DESIGN, PRODUCTION, AND FIRST RESULTS FROM THE ICECUBE DIGITAL OPTICAL MODULE

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The first string of IceCube - a kilometer-scale, high energy neutrino detector - was deployed in January this year deep in the Antarctic ice. At completion, IceCube will consist of at least 70 strings each with 60 Digital Optical Modules (DOMs) and a surface array of 280 DOMs. 2004 was the first year of real production and testing of these DOMs: 400 DOMs were produced in the US, Sweden and Germany. A series of tests such as basic functionality, phototube dark noise, optical sensitivity, linearity, time resolution, and high voltage tests were performed in special Dark Freezer Laboratories at temperatures ranging from +25 °C to -55 °C. 280 DOMs were sent to the South Pole for deployment and tested there again prior to deployment. Now frozen in the ice, the DOMs are showing exceptionally promising functionality. Here DOM production and testing procedures and corresponding results are discussed and data from the first in-ice string are presented.

1. Physics Motivation

The main goal of the IceCube experiment is to reach an understanding of the origin of high-energy cosmic rays as well as to test a fundamental lows of physics. Low fluxes of HE neutrinos require kilometer-scale detector volumes to provide information about the sources of these particles with reasonable statistics. IceCube is designed to search for sources of high-energy neutrinos such as Active Galactic Nuclei (AGN), Supernova Remnants (SNR), microquasars or Gamma Ray Bursts (GRB). The sensitivity of IceCube to astroparticle sources is discussed in Ref.[1]. Due to low ambient noise in the ice, IceCube has the opportunity to detect low-energy (MeV) neutrinos from supernovae of your galaxy. In addition to high-energy astronomy IceCube physics extends to the field of particle

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physics by searching for neutrinos from possible cold dark matter candidates, weakly interacting massive particles (WIMPs), magnetic monopoles etc.[2,3]

2. The IceCube Detector

IceCube is a kilometer-scale, high energy neutrino observatory located at the South Pole in Antarctica (Fig. 1). The construction of the detector has started in January 2005 and at completion it will consist of two sub-detectors made of more than 4200 optical modules[5]. The in-ice part includes up to 70 strings mounted at depths of 1450 to 2450 m in the ice. Strings are regularly distributed 125 m apart. Each of them carries 60 optical sensors vertically spaced by 17 m. Above the in-ice part of the detector an air shower array IceTop is located at the surface. IceTop modules are being build on top of in-ice part at the surface. IceTop consists of 160 stations (2 modules each) and covers an area of 1 km^2. These two sub-detectors can be used either in anti-coincidence mode where IceTop provide a veto for down-going muons (main background for IceCube) or in coincidence mode synthesizing information on chemical composition of cosmic rays for energies up to 10^{18} eV. It also can be used for detector cross-calibration. The detector will provide an effective detection area of 1 km^2 for upward-going muons in the TeV range. Above 100 TeV detection of down-going neutrinos (*i.e.* observation of the southern hemisphere) will be possible. The effective area for PeV muons is above 0.6 km^2 and increases towards the horizon.

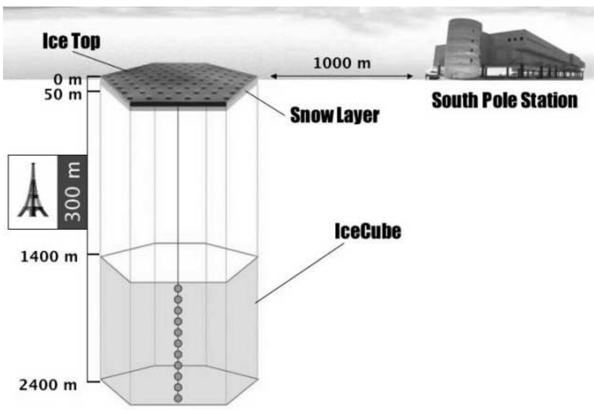

Figure 1. The IceCube detector at the South Pole.

3. Digital Optical Module (DOM)

3.1. *DOM Design*

The Digital Optical Module (DOM) (Fig. 2) is the most important component of the IceCube detector. The main principle of the DOM is a combination of large area photo multiplier coupled with support electronics for PMT power and digitization of the PMT anode pulses. PMT signals are digitized inside the DOM and get a global time stamp with a precision of better than 5 ns. This is a key concept for IceCube as it overcomes many problems associated with analog signal transmission over long distances, up to 3.5 km in the case of the IceCube detector array. DOM technology as well as the installation procedure of IceCube are built on the wealth of experience gained with its smaller prototype - the AMANDA detector[4].

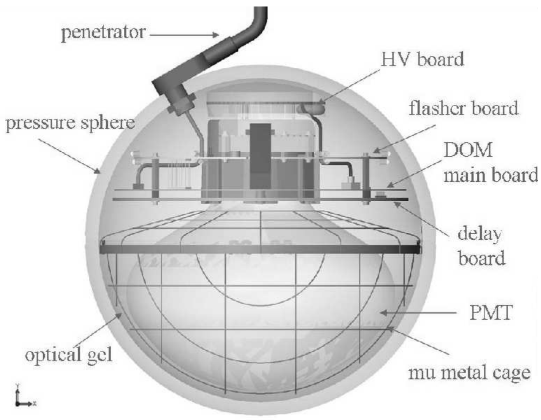

Figure 2. The IceCube Digital Optical Module components.

For IceCube the Hamamatsu R7081-02 photomultiplier tube (PMT) has been chosen. It has low noise (200-300 cps @ -40 °C) and high gain as well as fast PMT pulse risetimes (4 ns). PMT high voltage bias is supplied by a HV generator board that is mounted on the PCB stack around the PMT's neck. It produces voltage from 0 up to +2048 V controllable from the surface. The divider circuit is a high impedance (130 $M\Omega$) resistive bleeder (I_{bias} = 10 μA nom) with a toroidal transformer at the anode signal output to block the DC high voltage of the PMT. The phototube and electronic is potted into the glass pressure sphere using a clear RTV gel. Gel holds the PMT providing a good optical coupling and mechanical support. The magnetic metal cage shields the terrestrial magnetic field to improve photoelectron collection efficiency.

Each DOM contains 12 individually selectable LED's installed on a DOM flasher board. This is a powerful tool to obtain optical properties of the surrounding ice and geometrical calibration information. One LED is capable to emit 10^{10} photons per pulse. This light can be detected by modules located few hundred meters away.

3.2. *The Data Acquisition System (DAQ)*

The core of the IceCube data acquisition system (DAQ) is the DOM Mainboard. Mounted inside the DOM affixed to the neck of the PMT, it contains the electronic circuits for controll, readout, digitizing, processing, and buffering of PMT signals (Fig. 3).

The PMT signals are fed to the front end electronics where they are split into two paths: one travels directly to a trigger discriminator system which can start the acquisition when the pulse height exceeds a programmable level; the other path is delayed and then is further branched into several independent waveform capture channels. Two parallel Analog Transient Waveform Digitizer (ATWD) chips capture fast waveforms with 10-bit resolution and with sampling speeds programmable from 250 MHz to 1 GHz. Each ATWD has 4 input channels. Three of them are used with different gain paths, $16\times$, $2\times$, and $0.25\times$ resulting in a large dynamic range and giving an effective resolution of 14 bits. The fourth channel is used for monitoring and calibration purposes. A 40 MHz, 10-bit flash ADC digitizes slow waveforms from distant high-energy events which are spread out over timescales of microseconds by scattering in the ice.

Digitization is controlled by the Altera Excalibur FPGA and a hardcore ARM CPU on a single die. The FPGA provides the real-time interfacing to the digitizers, various on-board electrical and optical calibration devices, flasher board, and the communications DACs and ADCs. Waveform signal processing is also done in firmware. The CPU executes application codes such as DOM self-test and self-calibration applications and data acquisition programs that buffer the waveform data from the digitizers, packages it with time stamps from the local oscillator and other local state information, and send the data packets to the surface DAQ. System software can be downloaded to the DOM at any time before and after modules are deployed in the ice.

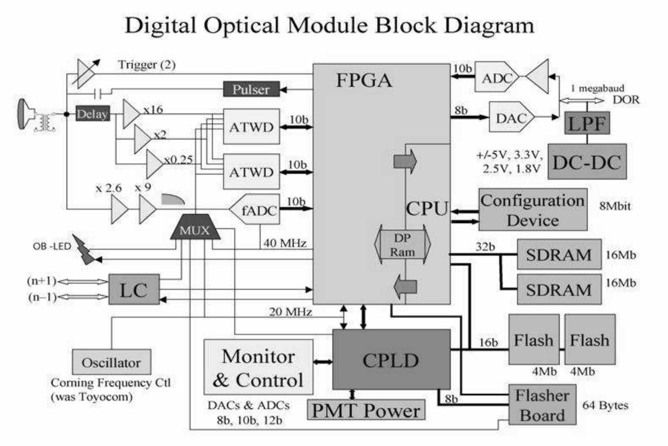

Figure 3. DOM Block Diagramm.

3.3. *DOM Integration*

DOM assembling is supported at 3 institutions of the IceCube collaboration: UW - Madison (USA), DESY (Germany), Stockholm University (Sweden) and each production site is provided by all necessary DOM components. The procedure of DOM integration requires special equipment and includes several steps:

(1) A molded plastic collar is attached to the PMT neck to provide a base for electronics installation.
(2) The HV divider is soldered onto the PMT flying leads.
(3) The phototube is placed into the lower hemisphere of the glass pressure vessel surrounded by the magnetic shield and the RTV gel, properly mixed and degassed.
(4) In 24 hours the gel is cured and all electronics components such as the delay board, mainboard, HV control board, and flasher board are installed.
(5) The penetrator cable is soldered to the mainboard.
(6) Finally the glass sphere is sealed with an internal pressure of 0.5 atm.

Those DOMs which pass the final acceptance testing are attached with a harness assembly and sent to the South Pole.

4. Final Acceptance Testing (FAT)

Before the DOMs are sent to the South Pole series of tests such as basic functionality, dark noise, optical sensitivity, PMT calibration, time resolution, and linearity are performed on all of them in the dark freezer laboratory (DFL). This is final acceptance test (FAT) lasts for about three weeks. During this time DOMs experience a temperature ranging from -55 °C to +25 °C. This proves the operativeness of the DOMs ander real in-ice conditions. Each FAT includes also a long stability test (at least 180 hours) at a temperature of -45 °C what is very close to the temperature of the antarctic ice at the depth of IceCube.

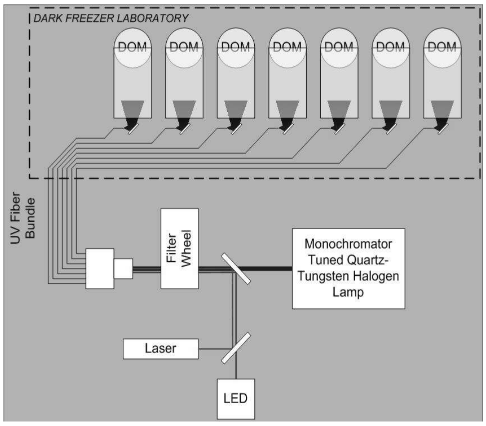

Figure 4. Dark Freezer Laboratory Setup.

DOM test stations are arranged on shelves inside the DFL. Each DOM is placed on a plastic cylinder which is foiled on the inside to reflect more light and compensate for the bias towards illuminating the center. Three light sources are used during the FAT: a 405 nm diode laser, monochromator-tuned tungsten lamp, and a fast LED pulser. Light is distributed to the station via optical fibers which are packed together into a tight bundle at the input. Light from each source is focused directly onto the ~mm-sized spot of bare fiber ends (Fig. 4). A computer-controlled filter-wheel attenuator is installed just in the front of the bundle to regulate overall intensity. At the station end, the light exiting the fiber is diffused using a holographic diffuser material to distribute light uniformly over the cylinder. The optical fiber system was designed to be invariant over the wide temperature range.

5. South Pole Deployment

During the last austral summer season the first in-ice string of IceCube was deployed. About 300 DOMs were shipped to the South Pole and tested there again prior to deployment. To drill IceCube holes an enhanced hot water drill (EHWD) was developed. Using this technology it takes slightly less than 50 hours to drill holes of 2.5km depth and 60 cm diameter in the ice. In addition 4 IceTop tanks (8 DOMs) have been installed on the surface what makes a total of 76 deployed DOMs which are functioning and producing physics data. All DOMs are operational and meet the design requirements. Obtained noise rates for in-ice modules are about 700 Hz on average. Time resolution measured with flashers is better than 2 ns. Data taking had started after the first surface tanks and the in-ice string were deployed and will continue during the detector construction. The plan for the next season is to deploy up to 10 in-ice strings and 32 IceTop stations. Continuing at a rate of 16-18 strings and 32-36 IceTop tanks per year IceCube will be completed within the next 5 years.

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References

1. J. Ahres et. al., *Astropart. Phys.* **20**, 507 (2004).
2. F. Halzen, astro-ph/0311004.
3. C.Spiering for AMANDA collaboration, Proc 27th ICRC (2001) 1242.
4. http://amanda.wisc.edu
5. J. Ahrens et. al., The IceCube Proposal to NSF (2000), J. Ahrens et. al., PDD:IceCube Conceptual Design Document (2001).