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Transit Time and Gain Matching in XP20D0 Photomultiplier Tubes by Bias Voltage Perturbation

Abstract

Positron Emission Tomography (PET) is a medical imaging modality that detects gamma radiation from positron-electron annihilation events. Gamma rays created by an annihilation event travel in opposite directions defining a line of response (LOR). Given the LORs, an image can be reconstructed that locates the origin of the annihilation events inside the scanner.

One form of detector that meets the requirements of PET is a scintillation detector. Gamma rays are converted into visible light by scintillators through the photoelectric effect. The visible light is then detected by photomultiplier tubes (PMT) which convert the incoming light to an electrical signal. With sensitive electronics, fast scintillators and PMTs with good timing resolution, it is possible to detect where on the LOR the annihilation event occurred; this is called time of flight (TOF).

LaPET is a TOF-PET scanner at the University of Pennsylvania that uses 432 XP20D0 PMTs in a circular ring. Models of the LaPET scanner predict system timing resolution of ~315ps, but a resolution of 376ps has been measured. In its current form, LaPET triggers on PMT signals using a leading edge discriminator, but the PMTs have as much as a factor of 4 difference of gain and up to 2ns transit time variations. The variability in gain and transit time between different PMTs affects the system wide timing resolution by biasing the triggers to PMTs with faster transit time or larger gain. PMT gains have been matched to 20% by signal attenuation, but this is not ideal because it is a hardwired and the resistors add signal noise. Alternatively, selecting PMTs from the manufacturer that are gain and transit time matched well is also cost prohibitive.

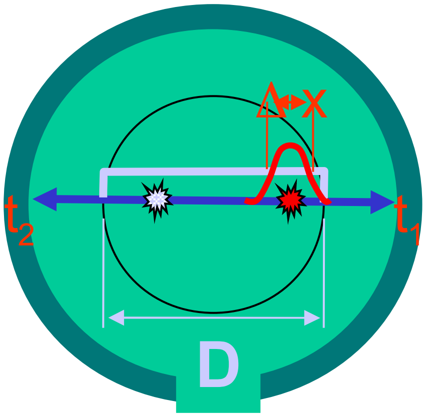

Figure 1: Line of Response and with Time of Flight detection.

A method is devised for changing the gain and timing characteristics of XP20D0 PMT by perturbing the input high voltages. Data from a single tube is analyzed to characterize the general response of XP20D0 PMTs to changes in the biasing voltage. The derived method is then tested on multiple tubes by attempting to match the gains and transit times of seven PMTs. It is discovered that each PMT's characteristics respond with different sensitivity to changes in the input voltages. However, it is shown PMTs can still be well matched in gain and timing though their responses differ.

Method

One solution for matching the signal arrival time from PMTs is to slow faster PMT signals with delay lines. But this adds additional cable length to the signal path creating more noise in the signal. Furthermore, it is a hardwired solution. However, perturbing the high voltage input neither adds noise to the signal nor is it a static solution. A previous study of altering input voltages to obtain gain and transit time matching utilized a technique that degraded timing resolution. Although that experiment found it possible to well match gain and transit times, the timing resolution degraded by as much as 50%. A primary goal of any new method of signal matching must be to maintain or improve individual PMT timing resolution while matching signals and not adding noise.

Perturbing the input voltages to the PMTs compensates for manufacture differences in the physical structure. Changing the voltage applied to the PMT changes the magnitude of the electrical force used to accelerate electrons in the PMT to the anode where a current is detected. The greater the force applied to each electron, the more energy each electron has when it hits the next dynode inside the PMT. More energy corresponds to a greater velocity thus it takes less time for electrons to traverse the length of the tube to generate a signal. The additional force applied to each electron increases linearly with an increase in applied voltage. More energy for each electron also means that each electron has additional energy above the work function to free the electrons at the next dynode surface. Thus releasing more electrons and increasing the electrical gain of the PMT. The gain effect is exponential because at each dynode more electrons are freed and each freed electron frees more electrons.

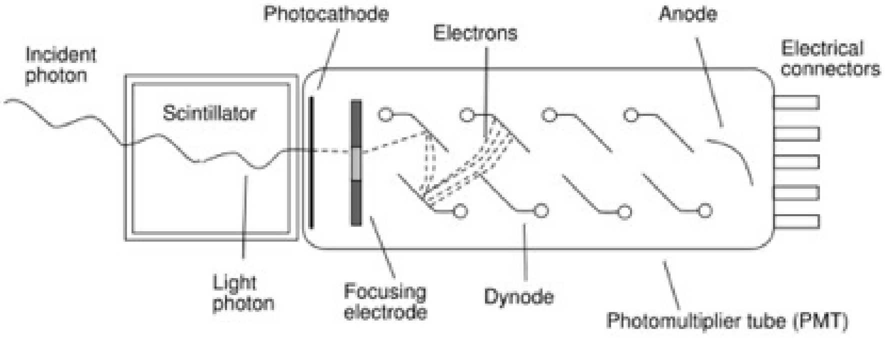

Figure 2: Cartooned Photomultiplier Tube

The XP20D0 PMT contains a photocathode, two focusing electrodes called grids, and eight amplification dynodes labeled one through eight with one being at the highest voltage. Grid one is located between the photocathode and dynode one, and grid two is located just before the anode. The previous method to match transit time and gains perturbed the voltages at the photocathode and the fifth dynode. As noted, this caused a degradation in the timing resolution of the PMT. It is guessed that the loss in timing resolution is due to not maintaining the proper voltage ratios between dynodes.

The new method tested here works by linearly scaling the potential between all dynodes as well as increasing the photocathode voltage. A handmade board took input from two different power supplies and used low pass filters and resistor divider chains to create the input voltages for a single PMT. Then the output voltage of the two power supplies was changed directly on each of the supplies. One supply was operated between 1450V and 1150V to scale the photocathode and grid one together. The other supply was operated between 760V and 920V to perturb the first dynode and scale the other dynodes and grid at lower voltages.

Figure 3 demonstrates this method applied to a single PMT. Each of the three lines in figure 3 are perturbations of the photocathode at fixed dynode voltage. The data labels on the points are the measured timing resolution for that setting of the PMT. Mostly, the trend is for the

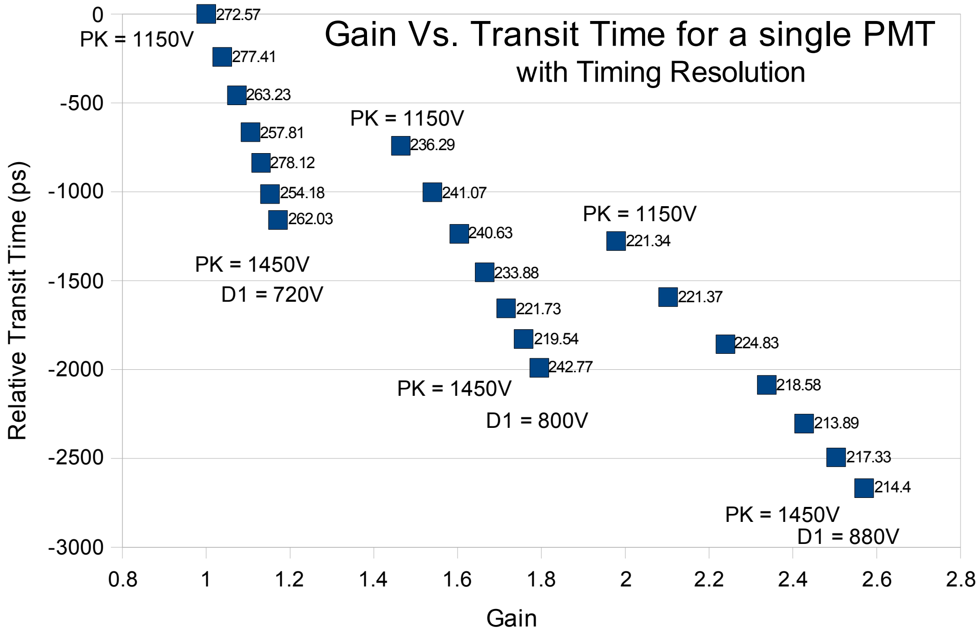

Figure 3: Input voltage perturbation response of characteristics from a single PMT.

timing resolution improves as the voltage increases.

From this data it is possible to relate the input voltages to the transit time and gain of the PMT in two linear equations; one equation for each characteristic. Four constants then relate the input voltages to the transit time and gain properties of PMTs. The constants are found the linear relationship in the transit time and an exponential relation in the gain:

$$TT_f = TT_0 - C_{Tpc} V_{pc} - C_{Td} V_D \tag{1}$$

$$G_f = G_0 e^{C_{Gpc} V_{pc}} * e^{C_{Gd} V_D} \tag{2}$$

Each PMT has an initial transit time TT_f and gain G_0 that are measured first. Equation (2) is then put into a linear form so that it can be solved simultaneously with (1) for a group of PMTs.

$$\log(\frac{G_f}{G_0}) = V_{pc} \log(C_{Gpc}) + V_D \log(C_{Gd}) \tag{3}$$

Three requirements must now be met when matching gain and transit time for all the PMTs:

1. A common gain and transit time must be selected for every PMT.
2. The resultant voltages for every PMT must be within the operating range.
3. The timing resolution for each PMT must not be degraded by the new voltages.

Requirement 3 means that voltages can only be increased. So only a larger gain than the PMT with the highest gain and shorter transit time than the PMT with the shortest transit time will satisfy the system.

A computer program than sequentially checks a large range of final gains and transit times and discards any solutions that don't satisfy all the requirements. It is possible however that not all PMTs are able to be perfectly matched inside the allowed operating range of voltages. This was the case for the sample of PMTs used in this experiment, so the system was solved again and PMTs found outside of the range are given input voltages at the nearest valid input voltage.

Results

Figure 4 shows the results of applying the new voltages derived from the method described above.

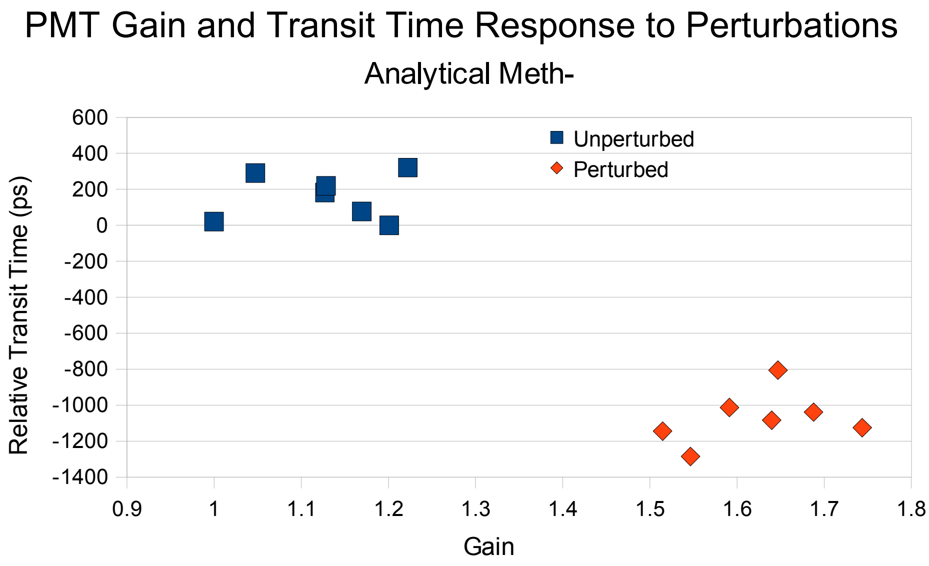

Figure 4: New gains and transit times from voltage increases.

The spread in both gain and transit time of the perturbed voltages is almost identical to the spread in gain and transit time of the tubes when each is given the same input voltages. The most likely cause of this is that the constants C_{Tpc}, C_{Td}, C_{Gpc} and C_{Gd} are different for each PMT. Solving the (1) and (3) simultaneously then doesn't make sense and would not actually help to find voltages to match gain and timing. Furthermore, this means that this system may be impossibly tedious because finding the constants for each of the 432 PMTs in LaPET would take too long. An automated system to generate calibration curves for each PMT would be necessary to make this method practical.

A brute force approach to varying the input voltages was tried next with more successful results (figure 6). The range in transit times decreased from 320ps to under 132ps, and that range could probably be narrowed further with more precise changes to the input voltages. Requirement 3 is also held as the timing

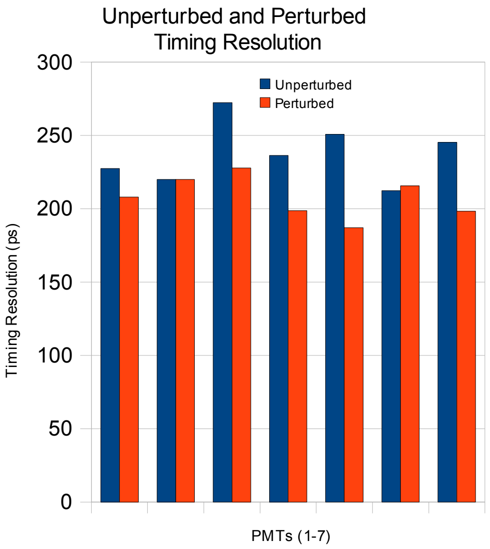

Figure 5: Resultant timing resolution before and after brute force approach.

resolution generally improved (figure 5). Timing resolution is measured as the full width at half max (FWHM) of a distribution of the transit times of many events. A decreased FWHM means improved resolution because there is more confidence in the actual transit time of the PMT.

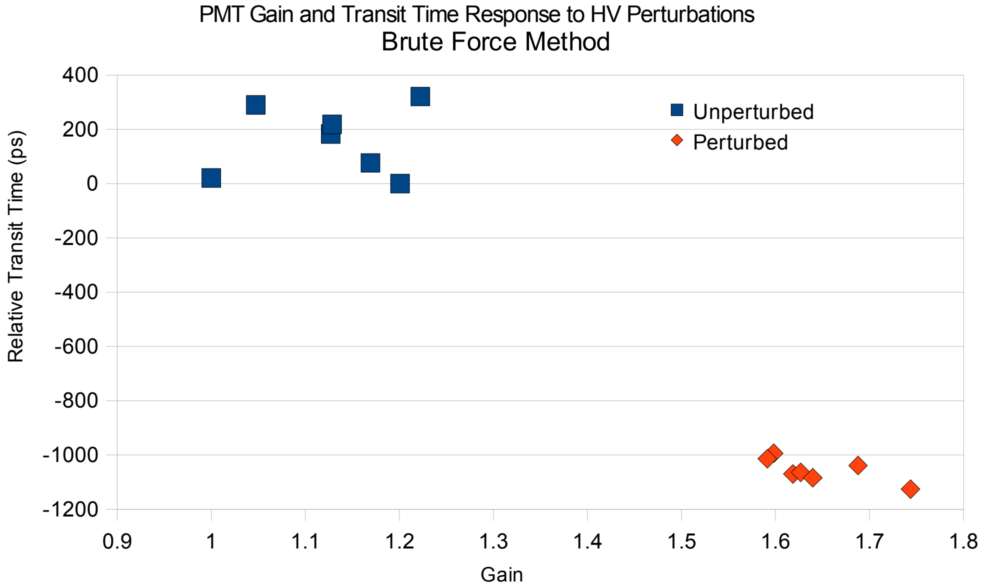

Figure 6: New gains and transit times from voltage increases with brute force approach.

Implementation on Full Detector

On LaPET, rather than having two power supplies for each PMT, there will be just a few distribution boards that take a constant input from two power supplies in normal operation. Each board will break down the two voltages supplied by utilizing potentiometers at the top of resistor divider chains to perturb the voltages for each PMT's photocathode and first dynode. The calibration curves for each PMT can then be discovered by changing the power supply voltages. In this way a graph like figure 3 could be generated for each PMT in the scanner and the four calibration constants can be found making it possible to solve a new system of equations where the constants as well as the initial gain and transit time are different for every PMT. A board to perturb the voltages for a detector's worth (24) of PMTs has already been designed (Figure 7) and laid out on PCB.

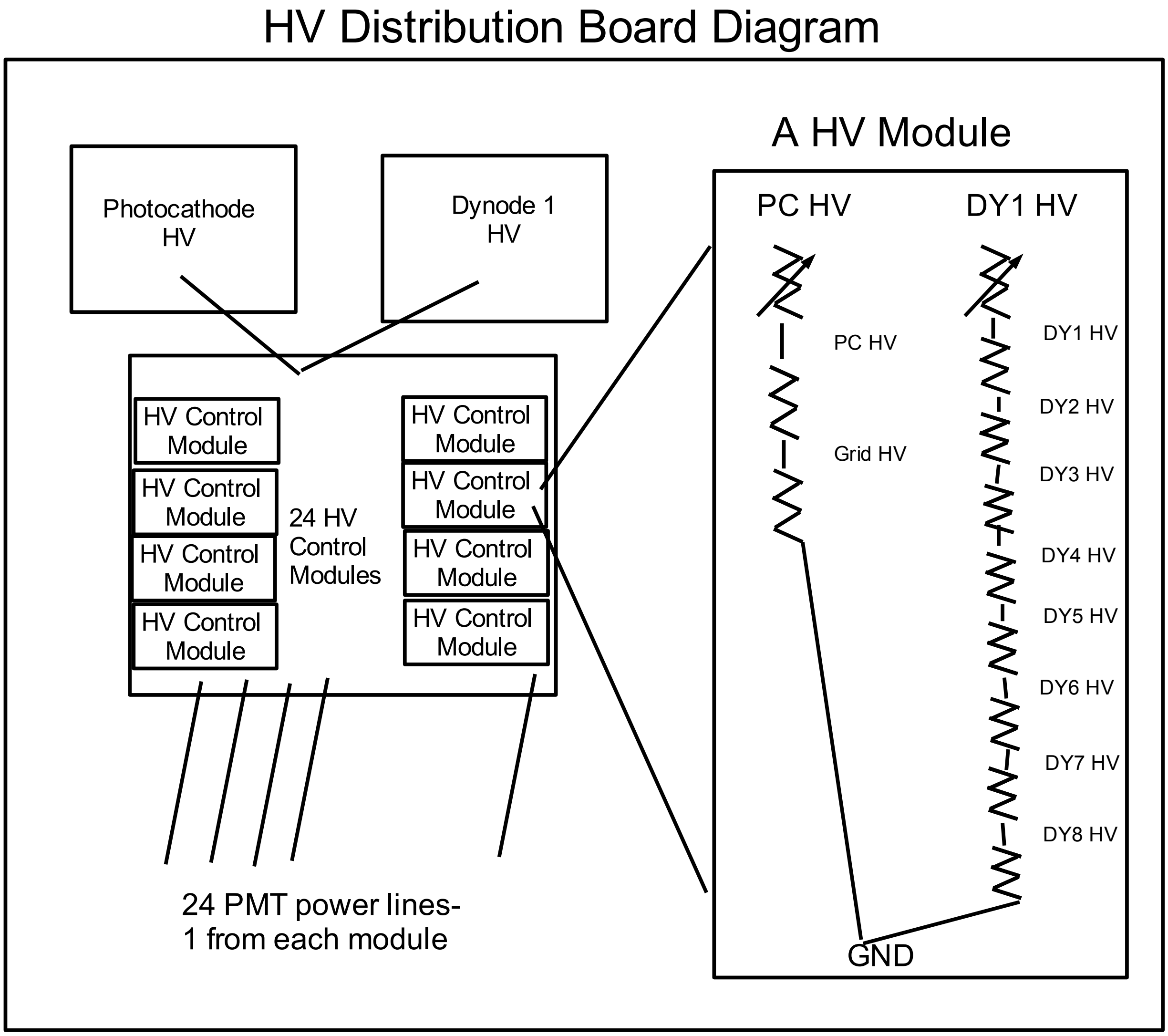

Figure 7: Diagram of New HV Distribution System for each Detector of PMTs

Conclusion

The results from the brute force approach indicate that the described method of voltage perturbations is capable of matching the characteristics of signal output from the PMTs while improving or maintaining timing resolution for each PMT. However each PMT has a different calibration curve that must be discovered first before meaningfully perturbing the voltages. A simple method for generating the calibration constants for all PMTs in the scanner may be possible.

The next step in testing this system would take two 24 PMT detectors, and using two high voltage distribution boards try to match the trigger timing by matching each PMTs transit time. If transit times can be matched for every PMT in the detector without increasing the distribution of gains or degrading timing resolution, then the system might next be tried on the entire scanner.

Furthermore, in the planned move to digital signal analysis, gain matching will become more important. The energy resolution in a digital system is determined by the largest signal because the number of bits available to represent a point sampled in the signal is fixed. Thus the smaller signals suffer from larger resolution.