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New Front end and trigger electronics for the ALPACA experiment

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A new air-shower array experiment with high sensitivity for sub-PeV γ-rays is currently under construction in the Chacaltaya Plateau in Bolivia. This experiment, called ALPACA, will search in the southern sky for γ-ray sources using surface detectors and underground muon detectors to discriminate against the cosmic ray background. Beyond ALPACA, a future mega-square meter air shower array, Mega ALPACA is proposed to determine the acceleration limits in our Galaxy. Considering this, our goal is to design new front and trigger electronics which provide long-term stable operation, meanwhile being capable of processing the required number of channels. For the Front end electronics, we designed a system with high resolution and wide dynamic range. The circuit also digitizes the signal from the detectors and transfers the information to the rest of the system using FPGA. For the trigger electronics, we are designing an all-digital sum trigger, which selects events using the arithmetical sum of the number of detectors above a given threshold. To evaluate the performance, we developed a custom-made pulse generator capable of reproducing the timing characteristics of the air-shower experiment. In this paper, we will present the details of the design of both systems and the results as well as the performance evaluation to measure resolution and linearity. We also present the results of the testing of the modules done at the site of the ALPACA experiment in comparison with the DAQ electronics currently used in the array.

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1. Introduction

The observation of CR at the PeV scale is essential to solve the question on the origin of cosmic rays. Recent evidence propose Supernova remnants (SNRs) as Galactic CR accelerators. However, because PeV CR are affected by magnetic fields, observation of the γ-rays at 100 TeV is an excellent tool to search for sources in our galaxy. The production of γ-rays comes from the interaction of parent CR with the environment around the source.

On the other hand, observation of >100 TeV γ-rays (UHE) requires great sensitivity. In this sense, Imaging atmospheric Cherenkov telescopes (IACT) cannot achieve this because their limited exposure time. Conversely, in 2019 the Tibet ASγ [1] collaboration open a new window with the reported detection of 100 TeV γ-rays coming from Crab Nebula. For this the Tibet ASγ uses a surface area array in conjunction with an underground water Cherenkov muon detector (MD) to suppress hadronic showers, in addition to long exposure. Besides this, observations from HAWC [2] and LHASSO [3] have helped to find sources of UHE γ-rays in the northern hemisphere.

With this motivation, the Andes Large area PArticle detector for Cosmic ray physics and Astronomy (ALPACA) is a new air shower array project in collaboration between Bolivia, Japan and Mexico. The detector is currently under construction near the Chacaltaya mountain and will be the first experiment to observe high energy γ-rays in the southern hemisphere. This location is well-suited, since the detector will be able to point to the Galactic plane around the Galactic center, which is rich in high energy objects.

2. The ALPACA experiment and future extensions

The ALPACA detector is currently under construction in the Chacaltaya plateau, Bolivia. The location in the Southern Hemisphere (16°23′**S**, 68°8′**W**) is an ideal place for a Cosmic ray observatory, due to its large and flat area and high altitude of 4740 m (572 g cm^{-2}). ALPACA is an hybrid array, composed of a surface air shower (AS) array and underground water Cherenkov muon detectors. The AS array will cover and area of 83 000 m^2 and comprises 401 plastic scintillators of $1 \times 1 \times 0.05$ m^3 each. The separation between each detector is 15 m.

The MD array of ALPACA is composed of four 900 m^2 underground pools, each divided in 16 cells of 7.5×7.5 m^2. A 20-inch PMT is installed on the ceiling of each cell facing downward to collect the Cherenkov light produced by the particles that reach underground. Because the total thickness of soil above the MD array is 2.0 m, only high energy muons (>1.2 GeV) produced in the air shower are capable of penetrating, therefore they are useful to discriminate between γ-rays and CR. In 2022 the prototype of ALPACA (ALPAQUITA) started observations with around 1/4 of the total size of the full array. The current status of the array and its performance is presented separately in this conference [4] [5].

After successful observations using the full ALPACA array, we plan to extend the array to cover an area of 1 km area. We call this experiment Mega ALPACA. The main goal with this array is to study the limits of particle acceleration within our Galaxy, by studying the energy spectra above 1 PeV. To achieve the required sensitivity, Mega ALPACA will require around 1500 surface detectors and 50 MDs. A more detailed description of this experiment in presented in another paper in this conference [6]. Taking into account the future needs of the experiment and to guarantee the

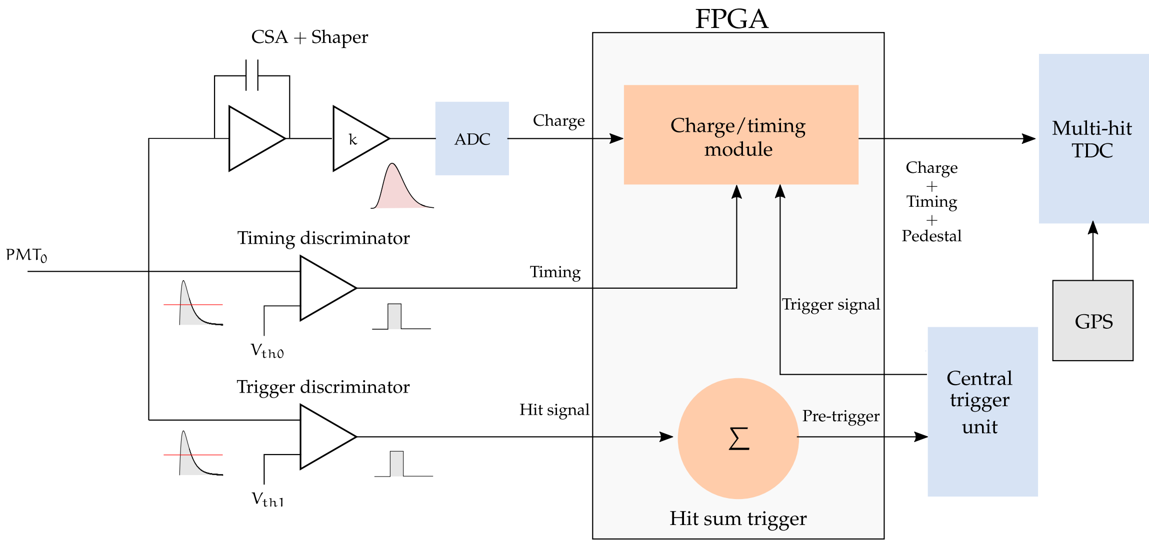


Figure 1: Schematic diagram of the DAQ system of the ALPACA experiment including the New front end electronics.

long-term stable operation, we have started to develop new front end and trigger electronics using state of art technology. In the following section we will present the design of the systems, as well as the results obtained with the first prototypes.

3. Development of new front and trigger electronics

The data acquisition system (DAQ) of ALPACA/ALPAQUITA is based on the system of the Tibet ASγ experiment. In this system the signal from each PMT is divided in three paths: one for charge measurement, one for timing information and the last one for triggering (hit signal). For the timing and trigger process, the PMT signal passes through two different discriminators. After this, the charge and timing measurement is performed by the **MQT300A** charge-time converter (QTC) integrated circuit develop by LeCroy [7]. The output of the circuit is a digital pulse of width proportional to the input charge. The rising and falling edges provide the timing information of the particles that hit the scintillator. In this setup, one front end (FE) module process in parallel the signals from 16 PMT.

The trigger signal of the experiment is done by the linear sum of all hit signals from the surface array. The trigger condition is meet when 4 or more detectors produce a hit signal. After trigger, the signal from the QTC circuits is send to a multi-hit TDC and then transfer to the DAQ server by VME bus. As a result the DAQ system offers high resolution, wide dynamic range and low dead time.

Because the **MQT300A** is not widely available anymore, the development of the new front end electronics is based on FPGA to replace its functions. The schematic diagram in fig 1 summarizes the basic structure (one channel) of the new front end and trigger electronics. In this system, the signals from PMT are also separated in three paths. For the timing and charge the measurement the pulse goes through a discriminator and amplifier/shaper, respectively. The amplifier stage is a charge sensitive amplifier (CSA). The shaping circuit is composed of a pole-zero cancellation

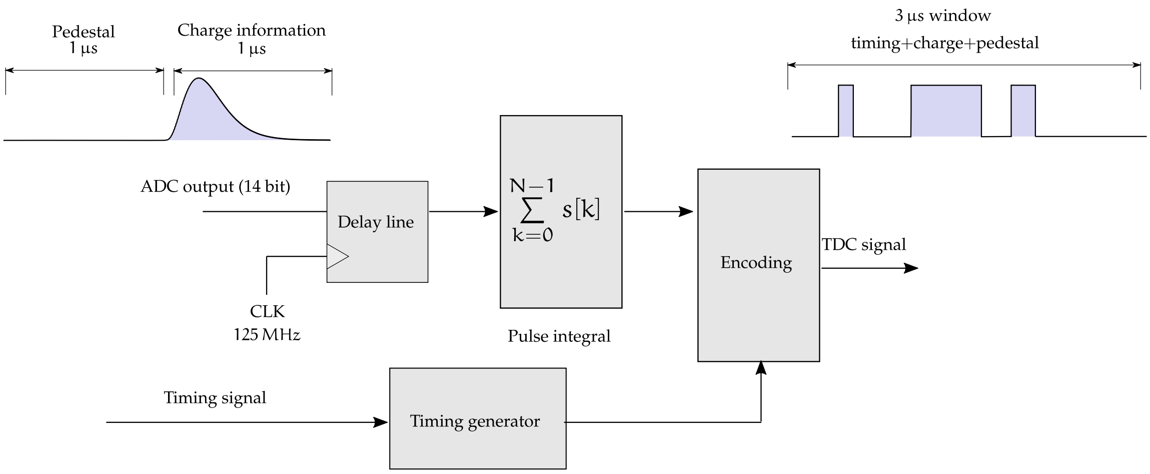
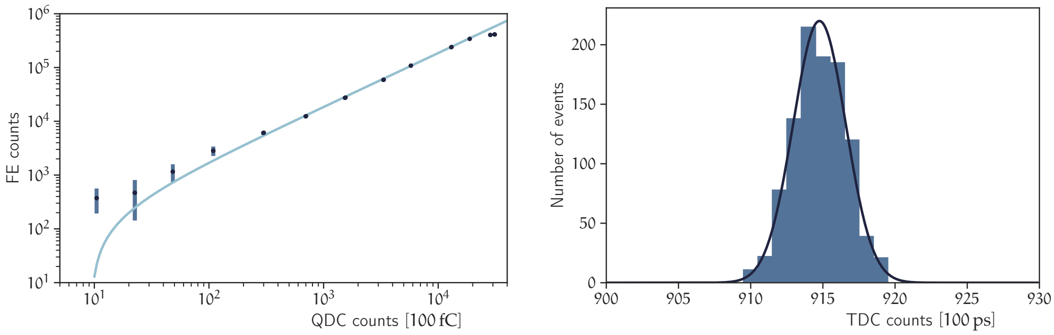


Figure 2: Schematic diagram of the analog/digital processing modules for timing and charge information.

circuit and an low-pass filter. The output of the waveform shaping circuit goes to an **AD9648** ADC and then to the FPGA. The ADC is capable of processing two input channels and has 14 bit of resolution. The system is operated at a sampling frequency of 125 MHz. It is important to notice that both the pulse shaping circuit and the ADC are designed using the LVDS standard, which allows low power consumption and is noise resistant.

After the conversion, the samples from the pulse are fed to the FPGA. To measure the charge in the signal the digital pulses are integrated using the architecture shown in fig 2. In this diagram, the samples pass through a delay line (register bank) which stores around 1 µs of the signal. When the delay line is full, the integral of the pulse is performed by summing all the samples in the bank. The pedestal value of the pulse is measured with a similar method, but using the samples from 1 µs before the starting of the signal. The FPGA encodes the information of the start timing, the charge information and pedestal, into a single logic sequence of 3 µs duration that is send to the multi-hit TDC. The multi-hit TDC measures the starting time registered by PMT with the rising edge of the pulse (see fig 2) and the charge and pedestal with the duration of the pulses in the sequence. Besides this, a GPS module also provides time stamp with high accuracy.

The processing of the hit signals by FPGA requires the 1 bit sum of the 16 input channels, each distributed randomly in a time window corresponding to the air shower profile (about 600 ns [8]). To reliable process the sum, the FPGA first detects the starting of each pulse and produces pulses of fixed width. The digital sum is then produced using a lookup table (LUT), which generates a 4 bit output called *partial sum*. The partial sums from all the modules are then send to a central trigger unit to obtain the total sum and produce a trigger signal. The required LUTs are large (2^{16} locations), however, we choose this method because it is flexible and only introduces a fixed delay in the processing chain, independent of the number of inputs (in contrast with other methods in which the propagation delay depends on the number of inputs).



(a) Linearity of the FE module.

(b) Timing precision.

Figure 3: Performance test of the FE module. Left panel: evaluation of linear response from the FE module using a high resolution QDC system. The data is fitted with a linear function: $y = 18.6139x - 173.325$. The prototype have a linear response in the range from 10 pC to 2000 pC. Right panel: timing precision of the FE module using TDC. The histogram represents the time difference between the output of the function generator and the FE module. The solid line represents the fitting to the data

4. Evaluation of the new front end and trigger prototypes

A prototype for the new front end electronics has been developed and tested to measure its performance. The prototype is designed with 6 input channels and it is layout as a NIM module. The power consumption per channel is about 0.45 W. To test the linearity of the unit we injected PMT-like pulses with know charge in the range from 1 pC to 3000 pC. The input signal is produced by a function generator in conjunction with a CR differentiator circuit. The output from the CR circuit is then fed to the FE prototype and a high resolution (100 fC) charge digital converter (QDC).

The result of this test is shown of figure 3a. The horizontal axis represents the output from the QDC (1 count=100 fC) and the vertical axis is the output from the FPGA in FE units (the numerical value of the integral). Each data point represents the measurement of 1000 different events and the error bars correspond to $\pm\sigma$. The data is fitted with a linear function of the form: $y = 18.6139x - 173.325$. From this figure it is clear that the response of the prototype is linear in the range from 10 pC to 2000 pC. For values of charge lower than 10 pC, the large deviations are probably generated by noise. We will improve the performance of the circuit in this range in the near future, nevertheless, even at this stage we can say that the response of the new module satisfies the needs of the experiment.

The next test was to evaluate the timing precision of the FE module. In this experiment we use the signal from the function generator as the start pulse to the TDC. The same signal is send through the FE module and the output is connected to the stop of the TDC. The results of this test are shown in figure 3b. The blue histogram corresponds to 1000 time intervals measured by the TDC, while the solid line represents the fitting using a Gaussian distribution with $\mu = 91.5$ ns and $\sigma = 0.188$ ns. In this case, the most important parameter of the distribution is the σ as this measures the precision of the system. Taking into account this, and considering that our main goal is to achieve a timing precision of about 0.1 ns, we can conclude that we timing precision requirement is almost fulfill.

For the case of the trigger electronics, we have developed a 16 channel prototype using an

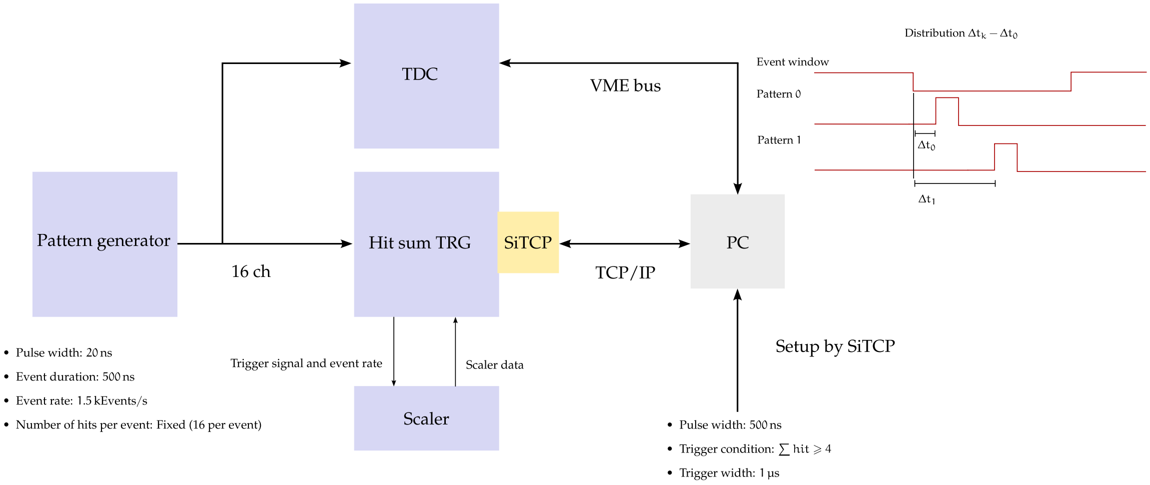


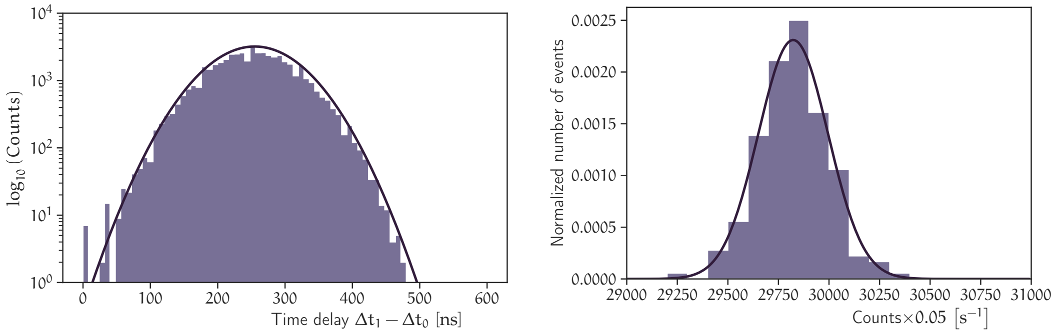
Figure 4: Experimental setup for the evaluation of the trigger electronics module and the pattern generator.

FPGA development board. However, to be able to test the module we require a special purpose pattern generator, since commercial units are not capable of producing large number of independent patterns. Considering this and the need to test the trigger system for larger number of inputs, we decided to develop a custom made pattern generator. The pattern generator is designed using an FPGA development board and its architecture makes it possible to increase the number of output channels easily. The generator uses special purpose random number generators to simulate the random occurrence of an air shower (simulated as a Poisson process [9] and the timing distribution (start time) of each detector in the time window of the event. Both, the event generation rate of the system and the timing distributions of the pulses can be controlled externally.

The schematic diagram in figure 4 shows the setup for testing the trigger electronics. The generator is configured with a event generation rate of 1.5 kEvents/s and a Gaussian distribution for the timing of the pulses. Each pulse has a duration of 20 ns and its distributed randomly in a time window of 500 ns. In each event, all 16 channels are generated which means that the trigger signal should be produced at the same rate of the event generation. In addition to the 16 signals we include an extra signal to timestamp the beginning of each event. We call this timestamp pattern 0.

The output of the generator is send to a TDC and to the trigger module. The use of the TDC is to test the timing distribution of the patterns and verify if it is corresponds to the input distribution. This is done by measuring the time delay of patterns against the pattern 0 (as shown in figure 4). The result of this measurement is shown in the histogram of figure 5a. From this it can be seen that the generated pattern reproduces the expected distribution (solid line in the figure). The input parameters set in the generator are: $\mu = 260$ ns and $\sigma = 60$ ns. One point to notice is that the average value of the data is shifted 30 ns to the right, this however is expected, as it is the time it takes for the generator to produce a new random event.

On the other hand, the performance of the trigger module is evaluated using a scaler system. The scaler was included in the description of the trigger module and it uses SiTCP [10] to communicate with the PC by TCP/IP protocol. The scaler system accumulates the number of trigger signals and pattern 0 every 20 s. Figure 5b shows the histogram of the scaler values for the trigger signal obtained during one hour of operation. In all recorded data the number of trigger signals



(a) Timing distribution of pattern generator. **(b)** Event rate distribution of trigger signals.

Figure 5: Results of from the testing of trigger modules. Left panel: time delay distribution for one channel of the pattern generator. The solid line represents the expected distribution configured directly to the memory of the pattern generator. Right panel: distribution of scaler counts per 20 s time window, for all events that produced trigger signal. The solid line represents the expected number of counts for a Poisson process of $\mu = 1.49\,\text{kEvents/s} \times 20\,\text{s}$.

is always equal to the number of pattern 0, which means that the trigger module is processing the patterns with high precision. In this case the expected distribution is a Poisson distribution with a $\lambda = 1.5\,\text{kEvents/s} \times 20\,\text{s}$. The fitting however (solid line) represents a distribution with $\lambda = 1.49\,\text{kEvents/s}\times 20\,\text{s}$. The difference from the expected values may be explained as a limitation of the method used to approximate the Poisson distribution and not an actual flaw of the electronics.

5. Summary

The ALPACA experiment is new air shower experiment designed with high sensitivity for UHE γ-rays. This experiment is currently under construction in the Chacaltaya plateau in Bolivia, and its prototype ALPAQUITA has started observations recently. It is expected that the full ALPACA array shed light into the origin of Cosmic rays in our Galaxy. Taking into account the future extension (Mega ALPACA) and operation of the detector in the long term we have started to design new electronics. So far we were able to produce two prototypes for the new FE electronics and the trigger system and we have found that the initial performance is close to the expected goals. In the incoming year we will improve the performance of these system and test them at the ALPACA experimental site to evaluate its reliability under real conditions.

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