Status and performance of mass-produced IceCube Upgrade mDOMs

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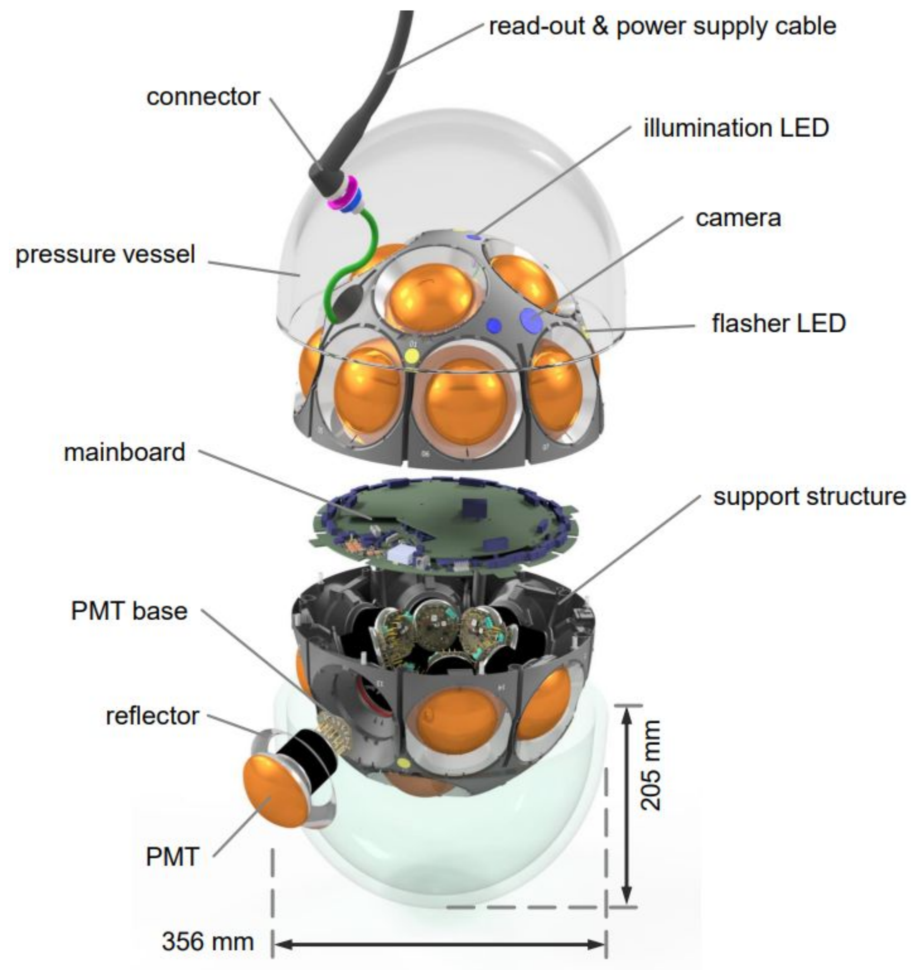
The IceCube Upgrade

- **New optical modules** on 7 strings to be deployed densely in the IceCube central region
- Includes **~400 multi-PMT Digital Optical Modules** (**mDOMs)** [1]
  - developed jointly by DESY, KIT and the German IceCube university groups
  - **~230/~200** produced at DESY Zeuthen/Michigan State University (MSU)
- **Science goals:**
  - precise neutrino oscillation measurements / GeV neutrino transient searches [2,3]
  - re-analysis of archival data with reduced uncertainty on the ice properties

mDOM Design

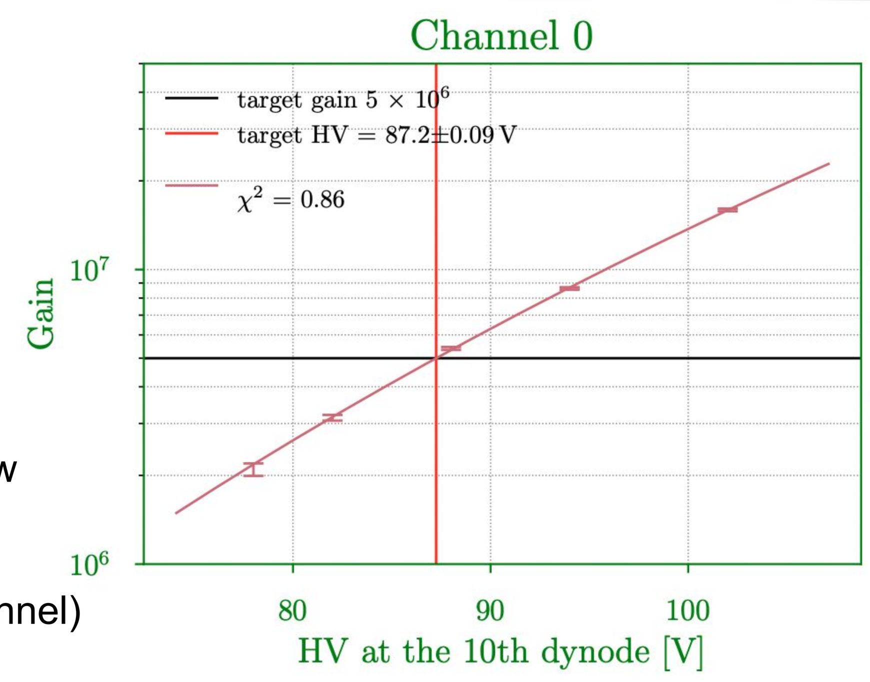
- **24 three-inch photomultiplier tubes (PMTs)**
- 10 calibration LEDs and 3 cameras
- Electronics mainboard
- 3D printed support structure
- Borosilicate glass pressure vessel
- Optical gel between structure and vessel

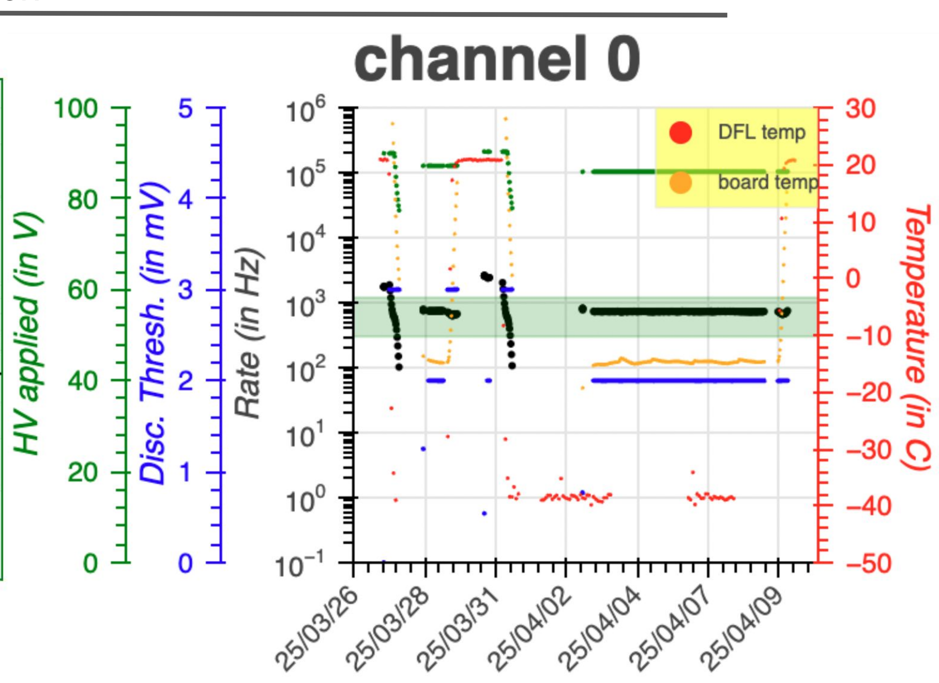


credit: S.Niedworok

Production/Testing/Evaluation Status

- **All the ~430 mDOMs have been produced.**
- **Testing have been done on most of the modules** at two setups [4]
  - one setup mainly for tests at -40°C and the other setup using a UV laser
- **Evaluation has been complete at DESY, majority done at MSU**
  - all the measurements are compiled into **pdf / interactive plots** to facilitate review
  - results evaluated by at least two experts
  - strict requirement for PASS modules (allow up to only 1 PMT malfunctioning channel)
  - **194 PASS modules from DESY**, the rest being reviewed as of June 2025





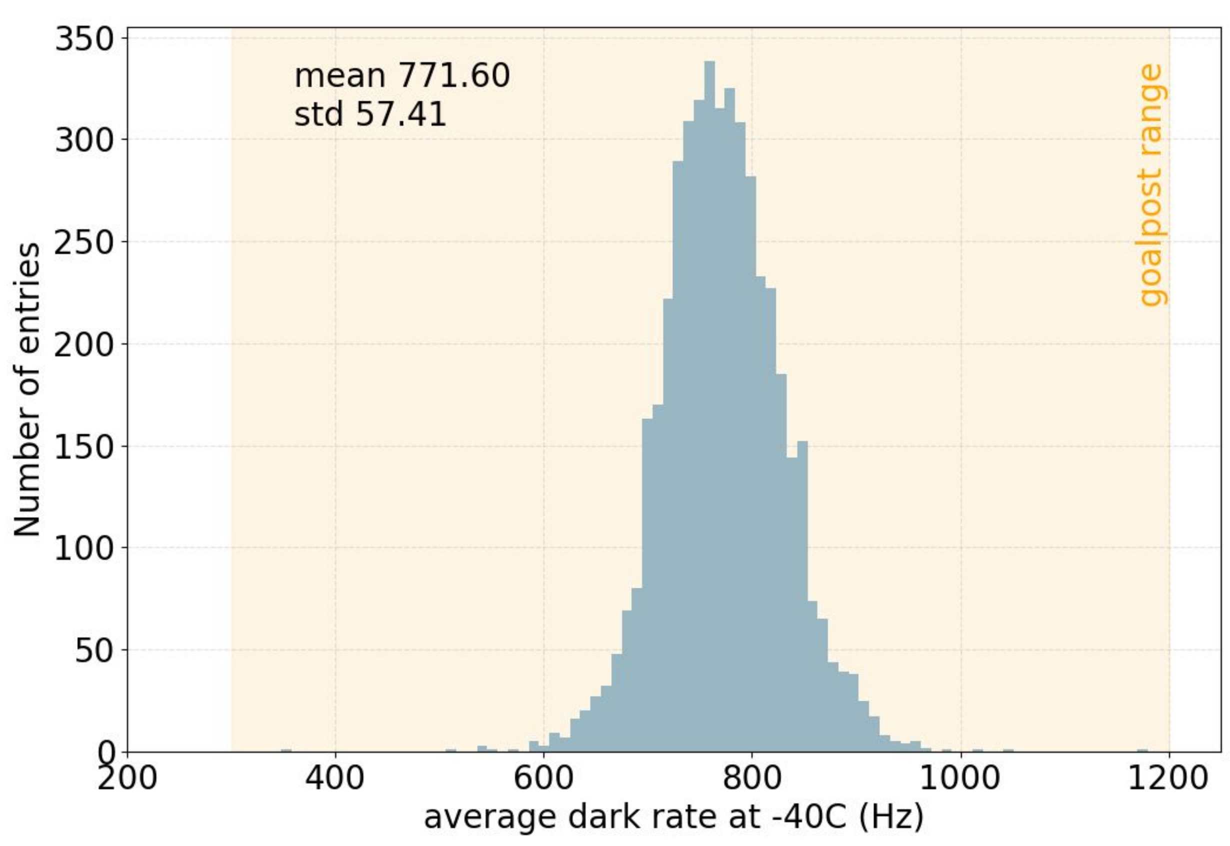
example snapshot of summary PDF / interactive plot (html)

Testing Results

Key parameter distributions for 194 mDOMs that passed our criteria

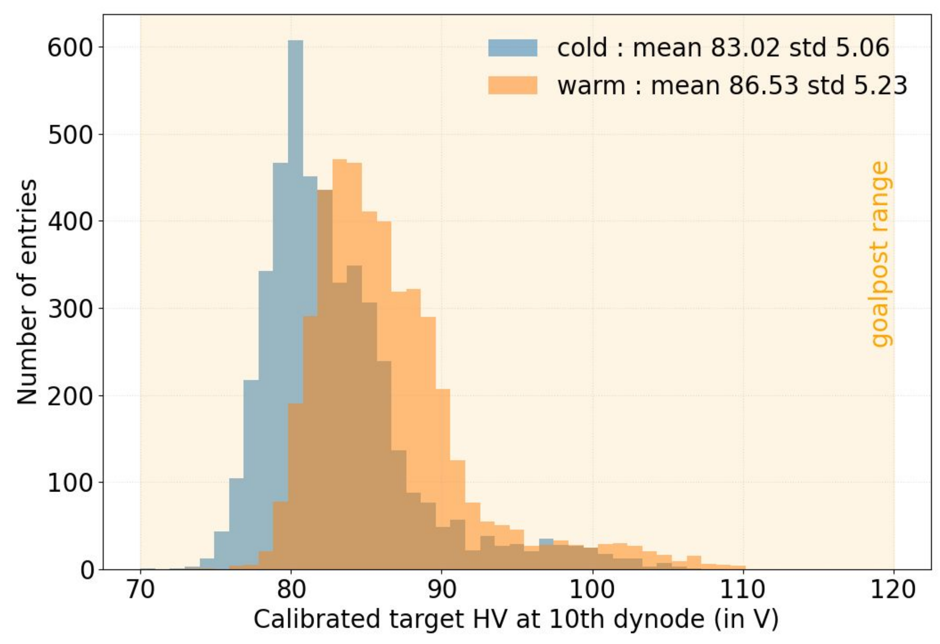
Dark Rate

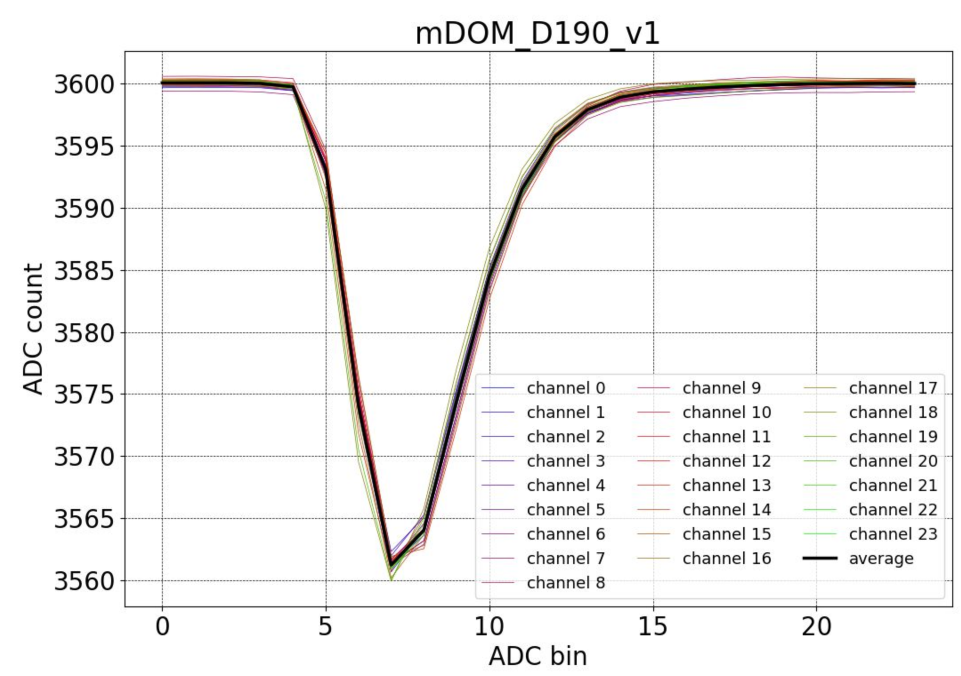
- 5-10 days dark rate monitoring at -40°C
  - calibrated voltage applied to PMTs
  - fixed discriminator threshold ~0.4 P.E.
- **Most modules have stable dark rates ~800 Hz**
  - mostly due to radioactive decays inside either the PMT or the pressure vessel
  - dark rates should be lower in the ice (testing done in the air)
  - only ~10-20 malfunctioning PMT channels, not shown in the plot (as well as plots on the right)



Calibrated PMT Voltage

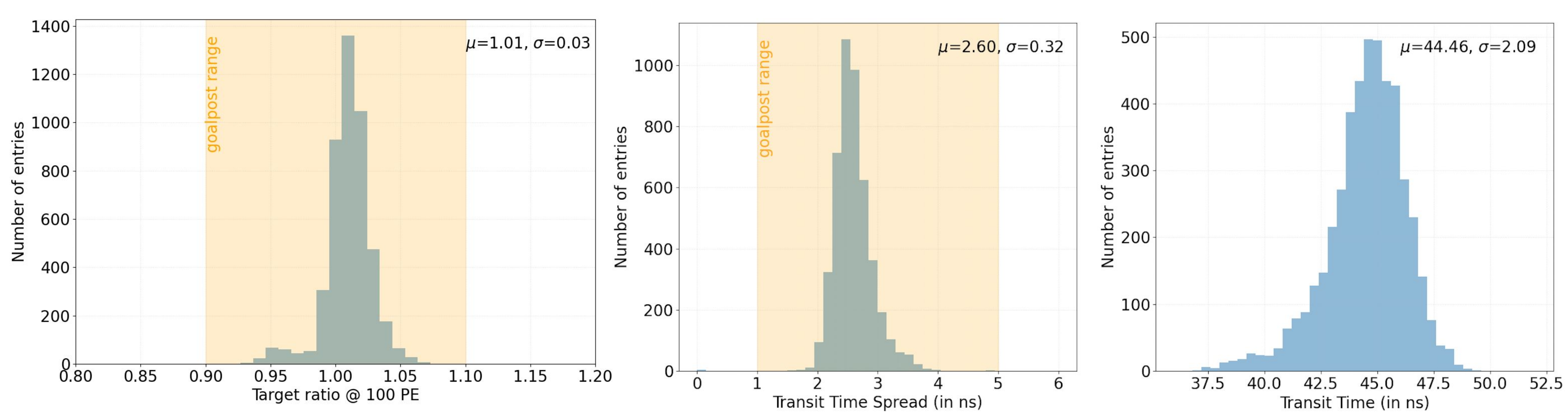
- PMT voltage calibration to set the nominal gain 5e6 at +20°C and -40°C
  - calibration LEDs adjusted to single-PE level
- **Calibrated voltages are well distributed within the expected range**
  - 75-110 V at the 10th dynode (1/12 of the total applied voltage)
  - digitized PMT signal waveforms (integrated for charge estimate in this test) expected as well





Linearity and Transit Time

- Linearity at 100 P.E. and Transit Time (Spread) measured using the laser setup at room temperature
- **The measured values are within the expected range for most of the modules**



Shipment and Deployment Schedule

- After the evaluation, mDOMs are attached with metal ropes and go through the load-tolerance test before shipment
- **128 mDOMs were shipped from DESY to the South Pole in summer 2024**
  - They have arrived onsite and passed the final acceptance test
- **All the rest will be shipped by August 2025**
- **All the mDOMs will be deployed in ice during Antarctic summer season 2025/2026 with other Upgrade modules**

credit : Colton Hill

[1] The IceCube Collaboration, L. Classen et al., *Pos* **ICRC2021** (2021) 1070

[2] The IceCube Collaboration, A. Ishihara, *Pos* **ICRC2019** (2019) 1031

[3] Partenheimer et al, *ApJ* **982** (2025) 94

[4] The IceCube Collaboration, *Pos* **ICRC2023** (2023) 1183