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Development of the Fiber Optic Module (FOM) as a Light Collector for IceCube Gen2

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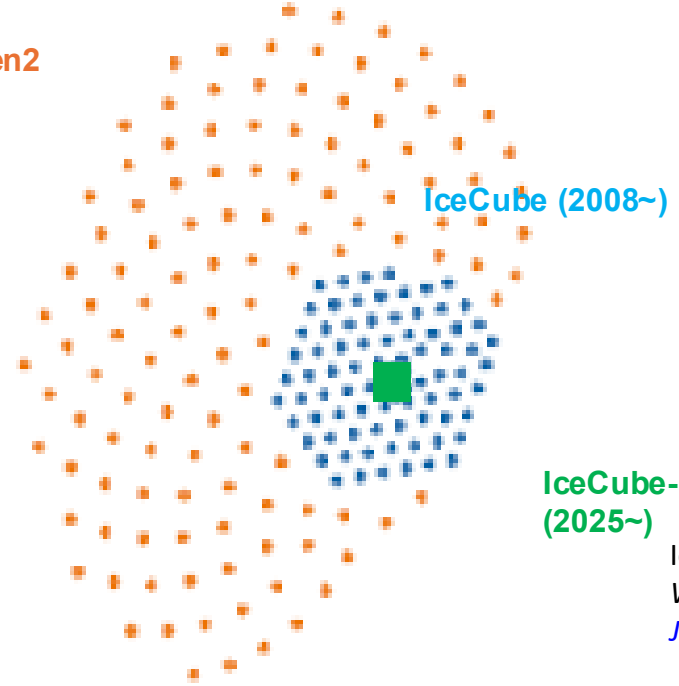
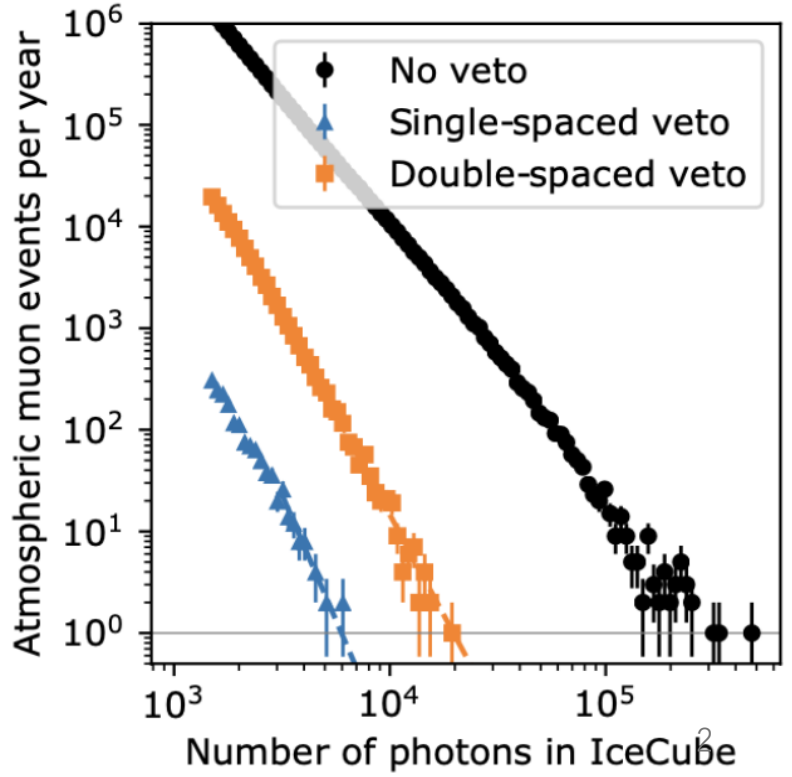
IceCube-Gen2

- String pitch roughly doubled (125m -> 240m), a sparser geometry
- Weakens the veto performance for atmospheric background
- Effectively raises the neutrino energy threshold unless capturing more light per Optic Module.

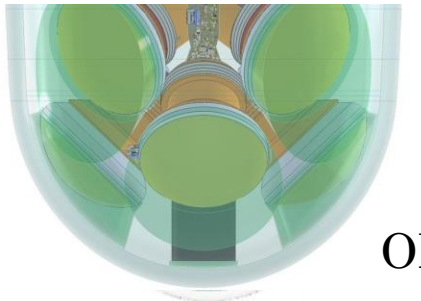


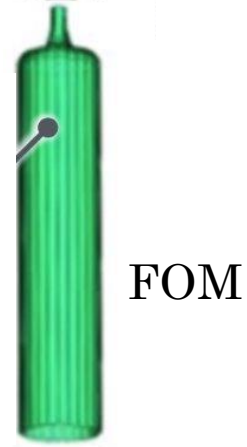
IceCube Collaboration, *IceCube-Gen2: The Window to the Extreme Universe*, *J.Phys.G* (2021) .

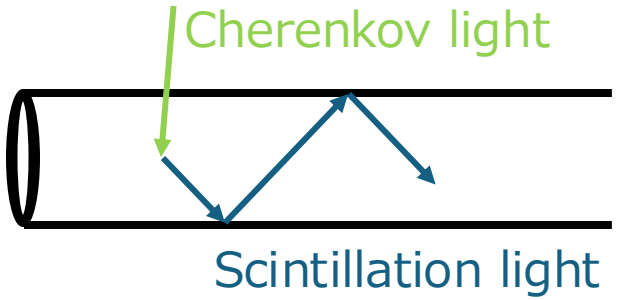


To Increase OM Sensitivity

- Conventional levers (costly)
  - Add more PMTs per OM
  - Use PMTs with higher Quantum-Efficiency
- A low-cost path: Use *light collectors*
- Concept of *FOM – fiber optical module*
  - A slender bundle of optical fibers (wavelengh-shifting scintillation fibers)
  - Deploy on outermost OMs
- We need to quantify
  - Light collection efficiency
  - Attenuation
  - Resulting effective area of fibers relative to a bare OM

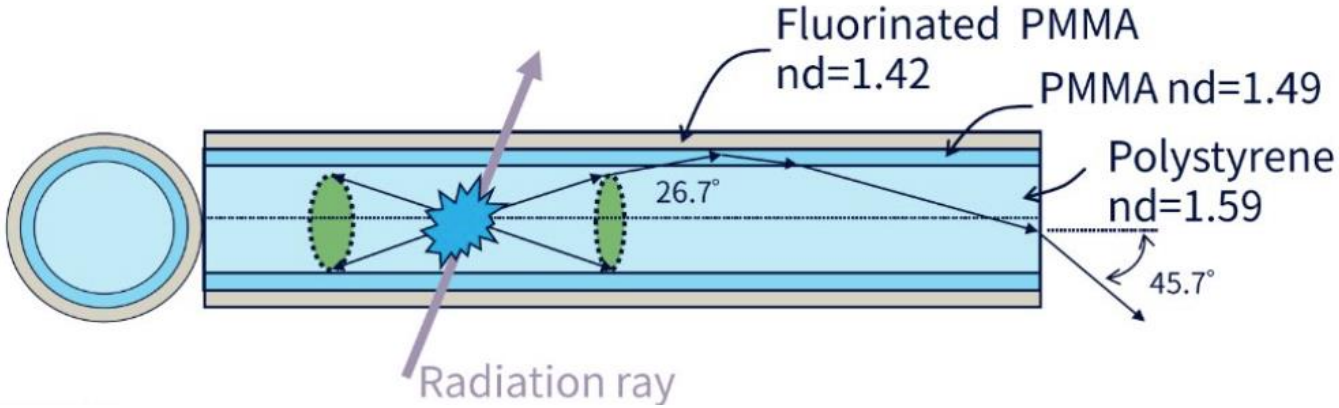


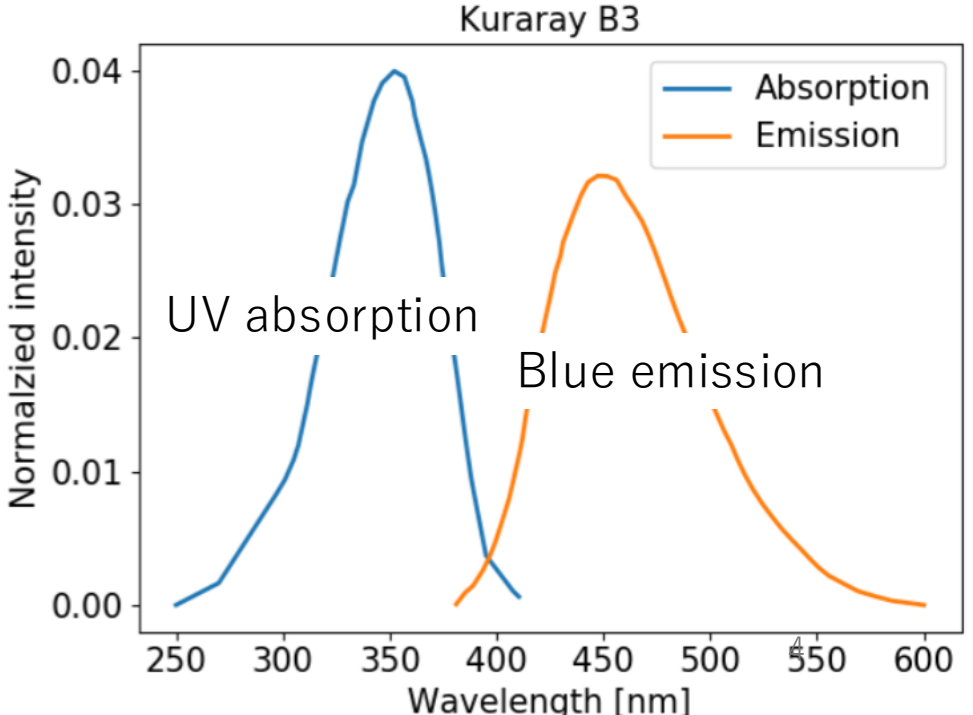




Candidate Fiber

- Kuraray B-3(200)M, 1mm diameter
- Plastic, double-cladding **W**ave**L**ength-**S**hifting scintillation fiber
- The core absorbs incoming Cherenkov photons, and re-emit at longer (blue) wavelength
- Guided by total internal reflection at the readout end(s)

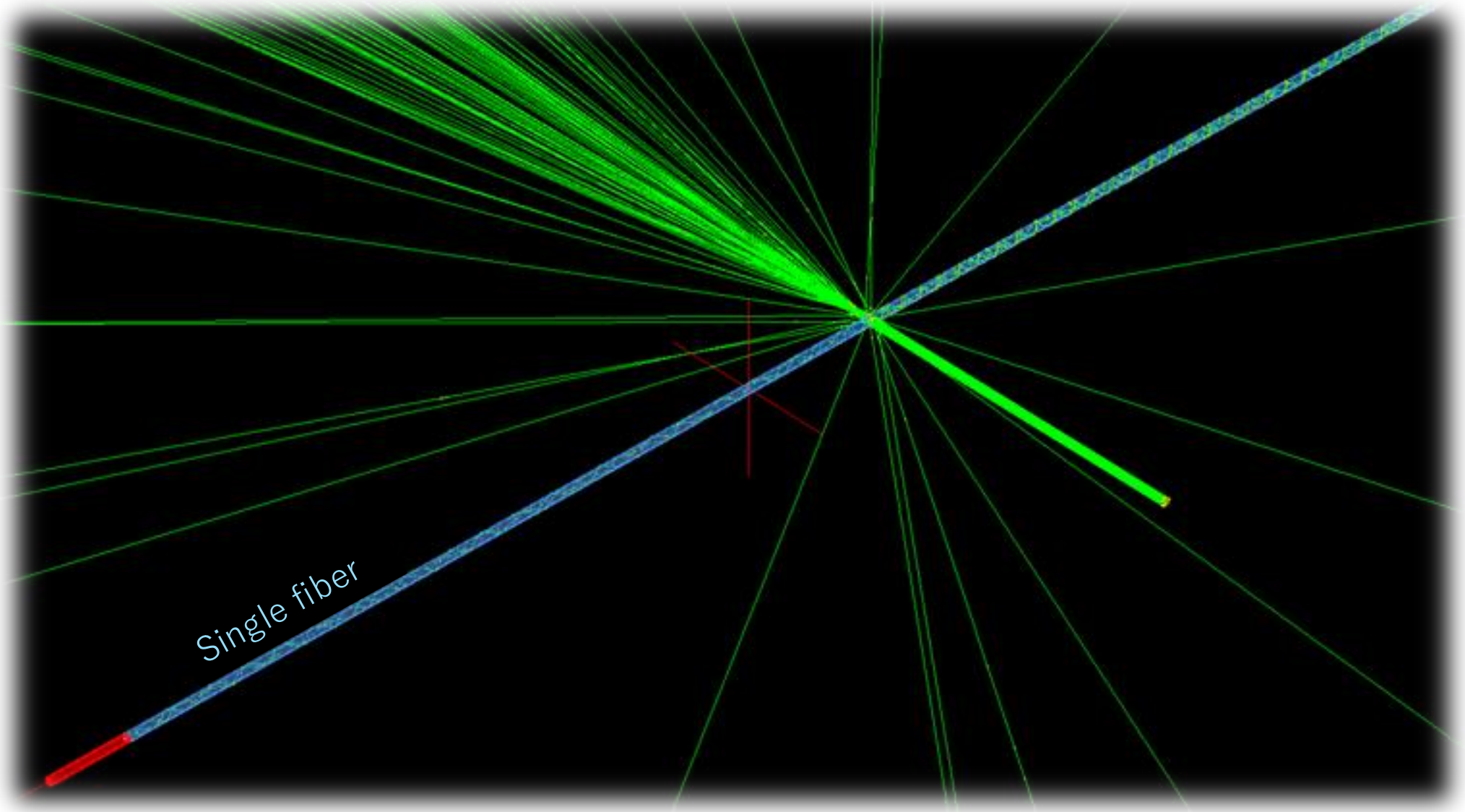




Light Collection Efficiency: An Estimate

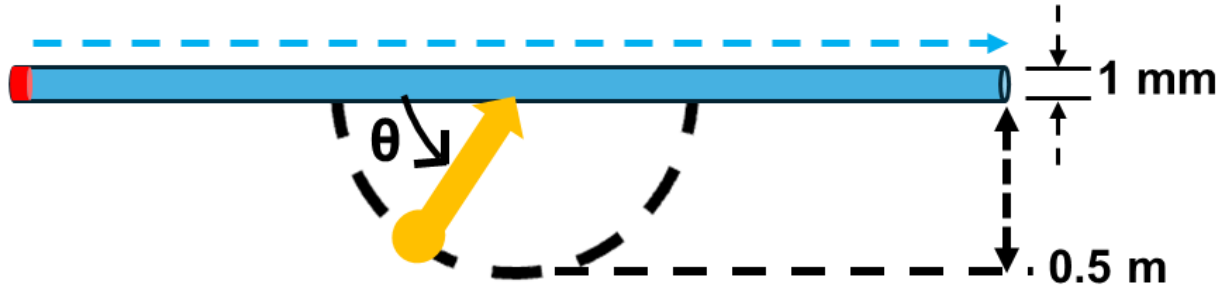
- $\varepsilon_{\text{det}} = \varepsilon_{\text{abs}} \times \varepsilon_{\text{emit}} \times f_{\text{trap}} \times T_{\text{bend}} \times e^{-\ell/L_{\text{att}}} \times \varepsilon_{\text{end}} \times \text{QE}$
  - ε_{abs} ~ 95%: Photons absorbed
  - f_{trap}~10%: Probability of satisfying the total-reflection condition
  - L_{att} ~ 4m, ℓ ~ 1m
  - ε_{end}~80%: Fraction of photons at the edge of the fiber < 45 degrees
  - QE ~ 27%
- ε_{det} ~ $O(1\%)$
- (1mm diameter x 400cm length)/fiber x 250 fibers = 10,000 cm^2
  - -->100 cm^2 , comparable to a bare Gen2DOM effective area

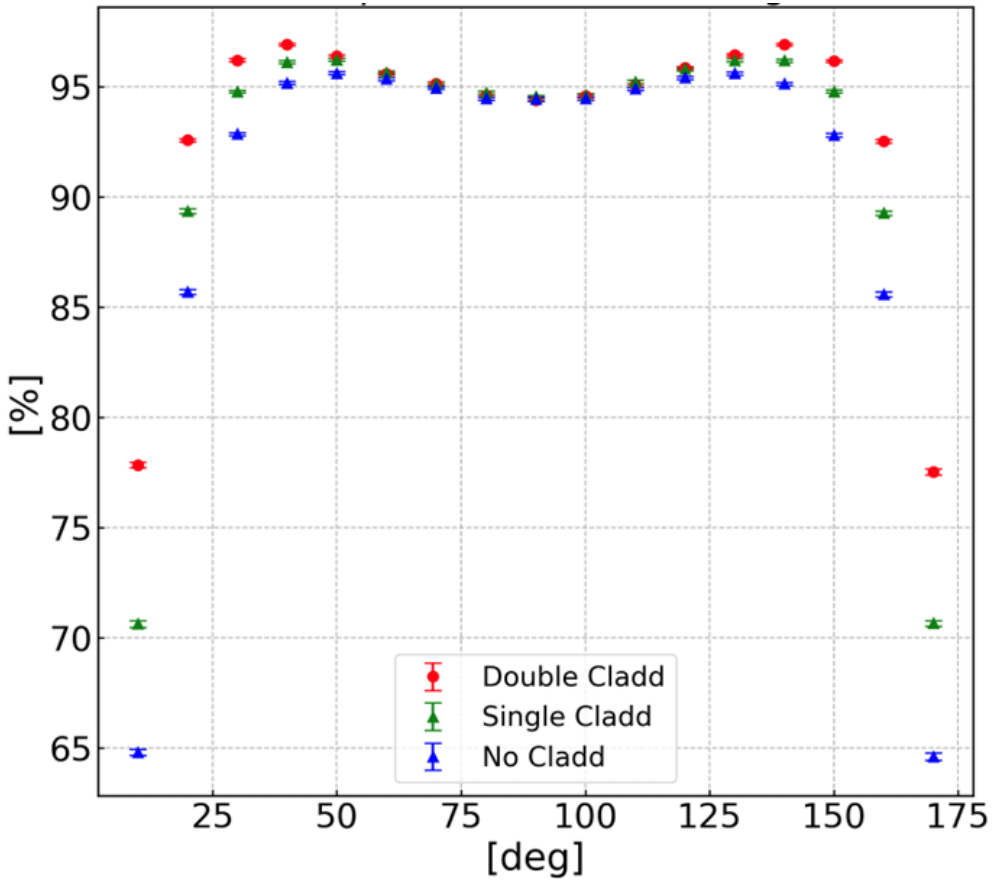
GEANT 4 Simulation



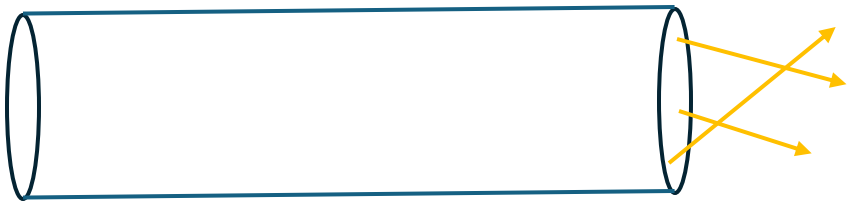
GEANT4 Simulation: Absorption

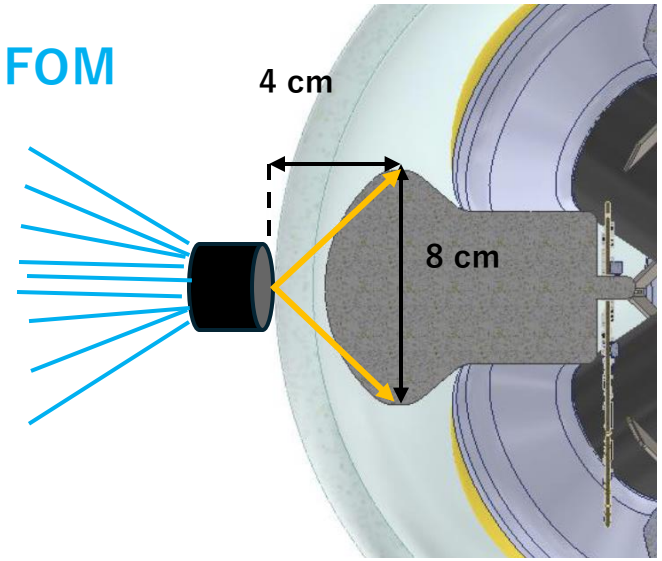
$$\text{Absorption efficiency} = \frac{\text{wavelength-shifted photons}}{\text{total phtons}}$$

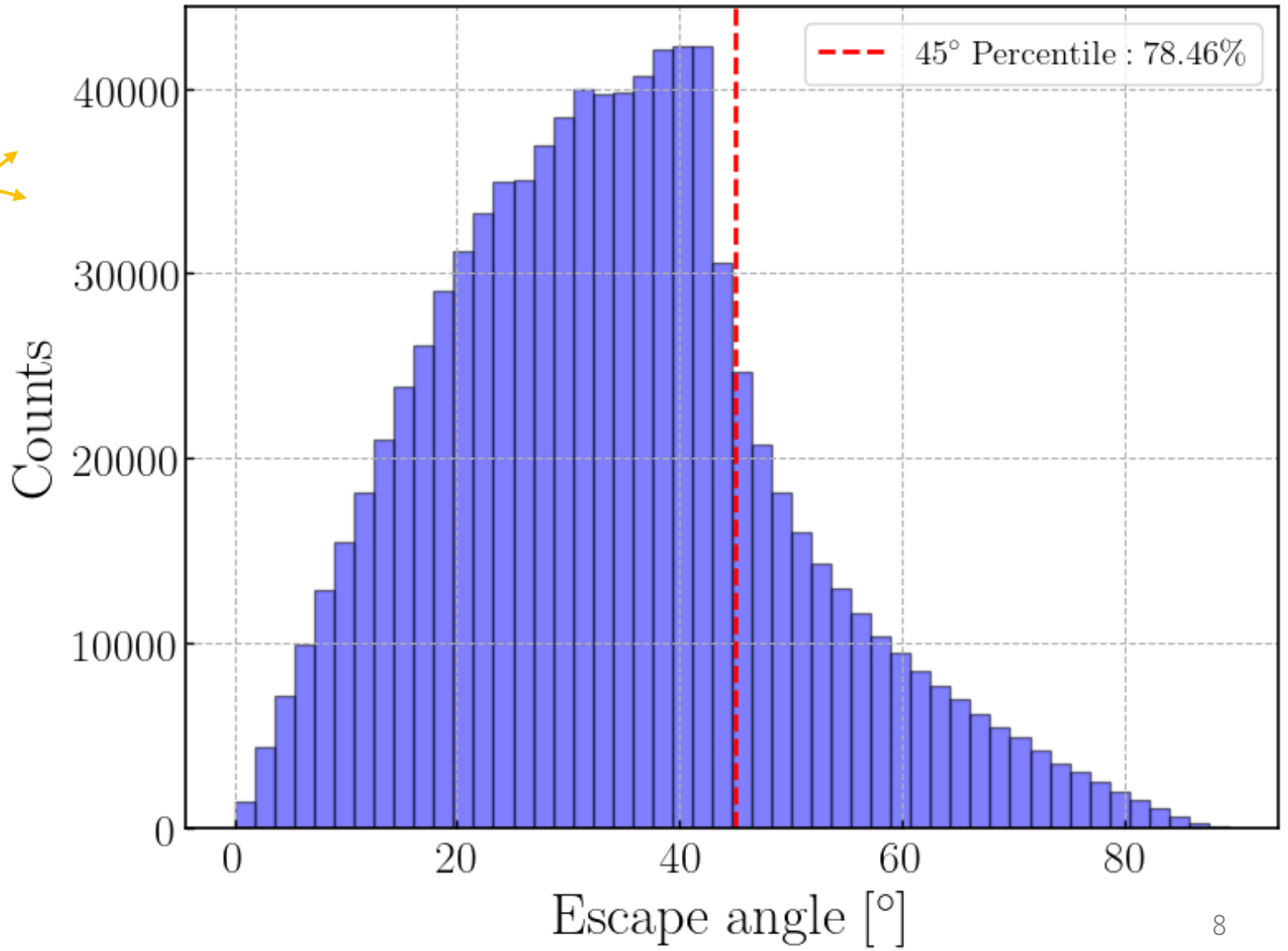




GEANT4 Simulation: Exiting Angles

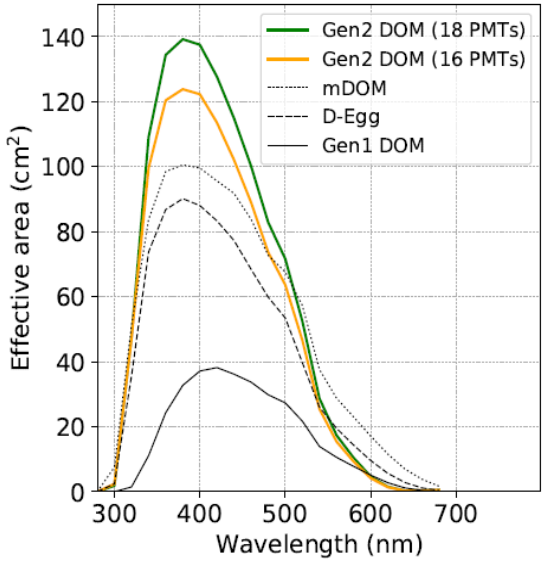


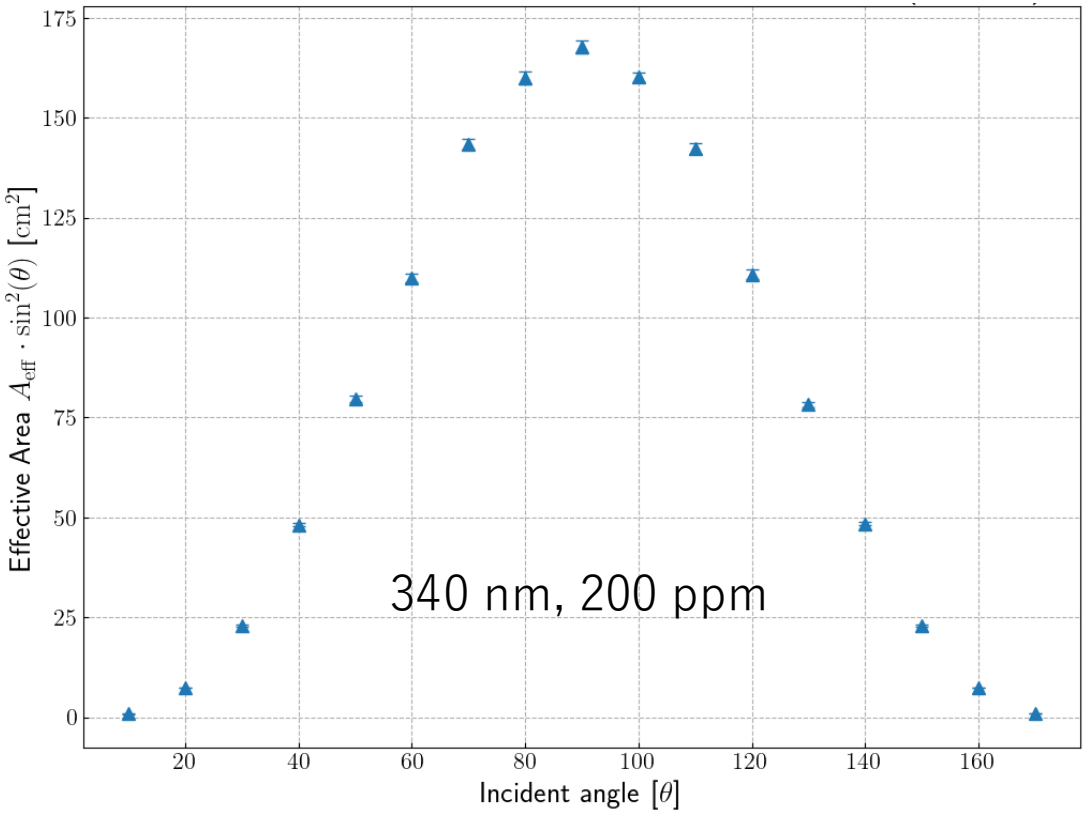


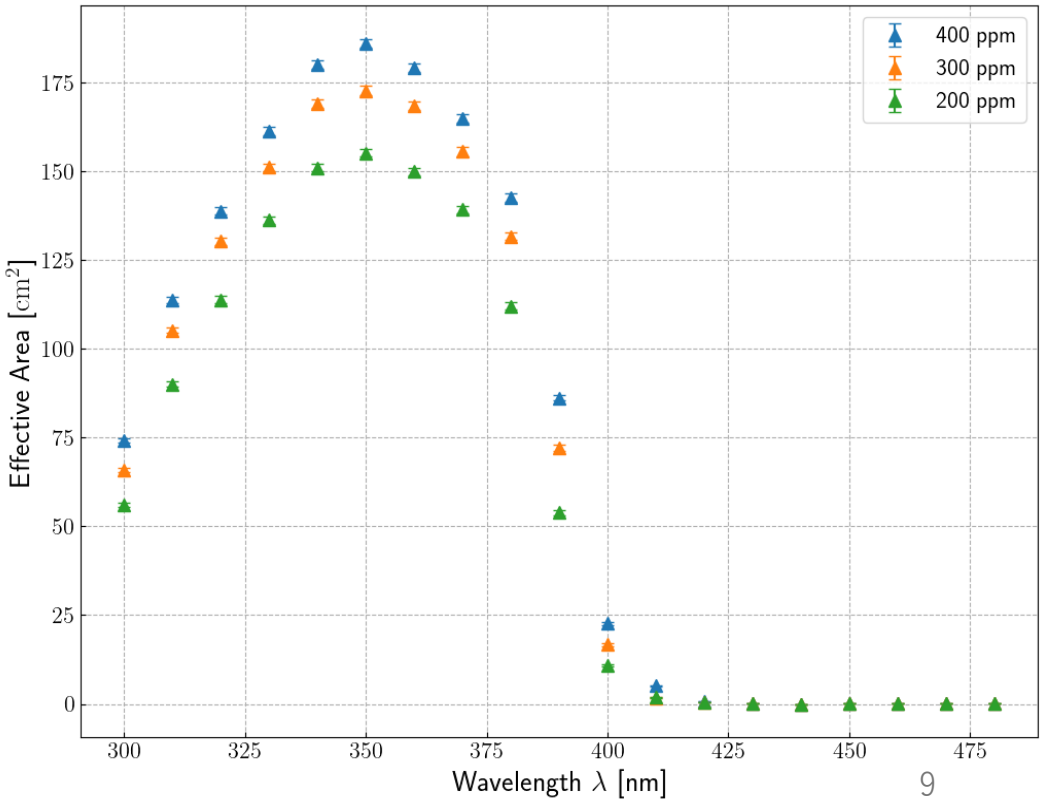


Geant4 Simulation: Effective Area

- 250 4m fibers (1mm diameter), uniform injection, double-sided readout
- No shadowing effect included
- Photon exiting angles and QE included
- Effective area is comparable to a bare OM for Gen-2.







Experiments

High pressure test

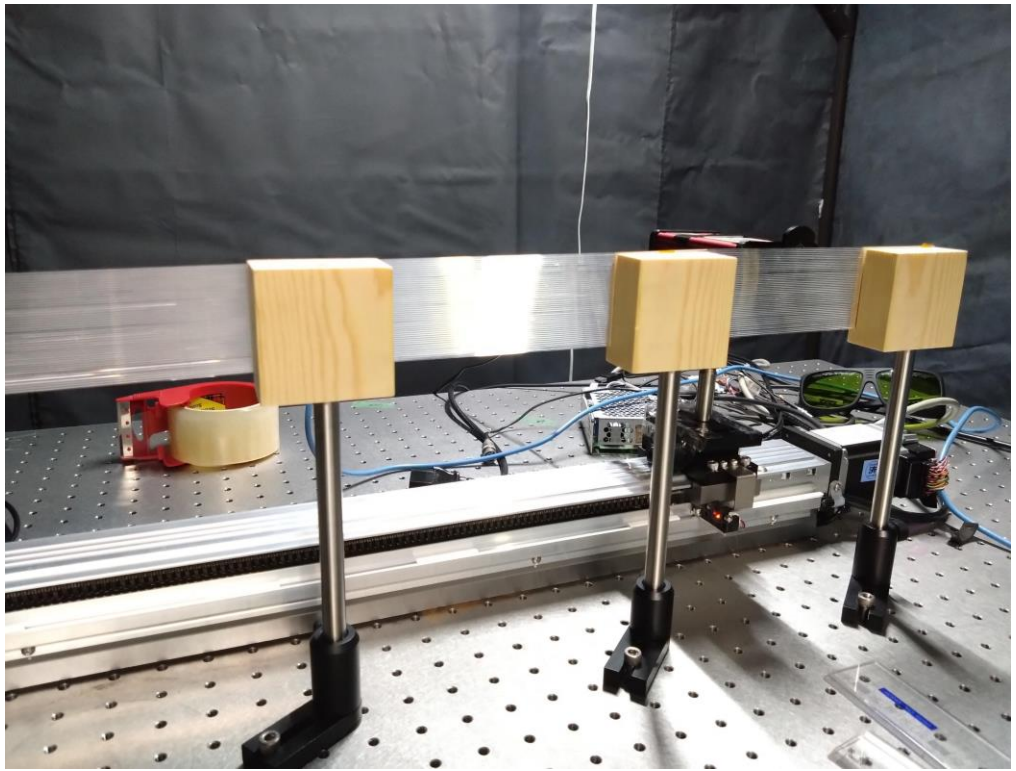
- The fiber bundle was co-submerged in the same setup during the test.
- No apparent damage
- No significant changes in attenuation

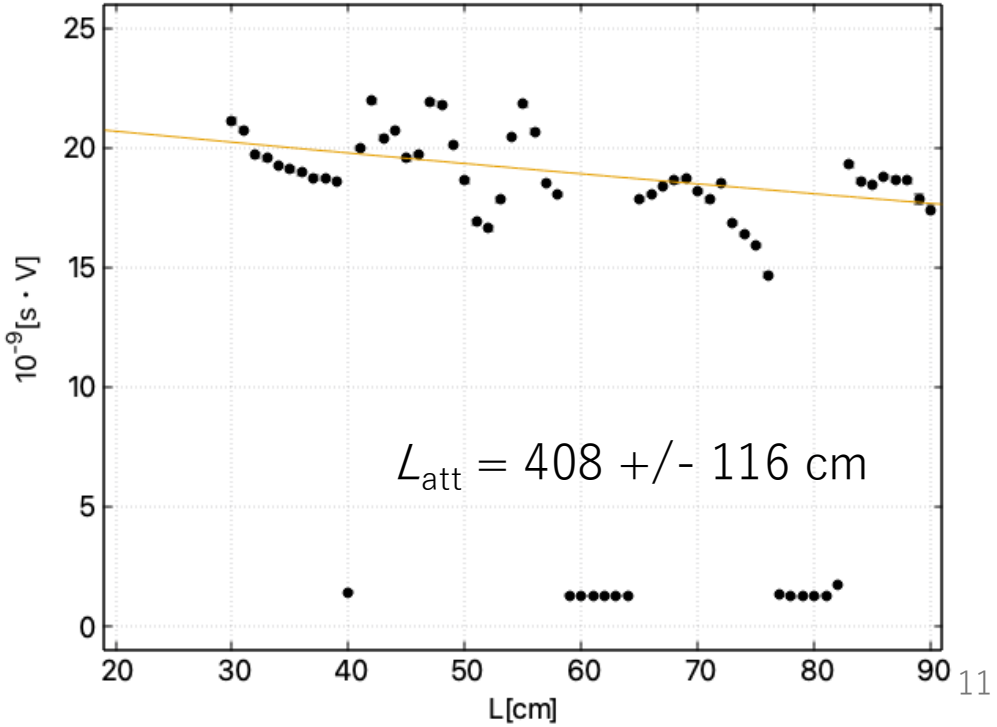
Low-temperture test

- Room temperature (30 degC): 121.49 +/- 0.01 cm
- Low temperature (-60 degC): 121.45 +/- 0.01 cm
- 10-6 expansion/contraction
- Attenuation and other optical properties: to be measured.

Measurement: Attenuation length

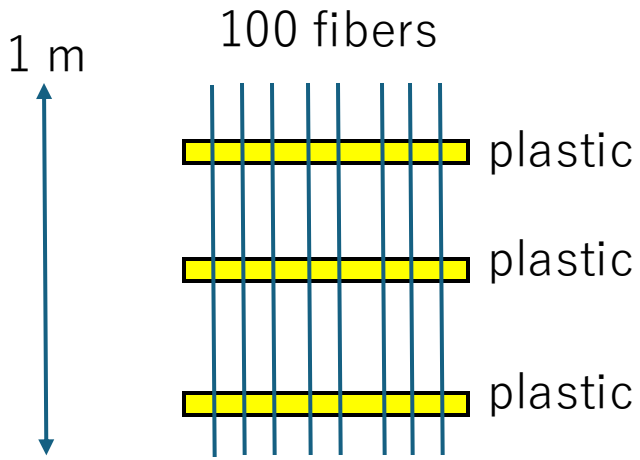
- Catalog value: > 4.0m
- We illuminate an optical fiber with a ~5 mm laser spot and measure transmitted light at the fiber end using a PMT.
- A single fiber cannot be held perfectly straight → laser spot may not always align with the fiber center.
- To reduce this effect, we aligned 50 1 mm–diameter fibers side by side, forming a “fiber sheet.”
- The sheet is wider than the laser spot, ensuring consistent light coupling despite fiber waviness.

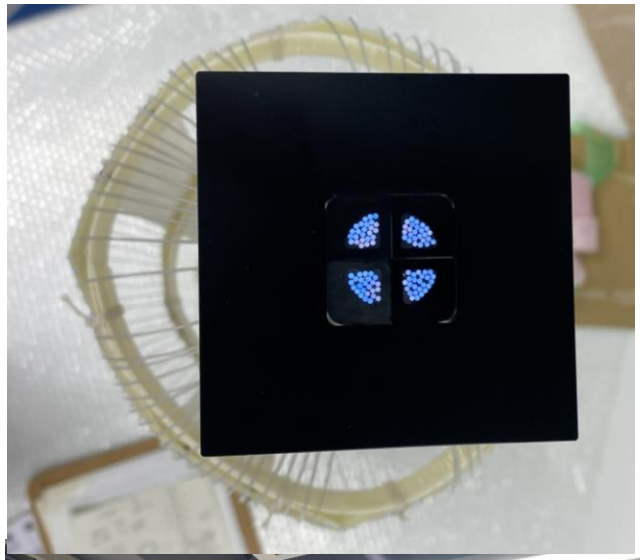


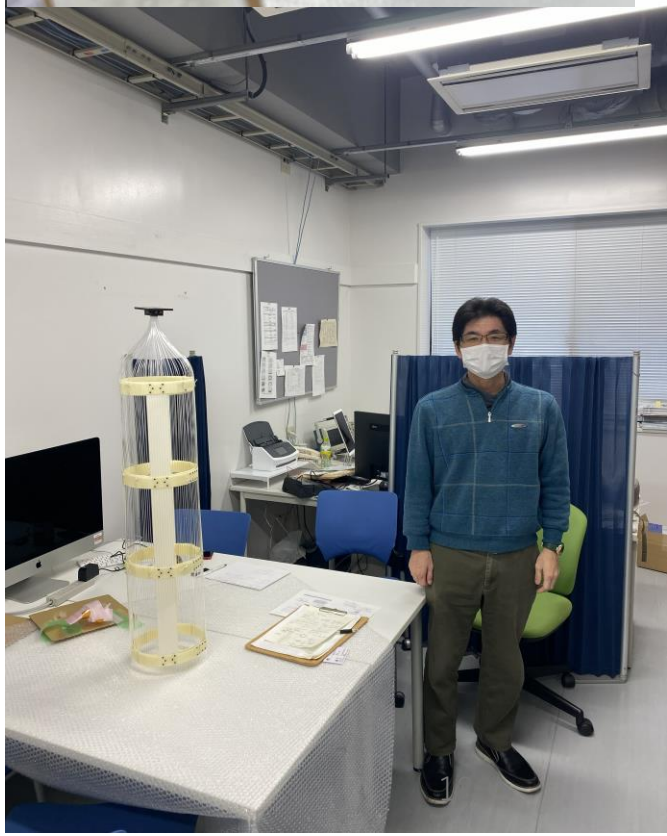


FOM 1st Prototype

- **Build**
  - Form a sheet of 100 1-meter fibers held on thin plastic ribs
  - Roll the sheet into a cylinder
- **Readout**
  - Single-ended, gathered all the fibers
  - Opposite ends are left open

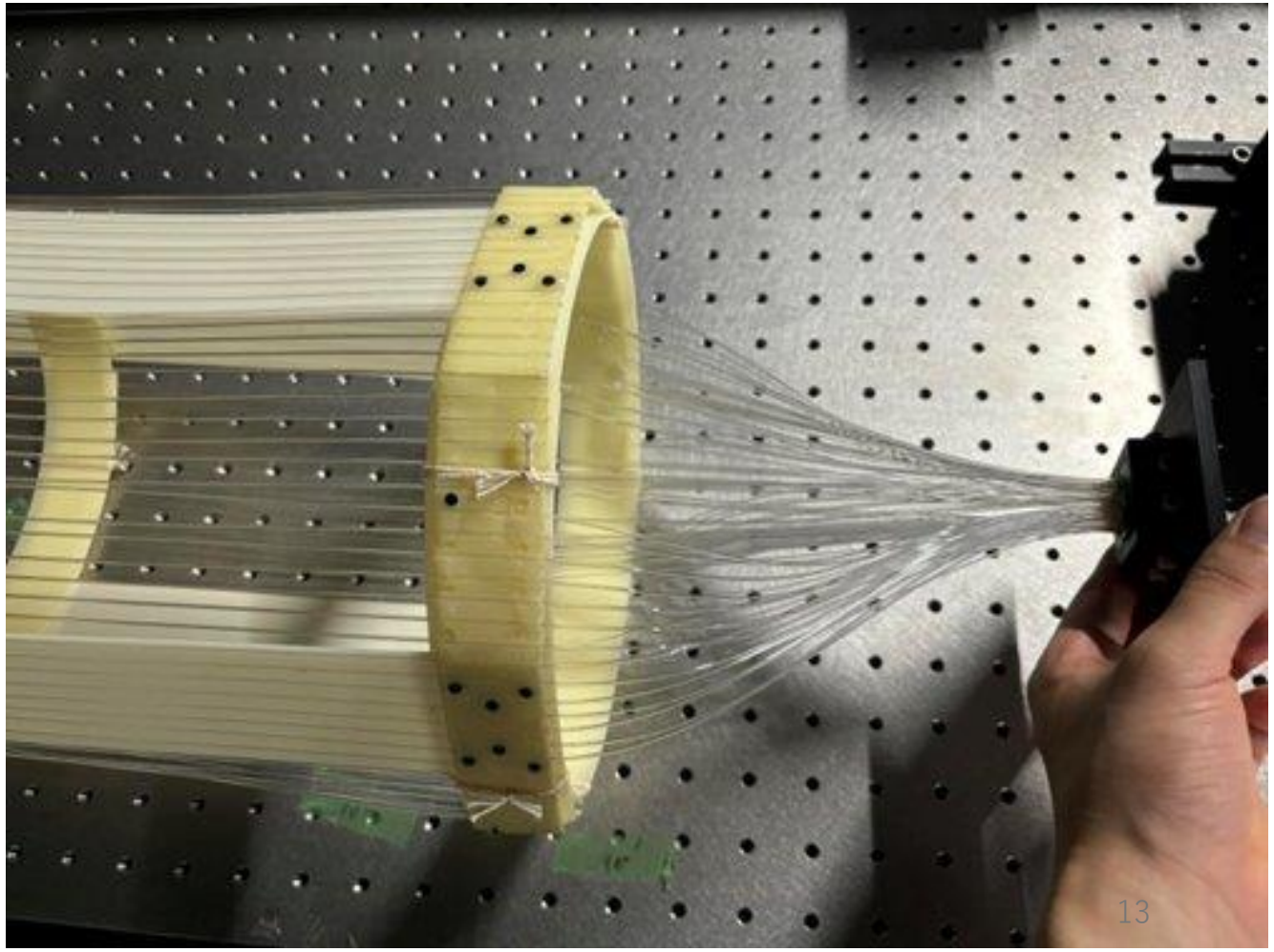






Breakage at the bundled end

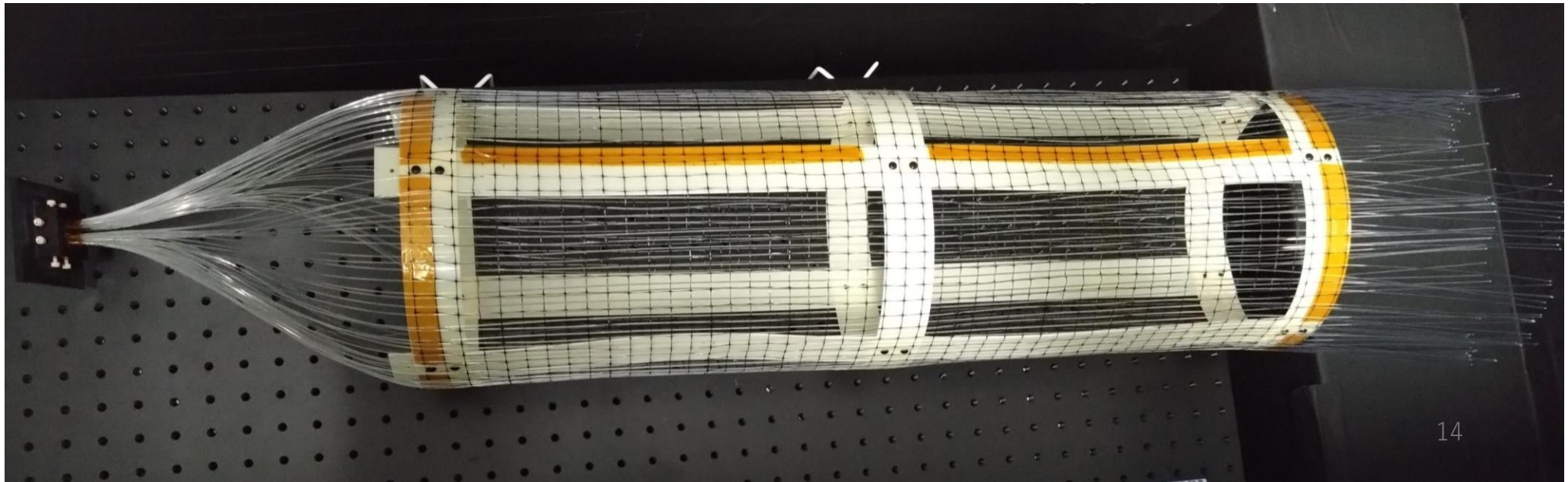
- The fibers were glued to thin plastic ribs. Many fibers snapped, due to uneven tension at the curved and bundled parts
- Lessons learned:
  - Rigid bonding ---> no compliance at bends
  - Strain mismatch along curvature ---> local over-strain



13

FOM 2nd Prototype

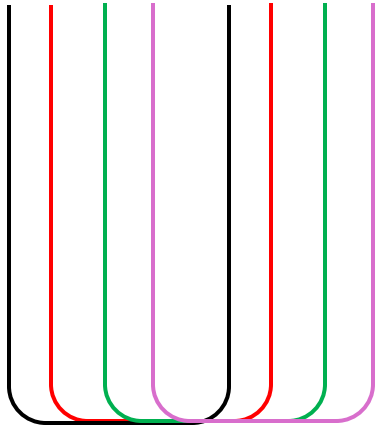
- No glue.
- Fibers kept parallel and stitched through a fine wire mesh (over-under).
- Maintains spacing while allowing flexibility → mitigates tension and fiber breakage.
- 1.2m, single ended



14

Next Prototype plan

- Use longer fibers and fold into U-shapes.
- Lay U-bent fibers side by side ---> forms one sheet, then roll into a cylinder.
- Bring both ends to one side ---> collect light from both directions with single PMT
- 1 mm × 4 m fibers, folded in half; 250 loops → 500 legs.
- Support structure TBD



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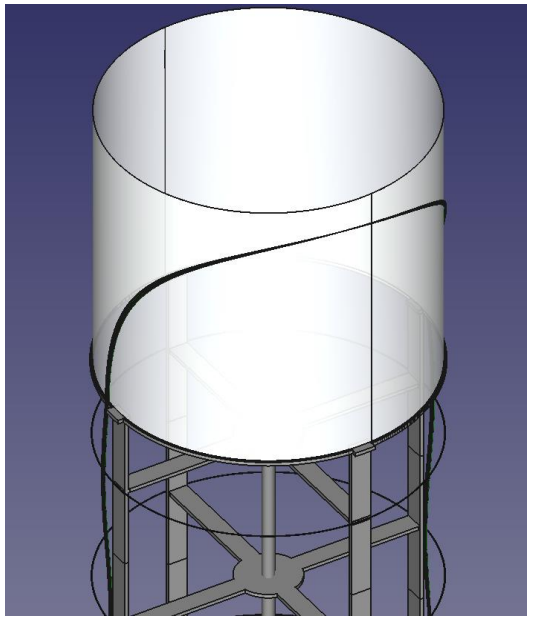

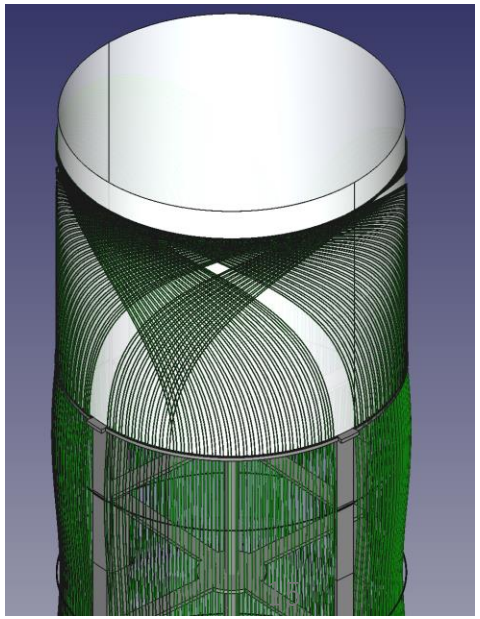

Summary and Plans

- FOM: Fiber optical module
- Comparable effective area of the OM with ~250 4m fibers
  - Need a polar PMT for Gen-2
- Plans
  - Fiber attenuation measurements at low temperature, and bent – this year
  - Freeze-in test: fiber bundle submerged in water and frozen – next year (2026)
  - Fabrication of the next prototype in 1H 2026