PROCEEDINGS OF SCIENCE

ALBERT: A Little Bar ExpeRimental Tracker, a portable cosmic ray telescope for outreach and teaching purposes

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We present a portable, versatile cosmic ray telescope ALBERT (A Little Bar ExpeRimental Tracker) for outreach and teaching purposes. ALBERT is based on plastic scintillator bars containing WLS fibers equipped with Silicon Photomultipliers. It is composed of four xy modules with 8 bars each and its overall dimensions are about $50 \times 30 \times 30$ cm^3. The SiPM readout is based on a custom front-end board using the PETIROC 2A ASIC. The instrument is also equipped with additional sensors for environment characterization. To allow portability, data acquisition and online analysis are performed using a Raspberry Pi. Different complexity level DAQ and analysis software interfaces have been developed in order to be flexible in any kind of application. In this contribution we present the design of the instrument and characterization measurements.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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PoS(ICRC2023)1615

1. Introduction

First-hand contact of the audience with detectors has a crucial role in astroparticle physics outreach and teaching activities, and the use of a dedicated educational equipment can further enhance its impact. Astroparticle physics is a complex field that combines elements of astrophysics and particle physics. By providing direct access to a specialized equipment designed specifically for educational purposes, outreach activities and laboratories allow participants and students to engage in authentic scientific investigations. These tools create a tangible connection between theoretical knowledge and practical experimentation, stimulating the learning process. The hands-on experience not only deepens the understanding of fundamental concepts, but also nurtures critical thinking skills and problem-solving abilities.

In this work we present ALBERT (A Little Bar ExpeRimental Tracker), a portable cosmic ray detector dedicated to educational and outreach activities. The present detector is the full upgrade of a prototype previously described in Ref. [1]. A portable cosmic-ray detector enables participants to directly observe cosmic rays (CRs).

2. Detector assembly

ALBERT is a cosmic-ray tracker composed of 64 scintillator bars. Each bar is made of extruded plastic scintillator, has a cross section of 19×15 mm^2 and is 200 mm long, and is coated with a layer of TiO_2. A central 4 mm diameter hole is drilled to accommodate a wavelength shifting (WLS) fiber. The WLS fibers are made of plastic scintillator BCF-92 by Saint-Gobain-Crystals. They are 215 mm long and have a 2 mm diameter. The bars are arranged in a hodoscopic configuration, with 8 planes, each equipped with 8 bars. The bars in each plane are oriented perpendicularly to those in the adjacent planes to provide x-y tracking information. The two ends of each WLS fiber are readout with two Silicon Photomultipliers (SiPMs).

The bars are hold in place by 3D printed frames made of black material, to prevent ambient light leaks. Each frame hosts one x-y module. The frame also serves as holder for the WLS fibers. All planes are placed on a support structure that is wrapped by 5 panels for optical isolation (see Fig. 1). The support structure has an additional space below the scintillator bars to host the front-end electronics. Specific printed wired boards (PWBs) hosting the SiPMs are placed in front of the WLS fibers and are attached to the frames. Each bar is readout by 2 SiPMs of different size. We have used ASD-NUV1S-P and ASD-NUV3S-P by AdvanSiD, with a breakdown voltage $V_{bd} \simeq 26V$. Each PWB hosts 8 SiPMs and their signals are routed to 4 mezzanine boards, one for each side, that collect the signals from all SiPMs and route it to the readout electronics. The SiPM signals are read-out by means of four high speed HLCD 50Ω multi-channels Samtec cables [2].

3. DAQ system

The data acquisition (DAQ) is performed using the PETIROC Front-End board (FEB) featuring the PETIROC2A ASIC [3]. This FEB has been developed for the characterization of several fiber tracker prototypes [1, 4–6]. The PETIROC FEB hosts 4 ASICs and can readout a total of 128 channels. The bias voltage is provided by a CAEN A7585D SiPM voltage module [7]. The

Figure 1: Left panel: ALBERT modules on the support structure. The scintillator bars (in white, due to the TiO_2 coating) and the PWBs hosting the SiPMs and the cables are visible. Right panel: ALBERT with optical isolation made with thick plastic panels and wrapping tape.

ASIC configuration and the DAQ is managed by a Kintex-7 FPGA mounted on a Mercury+ KX2 module [8]. The DAQ is controlled by a Raspberry Pi 4 or by a PC through a TCP interface. An easy-to-use python wrapper of the underlying C++ software allows the user to manage the DAQ settings and runs.

The PETIROC 2A ASIC is DC-coupled to the SiPMs (positive signal inputs). It employs a fast trigger line that consists of an inverting preamplifier with a bandwidth of 1 GHz (with a nominal gain of 40) followed by a fast discriminator. To adjust the trigger level, a common 10-bit DAC is used in conjunction with individual 6-bit DACs. This adjustment allows for a range of trigger levels from 0.5 to a few tenths of photoelectrons (p.e.), depending on the SiPM gain. With the PETIROC 2A ASIC it is possible to obtain 32 trigger signals along with the logical OR of all signals. Additionally, individual channels can be masked, thus enabling the rejection of noisy SiPM strips. The preamplifier gain and trigger level range cannot be modified through the ASIC configuration. However, they can be adjusted externally, using resistors connected to proper pins on the ASIC. This external adjustment allows for gain reduction and slight modifications to the threshold window [9]. In addition, the ASIC front-end incorporates an 8-bit DAC for each channel, allowing for the adjustment of the high voltage applied to each SiPM. The DAC is controlled through the configuration, enabling the bias voltage to be changed from 1 V (DAC code = 0) to 2 V (DAC code = 255) with respect to the voltage provided by the CAEN A785D module. The ASIC also includes 10-bit ADCs for measuring charges and 37 ps resolution TDCs for measuring time.

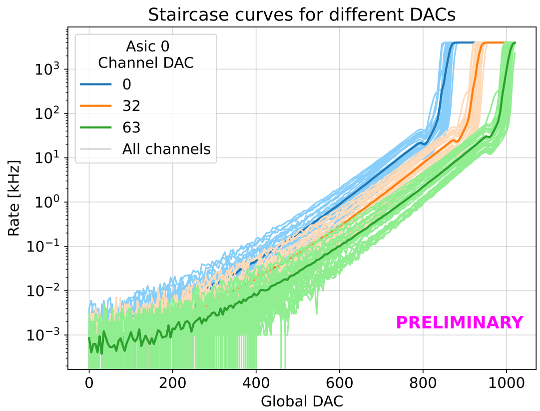

Figure 2: *Staircase* curves for three values of the individual channel threshold 6-bit DAC (0, 32 and 63). The lighter lines correspond to all individual channels of ASIC 0, while the darker ones indicate the average of all channels.

3.1 The Trigger

The availability of the trigger outputs of all channels, allows the implementation of a topological trigger logic. We require the coincidence of the two SiPMs at the two ends of each bar and that at least two bars per view are hit, in order to have maximal angular acceptance. The coincidence time window is set to the minimum time allowed by the FPGA clock, corresponding to 25 ns.

3.2 Channel trigger response equalization

To equalize the response of all channels, we use the single channel 6-bit DAC, that allows small single channel adjustments with respect to the global 10-bit DAC ASIC discriminator threshold. For this purpose, we perform runs in a dedicated DAQ mode, where the digital parts (ADC and TDC) of the ASIC are deactivated, and the triggers received from each channel are individually counted in a time window set by the user. In this way it is possible to obtain a measurement of the event rate after the discriminator, without the dead time due to digital conversion. The single channels are readout individually and in parallel, hence all channel rates are measured simultaneously in one single DAQ run.

For each value of the single channel DAC, we perform a rate scan, measuring the trigger rate as a function of the global 10-bit DAC threshold. Such curves are called *staircase* curves since, in the case of a SiPM with small capacitance, one can identify the *steps* corresponding to different numbers of collected photoelectrons, with the rate decreasing exponentially with increasing threshold (decreasing DAC values), as expected for the dark counts rate. With our setup the *steps* are not well resolved, resulting in a smooth *staircase* curve.

Fig. 2 shows a few examples of staircase curves obtained for one of the ASICs. In Fig. 2 three families of staircase curves are shown, representing the response of all the 32 channels of the ASIC 0 when the 6-bit DAC threshold is set to 0, 32 and 63 respectively. The darker lines represent the average of the 32 channel curves. The steepening and the subsequent plateau above $\sim$ 800 DAC

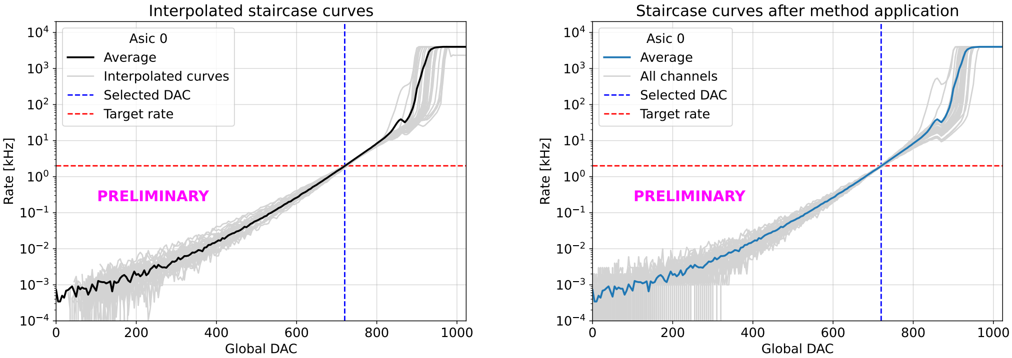

Figure 3: Left: combination of the interpolated *Staircase* curves that minimizes the spread in a 100 DAC interval around the global DAC value given by the target rate. The red dashed line represents the target rate per channel value and the blue dashed line the corresponding global DAC value. Right: *Staircase* curves for each channel of ASIC 0 obtained from a trigger run with the optimized 6-bit single channel DAC values.

correspond to the pedestal. Since the output signals from the preamplifier are negative, lower DAC values correspond to higher thresholds in terms of signal amplitude.

In Fig. 2 we clearly see a spread in the rates for a fixed threshold of the global 10-bit DAC, resulting in a non-uniform response of the channels. To equalize the trigger rates, we can use the individual 6-bit DACs. The three families of staircase curves shown in Fig. 2 correspond to the 6-bit DAC values 0, 32 and 63, i.e. the lower edge, the center and the upper edge of the scale. These curves can be used to evaluate the corrections that can be applied to minimize the spread.

We have implemented the following procedure to equalize the trigger rates:

1. for each channel, we take the *staircase* curve $r_i(g, l)$, where i is the channel index ($i = 0 \ldots 31$ for each ASIC), g is the global 10-bit DAC value ($g = 0 \ldots 1023$ and l is the individual 6-bit DAC value ($l = 0 \ldots 63$);

2. we then evaluate the central average curves $\overline{r}(g, l)$ by averaging all channels (darker lines in Fig.2;

3. we fix a target rate $r_0 = 2$ kHz and we take the value g^* such that $\overline{r}(g^*, l = 32) = r_0$;

4. we set $g = g^*$ and, for each channel, we evaluate the value of l_i^* such that $r_i(g^*, l_i^*) = r_0$. This value is obtained from an interpolation of the *staircase* curves of the i-th channel.

The left panel of Fig.3 shows the average *staircase* curve $\overline{r}(g^*, l = 32)$ superimposed to the individual interpolated curves $r_i(g^*, l_i^*)$. We see that the spread of trigger rates of individual channels with respect to the target rate is reduced. The right panel of Fig.3 shows the staircase curves obtained setting the optimized 6-bit DAC values l_i^* along with the average curve. The measured curves are in good agreement with expectations.

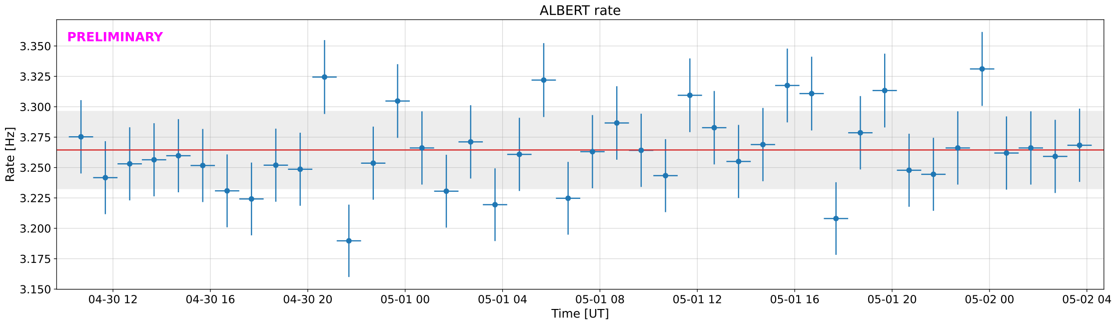

Figure 4: Cosmic Ray trigger rate measured by the ALBERT instrument during three days of data taking. The red line indicates the average rate, while the light gray band indicates the $\pm 1\sigma$ interval.

4. Tests with Cosmic Rays

After calibrating the instrument to have uniform trigger rates among channels, we performed some data taking runs with CRs. We acquired a set of 1-hour long runs for three days. Fig. 4 shows the trigger rate during the three days. The rate is compatible with expectations, given the active volume.

We consider a bar hit if the signal from both SiPMs at its ends exceeds the pedestal of at least 3 standard deviations. For each plane we apply a clustering algorithm as described in Refs. [4] and [9]. We group adjacent hit bars to form clusters. We then evaluate the charge center-of-mass of each cluster and we fit the track with a straight line in both $x - z$ and $y - z$ views. Fig. 5 shows the reconstructed track parameter distribution. The left panel shows the reconstructed position of the impact point on the uppermost plane. From this plot we can see that, thanks to its low-bias topological trigger, ALBERT accepts CRs with impact points not only on the top face, but also on the sides. The right panels of Fig. 5 show the zenith and azimuth (θ and ϕ) distribution of the reconstructed tracks[1]. The discrete structure of the distribution is due to the square symmetry of ALBERT's geometry and to the coarse bar pitch. The top right panel of Fig. 5 shows the instrument zenith angle distribution: from this distribution we see that most events have $\theta < 45°$. The bottom right panel of Fig. 5 shows the azimuth angle distribution, that is almost uniform, with an exception for the discrete peaks at multiples of 45° and 90°, due to the geometry of the instrument, as discussed before.

When computing the total charge released by the incoming particles, summing the cluster charges for the different SiPMs at the end of each bar, we obtain a Landau distribution as expected. The distributions obtained with the ASD-NUV1S-P and ASD-NUV3S-P SiPMs are shown in Fig. 6. We point out that the charge calibration among channels is not optimized. For geometrical reasons the ASD-NUV1S-P SiPMs should detect approximately $\frac{1}{3}$ of the photons detected by the ASD-NUV3S-P SiPMs. The Landau peaks of the latter is slightly lower then three times the peak of the ASD-NUV1S-P distribution. This could be improved optimizing the individual channel charge calibration.

[1]The zenith and azimuth angles are evaluated in the instrument frame.

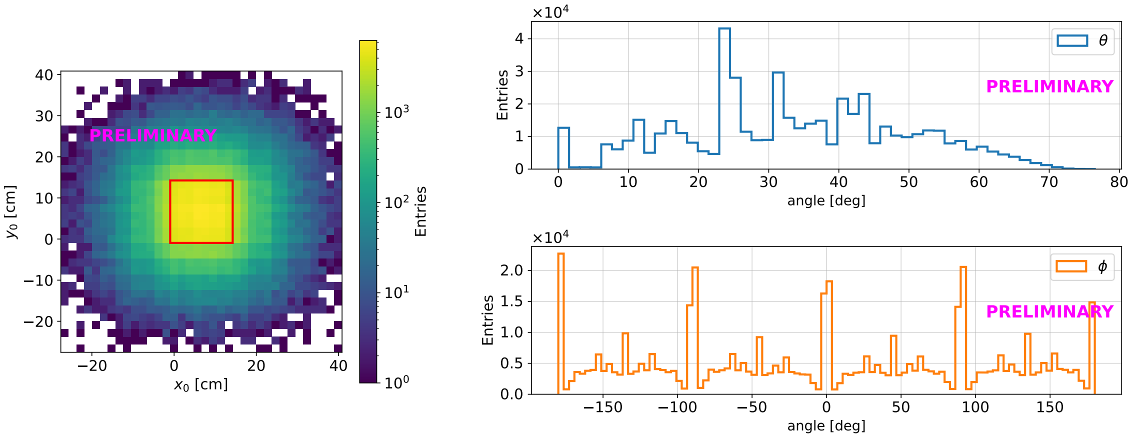

Figure 5: Left panel: Impact points projection on the uppermost plane corresponding to z_0 = 16.2cm. The red square represents the ALBERT top face. Right panel: Top: zenith angle distribution. Bottom: azimuth angle distribution. The discrete peaks are due to the square symmetry geometry.

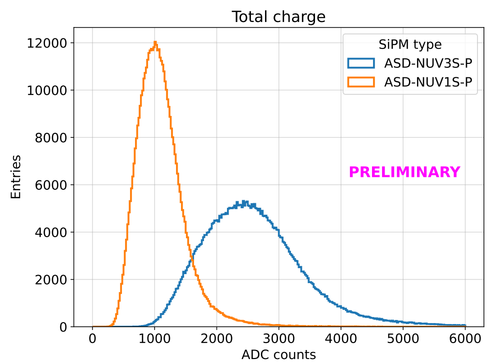

Figure 6: Total charge distributions for ASD-NUV3S-P and ASD-NUV1S-P SiPMs.

5. Conclusions

With this upgraded version ALBERT, has undergone significant improvements with respect to the previous prototype illustrated in Ref. [1]. We have assembled the full instrument and partially optimized the procedures for the its calibration. Preliminary CR measurements show promising results. Further optimizations and improvements are in progress.

Acknowledgments

We acknowledge all the INFN Bari staff, in particular P. Dipinto, M. Franco, N. Lacalamita, F. Maiorano, S. Martiradonna, M. Mongelli, M.G. Papagni, C. Pastore and M. Rizzi for their significant help in the realization of the prototype.

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