Performance studies for a next-generation optical sensor for IceCube-Gen2

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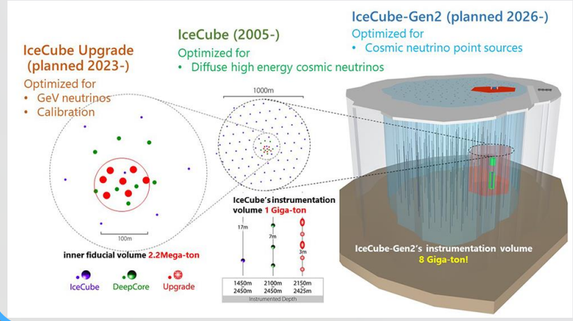
① Upgrade projects of IceCube



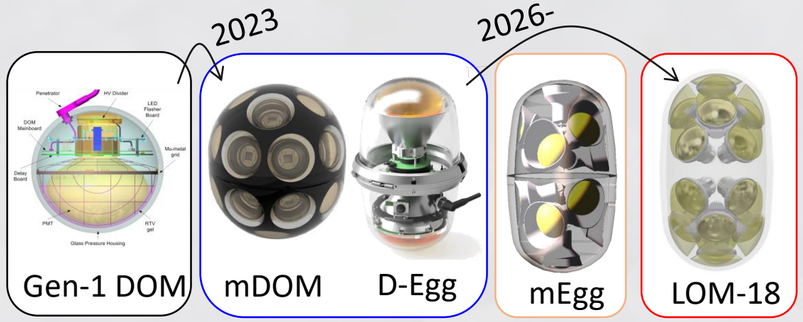
- **IceCube** is a cubic kilometer neutrino telescope deployed in Antarctica. It consists of 5160 Digital Optical Module (DOM) to detect Cherenkov photons induced by secondary particles from neutrino interactions.
- **The IceCube Upgrade** plans to install ~700 new optical modules to detect GeV neutrinos and to get better knowledge of ice properties.
- **IceCube-Gen2** will increase the volume of the current IceCube detector by one order of magnitude by installing O(10,000) new optical sensors.

② Optical modules for the Upgrade and Gen2

Name	PMT diameter [inch]	Number of PMTs	Glass diameter [mm]	Glass height [mm]
Gen1 DOM	10	1	330	330
mDOM	3.15	24	356	411
D-Egg	8	2	300	534
mEgg	4	14	300	534
LOM−16	4	16	313	444
LOM−18	4	18	305	540

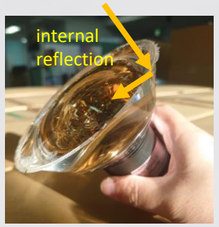
Requirements of new optical modules are

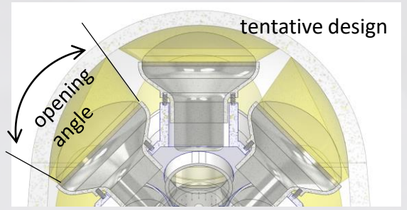
- larger sensitivity than that of Gen-1 DOM
- uniform sensitivity for all incident angles
- low cost per optical sensitivity
- low power consumption
- high reliability in harsh environment
- tolerance to high pressure (up to 70 MPa)

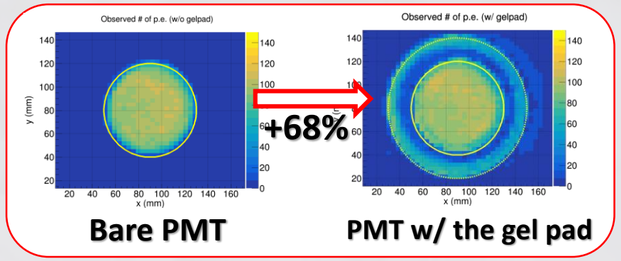


- Optical modules are installed in ice holes drilled by hot water. To reduce the cost, the diameter of hole is limited to ~ 12''. (smaller than that of Gen-1 hole)
- Long optical module (LOM) has a diameter of 12'' and includes 16 or 18 four inch PMTs in the (elongated) pressure vessel.

③ Enhancement of the effective photo-sensitive area with gel pads







- All existing modules use UV-transparent optical silicone elastomer for coupling.
- For Gen-2 optical modules, because of the elongated shape of the pressure vessel, gel pads are adopted.
- Gel pad has a conical shape and acts as photo collector thanks to total reflection at the side walls. GEANT4 study suggests 60-80 degrees is the optimal opening angle.

- Using a parallel spot beam (470 nm), we measured the obtained charge as a function of hit position.
- The gel pad increased the effective photo-sensitive area by 68%, which is in good agreement with the 75% obtained from optical photon simulation.

④ Evaluation of effective area

- The performance of optical modules is compared using their effective areas, which are evaluated by Monte Carlo simulation:

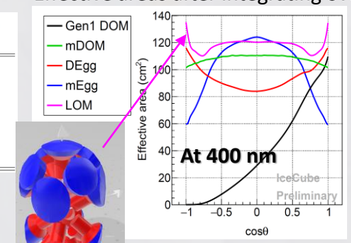
$$A(\theta,\phi,\lambda) = \frac{A_0}{N_{\text{gen}}} \sum_{i:\text{hit}} P(\lambda,\vec{r}_i)$$

A_0: area of generation
$P(\lambda,\vec{r}_i)$: photo detection efficiency

Effective areas after integrating over θ and ϕ

Name	Effective area (400 nm) [cm^2]	Cherenkov-averaged effective area [Ratio to Gen-1 DOM]
Gen1 DOM	34 – 37	1
mDOM	108	3.5 – 4.0
D-Egg	94	2.8 – 3.2
mEgg	103	3.2 – 3.6
LOM−16	105	3.2 – 3.7
LOM−18	118	3.6 – 4.2

Effective areas after integrating over ϕ



Tentative implementation of the internal components of LOM-18 →

- Due to absorption in ice, 400 nm is a typical wavelength of arrival photons. We use this wavelength as a benchmark. Another choice is an average weighted with Cherenkov spectrum (useful for close sources).

- We evaluated the performance of a tentative LOM-18 design.
- LOM-18 shows 3 times higher effective areas than Gen-1 IceCube optical sensor.
- In addition, LOM design shows homogeneous sensitivity on the incident angle.

Conclusion

- Choice of gel pads can increase the efficiency by 70% thanks to total internal reflection.
- LOMs achieve ×3 higher effective area than Gen1 DOM and almost (20%) uniform angular coverage.