Project/Proposal Title: A New Electrostatically-focused, UV HPD for Liquid Xenon

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Priscilla Cushman

Under an Advanced Detector grant we redirected the work in the University of Minnesota optics lab from hybrid photodiode (HPD) quality assurance for hadronic calorimetry at the Large Hadron Collider to the development of ultra-violet sensitive photodetectors for liquid xenon readout. In dual-phase liquid xenon detectors, the charge signals are converted to photons: free ionization electrons are extracted from the liquid to the gas phase where in the strong electric field they induce proportional scintillation light. The sequence of a small primary photon signal, followed by larger ionization-induced signal requires photodetectors able to detect only a few ultraviolet photons with good leading edge timing, yet which can react proportionately to the larger signal. In addition, the photodetectors must be able to withstand temperatures down to 165K and be made of ultra-clean, low background materials. A large open area ratio is important for maximum coverage.

Figure 1. The Minnesota setup for measuring UV quantum efficiency. Nitrogen purges the interior of monochromator as well as a box which normally surrounds the device (not shown). Cold nitrogen LN boil-off (not shown) keeps the photosensor below 0°C. The QE of Vacuum devices is quantified by putting a stable battery across the photocathode and measuring the current, whereas for silicon devices, the gain is first calibrated in a separate system.

Our first step was to modify the lab monochromometer to handle UV light by replacing the light source with a deuterium lamp, purchasing a UV grating, replacing the glass optics with quartz, and flushing the whole system with nitrogen. We calibrated its response down to 175 nm using a UV vacuum diode. This setup (figure 1) enabled us to make quantum efficiency measurements for a set of potential liquid xenon photosensors, including a hybrid photodiode with a quartz window, Hamamatsu R8520 PMT and R9280 PMT, and two Advanced Photonix large area APDs (LAAPD) lent to us by the XENON collaboration. After correcting for the lamp's wavelength-dependence, we found that the quantum efficiency of the LAAPD peaks close to 60% QE at 200 nm, falling to 50% at 250 nm and then rising slowly to 80-90% into the visible and IR, as expected (figures 2 & 3).

Figure 2. The response of CMS-style HPD with UV-enhanced photocathode, two different Hamamatsu PMTs and an LAAPD as measured in the UV monochromometer.

Figure 3. Dividing out the light intensity requires a calibrated sensor (requested in this proposal), but we can estimate the quantum efficiency by assuming a standard QE and known gain for the HPD and anchoring it to the calibrated photodiode at 4350 nm. For 175 nm, the QE of the HPD is 15% and the other QE's are 19% (R9280), 20% (R8520), and 38% (LAAPD) with large error bars (~5%).

The enhancement at 200 nm is not the >100% advertised by Advanced Photonix. It is probably caused by the release of multiple photoelectrons for one energetic photon. Since what we measure at high light levels is the product of the average number of photoelectrons released per photon multiplied by the probability of a conversion, this effective quantum efficiency is not the photon detection probability at low light levels. The quantum efficiency derived from source measurements directly in liquid xenon may very well have a different ratio of these two components and the actual primary scintillation light will be different still. The true photon detection probability for one photon can only be properly measured using a combination of UV calibrated stations and alternate photodetectors with photoelectron counting to provide normalization.

This new UV optics lab was used to characterize a silicon PM, which was then tested in liquid xenon in the XENON-10 test chamber at Nevis Labs in collaboration with Columbia, and produced a joint paper on the results [1]. We did the same with an RMD APD array. This time we collaborated with the XENON group at Rice.

An HPD is a vacuum device which uses a photocathode to convert the photons to photoelectrons and an applied accelerating field, V_{app} , to produce the gain. Photoelectrons at high kinetic energy impinge on a reverse-biased silicon diode junction, creating $(V_{app} - V_{thr}) / V_{ep}$ electron-hole pairs, where V_{thr} is the threshold voltage required to penetrate the diode dead layer and $V_{ep}=3.6$ eV is the energy required to produce one e-p pair in silicon. The gain is thus linear with applied voltage and limited by space charge or breakdown in the packaging itself, not by anything intrinsic in the design. A custom electrostatically-focussed HPD with UV photocathode was designed in collaboration with DEP and had two main elements that were optimized: (1) the diode and (2) the vacuum tube.

Diode: A single 2 mm diameter diode was fabricated using epitaxial growth by Canberra. In this design the photoelectrons are converted to electron-hole pairs within the first few micrometers of the surface of the lightly-doped (n+) bulk n-type layer. The holes drift through the silicon and are collected from the backside p+ implant. Additional p+ structures on the back define grounded and floating guard rings that maintain uniformity near the edge and aid in maintaining a high breakdown voltage. The outermost n++ ring supplies the bias voltage from the back of the diode to the front n++ surface through the bulk material. The small diode will have a capacitance of 2 pF expected from an 8 times reduction in area. This improves its noise and risetime performance.

Vacuum Tube: For this application, we require an electrostatically-focused HPD with the largest possible demagnification and the highest gain. To further improve the open area ratio, the input window was curved. Hexagonal and square tubes for close-packing were examined, but the area ratio was actually smaller, due to the flat window and the necessary thickness of the potting. Moreover, the tube construction and electrostatic design was much more expensive, whereas our aim was to design a tube which can inexpensively cover large areas as sensitively as possible. The finished device, including the mounting in a holder, had an open area ratio of just over 70 %, a demagnification factor of 36, and a risetime of 4 ns. Conventional electrostatically-focused HPDs have demagnification factors in the range of 5. A rendering of the tube body is shown in figure 4.

Figure 4. A drawing of the 72 mm tube body with the LHCb pixel structure at the focus.

Since the HPD's must be operated at low temperatures and have to be free of radioactivity, conventional high voltage rubber insulation cannot be applied. A new special housing made of Teflon was designed to hold the HPD module in a temperature environment of -111°C . All the materials were low radioactivity, and this was validated after the fact by screening in the high purity germanium detectors at the Soudan low background counting facility. With respect to trace radioactivity, HPDs are inherently better than PMTs since they consist of a simple silicon target in a metal housing and they do not require a base.

For older electrostatically-focused HPDs, the diode is mounted in the module body via clamping. For this new type of HPD, the diode mounting was done on a carrier via bump-bonding. This gave rise to a better performance (e.g. lower dark current), made them easier to install in the experiment using a pin grid array PGA, and were more robust for use at extremely low temperatures.

The curved window was quartz with a UV-enhanced multi-alkali photocathode. The quantum efficiency was measured to be $\sim 15\%$ at 175 nm at room temperatures. Some photosensors, notably the large area APDs, claim quantum efficiencies in excess of 100% in the hard UV, but as stated above, this is most likely the release of several photoelectrons per incident photon, rather than an increase in the probability of a photon conversion.

The first tube produced was tested and found to have poor focusing properties, although its quantum efficiency and noise response was as expected. A second round of design work was then begun in order to improve the electrostatic focusing and thus the final gain. Unfortunately, the lead engineer on the project tragically died of a sudden heart attack. His loss caused a two year delay in producing the second prototype. When the prototype was delivered, it was found to have major charge instabilities, including sparking at high operating voltage. The final product

was tested at lower voltages at Case-Western in a Xenon setup from Tom Shutt. The quantum efficiency and low noise were acceptable and it worked in the harsh cryogenic environment of the liquid xenon cell. However, without the possibility of going to high voltages, the promise of this tube design was not realized and by then (3 years later) other advances by Hamamatsu made this design less interesting for the company, and any further improvements were not pursued.

1. E. Aprile, P. Cushman, K. Ni, P. Shagin Detection of liquid xenon scintillation light with a Silicon Photomultiplier, Nucl. Instr. and Meth. **A556**, pp 215-218 (2006).