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A multi-PMT optical sensor for IceCube-Gen2

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Abstract: A new long optical module (LOM) is under development for IceCube-Gen2, the proposed expansion to the IceCube neutrino observatory at the South Pole. The module is housed in an elongated borosilicate-glass pressure vessel, the size of which is constrained by the borehole diameter, which impacts drilling economy. The designs under consideration use either 16 or 18 4-inch PMTs, conditional on future performance tests, mounted so as to guarantee full angular coverage. Modular electronics have been custom-designed to fit into the available space and to minimize cost and power requirements for the ∼ 10000 modules to be installed. We will provide an overview of our approach to these design considerations and summarize the results of our tests and simulations. Prototype modules will be installed in the upcoming IceCube Upgrade.

Keywords: Cherenkov detectors; Neutrino detectors

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[1]Full author list and acknowledgments are available at icecube.wisc.edu.

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Contents

1 Introduction

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector at the geographic South Pole [1]. Reconstruction of the direction, energy and flavor of incident neutrinos relies on the detection of Cherenkov radiation emitted by charged particles produced by neutrino interactions with a nucleon in the ice or bedrock. The photons are collected by Digital Optical Modules (DOMs), installed in boreholes drilled into the ice at depths ranging between 1450 m and 2450 m. The IceCube Upgrade will consist of nearly 800 new optical modules on 7 strings. There are two main optical module designs for the Upgrade: the mDOM [2] (figure 1), featuring 24 Photomultiplier Tubes (PMTs) of 3″ diameter, yielding an almost homogeneous angular coverage, and the DEgg [3] (figure 1), with two 8″ PMTs opposite each other. The Long Optical Module (LOM),

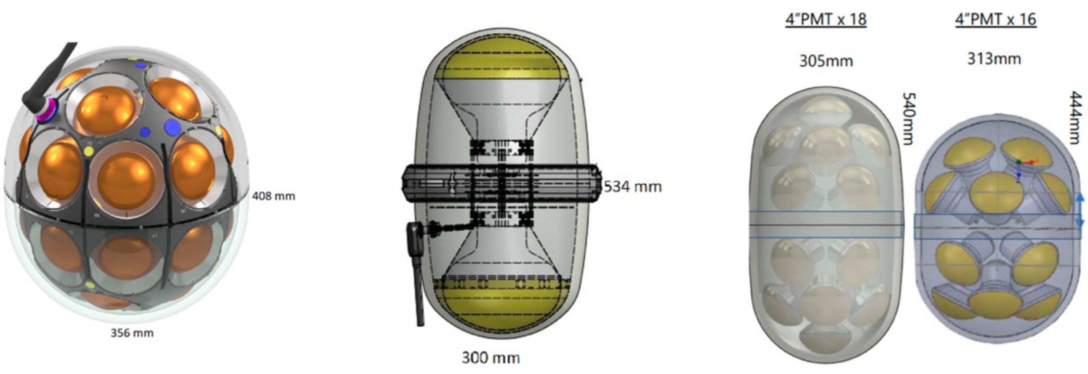

Figure 1. Left: the multi-PMT Digital Optical Module (mDOM). Middle: The dual-PMT Optical Module (DEgg). Right: the two LOM designs.

developed from the multi-PMT Upgrade modules, has a reduced diameter (12″) to enable the module to fit in a narrower hole, saving time and fuel costs for drilling. Multiple 4″ PMTs have been used to maximize effective area with fewer channels. The waveform processing has been shifted to the PMT base, integrating digitization and high voltage (HV) generation, and reducing power consumption. Two variations of this design are currently under development (figure 1), with 18 and 16 PMTs. In the near term, the goal is to build ten modules of each type, and deploy 12 modules for the Upgrade. These will be developed into a single baseline design for Gen2, which will have 9600 modules distributed across 120 strings [4].

2 Mechanical structure

Each PMT is coupled to the glass vessel with optical gel, which is a transparent addition-curing silicone. The gel, while liquid, could be injected into a clear plastic 'shell' around each PMT photocathode (**in situ** method (figure 2)). Another alternative is investigated for the LOM, where gel is moulded onto the PMT photocathode as 'pads' (figure 3), which are then coupled to the vessel. This approach is more economical as the pad moulds can be reused. Our implementation of the gel pad is to cast a conical pad directly onto the PMT photocathode. A cavity is formed when the rim of the base makes contact with the curved pressure vessel (figure 4). Silicone caulk is used to seal the rim of the pad to the pressure vessel. The cavity is then filled with liquid gel, and degassed to remove any bubbles.

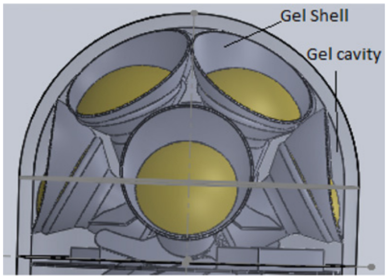

Figure 2. Plastic 'gel shells', filled with liquid gel in in situ method.

Figure 3. A gel pad coupled to a PMT.

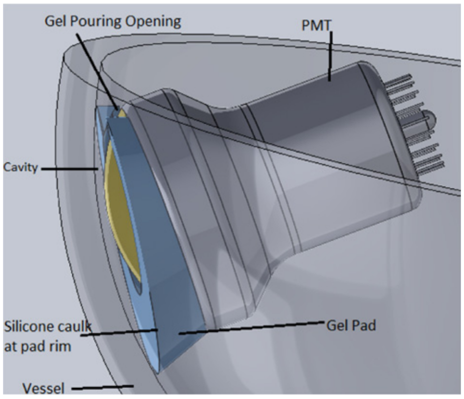

Figure 4. The cavity seal method.

The PMT-and-pad assembly must be precisely oriented for proper interfacing, and the PMT must be pushed against the vessel by the support structure. Some options to exert the outward pressure are springs or an inflatable collar around the PMT neck.

3 Simulation results

The use of conical gel pads provides photon capture efficiency comparable to metallic reflectors, due to total internal reflection at the surface of the pad (figure 5). This was experimentally verified using a gel pad mounted on a 3″ PMT, and counting the number of photons captured when a spot beam is moved across the photocathode area [5].

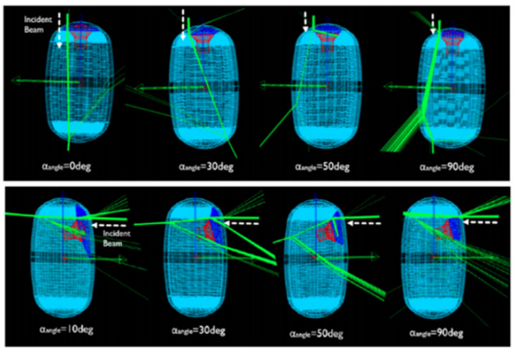

Figure 5. GEANT simulations of the response of the PMT-and-pad assembly. Photons incident outside the rim of the PMT photocathode are captured via total internal reflection off conical pad walls. The parameter α_{angle} denotes the angle between the pad wall and the normal to the pad axis.

GEANT4 [6] studies were also performed to optimise the pad shape for greater photon capture efficiency. The probability of the photons arriving at the PMT photocathode was evaluated as a function of the gel pad cone opening angle, and found to be largest at opening angles of 60°–80°.

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The 4″ PMTs used are assumed to have the optical response of the 3″ PMTs used in the mDOM, scaled to account for the greater photocathode area.

GEANT4 simulations also enabled the comparison of the module effective area and angular acceptance with other optical modules (figure 6). These yielded an increase in Cherenkov spectrum-weighted effective area of 3.2–4.2 times for the 16- and 18-PMT LOMs respectively, relative to the IceCube Gen1 DOM, at photon wavelength 400 nm [5].

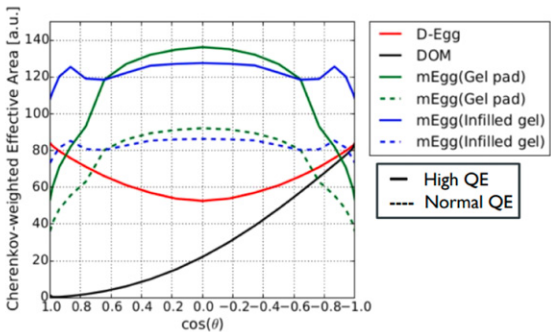

Figure 6. Using a model with $14 \times 4''$ PMTs in the D-Egg vessel (mEgg), gel pad performance is compared to the DEgg and Gen1 DOM as baselines. A comparison is also made to an mEgg with a gel-filled interior (infilled gel).

4 Electronics design

The electronics design for the LOM builds upon the mDOM design, adding data acquisition (DAQ) functionality to the mDOM MicroBase, which has the PMT biasing circuit. The new base, called the Waveform MicroBase, is shaped to optimise board surface area to fit the DAQ components in the space between PMTs.

Following the existing IceCube Upgrade designs, a central processor will provide common data management and control. Communications to the hub surface computers via the in-ice cables (figure 7) is managed by the Ice Communications Module (ICM) with a dedicated FPGA. Ribbon cables carry UART communication, time synchronization clocks, and power to the PMT bases. To facilitate a multi-level detector trigger, hit data are temporarily retained in a flash memory chip [7]. The Waveform MicroBase (figure 8) has been optimized for low power consumption and wide dynamic range. We use a 5 mW Cockcroft-Walton generator for HV bias. To accommodate IceCube neutrino events with PMT signals of varying intensity, the base includes two analog channels, one for the anode and another connected to a dynode (Dy8) with lower gain. These signals are digitized continuously in a 2-channel ADC at 60MSPS, and captured in a low power FPGA. For an inter-string spacing of 240 m, as anticipated for IceCube Gen2, photon arrival time distributions have widths >25 nsec, and the choice of 60MSPS is a suitable compromise between power consumption and time resolution. The anode channel remains linear for intensities up to 50PE/25 nsec. A delay line module in the FPGA records the leading edge time with resolution about 1 nsec.

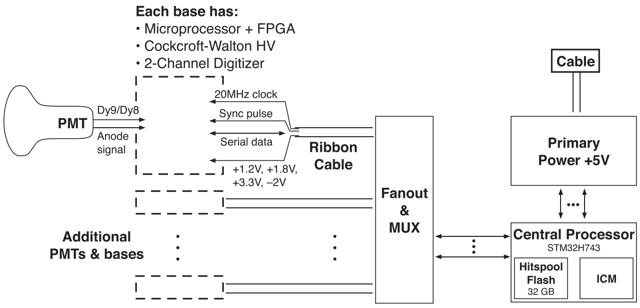

Figure 7. The distributed processing architecture.

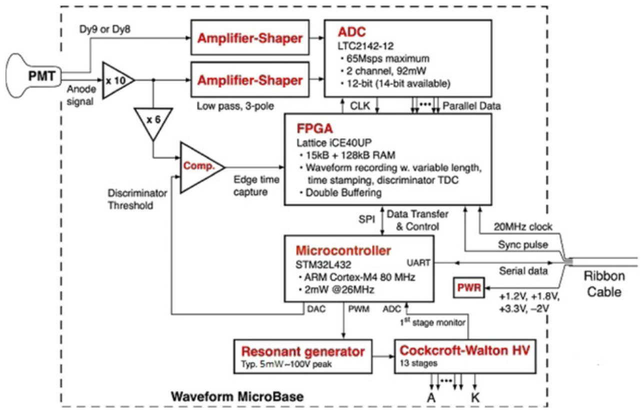

Figure 8. A block diagram of the Waveform MicroBase.

Figure 9 shows the response to LED flashes of varying brightness and duration. The channel 1 signal path saturates for large signals, while channel 2 remains linear up to 5000PE/25 nsec. Figure 10 shows the single photon charge distribution from channel 1, indicating the gain of 5×10^6 and a sharp discriminator threshold set at 0.15SPE with baseline noise of about 1 ADC count.

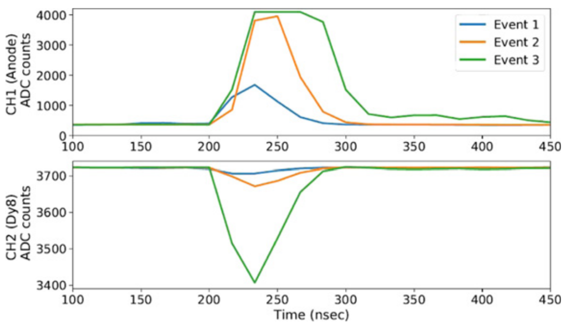

Figure 9. A sample event readout. Event 3 saturates the anode readout on ch. 1, but the readout on ch. 2, from dynode 8, retains event information.

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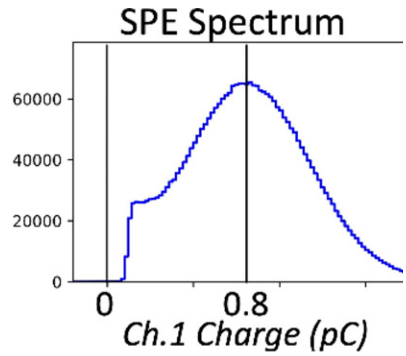

Figure 10. The measured charge distribution for single photoelectrons at a gain of 5×10^6.

5 Outlook

An overview of the design of a new optical module for IceCube-Gen2 is presented. The guiding principle is to arrive at a procedure that is economical, reliable and scalable for mass production. Simulation efforts are in progress to optimize the gel pads, and to determine the photon effective area of the prototype designs. The enhancement of the photon effective area of a PMT with a gel pad has been experimentally verified. The design, testing and verification of the electronics systems are proceeding apace, with testing of the Waveform MicroBases underway at various sites. First prototypes are expected to be completed soon and will be ready for deployment as R & D modules in the 7 string IceCube Upgrade.

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