IceCube-Gen2
Technical developments

J.P. Yanez for the **IceCube-Gen2 Collaboration**
NNN workshop
Beijing, November 2016
The IceCube-Gen2 facility
A wide band neutrino observatory

- Optical, radio & surface veto
- MeV to EeV $\nu$ detection range $\rightarrow$ supernovae ... astrophysical
- Requires additional 13k to 15k optical modules
IceCube Digital Optical Module

NIM A 601 (2009) 294
IceCube Digital Optical Module

» IceCube DOM

» Single, large (10") PMT per module
» Full waveform digitization
» Glass transmissivity of 0.5 at ~350 nm
» Calibration LEDs on-board
» Power consumption ~3W
» Discriminator
» Local coincidence logic for readout
» Delay line: 75ns
» Redundant digitizers

» Photon counting capabilities to high charge (1-thousands pe)
» Withstand > 550 bar freeze-in pressure
» Survive shock vibration
» Gel cushioning for optical coupling, electronics
IceCube Digital Optical Module

**IceCube DOM**

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- Calibration LEDs on-board
- Power consumption ~3W

**Keep**

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- Withstand > 550 bar freeze-in pressure
- Survive shock vibration
- Gel cushioning for optical coupling, electronics

**Improve**

- Discriminator
- Local coincidence logic for readout
- Delay line: 75ns
- Redundant digitizers

**Get rid of**

-...
IceCube Digital Optical Module

Gen2 wish list

- Simpler, cleaner electronics
- Segmented modules, more but smaller PMTs
- Uniform angular coverage
- Directional information from single modules
- Dynamic digitization scheme
- Lower photon wavelength threshold
- Better understood LEDs
- Reduce power consumption to ~1W per OM
- Photon counting capabilities to high charge (1-thousands pe)
- Withstand > 550 bar freeze-in pressure
- Survive shock vibration
- Gel cushioning for optical coupling, electronics

Consider designs which improve these points
IceCube-Gen2 modules
Design of new sensors - Baseline

» Same performance, simpler design
» Mechanical design tested, reliable
» Performance in-situ well understood

IceCube DOM

Gen2 DOM

KEY:
Component identical
Component eliminated
Component redesigned
Design of new sensors - D-Egg

- 2x8” PMTs – Up/down = 12” diameter
- Strain measurement @ 700bar
- Towards uniform acceptance
- Self-veto potential
- Benefits from glass + higher QE
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*Transmittance cutoff of the D-Egg glass appears to be very sensitive to impurities*
Design of new sensors - mDOM

- Adapted from KM3NeT mDOM
- 24 x 3-inch PMTs
- Diameter 14 inch = 355 mm
- Pressure rating 700 bar
- 3D printed PMT holding structure
- $4\pi$ angular coverage
- Reflectors
- Main challenge: power for sampling complex waveforms
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Glass of mDOM and D-Egg becoming comparable

*Transmittance cutoff of the D-Egg glass appears to be very sensitive to impurities*
Design of new sensors - WOM

» Wavelength-shifter optical module

» Custom paint shifts light from UV (250-400nm) to blue (>400nm)

» Light captured travels in tube

» 2 small (1.5”) PMTs at the ends

» Low threshold

» Directionality lost
Design of new sensors - WOM

» Wavelength-shifter optical module
» Custom paint shifts light from UV (250-400nm) to blue (>400nm)
» Light captured travels in tube
» 2 small (1.5”) PMTs at the ends
» Low threshold
» Directionality lost

Initial attempt to assemble a prototype for noise measurements
Design of new sensors - LOM

» Wavelength-shifter optical module
» Move UV (250-400nm) to blue (>400nm)
» Multiple PMTs inside the tube
» Keep directional information
» Acceptance higher at horizon
Summary of new sensors

- **mDOM**
  - 36 cm
  - Directional information
  - More sensitive area per module
  - Precise timing

- **D-Egg**
  - 30 cm
  - Directional information
  - More sensitive area per module
  - Smaller geometry

- **WOM**
  - ~26 cm
  - More sensitive area per module
  - Small diameter
  - Lower noise rate
  - Lower UV threshold

- **LOM**
  - 13 cm
  - Small diameter
  - Directional info.
  - More area per module

PoS(ICRC2015)1147
PoS(ICRC2015)1137
PoS(ICRC2015)1134
Readout schemes

ADC

» Measure amplitude at fixed times
  » Conventional approach, used in IceCube
  » Power consumption too high for multiple PMTs

Leading edge time and time-over-threshold*

» Measure at a fixed amplitude
  » Low power, no current flow below threshold
  » Need multiple thresholds/discriminators

*Readout scheme designed for mDOM, but the idea is applicable to all modules
Readout block diagram

Time-stamping of leading and trailing edge time in FPGA

From T. Karg
Discriminators

» Multi-comparator design

» Pseudo-digital comparator output from base to mainboard

» Time-stamping of leading- and trailing- edge in FPGA

» Two-fold strategy
  » ASIC design: 63 comparators w/6-bit encoder
  » Four comparator discrete design

» Output: pseudo-digital signal

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Readout chain

3 main blocks:
- Front-end with 4 comparators
- Transmission of data
- Processing in a single FPGA

PM signal

channel 1
- Adjustable
  - 5mV
  - 10mV
  - 20mV
  - 50mV
- Comp A
- Comp B
- Comp C
- Comp D

channel 2 to channel 24

Cyclone 5 FPGA

Sampling @600MHz
Parallel processing @150MHz

SERDES 1:4
- 8 bit
- 4 bit
- 4 bit
- 4 bit

From T.Karg
Readout chain

3 main blocks: front-end with 4 comparators

PM signal

Transmission of data

Processing in a single FPGA

Channel 1

Channel 2 to channel 24

On PMT base

From T.Karg
Readout chain

3 main blocks:
- front-end with 4 comparators
- transmission of data
- processing in a single FPGA

PM signal →

<table>
<thead>
<tr>
<th>channel 1</th>
<th>adjustable</th>
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<tbody>
<tr>
<td>5mV</td>
<td>comp A</td>
</tr>
<tr>
<td>10mV</td>
<td>comp B</td>
</tr>
<tr>
<td>20mV</td>
<td>comp C</td>
</tr>
<tr>
<td>50mV</td>
<td>comp D</td>
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</tbody>
</table>

channel 2 to channel 24

Cyclone 5 FPGA

sampling @600MHz
parallel processing @150MHz

SERDES 1:4 → 8 bit
SERDES 1:4 → 4 bit
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From T.Karg
Readout chain

From T.Karg

readout PC
Pulse reconstruction example

Example pulse reconstruction (63 discriminators)

From A. Kappes
Pulse reconstruction example

From A. Kappes
IceCube-Gen2 schedule

Proposed Gen2 Phase 1 activity (7 strings)

Today

R&D

Design

Production

Deployment

Surface air shower

Phase 1 deployment
Conclusions

» IceCube-Gen2 science can benefit from new optical sensors
  » Baseline: IceCube revamped
  » New designs and adaptations under study

» Mechanical & partial prototypes built
  » Characterization of properties underway
  » Functional devices expected within a year

» Simulation, reconstruction with new modules ongoing

» Promising low-power readout for mDOM developed
  » No physics losses, applicable to other modules
Backup slides
## mDOM PMT Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTS (FWHM)</td>
<td>&lt; 4 ns</td>
</tr>
<tr>
<td>QE @ 470 nm</td>
<td>22%</td>
</tr>
<tr>
<td>QE @ 404 nm</td>
<td>27%</td>
</tr>
<tr>
<td>dark rate @ 20°C</td>
<td>400 – 1500 Hz</td>
</tr>
<tr>
<td>dark rate @ -30°C</td>
<td>&lt; 100 Hz</td>
</tr>
<tr>
<td>supply voltage</td>
<td>&lt; 1400 V</td>
</tr>
<tr>
<td>gain</td>
<td>$3 \times 10^6$</td>
</tr>
<tr>
<td>peak-to-valley ratio</td>
<td>&gt; 3.5</td>
</tr>
</tbody>
</table>

*Based on KM3NeT spec's / measurements*
mDOM effective area

θ = 0°

θ = 180°

310 nm

320 nm

470 nm

380 nm

mean effective area [cm²]

effective area [cm²]

wavelength [nm]