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The MU-RAY experiment. An application of SiPM technology to the understanding of volcanic phenomena

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ABSTRACT

The purpose of the MU-RAY project is to develop an innovative approach to the study of volcanoes and their monitoring based on a particle physics approach. The test site is Vesuvio: one of the higher risk volcanoes in the world. In this context, muon radiography is an innovative method of enormous impact. This is an imaging technique which relies on the measurement, by means of a cosmic ray telescope, of the absorption in the volcano of muons with near-horizontal trajectories, produced by the interactions of cosmic rays with the atmosphere. Since 2003 this technique has been successfully used on volcanoes in Japan, providing pictures of their vertices with resolutions much better than those obtained with the traditional techniques based on gravimeters. Researchers from Naples and Florence are currently involved in the construction and testing of a prototype telescope based on the use of bars of plastic scintillator with a triangular section whose scintillation light is collected by special fibres (wave length shifters) and transported to SiPM (Silicon photomultipliers). A complete prototype telescope, consisting of three *xy* scintillation planes and 1 m^2 active area has been assembled and is now under test.

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1. Introduction

Muon radiography is an imaging technique to measure density variations within a volcanic cone down to a depth of hundreds of metres.

In optimal conditions with sufficient statistics one can expect to obtain resolutions of the order of 10 m. These compare very favorably with what can be obtained by traditional gravimetric techniques. If these goals can be achieved, this type of measurement can provide significant complementary information on eventual anomalies in the rock density (i.e. like those given by the presence of lava conduits).

In fact, particle showers are created from the interaction of primary cosmic rays with the nuclei of the earth's atmosphere in a way similar to what shown in Fig. 1. In practice only muons survive at ground level (together with a small fraction of electrons and protons that are not relevant to this application). Of these, only the near horizontal component is useful for muonic radiography as evident form the schematic shown in Fig. 2. Unfortunately horizontal muons have very low rates thus relatively large detectors are needed to collect a meaningful sample of events in a reasonable time (i.e. weeks to months).

Once the data is acquired, a precise knowledge of the morphology of the terrain under investigation is required to reconstruct the

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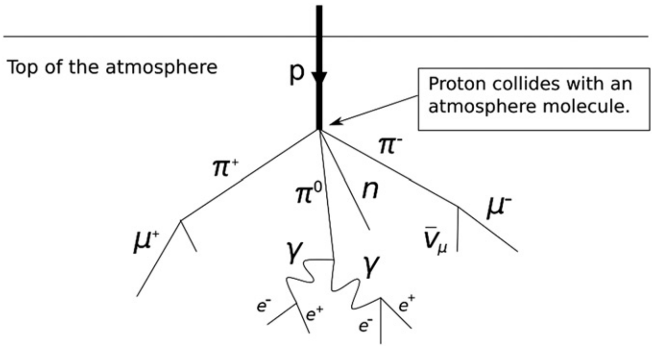

Fig. 1. Schematic drawing of a primary cosmic ray interaction with the earth's atmosphere. Muons are the main shower component reaching the earth's surface.

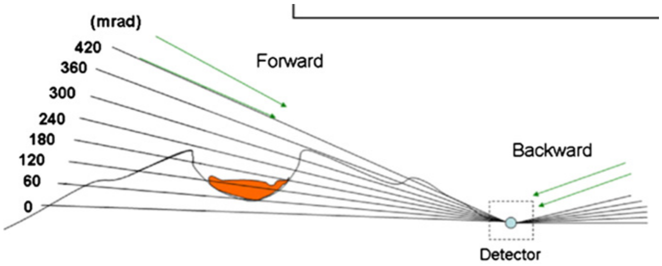

Fig. 2. Principle of muonic radiography. Near horizontal muons are absorbed by the volcano depending on the total rock in front of the detector. Backward flux is used for normalization.

rock density variation along the muons line of sight. This procedure can result in a spectacular rendering of the volcanic cone as shown by Tanaka et al. [1]

2. The MU-RAY telescope

A muon hodoscope for volcanic reconnaissance must satisfy many requirements of which these are the most important:

1. a tracking capability such as to determine the direction of muons with relatively high spatial/angular resolution (few millirads),
2. uniformity of response across m^2 surfaces,
3. redundant background suppression capability (i.e. TOF and/or three planes of detection),
4. low cost per channel (which translates in a larger telescope area and/or higher resolution),
5. rugged and modular structure for usage in volcanic area,
6. low energy consumption (again for usage in volcanic area where no external power supply exists),
7. electronics and sensors must perform from below zero to 50–60 °C (again for usage in volcanic area).

For example showers of charged particles created in the atmosphere can mimic a straight track if only two planes of detection are used. Thus one should use at least three planes, and increase the resolution. Also at low angle re-scattered "albedo" muons coming from the opposite direction (where there is no volcano) can mimic a frontal muon, so one should measure the Time Of Flight (TOF) and discriminate between the two.

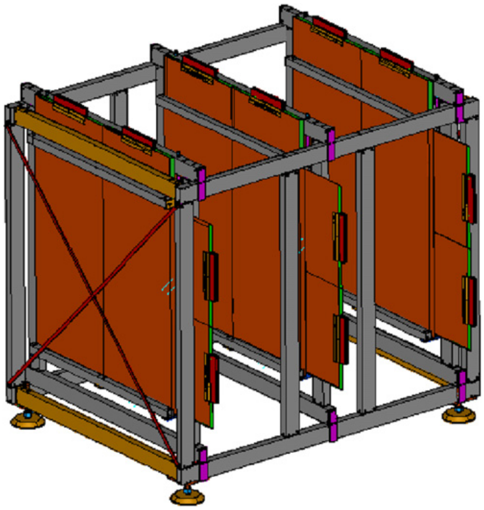

Fig. 3. Schematic drawing of the Mu-Ray telescope with its three *XY* detector planes held in an aluminium cage. Each plane consists of two *X* and two *Y* modules with 32 fibres (100 cm by 50 cm) each weighing 17 kg.

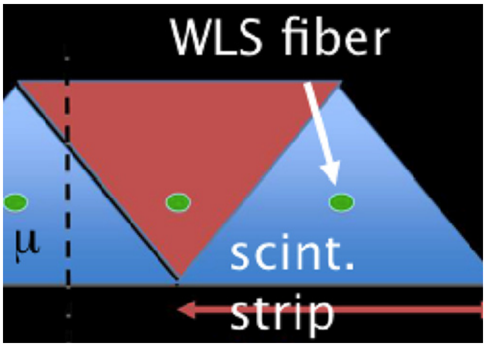

Fig. 4. Thanks to the triangular profile of the scintillators, the muon intersection can be precisely measured as the ratio of light output between two scintillators.

The Mu-Ray project addresses all of these requirements in an original manner [2]. In fact several solutions originally proposed by Mu-Ray are nowadays "standard" design practice for proposed detectors in the muon tomography field: i.e. at least three planes, each with *X* and *Y* measurement, and azimuthal rotation for flux calibration.

TOF is still unique to Mu-Ray, due to its unique time resolution which allows to distinguish the direction of the detected muons.

The Mu-Ray telescope consists of three *X*–*Y* stations of 1×1 m^2 sensitive area (Fig. 3), divided into 12 modules easy to transport and to assemble on a volcano shoulder. Each module is built with 1 m long triangular plastic scintillator bars (emission time $\simeq 3$ ns, polystyrene produced NICADD_FNAL by extrusion with 0.25 mm TiO_2 coating and a ~ 1.8 mm hole), coupled to a fast wavelength shifting (WLS) fibre (BCF92 multi-clad, fast emission time, $\simeq 2.7$ ns, mirrored at one side) for photon collection, following the scheme of Fig. 4. The light output is then converted in an electrical signal by Silicon Photo Multipliers (SiPM).

SiPMs are a relatively new concept in light detection. They consist of an array of APD cells working in self-quenching Geiger mode, highly miniaturized and integrated. They offer a higher light detection efficiency and a gain comparable to traditional PMTs. Typical photo-detection efficiencies range from 10% to 60%, with gains of the order 10^6. They are capable of single photon detection sensitivity, are very fast ($\simeq 1$ ns rise time) and thus capable of very good time resolution (< 100 ps). Also they only need low bias voltages (< 100 V) and have very low power consumption (10 μW).

The SiPM used for the first Mu-Ray prototype was produced by FBK-IRST (see Fig. 5) and is an extremely compact and robust device with a circular active area of 1.4 mm diameter, a pixel size of 70 μm^2 (number of pixels: 292). The bare die is covered with a

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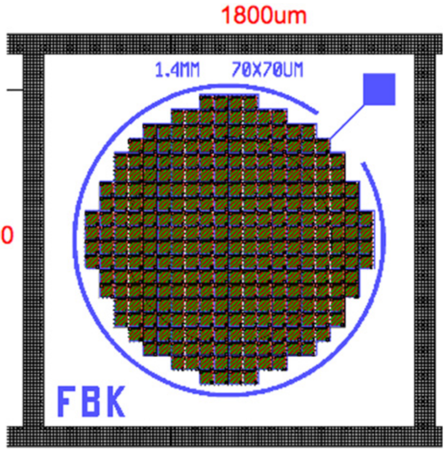

Fig. 5. Schematic layout of the FBK-IRST SiPM used for the Mu-Ray prototype.

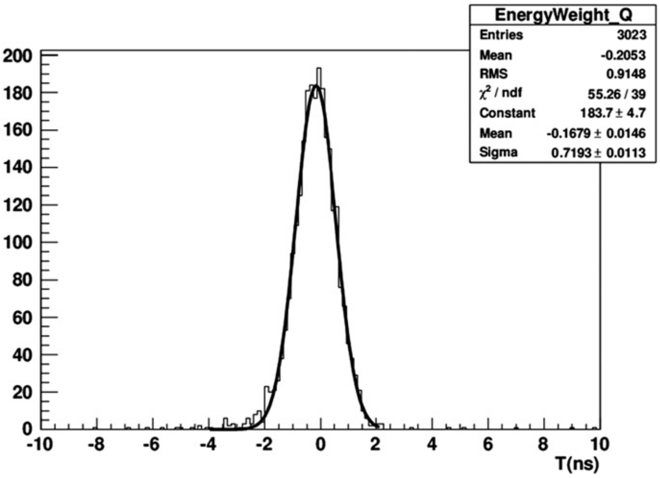

Fig. 6. TOF resolution obtained with a system identical to the one used by Mu-Ray but with Hamamatsu SiPMs (MPPC S10362 13-50C).

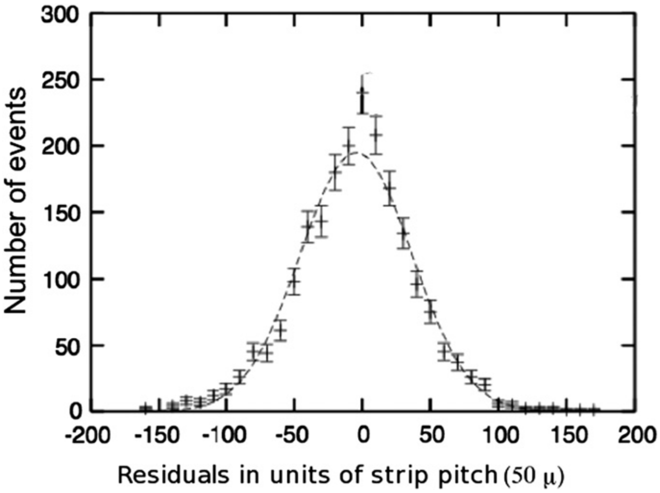

Fig. 7. Spatial resolution obtained with the triangular scintillator bars, as measured with the help of a silicon microstrip tracker. The σ is less than 2.5 mm.

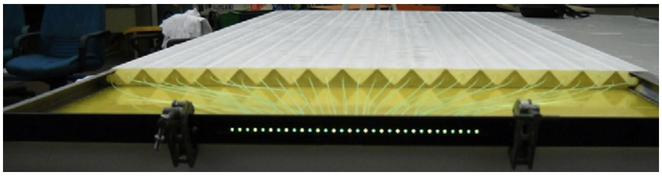

Fig. 8. Photo of an assembled module. The 32 fibres are collected in one single precision machined connector.

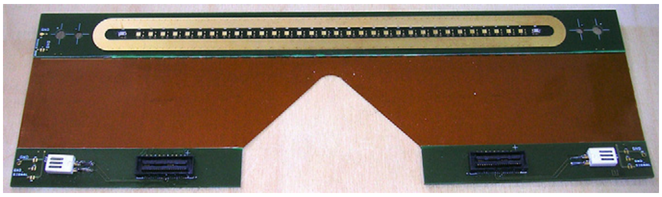

Fig. 9. Photo of the SiPM carrier hybrid. The SiPMs are glued (conductive) on the square pads and then bonded. On the hybrid there is also place for temperature and humidity sensors.

thin transparent protective epoxy layer (35 μm thick). The Mu-Ray system of light collection and detection is quite performant and well adapted to its needs. Laboratory tests performed by our group indicate that a TOF resolution of 700 ps and a spatial resolution of 2.5 mm can be obtained as demonstrated by Figs. 6 and 7 respectively.

Twelve modules were constructed in spring 2011. Each module, see Fig. 8, consists of 32 scintillator bars glued on a G10 plate. The 32 WLS fibres are precut to the required length and a reflective coating is sputtered on one end. The fibres are glued inside the scintillator and the other ends are grouped and glued to a precision moulded connector cap. This connector is then plugged to the hybrid carrying the SiPMs of which more will be said later. The alignment precision is better than 50 μm and the fibre depth is also controlled to the same precision.

2.1. Hybrid carrier

The Mu-Ray collaboration has developed a carrier hybrid in kapton and G10 on which 32 SiPMs are glued and bonded. The hybrid is mechanically pressed against the fibre connector and allows the optical connection of 32 SiPMs in one go. A photo of the naked hybrid is shown in Fig. 9). SiPM breakdown voltage and dark rate depend strongly on temperature. Mu-Ray implements two possible approaches to the temperature dependance. One is to keep SiPM the temperature fixed (e.g. using Peltier cells) while the other, as shown later, is to routinely compensate the temperature drift by changing the Bias voltage to keep ($V_{\mathrm{bias}} - V_{\mathrm{break}}$) fixed. In this respect the hybrid was optimized for efficient heat (cold) transfer from a heat sink placed underneath the hybrid to the surface on which the SiPMs are mounted. As shown in Fig. 10 many blind vias connected to the bottom cold surface were added just under the SiPMs.

In the final implementation Peltier cooling should keep the SiPMs at 10–15 °C even with outside temperatures in the 30–40 °C range. Apart from working at a temperature within 15–20 °C below ambient temperature which also keeps dark counts at a manageable level, residual variations are then compensated by changing V_{bias}. Thus a full characterization of the SiPMs V_{break} has been obtained (see Fig. 11) for at least for one value of temperature (the slope is almost the same for all sensors). Also, as stated in the next section, each SiPM has its own independent biasing DAC.

2.2. DAQ board and SPIROC chip

The DAQ board (Fig. 12), designed by the Servizio di Elettronica in Naples, allows full acquisition of the signals from one module. Logic functions are implemented in a XILINX Spartan FPGA, and the heart of the board is a SPIROC (LAL-Orsay) chip [3]. The board has a time expansion TDC. A board with a PIC to control

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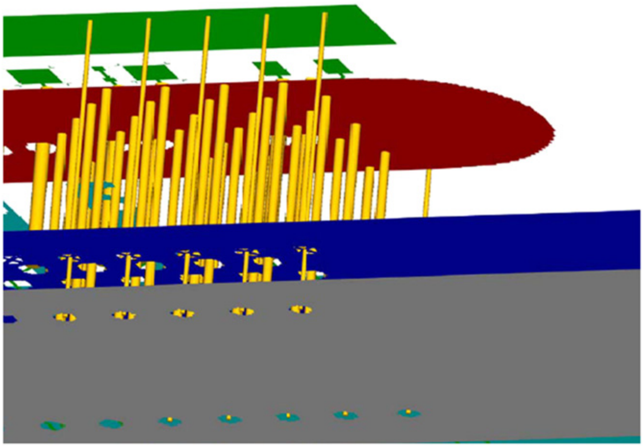

Fig. 10. 3D view of the hybrid layers. Note the amount of blind vias which connect the bottom cold surface (grey) with the copper cold plate 50 μm underneath the SiPMs.

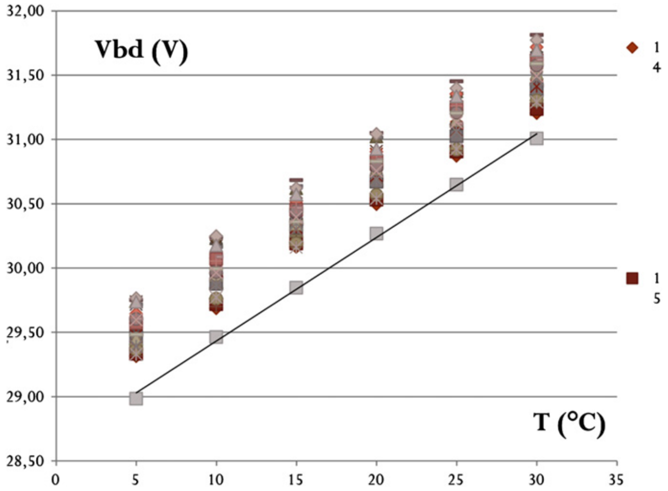

Fig. 11. Measured V_{break} for the 32 SiPMs on one of the hybrids as a function of temperature. All devices show the same dependance (80 mV/°C).

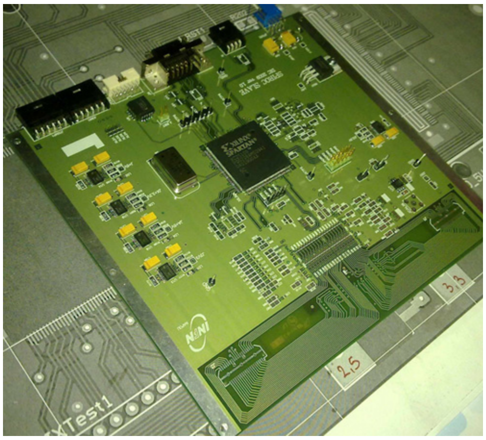

Fig. 12. Photo of the slave DAQ board. One board is capable of controlling 32 SiPMs.

temperatures (and other slow parameters) acts as Master and Trigger provider. All the SLAVEs (4 × 3 for the full telescope) work in RUN mode, i.e. until a trigger is produced the FPGA clock is OFF and all the logic is combinatorial and power consumption is limited. Power consumption is about 1.5 W/slave board (3 W for the Master). The assembled planes (see Fig. 13) were then fixed to the support structure into a complete hodoscope capable of tilting to 90°. With the telescope pointing to the azimuth cosmic ray tracks were reconstructed and using the three planes an efficiency curve was obtained as a function of the SPIROC DAC voltage bias for the SiPM.

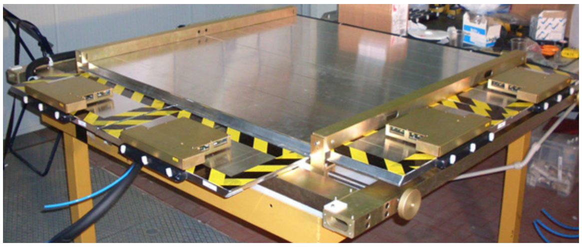

Fig. 13. Fully assembled plane consisting of four basic modules. The external aluminium serves as light shield. The DAQ boards sit on top of each plane in a brass box. Communications are handled through short length LVDS cables.

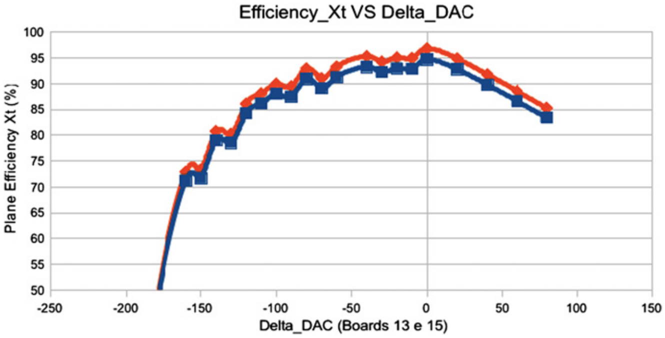

Fig. 14. Efficiency curve for a single plane of the Mu-Ray telescope as a function of SiPM bias (SPIROC DAC). A plateau of 95% is reached.

The SPIROC chip allows each SiPM to have an independent bias voltage thanks to a dedicated 8 bit DAC (0–5 V) for each channel. First the comparator threshold (common to all 32 channels) was set at a reasonable value then each individual biasing DAC was adjusted so as to have a 1–3 kHz counting rate for every single SiPM.

This defines the starting point from which the efficiency curves were obtained. First lowering the bias below the nominal value, and then increasing it. As shown in Fig. 14, the values obtained are above 95% notwithstanding the Dark Count rate (10 MHz or more) at room temperature.

3. Conclusion

The Mu-Ray telescope concept (MNT2012 workshop (Clermont Ferrand-France)) has now become the basis for new proposals in the field of Muon Radiography. This field is truly interdisciplinary and apart the obvious scientific interests involves also civilian protection and mineralogy interests. Our group is in the final stages of testing the 1 m^2 prototype and plans are ahead for a new production run of SiPMs at IRST. Also the SPIROC based FE board will be replaced by a newer and more functional one based on the EASIROC chip. Four 1 m^2 modules will be the next step the goal is a 10 m^2 modular structure for "real time" and/or stereoscopic observations.

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