GAP-96-041, Auger project technical note. Measurements of R1408 photomultiplier performance.

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Abstract

To fully understand the data coming from the current round of Auger prototype water Čerenkov tanks it is necessary to have detailed knowledge of the behaviour of the photomultipliers being used. Laser test results are presented which show the single electron spectrum to be poorer than expected. The anode pulse shape in reponse to a fast light input is also measured.

1 Introduction

If we are to expect simulations of water tank response to match the fine details of experimental data several parameters of phototube performance must be available as input. Principal of these are the anode pulse shape in response to a fast pulse light input, and the amplitude spectrum of pulses resulting from single photoelectrons. The Fermilab 6.6 m^2 [1] and 10 m^2 tanks [2], and the Japanese [3], and Argentinian [4] prototypes have all made use of Hammamatsu R1408 pmt units obtained from the IMB experiment [5]. Detailed measurements of the response of these devices have been made using the phototube test laboratory on the 10th floor of Wilson Hall at Fermilab; the results are presented below.

An upcoming paper will describe comparisons between detector simulation and experimental results from the Japanese tank using the data presented here as input.

2 Test setup and 200 mm pmts

The FNAL test setup consists of a nitrogen pulse laser emitting 337 nm light in 3 ns FWHM duration pulses. These pass through a variable density filter wheel into a dark box where they are used to excite a dye cuvette. This re-emits at 440 nm with a pulse width which is not known, but which is < 15 ns FWHM. Some of the re-emitted light passes through a pair of fixed (step) density filter wheels and enters an optical fiber which carries it to the pmt dark box. In the box the fiber termination is mounted in an xy translation stage allowing it to be scanned across the photocathode of a pmt if desired.

Two PIN diodes view the laser light. The first acts as a simple monitor of the raw laser output to provide accurate trigger time of the laser shots (and so avoid the time jitter between the laser receiving a trigger pulse, and actually firing). The second monitors the intensity of the light re-emitted by the dye cell, and hence can be used to correct for the variations in laser emission amplitude pulse-to-pulse (3%). The signals from this second PIN diode, and the pmt under test, are routed to a Le Croy 2249 charge integrating ADC (0.25 pC least count, 10 bit dynamic range). ADC gate width is set to 200 ns.

The complete system is controlled from a UNIX workstation allowing remote setting of variable and fixed filter wheel positions, the mounting stage position, and the laser firing rate. A simple menu driven program guides the test procedure. Please see [6] for more details.

The R1408 is a previous generation 200 mm diameter photomultiplier manufactured by Hammamatsu [7]. Two thousand of these were employed by the IMB experiment in a search for proton decay etc [5]. A number of the tubes, complete with waterproof housings and passive bases, were available for Auger project prototype work. The original passive divider tube base was slightly modified to allow separate HV and signal cables; the voltage distribution ratio remains as recommended on the manufacturer's data sheet for normal operation. Maximum HV permissible is 1.8 KV; most of the tests presented here were conducted at ≈ 1.4 KV, this being similar to the values in use on the prototype tanks. Also note that the tests were conducted with all but a few (central) mm^2 of the photocathode masked[1].

[1] This is necessary so that the tube receives $\ll 1$ mean photoelectrons per pulse with the attenuation wheels at maximum setting — a requirement for the single electron spectrum work in section 4. The same masking was used in all tests in the interests of self-consistency. This means that any possible detrimental effects due to non-uniformity of photoelectron collection characteristics and efficiency across the photocathode surface will

The R1408 is a 13 stage, high gain ($\sim 10^8$) device with a pseudo-hemispherical photocathode. Hamamatsu has now replaced it with the updated (but externally similar) R5912, having 10 stages, lower gain ($\sim 10^7$), and apparently superior time jitter, single electron spectrum, and photoelectron collection efficiency characteristics [8]. Eight of these new tubes have been obtained via the Milagro group and will be used on future prototype tanks.

3 Pulse shape performance

The Auger detector simulation code AGAsim [9] constructs the pmt waveform to be expected for a series of photoelectrons arriving spread over time by assuming that each pe contributes a fixed anode pulse shape (with variable amplitude), and then summing the contributions from each such sub-pulse. It is hence desirable to know the shape of single pe pulses, and if they are indeed similar pulse-to-pulse. Unfortunately it is difficult to measure the *shape* of individual single pe pulses against the RF pickup noise generated by the nitrogen laser firing. We thus adopted the compromise solution of measuring larger pulses induced by many near simultaneous photoelectrons; these at least show little variation in *shape* pulse-by-pulse.

A 1 GSPS (giga samples per second) digital scope was used to capture the waveforms resulting from 1000 laser shots, for several high voltage settings, and light pulse amplitudes. The average pulse shape at 1380 V is shown in the left half of figure 1. In [9] the Half Width at Half Maximum (HWHM) of the anode pulse was assumed to be 6 ns with a symmetrical Gaussian shape[2]. In [10] it was pointed out that real pmt pulses are asymmetric, and a good fit to the FNAL 6.6 m^2 tank data obtained[3] using HWHM-rise of 7 ns, and HWHM-fall of 12 ns. Here we find that HWHM-rise is 7.1 ns, and HWHM-fall is 10.5 ns, giving a FWHM of 17.6 ns. These observed numbers assume that the width of the dye cell light pulse is much smaller than the intrinsic pmt response, and thus represent upper limits. The manufacturer's stated anode pulse rise time is 6.5 ns 10% to 90%.

In the AGASA prototype water tank experiment the pmt signals are

not be included.

[2] We define HWHM as the widths measured about the pulse peak position at half peak height.

[3] Although in that work an incorrect value was assumed for the reflectivity of stainless steel; 85%, rather than $\approx 40\%$.

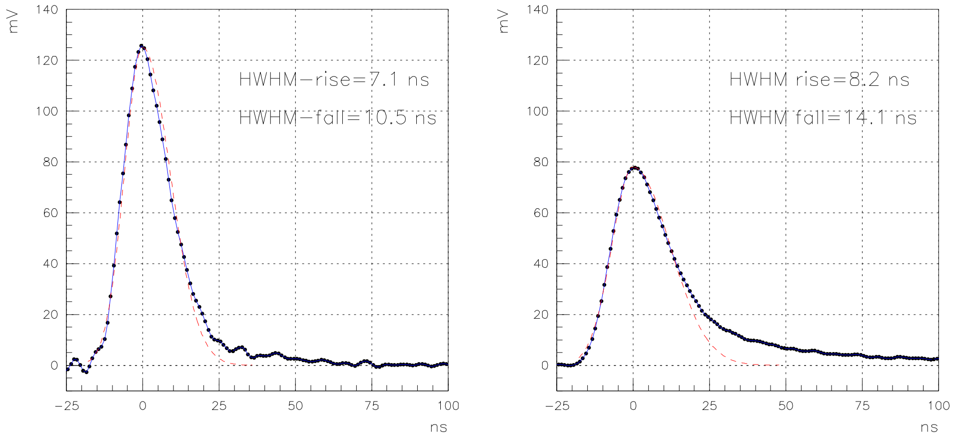

Figure 1: Average pulse shape observed for an R1408 pmt when exposed to a fast light pulse. On the left the shape is shown for a short cable, on the right after an 80 m length of RG58. In each case an attempt to fit the pulses to a dual Gaussian shape is shown, the rise and fall HWHM values being indicated.

routed through $\approx$ 100 m of cable to reach the control room where they are digitized [3]. This affects both the rise and fall time of the pulses significantly. The right half of figure 1 shows the observed pulse shape after 80 m of RG58 cable with conditions otherwise the same as for the left hand plot. Note that the pulse profile no longer has a double Gaussian shape; there is a long exponential tail which is due to the capacitive characteristic of the cable. It is of course possible to calculate the expected effect of a given length of coaxial cable [11] — this exercise remains to be carried out. The latest version of AGAsim now uses these observed pulse shapes for the construction of simulated tank output waveforms.

The light pulse amplitude in figure 1 is similar to that generated in the AGASA tank for a vertical muon. No significant change in pulse shape was observed over a wide range of light intensities. When varying the high voltage a small decrease in pulse width was observed at higher settings.

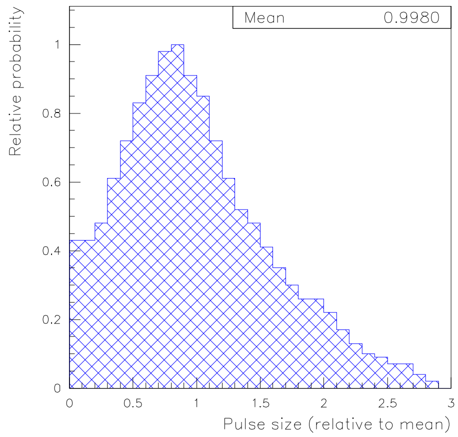

Figure 2: Single electron spectrum for R1408 pmt, derived from manufacturer's data sheet, and used in previous Auger simulation work.

4 Single Electron Spectrum

When pmts are operated in single photoelectron mode there is a large dispersion in the anode pulse amplitude distribution. To generate simulated output waveforms from a list of photoelectron release times it is necessary to sample from this distribution for the height of each sub-pulse. In [9] the distribution for the R1408 tube shown in figure 2 was used, having been extracted from a plot on the manufacturer's data sheet. It is surprising how important it is to include this effect when attempting to explain the characteristics of muon pulses in the water tank where each pmt may receive an average of ≥ 20 photoelectrons.

A controlled pulse system is the ideal apparatus for measuring the single electron spectrum. Since the tube output is only observed for the few 100 ns during which it is known that "real" signal may arrive problems due to dark noise, which plague the common DC light source tests, are essentially eliminated.

Using the FNAL laser test system we have measured the single electron charge spectrum of R1408 pmts and find it considerably worse than expected. The measurements where made at a high voltage setting of 1.4 KV as this is similar to the values in use on the prototype tanks. Using the variable

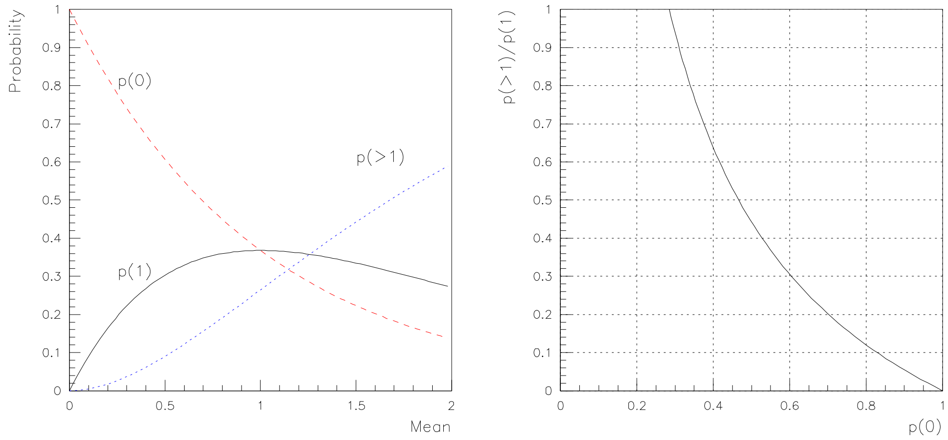

Figure 3: Poisson statistics relevant for measurement of single electron spectrum in a pulse system. To the left the probability of observing 0, 1 or >1 pes is shown for mean pe per pulse values from 0 to 2. On the right the "purity" of a sample of single pe events is shown as a function of the fraction of zeroes observed.

and fixed attenuation wheels it is possible to generate finely controllable light pulse amplitudes. Simple Poisson statistics dictate the probability of observing 1 or more photoelectrons when the mean number of photoelectrons per pulse ($\overline{\mathrm{npe}}$) has a given value; see the left part of figure 3. By reducing the light intensity until in $\geq 85\%$ of cases nothing is observed, in $\geq 90\%$ of the remaining events there is a single photoelectron only. This is shown in the right part of figure 3

Although the RF noise generated by the laser firing causes problems when trying to measure pulse shapes, for measurements of pulse amplitude using the charge integrating ADC it is much less of a limitation — the RF is bipolar, and integrates to zero during the gate time (200 ns). Hence the pedestal values observed in zero photoelectron events are well behaved, as seen in the left part of figure 4. The non-pedestal events have an approximately exponential distribution with *no sign* of a single electron peak or plateau region. This is disappointing, but as will be seen below the measurements appear convincing. We use the data at ADC counts ≥ 21 in the left part of figure 4 to infer the single electron spectrum in the right part of the figure; the

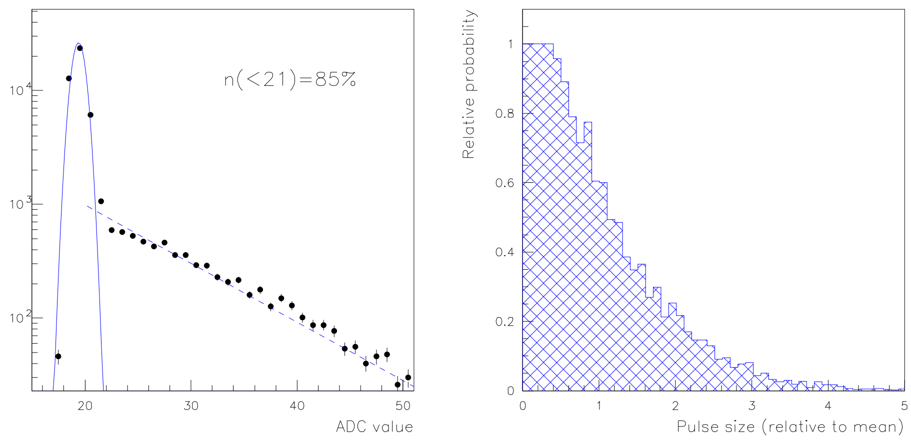

Figure 4: Single electron charge spectrum observed for an R1408 pmt at 1.4 KV. The left plot shows the distribution of ADC values for a run of 50,000 laser shots. A Gaussian fit to the pedestal is shown which contains 85% of the events; the remainder of the distribution is approximately exponential as indicated. The right plot shows the single electron spectrum which we infer from the data; cf figure 2.

pedestal is subtracted. We neglect the fact that $\approx 10\%$ of the non-pedestal events are actually 2 or more photoelectrons. The mean size of a single pe derived is 9.65 ADC counts, or 2.45 pC at 0.25 pC per count. This implies a pmt gain of 1.5×10^7 which is somewhat lower than the data sheet value of 6×10^7 at 1.4 KV, but probably within the bounds of tube-to-tube variation.

It is possible to test if the inferred distribution is correct by making runs at higher light pulse intensities and attempting to reproduce the observations assuming the inferred spectrum. If we sample from the Poisson distribution to get npe, and then draw from the single electron spectrum for each pe, we can generate the expected charge distribution for any given $\overline{\mathrm{npe}}$ value. Figure 5 shows the results of 9 runs at increasing light levels, and the generated distributions using $\overline{\mathrm{npe}}$ values which yield the same mean values as the data. When $\overline{\mathrm{npe}} > 10$ Poisson behaviour becomes approximately Gaussian and we expect the mean values divided by 2.45 pC per photoelectron to equal the $\overline{\mathrm{npe}}$ values being used to generate the simulated spectrums. This is indeed the case for the 3 data sets shown in the bottom line of figure 5, and provides a further consistency check.

A second R1408 tube was tested in the same way and the results were near identical except for the gain value derived, which was approximately a factor of 2 higher. It was not possible to test the new R5912 pmts in the same way as their gain is too low for single pes to be recorded by the 0.25 pC per count ADC at 1.4 KV. We tried amplification but it seems that the RF laser noise does not integrate to zero during the gate time perfectly, and there was no increase in the measurement sensitivity.

It is possible to observe a single pe peak with the R1408 tubes when operating at the maximum HV setting of 1.8 KV. Figure 6 shows a test run with $\approx 90\%$ single pe "purity". A peak is clearly present although the peak-to-valley ratio is of the order of only 1.1 : 1. Whether or not a single pe peak is observed is governed largely by Poisson fluctuations in the multiplication at the first dynode. Hence at increased HV this characteristic improves.

5 Linearity

In The FNAL test setup a PIN diode with excellent linearity characteristic monitors the dye cell re-emission intensity for each laser shot. Hence a simple linearity test can be made by rotating the variable filter wheel while firing the laser. Figure 7 shows the results of this test for two R1408 pmts. Linearity is seen to be good, although the range tested corresponds to only ≈ 4 near simultaneous muons in the AGASA tank, in terms of peak current flow.

6 Conclusions

Enough information has been collected about the actual performance of the ex-IMB R1408 pmt/base units being used on prototype Auger water tanks that we can expect the simulations to reproduce the fine details of the experimental data; that work is on-going. The single electron charge distribution is much poorer than expected from the manufacturer's data sheet, and assumed in previous simulation work. When the new R5912 pmts are in use it will be necessary to make similar measurements on those tubes. A higher sensitivity ADC will be required and/or an optical fiber delay cable to mitigate the effects of laser noise on the measurements.

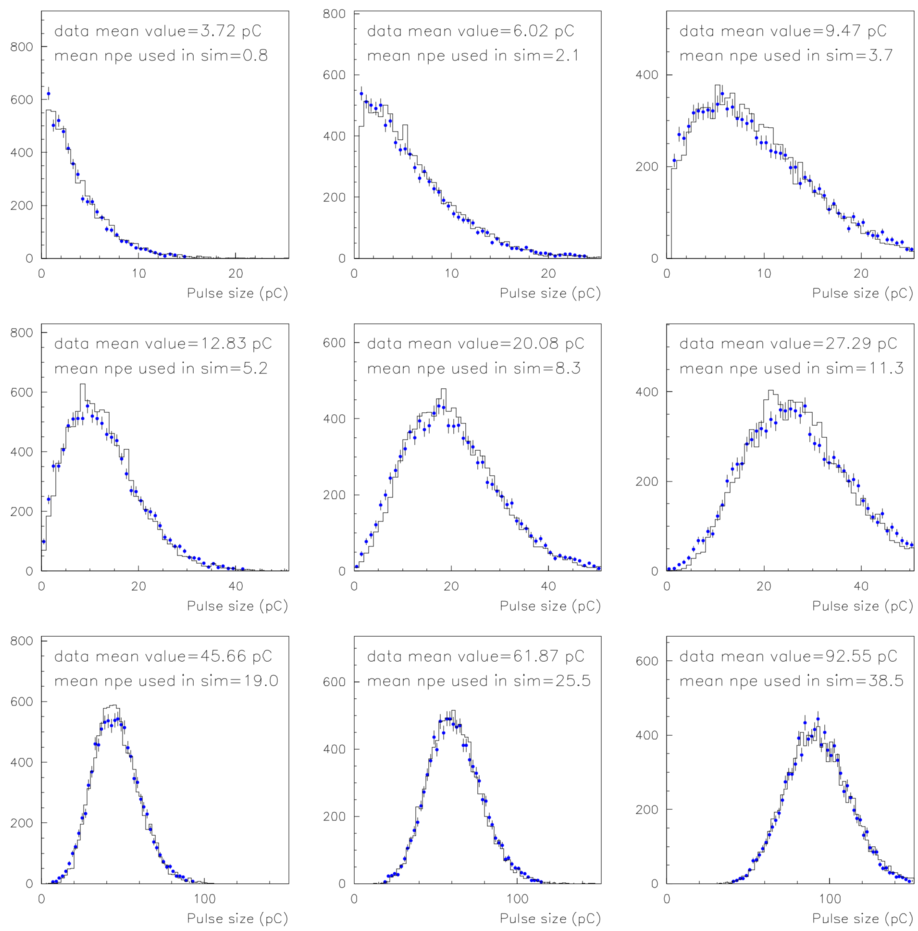

Figure 5: Pulse size distributions for data sets taken at 9 increasing light intensities. The points represent the experimental data, while the solid histograms are simulated data on the basis of Poisson statistics, and the single electron spectrum shown in right half of figure 4. In each case the mean number of pe used in the simulation is indicated, together with the mean value of the data. Note that the horizontal scale changes between each line of plots.

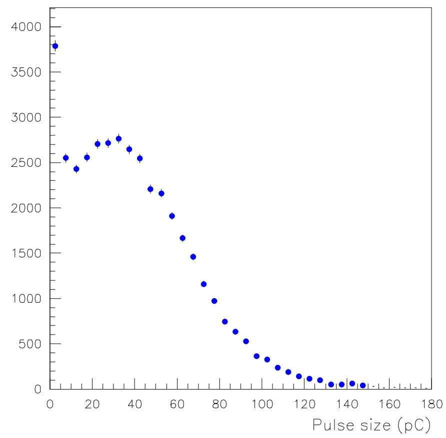

Figure 6: Single electron spectrum for an R1408 pmt running at 1.8 KV. The distribution of pulse charges is plotted for a 200,000 laser shot run.

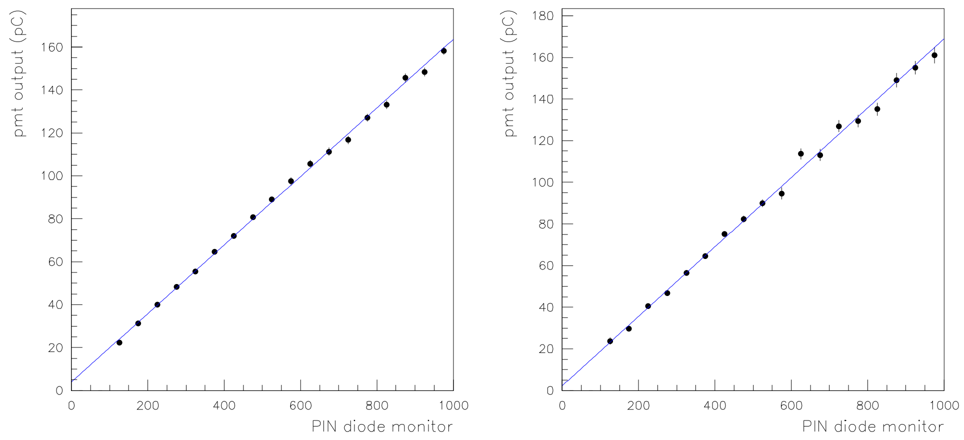

Figure 7: Linearity scans for 2 R1408 pmts at 1.4 KV. A pin diode with excellent linearity monitors the intensity of each laser pulse before it passes through attenuation filters on its way to the pmt.

7 Acknowledgements

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