Photosensor Development for the IceCube Upgrade

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Data is collected here and sent by satellite to the data warehouse at UW-Madison

1450 m

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

2450 m

IceCube detector
86 strings of DOMs, set 125 meters apart

DeepCore

Antarctic bedrock

IceTop

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

60 DOMs on each string

DOMs are 17 meters apart
• 10” Hamamatsu PMT (super-bialkali in DeepCore)

• Onboard capture of PMT waveforms
  • Two sets of digitizers operating in ping-pong mode
  • 300 MSPS x 400 ns: custom ATWD chip
  • 40 MSPS x 6.4 µsec with fADC
  • Dead time < 1%
    • Dynamic range ~1000 p.e./10 ns

• Absolute timing < 2 ns RMS

• Noise rate ~600 Hz (underlying Poisson rate 260 Hz)
Next Step: the IceCube Upgrade

- Seven new strings of multi-PMT mDOMs in the DeepCore region
  - Inter-string spacing of ~22 m
- Suite of new calibration devices to reduce detector-related systematics
- R&D for IceCube Gen2
- Technical constraints:
  - Radius (drill time)
  - Power (target <4 W/chan)
Form & Function

- Densely instrumented neutrino physics region within DeepCore
- Calibration light sources and detectors embedded in physics region and in deeper and shallower ice
  - Measure properties of “bulk” (undisturbed) and “hole” ice around DOMs
- R&D devices taking advantage of available connections
IceCube Upgrade Optical Sensors

1600 m: calibration

PDOM: 1 x 10" PMT

2150 m: neutrino physics

MDOM: 24 x 3" PMT

2425 m: deep ice

D-Egg: 2 x 8" PMT

2600 m
Updated IceCube DOM (pDOM)

IceCube DOM with revised electronics: commercial 250 MSPS ADC and modern FPGAs for data buffering and compression

Primarily for cross-calibration
Double-PMT Digital Optical Module (DEgg)

- Evolutionary design from the Chiba University group
- Two 8” Hamamatsu high-QE PMTs in elongated pressure vessel
  - Roughly 2x the effective photon collection area of an IceCube DOM (wavelength dependent)
- Common electronics with pDOM
- Available volume for calibration devices, etc.
Multi-PMT Digital Optical Module (mDOM)

- 24 x 3” PMTs in a 14” DOM with independent readouts
  - KM3NeT-inspired, implemented in Germany
  - 2.2x the photocathode area of IceCube DOMs
  - Segmentation provides directional information for detected photons

- Onboard LEDs
  - Ice and hole calibration
  - Ability to mimic tau events
mDOM Readout

- Off-the-shelf circuits, readout power 3.4 W (plus comms, management)

- Continuously running, no wake-up, no dead time

- Recorded data:
  - 12-bit continuous waveform at 100 MSPS
  - Leading edge time resolution of ~1 ns
  - Exploit low-amplitude physics target to reduce power requirement

PMT signal

ADCMP600

Sampling @ ~1 GHz

Sampling @ 100 MHz (can switch to 125 MHz in FW if needed)

FPGA

Front-End (24x, 6x 4-ch. ADC)
mDOM Circuit Board Design

- 24 analog channels
- "noisy" sector
- FPGA
- USB_1
- USB_2
- Flasher-ctrl
- HV-ctrl
- ADC
- DCDC prim.
- DCDC sec.
- PCB fixing
- Axels chan.
- conn. HV-ctrl
- PMT signal
- empty chan.
- cable notch
- prim. DCDC
- sec. DCDC

B-B (1:2)
R&D: Wavelength Shifting Optical Module (WOM)

Measurement setup

- Quartz glass cylinder ($\text{Ø} 11 \text{ cm}, L=113 \text{ cm}$)
- Wavelength-shifting tube inside
- UV absorbed and re-emitted as optical light
- Light collection via total internal reflection

Advantages:

- Large effective area
- Low noise (<75 Hz/PMT)
- Cost effective

Two small (e.g. 3”) PMTs reading out a WLS-coated tube: 45% opt. eff.
R&D: Fiber Optical Module (FOM)

- Bare WLS fibers channel photons to a single small PMT (double-ended readout also possible)
  - Light collection with fibers (~$2/m for 1 mm), cheaper than large PMTs
  - No absorptive glass surrounding the main light collector – more UV collection
  - Easy to transport, deploy in narrow hole

- Many fibers required for reasonable collection area, but could provide quasi-continuous sensitivity

- Reduced timing precision (like WOM)