Response Magnitude Uniformity of Two Commercial 5-Inch Photomultiplier Tubes

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ABSTRACT

We investigated the response magnitude across the full spatial extent of two commercially produced 5-inch photomultiplier tubes, the Hamamatsu R1250 and the Adit B133D01S. Each tube was translated by motorized stages across an incident light source. The response of the photomultiplier tube was recorded, as well as the response of a fast photodiode that simultaneously measured a portion of the incident light. Peak height and area responses were analyzed, with constant fraction discrimination implemented to determine the start and stop times of the peaks for the area calculations. The Hamamatsu response varied linearly across the tube, but had responses that varied by up to a factor of 10 when normalized to the center. The Adit was much more uniform, varying only by a factor of 0.3 across the majority of its spatial extent. These results indicate that the Adit is superior for magnitude of response experimental applications.

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INTRODUCTION

Background and Purpose

Photomultiplier tubes, abbreviated as PMTs, are light-sensitive devices that have many uses in varied physics experiments. They work via the photoelectric effect, converting incident photons into electrons in the photocathode material at the front of the PMT. These photoelectrons are accelerated into the PMT by the presence of a dynode held at a high voltage. Upon striking the dynode, more electrons are produced through secondary emission. These new electrons accelerate towards a series of dynodes held at successively higher voltages, exponentially increasing the number of electrons through repeated secondary emissions until arriving at the final anode. The arrival of this electron cascade at the anode registers as a sharp spike of electrical current which can be output by the PMT. Ideally, a known number of incident photons with known energies all accelerating towards the dynodes should produce exactly the same spike in current. In practice, however, differences in the output of the PMT can occur due to differences in the initial trajectories of photoelectrons, dependent on their location of origin in the photocathode surface. The purpose of my research is to investigate and characterize the response characteristics across the spatial extent of two commercial 5-inch PMTs, the Hamamatsu R1250 and the Adit B133D01S.

Motivation

PMTs can be used with scintillating materials as a means of detecting particle radiation; they are sensitive enough that they can detect the light output from a single interaction, even if the output is a single photon. However, when many photons strike the photocathode, spatial differences in the characteristics of the PMT response can cause the output signal to be inconsistent. A large number of photons striking a less-sensitive region of the PMT could produce a similar response to a small number of photons incident on a highly-sensitive region. In the typical operating conditions of a PMT, which uses a large scintillator to simultaneously illuminate the entire photocathode, this is not an issue. Uniform illumination of the photocathode causes the many varied signals from each of the spatial locations to be superimposed into a smooth, Gaussian-shaped response curve, which minimizes the spatial non-uniformity of the PMTs response. However, PMTs do not benefit from this averaging effect in applications that utilize only portions of the photocathode. For example, the BYU nuclear physics group is working with a neutron detector that employs optically separated slabs of scintillator. Because of this separation, the full surface of the PMT is not simultaneously illuminated; only small regions are illuminated at a given time. If the response characteristics of one region vary from those of another, the output is made less accurate. This is why this research is important: by characterizing the spatial non-uniformity of the PMT, these differences can be accounted for, their effects can be minimized, and experimental results can be improved.

Context

Research conducted by Robert Haight at Los Alamos National Laboratory shows that PMTs do have spatially varying responses, and that light guides can be constructed to compensate for these effects. Using a sodium-iodide scintillator and a radiation source to produce light, Haight determined the response characteristics of the 14-stage Hamamatsu R1250A and the 8-stage Hamamatsu R4144. The constructed light guide, placed over the PMT face, smoothed out inconsistencies between neighboring locations at a loss of only 10% of the incident light in further experiments [2].

METHODS AND MATERIALS

Materials

Both the Hamamatsu R1250 and the Adit B133D01S are 5" diameter, head-on type photomultiplier tubes that use bialkali photocathodes with a minimum useful diameter of 120 mm. The Hamamatsu has a 14-stage linear focused dynode structure with a maximum operating voltage of 2000 V. The Adit employs a 10-stage box-and-grid dynode structure with a maximum operating voltage of 1500 V. We used an Ortec Model 266 short base with the Adit, and a custom base for the Hamamatsu. As our pulsed light source, we used collimated light from a blue LED with a wavelength of approximately 425 nm, a rate of 1000 Hz, and a pulse length of 25 ns. This mode of operation was ideal for our experiment because both tubes had maximum quantum efficiency and maximum absolute sensitivity near this wavelength [3,4]. At its normal incidence on the PMT surface, it had 1 mm diameter spot size.

Experimental Set-Up

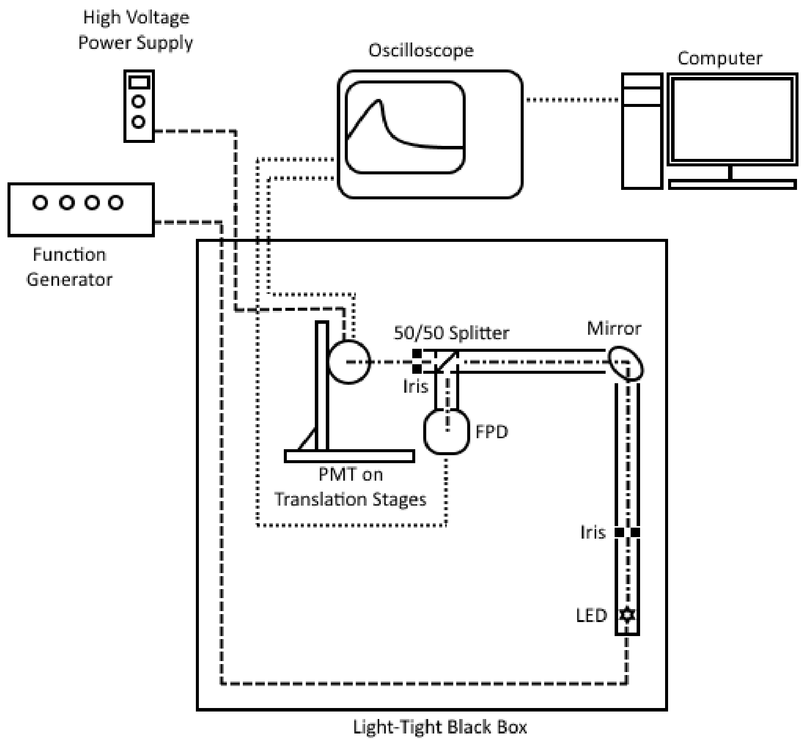

Fig 1. A simplified diagram of the experimental setup

Figure 1 illustrates the basic experimental design. The majority of the components of the experiment are contained inside of the black box in order to minimize light leakage. Additionally, all optical components are connected with ThorLabs lens tubes to further eliminate light leakage. The LED is controlled by the function generator to emit light pulses of the desired frequency and length. Because the manufacturer's lens on the LED distributes the light non-uniformly, employing a corrective lens system to collimate the light is not ideal. Instead, the light is passed through a series of ThorLabs SM2D25 irises separated by a considerable distance. These irises "pick off" the majority of the non-parallel light, leaving the remainder reasonably well-collimated. A reflective mirror is utilized midway through the course of the light's path to extend the distance between the first and last iris. Before the light reaches the final iris and the PMT, it passes through a ThorLabs CM1-BS013 beam splitter, which sends half of the incident light to the ThorLabs DET210 fast photodiode (FPD). The signal from the FPD is recorded in the Tektronix DPO7104 oscilloscope on channel 3. The other half of the beam passes through the final iris, after which it illuminates the PMT surface at normal incidence. Two programmable motorized stages translate the PMT coplanar with the front surface of the PMT and normal to the incident light pulse. The signal from the PMT is recorded in the oscilloscope on channel 4. Final adjustments to the experimental setup will be discussed in the "Results" section.

Experimental Procedure

After securing the PMT and the attached base to the metal clamp on the motorized stages, the protective cover was removed and the glass surface properly cleaned. After turning on the LED and verifying proper operation, the path was cleared through the equipment. A level was used to verify that that the PMT face was normal to the incident light and that the PMT would be translated in the normal plane. We employed a LabVIEW VI to control both of the motorized stages, and moved the PMT into its starting position. After turning on the FPD, we then sealed the light-tight black box and turned off all of the ambient lights to further lower light leakage and ensure optimal operating conditions for the PMT. We then turned on the oscilloscope and high voltage power supply, and waited several minutes for the power supply to warm up and reach its steady-state operation. Each of the PMTs were operated at their maximum operating voltages (2000 V for the Hamamatsu, 1500 V for the Adit) because the best performance is obtained by operating each PMT at its respective maximum [1]. We then set the oscilloscope parameters. We used 1 MΩ termination for both channels, with a sampling rate of 5 GS/s or 400 ps/pt, and 0.25 V rising edge manual trigger on the FPD channel. The horizontal scale was set so that only a single pulse would be displayed at a given time. The vertical scale was only set after a quick preliminary scan was performed over the entire surface of the PMT. During this scan, we checked for saturation in the oscilloscope and adjusted the scale as needed. The PMT channel 4 was set to 1 V/div and the FPD channel 3 was set to 6 V/div. Both the PMT and FPD outputs for each trigger event were recorded on the oscilloscope and saved to the computer as .csv files. Finally, we programmed the LabVIEW VI to perform a square raster scan across the full face of the PMT surface. We divided the step size into 5 mm increments in both the X and Y directions for a total of 729 spatial locations (135 mm in each direction). Although it was possible to increase the spatial resolution with a smaller step size, limits on time and computational resources necessitated a lower resolution. The LabVIEW VI recorded 10 waveforms for both the PMT and FPD at each spatial location, along with the coordinates of the location and the timescale used. The decision to record 10 waveform pairs was made for the same reasons as the choice of resolution.

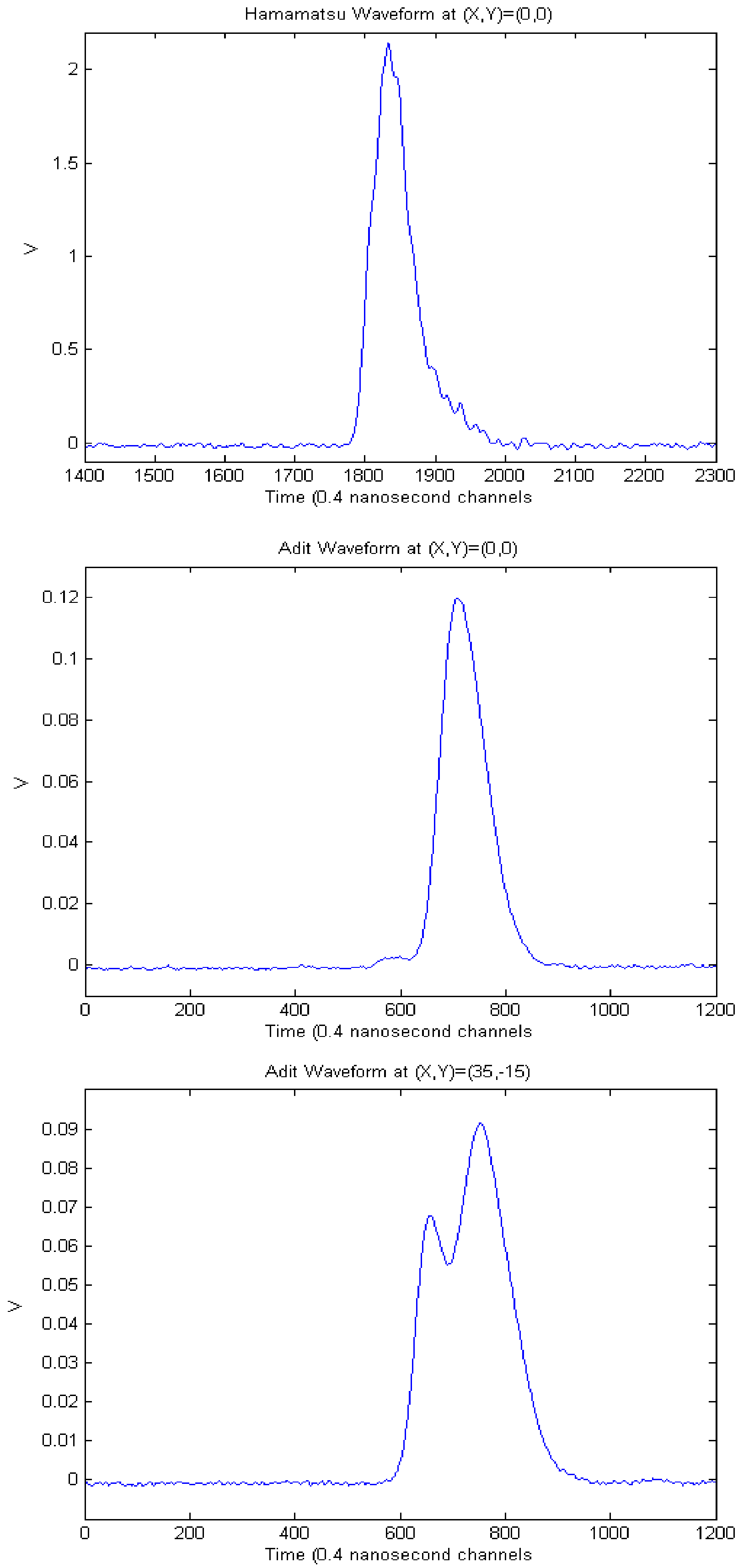

Fig. 2 Typical Hamamatsu (1) and Adit (2-3) waveform examples

Data Analysis

We began our data analysis by using MATLAB to plot a few typical responses from locations across the face of the PMT. All waveforms exhibited some voltage noise as well as a small offset. The noise was smoothed using a moving average filter of 5 adjacent data points, and the offset was compensated for by subtracting an average calculated from 1000 points of noise. The variables we measured from the waveforms were: the start and stop channel of the PMT and FPD waveforms, maximum peak height, and area response. We used a zero-crossing algorithm to find the start time of the pulse. This algorithm first reduces the response pulse to a fraction of its original amplitude. It then inverts this altered pulse, delays it, and sums it with the original pulse. The resulting waveform crosses zero at the point in time when the leading edge of the original response pulse reaches the preset constant fraction of pulse amplitude. This algorithm provides consistent results across a large range of input pulses. A proper attenuation level was selected which minimized the variance of start times at a given location. The stop time was calculated using a trailing-edge constant fraction technique set to 10% of the maximum peak height. We tried using a smaller fraction, but saw no significant changes in our results. The area response of the PMT pulse was calculated by summing the region beneath the peak from the start time to the calculated stop time on the backside of the pulse. Finally, because not all of the saved data locations corresponded to a physical location on the surface of the PMT, we choose a minimum voltage threshold to define which PMT waveforms constituted a real response. We also required that at least 7 of 10 events meet the response criterion in order for a given spatial location to be saved, averaged, and included in the analysis. This was implemented to account for variances in the light over time. We choose to require at least 7 of 10 events because all measurement variables are represented as averages at a given location. Averaging fewer than 7 events could produce skewed results given a few outliers. After we were satisfied that the threshold requirements were valid, we discared all spatial locations that were not contained within the manufacturer's minimum useful diameter of 120 mm. For each of the 10 waveform pairs at every location, we calculated and saved the start channel, stop channel, integrated area, and max peak voltage.

RESULTS AND DISCUSSION

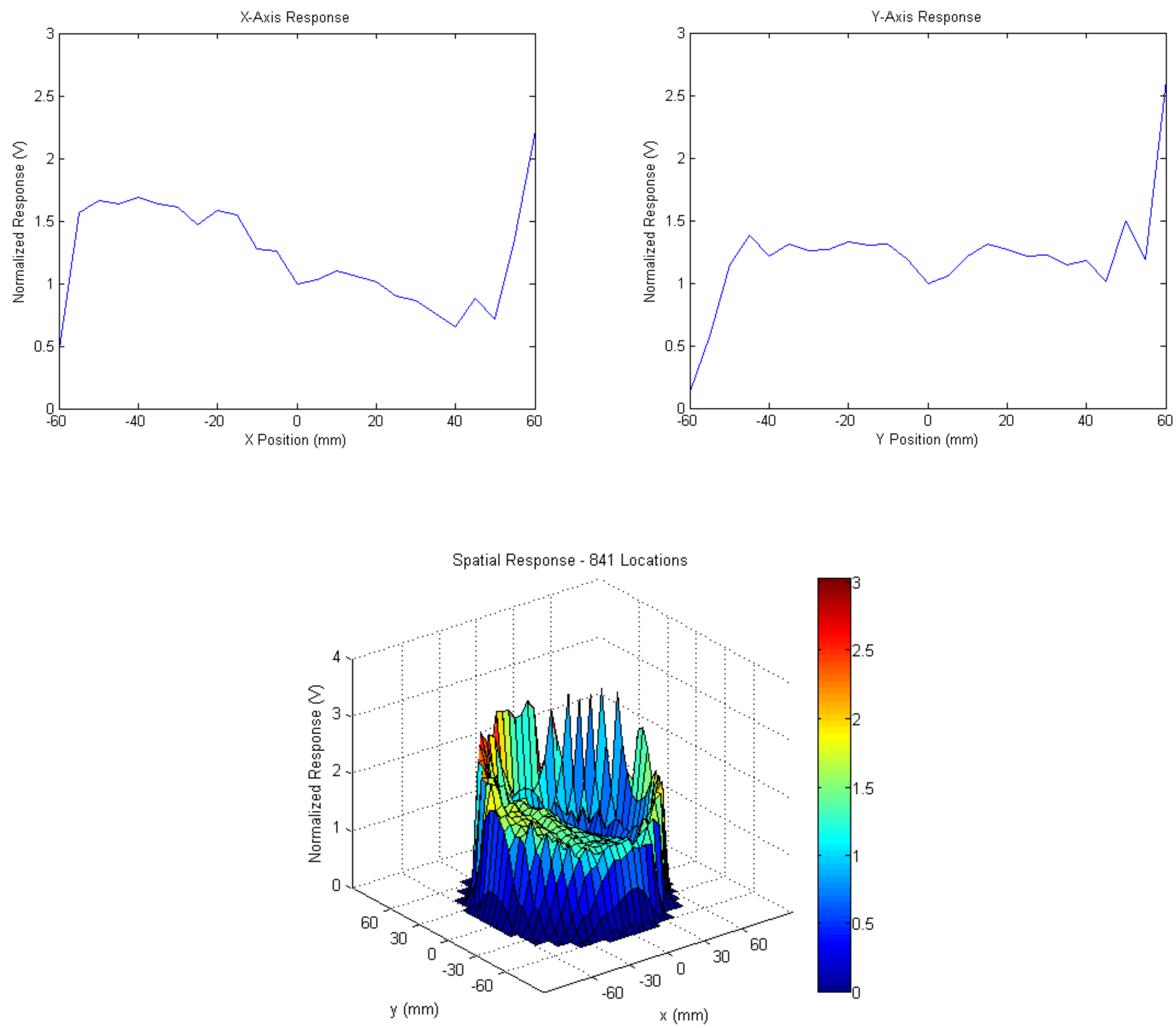

Fig 3. Peak response characteristics of the Hamamatsu R1250

The magnitude of the peak response across the spatial extent of the Hamamatsu is not uniform. When normalized to the center of the PMT face, the response varies by as much as a factor of 10 between locations, particularly on the edges of the PMT. However, the response of the PMT does vary approximately linearly along the x-direction and is fairly uniform in the y-direction. This can be seen in the corresponding plots of the responses in Figure 3, as well as in the surface plot of the response across the entire spatial extent of the PMT.

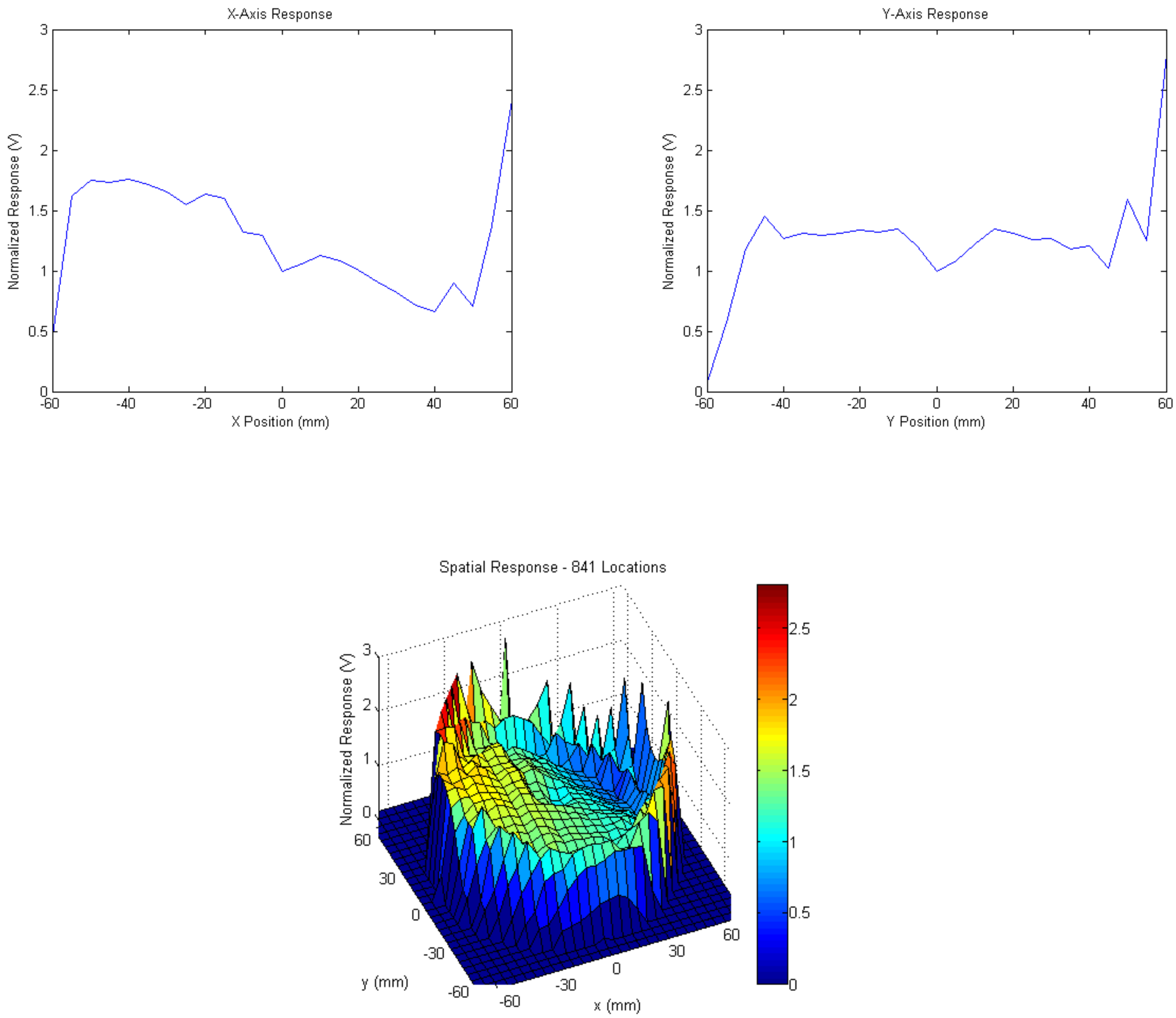

Fig 4. Area response characteristics of the Hamamatsu R1250

The magnitude of the total response area across the spatial extent of the Hamamatsu is nearly identical to the peak response when both are normalized to the center of the PMT. This suggests that the magnitude of the Hamamatsu's response peak is directly proportional to its area. In both cases, the edge of the PMT is consistently far more responsive than any location entirely within the PMT face. We are convinced that these are valid responses, as they fall within the minimum useful diameter and the response falls off to zero quickly beyond them.

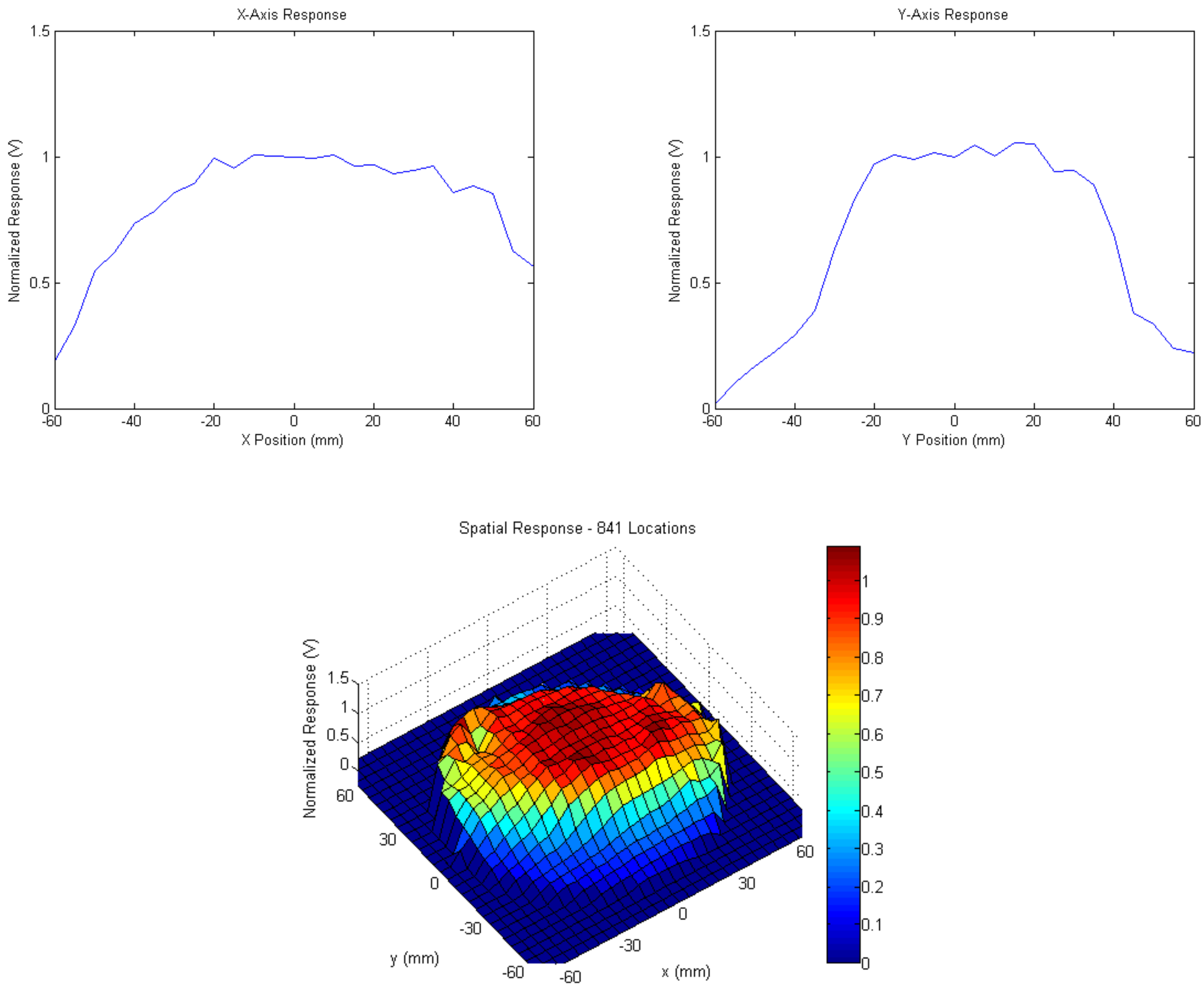

Fig 5. Peak response characteristics of the Adit B133D01S

The Adit has a fairly uniform peak response across its spatial extent. The response is uniform in an ellipsoidal area spanning the PMT from the top-left to the bottom-right, as shown in the surface plot in Figure 5. The response outside of this area falls off nearly linearly to zero at the edge of the PMT, and varies by a factor of 0.3 at most. At each end of the area there are small dips in the peak response. This is because there are two distinct responses that the Adit produces; one is a tall Gaussian-shaped peak, and the other is a smaller double-peak that is the superposition of two regular peaks (Figure 2).

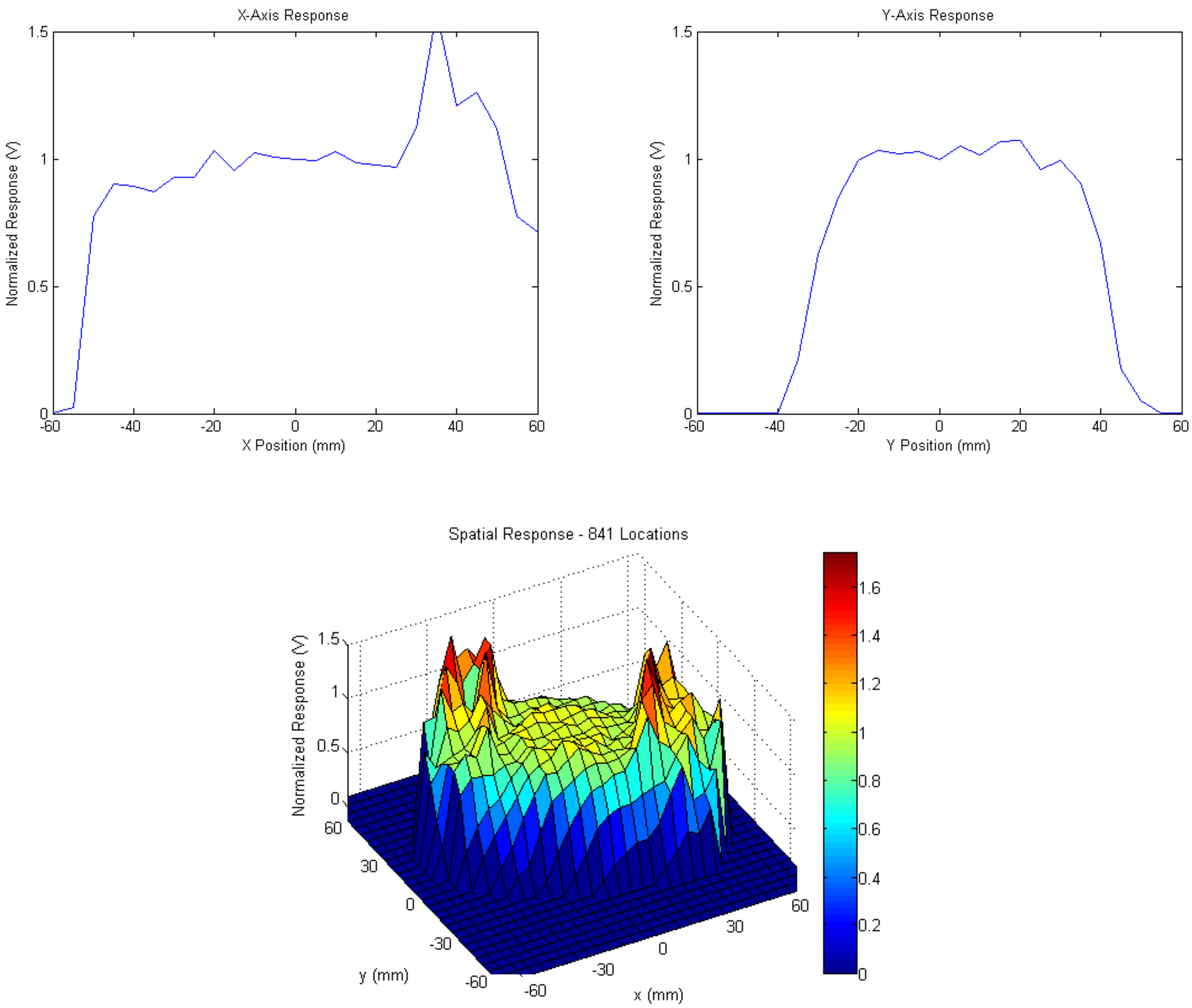

Fig 6. Area response characteristics of the Adit B133D01S

The area response across the spatial extent of the Adit is mostly uniform. The ellipsoidal area of uniform response seen in the peak response is present in the area response as well. However, at each edge of the ellipsoid, in the same locations as the dips in the peak response, there are peaks where the area response increases to a factor of 1.6 of the response at the center. These are the result of the unique double-peaked responses. Though the height of each of the individual peaks in the double-peaked response is lower than the height of the single-peaked response, the added area from the second peak is enough to significantly increase the area.

The validity of the results of this experiment, as well as those of the similar experiment done by Taylor Richards with regards to the timing response of the individual PMTs, is questionable. Though seemingly realistic results were obtained with the left-to-right raster scanning method, and a spatially varying distribution of response magnitudes was observed, they appear to be the result of more than simply the location of the light striking the PMT photocathode. In both experiments, when the tube was rotated 90° clockwise and the scan repeated, the results did not rotate with the tube. That is to say, an identical distribution of response magnitudes was obtained but correlated with a new set of spatial locations on the PMT face. We suspected several causes for this phenomenon and took steps to eliminate it, but were not successful. Our initial concern was that there was a light leak into the black box that consistently struck the PMT in the same positions and washed out any response to the LED light source. However, this was easily ruled out after repeating the scan with the LED turned off and seeing no response apart from noise. Our next suspicion, though much more unlikely, was reflections of the LED light off of the PMT face, around the box, and back into the PMT at some other location. To address this, we constructed a black mask with a pinhole out of heavy black felt, secured it so the PMT was free to move behind it while remaining in constant contact, and repeated our scans. Again, we saw no significant differences between responses from the PMT in different orientations. We also changed the direction of our raster scan from left-to-right rows to top-to-bottom columns, with no effect. The change to the experimental setup that produced the only significant effect was rotating the orientation of the translation stages inside the black box. Holding all other experimental factors constant, changing the position of the stages resulted in a drastically different response, with no correlation to previous scans. This led us to believe that some other spatial factors had an effect on the response of the PMT, such as a localized electromagnetic field. We took further steps in this direction on the assumption that this was the sole cause of the unusual PMT responses. Both the black box and the PMT were wrapped in aluminum foil and grounded, to shield the PMT from external electromagnetic fields. However, no further changes in the experiment were recorded, and scans of the PMT rotated in different orientations continued to produce similar responses. This suggests that the source of the electromagnetic fields, if they are the cause of these responses, originates from inside the black box or the PMT itself.

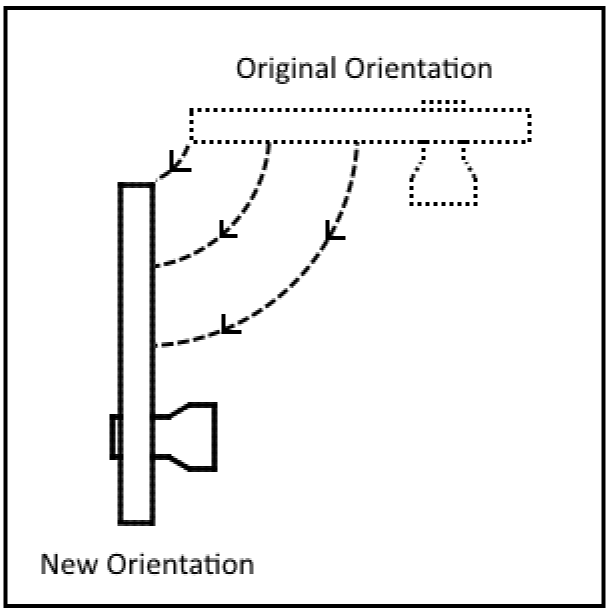

Fig 7. Reorientation of the experimental setup

CONCLUSION

The investigation of the response magnitude across the full spatial extent of two commercial 5-inch photomultiplier tubes, the Hamamatsu R1250 and the Adit B133D01S, showed that there are important non-uniformities on each tube, and differences between the individual tubes, that would determine which tube is best suited for different experimental applications. The Hamamatsu offers a very non-uniform peak height and area response, varying by as much as a factor of 10 between spatial locations, and it has no spatial symmetry. However, it provides a very strong response in all spatial locations, making it useful in experiments requiring the detection of very low levels of light that do not need to discriminate between detected particles and their spectra. On entirely the other hand, the Adit provided a very consistent peak height and area response across almost the full spatial extent of the tube. Within the minimum useful diameter of the photomultiplier tube, the peak height varied only by a factor of 0.3 over a majority of the spatial extent. The area response varied by a similar factor except for two localized regions varying by a factor of 8. These differences were a result of a variable-size peak occurring before the main Gaussian response curve. They seem to be real responses that are superimposed with the main response at that location. It is possible that these first peaks are produced by a fraction of the incident light scattered towards another location on the photocathode, resulting in the superposition of the two responses. Overall, the Adit provides a much more consistent response than the Hamamatsu, but its responses in both peak height and area response are in general much weaker. However, these results are questionable because the results are independent of the orientation of the photomultiplier tube. Further research on this topic could investigate the causes of this phenomenon, and apply the analysis methods developed to characterize a wide range of photomultiplier tubes.

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