Musings on the Extraction and Preservation of PMT Signals

David Nygren
17 January 2012

This note is an attempt to figure out the range of possibilities for optimal or near-optimal signal extraction. Conceptual and numerical errors may be present. Numbers and comments in red indicate uncertainty.

Goals:

1. Negligible degradation of PMT signal quality, so that energy resolution is unaffected by signal extraction from PMT and subsequent signal propagation and processing.
    a. Small to negligible baseline shift, consistent with other requirements such as radioactivity. This ultimately implies, in our case, the presence of some large capacitors.
    b. Provide a margin of safety with regard to noise, since we will not really be able to predict the noise environment at LSC until the system is set up.
    c. Adequate dynamic range, to record properly large contained energy deposits from α-particle events, to 5 keV x-rays, and even single-photoelectrons (SPE).
    d. Clear measurement of SPE pulses to enable calibration.
2. Optimized part count on the PMT base to minimize bulk, radioactivity.
3. Reduction of power dissipation within PMT enclosure, maybe by a factor of three, or perhaps more – needs quantitative study.
4. Robust physical implementation – no costly electromechanical gymnastics.

How do these goals translate to a set of requirements and a practical implementation?

Requirements and Discussion

1. The absolute gain G of the PMT should be set to: $G = 4 \times 10^6$.
    a. This gain should allow us to measure the single photoelectron (SPE) spectrum with sufficient accuracy; noise must be small on this scale (noise less than 0.05 <spe>?).
    b. This gain avoids PMT saturation for largest signals expected (simulation needed).
2. Each PMT gain must be monitored for both absolute gain and gain drift with better than 0.5% accuracy.
    a. We might prefer to keep the HV unchanged for long periods, and correct the data for drift and relative gain.
    b. The SPE spectrum shall be measured with two or three ΔT windows, to establish the levels and impact of afterpulsing versus ΔT.
        i. One window should be about 20 ns wide, while the other two can be in the range of 3 – 20 μs.
        ii. This can be done using an LED pulsed regularly to produce SPE signals with less than 1% probability per pulse. Ideally, the LED pulse should be suppressed during any time window during which

a trigger has occurred, in principle. In practice, this is probably impossible since the trigger will be based on S2, so the deadtime for this continuous calibration should be limited to not more than something like 1×10^{-3}.

3. Baseline excursions must be small enough to be negligible, or compensated for by a fairly simple correction algorithm on an event-by-event basis.
    a. The baseline for each PMT must be measurable with ~0.1% accuracy within each event.
4. Signal transmission should be as simple as possible, *but not simpler*: it must meet specs with some margin since we won't know the environment well until the system is in place.
    a. Simple coax with good differential signal reception, treating the braid as the other element of the "pair" should be tried first. These tests could show whether more complex approaches are necessary, as elaborated below. The full HV needs to be supported across the coax dielectric in the positive HV polarity case, a problem likely only for the penetrator. The braid will of course be grounded at the amplifier input, but should be protected against floating to HV if the cable is unplugged.
5. The PMT base resistive divider chain system must provide adequate recharge current for the capacitors supporting the last 3 – 4 dynodes; however, the last dynode potential may, in a differential scenario described below, be supported externally. This has the benefit that the power dissipation in the base could be smaller by a factor of three or more.

Signal formation occurs between the last dynode and anode.

Implications and considerations:

- No genuine local low-impedance "ground or ground-plane" exists within the PMT or base. The signal is best extracted by matched quasi-differential low-impedance connections between the last dynode and the PMT anode.
- The PMT anode/last dynode pair is very weakly connected electrically (MΩ and pF) to the photocathode and external world.
- Each PMT should be viewed as an independent relatively low-impedance signal source, very loosely connected to all other PMTs (MΩ and pf). It is not safe to consider any low-impedance common ground, as this will be the source of ground loops.
- With either positive or negative HV, there is always an AC coupling somewhere – inevitably coupling the anode or last dynode, or both, to the signal path.
- The last dynode signal and anode signal are not exactly equal and opposite in sign. The signal is really a consequence of electrons leaving the last dynode and arriving at the anode. Since a component of the opposite sign (electrons arriving at the last dynode from the next-to-last dynode) and about 1/3 amplitude arrives at the last dynode, an imbalance will exist.
- Except for the idealized case of transformer coupling (but inevitably also with one or two capacitors somewhere), the signal derived with a

transmission line connected to the last dynode (AC-coupled somewhere) and the anode (DC or AC-coupled) consists of a balanced and unbalanced component.

- The existence of an unbalanced component can lead to non-zero net currents flowing in the shield, even with twin-ax or tri-ax. Could this be avoidable by a simple resistor network that balances the signal?
- Overall, there appear to be potentially large (but difficult to quantify) benefits to be realized in noise rejection by trying to preserve a high level of differential signal extraction, propagation, balanced termination and differential signal reception,
- After differential signal reception and preamplification, subsequent shaping and digitization do not necessarily need to be differential.

Issues:

- Signal propagation through penetrators – how much voltage can be supported across pins? TBD
- Signal propagation through penetrators – distortion/reflections at penetrators? Probably not too big a deal since some shaping will need to be in place to match 65 MHz sampling rate.

Choices:

1. **Positive HV on anode?**
   - The main advantage of individually adjustable positive HV is that all PMT photocathodes are at ground. Thus the PMT case and copper can + honeycomb can all be grounded, offering important mechanical and electrical simplicities.
   - Baseline shift with positive HV is unavoidable due to capacitive coupling.[1]
   - Since full HV is present across in the capacitors that transfer signal to a transmission line, the capacitors are physically larger, and store larger energy than for the negative polarity case.
   - For a given recharge impedance, the baseline shift is inversely related to the size of these capacitor.
   - About 1500 V must be transmitted through pressure wall penetrators for each PMT. This may reduce the number of available pins, and may reduce robustness of HV as a system, as discharges, sparks, etc, could be very damaging since stored energy for discharges is large. This unknown is probably the major concern for this polarity. This could conceivably drive a requirement either on vacuum quality, or lead to a fill gas (N_2, neon?) to obtain better HV robustness.
   - ...?
2. **Negative HV on photocathode?**

[1] The baseline shift in the IceCube DOMs required a lot of effort within IceCube to solve. Eventually, a good solution was found using a transform, but the RC time-constants must be known *very* accurately to avoid the introduction of surprisingly large errors in the corrections. This expertise in IceCube could be tapped.

- The advantage is direct coupling of the anode signal; there is still a capacitor coupling the last dynode signal component.
- The major difficulty is the need to avoid a large potential difference between the PMT can/window and the PMT shell/photocathode.
- Floating all the PMT cans at some average negative HV introduces serious electromechanical design issues to provide dielectric insulation.
- A relatively small but variable HV, about ±250 V, on PMT photocathode may be possible without inducing sparks/discharges to the PMT can.
    i. If all PMT cases and the copper can/honeycomb structure are held at a common average negative HV, approximately -1500V, then in principle, only one HV connector with -1500 V is needed.
    ii. Alternatively, it may be possible to vary the PMT photocathode potential over the range $\sim|250|$ V from the nominal -1500V. In this case up to 60 individual HV penetrations are necessary (or, more likely, some grouping of HV). In this scenario the benefit is zero potential for all anodes. The tradeoff risk is that, with vacuum, the PMT may spark to the can, even for a difference of 250 volts. A robust insulation scheme may be necessary.
- Much smaller voltage is imposed across signal coupling capacitors, which can then have a proportionately larger value, or may permit some other advantage such as using polypropylene capacitors in the base. [2]
- PMT gains can be equalized if the PMT anodes (last dynode must follow appropriately) potentials are variable over a range likely to be about ±250 V from zero potential.
- Relatively low-impedance voltage sources (~5kΩ) can be external, providing ΔV at high recharge current to both capacitors connected to anode and last dynode in a differential transmission scenario.
- In the twinax[3] scenario with negative HV polarity, the twinax wires are near ground potential, and will not stress the penetrator. The braid, however, can be at some potential of our choice if the twinax wire insulation is good for 2kV.
- The outer braid of the cable inside the pressure vessel could be kept at the nominal -1500. Since the copper tube is at the nominal negative HV, the insulation of the braid has to be good only for the ±200 V, not the 1500 volts.

A possible design:

- Positive HV
- Differential signal transmission from anode/last dynode on twinax
- About 250 V difference between last dynode/anode
- Stiff external power supply for last dynode/anode voltage stabilization
- Low power dissipation in the PMT can

[2] Both Daya Bay and DEAP-3600 found that ceramic capacitors introduced a large amount of ringing, possibly a piezoelectric effect.

[3] It may well be that triax will work as well; "twinax" is used here generically.

- Negligible baseline shift.
- Large capacitors are external

The general idea is illustrated in the attached figure. The main challenge is propagation of signals at ~+1500 V (anode) and ~+1250 V (dynode) through the penetrators. If the problem of sending anode signals through penetrators at +1500 V (+ the dynode signal at around +1250 V) can be solved, then all photocathodes are at ground, and no severe electrostatic stress exists in the PMT + window + can system. The twinax shields might be OK with common ground at 1500 V inside the PV, reduced to zero V (or perhaps about HV/2) by a blocking capacitor inside.

Very large signal decoupling polypropylene capacitors exist outside the PV in separate little enclosures. This reduces baseline shift within one event to negligible values. These enclosures reduce crosstalk, and could be in NIM or other style boxes, several channels to a box, but each channel adequately shielded from the others. Protection diodes should be present to protect the preamplifier from turn-on/off transients.

Power to the PMT chain and last dynode is introduced within this box. This box is where the low-impedance ΔV ~250V is established, using a zener diode or possible active component. The internal base has a high-value resistor across the anode/last dynode to ensure that a current path exists internally (not shown in diagram). The value of the resistor is chosen to maintain a larger voltage difference than is imposed by the external circuitry. This ensures that the proper ΔV ~250V is maintained by the low-impedance external circuitry, not by the high-value resistor.

The signal is differentially transmitted received by an appropriate fairly high impedance preamplifier at this box. After preamplification, differential signal propagation to shaping amplifiers might not be necessary.

While none of this complexity can be shown to be necessary at this time, it might not be expensive to just do this. Tests should occur soon.

For an optical system efficiency of, *e.g.* 24 PE per primary electron, each PMT (of 60 total) receives about 40,000 PE for a Q-value event. With a PMT gain of 4×10^6, the total charge delivered per PMT is about 25 nC.

Taking an event length of 100 μs, each PMT delivers an average current of ~250 μA. This current is dissipated primarily in the two R2. Taking 100 ohms as the likely impedance, the typical voltage developed is 25 mV. The two C3 bring this voltage developed across the two R2 to the preamplifier. For R3 = 5 KΩ, the current flowing into/out of C3 is 1% of that in the twinax. The charge change in C3 is about 0.25 nC; if C3 is 10 nF, then a baseline shift of ~25 mV occurs from beginning to end. C3 can be made larger, and R3 varied as well. For these values, the RC time is 1×10^{-4} s. A time constant 10x larger would be better, and likely straightforward. It would be useful to have these notions reviewed by an expert.

QuickTimeª and a
decompressor
are needed to see this picture.