PROCEEDINGS OF SCIENCE

R&D and production of the scintillation detectors for the IceCube Surface Array Enhancement

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The IceCube Neutrino Observatory is a cubic kilometer scale detector deployed in the Antarctic ice. The surface array of IceCube, IceTop, serves as an air-shower detector for primary cosmic rays in the PeV energy range and operates as a veto and calibration detector for the astrophysical neutrino searches for the IceCube in-ice instrumentation. Enhancing IceTop with a hybrid array of scintillation detectors and radio antennas will lower the energy threshold for air-shower measurements, provide more efficient veto capabilities, enable the separation of the electromagnetic and muonic shower components, and significantly improve the detector calibration by compensating for snow accumulation.

A prototype station consisting of 3 radio antennas and 8 scintillation detectors was deployed at the South Pole in 2020, and has yielded promising results since. The production of the full surface array enhancement is ongoing. In this contribution we will focus on the status of the production and calibration methods for the scintillation panels. A brief introduction to the expected data and proposed analysis from the enhancement is also discussed.

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1. Introduction

A cubic kilometer scale observatory built at the South Pole, the IceCube Neutrino Observatory [1], comprises of an in-ice detector and an array of surface detectors called IceTop [2]. IceCube is primarily aimed at the detection and study of astrophysical neutrinos, but at the same time, the IceTop surface array provides a unique possibility for studying cosmic ray physics. The IceTop array consists of 81 pairs of ice-Cherenkov tanks (Fig. 1) which are imperative for the vetoing of down-going muons from cosmic ray air-showers into the in-ice detector and consequently its calibration. This is useful for a good understanding of the background from the atmospheric neutrinos and muons.

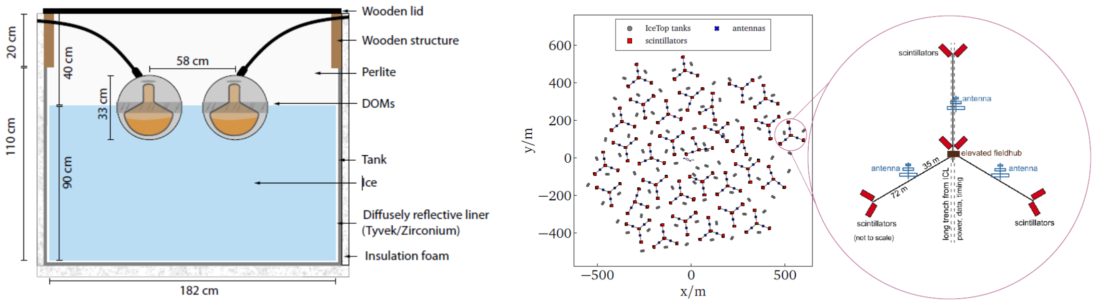

Figure 1: Left: Schematic of an IceTop Cherenkov tank. Each tank consists of two PMT detectors suspended in ice. Right: The footprint of the proposed surface enhancement. A zoom-in of one of the stations is also included to show the positioning of each component [5].

The increase in the snow accumulation on these surface detectors over time, however, results in an increase in the uncertainty in the detected signals, as well as an increase in the energy threshold for air-shower detection [3]. To study the effects of this accumulation, develop an independent mode of detection, and improve the combined cosmic-ray measurements, an enhancement of this surface array is planned. This enhancement will consist of 32 stations, each of which will include 8 scintillation detectors, 3 radio antennas and a central DAQ system [6]. This array will be deployed within the footprint of the IceTop array and is expected to be complete by 2028 (footprint shown in Fig. 1). A fully functional prototype station, following the successful run of previous prototypes at the Pole since 2018 [7], was deployed at the South Pole in January 2020 [8]. After the initial commissioning period, it has been recording air shower data and and has observed coincident events with the IceTop array [9]. In Fig. 2, An example of such an event observed by the prototype station is shown. For scintillators, the timestamp of the first panel hit is taken into account. Since the radio antennas are triggered by scintillation detectors, their trigger time is used. Finally, for IceTop data, the reconstructed time of the shower hitting the surface is used. The events coincident within 2 μs for all three sources, are considered a single coincident event.

Following the success of the prototype station, the series production for the full enhancement array is ongoing. This work will present the current status of the production, functionality tests, and pre-calibration of the scintillation detectors for the enhancement stations. Details of the radio antennas as well as the hybrid data acquisition are available in [4].

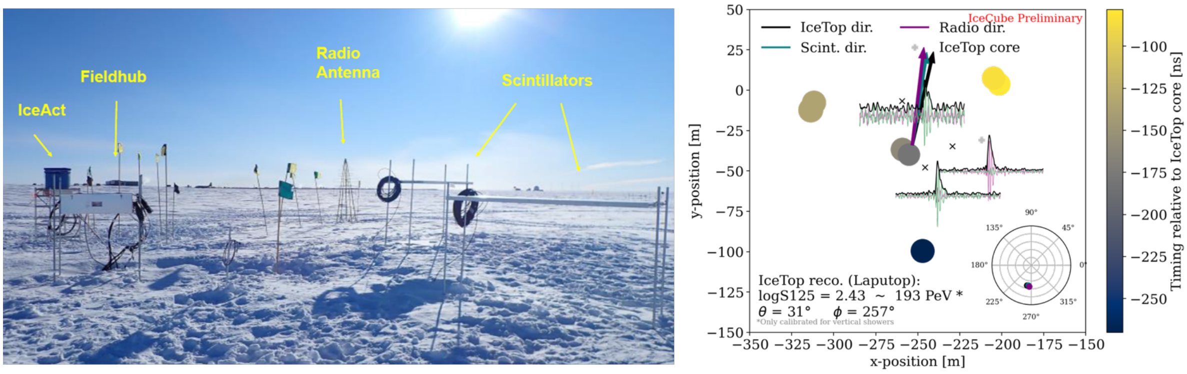

Figure 2: Left: The prototype station currently at the South Pole. Right: An air shower event observed by all three detectors, namely, scintillators, radio and IceTop [9]. The large colored circles signify the scintillator locations and the × marks the radio detectors.

2. Production and Pre-calibration

2.1 Scintillation Detector

The scintillation detectors for the surface enhancement, (Fig. 3) [10] consist of 16 plastic scintillation bars made of polystyrene (produced at FNAL) and have a sensitive area of 1.5 m^2 each. Wavelength-shifting fibers (Y-11(300) by Kuraray) are routed through two holes in the scintillation bars and glued to a silicon photomultiplier (SiPM) using a PMMA (Poly methyl methacrylate) coupler.

When an ionizing particle passes through the volume of the detector, scintillation light is produced due to its interaction with the detector volume, and is then collected by the optical fibres and transported to the SiPM. The fibres are wound such that each fibre is of the same length. A custom data acquisition board, called uDAQ [7], is used to digitize and read out these SiPM signals, following which the processed data is transferred to the central DAQ system. The central DAQ of the station consists of the TAXI board [13], the fanout board, the radioTads and the WR-LEN (for timing precision) [11]. A temperature sensor is also included next to the SiPM to account for the dependence of its sensitivity on the ambient temperatures.

Figure 3: Left: In-lay of the scintillation detectors with the optical fibres. Center: The coupling of the optical fibres to the SiPM. Right: A uDAQ connected to SiPM and the temperature sensor.

2.2 Production Chain

The series production of the scintillation detectors is a multi-step process involving many contributions. The initial step is the calibration of the SiPM. This includes the study of IV characteristics, dark spectrum and temperature experienced by the SiPM. The dark noise for all the SiPMs have been observed to be of the order of 10 mV during these preliminary measurements, which is nominal compared to the expected signals from the air shower measurements of the order of 1 V. The breakdown voltage of the SiPM is also studied, and verified with the data sheet values. This is further useful in determining the bias voltage requirements of the scintillators upon deployment.

Also in parallel, functionality tests of the uDAQ in a freezing chamber from +30°to -70° C are performed. Once the individual components are thoroughly tested, coupling of the SiPM to the PMMA coupler and preparation of the in-lay with scintillation bars and optical fibres is carried out. Following this, the uDAQ and the cabling is connected in place. Finally, the assembled in-lay is covered in a vacuum tight black foil to achieve light tightness. The detector is placed in an aluminium casing which is riveted and glued shut.

2.3 Calibration measurements

uDAQ is a microprocessor based DAQ, and has three amplification channels to obtain a wide dynamic range. The charge from the scintillator is evaluated from the shaped pulse obtained from a shaping network on the uDAQ, which is read out by a 12 bit ADC. It has two modes of measurement which can be used to calibrate and measure with the scintillation detector [11].

- Hitbuffer Measurement: In this mode, for each particle interaction, the timestamp, the charge of the pulse for all three amplifications, and whether the measured pulse was CPU-triggered or signal over threshold are recorded. A CPU-triggered pulse is also saved per second to facilitate baseline studies.
- Histogram Measurement: In this mode, the charge of the pulses is saved as a histogram in the buffer of the microprocessor, so this charge histogram is already built on uDAQ allowing longer measurement runs for calibration purposes.

The calibration tests prior to production of a scintillation detector involve two sets of five minute hitbuffer and histogram measurements. With these measurements, the interaction peak of a minimally ionizing particle (MIP peak) is determined, which is further used to calibrate the charge deposited in the detector. Additionally, a threshold scan for the detectors comprising of 110 s long hitbuffer measurements at each threshold is performed to study the baseline, account for electronic noise, and also finally determine a favorable threshold for measurements.

3. Findings and Subsequent Field Measurements

To construct the test setup for the calibration measurements of the mass-produced scintillation detectors, functionality tests were performed on the first two fully assembled detectors in 2021. A previously used scintillation detector from the 2017 station was also included as a reference detector with the updated uDAQ for readout. It was observed that the MIP peaks in these measurements for all three detectors were not significantly visible indicating background noise in the test environment. To account for this noise and validate the behavior of the detectors in different environments, a number of field tests were performed.

Low temperature measurements (at -10 and -20°C) were carried out at a freezer facility. The setup is shown in Fig 4. This was done to study the gain of the SiPM which is inversely proportional to the temperature, and can be evaluated from the distance between the single photo-electron peaks in the charge histogram. These peaks/finger spectra, are distinctly observed at negative temperatures because of the high gain. A histogram of the charge measurements is shown for each temperature in Fig 4. The finger spectrum for each measurement is also included for comparison. With these measurements, the MIP peak which was expected around 2100 ADC was still observed to be significantly suppressed. This can be explained by the location of the freezer facility in an underground stage of a concrete building, providing additional shielding to the detectors.

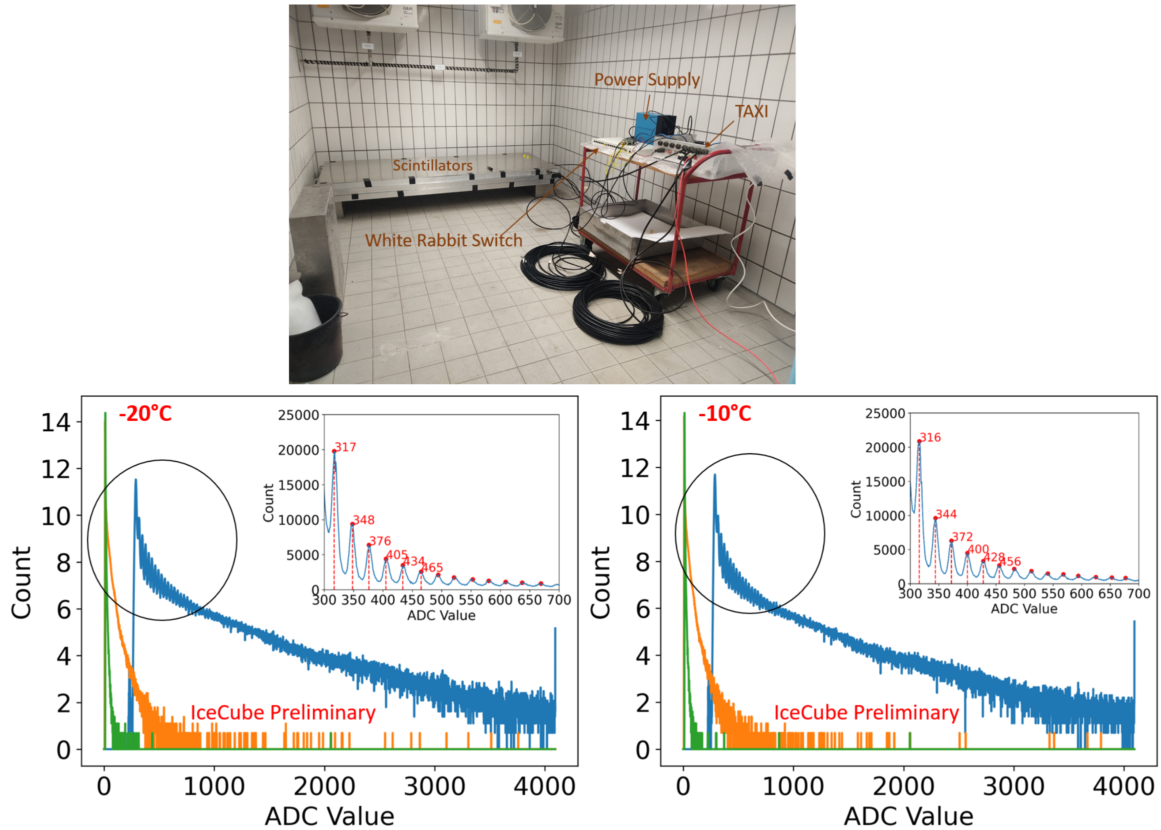

Figure 4: Top: The measurement setup for the low temperature measurements. Bottom: A histogram for the 5 minute measurement, with a focus on the finger spectra, at both temperatures. The blue, orange, and green curves correspond to high-, medium- and low-gain respectively.

A series of outdoor measurements were also conducted to investigate the effects of RFI (radio frequency interference) noise in a remote environment opposed to the laboratory. The MIP peak was observed (at 800 ADC value) to be more defined in these measurements (Fig. 5) confirming the suspicion. These field tests were instrumental in validating the functionality of the updated scintillation detectors, and determining the requirements for the test setup for the series production.

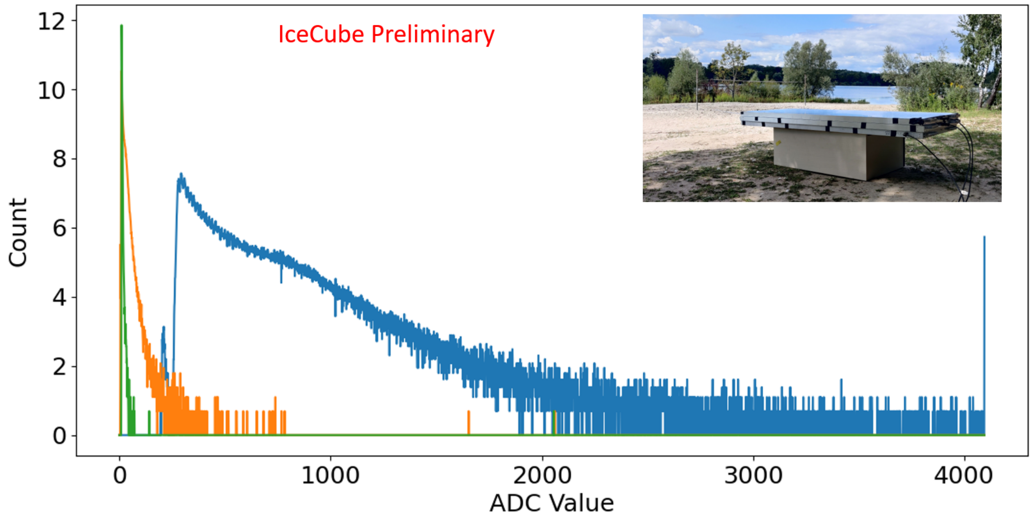

Figure 5: A histogram for the 5 minute measurement for all gains.

Parallel to the construction of the setup, a full station was tested at another freezer facility at temperatures down to -40°C. A histogram of the high-gain channel at different temperatures is shown in Fig. 6. The MIP peak shifting to a higher ADC value signifies an increase in gain. The MIP is still within the dynamic range, at -40°C, which the detectors are expected to experience at the pole. In the future, low-temperature measurements will be used to automatically adjust for the changes in temperature to stabilize the MIP-peak location.

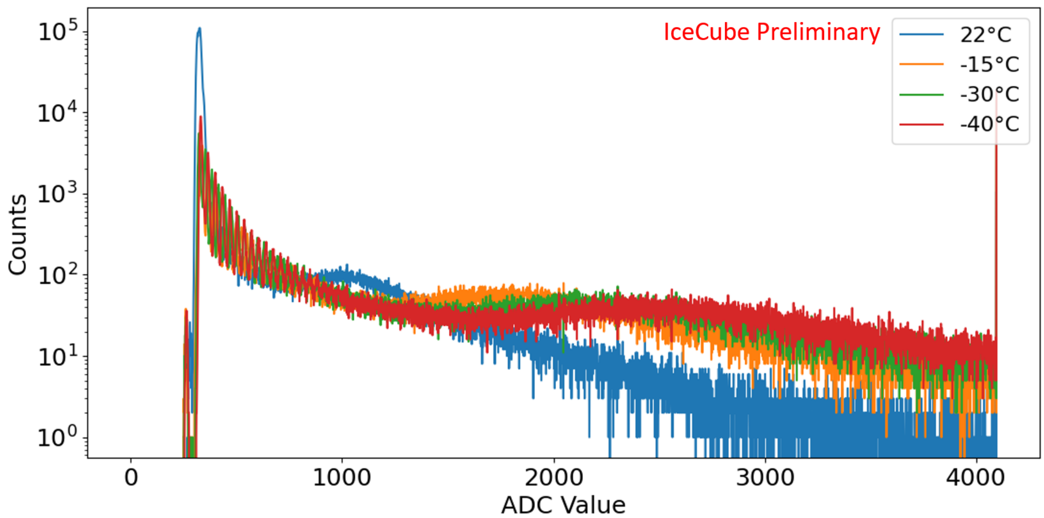

Figure 6: The multi-plot contains high-gain channel histograms for measurements performed at varied temperatures for the same panel.

3.1 Test Setup

The setup for calibrating the scintillation detectors for the surface array enhancement is placed in an all-metal wall structure. This was chosen to minimize the RFI from the surrounding building and laboratory equipment. Additionally, a shielding setup is in place to further reduce the background from natural radioactivity. A modification to the TAXI for incorporating a cooling system, which will include two automated fans on the lid are planned. This is in preparation of measurements during summer with high ambient temperatures to study the impact on the electronics at high temperatures. The complete setup is shown in Fig. 7.

Figure 7: Left: The metal walled building where the test setup is placed. Right: The setup with lead shielding bed on top and bottom. Two panels can be tested simultaneously in this set-up with a slider to position the panels.

One of the histogram measurements obtained with this setup is shown in Fig. 8. It is observed that the MIP peak becomes more distinct with the test setup indicating a significant background, expected due to natural radioactivity. The station planned to be deployed at the South Pole in the antarctic summer of 2022-23 was tested with this setup. An additional six stations are also under calibration with the setup.

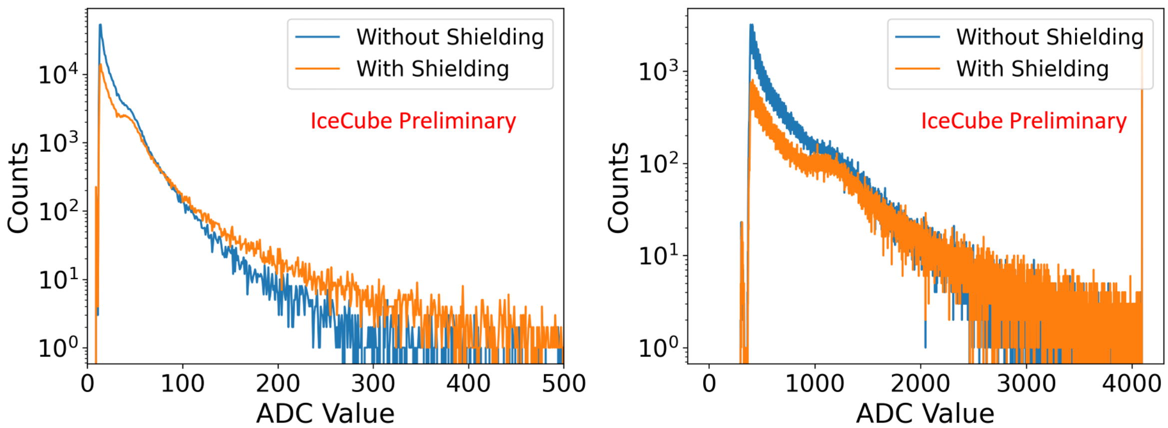

Figure 8: Left: The medium channel histogram, Right: High channel histogram. The orange curves signify measurements done without lead shielding around the scintillators. The blue curves are for the cases where shielding was used.

4. Conclusion and Outlook

The series production of the scintillation detectors for the coming deployment seasons for the surface array enhancement are ongoing. The revised detectors with an updated version of the electronics, and assembly procedure has been well tested, and is proven to be comparable in functionality to the existing prototype station. An additional six stations have been assembled and are undergoing calibration measurements. The test setup for these has been optimized and operational.

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