and possibly with different PMT's.

3.1 Testing Apparatus and Measurements

In this experiment, a PMT attached to a PMT base is placed into a light-tight box along with an fast-pulsing LED.

The LED is driven by an Agilent function generator capable of generating signals up to 30MHz. The LED's intensity is attenuated by a neutral density filter (NDF), with a rating D=3.0, where the NDF allows 1 in 10^D photons through (1 in 1000 for D=3.0).

A separate rudimentary DAQ of an amplifier, discriminator, and scaler was used to ensure that the PMT was firing off at the rate as is set by the function generator.

The PMT base is powered by a high voltage supply with an ammeter between the two in order to measure the amount of current drawn from the HV power supply, or bleeder current. The PMT signal is processed by an oscilloscope, averaging the pulse over 300 pulses, and then measuring the area of the pulse (in V·s).

The signal from the PMT is terminated by 50Ω, so we calculate the signal current over the anode as:

$$Q_{pulse} = \frac{\int V dt}{R} \tag{1}$$

$$I_{signal} = f Q_{pulse} \tag{2}$$

where f is the frequency of the pulsing.

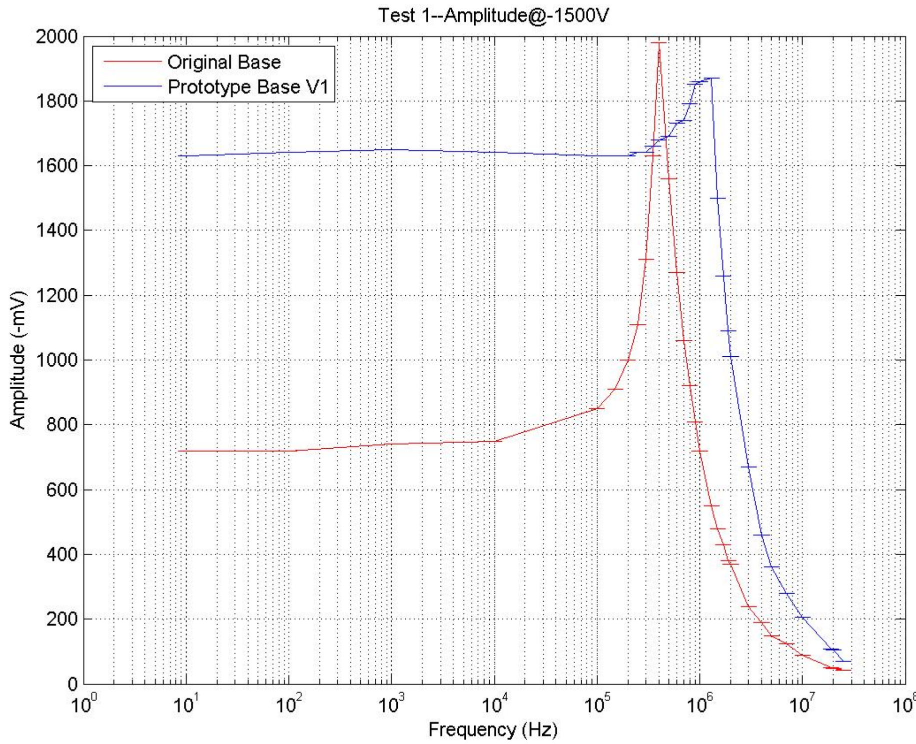
We also measure the amplitude of the pulses, as this is important information in considering removing the amplifiers from the SeaQuest stations 1 and 2 DAQ setup.

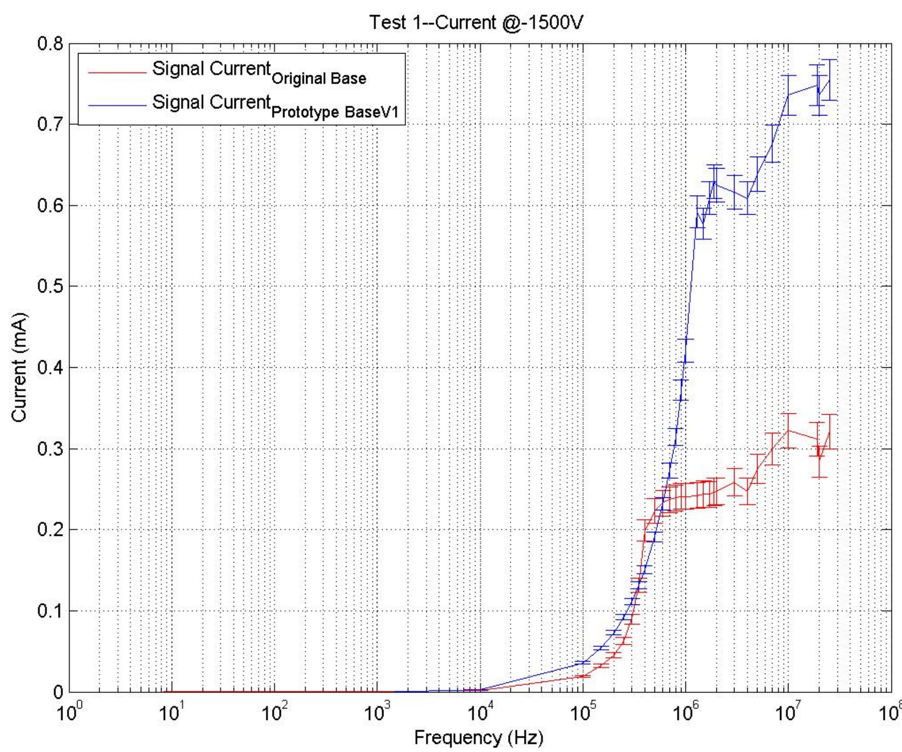
So, our measurements are:

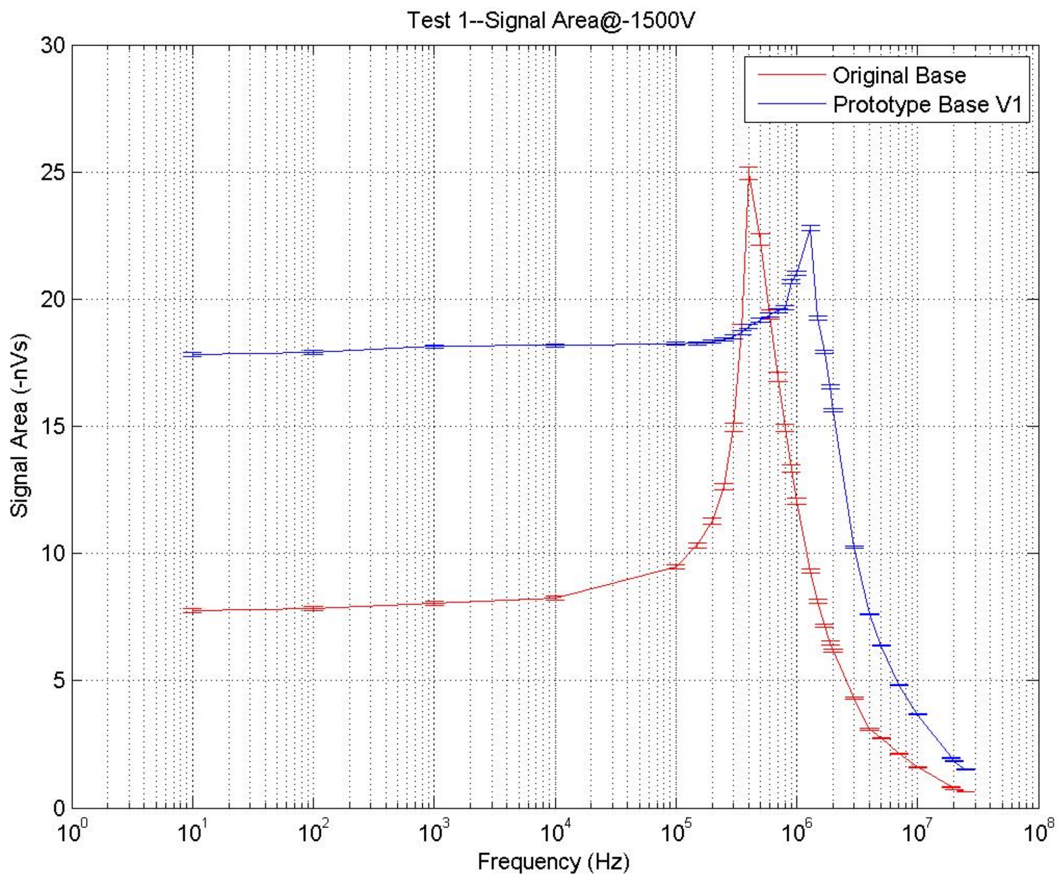
- HV supply current, or "bleeder current"
- Averaged signal amplitude
- Averaged signal area
- Signal current over the anode (derived from signal area, termination resistance, frequency)

Figure 9: Inside of a lightbox, we have our prototype board (left) wired up to an ARGUS PMT (middle), facing a fast-led source (right)

3.2 Test 1: Original Base vs. Prototype Board v1





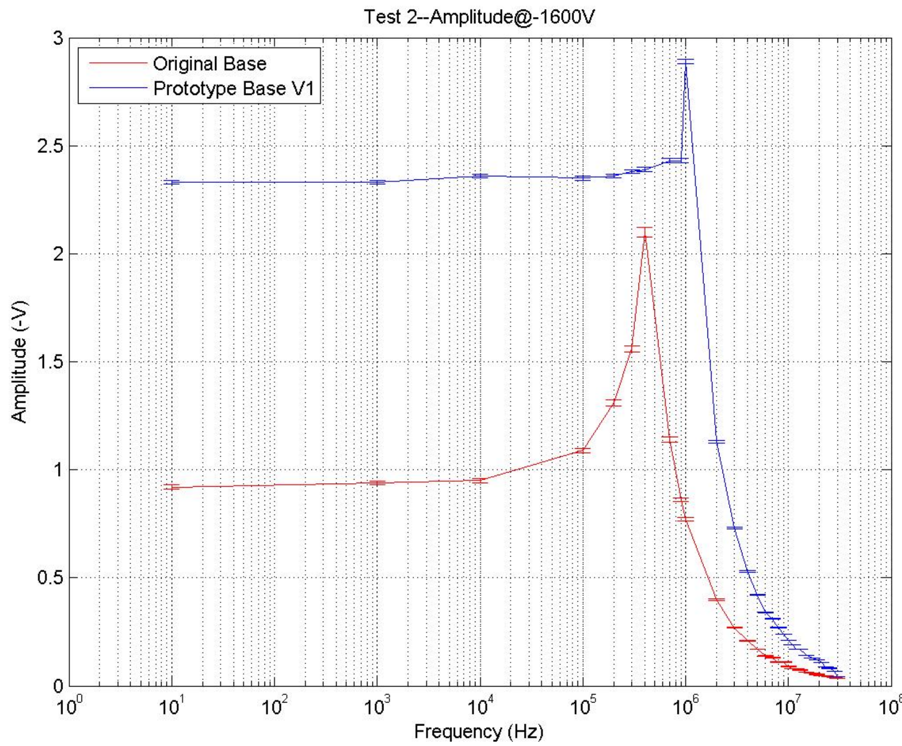


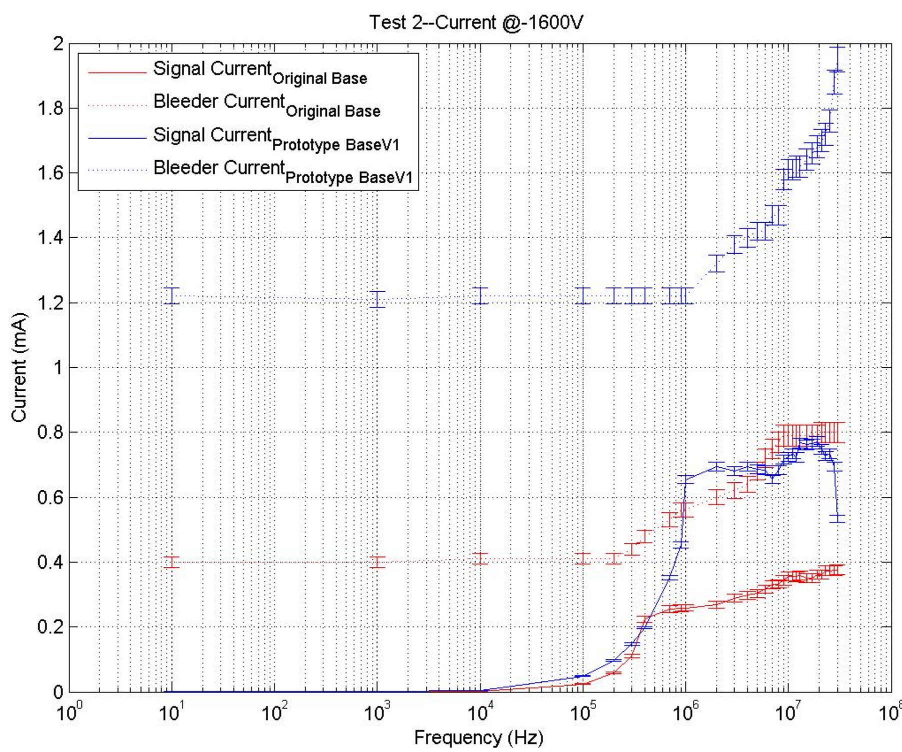
As the frequency of our LED surpasses 100kHz, we see the original base beginning to behave atypically, and we see a similar, but less pronounced behavior for the Prototype v1 base at around 600kHz.

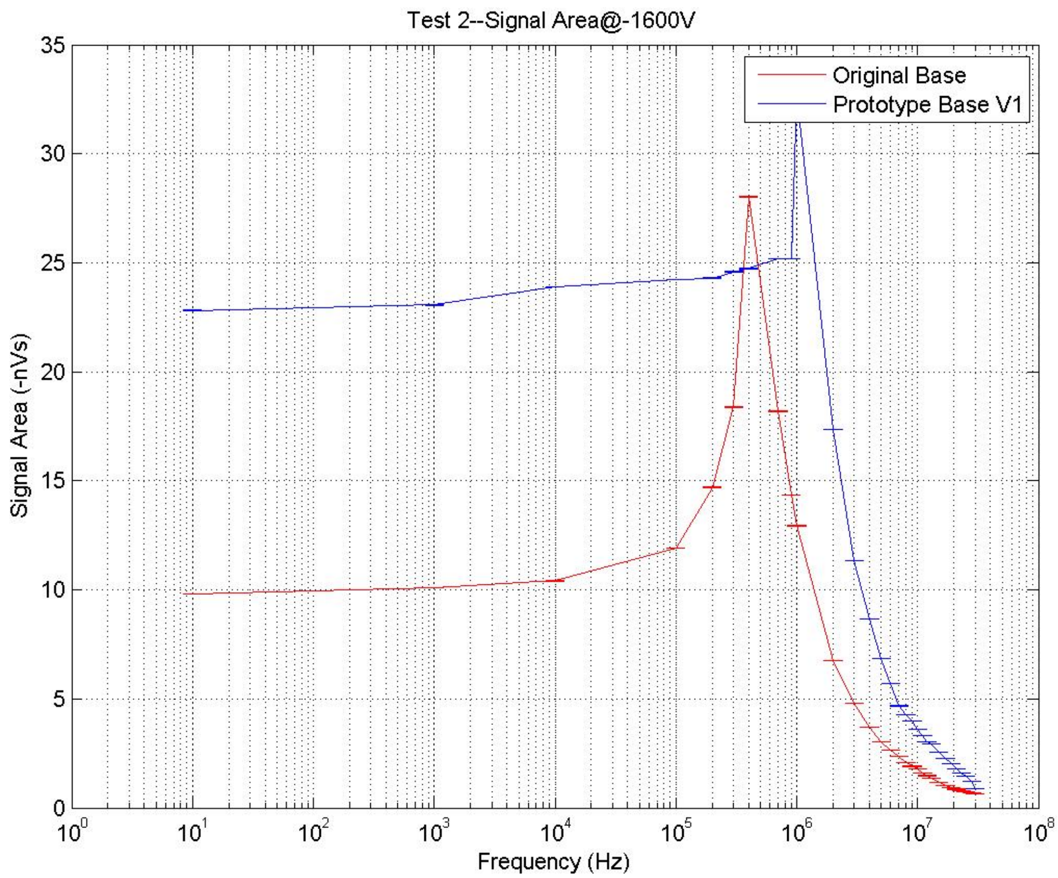
It is difficult to identify the point at which the PMT's become unusable, but there appears to be a shift in the qualitative behavior of the two bases by a rate factor of about 3-4x.

While we were able to derive the signal current, we did not measure the bleeder current in the first test. As a result, we performed the same set of tests, but while measuring the bleeder current in Test 2.

3.3 Test 2: Original Base vs. Prototype Board v1 (With Bleeder Current)

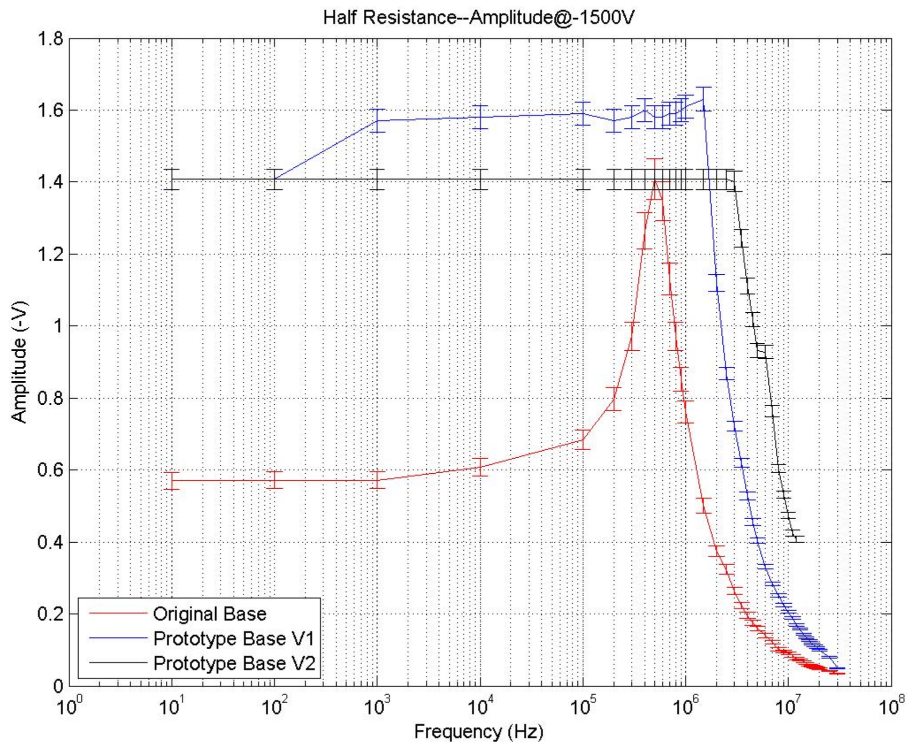


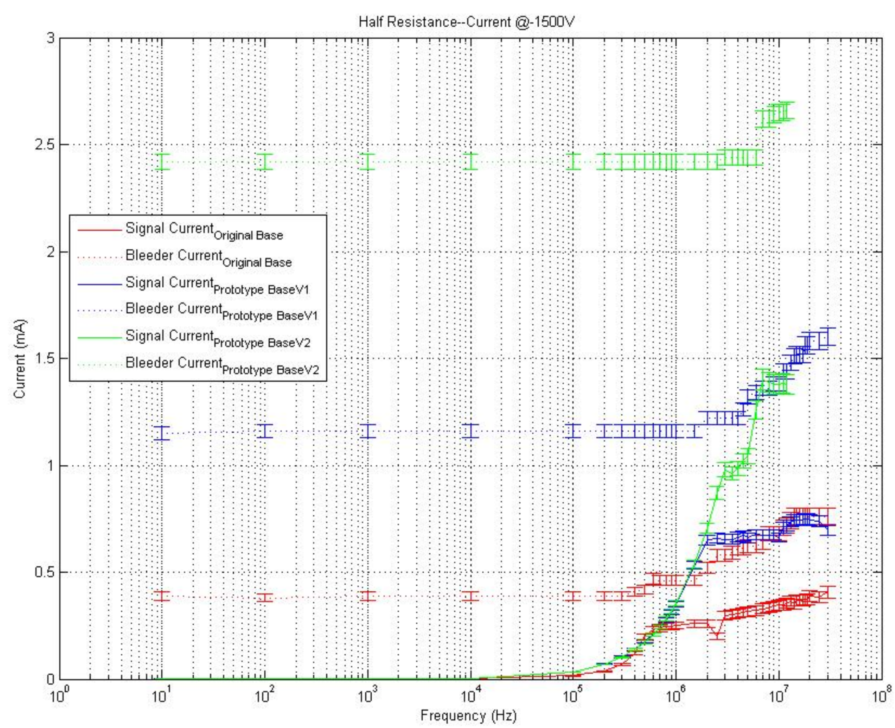


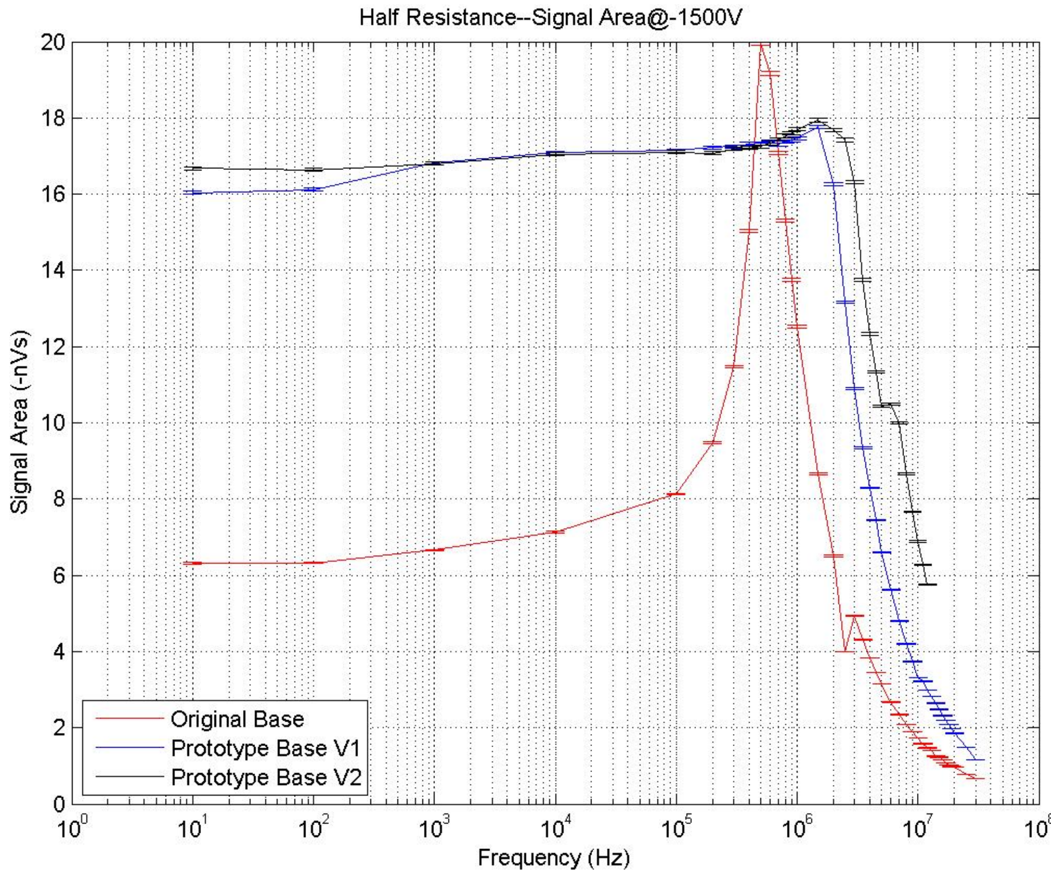


In this test, the results are consistent with the Test 1 results. In addition, we see that the destabilization occurs at the point where the signal current (across the anode) becomes about half of the bleeder current.

3.4 Test 3: Original Base vs. Prototype v1 vs. Prototype v2



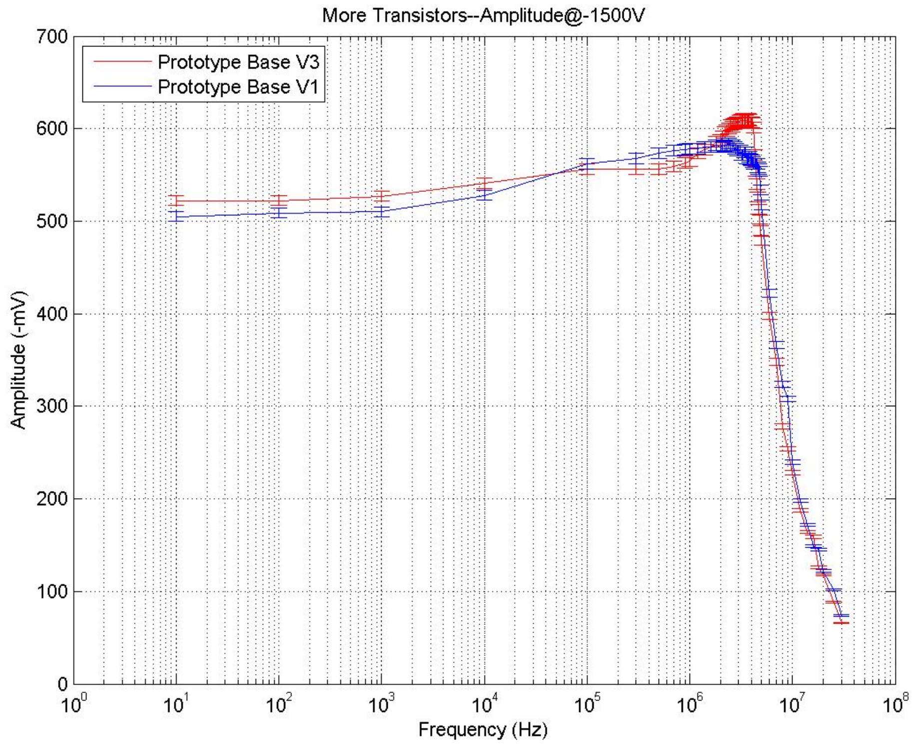


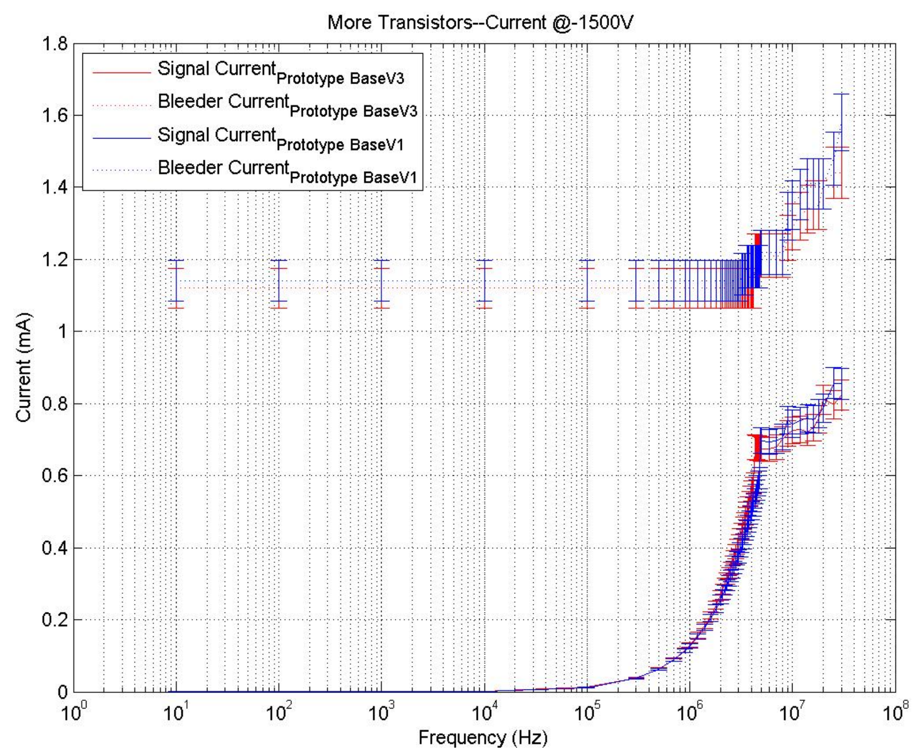


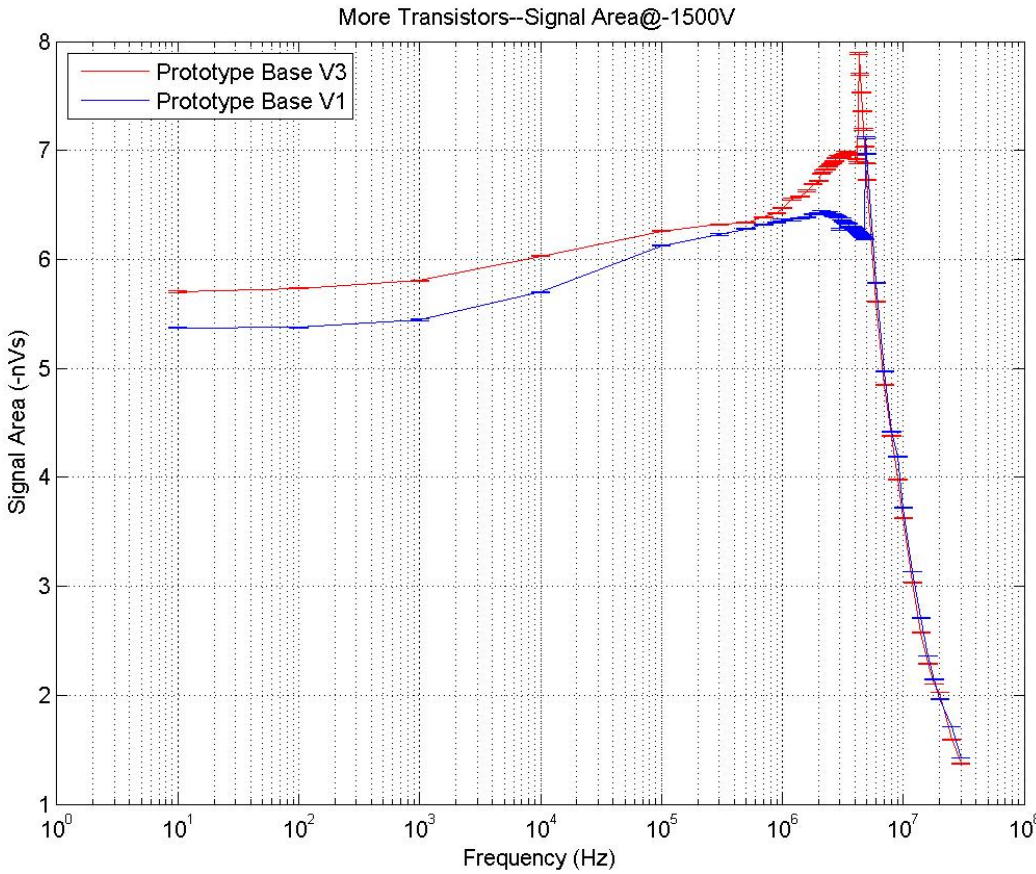
By halving the total resistance, we see approximately a 50% increase in rate capability. Unfortunately, the increase in the bleeder current not only exceeds the maximum current allowed by our LeCroy power supplies at NM4, but also pushed the resistors used beyond their power rating.

The Prototype v2 data stops at 12MHz due to a resistor failing.

3.5 Test 4: Prototype v1 vs. Prototype v3

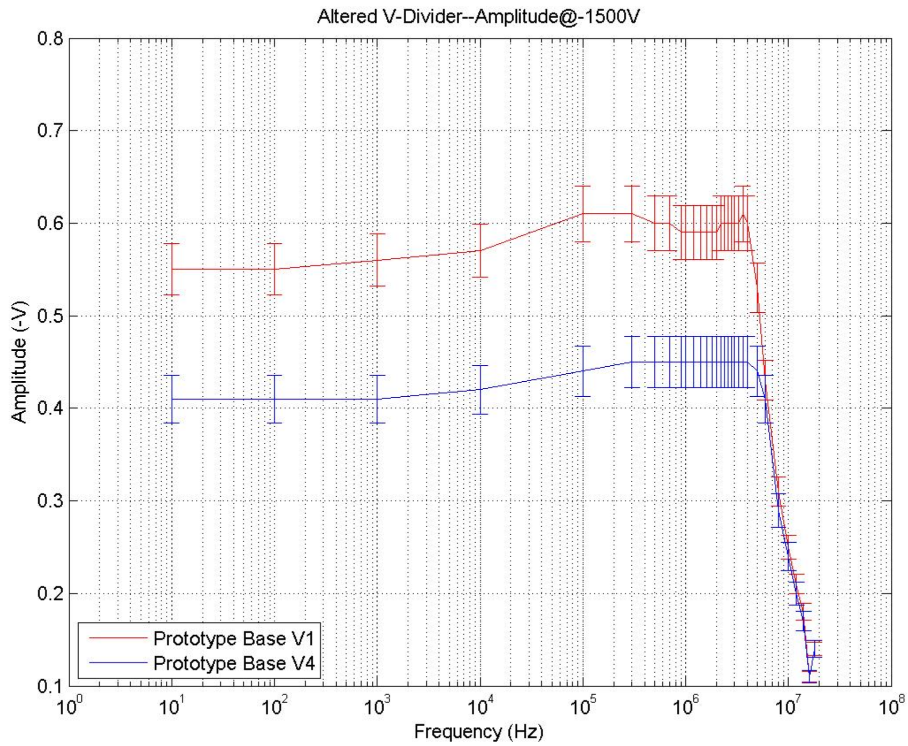


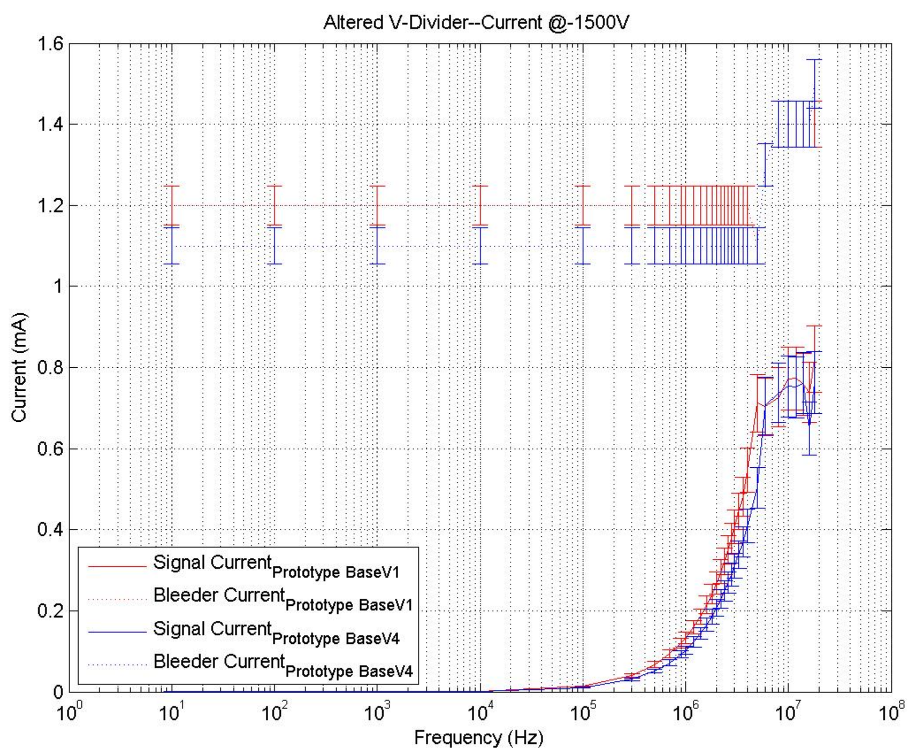


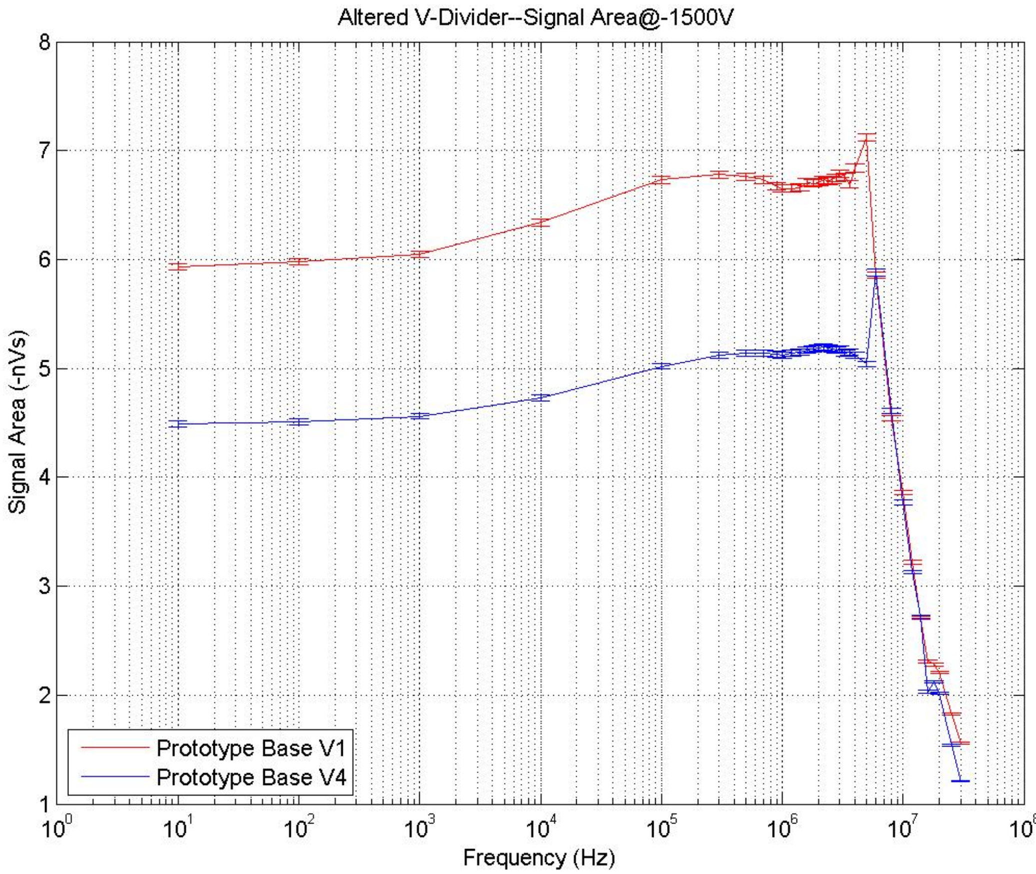


There does not seem to be any appreciable benefit to having additional transistorized stages.

3.6 Test 5: Prototype v1 vs. Prototype v4

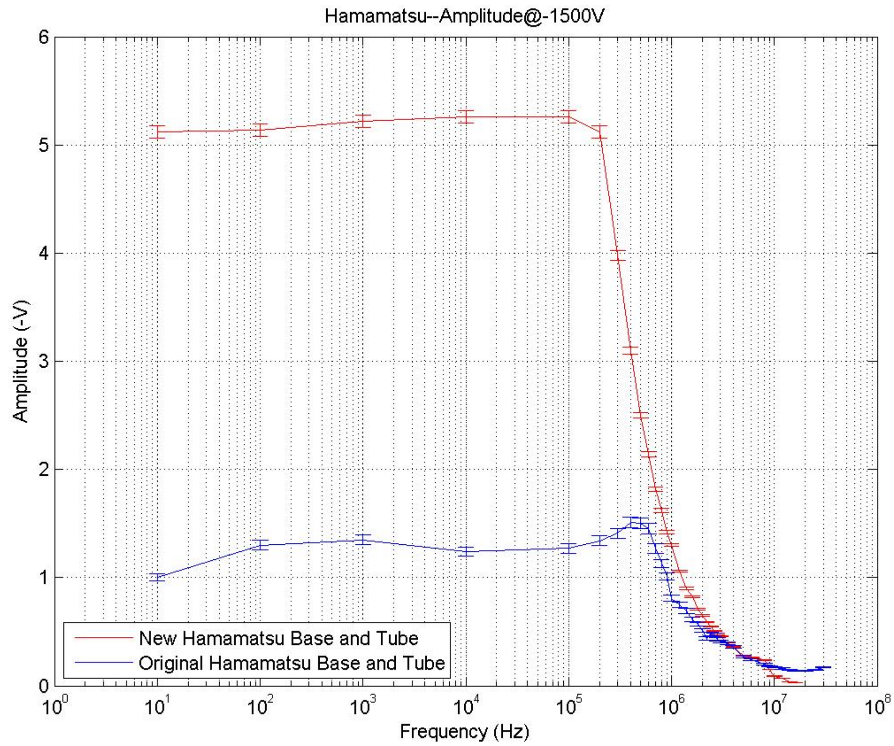


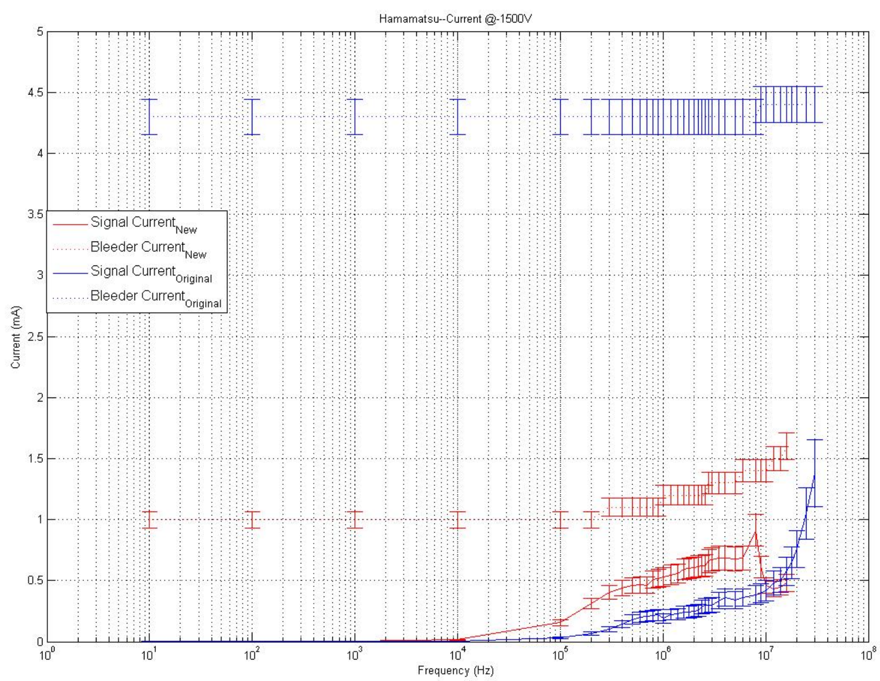


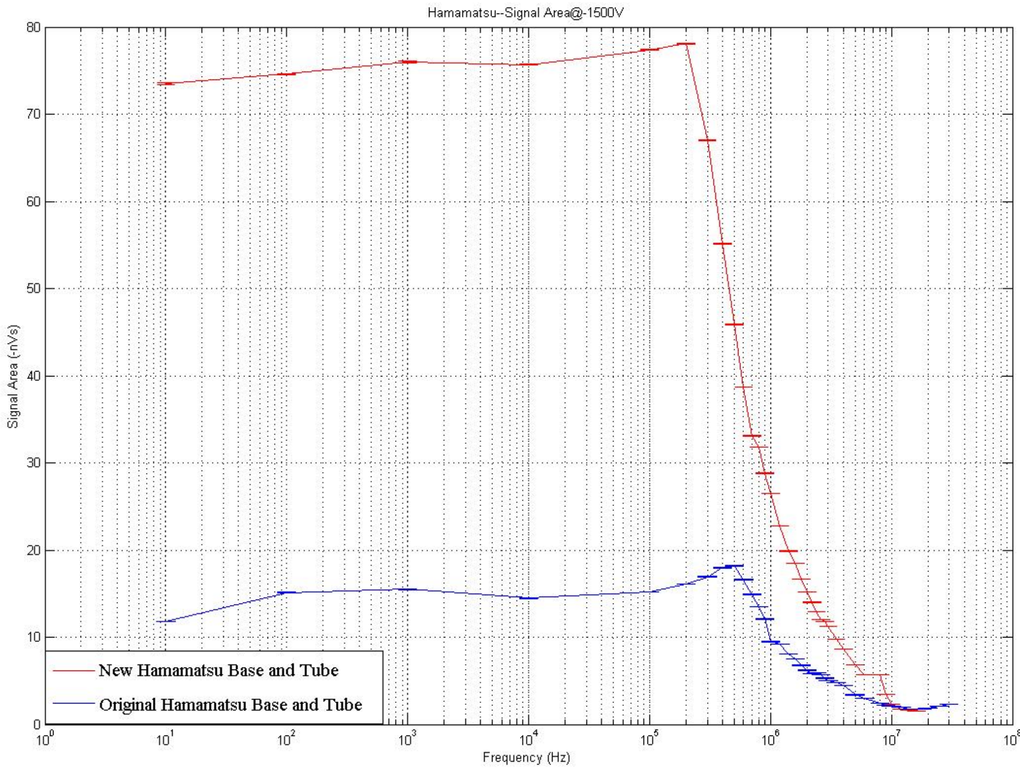


The altered voltage divider seems to supply a higher amplitude and signal area while slightly increasing the bleeder and signal currents. However, no change in the rate capability appears to result from the alteration.

3.7 Test 6: Hamamatsu Bases

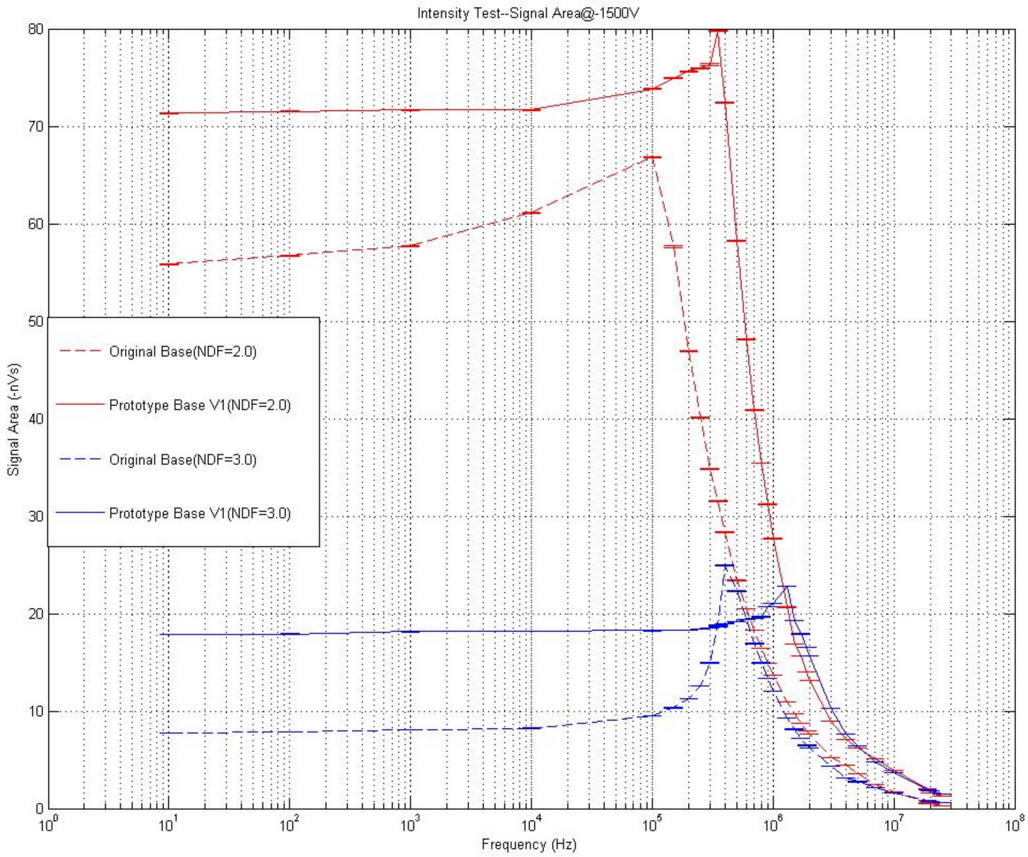






The "original" Hamamatsu base is labelled as a "high current, high rate" tube and base. The "new" Hamamatsu's are the ones that are used in our Station 3 and 4 hodoscopes at SeaQuest. While they appear to have more stable behavior, we see that they begin to "sag" at between 100-500kHz.

3.8 Test 7: NDF D=3.0 vs NDF D=2.0



To observe the behavior upon 10x more intensity, we measured the signal area for the D=2.0 NDF's in the case of the Original and Prototype v1 bases. We see similar qualitative behavior with the sagging beginning at lower frequencies with signal area eventually converging.

4 Conclusions

The Prototype PMT Base yields a clear improvement in both signal amplitude (∼2x) and current capability (∼3x) at the expense of requiring thrice the current as the original base design.

Further modifications of this design by modifying the voltage division or transistorizing additional dynode stages do not appear to improve the capabilities of the base.

Decreasing the overall resistance does increase the rate capabilities of the base, but not by any appreciable amount before (1) the power rating of the components is exceeded or (2) the maximum allottable current is exceeded.

5 Acknowledgements

- Sten Hansen (FNAL), for supplying the base design
- Allison Sibert, Todd Moore, and the UIUC High Energy Physics group, for a great amount of assistance, lab space, and various electronics
- Dave Christian (FNAL), for advisement along the way
- Steve Errede (UIUC), for the use of the fast-pulsing LED circuit, the NDF's, and for advice on procedures
- Daya Bay collaboration, for the use of their lightbox

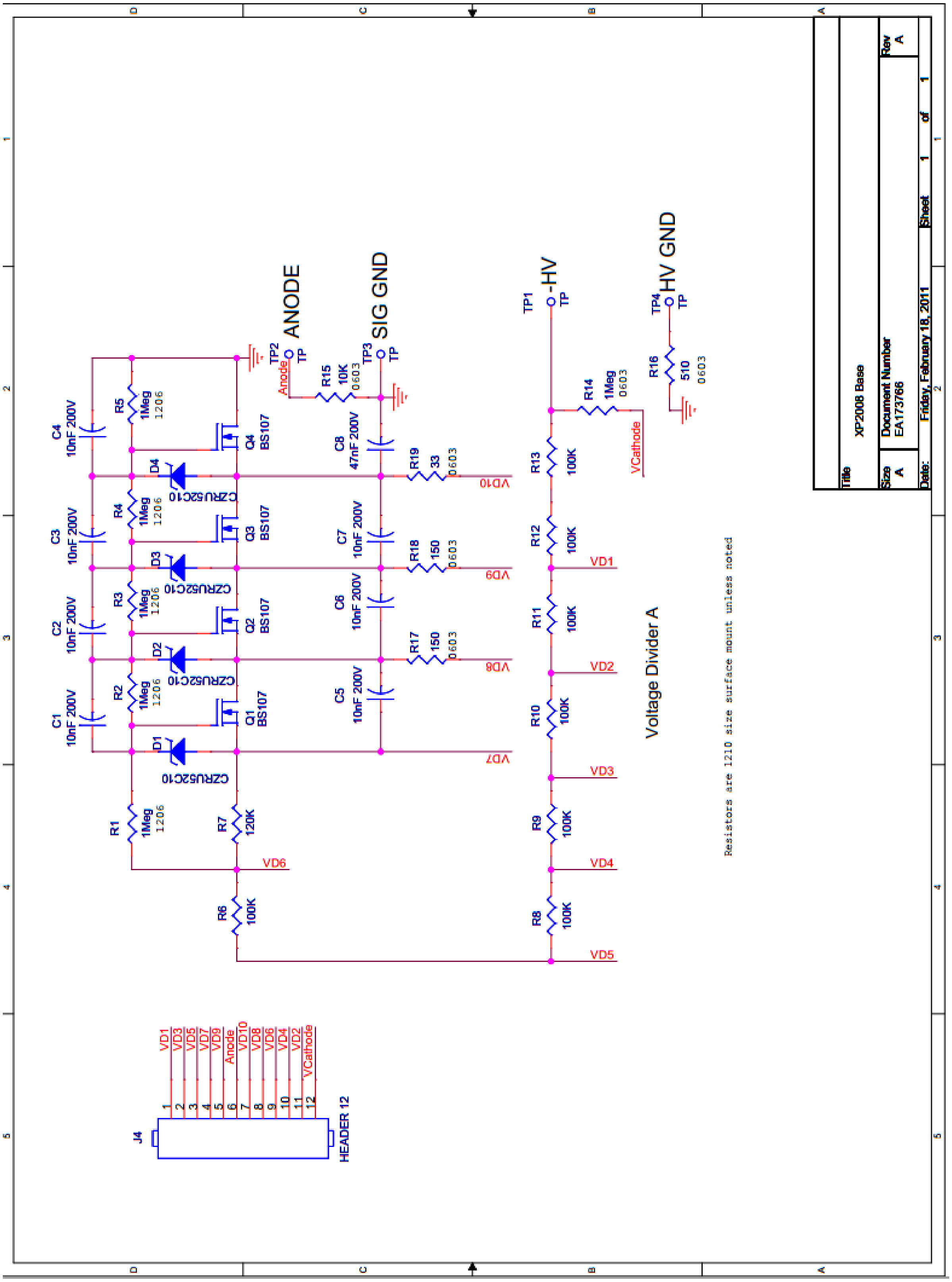
References

[1] University of illinois e906 twiki - hodoscope hardware
https://www.npl.illinois.edu/cgi-bin/twiki/bin/view/E906/HodoscopeArrays.

[2] Photonis xp2072 photomultiplier tube specification sheet
https://www.npl.illinois.edu/twiki/pub/E906/HodoscopeArrays/XP2072B-Characteristics.pdf. April 1999.

[3] M. Diefenthaler. Seaquest elog entry #1787: Hodoscope sagging
http://e906-gat2.fnal.gov:8080/SeaQuest/1787. April 2012.

6 Appendix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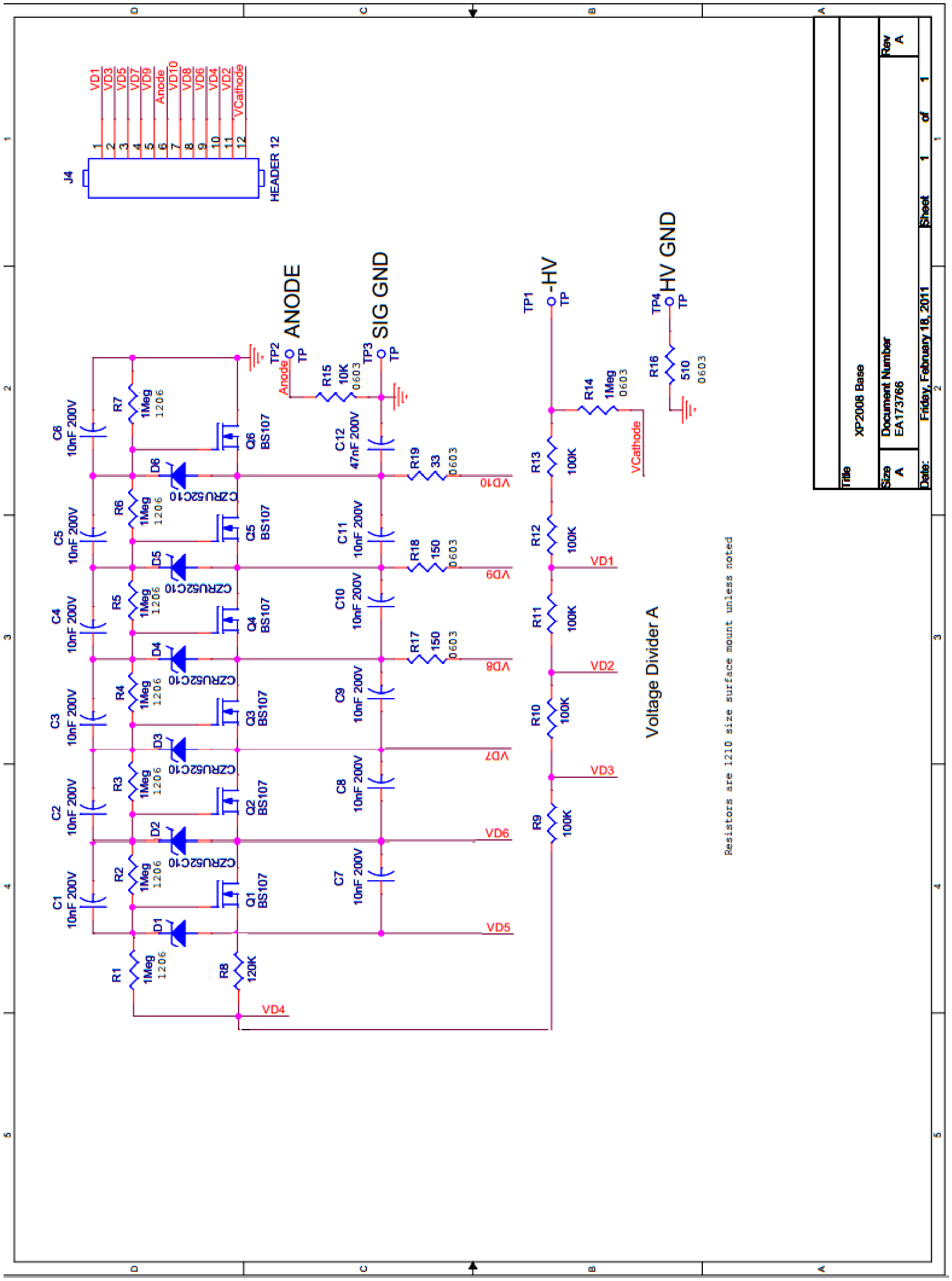
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