The MU-RAY project: volcano radiography with cosmic-ray muons

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Abstract

Cosmic-ray muon radiography is a technique for imaging the variation of density inside the top few hundred meters of a volcanic cone. With resolutions up to tens of meters in optimal detection conditions, muon radiography can provide images of the top region of a volcano edifice with a resolution that is considerably better than that typically achieved with conventional methods. Such precise measurements are expected to provide us with information on anomalies in the rock density distribution, like those expected from dense lava conduits, low density magma supply paths or the compression with depth of the overlying soil. The MU-RAY project aims at the construction of muon telescopes and the development of new analysis tools for muon radiography. The telescopes are required to be able to work in harsh environment and to have low power consumption, good angular and time resolutions, large active area and modularity. The telescope consists of two X-Y planes of 2×2 square meters area made by plastic scintillator strips of triangular shape. Each strip is read by a fast WLS fibre coupled to a silicon photomultiplier. The readout electronics is based on the SPIROC chip.

Key words: Muon radiography, Vulcano structure, Silicon Photomultiplier

1. Introduction

Muon radiography is based on the measurement of the absorption of cosmic muons inside matter. First proposed to determine the thickness of snow layers on a mountain [1] , the first application was realized in 1971 by Alvarez and collaborators for the search of unknown burial cavities in the Chephren pyramid [2]. In recent years Tanaka and collaborators [3, 4, 5] have demonstrated the possibility to use this technique, using quasi-horizontal muons, to study the internal structure of volcanoes. The spatial resolution that can be obtained with this method is of the order of 10 m, which is difficult to achieve with the standard techniques used in volcanology. The MU-RAY project [6] is an international collaboration aiming at the development of muon telescopes and analysis tools to perform volcano radiography, in particular Mt. Vesuvius and Stromboli.

2. Motivations

Volcano-eruption dynamics mostly depend on the gas content, the chemical composition of the magma and the conduit dimensions and shape. With respect to the last two items, traditional measurement methods (gravimetric, seismological and electromagnetic), can achieve resolutions of the order of several hundred meters, in optimal acquisition conditions. Muon radiography can improve resolutions by one order of magnitude. Besides the scientific interest, most pronounced in the case of the so called "Strombolian" eruptions, understanding eruption-dynamics can have relevant social impact too, as in the case of Mt. Vesuvius, the highest volcanic risk in Europe with about 600,000 people living in the red zone around the volcano or on its slopes.

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3. Detector layout

3.1. Technological choice

Recent measurements of volcanos' inner structures using cosmic muons have been performed using two different technologies: emulsion imaging systems and particle trackers based on scintillator bars and photomultiplier tubes [3, 4, 5]. The tracker was a segmented detector composed by two stations. Each station has two planes, measuring the two orthogonal coordinates X-Y. Each plane consists of an array of $100cm$ length $\times 10cm$ width $\times 3cm$ thickness plastic scintillator coupled with $52mm$ in diameter photomultiplier tubes. The two stations were placed at a distance of 1.5 m in order to achieve $66mrad$ angular resolution. The use of emulsions in principle gives much better resolution, but is in practice limited by the statistics accumulable in each bin of the measured angles due to sensitive area size and to the maximum exposure time. Moreover, they are not real-time detectors and emulsion development and scanning are not trivial tasks.

The goal of the MU-RAY collaboration is to realize a tracker with angular resolution comparable with that obtainable with emulsions, but with real-time data acquisition and larger sensitive area. The system must be able to work in volcanic areas. For this reason a modular structure is required, with each module light enough to be easily transported by hand. Further requirements are mechanical robustness and easy installation. Power budget must fit a small solar panel system's capability. Good time resolution can improve background suppression by measuring the muon time of flight. Last, but not least, the technology should be low cost, in order to allow for a large active area and the possibility to have more telescopes taking data simultaneously from different positions to obtain a volcano tomography. Some of these requirements such as the rugged running conditions suggest to avoid gas detectors like RPCs or MultiWire Chambers.

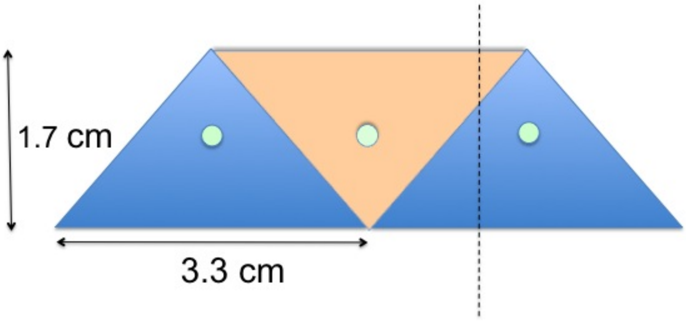

Figure 1: A sketch of the triangular scintillator bars.

3.2. Detector description

We decided to use plastic scintillator bars with Wave Length Shifter (WLS) fibers. The scintillator bars used for D0 [7] and Minerva [8] experiments and produced at FERMILAB offer several advantages. They are produced, by extrusion, in bars as long as 6 m, with a hole along the center. The core (Dow Styron 663 W) is doped with blue-emitting fluorescent compounds (PPO 1% and POPOP 0.03%). The surface has a co-extruded TiO_2 coating (0.25 mm thick) to increase internal reflectivity and to shield from environment light. The bars can be produced with both a triangular or rectangular transverse shape. The use of isosceles triangular shape (see fig. 1) allows the construction of very compact, crack-free planes. Moreover, the measurement of the light output produced by two adjacent strips permits the determination of the particle crossing distance between two contiguous fibers, which allows improving the spatial resolution with respect to squared section scintillator of similar transverse area. Using this technique a spatial resolution of 3 mm was obtained using multi-anode photomultiplier tubes [8] .

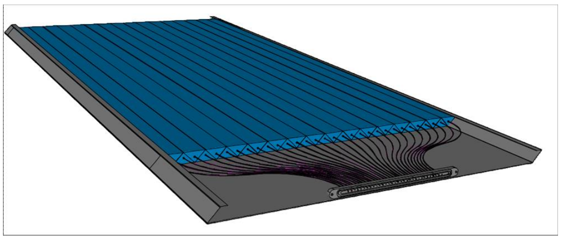

Figure 2: Schematic view of a 32 bars module

The muon telescope will be composed by two X-Y stations with a sensitive area of 4 m^2. A third station will be used to study possible backgrounds, as the one induced by cosmic-ray showers. The planes will be composed of 4 modules, each composed of 32 bars, $2m$ long and $\sim 0.5m$ wide (see fig. 2). The triangular bars will be glued to each other and over two $2mm$ thick aluminum plates, creating a very solid module. Light from scintillator is collected by $1mm$ diameter fast-decay WLS fiber BICRON BCF92. BCF92 fibers were preferred to KURARY Y11 fiber, used by the Minerva experiment [8], for the fast decay constant ($\sim 2.5ns$ vs $\sim 10ns$), in order to optimize time of flight performances with respect to light yield (Y11 produce $\sim$ 30% more light than BCF92). The extruded hole in the bar is larger than the fiber diameter. The fiber will be glued with epoxy transparent glue, with refraction index of ~ 1.5, matching the scintillator's refraction index. In this way we measured an increase in the light collection efficiency of more than 50%. Fibers are mirrored at one end using the Al sputtering facility of the Frascati INFN laboratory [10].

To read the light from the fibers we decided to use silicon photomultipliers (SiPM) instead of multi-anode standard phototubes. SiPMs offer several advantages. Their robustness is mandatory for the environmental conditions; their very low power consumption (less than 1 μW per channel) is relevant due to limited power budget for the system when working with solar panels. They also need low operating voltage and their typical sensitive area matches that of the fiber. The two main drawbacks are the high dark count rate and the temperature dependence of gain and signal amplitude.

A single photoelectron dark noise rate of the order of 1 MHz is measured at ambient temperature. However, the rate of signals of higher amplitude decreases by approximately one order of magnitude per photoelectron. Therefore a threshold high enough to suppress accidental coincidences without reducing the detector efficiency has to be chosen. We measured a mean number of photoelectrons produced in a plane of the order of 30. Setting the threshold for a single strip to 3-4 photoelectrons we reduced the single strip rate to about 1 kHz. The standard requirement to define a track is the presence of two adjacent strips firing in each plane for a total of eight strips. In the case in which a muon crosses a strip close to the center, only a thin part of the adjacent strip is passed through. Therefore this strip may produce a signal below the threshold. For this reason we have to require a minimum of 4 strips firing together. A 100-ns coincidence window reduces the number of accidental triggers to a negligible level.

The dependence of SiPM on temperature affects the performance of the detector. Indeed the dark noise rises strongly with temperature and the detector should operate at a controlled temperature below $\sim 25°C$. For this reason the SiPMs' temperature will be controlled using Peltier cells. In order to optimize the power consumption, we decided to group together 32 SiPMs in a single PCB. The fibers are glued to a custom 32-channel optical connector, which will be fixed to the module chassis (see Fig. 2). The fiber connector is mechanically coupled with a dedicated SiPM connector. The die SiPM are bonded on a precision PCB (see fig. 3). One side of the Peltier cells is thermally in contact with the back side of the PCB while plastic guarantees a good thermal insulation with respect to the environmental temperature. A rubber O-ring around the sensitive area is used to ensure light and air tightness. Two temperature sensors are located on the PCB for the Peltier cells control circuit. All the mechanics for both the fiber and the SiPM connectors must guarantee 100 μm precision in the relative positioning of each SiPM and fiber in order to have full light collection efficiency. The SiPMs we are using are produced by Fondazione Bruno Kessler. Their sensitive area will be circular, 1.4 mm in diameter and $70 \times 70\ \mu m^2$ cell area, for 292 cells in total.

3.3. Front-end electronics

The front end electronics is based on the SPIROC ASIC [9]. The SPIROC (SiPM Read-Out Chip) has been developed by OMEGA group, at IN2P3/LAL at the Orsay laboratory, specifically for SiPM read-out and very low power consumption ($\sim 20mW$ per channel). Realized with 350 nm Si-GE technology each chip has 36 channels. One of the distinguishing features of SPIROC is the possibility to choose a fine setting of the operating voltage for each SiPM. Indeed a programmable voltage between 0 and 5 V range with 10 mV step can be added to a common reference voltage for fine control of the working point of the SiPMs. This chip has been designed in order to give digitized amplitude and timing information of each single SiPM output signal. Two variable preamplifiers allow to obtain a dynamic range from 1 to 2000 photoelectrons with a noise level of 1/10 photoelectrons. These charge preamplifiers are followed by two variable CRRC slow shapers (50 ns-175 ns) and two 16-deep Switched Capacitor Arrays (SCA) in which the analog voltage will be stored. A HOLD signal must be provided in order to store the analog information to be digitized. This signal can be generated by the chip itself, using internal trigger outputs, or can be provided from an external trigger logic. The internal trigger outputs are generated via fast shapers followed by a discriminator. The trigger discriminator threshold is given by an integrated 10-bit DAC common to the 36 channels. This threshold is channel by channel fine-tunable by using additional 4 bits. A logic OR (LOR) of the internal trigger signals of the 36 channels is available as output signal from the chip. We use these LOR to generate the external HOLD trigger for all the SPIROC. A dedicated board (Master Board) with an FPGA collects the LOR signals from all the modules and generates the common HOLD signal by using a programmable trigger logic. Although the SPIROC is designed for complete charge and time digitization, we prefer to perform these conversions on dedicated boards (Slave Boards). Each 32 strips module is therefore read out by a Slave Board, where a SPIROC, an FPGA and a flash ADC are located. Once the HOLD signal has been formed by the Master Board and distributed to the Slave Boards, the FPGAs provide the serial download of the single analog amplitudes stored in the SPIROC, which are digitized, collected and transmitted to the Master Board. This board also provides the final event building and storing. Besides the amplitude digitization, the Slave boards measure the LOR timing information using a time expansion.

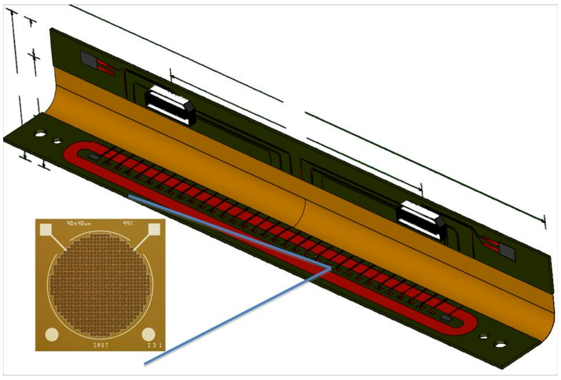

Figure 3: Drawing of the precision PCB to which the SiPM are bonded

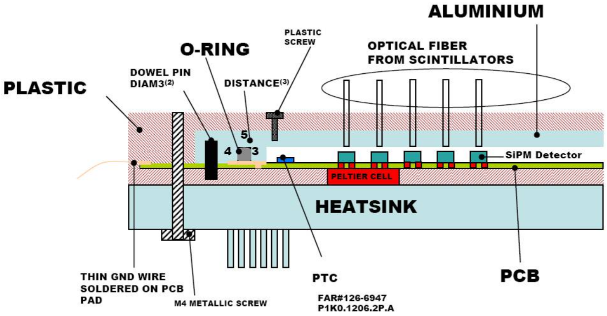

Figure 4: Schematic view of the final assembly of fiber connector and SiPM board

4. Data analysis principles

We intend to measure the volcano's mean density $\bar{\rho}(\theta, \phi)$ along an ideal line crossing the volcano at zenith and azimuth angles θ and ϕ with respect to the telescope position. The mean density can be obtained by measuring the absorption factor $A(\theta, \phi)$ directly from data. The observed number of muons $N_{\mu}^{obs.}(\theta, \phi)$ can be written as:

$$N_{\mu}^{obs.}(\theta, \phi) = N_{\mu}(\theta, \phi) \times (1 - A(\theta, \phi)) \times \epsilon(\theta, \phi) \tag{1}$$

where $N_{\mu}(\theta, \phi)$ is the muon flux impinging on the volcano and $\epsilon(\theta, \phi)$ is the detector efficiency. Performing special runs, pointing to free sky regions with the same angle θ but with a common phase ϕ_0, we can collect calibration data samples:

$$N_{sky}^{obs.}(\theta, \phi + \phi_0) = N_{\mu}(\theta, \phi + \phi_0) \times \epsilon(\theta, \phi) \tag{2}$$

In the limit of neglecting the ϕ dependence of the cosmic flux [11], which should not exceed 10%, we can evaluate the product $N_{\mu}(\theta, \phi) \times \epsilon(\theta, \phi)$ and then the absorption factor A. This quantity can be expressed as function of the critical energy $E_C(\theta, \phi, \bar{\rho})$, defined as the minimum energy for a muon to cross the volcano in the (θ, ϕ) direction. E_C depends on the volcano thickness $d(\theta, \phi)$, which is precisely measured and available in digital elevation maps, and the average density $\bar{\rho}$ that we want to measure. To extract this information we need to rely on the probability distribution function $f(E, \theta)$ of the muons, which depends on two main parameters: energy and zenith angle θ, and can be computed using the Thompson and Whalley expression [12]. Then the absorption factor can be written as:

$$A(\theta, \phi, \bar{\rho}) = \int_0^{E_C} f(E, \theta)\, dE \tag{3}$$

Comparison of the measured and the expected value of A allows determining the mean density $\bar{\rho}$ along the $\theta - \phi$ direction.

5. Summary

The MU-RAY project aims at the construction of a new generation of muon telescope, designed for muon radiography of volcanoes. Motivation and detector base-line as well as the measurement principles have been presented.

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