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5 Development of the New Optical Sensor for IceCube-Gen2

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10 ABSTRACT: A new digital optical module (DOM) has been developed for the proposed expansion to the
11 IceCube detector at the South Pole, IceCube-Gen2. The “Gen2-DOM” has 4 times the integrated photon
12 sensitivity of the current IceCube DOMs and has built off the design features of the IceCube Upgrade
13 modules. The Gen2-DOM has up to 18 4" photomultiplier tubes (PMTs) in a borosilicate glass pressure
14 vessel, arranged in a uniform 4π angular distribution. The mechanical design has been optimized to fit
15 into a reduced borehole diameter which, in turn, will reduce drilling costs during installation. Each PMT
16 has a dedicated readout board, designed to increase sensitivity to high-energy events aligned with the
17 science goals of IceCube-Gen2. Internal storage enables multi-level triggering schemes with reduced
18 overall flow of data on the long cables. Twelve prototypes of the Gen2-DOM will be deployed in the
19 IceCube Upgrade in the 2025/2026 austral summer. This article will focus on the current status of design
20 development and initial performance testing results.

21 **1 Introduction**

22 IceCube-Gen2, the proposed expansion to the IceCube South Pole Neutrino Observatory [1], plans to
23 enhance the detection capabilities for astrophysical neutrinos. The 8 km^3 in-ice optical array will be
24 composed of 120 strings, with 80 optical modules per string and a total of 9600 optical modules. With
25 the science goals focused on high energies [2], the array will be sparser than IceCube, with inter-string
26 spacing of 240 m instead of 125 m. With such a sparse array, the optical modules must have high photon
27 detection efficiency and dynamic range, intended to achieve a factor of four improvement compared to
28 the existing Digital Optical Modules (DOMs) in IceCube. In addition, the newly designed Gen2-DOMs
29 must fit within a power budget of $< 4 \text{ Watts / module}$, and have a diameter of less than 12.5 inches to save
30 drilling costs during installation.

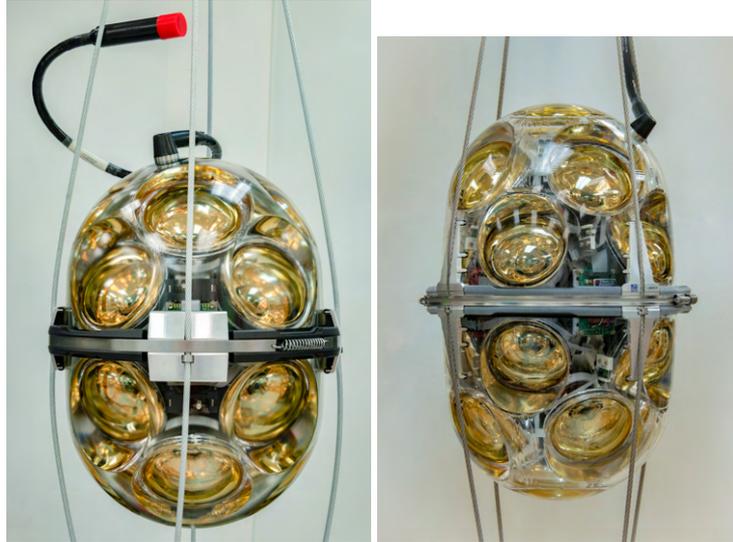


Figure 1: Completed prototype for Gen2 Design Candidate-16 (left) and Gen2 Design Candidate-18 (right).

31 2 Sensor Design

32 Building off the reliability of the IceCube DOM and the design features of the mDOM [3] and DEgg [4]
 33 modules of the IceCube Upgrade [5], the Gen2-DOM has a segmented photocathode surface with up to
 34 18 photomultiplier tubes (PMTs) arranged with uniform 4π angular coverage inside an elongated glass
 35 pressure vessel. The design of the new sensors will be tested in-situ in the IceCube Upgrade, where 12
 36 prototype modules will be deployed in the 2025/26 austral summer. Two prototype designs of the Gen2-
 37 DOM have been implemented: one with 16 PMTs and one with 18 PMTs. They are called the "Gen2
 38 Design Candidate-16" (Gen2DC-16) and "Gen2 Design Candidate-18" (Gen2DC-18), respectively, and
 39 the completed designs are shown in Figure 1. Both prototype designs have the same central components,
 40 while testing different integration methods and component manufacturers. Six of each prototype will be
 41 deployed in the IceCube Upgrade, and the different designs will be merged into one module which is
 42 developed and optimized for mass production: the Gen2-DOM. The primary components of each of the
 43 prototypes are discussed in the following sections.

44 2.1 Photomultiplier Tubes

45 Both the number of PMTs in the module and the size of each PMT were considered when designing
 46 each of the Gen2-Design Candidates. Studies to optimize the effective area of the modules showed a 4"
 47 diameter PMT with a short neck (105mm total length) as the best option. This study was heavily informed
 48 by the 3" PMT design used in the mDOMs. We approached two manufacturers to design these PMTs:
 49 Hamamatsu Photonics KK (HPK) ¹ and North Night Vision Technology (NNVT) ². Both companies
 50 proposed their initial designs for new 4" PMT models, which were then characterized thoroughly and
 51 met all requirements [6]. With almost 10,000 modules planned for IceCube-Gen2, having two PMT
 52 manufacturers benefits the rate and security of mass production.

*Full author list and acknowledgments are available at icecube.wisc.edu.

¹Hamamatsu Photonics K.K., Shizuoka, Japan

²North Night Vision Technology Co., Ltd, Nanjing, China

53 2.2 Pressure Vessel

54 The two modules' designs have different number of PMTs, and therefore have different shaped pressure
55 vessels. Two manufacturers were chosen for the different modules. The Gen2DC-16 vessel is produced
56 by Nautilus³ and has an outer diameter of 312 mm and a height of 444 mm. The Gen2DC-18 vessel is
57 produced by Okamoto⁴ and has a more elongated shape, with a diameter of 318 mm and height of 540
58 mm. Each vessel is designed to protect the interior components of the module, which faces pressures up
59 to 550 bar as measured during IceCube deployment. Both vessels are rated up to 700 bar, have diameters
60 less than 12.5 inches, low levels of radioactive contamination, and good transmissivity between 300-500
61 nm. Both vessels are made of borosilicate glass with thickness in the range of 12-16.5 mm and meet all
62 design requirements.

63 2.3 Gel Pads

64 Any air gaps between the photocathode and the pressure vessel can cause photon losses due to the
65 differences in index of refraction. To minimize these losses, the PMTs are coupled to the vessel with
66 silicone optical gel. The index of refraction of the gel at 400 nm is 1.41, which is similar to that
67 of borosilicate glass, 1.49. The gel pad acts as a sort of funnel for the photons, guiding them to the
68 photocathode via total internal reflection.

69 We cast these gel pads in a two step process. The first step is to cast a hollow gel pad directly onto the
70 photocathode face with a custom mold that creates a highly smooth exterior with a ring shaped boundary
71 [7]. We then adhere the edges of the hollow gel pad to the interior of the pressure vessel with gel, and
72 finally backfill the hollow cavity with uncured gel. The gel then cures directly to the glass, creating a
73 strong and bubble-free bond.

74 2.4 Electronics

75 The Gen2-DOM utilizes newly developed PMT readout bases with self-contained DAQ functionality,
76 called the wuBase [8]. The wuBase includes the same active Cockcroft-Walton high voltage generator
77 developed for the IceCube Upgrade's mDOM PMTs, with the new DAQ functions on an extended
78 part of the board which fits into spaces between PMTs in the Gen2-DOM. Each base includes a fully
79 digitized readout with a two channel, 12-bit ADC at a rate of 60 megasamples per second (MSPS) and a
80 single photoelectron (SPE) timing resolution of 2.5 ns. The ADC digital outputs are streamed to a low
81 power FPGA where triggered waveforms are accumulated in buffers. The wuBase includes an ARM
82 microcontroller that reads these waveforms, performing first level computations as well as managing all
83 other DAQ and control functions. The high gain channel records the waveform from the anode, while
84 the low gain channel records the signal from dynode 8 out of 10. This combination achieves the high
85 dynamic range of 5000 photoelectrons within 25 ns, with electronic noise below 2% of the SPE level.

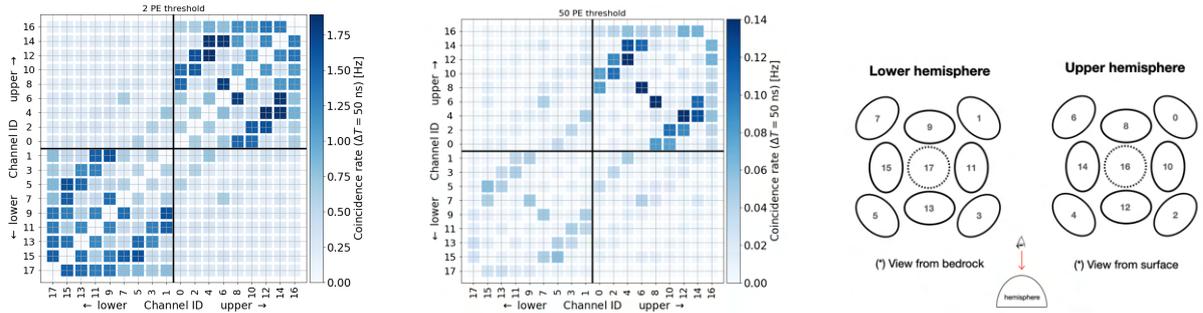
86 The self-contained functionality of the wuBases goes along with the use of a "Mini Mainboard"
87 (MMB), which serves as the command and communications hub for the Gen2-DOM, while squeezing
88 into a space between PMTs. Two fanout boards have been developed to multiplex the communication
89 between the MMB and the wuBases, which operates at 3 Mbaud.

90 3 First Lab Measurements

91 Before integration into the full module, each PMT was tested as a subassembly with its wuBase and gel
92 pad already attached. The tests were performed at low temperatures, including PMT gain, electronics

³Vitrovex by Nautilus Marine Service, GmbH, Buxtehude, Germany

⁴Okamoto Glass Co., Ltd, Kashiwa, Chiba, Japan



(a) Dark noise coincidence rates on pairs of PMTs for 2 PE threshold.

(b) Dark noise coincidence rates on pairs of PMTs for 50 PE threshold.

(c) Channel ID number assignment in Gen2 Design Candidates.

Figure 2: Dark noise coincidence rates and PMT numbering scheme.

93 performance, dark count rate, and time resolution [9]. The pre-integration dark rates for the PMTs
 94 are fairly low, between 100-250 Hz. The dark noise of the fully integrated module is dominated by
 95 radioactive contaminants in the pressure vessel. The radioactive decay processes produce bursts of
 96 scintillation photons, which can be captured across multiple PMTs. Figure 2a showcases the coincidence
 97 rate between pairs of PMTs within a time window of 50 ns and at a threshold of 2 PE. The PMT numbering
 98 scheme is shown in Figure 2c. We can see there is a strong symmetry between the hemispheres, with
 99 neighboring PMTs showing the highest coincident noise rates. If we increase the threshold to 50 PE,
 100 the coincidence rate of noise hits is largely suppressed. In Figure 2b, we see that high-charge coincidences
 101 are observed much more in the upper hemisphere. The pattern and rate support interpretation of these
 102 events as down-going atmospheric muons.

103 4 In-Ice Triggering Scheme

104 IceCube-Gen2 will use a multi-level trigger and readout protocol, which will reduce the data flow on the
 105 long cables to below the level of IceCube. In the new trigger scheme, PMT hit details are temporarily
 106 saved in in-module flash memory buffers. If a number-of-PMTs threshold is met in the module, a trigger
 107 message is sent to the surface. At the surface, streams of trigger messages are combined while selecting
 108 events with defined requirements on numbers of modules and strings contributing in a time window.
 109 Only for these time windows, the system will issue readout requests for all corresponding stored hits,
 110 which greatly suppresses the amount of noise hits sent to the surface. A detailed simulation with various
 111 candidate requirements shows that physics hits trigger the module more often than noise hits when
 112 requiring a minimum of 3 (out of 16 or 18) PMTs to record a hit within a 500 ns window [10], as shown
 113 in Figure 3.

114 In reducing the bandwidth usage up the main cable assembly, IceCube-Gen2 is able to increase
 115 the number of devices per wire-pair on the cable. In IceCube, there are 2 DOMs per wire-pair; in the
 116 Upgrade there are 3 devices per wire-pair; in IceCube-Gen2 there will be 6 devices per wire-pair. Taking
 117 into consideration the increase in photon sensitivity per device, this results in a factor of 18 increase in
 118 photon detection efficiency per wire-pair, and a substantial savings in cost and logistics from reduced
 119 cable size.

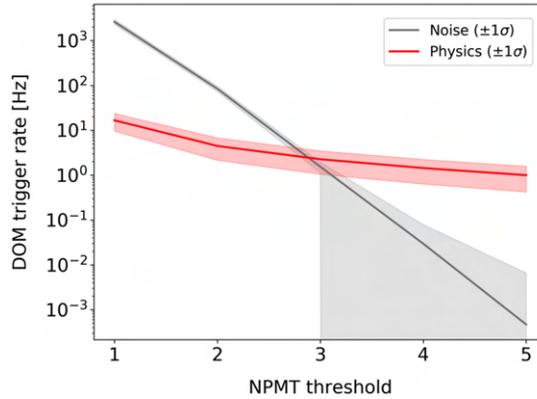


Figure 3: Simulated cosmic rays trigger more than noise hits when requiring a minimum of 3 PMT channels to record a hit.

120 5 Conclusion and Outlook

121 In order to meet the design and functionality requirements of IceCube-Gen2, two sensor designs have
 122 been developed in parallel to test the practical aspects of electronic and mechanical assembly, as well as
 123 performance in the ice. While both designs feature the same central components of PMTs, electronics,
 124 and gel pads, each design offers a beneficial internal structure concept and assembly processes which
 125 will contribute to the final Gen2-DOM. Both the Gen2DC-16 and Gen2DC-18 fulfill all requirements
 126 and six prototypes of each module will be tested in-situ as part of the IceCube Upgrade. Work to merge
 127 the two designs into a final Gen2-DOM design is underway, with the focus lying on manufacturability
 128 and reliability for mass production.

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