Plan for Testing the Hamamatsu H8500 Multianode Phototube for TRICE Use

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Abstract

While the Hamamatsu H8500 pixel size of 5.8mm makes it an inviting candidate for use in the Track Imaging Cerenkov Experiment (TRICE), initial measurements of the pulse height distribution for low light level raise questions as to its viability for the experiment. The existing base structure appears to have too little gain in the first dynode resulting in a wide variation in pulse height for a single photoelectron. It appears that the photoelectron frequently fails to produce any secondaries in the first dynode. In this note I outline a testing plan for the immediate future to help resolve whether we continue with this tube as our baseline.

1 Introduction

We acquired our first Hamamatsu H8500 several months ago. Testing has proceeded slowly due to hardware problems with high voltage and noise pickup; and also due to lack of understanding of the pulse height spectrum in the tube. In this note, I will first illustrate the results of few photoelectron measurements made recently which we believe we finally understand to some extent. Next, I'll present the results of other tests. Finally, I outline a plan of testing for the immediate future for the tube with the standard base and possibly with a base modified to increase the gain of the first dynode.

2 Few Photoelectron Measurements

In this section, I present and discuss measurements made on the H8500 that involve producing a few photoelectrons in the photocathode per event. Few ranges from $0- \sim 8$. I begin with a description of the measurement setup.

2.1 Experimental Setup

The measurement setup consisted of the following:

- Dark box containing
  - Hamamatsu H8500 64 anode phototube
  - Hamamatsu R580 reference phototube
  - Blue LED pulsed from an external circuit
  - Graded neutral density filter wheel going from nearly opaque to transparent driven by a stepper moter controlled externally.

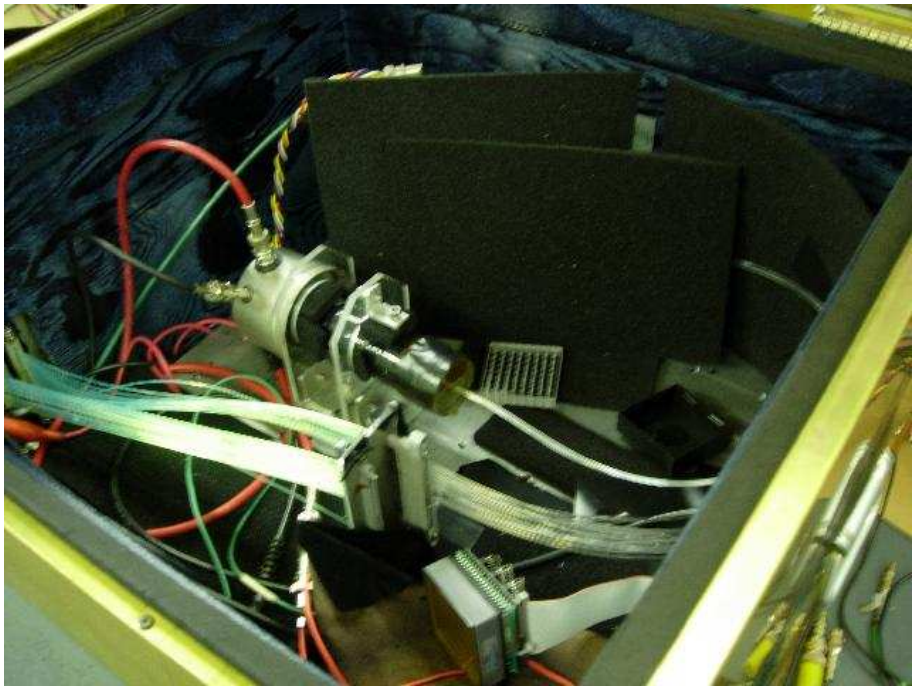

Figure 1: R580 and H8500 shown in dark box. The fiber routing to the R580 is seen. The H8500 has not been configured with fibers in this photo. The LED and filter wheel are screened by the black foam. Fibers exiting the box were used for separate testing of a Hamamatsu R5900-00-M64 tube.

  - Wratten ND1.0 gelatin neutral density filter
  - Clear fiber to transport LED light pulses to R580 and H8500

- Separate high voltage power supplies for the R580 and H8500. The R580 used an old Northeastern Scientific model RE-5002 supply. The H8500 used a Power Designs model HV-1565 supply. The H8500 supply output was checked with a DVM which verified the output corresponded to the dial setting to within 1-2V over the range used for the supply.

- RABBIT crate outfitted with EWE ADC board, BAT Before/After controller board, Wire Amplifier Card (gain: 1 ADC count/1.144 fC), two TCAL dirver boards: one for producing control pulses for the LED and one for the filter wheel stepper motor.

- PC for data acquisition.

The setup inside the dark box is shown in figure 1. The EWE contains one 16 bit ADC that services all analog channels; specifically it digitizes the phototube signals from the Wire Amplifier board. This board was originally designed to readout the CDF central shower maximum detector wire channels. It was used because of its high gain: 1.144 fC/ADC count.

Briefly, the data acquisition process proceeds with the BAT continually issuing Clear & Strobe (C&S) pulses. This resets the Before/After switches to begin sampling the integrated charge from the phototubes via the wire amplifier. The Before switch is opened holding the baseline value, the LED pulse is triggered via a signal from the TCAL Driver board timed with the C&S, the After switch is opened once the resulting LED signal from the phototube has integrated to its

maximum value. The Before/After gate width was 20μs. The decay time of the sample and holds is much longer than this so that we get a faithful representation of the charge output. The ADC digitizes the Before/After difference so that common mode noise is greatly reduced. A second TCAL Driver board provides a signal capable of triggering a pulse in the stepper motor for the neutral density filter wheel. This allows a selected number of events to be taken at each of a user specified number of filter wheel settings. This mode is used for linearity measurements. For measuring gain and photoelectrons at a fixed light level, the stepper motor pulse circuitry is disabled by simply powering it off.

It was found that even at the most opaque settings of the filter wheel, the LED produced too many photons per pulse to get into the single photoelectron region on the R580 and H8500. To further reduce the light output, a 1.0ND Wratten gelatin filter was placed between the LED and the fiber bundle transporting light to the photocathodes. This allowed operating in average photoelectron per pulse ranges of $0- \sim 8$.

For the gain measurements described in the next subsection, the system was operated with the filter wheel in a fixed position and the extra gelatin filter inserted.

2.2 Gain Measurement with Few Photoelectrons

To search for a single photolelectron signal, a plastic template was placed on top of the H8500 photocathode. This had 64 holes drilled in it in an 8×8 matrix. The holes allowed a fiber to be inserted and be centered on any given pixel in the tube. For the initial photoelectron measurements, pixel 39 was chosen which is located in a row adjacent to the center line and one column in from the edge of the tube. The H8500 anode readout is grouped four columns of 16 channels each with an associated ground pin. The configuration is designed for a 2×18 mass termination connector. The extra four pins are allocated to two grounds, one unique locator with no pin, and either another ground or a summed last dynode output. At this writing, we had only one mass termination connector that was broken out into 16 anodes plus the one dynode sum. Since this connector uniquely fits onto only one of the four 2×18 pin sets, we had a choice of only 16 pixels. Pixel 39 was chosen to be as close to the center of the tube as possible.

The standard H8500 base voltage divider circuit that comes with the tube seems inadequate for measuring a single photoelectron peak. The potential difference between the photocathode and the first dynode and between each of the 12 dynodes is identical. The value is about 65-77V for a supply voltage of 850-1000V. The last dynode to anode voltage is also identical to the other interdynode voltages but has a guard ring with voltage that is 6-7V with respect to the anode. The single photoelectron peak width seen at the anode is at least as large as the net signal mean in general. To determine an initial filter wheel setting to provide adequate light, the H8500 was set to 850V and a series of 4000 event runs was taken at different filter wheel settings. This voltage gives a tube gain of $2 - 3 \times 10^5$ for a "typical" tube.

The data acquisition program has a run mode to determine the position of least light output from the filter wheel. This position is called the beginning. The initial runs were taken at 25-50 steps from the beginning in 5 step increments. One revolution of the wheel corresponds to about 400 steps. The resulting pulse height distributions are shown in figure 2 on a semi-log scale. The semi-log scale is used due to the large number of pedestal events and the narrow width of the pedestal ($\sim$ 5 ADC counts). The main differences seen as the filter wheel setting increases from 25 to 50 are the reduction by about a factor of two in the number of pedestal events and the broadening of the tail of the distribution. The "peak" of the signal distribution remains at about 7000 counts. Nothing corresponding to a peak for a single photoelectron is seen. For a gain of about 3×10^5 and an ADC conversion of 1 ADC count/1.144fC, one photoelectron should give a

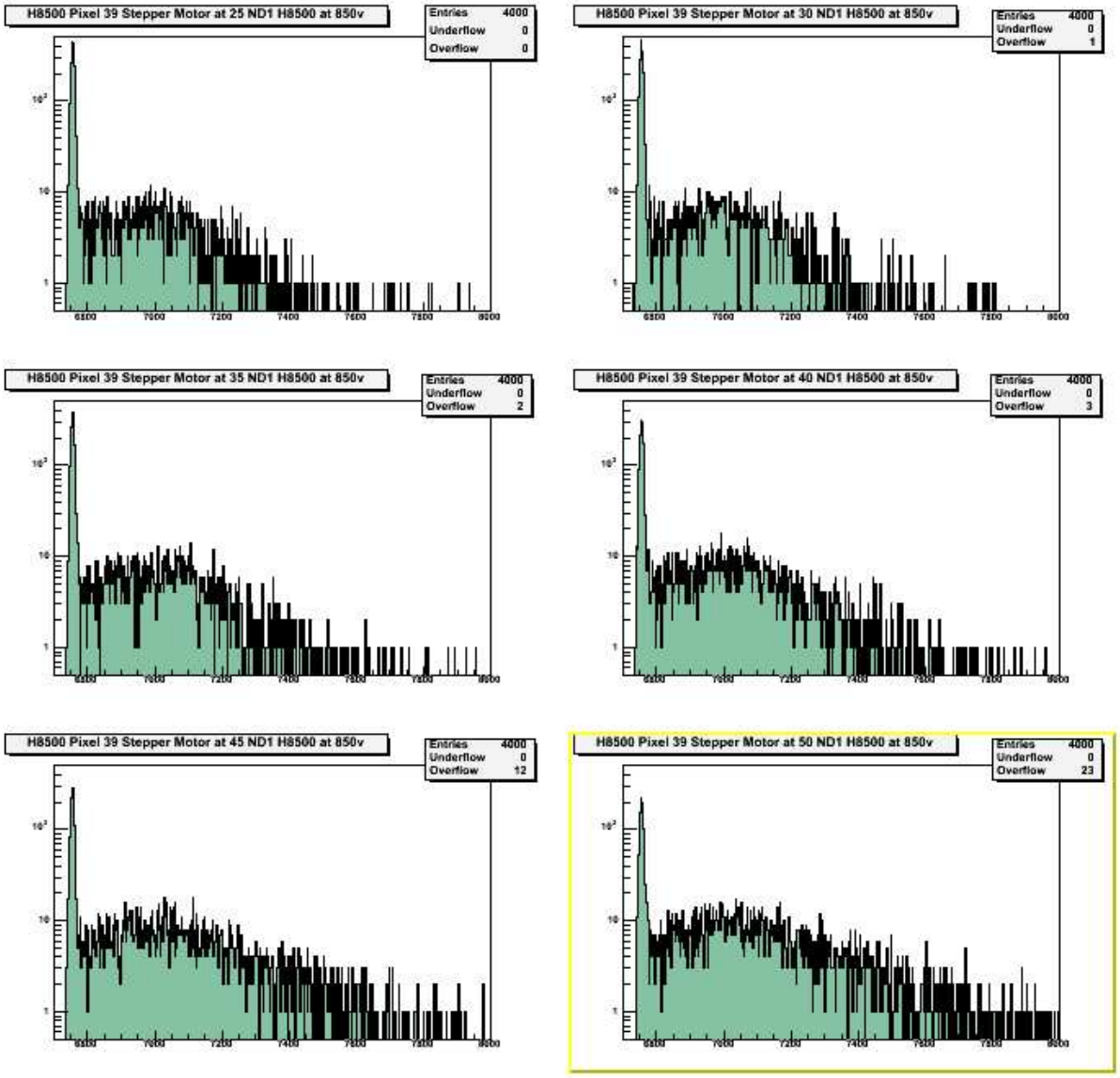

Figure 2: Pulse height distribution with H8500 set to 850V and filter wheel at settings of 25-50 steps from beginning minimum light transmission position. Note the large number of pedestals necessitates the log vertical scale to observe the signal structure versus filter wheel setting.

net signal of about 42 ADC counts. Added to the pedestal of about 6750 counts, we would expect the single pe peak to be at about 6800. The peak around 7000 would seem to correspond to about 6 pe. The lack of pe definition in the plot indicates that the multiplication in the first dynode is fairly low. A model that worked well for similar behavior seen by MINOS in their Hamamatsu R5900-00-M64 and R7600-00-M64 multianode phototubes treats the production of photoelectrons and secondaries from the first dynode as a convolution of two Poisson distributions [1]. The anode output is represented by a Gaussian whose mean and variance are related to the tube gain, the number ofsecondaries from the first dynode, and a parameter that is approximately the secondary emission ratio of the tube. The specific form is given in equation 1:

$$F(q) = \sum_n \frac{(N_{pe})^n \exp(-N_{pe})}{n!} \sum_m \frac{(n\epsilon)^m \exp(-n\epsilon)}{m!} \frac{1}{\sqrt{2\pi}\sigma} \exp(-\frac{(q - mge/\epsilon)^2}{2\sigma^2}) \tag{1}$$

where the fit parameters are N_pe, the number of photoelectron; ϵ, the secondary emission ratio; and g, the phototube gain. The number of photoelectrons, n, is summed over as is the number of secondaries from the first dynode, m. The Gaussian mean is given by mge/ϵ and the variance is $\sigma^2 = (m/\epsilon)(ge/\epsilon)^2$. The measured spectra were fit to a Gaussian pedestal with parameters giving number of pedestals, mean and variance plus the three parameter signal form given above.

I chose to take a larger statistics run at a setting of 50 steps with the H8500 voltage set to 850V. A total of 40,000 events were acquired and a fit to the distribution performed. The result is shown in figure 3. If the fit is to be believed, the secondary emission ratio is 0.83 and 43% of single photoelectrons fail to produce any secondaries from the first dynode that are propagated for further multiplication. This would clearly indicate that the voltage of the first dynode with respect to the photocathode needs to be boosted. The fit gives a gain of 3.7×10^5 which is reasonable for the typical specifications supplied by Hamamatsu. The average number of photoelectrons of 6.8 is also reasonable given the peak of the distribution falls around 7000 ADC counts which we noted above would correspond to about 6 pe. I note though that getting good convergence of the MINUIT minimization routine used for fitting is difficult. I suspect this derives from the fitted form having a very shallow minimum and large correlation between the gain, secondary emission ratio, and number of photoelectron parameters. One can also infer that a substantial fraction of the photoelectrons fail to produce enough secondaries to produce an anode signal by using the number of pedestal events to estimate the number of photoelectrons. For Poisson statistics, the probability of getting zero photoelectrons given an average number of photoelectrons, N_{pe} is

$$\text{Prob}(0) = \exp^{-N_{pe}} = \frac{\#\text{pedestals}}{\#\text{total}}$$

For 13,190 pedestals in 40,000 events, we would estimate the average number of photoelectrons as 1.1 using the above formula. This contradicts the fitted value of 6.8 and also is inconsistent with the pulse height distribution observed.

Data were subsquently taken at 900, 950, 1000V for the H8500 voltage and the filter wheel at step 50. I succeeded so far in getting a convergent fit for only the 950V data. Here the gain was fitted as 6.06×10^5, the secondary emission ratio was 0.82, and the average number of photoelectrons was 8.0. The latter probably results from the peak having moved out to 7200.

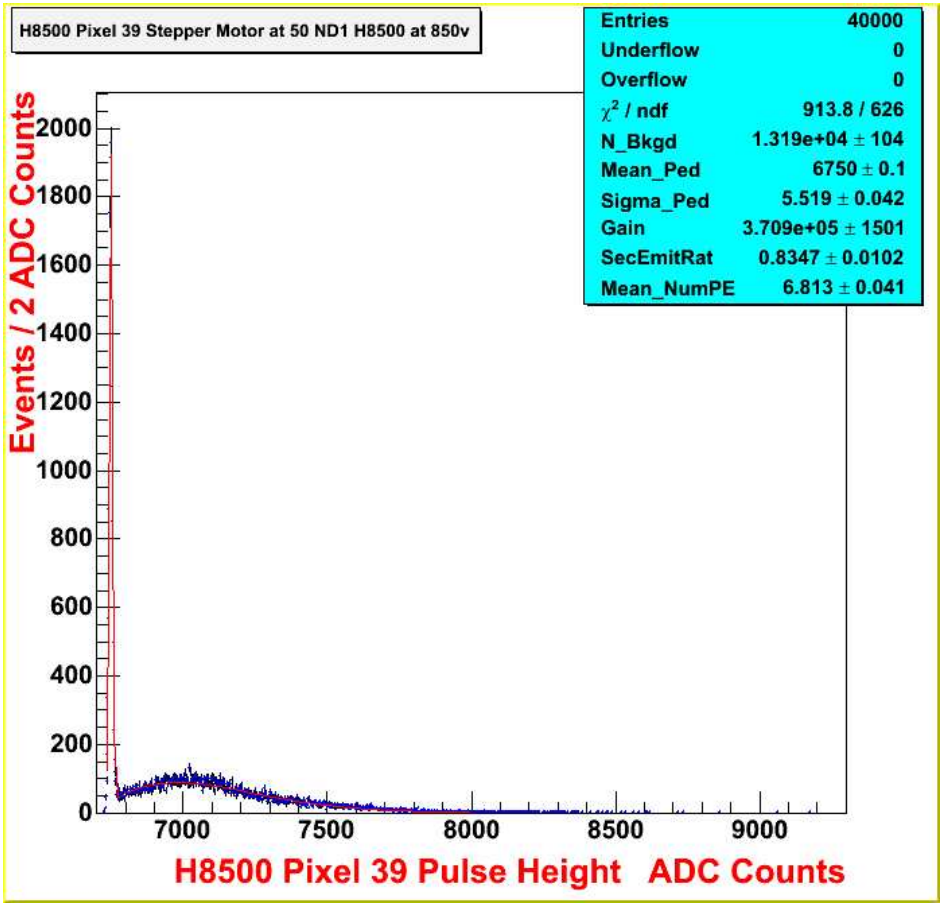

Figure 3: Pulse height distribution for H8500 pixel 39 fit to pedestal plus signal form given in equation 1.

3 Other H8500 Measurements

3.1 Introduction

When we first acquired the H8500 multianode tube, we made a few measurements of linearity and crosstalk. We also took the tube to the TRICE site and recorded the summed anode output on a digital oscilloscope triggered by the threshold setting for the channel recorded on the oscilloscope. The high voltage supply used had some problems that caused the output to be much lower than the dial setting. We would, therefore, plan to repeat these measurements as part of our determination that the H8500 is a viable tube for TRICE.

3.2 Linearity of H8500

The first tests with the H8500 were performed on 1 Apr 2004 with the high voltage on the Fluke supply set to 825V. As noted the actual voltage was substantially below the dial reading. Based on measurements made later by Rich Talaga, the actual voltage estimated for a dial setting of 825V is $\sim 635V$. This would give a gain of only a couple times 10^4 for the tube. For the measurement, pixel 7 was readout as well as the R580 pulse height. The latter was used as a normalizer. The R580

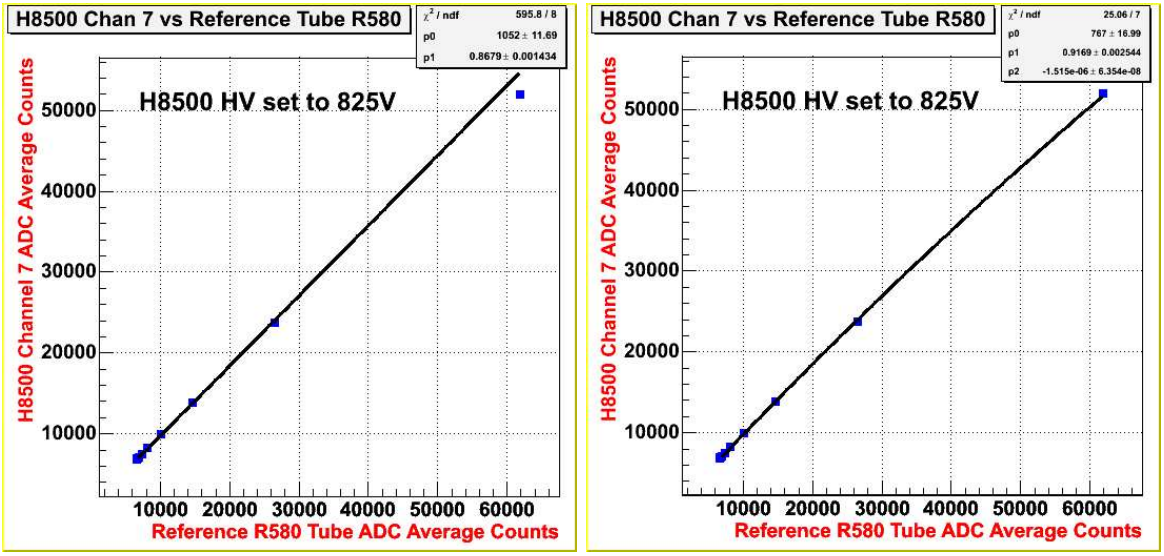

Figure 4: H8500 pulse height vs. R580 pulse height. The acutal voltage of the H8500 was about 635V corresponding to a gain of a couple times 10^5. The plot on the left is a linear fit to the response correlation while the one on the right is the same data fit to a quadratic.

voltage was set to 620V. The R580 has been used on CDF for 20+ years and has good linearity. At the low gain one gets at 620V, the tube should give a linear response over the whole range of the RABBIT ADC (65535 counts). So we assume any deviation from a straight line for H8500 versus R580 pulse heights was due to nonlinearity in the H8500. However, we have no definitive evidence that the R580 is not the nonlinearity source.

Data were taken using the filter wheel and LED pulser at 10 different steps on the filter wheel. The H8500 response versus the R580 response was fit to both a straight line and a quadratic. The results are shown in figure 4. The H8500 has good linearity up to at least 24000 counts ($\sim$ 21pC). There is a small deviation from linear response at the highest light levels corresponding to about 52k counts for the H8500 in the RABBIT system.

3.3 Night Sky Background Simulation

An important consideration for us is the performance of the tube in the presence of a constant night sky background. The questions are at what DC light level does the gain of the tube begin to diminish and can we adequately discriminate a signal pulse in the presence of this background. To simulate the night sky background, an incandescent flashlight bulb was placed in the dark box and the performance of the H8500 was measured using the pulsed LED as the voltage on the bulb was increased to give higher DC current in the phototube. The H8500 high voltage supply was set to 700V to avoid saturating the ADC reading as the filter wheel stepped through one revolution. The dial setting of 700V corresponded to an actual voltage delivered of 540V; so the gain of the H8500 was quite a bit lower for this test than we will eventually want. A baffle was setup around the R580 to shield it from the incandescent bulb so its response was unaffected during the test. With the bulb off the R580 dark current was 6pA. With the bulb voltage at 0.8V corresponding to the highest light level for the test, the R580 dark current was 10pA. Thus, the R580 gain was negligibly affected.

The output from the H8500 pixel 31 was readout along with the R580. The voltage on the

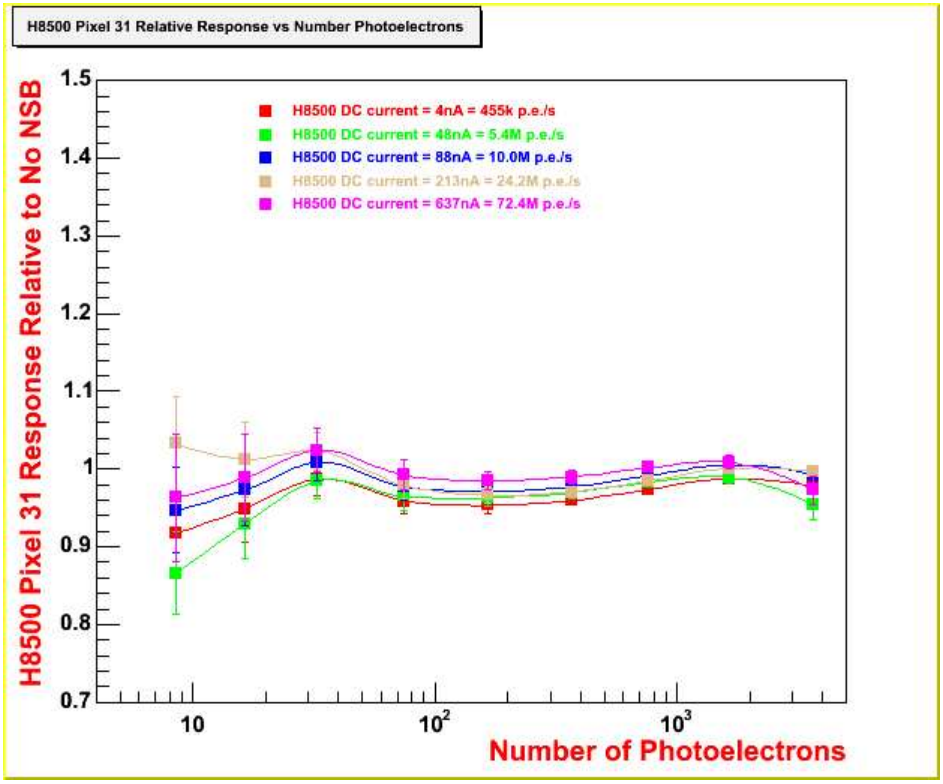

Figure 5: Response of pixel 31 of the H8500 in the presence of a simulated Night Sky Background (NSB) relative to the response with no NSB. The relative response is plotted versus signal size converted to an equivalent number of photoelectrons. Curves are shown for five different background light levels also converted to an equivalent number of pe/s. The lines simply connect the points from a given run at a set light level and are not fits.

incandescent bulb was set at six different levels: off (used to normalize the H8500 pulse height) and 5 nonzero values giving a DC current from pixel 31 ranging from 4-637nA. At each filter wheel setting, the average response of the H8500 from pixel 31 and the average response of the R580 were recorded. Using the bulb off run, the response of the H8500 versus the R580 was fit. Then with the bulb on, the R580 response was used to infer what the H8500 response would have been with the bulb off. The actual average response was divided by the inferred bulb off response to obtain the response relative to no Night Sky Background (NSB). The average ADC reading was converted to an equivalent number of photoelectrons. In figure 5 is shown the relative response versus number of photoelectrons for the five different NSB levels simulated with the bulb. The H8500 showed little change in gain over most of its range even at the highest light levels. Not shown on the plot are data corresponding to near saturation of the ADC. At this level, substantial dimunition of the H8500 gain was observed for most DC light levels.

Given the low gain at which the H8500 was operated for the test, it will be necessary to repeat this test at higher gain for determining the feasibility of the H8500 for use in TRICE.

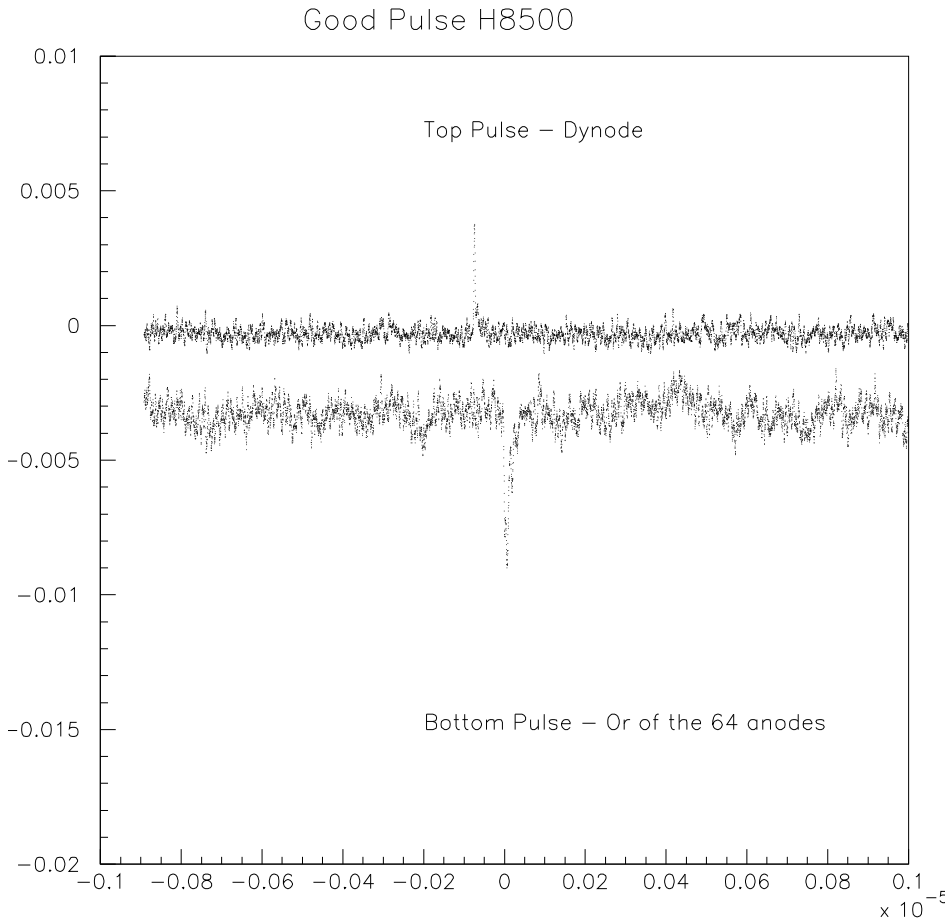

Figure 6: Summed anode signal for the H8500 triggered in response to presumed Cerenkov light from a cosmic ray shower in the upper atmosphere above the TRICE site. The plot represents a digital oscilloscope trace with a time span of 1μs before to 1μs after the pulse. The vertical scale is in volts with the net anode signal height being about 6mV.

3.4 Observation of Actual Signals at the TRICE Site

In late September, 2004, we took the H8500 phototube to the TRICE site and measured actual Cerenkov light pulses from cosmic ray showers. To shield the tube from horizon light, we used a $6 \times 6 \times 6\text{ft}^3$ unistrut framework to support a plastic sheet surrounding the work area. The tube was placed with photocathode facing straight up on a box whose height was about 15 inches. The voltage was set to 700V on the Fluke supply again corresponding to an actual voltage of about 540V. All 64 anodes were summed and put on a single connector that was input to a digital oscilloscope. The scope was triggered on the summed input with a threshold of 3.72mV. Before recording data on the scope, the dark current from the anode sum was measured to be 64.8μA. We observed triggers at a rate of about 0.1Hz. We also input the last dynode signal of the tube to the scope. One of the recorded pulses is shown in figure 6. The summed anode signal and the dynode signal are noted. Note the DC offset of the anode signal caused by the constant Night Sky Background signal. This is probably a combination of the actual NSB present from outer space plus light from the surrounding urban environment.

3.5 Attempt to Detect Single Photoelectrons From Dark Current Using a Dynode Trigger

A final test that was attempted before our success with fitting the few photoelectron spectrum with the improved model described in section 2.2 was to attempt to operate the tube with no external light input and trigger on the output of the dynode signal from presumed photoelectron signals caused by the dark current. Since the dynode signal represented the sum of all 64 pixels while we read out only a single or few pixels, the pulse height spectrum for each pixel recorded was mostly pedestal. The test was inconclusive due to low statistics and our success with fitting the data to a model accounting for secondary electron production at the first dynode lead us to abandon further tests with the dark current signal triggered on the dynode.

4 Conclusion on Test To Date

The testing of the Hamamatsu H8500 multianode phototube for viability in TRICE has been minimal so far. The slow progress was somewhat due to the extended time it required to understand the pulse height spectrum of the tube in the few photoelectron range. I believe we understand this performance now well enough to proceed with further testing. The data indicate that the base as it comes from the manufacturer is not suited to our needs and needs to be redesigned with a much higher gain in the first (few?) dynode(s). The signal though does separate from the pedestal fairly well, so I believe we can retain an optimism about the ultimate feasibility of using the tube. The signals recorded by actually pointing the tube at the night sky were encouraging. At low gain, the tube easily produced pulses that could be distinguished from the constant DC current provided by the NSB. The simulation of the NSB also showed the tube's relative response was retained to high background light levels. In all this though, the tube was operated at a much lower gain than we will want for its use in TRICE. The tube appears to have good linearity for signals providing up to tens of picocoulombs of charge from the anode.

At this point, I believe the primary concerns about the feasibility of the tube are

1. Can the base be redesigned to give adequate gain in the first dynode so that a more well-defined single photoelectron signal can be discerned?

2. With a higher initial stage gain in the tube, does the DC current level stay nearly the same for a given background light illumination?

3. Can the tube be operated with a gain of at least a few times 10^5 and the DC current from NSB be held at a level that is both safe ($< 100\mu$A) and allows discrimination of our expected signals on top of the DC current?

4. Is the uniformity of gain across the face of the photocathode adequate for the front end electronics we plan to use?

5 Plan for Future Testing of H8500

With the above considerations of feasibility in mind, I now outline our plans for immediate future testing of the H8500 to determine if we proceed with it as our baseline tube for TRICE.

Since our ability to accurately measure the gain of the tube is critical and since the base configuration in the standard base makes this difficult, I think it is important to measure the pulse height spectrum in the few photoelectron region with a modified base as soon as possible. The

fit of the spectra to our model incorporating the gain, number of photoelectrons, and secondary emission ratio frequently fails. The failure in MINUIT is typically that of not having a positive definite covariance matrix while the actual parameters provide a reasonable fit to the data. There is an indication though that this failure points to a problem with the "shallowneess" of the fit minimum. It appears that gain, number of photoelectrons, and secondary emission ratio are highly correlated. One, thus, can't have good confidence that the fitted values represent reality. Providing higher gain in the initial stages of the tube should help to narrow up the single photoelectron peak and allow a more robust fit for extracting the tube gain.

Verifying that the spread in gain amongst the anodes is at an acceptable level can be done with the current tube setup as long as an operating point can be found that provides believable fits to the gain. The measurement with the voltage set to 850V and the filter wheel set to 50 steps from the beginning seems to have provided a reasonably robust fit. So I would propose to proceed with this measurement next.

It is important to determine our ability to operate the tube in the presence of the NSB with a gain of a few 10^5. So this measurement should also be repeated in the near future.

The level of crosstalk between pixels is probably of lesser concern that the above items but it is probably good to attempt this measurement since it is straightforward to do now. The crudeness of our current setup for injecting light raises some concern that the crosstalk will have a substantial component from misalignment of the light fiber with the pixel center or light "leaking" from the fiber into adjacent pixels. However, we can at least get an idea of the size of the crosstalk in the tube.

Since the linearity of the tube was again measured at low gain, it would be worthwhile to characterize this at a more usable gain level.

There are many other tests that will be useful for determining the limitations of the tube for use in Imaging Air Cerenkov Telescopes such as double pulse resolution, recovery time of a pixel after a large pulse, effect on other pixels of a large pulse in one pixel, etc. I would put these tests at a lower priority than the above measurements that will tell us whether the tube might be rejected out-of-hand as a candidate.

So I list below the tests I would suggest in the immediate future:

- Measure the gain for many pixels at a common operating point for the tube. To first order it is possible to simply compare the pulse height distributions pixel-to-pixel, e.g. what is the net ADC count for the peak of the distribution.
- Measure the crosstalk for a few pixels to understand its size and variation.
- Setup the NSB simulation and determine at what NSB rate the tube can operate.
- As soon as possible, provide a modified base for the tube to determine if the single photoelectron signal is improved with higher first dynode gain. If necessary, provide a different tube with a modified base although this makes direct comparison difficult.

This paper is meant as a starting point for discussion of tests to be performed on the H8500 in the immediate future. Feedback is encouraged and the paper will be revised based on the wisdom of the whole of the collaboration.

References

[1] N. Tagg, A. De Santo, A. Weber *et al. Performance of Hamamatsu 64-anode photomultipliers for use with wavelength-shifting optical fibers*, NuMI Note 1040 (2004).