High Voltage Photodetector Calibration for Improved Timing Resolution with Scintillation Detectors for TOF-PET Imaging

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***Abstract* -- The development of scintillators, photodetectors and electronics with excellent timing properties has made possible bench-top time-of-flight (TOF) measurements with sub 200 ps coincident timing resolution. In a light sharing configuration, losses in light collection result in degraded detector timing resolution. Photodetector uniformity in a light sharing configuration between many detectors is a significant limiting factor in the achievement of similar whole detector timing resolution. Furthermore, it is noticed that low gain photomultiplier tubes (PMT) have poorer timing resolution, but timing resolution improves as gain is increased. We implement a method of individually programming the photocathode and dynode bias voltages of a detector of Photonis XP20D0 PMTs. High voltage calibration of photodetectors will achieve better signal-to-noise-ratio (SNR) than variable-gain-amplifiers (VGA) or delay circuits in the signal path that introduce new sources of noise. Independent control of both the photocathode and dynode voltages allows for nearly orthogonal changes to the gain and transit time. By adjusting the lowest energy PMTs to higher gains, we also improve the intrinsic timing performance of those tubes thereby further improving system timing resolution.**

I. Introduction

LaPET, a $LaBr_3$-based whole-body TOF PET scanner, has been designed and evaluated by our lab **[1]**. The scanner comprises of 24 pixelated crystal modules, coupled to a contiguous array of hexagonally-packed Photonis XP20D0 PMTs via a light guide. Each crystal module is made of an array of 60 by 27 $LaBr_3$ crystals each $4x4x30mm^3$. The light guide couples each module is with two columns of six PMTs, and with additional columns of PMTs overlapping with adjacent detector modules, as shown in Figure 1 **[2]**. The light sharing configuration allows detected events interacting in the scanner's 38,880 crystals to be positioned to a single crystal using only 432 PMTs. A scintillation event's location is determined by weighting the measured anode current in the surrounding PMTs. Likewise, a copy of the nearby PMT signals are summed to measure the relative arrival times of coincident events. To achieve both high spatial and timing resolution in a light sharing detector, it is necessary to calibrate the photodetectors to properly decode event positions and arrival times. During construction of the scanner we did not pre-select or measure gain and timing characteristics of PMTs before coupling to detector modules. Since timing measurements are made by summing the input of seven PMTs near an event location, signal timing mismatch caused by large variation between adjacent PMTs could result in a degraded timing measurement.

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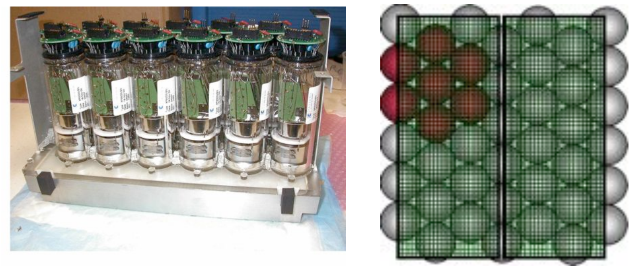

Fig. 1. Left, one of 24 detector modules with phototubes. Right, top view of hexagonally packed, pixelated, light sharing scintillation detector with two modules and overlap PMTs. The red PMTs indicate a triggered cluster from which time, energy, and position are determined. Seven PMTs are chosen to read out position, energy and timing information.

Position	Δt
1	295 ps
2	326 ps
3 (Triple Point)	338 ps

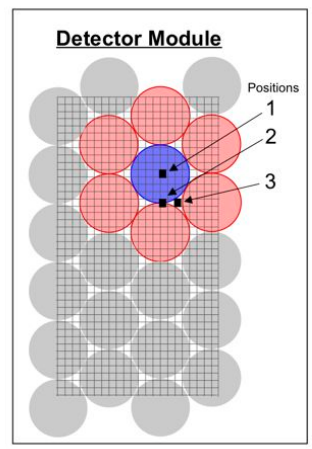

Fig. 2. Timing resolution has position dependence even when PMTs have well matched gain and timing characteristics. **[3]**

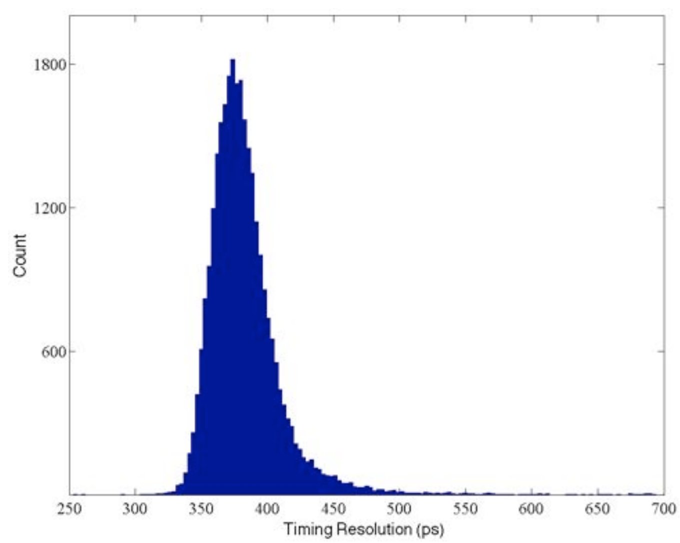

Fig. 3. Histogram of coincident timing resolution for all crystals in LaPET scanner on a crystal by crystal basis. Mean value of 375 ps with 24 detectors.

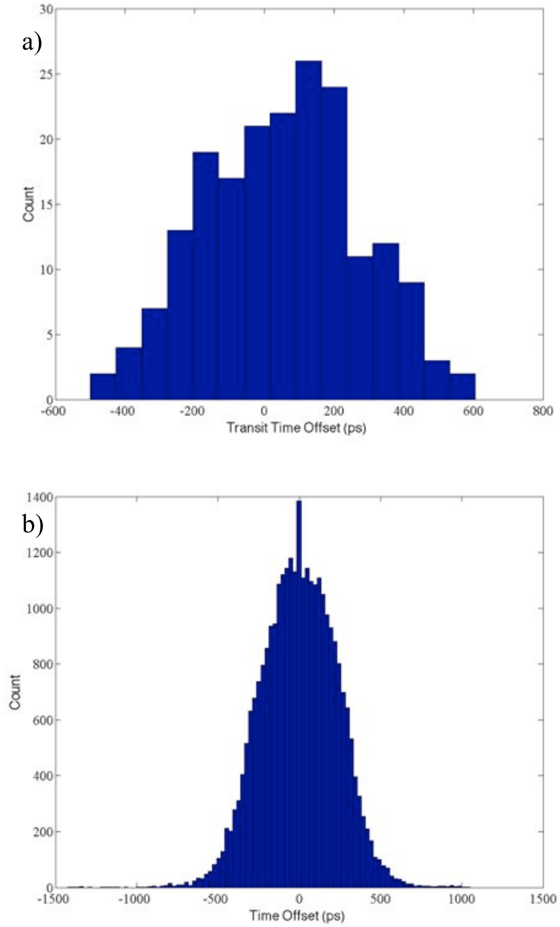

Fig. 4. a) Intrinsic transit time offsets of all PMTs on LaPET determined from crystal selected near PMT centers. b) Transit time offsets of all crystals on LaPET. The similar range in offset times indicates PMT transit time variance is the dominant factor.

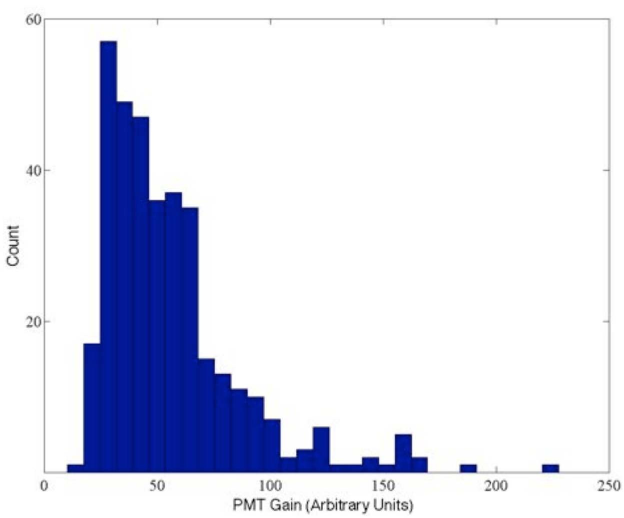

Fig. 5. LaPET PMT gains prior to attenuation and VGA corrections in arbitrary units.

II. Detector Module Characterization

Bench top measurements of pixelated $LaBr_3$ modules with well-matched photomultiplier tubes find a mean coincidence timing resolution of approximately 320ps. Position-dependent variations in collection efficiency and in light path length result in systematic variations in timing performance across the detector. By calibrating response across photodetectors, these variations may be reduced, achieving relatively small variation in response, as measured on a bench top, figure 2. The most recent timing resolution capabilities of the LaPET scanner are summarized in figure 3. The long tail of poor resolution is evidence of crystals whose timing is determined by mis-matched PMTs as well as suboptimal light collection near module edges. Bench-top measurements have shown that timing resolution degrades when adjacent PMT transit time variation is greater than several hundred picoseconds. There is not at present any effort made to correct for PMT transit time differences. The variation in PMT transit times can be approximated from the transit time of crystals coupled to the light guide directly above the PMT center. For these crystals, ~50% of light is collected by a single PMT, resulting in good correlation between measured crystal timing offset and PMT transit time. The resulting range of transit times, approximately +/- 500ps, can be seen in Figure 4a. For crystals not directly above a PMT center, crystal timing offset is affected by the transit time of several PMTs, as well as by path length variations in light transport. The variation in crystal timing offsets measured across all crystals in the scanner spans a range approximately +/- 500ps, as seen in Figure 4b. The similar range of PMT transit time variations and crystal timing variations suggests that differences in transit time across PMTs are the dominant factor in detector timing offset non-uniformity.

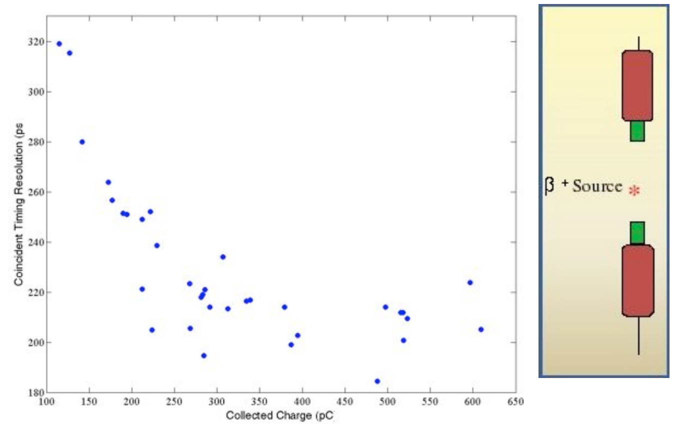

Fig. 6. The timing and energy properties of 34 PMTs were measured against a common reference detector using the same LaBr crystal. Bench top operated at -1150 V.

The PMTs on LaPET have a variation in gains by as much as a factor of four, figure 4. Currently the scanner uses a system of VGA and signal attenuation to calibrate the amplitude response of the PMTs. VGAs are an additional source of noise in the signal path, and attenuation increases susceptibility to noise while reducing the dynamic range capability in a planned upgrade to system wide signal digitization. Additionally we also notice in bench-top measurements that lower gain PMTs tend to also have poorer timing resolution. See Figure 6. This suggests that by increasing the biasing voltage and thus the gain of a low energy PMT, a better intrinsic timing resolution is achievable. Improving the poorest performing PMTs will improve overall system timing resolution.

III. Method Of Calibration

We have tested several methods of bias voltage adjustment previously in a manner similar to **[4]**. In implementations that vary the biasing voltage to a single middle stage dynode we find that transit time and gain vary together. Furthermore single stage alterations degraded the a)

b)

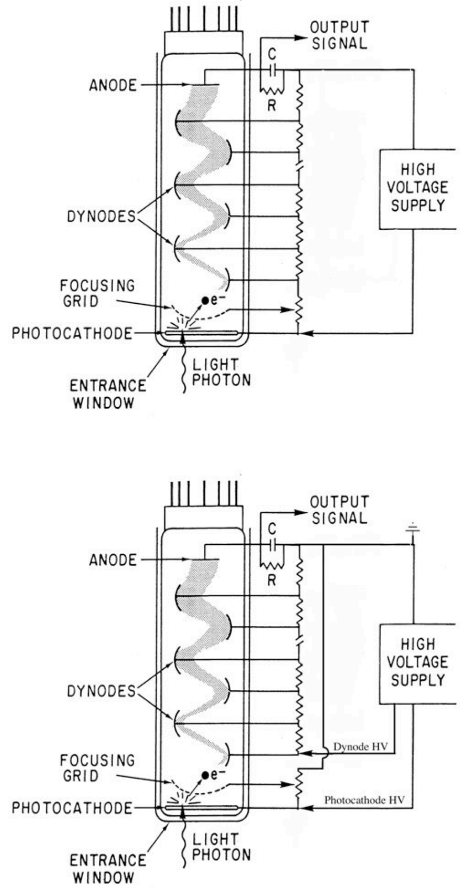

Fig. 7. a) Schematic of standard PMT power supply, and b) modified supply with independent control of photocathode and dynode voltages.

timing resolution of the individual PMT. For these reasons, in developing a new calibration method we seek a design that allows independent control of timing resolution and gain adjustment while maintaining good timing resolution.

The photocathode to first dynode potential is a determinant of the total signal transit time, but it has little effect on the overall signal gain since there is little current at that stage. The photocathode potential is then an obvious selection for adjusting the transit time of a PMT signal. The dynode chain, which contains the most amplification stages, is adjusted in an accordion like manner so that the electric potential between stages in the PMT never decreases below a lowest value.

IV. Results

Bench tests on individual PMTs using a prototype power supply demonstrate a large dynamic range of achievable transit times and gains over a conservatively small range of biasing voltages. We find an increase of approximately 250 volts in photocathode voltage reduces the transit time by about 800 ps while increasing the gain by less than 5% at less negative dynode voltages. However at more negative dynode voltages, changes in the photocathode potential have a greater impact on both transit time and energy, see figure 8a. The specification for the final power supply design provides for a 400 volt range for the photocathode which will supply a greater range of gains and transit times. It is expected that correcting for transit time differences will reduce the tail shown in Figure 3, thereby reducing the number of crystals

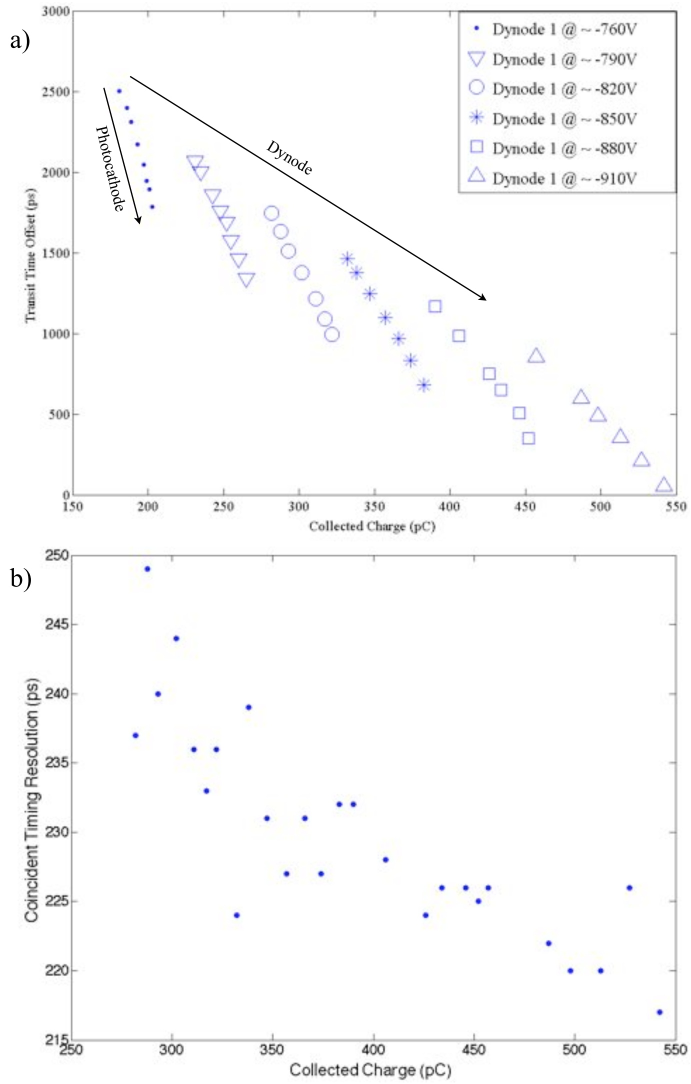

Fig. 8. (a) The changes in transit time and gain due to adjustments in the photocathode voltage over a series of dynode voltages for a single PMT. The arrows indicate more negative photocathode and dynode voltages. (b) Intrinsic timing resolution vs. charge resulting from adjustments in photocathode and dynode voltages as shown in (a). The circles indicate possible ideal parameters of operation.

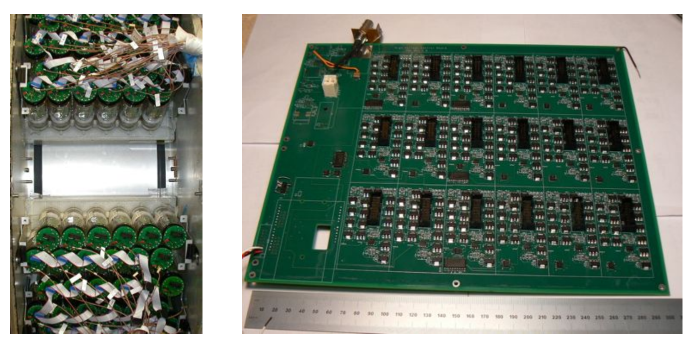

Fig. 9. Left, a section of the LaPET scanner with a single module and overlap PMTs removed. Right, a partly constructed custom PMT power supply with 18 channels for one detector module.

with poorer timing resolution. Furthermore increased dynode biasing voltages also decreases the transit time. For the PMT, over the same range of gain and timing calibrations, we find a trend that suggests increasing our base operating voltage in low gain PMTs will also improve the intrinsic timing resolution of those tubes as in Figure 8b. This is consistent with our findings in figure 6. We expect the intrinsic gains to shift the peak in Figure 3 to better overall system timing resolution.

It is clear from figure 8a that a large range of gains and transit times are achievable for each PMT by adjusting individual power supplies. However our preference will be for higher gains due to the correlation with improved timing resolution.

V. Summary and conclusions

Precise and accurate PMT timing and gain calibrations are necessary in light sharing detectors and PMTs tend to achieve their best intrinsic timing resolutions at higher gains. Independent control of photocathode and dynode biasing voltages can achieve simultaneous time and gain calibrations while improving intrinsic performance. We have developed a digitally programmable eighteen channel power supply capable of independently controlling the dynode and photocathode biasing voltages, figure 9. A full system implementation is planned for the coming months to individually control the power supplies of every PMT in the scanner. We have manufactured 24 boards, each capable of controlling 18 PMTs. An iterative calibration procedure is under development to digitally control and automate fine tuning of PMT gain and transit time characteristics. The calibration procedure will ultimately find an optimal balance between improving PMT intrinsic timing resolution through increasing gain and matching transit times and gains. We expect these calibrations to improve overall system timing resolution.

VI. Acknowledgments

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VII. References

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