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Detector developments for a hybrid particle and radio array for cosmic-ray air-shower detection

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Abstract. Large-scale air-shower arrays could profit from a radio sub-detector as the radio emission in air showers is sensitive to the electromagnetic component. In particular, with an array of radio antennas in combination with particle detectors highly inclined EAS can be detected. This gives rise to new science cases, e.g. the search for PeV gamma rays coming from the Galactic Center at the South Pole, from where it is visible all over the year at an inclination of 61° degree. We report on progress and plans in the development of an optimized hybrid detector.

1. Introduction

The planned upgrade of the IceCube experiment to IceCube-Gen2 foresees a considerable extension of the in-ice detector volume [1]. With this, also the surface-detector array IceTop has to be extended to fulfill its primary goal as a veto detector regarding the search for ultra-high energy neutrinos. With an extended surface array also the detection and precise measurement of cosmic-ray air showers can be lifted up to a new level. As a first step towards a IceCube-Gen2 surface array, new detector designs and detection techniques are tested within the IceTop Enhancement. This is an upgrade of the already existing IceTop detector array with new detector prototypes of different kind [2]. Aim of the IceTop Enhancement is not only a study for the future Gen-2 surface array but also to establish IceTop as a world-leading detector for measuring cosmic rays.

A new hybrid detector consisting of a scintillation particle detector and radio detection is at the moment under development. When compared to the already existing ice-Cherenkov detectors of IceTop, scintillation detectors have several advantages like an easier and cheaper deployment. This enables a denser spacing of detectors with the effect of a lower energy threshold to detect and reconstruct cosmic-ray air shower. Exploiting also the radio signal of cosmic rays with a hybrid detector improves reconstruction accuracy of cosmic-ray events and opens whole new physics studies and science cases which will be discussed in the next section.

Regarding the scintillation detectors, a first version prototype detector has been developed and a



first station consisting of seven detectors and the associated DAQ has successfully been deployed at the South Pole in the summer season of 18/19 [2]. The radio extension is at the moment under development and the deployment of two antennas at the South Pole has been proposed for the season 18/19. The future plan for the IceTop Enhancement is a deployment of 37 detector stations consisting of 259 scintillation detectors potentially enhanced by 74 radio antennas inside the footprint of the existing IceTop detector array [3].

2. Benefits of a radio surface array at the South Pole

Radio measurements with first prototype antennas a decade ago confirmed excellent background conditions at the South Pole [4]. Meanwhile the radio technique for cosmic-ray air showers has matured, and its potential for precise measurements has been experimentally demonstrated [5, 6]. A deployment of radio antennas as part of a hybrid detector has practical advantages, such that both detectors can share a common DAQ and that the deployment infrastructure can be used for the simultaneous deployment of both detectors. Beside this practical reasons there are multiple advantages to the measurement of cosmic-ray air shower as well as to the search for neutrinos and even new science cases which can only be reached with a combination of radio and particle detectors.

The main purpose of the IceTop array is vetoing atmospheric neutrinos to support the search for galactic and extra-galactic neutrinos with the IceCube detector. Due to the sensitivity of radio to highly inclined events up to an inclination of $\Theta = 70^\circ$, the veto capabilities of the IceTop veto detector will increase with the use of radio antennas. Due to the increase of the radio footprint with inclination of the shower, inclined showers can be reconstructed successfully even if the shower core is hundreds of meters outside of the area of IceTop. Of course, this high sensitivity for inclined events is also a benefit for the search for cosmic-ray events in general and turns the IceTop detector into a high-potential cosmic-ray observatory.

With the high sensitivity for inclined shower, radio enables the search for PeV gamma rays from the galactic center which is not possible with particle detectors alone. The IceCube site has the very unique feature that the center of our Galaxy is visible all over the year in an inclination of 61° . Measurements performed with the High Energy Stereoscopic System (H.E.S.S.) telescope suggest that our Galactic Center houses a Pevatron [7]. Due to the high inclination in which the Galactic Center is seen from the IceCube site, the detection of these PeV gamma rays is only possible with a combination of radio antennas and particle detectors. An energy threshold of below 1 PeV with radio detection can be achieved by measuring in a higher frequency range of 100 - 190 MHz [8].

In addition to this, radio measurements together with particle-detector measurement and in-ice measurements of atmospheric muons will probe and improve present hadron interaction models used in air-shower simulations [3].

3. The scintillation detector and the data acquisition system

The IceCube-Gen2 Collaboration has designed, tested, and deployed a scintillation detector at the South Pole [2].

Each scintillation detector consists of 16 scintillator bars manufactured by Fermi Lab. Two



Figure 1. SKALA-2 antenna in the South-Pole design with a height of 0.3m from ground to the lowest lobe.

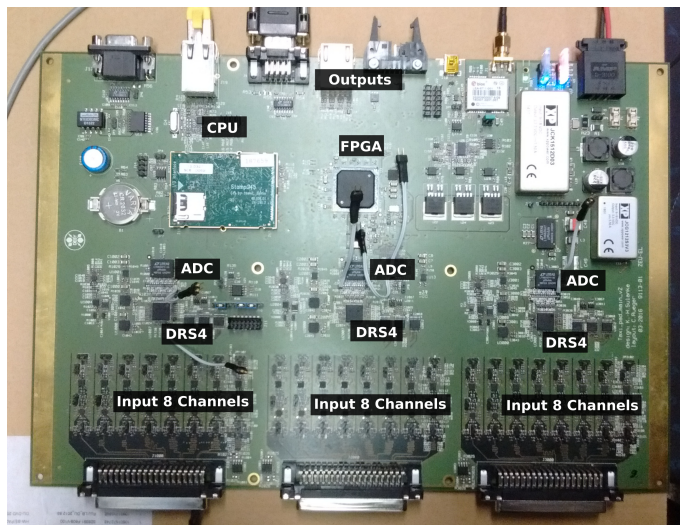


Figure 2. The IceTAXI DAQ equipped with three DRS4 sampling chips.

Wavelength shifting fibers go through each bar and return through the next but one bar back to the optical readout. All fiber ends are bundled and optically coupled to a $6 \times 6 \text{ mm}^2$ Silicon Photomultiplier *S13360-6025* from Hamamatsu [9]. The electronics inside of the detector houses the Hamamatsu SiPM power supply *C11204-02* which includes a temperature control loop to stabilize the over-voltage of the SiPM at variable ambient temperatures. The SiPM signal is amplified in two amplification stages in a high-gain channel (10x) and a low-gain channel (1x) and transformed to a differential signal. The differential analog signal is sent via 70 m of cable to the DAQ (IceTAXI). Only the high-gain or the low-gain signal can be transferred at one time. The purpose of two different amplifications of the SiPM signal is doing the in-field characterisation of the SiPM with the high-gain channel and use the low-gain channel for cosmic-ray measurements.

The DAQ of the scintillation detectors samples the incoming analog signals with DRS4 (Domino Ring Sampler) sampling chips [10]. Figure 2 shows a picture of the IceTAXI DAQ. The IceTAXI DAQ can be equipped with three DRS4 chips. Each DRS4 has 8 input channels and can sample the incoming signal with a variable sampling rate of 0.7 - 5 GHz. For sampling the seven scintillation detector signals, one DRS4 chip is used. A trigger signal is generated with a discriminator of variable threshold. When a trigger occurs, the samples stored with capacities inside of the DRS4 are read out with a 33 MHz ADC and send to an FPGA which processes the data and sends it to a UNIX based operation system running on an ARM chip on the TAXI board. Data transfer and time synchronization are realized with a White Rabbit Network [2].

4. The radio antenna candidate SKALA

The SKALA antenna developed for the SKA (Square Kilometer Array) observatory is considered as antenna [11]. The SKALA antenna is at the moment under development for the low-frequency part of the SKA experiment [12]. First measurements have been made with the first prototype version of the SKALA antenna at KIT. With four

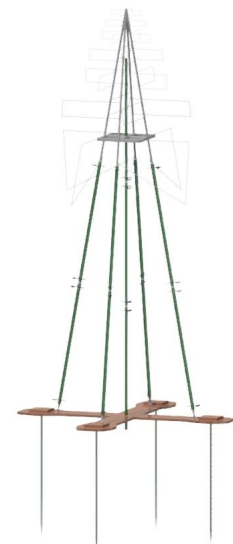


Figure 3. CAD drawing of the highest South-Pole antenna design. The distance of the lowest antenna lobe to the ground level is 1.8 m.

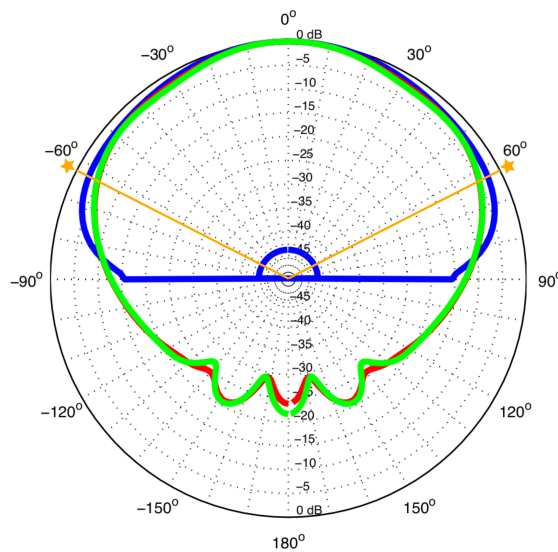


Figure 4. Simulated direction pattern of the SKALA antenna. The blue line shows the response for infinite ground, the red line for soil and the green line for a mesh over soil ground. The important angle of 61° is emphasized in the plot for better orientation. (Adopted from [14])

antennas of the second version prototype kindly provided to KIT, a small test array has been build up together with scintillation detectors and particle detectors of the former KASCADE experiment [13]. Two of these version two prototype antennas are considered to be deployed at the South Pole. Figure 1 shows a picture of the SKALA antenna.

The SKALA antenna meets the requirements for the deployment and use at the South Pole. The frequency bandwidth of the antenna is 50 - 350 MHz which contains the target frequency band of 100 - 190 MHz. Especially regarding the aim of measuring PeV gamma rays from the Galactic Center a good sensitivity for inclined signals is of great importance. Figure 4 shows the simulated directive pattern of the SKALA antenna for a signal frequency of 150 MHz and a 45° cut [14]. For all simulated grounds the attenuation for an inclination of $\Theta = 61^\circ$, which would be the inclination at which the Galactic Center is visible, is only about 5 dB compared to the zenith, which is an acceptable value. The simulated LNA noise with 30 - 40 K is sufficiently low to detect cosmic-ray signals down to the PeV regime. The LNA noise becomes even more important since it is the limiting factor for measurements in higher frequency bands like it is planned for the measurements at the South Pole.

5. Preparations of the antenna for a deployment at the South Pole

It is foreseen to deploy in a first step two version-two prototype SKALA antennas at South Pole. The antennas will have different heights to study the effect of snow accumulation around the antenna. To prepare the antennas for a deployment at the South Pole, special care has to be taken regarding the stability of the used material and the antenna electronics at temperatures of lower than -70°C and a high radiation of UV light.

Figure 3 shows a CAD drawing of the antenna design. The antenna legs as well as the middle pole and the snow spikes are made out of glass-fiber reinforced plastic material. For the antennas which are to be deployed at the South Pole, three mountings have been assembled with antenna legs of a length of 0.5 m, 1.0 m and 2.0 m. This resembles a distance of the lowest antenna lobe to the snow level of around 0.3 m, 0.8 m and 1.8 m. The middle pole stabilizes the antenna structure but serves primarily as a cable guide. The antenna sits on a base made out of multiplex plywood. The base is attached with snow spikes made out of glass-fiber reinforced plastic poles to the snow and ice surface.

All original plastic parts of the antenna like the LNA housing or the stabilizing plate in the middle

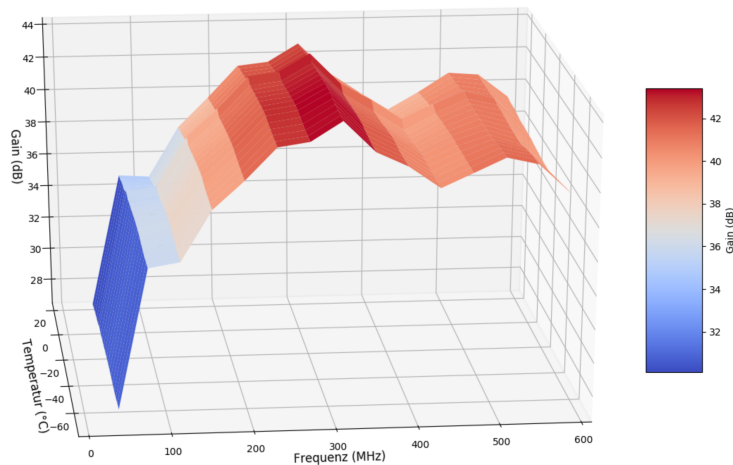


Figure 5. Measurement of the SKALA LNA gain for a temperature range from 20°C to -72°C.

of the metal antenna legs have been stress-tested down to a temperature of -70°C. During these tests no cracks or deformations have been observed.

Special care was taken about the low-temperature test and characterization of the antenna LNA. The LNA has been characterized down to a temperature of -72°C within a wide frequency range of up to 1 GHz. For this, a frequency generator was attached to the inputs of the LNA. During temperature cycles in the temperature chamber, the LNA response to signal pulses from the frequency generator have been recorded. The gain of the LNA depending on the frequency and the temperature has been received by comparing the Fourier spectra of the pulse from the frequency generator and the corresponding LNA response. Figure 5 shows the result of the LNA gain measurement depending on the temperature and the frequency. The gain measurements of the LNA show no significant dependence of the gain regarding the temperature.

6. Modifications to the IceTAXI DAQ for radio

To include the sampling and digitization of the radio signals into the current DAQ of the scintillation detectors, IceTAXI, some modifications have to be applied to the IceTAXI DAQ. Figure 6 shows a sketch of the planned layout of the DAQ. The IceTAXI DAQ is equipped with three DRS4 sampling chips of which one is sampling the scintillation detector signals. It is foreseen to operate two antennas with two polarizations each with one IceTAXI DAQ. For this, each of the remaining two DRS4 will sample one antenna with two polarizations. For this, the DRS4 chips are operated in channel cascading mode, which means that the incoming signal is given to multiple input channels of the DRS4 chips. The DRS4 chip cascades the sampling of the incoming signal which results in longer trace length. With this, a trace length of 4.1 μs at a sampling frequency of 1 GHz can be achieved.

Additional electrical parts to process the radio signal are added to the IceTAXI by including additional PCBs. These PCBs house the bias-tees for powering LNAs in the antennas, filters and amplifiers. Since the DRS4 is operated in channel cascading mode, the signal line of each antenna polarization has to be fanned out into 4 DRS4 inputs. Additionally the incoming 50 Ω single-ended signal from the antenna LNA has to be transformed to a 100 Ω differential signal to be processed with the DRS4. For this, the antenna signal is fanned out into four identical amplifiers which amplify the antenna signal by a factor of 10dB to compensate attenuation by the bias-tee, filters and the fan-out of the signal. At the same time, the amplifiers transform the incoming single-ended signal into the needed differential form.

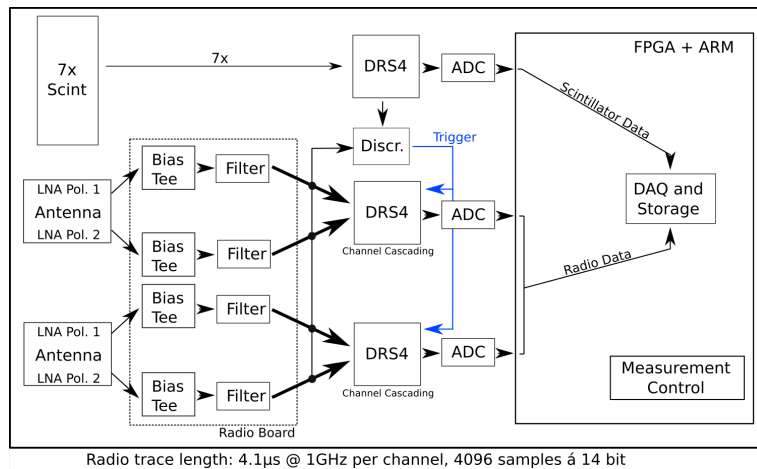


Figure 6. Block diagram of the hybrid IceTAXI DAQ digitizing seven scintillation detectors and two radio antennas with two polarizations each.

7. Conclusion

A scintillator-based particle detector with silicon photomultiplier (SiPM) has been developed and deployed by the IceCube-Gen2 Collaboration. We have designed a radio extension and test measurements with prototype radio antennas are ongoing. The SKALA antenna developed by the SKA observatory is considered as candidate. For a deployment at the South Pole a low-temperature and UV-light resistant antenna structure based on glass-fiber reinforced plastic material has been designed and successfully tested. Processing of the radio signal will be integrated into the existing scintillator DAQ. The DAQ will sample the signals of two antennas with two polarization channels each. Sampling is realized with DRS4 sampling chips triggered by the particle detectors. This enables the measurement of radio signals in the target frequency range of 100-190 MHz with a sampling rate of 1 GHz and a sampling depth of 14 bit. This will be used to test the predicted low PeV threshold of the radio measurement in radio-quiet environments.

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